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Evaluation of Density Estimators Used in Rockfish Hydroacoustic Surveys

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Abstract

The Alaska Department of Fish and Game conducts hydroacoustic surveys in the northwestern Gulf of Alaska to provide density and abundance estimates of black rockfish *Sebastes melanops*. These surveys are conducted using either a grid or star pattern, depending on the habitat being surveyed. Simulation analyses are used to investigate whether the density estimator using the survey data produces biased density estimates. Forty distinct simulation spaces are populated with virtual fish schools. Individual fish locations (x, y, z) are drawn from either a uniform or normal distribution using four different school configurations and five population densities. Simulated schools are sampled following methods employed in the grid- and star-pattern surveys. Simulations were repeated 200 times for each distribution, school configuration, and population density combination.

The grid-pattern survey design and the density estimator produce accurate estimates of simulated fish densities with a mean bias of 0.00011 (SE = 0.00015). The star-pattern survey design using the same density estimator produces biased estimates of fish densities due to transects crossing at a common center and increasing the probability of a fish near the center of the pattern being sampled. To correct for the bias, a fish's contribution to transect density is determined empirically and a linear model based on its distance from the star-pattern center is developed. Using this linear model, biases for the adjusted star-pattern survey density estimates are two orders of magnitude less than the unadjusted method with a mean bias of –0.00027 (SE = 0.00022).

Introduction

The Alaska Department of Fish and Game (ADF&G) is responsible for management of commercial black rockfish *Sebastes melanops* fisheries in the Gulf of Alaska from southeast Alaska west to the Alaska Peninsula and within the state waters of the Bering Sea and Aleutian Islands. Prior to state management, stock assessment was limited to trawl surveys, which proved ineffective in catching nearshore, midwater distributions of black rockfish over rocky high-relief areas, and provided little fishery-independent information to gauge the status of the populations (NPFMC 1998). In an effort to assess black rockfish stocks in the Kodiak region, hydroacoustic surveys are used to provide density and population estimates (Worton and Tschersich 2015). Acoustic backscatter data are collected during the survey over known black rockfish habitats using a Biosonics DT-X 210 kHz split-beam echo sounder (biosonicsinc.com, Seattle, WA). The backscatter data are analyzed using Echoview (Myriax, Hobart, Australia) to identify individual fish and provide their location (latitude and longitude) and depth. The individual-fish spatial data are then used to estimate fish densities for the surveyed areas. Schooling behavior of black rockfish, which typically concentrate over high relief rocky habitats, is an important consideration in the choice of a survey design. Fixed-grid sampling is commonly employed in acoustic surveys to simply find the fish stock (Simmonds et al. 1991), and to determine the extent of their distribution over certain habitats, whereas star-pattern survey designs have been used with echo integration surveys of more concentrated fish aggregations (Josse et al. 1999, Doonan et al. 2003).

The individual fish location data used in this study is substantially different from echo integration methodologies employing the star pattern. Both of those survey designs have been utilized by ADF&G to collect rockfish hydroacoustic data. The grid pattern is employed where rockfish are associated with multiple bottom structures that are reef-like, being much longer in one horizontal direction than the other (Fig. 1). Star patterns are used where rockfish are concentrated near a single pinnacle or mound (Fig. 1) where the grid pattern is much less effective. The grid pattern is the preferred survey pattern and is based on simple line-transect methods and the mean of the individual transect densities should be an unbiased estimate of the rockfish density in the surveyed area. The density estimator employed is based on a method described by Yule (2000). The estimator standardizes individual fish to a 1 m wide transect based on their depth. However, because transects in a star pattern intersect at a common center, the Yule estimator is not expected to provide unbiased density estimates. Using computer simulations the expected bias in the star-pattern method is confirmed,

