Using poststratification to improve abundance estimates from multispecies surveys: a study of juvenile flatfishes

Sherri C. Dressel

Brenda L. Norcross

Institute of Marine Science
School of Fisheries and Ocean Sciences
University of Alaska Fairbanks
245 O'Neill Building
Fairbanks, Alaska 99775-7220
Present Address (for S. C. Dressel): Alaska Department of Fish and Game
Commercial Fisheries Division
802 3rd Street
P.O. Box 240020
Douglas, Alaska 99824-0020
E-mail address (for S. C. Dressel): sherri_dressel@fishgame.state.ak.us

Abstract—Population assessments seldom incorporate habitat information or use previously observed distributions of fish density. Because habitat affects the spatial distribution of fish density and overall abundance, the use of habitat information and previous estimates of fish density can produce more precise and less biased population estimates. In this study, we describe how poststratification can be applied as an unbiased estimator to data sets that were collected under a probability sampling design, typical of many multispecies trawl surveys. With data from a multispecies survey of juvenile flatfish, we show how poststratification can be applied to a data set that was not collected under a probability sampling design, where both the precision and the bias are unknown. For each of four species, three estimates of total abundance were compared: 1) unstratified; 2) poststratified by habitat; and 3) poststratified by habitat and fish density (high fish density and low fish density) in nearby years. Poststratification by habitat gave more precise and (or) less design-biased estimates than an unstratified estimator for all species in all years. Poststratification by habitat and fish density produced the most precise and representative estimates when the sample size in the high fish-density and low fish-density strata were sufficient (in this study, $n \geq 20$ in the high fish-density stratum, $n \geq 9$ in the low fish-density stratum). Because of the complexities of statistically testing the annual stratified data, we compared three indices of abundance for determining statistically significant changes in annual abundance. Each of the indices closely approximated the annual differences of the poststratified estimates. Selection of the most appropriate index was dependent upon the species' density distribution within habitat and the sample size in the different habitat areas. The methods used in this study are particularly useful for estimating individual species abundance from multispecies surveys and for retrospective studies.

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Scientists must be able to assess population abundance with a high degree of confidence to achieve the goals of fishery management (Quinn, 1985). To do this, survey designs and estimation methods that minimize the variance in estimates of abundance are needed. Recently, the National Research Council (NRC, 2000) recommended incorporating habitat information and commercial fisheries data in population assessments. Both of these data may result in lower variances in estimates of abundance.

Habitat type and habitat quality are becoming more widely recognized as primary determinants for the distribution and survival of marine fish species (Murawski and Finn, 1988; Gadomski and Caddell, 1991; Reichert and van der Veer, 1991; Norcross et al., 1999). Until recently, however, few studies have been directed toward defining fish habitat or using habitat associations to help decrease the variability in abundance estimation (Scott, 1995). In response to the growing recognition of the importance of habitat, the Magnuson-Stevens Fishery Conservation and Management Act was amended in 1996 (Public Law 104–297) so that the National Marine Fisheries Service (NMFS) and regional fishery management councils must describe and identify essential fish habitat (EFH) for managed species. Similarly, a recent report from the NRC calls for methods that link environmental data to stock assessments (NRC, 2000).

Poststratification can be used in a number of different ways to address the NRC recommendations. Although poststratification is not a new statistical method, it is one that is not commonly used for estimating groundfish population abundance and can be used to meet these newly defined challenges. In contrast to a stratified sampling design, poststratification is a method that allocates samples to strata after they have been collected. As a result, habitat data collected during a survey can be used for stratification. When poststratification is applied to data that have been collected under a simple random sampling design, the poststratification estimator is unbiased and may produce more precise estimates than those from a simple random sampling estimator. Poststratified estimates will be nearly as precise as stratified sampling with proportional allocation, in which the sample sizes in each stratum are proportional to stratum sizes, if stratum sample sizes are large ($n>20$) and errors in estimates of strata areas are negligible (Cochran, 1977; Pollock et al., 1994;

Scheaffer et al., 1996). If poststratification is applied to data from a multispecies survey, 1) abundance data for each species can be poststratified with different habitat variables or 2) abundance data for every species can be poststratified with the same variables, but different stratum boundaries can be used for each species.

Many large-scale multispecies groundfish surveys are conducted by using a stratified random sampling design (Azarovitz, 1981; Halliday and Koeller, 1981; Pitt et al., 1981; Martin[1]; Weinberg et al.[2]). Depth, distance from or along shore, latitude, distance along depth contours, or broad geographic features (such as bays, capes, banks, gullies, and slopes) are used as stratum boundaries in trawl surveys because they have been shown to be related to species distributions. These factors are fixed spatially, allowing samples to be allocated to strata prior to sampling. The same boundaries are used for all species, and boundaries generally remain the same over years.

When conducting a multispecies survey with a stratified random sampling design, optimal stratification for one species may not be optimal for others (Koeller, 1981; NRC, 2000). Because the placement of strata boundaries is critical for precise stratified estimates (Cochran, 1977), use of a stratified sampling design for a multispecies survey may result in only small gains in precision for some or all species. Poststratification is possible for data that have been collected under a stratified design. It can be used to stratify data more finely for individual species. Under stratified random sampling, a simple random sample is taken in each stratum. Thus, data within each stratum can be poststratified separately with additional variables and the abundance estimates from each of the strata can be summed. The resultant estimator is unbiased and likely will be more precise than that of the original stratified design if sample sizes in poststratified strata are large enough.

Often, researchers need to estimate abundance from data sets that were not recorded under a probability sampling design (a design in which randomness is built into the survey design, such as simple random sampling or stratified random sampling). Finances and logistics, for example, may make it impossible to collect data under a probability sampling design, researchers may want to estimate species abundance from commercial fisheries or other nonsurvey data, or previously collected data sets that were not recorded under a probability sampling design may be used for retrospective studies. In this article, we refer to data collection without a probability sampling design as "haphazard sampling." The use of haphazardly collected data for estimating abundance is undesirable because they cannot be evaluated by the theorems of probability theory (Krebs, 1989). Although undesirable, it is often necessary to analyze haphazardly collected data and effective methods are needed to do so.

Poststratification can be applied to data that were not collected with a probability sampling design. When poststratification is applied to data not collected under a probability sampling design, the poststratification estimator, a design-based estimator, may be biased. When analyzing such data, it is important both to maximize the precision and to minimize the bias. Poststratification has been applied to nonprobability samples in other studies to increase the precision (Hall and Boyer, 1988) and decrease the bias of estimators (Buckland and Anganuzzi, 1988; Hall and Boyer, 1988; Anganuzzi and Buckland, 1989).

Poststratification can be useful, but has some drawbacks. With poststratification, sample sizes within strata are random variables—which are an additional source of variability over that of a stratified sampling variance estimator (Thompson, 1992; Scheaffer et al., 1996). The variance of a poststratified estimator can be estimated by using standard stratified sampling variance equations and by incorporating an additional approximate term to account for the random sample sizes present with poststratification (Scheaffer et al., 1996). Alternatively, the variance of a poststratified estimator can be estimated by conditioning on samples sizes and by applying the standard stratified sampling variance equation (Thompson, 1992). For accurate poststratification estimates, the proportion of total possible samples in each stratum (for this study the proportion of the total survey area included in each stratum) must be known or approximated closely enough that the error in the approximation is negligible (Cochran, 1977). Error in estimates of stratum sizes causes bias in poststratified estimates of abundance. Because error in the estimation of stratum size is unaccounted for in the estimated variance of poststratified estimates, the estimated variances may be underestimates of the true error (Cochran, 1977).

This study had two goals. The first goal was to evaluate the benefits and drawbacks of using poststratification to incorporate habitat and fish-density information into estimates of abundance from multispecies survey data that were not collected under a probability sampling design. To achieve this goal, this study compared three estimates of total abundance and variance (unstratified, poststratified by habitat, poststratified by habitat and estimates of fish density in neighboring years) for each of four species. The comparison was made to determine whether poststratification of haphazardly sampled data with habitat and fish-density information increases the precision and helps account for possible bias in abundance estimates.

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[1] Martin, M. H. 1997. Data report: 1996 Gulf of Alaska bottom trawl survey. NOAA Tech. Memo. NMFS-AFSC-82, 235 p. National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161.

[2] Weinberg, K. L., M. E. Wilkins, R. R. Lauth, and P. A. Raymore jr. 1994. The 1989 Pacific west coast bottom trawl survey of groundfish resources: Estimates of distribution, abundance, and length and age composition. NOAA Tech. Memo. NMFS-AFSC-33, 168 p., plus appendices. National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161.

Because this study is an observational study with haphazard sampling, the precision and bias cannot be directly assessed. Instead, we estimated and compared the precision by using unstratified and poststratified estimators. We qualitatively estimated the relative amount of design bias (i.e., how representative the estimates are) with the use of habitat. In previous studies (Norcross et al., 1995; 1997; 1999), depth and sediment were identified as habitat characteristics closely associated with the distribution of the four species in this study. From depth, sediment, and fish abundance data collected in this study we were able to identify ranges of habitat characteristics associated with areas of high, low, and no fish density. By estimating the proportion of area (km^2) in the study area characterized by the ranges of depth and sediment, it was possible to estimate the proportion of the survey area with high, low, and no fish density. Because samples in our study were not randomly allocated, the probability of selection was not equal among all samples in the survey area. The resulting numbers of samples taken in areas of high, low, and no fish density were not in proportion to the size (km^2) of those areas as it would have been with repeated simple random sampling. Therefore, by comparing the relative size of high, low and no fish-density areas in the survey area with the relative number of samples in those areas, we made qualitative estimates of the design bias associated with the estimators. Although an assessment of the relative amount of design bias made in this way is only an approximation, it is helpful when using haphazardly collected data in order to provide some indication of the amount of design bias based on the disproportion of samples in an area to the size of that area.