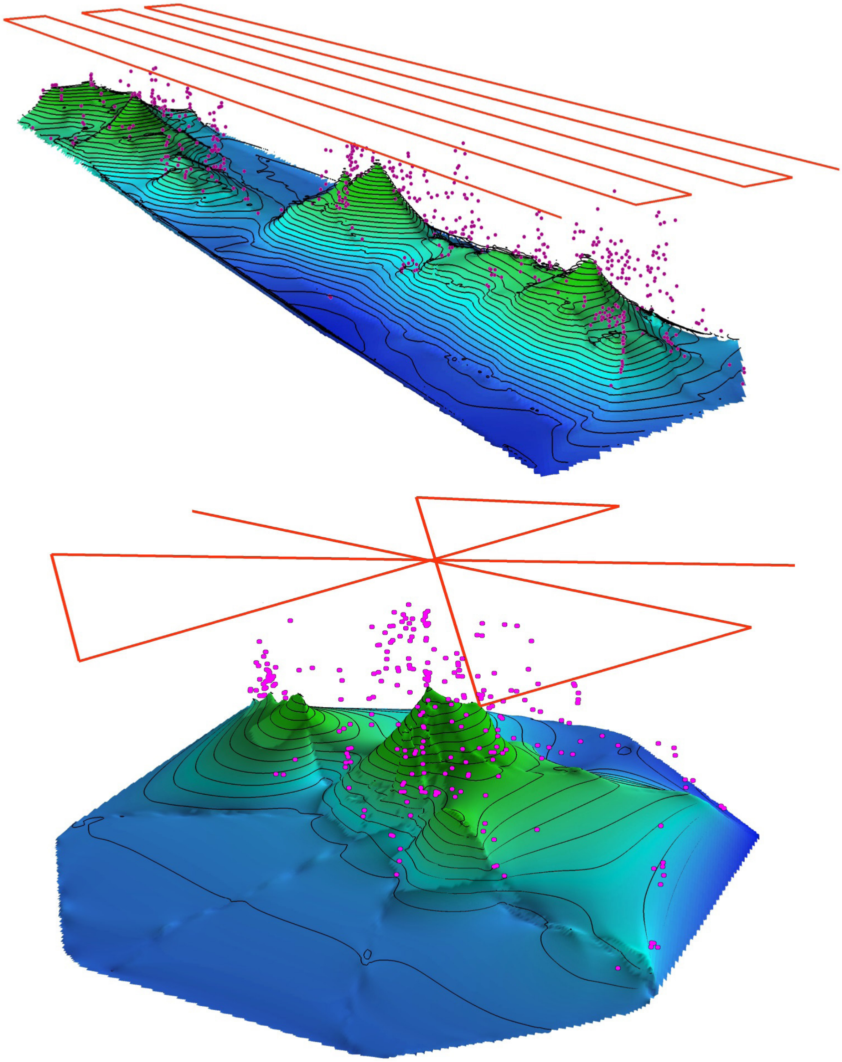

Figure 1. Typical grid-pattern survey track (top) and typical star-pattern survey track (bottom) used by the rockfish hydroacoustic surveys.

an unbiased estimator of mean rockfish density is developed, and the new estimator's performance is compared to the grid-pattern estimator.

Methods

Simulations

During surveys only fish within the acoustic beam are detected and counted. The survey acoustic beam is a right circular cone with a beam angle of 6.2° at its apex; greater depth results in a wider path swept by the acoustic beam. The simulations mimic survey detections by comparing the 3-D position of each fish to a transect line. If the location of a fish lies within the path swept by the simulated acoustic cone the fish is considered to be detected. (Details of this procedure exceed the available space here but are available from D. Barnard upon request.)

To assess the properties of the acoustic survey methods, computer simulations are created to evaluate the two survey patterns, grid and star, and the estimator used to arrive at density estimates. A 100×100×60 unit simulation space (x, y, z) is populated with virtual fish located randomly within the space. The simulation space is sampled and analyzed using transects that replicate the two survey methods. All simulation work is carried out using macros written for the statistical software Minitab (minitab.com, State College, PA). The simulated rockfish schools consist of three spatial variables x, y, and z which describe the position of each fish within the simulation space. The location variables x [0, 100] and y [0, 100] are analogues of longitude and latitude, respectively, and the variable z [–60, 0) represents depth. Eight simulated fish populations consisting of four school configurations drawn from either a normal or uniform distribution are created to explore the effects of school distribution, concentration, and location on the properties of data collection and analytic methods.