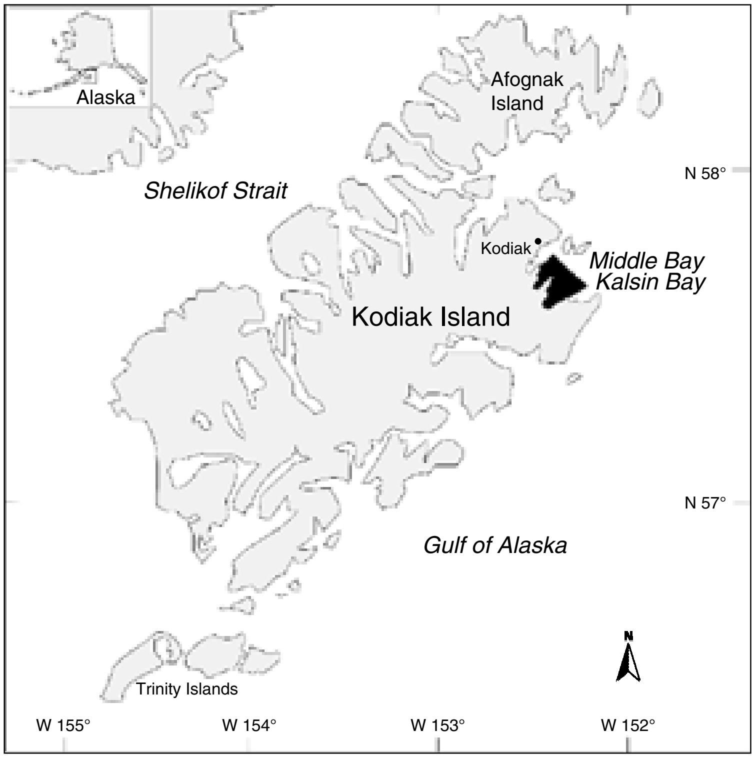

Figure 1

Study area (in black) in Middle and Kalsin Bays, Kodiak Island, Alaska.

Because of the complexities of statistically testing the annual stratified data, the second goal of our study was to develop indices of abundance that closely approximated the annual differences of poststratified estimates and that could easily be tested for statistically significant changes between years. To achieve the second objective, three indices of annual relative abundance were constructed and compared with respect to their estimated relative precision and design bias: one from all sites in the survey area, one from all sites within the species' habitat, and one from all sites within an area of high fish density within the species' habitat.

The data for this study were obtained from six years of juvenile groundfish surveys conducted in Kalsin Bay and Middle Bay, Kodiak Island, Alaska. The four species studied were age-0 rock sole (*Lepidopsetta* spp.), age-1 yellowfin sole (*Pleuronectes asper*), age-0 Pacific halibut (*Hippoglossus stenolepis*), and age-0 flathead sole (*Hippoglossoides elassodon*). The survey data were collected during the six-year survey under three different survey designs, none of which were strictly randomized, but each involved some degree of haphazard sampling due to weather, sediment structure, and other logistical restrictions for beam trawling in small bays off the Gulf of Alaska (Norcross et al.[3]). Although many trawl survey data sets to which these methods could be applied are collected under a probability sampling design where the estimator is unbiased, the haphazardly collected data set used in our study was chosen to show how poststratification can be applied when both the precision and the bias of the estimator are unknown.

Methods

Sampling

Middle and Kalsin Bays are part of Chiniak Bay, 10 nmi south of the town of Kodiak, Alaska. The total size of the study area, 87 km^2, included the combined areas of both bays and the areas directly outside the mouths of the bays (Fig. 1). Middle Bay is 8 km long and has depths of 50 m at the mouth of the bay and an area of 21 km^2. Kalsin Bay is 8 km long, has depths greater than 100 m

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[3] Norcross, B. L., B. A. Holladay, A. A. Abookire, and S. C. Dressel. 1998. Defining habitats for juvenile groundfishes in Southcentral Alaska with emphasis on flatfishes. Vol. I, Final Study Report, OCS Study MMS 97-0046, 131 p. Coastal Marine Institute, Univ. Alaska Fairbanks, Fairbanks, AK 99775.

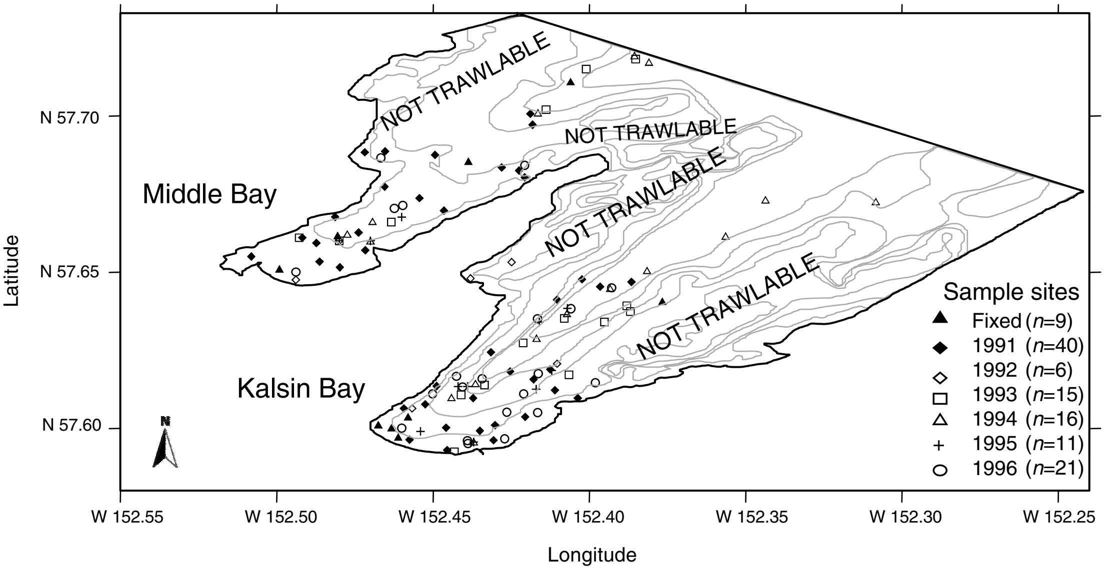

Figure 2

Kalsin and Middle Bay sample sites (1991–96) and bathymetry. Fixed (sampled every year) sites are noted.

at the mouth of the bay, and encompasses an area of 34 km^2. Rocky cliffs and islands surround the mouths of the bays, and rocks in the sediment made several areas untrawlable (Fig. 2). Although trawling was not conducted in these areas, depth and sediment data were collected. In this analysis, untrawlable areas were still considered possible flatfish habitat and were included in the measurements of the size of the total study area.

Annual cruises were conducted in Middle and Kalsin Bays for two weeks in August from 1991 to 1996. Juvenile flatfish were collected by using 3.05 and 3.66 m plumb-staff beam trawls (Gunderson and Ellis, 1986). Trawl nets were made of 7-mm square net mesh and had a 4-mm codend liner that retained flatfish as small as 11 mm. Sampling methods were consistent for all six years (Norcross et al., 1995; Norcross et al.[3]). Collections at each sample site included a tow of 10 minutes or less, a vertical CTD (conductivity, temperature and depth) cast, and a sediment grab (0.06-m^3 Ponar grab). The sampling area of each tow was determined by the width of the beam trawl, which was 0.74 of the beam length (Gunderson and Ellis, 1986), and distance towed was based on global positioning system (GPS) coordinates. Fish were identified to the lowest possible taxon and measured to the nearest millimeter total length. At the time of collections, all rock sole were identified as *Pleuronectes bilineatus.* Following Orr and Matarese's (2000) revision of the genus, we refer to these fishes as *Lepidopsetta* spp. in this article because both species, *L. bilineata* and *L. polyxystra*, were identified in the study area during 1996 sampling. Fish ages were determined by length-frequency analysis. Fish catch-per-unit-of-effort (CPUE) values were standardized to a 1000-m^2 tow area.

Sampling designs varied from year to year (Norcross et al.[3]). Extensive exploratory sampling was conducted from 1991 through 1994 to describe juvenile flatfish distributions in relation to habitat characteristics (Norcross et al., 1995; 1997). The goal in these years was to sample over the widest range of areas and habitat characteristics possible within the depth, sediment, weather, and logistical constraints. In 1995 and 1996, sampling was stratified by depth and percent sand in sediment. The sample allocation and the number of strata differed in 1995 and 1996 (Norcross et al.[3]). Because of logistical constraints, samples were not randomly allocated within each stratum. Within these sampling designs, nine fixed sites were chosen, each with different depth and sediment combinations and with high abundances of one of the four species. Each of the nine fixed sites was sampled at least once in each of the six years. For this study, survey data in each year were treated as unstratified samples that were not collected under a probability sampling design.