The four school configurations are created with x, y, and z coordinates that are randomly generated from either distribution with specific parameter values selected to arrive at desired school concentrations and locations within the simulation space (Table 1, Fig. 2). Schools 1 and 2 are centered on $x = y = 50$: school 1 is diffuse, occupying most of the simulation space; school 2 is more concentrated, occupying approximately 50% of the simulation space (Fig. 2). School 3 is displaced away from the center of the simulation space along the x axis and occupies approximately half of the simulation space, and school 4 is displaced along both the x and y axes and is highly concentrated, occupying approximately 25% of the simulation space (Fig. 2). Initially the eight school configurations are created with 1,000 fish each in the 100×100 unit simulation spaces (density = 0.10 fish per unit^2). To investigate the effects of population density (D) additional data sets of 800 fish

Table 1. Parameter values for the mean (μ) and standard deviation (σ) of normal distributions and the Lower (L) and Upper (U) limits of the uniform distributions used to generate random spatial data for the three dimensions of the eight fish distributions.

Fish school	X				Y				Z			
	Normal		Uniform		Normal		Uniform		Normal		Uniform	
	μ_x	σ_x	L_x	U_x	μ_y	σ_y	L_y	U_y	μ_z	σ_z	L_z	U_z
1	50	20	1	99	50	20	1	99	–30	10	–60	–1
2	50	10	15	85	50	10	15	85	–30	10	–60	–1
3	26	10	1	50	50	20	1	99	–30	10	–60	–1
4	75	10	50	99	75	10	50	99	–30	10	–60	–1

(0.08 fish per unit^2), 600 fish (0.06 fish per unit^2), 400 fish (0.04 fish per unit^2), and 200 fish (0.02 fish per unit^2) are created via random selection from the initial 1,000 fish data sets. For both survey patterns, a simulated survey or trial consists of five transects. Five transects are standard for star-pattern surveys and, for compatibility, grid-pattern simulations also used five transects per simulated survey.

The grid-pattern simulation is designed to be as simple as possible while retaining the essential properties of the field surveys. This simulation uses a systematically spaced sample of five transects per trial and all transects run parallel to the x-axis. The starting point $(0, y_s)$ on the y-axis for the first transect is randomly selected from a uniform distribution on the interval [0.5, 19.5]. Each additional transect start point is determined by adding 20 units to the previous transect start point and the five transect lengths are all the same ($l = 100$ units). The simulation is designed with a looping structure that allows multiple trials to be run for a given D, school configuration, and distribution, each with a different random start point.

The star-pattern simulation also uses a sample of five transects per trial. As with the grid-pattern method, the first transect starts on the y axis with a starting point $(0, y_s)$, with y_s being randomly selected from a uniform distribution on the interval [0, 100]. All transects transit the simulation space through the center point (50, 50). The first transect is defined by the center point and the starting point $(0, y_s)$ which are used to calculate the transect slope. Each subsequent transect is determined as a function of the center point (x_c, y_c) and the previous transect's slope. The slopes m_t for transects 2–5 are calculated as:

$$\text{for } t = 2,\ldots,5,\ m_t = \tan\,[\operatorname{atan}(m_{t-1}) + 72°]. \tag{1}$$

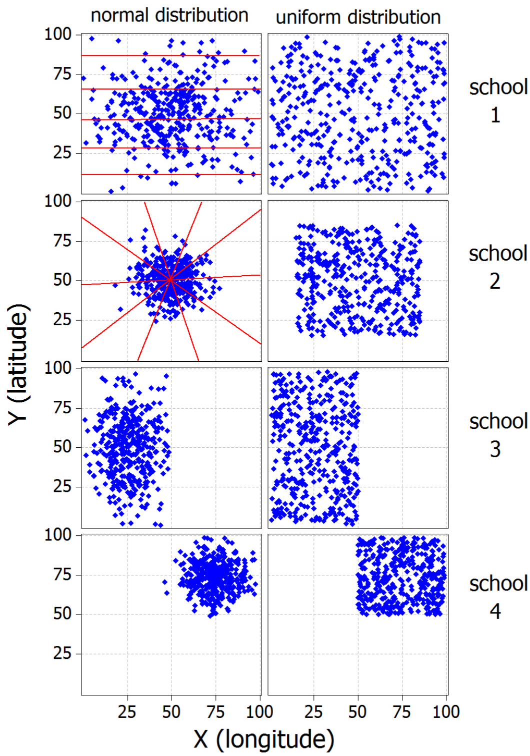

Figure 2. Plots of the eight simulated fish schools used to explore the effects of parent distribution, and school configuration on density estimates. Each simulated fish school consists of two distributions and four school configurations. Shown are schools of 400 fish (density = 0.04 fish per unit^2). Representations of grid and star transects are shown on schools 1 and 2 for the normal distribution.

Any generated slopes greater than 20/1 are divided by 20 to prevent extreme slopes. The star-pattern simulation also utilizes a looping structure allowing multiple trials to be run for a given D, school configuration, and distribution.

Estimator

The density estimator is based on a method described by Yule (2000). The procedure standardizes individual fish to a 1 unit wide transect based on their depth. For a single fish at depth z from a transect of length l, its contribution to the transect density is expressed by

$$density = \left(\frac{1}{2 \times \tan(beamangle/2) \times z}\right) \times \frac{1}{l} = \left(\frac{1}{0.1083 \times z}\right) \times \frac{1}{l}, \tag{2}$$

where 0.1083 = 2 × tan(6.2°/2), the transducer beam angle. The transect density is the sum of the contributions of each detected fish to a 1 unit wide transect divided by the transect length. That is, for transect i where f_i fish are detected at depths z_h (h = 1, … , f_i), the density d_i is calculated as

$$d_i = \frac{1}{l_i} \sum_{h=1}^{fi} \frac{1}{0.1083 \times z_h}. \tag{3}$$

The mean density estimate for each trial is calculated using the standard statistical formula for mean. That is, for n grid- or star-pattern transects sampled in a trial each with density estimate d_i the estimated mean density for a survey trial is

sp

$$\bar{d} = \frac{1}{n} \sum_{i=1}^{n} d_i \tag{4}$$

Simulation trials

For both the grid- and star-pattern methods, 200 survey simulations are run for each combination of the five fish densities, four school configurations, and the two distributions, resulting in 40 estimates of mean density. Following methodologies developed for bootstrap and Monte Carlo techniques (Efron and Tibshirani 1998), the standard deviation of the mean density estimates from the 200 simulated surveys is used as an estimate of the standard error of the estimated mean density for comparative purposes. In addition, the coefficient of variation (CV) and the bias of the estimated mean density for each set of trials are calculated where

$$CV = \frac{SE(\bar{d})}{\bar{d}}, \tag{5}$$

and

$$bias = \bar{d} - D \tag{6}$$

Bias adjustment for the star-pattern density estimator

Results for the star-pattern method using the originally formulated estimator (3) indicate a systematic positive bias in the mean density estimates. The irregular placement of the star-pattern method transects precludes using a theoretical mathematical model to correct the bias. Instead, a simulation is used to provide an empirical distribution of the sampling intensity which indicates the probability of an individual fish being sampled. A modified version of the star-pattern simulation model is used to explore a weighting scheme to compensate for the perceived unequal sampling probability.

For this simulation, a data set is created where a single "fish" or data point exists at each integer coordinate (including 0) within the 100 × 100 unit simulation space, for a total of 10,201 data points, each at a depth z of –10 units. This depth is selected to provide a uniform transect width of 1.08 units ensuring that only data points lying in the immediate path of a transect are detected. In addition, the distance from each data point to the center (50, 50) of the simulation space is determined. For each trial, five transects are simulated using the star-pattern design. Data points detected by transects are coded to provide a count of the number of times a data point is detected during a trial. The simulation then keeps a running sum of detections for each data point for all trials. Simulation trials are repeated 1,200 times for a total of 6,000 transects. The count of the number of times a data point is detected is used as the sampling intensity for that data point. The resulting sampling intensity and distance to the center for each data point are used to create a model to correct the bias observed in star-pattern density estimates.

Results

Results for the grid-pattern simulations indicate the density estimator provides accurate estimates of fish densities (Table 2). All 95% confidence intervals constructed for the bias estimates of each of the 40 combinations of school configuration, distribution, and population density cover 0, indicating no significant bias exists. The two largest absolute bias estimates occur in schools 2 and 4 for densities of 0.10 fish per unit^2 drawn from a uniform distribution. All other biases vary from –0.0012 to 0.0018 with a grand mean of 0.00011. Coefficients of variation for density estimates range from 0.06 to 0.36 with an average CV of 0.16 (Table 2). On average, CVs are considerably larger for schools drawn from the uniform distribution and for schools with densities of 0.02 fish per unit^2; in general CVs decrease with increasing population density (Table 2).