Analysis

Poststratification Habitat preferences of juvenile flatfishes, as defined by depth and sediment variables, have been identified as affecting the distribution and abundance of juvenile flatfish around Kodiak Island (Norcross et al., 1995; 1997; 1999; Mueter and Norcross, 1999) and elsewhere (Pearcy, 1978; Tanda, 1990; Burke et al., 1991; Rogers, 1992; Walsh, 1992). Four areas were defined for use in estimating total and relative abundance: habitat, nonhabitat, high fish-density (HFD) and low fish-density (LFD) areas. Percent sand was used as a continuous variable of sediment type. Suitable habitat (habitat area) was defined for each species as ranges of depth and percent sand in which the species was caught during one or more of the six sampling years. Unsuitable habitat (nonhabitat area) was defined for each species as ranges of depth and percent sand in which the species was never caught. Within the habitat area, the area of high fish density for each year was defined as ranges of depth and percent sand associated with CPUEs in the 75th–100th percentile of nonzero catches in the five other years. The area of low fish density was defined as the remaining habitat area not incorporated in the HFD area.

In order for the poststratification method to estimate abundance accurately (high precision and low bias), the size of each stratum must be known or closely approximated (Cochran, 1977; Scheaffer et al., 1996). When using habitat variables to determine stratum sizes, the accuracy of stratum sizes defined by the boundaries is heavily dependent upon the number and distribution of habitat variable measurements. For our study, 243 depth and percent sand measurements collected over the six years at trawl locations were used to determine stratum boundaries. The ranges of depth and percent sand that defined the four areas for each species were contoured over the study area by using a minimum curvature algorithm (Surfer, 1995). The size of each stratum in relation to the size of the entire study area was then visually estimated to the nearest square kilometer. Although not used in our study, a digital representation of the size of each stratum and the size of the study area is recommended to produce more precise estimates.

To assess the advantages and disadvantages of using poststratification to estimate abundance, three estimates of total abundance were calculated and compared for each species in each year. An unstratified estimate of total abundance was calculated from samples across the entire survey area, with no differentiation with regard to habitat. The unstratified estimate of total abundance was calculated with the standard simple random sampling equation

$$\hat{\tau} = N\bar{y},$$

where $\hat{\tau}$ = the estimated population total;
N = the total number of possible samples in the survey area; and
$\bar{y}$ = the mean CPUE of all sites sampled in a year.

The estimated variance for the unstratified estimator was calculated as

$$\hat{V}(\hat{\tau}) = N^2\left(\frac{s^2}{n}\right)\left(\frac{N-n}{N}\right),$$

where $\hat{V}(\hat{\tau})$ = the estimated variance of the population total estimate;
N = the total number of possible samples in the survey area;
n = the total number of samples taken; and
s^2 = the sample variance.

The estimate poststratified by habitat was calculated as

$$\hat{\tau}_{st} = \sum_{i=1}^{L} N_i \bar{y}_i,$$

where $\hat{\tau}_{st}$ = the estimated population total;
L = the number of strata (here L=2, habitat and nonhabitat);
N_i = the total number of possible samples in stratum i (samples were standardized to 1000 m^2, therefore $N_i \times 1000\ \text{m}^2$=stratum size); and
$\bar{y}_i$ = the mean CPUE in stratum i.

A third estimate, poststratified by habitat and fish density, was calculated with the same poststratification estimator with L=3. This poststratification estimator used the HFD area of that year as one stratum, the LFD area of that year as the second stratum, and the nonhabitat area as the third. An approximate variance estimator (Scheaffer et al., 1996),

$$\hat{V}_p(\hat{\tau}_{st}) = \frac{N(N-n)}{n}\sum_{i=1}^{n}\frac{N_i}{N}s_i^2 + \frac{N^2}{n^2}\sum_{i=1}^{n}\left(1-\frac{N_i}{N}\right)s_i^2,$$

was used to estimate the variance of each poststratification estimator,

where $\hat{V}_p$ = the estimated poststratified variance of $\hat{\tau}_{st}$, the estimated population total;
N = the total number of possible samples in the survey area;
n = the total number of samples taken;
N_i = the total number of possible samples in stratum i; and
s_i^2 = the sample variance in stratum i.

The first term of the variance equation is the variance of a stratified sample mean under proportional allocation. The second term shows the amount of increase in variance expected from post- rather than prestratification (Scheaffer et al., 1996).

Relative efficiency statistics were calculated for pairwise comparisons of the precision of the unstratified and the two poststratified estimates. Pairwise comparisons of the estimates were made for each species in each year. Relative efficiency was calculated as

$$R.E. = \frac{V_A}{V_B},$$

where V_A represents the variance of an unstratified estimate or a stratified sample with fewer strata than the estimate of variance represented by V_B.

The variance of an estimate is directly affected by the sample size (Zar, 1996). In our study, three total abundance estimates and their respective variances were calculated and compared for each of the 24 species-year combinations. One of the three total abundance estimates was most precise for each of the species-year combinations. For each species-year combination, the habitat stratum sample size (used in the estimate poststratified by habitat), the HFD stratum sample size, and the LFD stratum sample size (both used in the estimate poststratified by habitat and fish density) were plotted in relation to the total abundance estimator that was most precise in order to investigate the influence of sample size on the relative precision of the three total abundance estimators.

Indices of abundance Three indices were constructed for each species in each year to determine interannual variations in relative abundance (mean CPUE): an all-site index, a habitat index, and a HFD index. For each species and year, the all-site index was the mean CPUE from all sites sampled. The habitat index was the mean CPUE from all sites sampled within the species' habitat area. The HFD index was the mean CPUE from all sites sampled within the species' HFD area.

CPUE values were not normally distributed and therefore the Kruskal-Wallis nonparametric analysis of variance test was used to test the three indices for each species' differences in mean CPUE among years. For species that showed significant differences (α=0.05), a Tukey HSD (honestly significant difference) multiple comparison test for unequal sample sizes was conducted to determine which years differed (α=0.05). The Tukey multiple comparison test was used because it is robust with respect to departures from population normality and homogeneity of variance (Keselman, 1976). The results for the three indices for each species were compared to see how the differences in estimating abundance with the three indices affected conclusions of significant differences in abundance between years.

Numerous sources of bias can affect estimators of abundance from survey data. The poststratification estimator and other design-based estimators may be biased when applied to data that were not collected under a probability sampling design, as done in the present study. For a qualitative estimate of possible design bias in the estimates, the annual proportion of sample sites in each stratum (habitat, nonhabitat, HFD, and LFD strata) were compared with the proportion of area (km^2) in that stratum. First, we compared the size of the habitat area, in relation to the size of the total survey area, with the number of samples taken in the habitat area, in relation to the number taken in the total survey area.

$$\frac{\text{Size of the habitat area}}{\text{Size of the total survey area}} : \frac{\begin{array}{c}\text{Number of samples taken}\\ \text{in the habitat area}\end{array}}{\begin{array}{c}\text{Number of samples taken}\\ \text{in the total survey area}\end{array}}$$

Second, we compared the size of the HFD area, in relation to the size of the total habitat areas, with the number of samples taken in the HFD area, in relation to the number taken in the total habitat area.

$$\frac{\text{Size of the HFD area}}{\text{Size of the habitat area}} : \frac{\begin{array}{c}\text{Number of samples taken}\\ \text{in the HFD area}\end{array}}{\begin{array}{c}\text{Number of samples taken}\\ \text{in the habitat area}\end{array}}$$

Recognizing that the distribution of individuals varied within and across strata, two measures were used to better understand the distribution of each species in each year. The proportion of zero catches (e.g., a "zero catch" for rock sole indicates a tow in which no rock sole were caught) and the mean CPUE of nonzero catches were calculated for each species in each year over four areas: the total survey area, the habitat area, the HFD area, and the LFD area.

Results

Fish CPUE statistics were calculated for a total of 244 quantitative tows over the six sampling years (Fig. 2) in habitats ranging from 1 to 111 m depth and from 0% to 99% sand. Based on compiled data from all six years, the habitat area for rock sole was defined by 1–84 m depth and 2–99% sand; for yellowfin sole, by 2–43 m depth and 24–99% sand; for Pacific halibut, by 2–27 m depth and 2–99% sand; and for flathead sole, by 12–87 m depth and 8–97% sand (Fig. 3). The HFD area, defined by depth and percent sand, was determined for each of the four species in each of the six years (Table 1, Fig. 3). Although the range of depth and the range of percent sand were determined independently in each year, they remained quite constant for each species over the six sampling years.

The size of habitat area in relation to total area ranged across species from 0.62 to 0.92 and, for each species, the proportion of habitat sites to total sites varied among years (Table 2). The proportion of sample sites in habitat to sample sites in the total survey area ranged from 0.88 to 1.00 for rock sole, 0.60 to 0.87 for yellowfin sole, 0.52 to 0.93 for Pacific halibut, and 0.29 to 0.67 for flathead sole. The relative number of samples taken in each species' habitat area exceeded the relative size of their habitat area (i.e., a positive disproportion of samples in habitat), except for rock sole in 1991 and 1994, yellowfin sole in 1993 and 1994, Pacific halibut in 1993 and 1994, and all years for flathead sole. On average, rock sole had a 5% positive disproportion of samples in its habitat area, yellowfin sole and Pacific halibut had an 11% positive disproportion of samples in their habitat area, and flathead sole had a 15% negative disproportion of samples in its habitat area.

The size of the HFD area in relation to habitat area, and the number of sites sampled in the HFD area in relation to the number sampled in the entire habitat area, varied over the six sampling years for each of the four species (Table 2). On average over the six years,

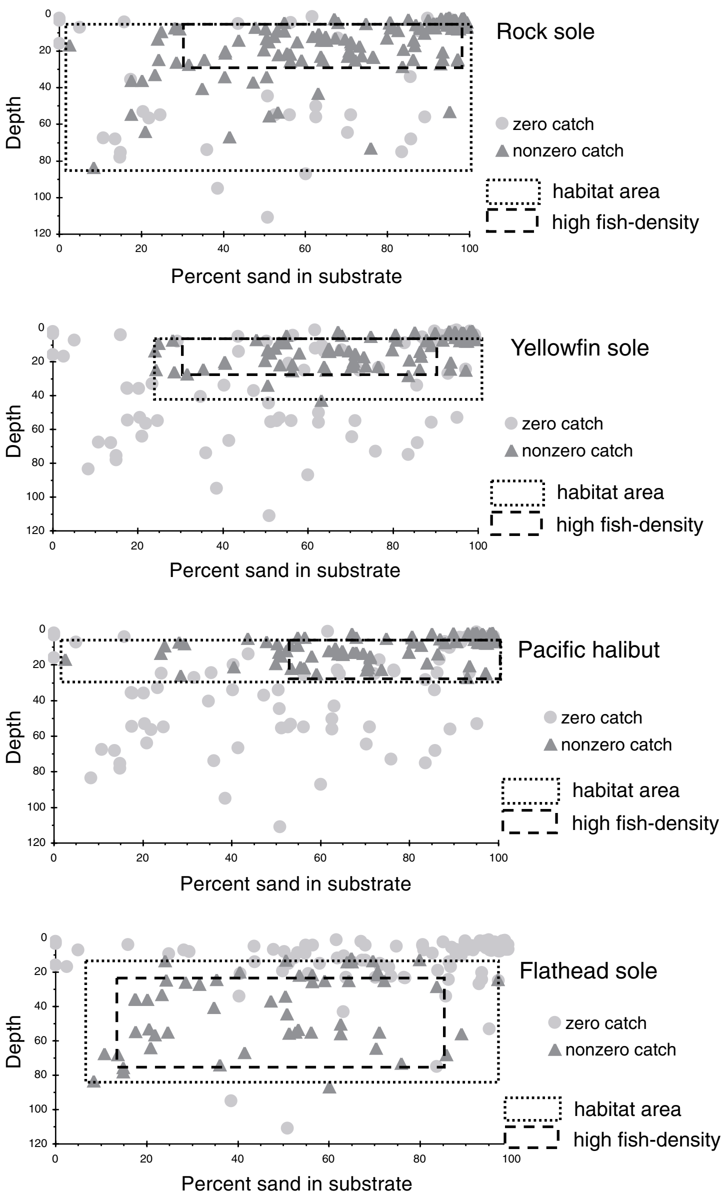

Figure 3

Summary of 1991–96 tows, in relation to depth and percent sand. Tows are divided into zero and nonzero catches for each species. The dotted line separates the depth and percent sand characteristics of habitat and nonhabitat areas. The dashed line separates the depth and percent sand characteristics of high and low fish-density areas within the habitat area.

rock sole had a 10% negative disproportion of samples in the HFD area, Pacific halibut had a 3% negative disproportion of samples in the HFD area, and flathead sole had a 28% negative disproportion of samples in the HFD area. For yellowfin sole, the average distribution of samples between the high and low fish-density areas was in direct proportion to the size of the areas, i.e., there was no disproportion of samples.

Two measures were used to characterize the distribution of a species within their habitat: the proportion of zero catches and the mean of nonzero catches in high and low fish-density areas. As expected, for all species the average proportion of zero catches over all sites was greater than the proportion of zero catches in the habitat or HFD areas (Table 3). For rock sole, yellowfin sole, and flathead sole, the average proportion of zero

Table 1

Characteristics defining 1991–96 high fish-density areas for each species of flatfish. Ranges of depth and percent sand, defining the high fish-density (HFD) area, and the associated spatial coverage within the bay (km^2). Each year's HFD area was determined as the range of depth and percent sand associated with the 75th–100th percentile of nonzero catch from the other five years.

		Depth (m)		Percent sand in sediment		
Species	Year	minimum	maximum	minimum	maximum	Size (km^2)
Rock sole	1991	3.0	27.3	31.5	99.2	52
(*Lepidopsetta* spp.)	1992	3.0	36.0	20.2	99.2	56
	1993	3.0	27.3	31.5	99.2	52
	1994	3.0	27.3	31.5	98.8	52
	1995	3.0	27.3	31.5	99.2	52
	1996	3.0	25.0	47.8	99.2	46
	average	3.0	28.3	32.4	99.2	52
Yellowfin sole	1991	1.7	23.0	40.5	98.6	33
(*Pleuronectes asper*)	1992	2.3	25.0	24.2	86.7	29
	1993	2.3	25.0	24.2	86.7	29
	1994	2.3	25.0	24.2	86.7	29
	1995	2.3	25.0	24.2	86.7	29
	1996	2.3	25.0	24.2	86.7	29
	average	2.2	24.7	26.9	88.7	30
Pacific halibut	1991	2.5	25.0	52.3	99.3	39
(*Hippoglossus stenolepis*)	1992	2.3	27.0	52.3	99.3	41
	1993	2.3	27.0	52.3	99.3	41
	1994	2.3	27.0	52.3	99.3	41
	1995	2.0	27.0	64.6	99.3	33
	1996	2.3	25.5	52.3	98.4	37
	average	2.3	26.4	54.4	99.1	39
Flathead sole	1991	19.8	87.0	17.4	89.1	42
(*Hippoglossoides elassodon*)	1992	25.5	87.0	10.7	89.1	38
	1993	19.8	87.0	8.4	70.7	34
	1994	19.8	67.5	10.7	89.1	40
	1995	19.8	87.0	17.4	89.1	42
	1996	19.8	64.0	17.4	89.1	39
	average	20.8	79.9	13.7	86.0	39

catches in the LFD area was higher than in the HFD area. For Pacific halibut, the average proportion of zero catches remained approximately constant across the entire habitat area. The relative mean nonzero catch between the LFD and HFD areas varied across species, ranging from 37% to 82% (Table 4).

In each of the 24 species-year combinations, three estimates of population abundance were compared, except for flathead sole in 1992 when no samples were taken in the flathead sole HFD area (Fig. 4). In every case in which the proportion of habitat stratum-size sites to total study area sites exceeded the proportion of habitat stratum size to total study area size (Table 2), the unstratified estimate was greater than the estimate poststratified by habitat (Fig. 4). In every case that the proportion of habitat stratum sites to total study area sites was less than the proportion of habitat stratum size to total study area, the unstratified estimate was less than the estimate poststratified by habitat. Similarly, in every case that the proportion of HFD stratum sites to habitat stratum sites exceeded the proportion of HFD stratum size to habitat stratum size (Table 2), the estimate poststratified by habitat was greater than the estimate poststratified by habitat and fish density (Fig. 4). In all but two cases in which the proportion of HFD stratum sites to habitat stratum sites was less than the proportion of HFD stratum size to habitat stratum size, the estimate poststratified by habitat was less than the estimate poststratified by habitat and fish density. The two exceptions were for Pacific halibut in 1991 and 1996, where the difference between poststratified estimates was small. In 1991, the estimate poststratified by habitat was 2.9% (8116 fish) greater than the estimate poststratified by habitat and fish density; in 1996, it was 0.56% (4905 fish greater).

Table 2

A comparison of the relative number of sample sites and relative size (km^2) of the habitat area, high fish-density (HFD) area, and total study area. Comparisons include the size of the habitat area versus the size of the study area, the number of sites sampled in the habitat area versus the number sampled in the total study area, the size of the HFD area versus the size of the habitat area, and the number of sites sampled in the HFD area versus the number sampled in the habitat area.

	Habitat size/Total study size (km^2)	Habitat sites/Total sites Year						
Species	All years	1991	1992	1993	1994	1995	1996	average
Rock sole (*Lepidopsetta* spp.)	0.92	0.92	1.00	1.00	0.88	1.00	1.00	0.97
Yellowfin sole (*Pleuronectes asper*)	0.66	0.78	0.87	0.63	0.60	0.80	0.80	0.75
Pacific halibut (*Hippoglossus stenolepis*)	0.62	0.73	0.93	0.58	0.52	0.80	0.80	0.73
Flathead sole (*Hippoglossoides elassodon*)	0.67	0.43	0.29	0.67	0.56	0.60	0.60	0.52

	High fish-density size/Habitat size (km^2) Year							High fish-density sites/Habitat sites Year						
Species	1991	1992	1993	1994	1995	1996	average	1991	1992	1993	1994	1995	1996	average
Rock sole (*Lepidopsetta* spp.)	0.65	0.70	0.65	0.65	0.65	0.58	0.65	0.64	0.73	0.42	0.45	0.55	0.50	0.55
Yellowfin sole (*Pleuronectes asper*)	0.58	0.51	0.51	0.51	0.51	0.51	0.52	0.76	0.46	0.47	0.40	0.50	0.50	0.52
Pacific halibut (*Hippoglossus stenolepis*)	0.72	0.76	0.76	0.76	0.61	0.69	0.72	0.69	0.86	0.79	0.62	0.63	0.54	0.69
Flathead sole (*Hippoglossoides elassodon*)	0.72	0.66	0.59	0.69	0.72	0.67	0.68	0.52	0.00	0.50	0.43	0.50	0.44	0.40

Calculations of relative efficiency among the three total abundance estimators showed increases in estimated precision with stratification (Table 5). In most cases (18 out of 24), the estimate poststratified by habitat was more precise (corresponding to a lower standard error in Fig. 5) than the unstratified estimate. Of the 16 (of 23) cases in which the precision of both poststratified estimates were greater than that of the unstratified estimate, in half the estimate poststratified by both habitat and density was more precise than the estimator poststratified by habitat alone.