The simulations for the unadjusted star-pattern surveys result in density estimates that have large, mostly positive biases (Table 3). The grand mean bias for the unadjusted star-pattern simulations (0.025) is over 200 times the grand mean bias for the grid-pattern simulations. Fourteen of the 40 density estimates (35%) resulted in bias estimates whose 95% confidence intervals do not cover 0, indicating significant biases exist, primarily for schools 1 and 2 drawn from the normal distribution. Coefficients of variation range from 0.06 to 0.35 with a mean of

Table 2. Summary of grid-pattern simulation results.

School	Distribution	Population density (fish/unit^2)	Estimated density (fish/unit^2)	Standard error	CV	Bias
1	normal	0.02	0.0197	0.0029	0.149	−0.0003
1	normal	0.04	0.0401	0.0049	0.122	0.0001
1	normal	0.06	0.0600	0.0053	0.089	0.0000[a]
1	normal	0.08	0.0794	0.0066	0.084	−0.0006
1	normal	0.10	0.1001	0.0088	0.088	0.0001
1	uniform	0.02	0.0205	0.0049	0.241	0.0005
1	uniform	0.04	0.0401	0.0053	0.132	0.0001
1	uniform	0.06	0.0607	0.0080	0.131	0.0007
1	uniform	0.08	0.0815	0.0081	0.099	0.0015
1	uniform	0.10	0.1012	0.0103	0.102	0.0012
2	normal	0.02	0.0205	0.0037	0.179	0.0005
2	normal	0.04	0.0395	0.0058	0.146	−0.0005
2	normal	0.06	0.0598	0.0069	0.115	−0.0002
2	normal	0.08	0.0794	0.0074	0.094	−0.0006
2	normal	0.10	0.0998	0.0079	0.079	−0.0002
2	uniform	0.02	0.0196	0.0070	0.359	−0.0004
2	uniform	0.04	0.0399	0.0092	0.230	−0.0001
2	uniform	0.06	0.0596	0.0126	0.212	−0.0004
2	uniform	0.08	0.0788	0.0143	0.181	−0.0012
2	uniform	0.10	0.0973	0.0193	0.198	−0.0027
3	normal	0.02	0.0206	0.0051	0.245	0.0006
3	normal	0.04	0.0400	0.0070	0.175	0.0000[a]
3	normal	0.06	0.0601	0.0061	0.101	0.0001
3	normal	0.08	0.0802	0.0070	0.087	0.0002
3	normal	0.10	0.0996	0.0062	0.062	−0.0004
3	uniform	0.02	0.0197	0.0053	0.271	−0.0003
3	uniform	0.04	0.0408	0.0076	0.187	0.0008
3	uniform	0.06	0.0610	0.0105	0.173	0.0010
3	uniform	0.08	0.0805	0.0117	0.145	0.0005
3	uniform	0.10	0.1010	0.0124	0.123	0.0010
4	normal	0.02	0.0199	0.0037	0.185	−0.0001
4	normal	0.04	0.0397	0.0059	0.149	−0.0003
4	normal	0.06	0.0591	0.0058	0.098	−0.0009
4	normal	0.08	0.0798	0.0073	0.091	−0.0002
4	normal	0.10	0.0996	0.0084	0.084	−0.0004
4	uniform	0.02	0.0199	0.0047	0.237	−0.0001
4	uniform	0.04	0.0399	0.0094	0.235	−0.0001
4	uniform	0.06	0.0599	0.0154	0.257	−0.0001
4	uniform	0.08	0.0818	0.0216	0.264	0.0018
4	uniform	0.10	0.1036	0.0239	0.231	0.0036

Densities are in fish/unit^2 (CV = coefficient of variation)

[a] Bias > 0

0.18, similar to the grid-pattern results (Table 3). Larger CVs are associated with schools 3 and 4.