Sample sizes across the survey area and in each subarea (habitat, high fish-density, and low fish-density areas) (Table 6) strongly influenced the precision of estimates. Habitat sample sizes for all species-year combinations ranged from 4 to 45 (proportion of samples taken in habitat ranged from 0.286 to 1.000); HFD sample sizes ranged from 0 to 29 (proportion of samples taken in the HFD area ranged from 0.0 to 0.8); and LFD sample sizes ranged from 4 to 16 (proportion of samples taken in the LFD area ranged from 0.125 to 0.583). Although the number of samples in both the high and low fish-density areas (Fig. 6, A and B) likely affected estimates poststratified by habitat and fish density, the number of samples in the HFD area appears to have had the primary influence on the precision of estimates. The species-year combinations for which the unstratified estimate was the most precise occurred when habitat sample sizes ranged from 4 to 22 (Fig. 7) and HFD stratum samples sizes ranged from 6 to 11 (Fig. 6A). The species-year combinations for which the estimate poststratified by habitat was the most precise occurred when habitat sample sizes ranged from 12 to 30 (Fig. 7) and when sample sizes in the HFD stratum ranged from 6 to 15 (Fig. 6A). The species-year combinations for which the estimate poststratified by habitat and fish density was most precise occurred when habitat sample sizes ranged from 15 to 45 (Fig. 7) and HFD stratum sample sizes ranged from 10 to 29 (Fig. 6A). Estimates poststratified by habitat and fish density were the most precise for all three cases in which the HFD stratum sample size was greater than 20 (corresponding to LFD stratum sample sizes ranging from 9 to 16) (Fig. 6, A and B). Both of the poststratified estimates were more precise than the unstratified estimate when habitat stratum sample sizes were greater or equal to 24 (Fig. 7) and when HFD stratum sizes were greater or equal to 12 (Fig. 6A).

Statistically significant changes in annual abundance varied among indices and species. There were significant changes in annual mean CPUE in all indices for rock sole and Pacific halibut, in two indices for yellowfin sole and in no indices for flathead sole (Table 7). Rock sole abundance was significantly greater in 1992 than all other years except 1996. Individual indices indicated that rock sole 1996 abundance was greater than that

Table 3

Annual and average proportion of zero catches in the total survey area, habitat area, high fish-density (HFD) areas and low fish-density (LFD) areas for rock sole (*Lepidopsetta* spp.), yellowfin sole (*Pleuronectes asper*), Pacific halibut (*Hippoglossus stenolepis*), and flathead sole (*Hippoglossoides elassodon*).

	Proportion of zero catches															
	Rock sole				Yellowfin sole				Pacific halibut				Flathead sole			
Year	Total survey	Habitat	HFD	LFD	Total survey	Habitat	HFD	LFD	Total survey	Habitat	HFD	LFD	Total survey	Habitat	HFD	LFD
1991	0.224	0.156	0.069	0.308	0.408	0.237	0.241	0.222	0.571	0.417	0.440	0.364	0.776	0.476	0.273	0.700
1992	0.133	0.133	0.000	0.500	0.533	0.462	0.167	0.714	0.267	0.214	0.250	0.000	0.714	0.250	—	0.250
1993	0.375	0.375	0.100	0.571	0.500	0.200	0.143	0.250	0.583	0.286	0.273	0.333	0.542	0.313	0.000	0.625
1994	0.360	0.273	0.100	0.417	0.800	0.667	0.833	0.556	0.520	0.077	0.125	0.000	0.520	0.143	0.167	0.125
1995	0.050	0.050	0.000	0.111	0.400	0.250	0.125	0.375	0.250	0.063	0.000	0.167	0.600	0.333	0.333	0.333
1995	0.133	0.133	0.067	0.214	0.433	0.292	0.250	0.333	0.333	0.167	0.154	0.182	0.733	0.556	0.250	0.800
Average	0.213	0.187	0.056	0.354	0.512	0.351	0.293	0.408	0.421	0.204	0.207	0.174	0.647	0.345	0.205	0.472

of 1992 and 1993. Tukey *post hoc* tests on the yellowfin sole all-site and habitat indices showed that 1991 yellowfin abundance was greater than that of 1994. All three indices showed that Pacific halibut abundance was greater in 1995 than in 1991 and 1993. Individual indices also indicated that Pacific halibut abundance was greater in 1995 than in 1992, 1994, and 1996.

Discussion

The Chiniak Bay multispecies survey was designed to estimate the abundance of four species with equal emphasis. Because the distribution of species varied greatly throughout the bay, what might have been an optimal stratification for individual species was compromised to develop a stratification scheme that was as effective as possible for all target species. Because we do not believe sampling was optimal for any one of the species, a poststratification method of analysis was investigated to increase the precision of abundance estimates for each species individually and to account for possible bias due to the uneven and nonrandom distribution of sampling sites over space and time.

The need for stratification and the concern about the distribution of sampling sites arise because of the varying distributions of species in the study region. Knowledge of the spatial distributions of species is important when estimating abundance from trawl surveys. A random distribution of individuals is often taken as a starting point for defining spatial distributions in ecology (Taylor et al., 1978). It is also a primary assumption for many survey sampling designs and analysis measures. The assumption of randomly distributed individuals often is not appropriate, however, because the concentration of fish varies over time and space in relation to environmental factors (Murawski and Finn, 1988; Gadomski and Caddell, 1991; Reichert and van der Veer, 1991; Norcross et al., 1999). If habitat (Fiedler and Reilly, 1994; Reilly and Fiedler, 1994) and related spatial population density distributions (Buckland and Anganuzzi, 1988) are not accounted for when calculating abundance estimates, precision can decrease and results can be seriously biased. Inaccurate results can have strong management repercussions.

In situations such as that of the present study, where the sample does not properly represent the population, poststratification is appropriate (Scheaffer et al., 1996). By comparing poststratified and unstratified estimates of abundance, we found that in every species-year combination for which the three estimates of abundance differed (Fig. 3), the poststratified estimates reduced the effect of the disproportion of samples allocated between habitat and nonhabitat areas and between high and low fish-density areas. For instance, in 1992, a disproportionately large number of samples were taken in Pacific halibut habitat (Table 2). We suspect, therefore, that the unstratified estimate of abundance was an overestimate of true population abundance. The disproportionately large number of samples taken in Pacific halibut

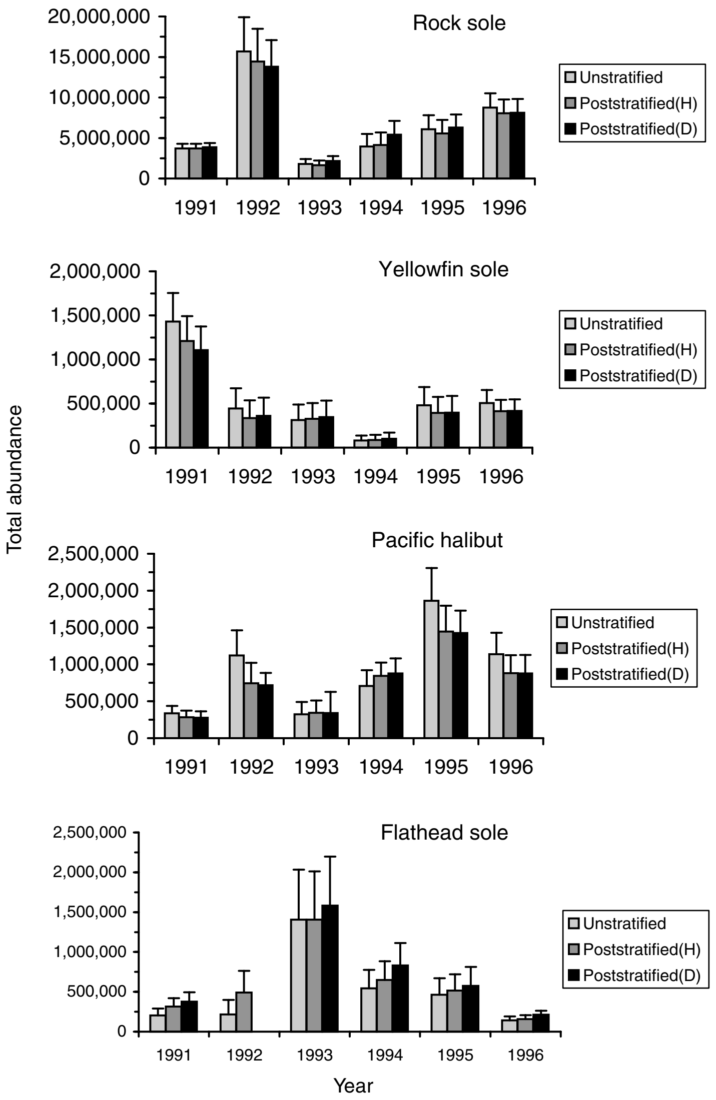

Figure 4

Three estimates of total abundance and standard error. Estimates are unstratified, poststratified by habitat (poststratified [H]), and poststratified by habitat and fish density (poststratified [D]).

habitat was adjusted by poststratifying by habitat. The estimate poststratified by habitat was less than the unstratified estimate of abundance, as we suspect the true abundance was. Poststratification by habitat and neighboring years' halibut density adjusted not only for the disproportionately large number of samples in the habitat area but also for the disproportionately large number of samples in the HFD area (Table 2). The estimate poststratified by habitat and halibut density was less than both the estimate poststratified by habitat and the unstratified estimate, as we suspect was the case for the true Pacific halibut abundance.

In 1992, the number of samples in yellowfin sole habitat was disproportionately large, but the number of samples in the HFD area was disproportionately small (Table 2). In this case, we suspect the unstratified estimate of abundance was an overestimate of true abundance because of the overabundance of samples in the habitat area. We also believe, however, that it was not a very large overestimate because of the disproportionately small number of samples in the HFD area. Poststratifying by habitat adjusted for the disproportionately large number of samples in the habitat area and produced an estimate that was less than the unstratified estimate. Poststratifying by habitat and fish density adjusted for both the disproportionately large number of samples in the habitat area and the disproportionately small number of samples in the HFD

Table 4

The mean catch per unit of effort (CPUE) of nonzero catches in the habitat, high fish-density (HFD), and low fish-density (LFD) areas and the proportion of the mean CPUE of nonzero catches in LFD and habitat areas in relation to those in the HFD area.

	Species			
	Rock sole (*Lepidopsetta* spp.)	Yellowfin sole (*Pleuronectes asper*)	Pacific halibut (*Hippoglossus stenolepis*)	Flathead sole (*Hippoglossoides elassodon*)
Habitat nonzero mean	85.3	15.6	16.8	16.0
HFD nonzero mean	105.4	20.7	17.9	20.6
LFD nonzero mean	52.2	7.6	14.7	9.5
Habitat mean/concentration mean	0.81	0.75	0.94	0.78
LFD mean/HFD mean	0.50	0.37	0.82	0.46

Table 5

Unstratified total abundance estimates (*U*), total abundance estimates poststratified by habitat (*H*), and total abundance estimates poststratified by habitat and fish density (*D*) are compared by using annual relative efficiency statistics.

		Year					
Species	Relative efficiency comparison	1991	1992	1993	1994	1995	1996
Rock sole	*H* to *U*	1.076	1.081	1.084	0.985	1.083	1.084
(*Lepidopsetta* spp.)	*D* to *H*	1.129	1.496	0.865	0.834	1.089	0.999
	D to *U*	1.214	1.618	0.937	0.821	1.179	1.084
	conclusion	*D>H>U*	*D>H>U*	*H>U>D*	*U>H>D*	*D>H>U*	*H>D>U*
Yellowfin sole	*H* to *U*	1.318	1.317	0.988	0.922	1.266	1.324
(*Pleuronectes asper*)	*D* to *H*	1.111	0.969	0.890	0.715	0.936	0.967
	D to *U*	1.465	1.277	0.880	0.659	1.186	1.280
	conclusion	*D>H>U*	*H>D>U*	*U>H>D*	*U>H>D*	*H>D>U*	*H>D>U*
Pacific halibut	*H* to *U*	1.272	1.521	1.007	1.369	1.607	1.440
(*Hippoglossus stenolepis*)	*D* to *H*	1.029	0.936	0.996	0.792	1.340	0.949
	D to *U*	1.309	1.424	1.003	1.084	2.155	1.366
	conclusion	*D>H>U*	*H>D>U*	*H>D>U*	*H>D>U*	*D>H>U*	*H>D>U*
Flathead sole	*H* to *U*	0.726	0.449	1.075	0.973	1.025	1.056
(*Hippoglossoides elassodon*)	*D* to *H*	0.786	—	0.976	0.705	0.746	0.992
	D to *U*	0.571	—	1.049	0.686	0.765	1.047
	conclusion	*U>H>D*	*U>H*	*H>D>U*	*U>H>D*	*H>U>D*	*H>D>U*

area. As a result, the estimate poststratified by habitat and fish density was greater than the estimate poststratified by habitat, but lower than the unstratified estimate. According to our results, it is unlikely that the estimates poststratified by habitat and fish density were the most representative estimates of abundance because poststratification adjusted for the disproportionate distribution of samples between areas.

Another reason to poststratify the data is to increase the precision of abundance estimates. Poststratified estimates in our study were generally more precise than unstratified estimates, given sufficient sample sizes (Table 5). Poststratification by habitat characteristics increased the precision of abundance estimates in three-quarters of all species-year combinations. This finding indicates a close link between habitat type and fish abundance and agrees with poststratification results in other studies (Pollock et al., 1994; Reilly and Fiedler, 1994). Estimates poststratified by both habitat and fish density were also generally more precise than

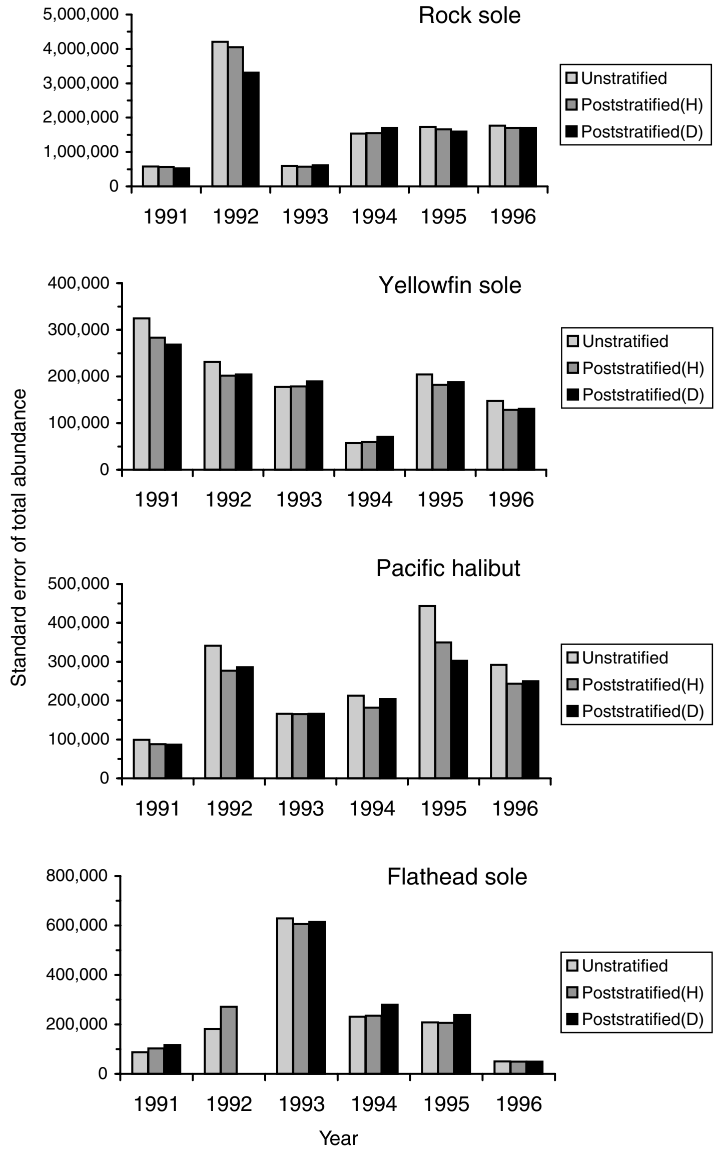

Figure 5

Three standard error estimates of annual total abundance. Standard error estimates are for the unstratified, poststratified by habitat (poststratified [H]), and poststratified by habitat and fish density (poststratified [D]) estimates.

unstratified estimates but were not consistently more precise than the estimates poststratified by habitat alone. The six cases in which estimates poststratified by habitat and fish density were the most precise show that some species have strong density gradients within habitat areas and that the incorporation of fish density information from neighboring years can be beneficial for increasing precision. Being able to predict the distribution of fish density in one year from that of neighboring years indicates annual consistency in species distribution in relation to habitat characteristics.

The present study indicates that when estimating abundance from haphazardly sampled data, the estimator poststratified by habitat is superior to the unstratified estimator regardless of sample size. The estimate poststratified by habitat was more precise than the unstratified estimate in 18 of the total 24 species-year combinations. These 18 species-year combinations occurred across nearly the full range of habitat stratum sample sizes, from 12 to 45. The six cases in which the estimate poststratified by habitat was less precise than the unstratified estimate were affected by the propor-

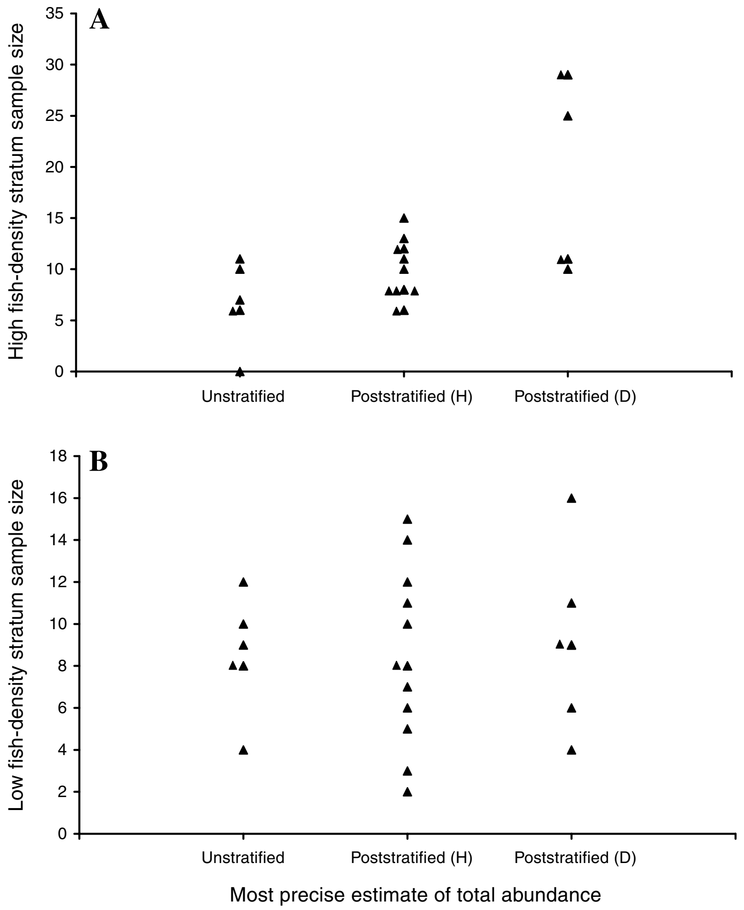

Figure 6

High and low fish-density stratum sample size in relation to the most precise estimate of total abundance. The (**A**) high fish-density and (**B**) low fish-density stratum sample size for each species-year combination is plotted in relation to the most precise estimate of total abundance—the unstratified estimate, the estimate poststratified by habitat (poststratified [*H*]), or the estimate poststratified by habitat and fish density (poststratified [*D*]).