Results of the modified star-pattern simulation used to determine sampling intensity are shown in Fig. 3. The maximum intensity occurs at the simulation-space center and decreases exponentially with increasing distance from the center. A desirable weighting scheme would reduce the influence of individual fish near the center of the star pattern relative to those farther from the center. A logical choice is the inverse of the mean sampling intensity (1/intensity). The relationship between the inverse of the sampling intensity and the distance to the center of the simulation space (Fig. 3) provides a plausible relationship for weighting the contribution of a fish to a density estimate. The minimum distance (a radius) from the center to the edge of simulation space is 50 units. Beyond 50 unit points exist only at the corners of the space resulting in less consistent sampling intensities (Fig. 3). To avoid areas of inconsistent sampling the distance to center data is truncated by removing data for points greater than 50 units from the center. Additionally, the distance to the center is transformed to a proportion of a maximum distance by dividing distances to the center by 50. Using the proportional distance allows the relationship with the inverse sampling intensity to be applicable to any sampling trial regardless of transect lengths. The distance to the transect endpoint farthest from the center of the simulation space provides a maximum distance that is used to scale the distance to center for each fish sampled within a trial as a proportion.

Examination of this relationship reveals it to be a simple linear function (Fig. 3). This linear function is then used as the basis for weighting a fish's contribution to transect density based on its distance from the center of the star. The base linear model between inverse sampling intensity (*ISI*) and proportional distance (*PD*) to the star center is:

$$ISI = 0.0241 \times PD + 0.0000511 \ (R^2 = 1.00,\ F = 2.97 \times 10^5,\ \mathrm{P} \ll 0.001).$$

The observed *ISI* values are too small to provide adequate weights, so a scalar is needed to increase the *ISI* values in the regression model. A logical candidate is the mean intensity for the modified star-pattern simulation output (72.5). Two values bracketing the mean intensity, 70 and 75, are selected as possible scalars and are multiplied by the *ISI* values; this product is regressed against the proportional distances and the resulting linear models are incorporated as weights into the density estimator. As before, the star-pattern method simulation is repeated for 200 trials with five transects per trial on each of the eight fish schools with a single population density of 0.06 fish per unit^2; adjusted estimates of mean density are calculated for each trial, each using the same simulated transects.

Table 3. Summary of unadjusted star-pattern simulation results.

School	Distribution	Population density (fish/unit^2)	Estimated density (fish/unit^2)	Standard error	CV	Bias
1	normal	0.02	0.0381	0.0043	0.113	0.0181[a]
1	normal	0.04	0.0734	0.0064	0.088	0.0334[a]
1	normal	0.06	0.1063	0.0085	0.080	0.0463[a]
1	normal	0.08	0.1397	0.0094	0.067	0.0597[a]
1	normal	0.10	0.1727	0.0100	0.058	0.0727[a]
1	uniform	0.02	0.0201	0.0048	0.239	0.0001
1	uniform	0.04	0.0384	0.0061	0.158	−0.0016
1	uniform	0.06	0.0616	0.0076	0.123	0.0016
1	uniform	0.08	0.0793	0.0091	0.115	−0.0007
1	uniform	0.10	0.1005	0.0107	0.106	0.0005
2	normal	0.02	0.0622	0.0070	0.112	0.0422[a]
2	normal	0.04	0.1251	0.0122	0.098	0.0851[a]
2	normal	0.06	0.1850	0.0156	0.084	0.1250[a]
2	normal	0.08	0.2461	0.0207	0.084	0.1661[a]
2	normal	0.10	0.3081	0.0233	0.076	0.2081[a]
2	uniform	0.02	0.0260	0.0045	0.171	0.0060
2	uniform	0.04	0.0541	0.0070	0.129	0.0141[a]
2	uniform	0.06	0.0819	0.0092	0.113	0.0219[a]
2	uniform	0.08	0.1107	0.0119	0.108	0.0307[a]
2	uniform	0.10	0.1386	0.0132	0.095	0.0386[a]
3	normal	0.02	0.0230	0.0054	0.234	0.0030
3	normal	0.04	0.0475	0.0100	0.211	0.0075
3	normal	0.06	0.0701	0.0122	0.174	0.0101
3	normal	0.08	0.0903	0.0146	0.162	0.0103
3	normal	0.10	0.1177	0.0183	0.156	0.0177
3	uniform	0.02	0.0198	0.0055	0.278	−0.0002
3	uniform	0.04	0.0403	0.0088	0.218	0.0003
3	uniform	0.06	0.0608	0.0119	0.195	0.0008
3	uniform	0.08	0.0815	0.0141	0.173	0.0015
3	uniform	0.10	0.0982	0.0169	0.172	−0.0018
4	normal	0.02	0.0184	0.0065	0.353	−0.0016
4	normal	0.04	0.0367	0.0113	0.308	−0.0033
4	normal	0.06	0.0575	0.0182	0.316	−0.0025
4	normal	0.08	0.0727	0.0247	0.340	−0.0073
4	normal	0.10	0.0926	0.0263	0.284	−0.0074
4	uniform	0.02	0.0214	0.0069	0.322	0.0014
4	uniform	0.04	0.0444	0.0114	0.256	0.0044
4	uniform	0.06	0.0636	0.0179	0.282	0.0036
4	uniform	0.08	0.0863	0.0215	0.249	0.0063
4	uniform	0.10	0.1078	0.0262	0.243	0.0078