tion of samples in unsuitable habitat. As a measure of variability, the magnitude of the variance is dependent on the magnitude of the data (Zar, 1996). Thus, the variances of trawl catches decrease as the observed means decrease (Taylor, 1953). A lower variance, therefore, does not necessarily indicate a better estimator, but instead may reflect lower population abundance. In the six cases in this study where the variance of the unstratified estimate was less than the variance of the estimate poststratified by habitat, the unstratified abundance estimate was less than the abundance estimate poststratified by habitat. The low unstratified abundance estimates in these six cases were the result of a disproportionately large number of samples in nonhabitat areas in relation to the size of the nonhabitat areas. Therefore, although the unstratified estimate was more precise, it was also likely to be an underestimate of the true abundance. Thus, we suggest that the estimate poststratified by habitat is the most desirable estimator in these situations, despite the decrease in precision in relation to the unstratified estimator.

In many cases, small sample size was likely the reason that the estimates poststratified by habitat and fish density were not the most precise of the three estimates. Poststratification produces precise estimates when the overall sample size and the sample size in each stratum are large (Scheaffer et al., 1996). In our study, the estimator poststratified by habitat and fish density was the most precise estimator of the three when sample size in the HFD stratum was 20 or greater and the sample size in the LFD stratum was 9 or greater. The number of samples in the HFD stratum appears to have had a larger influence on the precision of estimates stratified by habitat and fish density than the number of samples

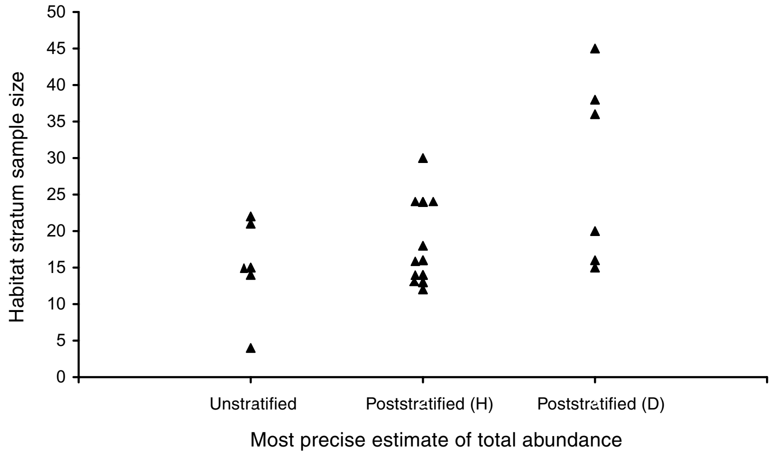

Figure 7

The habitat stratum sample size for each species-year combination is plotted in relation to the most precise estimate of total abundance—the unstratified estimate, the estimate poststratified by habitat (poststratified [H]), or the estimate poststratified by habitat and fish density (poststratified [D]).

Table 6

Annual number of tows made across all strata in habitat and nonhabitat strata, and in the high and low fish-density strata within the habitat stratum.

		Year					
Species	Stratum	1991	1992	1993	1994	1995	1996
Rock sole	all	49	15	24	25	20	30
(*Lepidopsetta* spp.)	habitat and nonhabitat	45 and 4	15 and 0	24 and 0	22 and 3	20 and 0	30 and 0
	high fish density and low fish density	29 and 16	11 and 4	10 and 14	10 and 12	11 and 9	15 and 15
Yellowfin sole	all	49	15	24	25	20	30
(*Pleuronectes*	habitat and nonhabitat	38 and 11	13 and 2	15 and 9	15 and 10	16 and 4	24 and 6
asper)	high fish density and low fish density	29 and 9	6 and 7	7 and 8	6 and 9	8 and 8	12 and 12
Pacific halibut	all	49	15	24	25	20	30
(*Hippoglossus*	habitat and non-habitat	36 and 13	14 and 1	14 and 10	13 and 12	16 and 4	24 and 6
stenolepis)	high fish density and low fish density	25 and 11	12 and 2	11 and 3	8 and 5	10 and 6	13 and 11
Flathead sole	all	49	14	24	25	20	30
(*Hippoglossoides*	habitat and non-habitat	21 and 28	4 and 10	16 and 8	14 and 11	12 and 8	18 and 12
elassodon)	high fish density and low fish density	11 and 10	0 and 4	8 and 8	6 and 8	6 and 6	8 and 10

in the LFD stratum (Fig. 6, A and B). This study supports the conclusion of Scheaffer et al. (1996) but also indicates that the sample size in the HFD stratum may have a larger influence on the precision of the resultant estimate.

As concluded in other studies (Fiedler and Reilly, 1994; Pollock et al., 1994; Reilly and Fiedler, 1994; Bernard et al., 1998), we found that poststratification can provide increased precision and decreased bias for estimates. Small stratum sample sizes, however, can make it impossible to detect heterogeneity among strata and fail to give increased precision (Powell et al., 1995; Friedland et al., 1999). The wide range of sample sizes among strata across species-year combinations exempli-

Table 7

Kruskal-Wallis test statistics for differences in annual relative abundance and, for significant Kruskal-Wallis statistics, the corresponding significant Tukey *post hoc* pairwise differences. Statistics were calculated for the all-site, habitat, and high fish-density indices.

Species	Index	Kruskal-Wallis (*indicates statistically significant difference)	Tukey *post hoc* significant differences
Rock sole	All-site	P=0.0003*	1992>1991 (P<0.0006)
(*Lepidopsetta* spp.)			1992>1993 (P<0.0001)
			1992>1994 (P<0.0009)
			1992>1995 (P<0.0124)
			1996>1993 (P<0.0301)
	Habitat	P=0.0008*	1992>1991 (P<0.0012)
			1992>1993 (P<0.0001)
			1992>1994 (P<0.0022)
			1992>1995 (P<0.0149)
			1996>1993 (P<0.0351)
	High fish density	P=0.0035*	1992>1991 (P<0.0005)
			1992>1993 (P<0.0003)
			1992>1994 (P<0.0127)
			1992>1995 (P<0.0206)
			1996>1992 (P<0.0145)
Yellowfin sole	All-site	P=0.0033*	1991>1994 (P<0.0096)
(*Pleuronectes asper*)	Habitat	P=0.0022*	1991>1994 (P<0.0374)
	High fish density	P=0.1240	
Pacific halibut	All-site	P=0.001*	1995>1991 (P<0.0013)
(*Hippoglossus stenolepis*)			1995>1993 (P<0.0012)
			1995>1994 (P<0.0359)
	Habitat	P=0.0004*	1995>1991 (P<0.0018)
			1995>1993 (P<0.0077)
	High fish density	P=0.0002*	1995>1991 (P<0.0002)
			1995>1992 (P<0.0127)
			1995>1993 (P<0.0004)
			1995>1996 (P<0.0249)
Flathead sole	All-site	P=0.1955	
(*Hippoglossoides elassodon*)	Habitat	P=0.2950	
	High fish density	P=0.5151	

fies an important drawback to using the poststratification method. Because strata criteria are unknown when sampling, it is not possible to insure that there will be sufficient samples in each poststratified stratum. When resulting sample sizes in some strata are small, poststratification may be ineffective at increasing precision. If the resulting sample size in one or more strata is one, the poststratification variance will be inestimable. If the resulting sample size in one or more strata is zero, poststratification may not be possible.

Because sample size is a limiting factor for increased precision with poststratification, there are strong implications for survey design. Many multispecies surveys are conducted by using a stratified random sampling design. There are two ways to apply poststratification to a stratified survey. First, for an unbiased estimator, each stratum of the stratified survey can be poststratified individually (Cochran, 1977). For the poststratification estimator to have increased precision beyond that of stratified random sampling, each of the original strata must have a large number of samples to allow sufficient samples in each poststratified stratum. Therefore, investigators who intend to poststratify data within a stratified random survey for unbiased estimates need to construct large strata with many samples in the original sampling design. Second, if poststratification is applied to data that were not collected under a probability sampling design, the estimator may be more precise, but may be biased. For the analysis of data that were not collected under a probability sampling design, developing an index of relative abundance from all samples, or samples in the habitat or HFD areas, is an easy and effective way to estimate statistically significant changes in abundance among years. To determine which tows should be included in an index to effectively approximate the variations in the annual total abundance estimates, it is helpful to compare the size of the habitat area over years and to study the distribution of species density within the habitat area. The goal of creating an index should be to include the most information possible, while avoiding undue influence from the haphazard distribution of sample sites.

If the total study area is the same in each year, the choice of whether to use the all-site index should depend on whether the size of the habitat area is constant over the compared years. In this study, the defined habitat area for each species was the same over the six years compared. Therefore, for an index of relative abundance, the habitat index retained all necessary information and reduced possible bias due to the disproportionate distribution of haphazard samples between habitat and nonhabitat areas. When a temporally dependent stratification variable, such as temperature, is used to define the placement of stratum boundaries, however, the size of the habitat area may vary between years. If the annual size of the habitat area varies, some common size would need to be chosen for the relative index to approximate the annual changes in the total abundance estimates. The all-site index could be used for this purpose, but the index will be affected by any disproportionate distribution of samples between habitat and nonhabitat areas. Another possible way to do this would be to include all tows from the habitat area each year, plus as many zero catches from the nonhabitat area necessary to be proportional to the annual size of the nonhabitat area. Such an approach would not depend on actual tows in nonhabitat area but would depend on the estimated size of the habitat and nonhabitat areas and the sample size in the habitat area.

If the size of habitat area is the same in each year, the choice of whether to use the habitat index should depend on whether the distribution of species density is constant throughout the habitat area. If a species' density distribution is approximately constant across the habitat area, a haphazard distribution of sample sites should have little influence. Constructing an index from all habitat tows may then be desired to retain the largest sample size and the most information possible. Alternatively, if a species has a strong density gradient within its habitat area, a disproportionate distribution of sites in relation to the size of high and low fish-density areas may provide an unrepresentative estimate of abundance from the habitat index. In this case, if a sufficient number of samples are taken in the HFD area, constructing an index from samples within the species' HFD area alone may provide an effective index while minimizing the effect of a disproportional distribution of haphazard samples within the habitat area.

A comparison of the number of zero catches and the mean nonzero catch between the high and low fish-density areas provides information about the density distribution of species within a habitat area. The proportion of zero catches of rock sole, yellowfin sole, and flathead sole and the mean nonzero catch between high and low fish-density areas indicated density gradients within the habitat areas. Unlike these three species, the proportion of Pacific halibut zero catches was approximately the same in the HFD area as across the entire habitat area and the difference in mean nonzero catch between low and high fish-density areas was only approximately half that of the other species. Therefore, it appears that the Pacific halibut density distribution across the defined habitat area varied little compared with the other three species.

In this study, we suggest that the habitat index was the most appropriate for all four species. For each species in our study, the size of the habitat area remained the same across all six years. Thus, the habitat index eliminated the influence of disproportionately allocated samples in habitat and nonhabitat areas. For Pacific halibut, the relatively homogenous distribution of abundance across the habitat area indicates that the effect of disproportionate samples between high and low fish-density areas is small and that samples across the entire habitat area are helpful in describing annual differences in abundance. For rock sole, yellowfin sole, and flathead sole, the difference in the proportion of zero catches and nonzero mean abundance between the high and low fish-density areas was considerable. As a result, differences in annual abundance suggested by the habitat index may be affected by the inconsistent disproportion of samples between high and low fish-density areas over years. Although it would be preferable to use the HFD index in these cases, annual sample sizes in the HFD area were so small that we recommend the habitat index instead. Recognizing that the habitat index will not account for the annual disproportion of samples between the high and low fish-density areas, we used the comparison of the size and the number of samples taken in high and low fish-density areas to flag differences in annual index abundance estimates that might be over- or underestimates. If this method is applied in a management context, the levels of the factors describing the density distribution of the species (i.e., difference in the percent of zero catches and the percent difference in mean nonzero catch between years) can be set as criteria and kept constant over years to eliminate subjectivity between years or between species. For example, if the percent of zero catches in high and low fish-density regions differ by 40% and the mean nonzero catch in the HFD area is 30% greater than that in the LFD area, the HFD index should be used. Otherwise, the habitat index should be used.

For many surveys, identifying habitat and fish-density areas for poststratification and index construction is possible with currently available information. The estimation methods used in the present study can be applied to any survey for which abundance and environmental measurements are available for each sampled site and the environmental measurements are related to species abundance in a consistent way. For example, the NMFS Bering Sea trawl survey includes measurements of depth and surface and bottom temperatures at all trawl sites (Goddard and Walters[4]) that could be used for poststratification. Similarly, the Pacific West Coast trawl survey includes measurements of surface and bottom temperature and salinity at all stations (Lauth et al.[5]) that could be used. Poststratification allows for use of a wide range of stratification variables, including temporally dependent variables that are not available before sampling is complete, e.g., temperature and salinity.

For surveys where habitat information is not collected at trawl sites, habitat information from other sources can be paired with fish distribution information after collections have been made. For instance, when habitat information is available, but has not been collected at each site, spatial statistics can be used to krige the habitat information over the study area and to predict the specific habitat data value at the sampling sites. If there is a consistent relationship between species abundance and the habitat variable, the catch and habitat data paired at sample sites can then be used to identify areas of suitable habitat and areas of high fish density within suitable habitat. How well habitat and HFD areas are estimated will depend on the number and distribution of habitat measurements, the contouring algorithms used, and the estimates of areas within contours. Even if species are not distributed in direct response to particular environmental characteristics, the characteristics may serve as proxies for effects that are more difficult to measure (Perry and Smith, 1994). Once habitat and HFD areas are identified, poststratification can be conducted for total abundance estimates, and statistically significant changes between years can be assessed with an index of relative abundance. These methods could yield more accurate estimates of abundance for use by managers. The goal of most sampling plans is to provide statistical estimates with the smallest possible confidence limits at the lowest cost (Krebs, 1989). Thus, being able to use data collected independently of a survey should be appealing.

The NRC (2000) recommends using data from commercial or sportfishing vessels in scientific assessments of abundance. A primary difficulty in using commercial fisheries data for scientific estimates of abundance is that the data do not represent random samples of the fish population. As a result, commercial fisheries data present a biased perspective of the population that may change over time and may not correlate well with actual fish abundance (NRC, 2000). Although commercial fishery-dependent data may provide biased estimates of abundance, fishery-dependent data also provide large sample sizes and a wide range of information not available from other sources. For example, commercial and sportfishing data often provide broader geographic and temporal coverage. Poststratification of haphazard data from commercial and sportfishing sources may be one way to reduce inherent bias and provide useable scientific information. For instance, Buckland and Anganuzzi (1988) described how data collected on commercial tuna fishing vessels can be used to estimate dolphin abundance when survey data are not sufficient. The data collection sites were not randomly selected. Instead, the sampling sites were directly related to dolphin sightings, because dolphins and tuna schools are often closely associated. As a result, areas of high dolphin density corresponded with areas of high fishing effort. Poststratification was used to decrease the bias resulting from nonrandom distribution of both search effort and dolphin schools. A second example is a retrospective study that combined survey and commercial fishing data. In this study (Halliday[6]), 1958–60 poststratified survey data were used to develop a relationship between the survey abundance of the 1954–1959 year classes and their abundance estimates from commercial fishery data. This relationship was then used, along with 1969 survey data, to predict the size of the 1966–68 year classes. The same process was used to predict the size of later year classes with later years of survey data.

Poststratification also facilitates the use of a single data set for multiple objectives. Collecting data is costly and many data sets are collected and analyzed for a single objective and then not used again. Although it is preferable to use data for multiple objectives, it can be difficult to meet statistical assumptions when the data are re-used for a different purpose. For example, a multispecies survey may be stratified according to the distribution of one or more of the most commercially valuable species collected. An example is the stratification of Pacific west coast bottom trawl surveys in 1980, 1983, and 1986, which were focused to improve the precision of canary and yellowtail rockfish abundance estimates (Weinberg et al.[2]). If the stratification used was not effective for decreasing the variance of abundance estimates for other species, treating the data as if they were haphazardly collected, recognizing that the estimator may be biased, and poststratifying the data by habitat variables that are closely related to the

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[4] Goddard, P., and G. Walters. 1998. 1995 bottom trawl survey of the eastern Bering Sea continental shelf. AFSC Processed Report 98-08, 170 p. Resource Assessment and Conservation Engineering Division, Alaska Fisheries Science Center, NMFS, NOAA, 7600 Sand Point Way N.E., Seattle, Washington, 98115.

[5] Lauth, R. R., M. E. Wilkins, and P.A. Raymore Jr. 1997. Results of trawl surveys of groundfish resources of the West Coast upper continental slope from 1989 to 1993. NOAA Tech. Memo. NMFS-AFSC-79, 342 p. National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161.

[6] Halliday, R. G. 1970. 4T-V-W haddock: recruitment and stock abundance in 1970–72. ICNAF Res. Doc 70/75, 12 p. Approved for citation by Tissa Amaratunga, Deputy Executive Secretary, Northwest Atlantic Fisheries Organization. [Available from the Secretariat Library, Northwest Atlantic Fisheries Organization, 2 Morris Drive, Burnside Industrial Park, Dartmouth, Nova Scotia, Canada, B3B 1K8.]

distribution of the other species may be a beneficial way to make multiple uses of the data. Although the poststratified estimator may be biased, poststratification may provide large gains in precision and a decrease in bias in relation to an unstratified estimator. Large increases in precision may be worth the acceptance of some bias.

Multispecies surveys are often not optimal for estimating the abundance of individual species but are often necessary because of limited time and financial resources. As a result, researchers need to explore alternative sampling and analysis designs to increase the precision of individual species abundance estimates (NRC, 2000). Poststratification is a method that can be applied to any number of species by using a wide range of habitat and other variables that can be stratified. Because of the dramatic increase in habitat information that is likely to be collected in response to the expanded emphasis in the Magnuson-Stevens Act (NRC, 2000) and because of the adaptability of poststratification for handling a multitude of types of data sets, the method of poststratification may provide increased usefulness for scientific researchers.

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