Densities are in fish/unit^2 (CV = coefficient of variation)

[a]Bias significantly different from 0

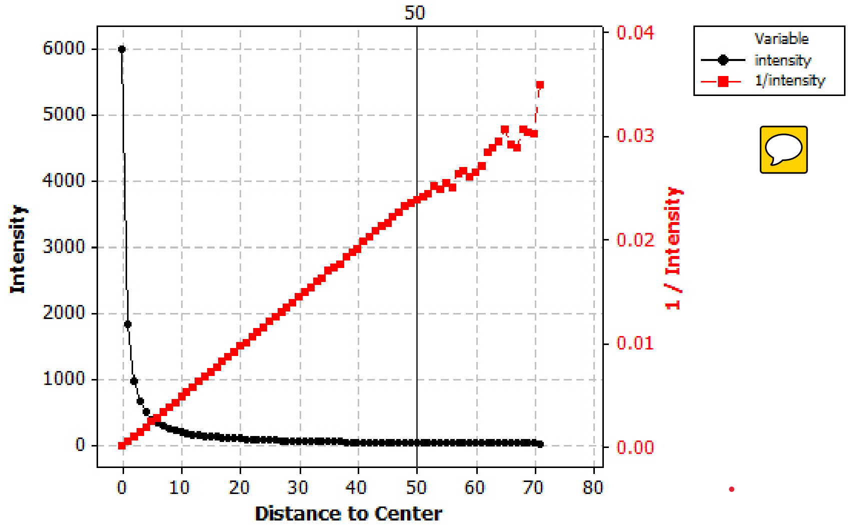

Figure 3. Plots of the mean intensity (black circles) and the inverse of the mean intensity (red squares) versus the integer distance to the center of the simulation space.

The resulting adjusted mean density estimates, while consistent over the eight fish schools, are both biased low (Fig. 4). Note that for the two scalars 70 and 75, the bias decreases (estimated density increases) with the magnitude of the scalar. Seven additional scalars, 80, 85, 90, 95, 100, 105, and 110, are applied as described above and the simulation trials are repeated. The subsequent adjusted mean density estimates exhibit a linear increase with the magnitude of the scalar (Fig. 4) with little variation in the adjusted mean density estimates associated with distribution or school configuration for any individual scalar value. Of the nine scalars used, the adjusted mean density estimates for the scalar value 95 are closest to the population density of 0.06 fish per unit^2 (Fig. 4). A linear regression for the magnitude of the scalar and the adjusted mean density estimates is calculated using the simulation results ($R^2 = 0.98$, $F = 3133.5$, $P \ll 0.001$) resulting in the equation

$$(\textit{estimated mean density}) = 0.00064 \times (\textit{scalar}) + 0.000079.$$

Solving this equation for the scalar and using a value of 0.06 for the estimated mean density results in an optimal scalar value of 93.8. This scalar value is used as discussed above to modify the star-pattern simulation. The resulting star-pattern density estimator is

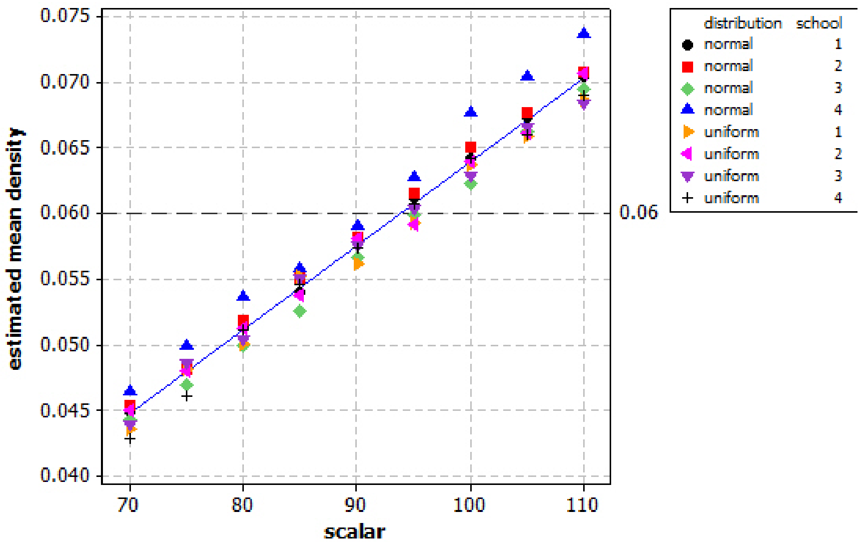

Figure 4. Plot of adjusted mean density estimates by scalar from 200 trials of the star-pattern simulation with regression line. The population density was 0.06 fish per unit² for all trials.

$$density = \left(\frac{1}{0.1083 \times z}\right) \times \frac{1}{l} \times (0.0048 + 2.26 \times pd) \tag{7}$$

where z and l are fish depth and transect length, respectively, as defined earlier, and pd is the proportional distance to the center of the star.

Results for the adjusted star-pattern simulations indicate the modified density estimator provides more accurate estimates of fish densities than the original star-pattern estimator (Table 4). When 95% confidence intervals are constructed for each bias estimate, all the intervals cover 0, indicating no significant bias exists. The largest absolute bias estimates occur for schools 1 and 4 with densities of 0.08 fish per unit². All other bias estimates ranged from –0.0021 to 0.0029 with a grand mean bias of –0.00027. Coefficients of variation for density estimates range from 0.07 to 0.35 with a mean of 0.16 (Table 4). On average, CVs are considerably larger for school 4 drawn from the uniform distribution and for schools with densities of 0.02 or 0.04 fish per unit².

Discussion

The grid-pattern method is based on simple line-transect methods with perfect detection of rockfish within the acoustic cone. The simulations of the grid-pattern survey show both the survey method and the density

Table 4. Summary of adjusted star-pattern simulation results.

School	Distribution	Population density (fish/unit^2)	Estimated density (fish/unit^2)	Standard error	CV	Bias
1	normal	0.02	0.0203	0.0025	0.124	0.0003
1	normal	0.04	0.0398	0.0045	0.113	−0.0002
1	normal	0.06	0.0602	0.0060	0.099	0.0002
1	normal	0.08	0.0802	0.0068	0.085	0.0002
1	normal	0.10	0.1004	0.0080	0.080	0.0004
1	uniform	0.02	0.0204	0.0048	0.233	0.0004
1	uniform	0.04	0.0387	0.0077	0.199	−0.0013
1	uniform	0.06	0.0593	0.0096	0.162	−0.0007
1	uniform	0.08	0.0770	0.0095	0.123	−0.0030
1	uniform	0.10	0.0998	0.0104	0.104	−0.0002
2	normal	0.02	0.0199	0.0023	0.115	−0.0001
2	normal	0.04	0.0402	0.0037	0.093	0.0002
2	normal	0.06	0.0594	0.0050	0.084	−0.0006
2	normal	0.08	0.0817	0.0060	0.074	0.0017
2	normal	0.10	0.1010	0.0078	0.077	0.0010
2	uniform	0.02	0.0194	0.0049	0.251	−0.0006
2	uniform	0.04	0.0393	0.0077	0.195	−0.0007
2	uniform	0.06	0.0591	0.0086	0.146	−0.0009
2	uniform	0.08	0.0794	0.0112	0.142	−0.0006
2	uniform	0.10	0.0985	0.0112	0.113	−0.0015
3	normal	0.02	0.0196	0.0050	0.256	−0.0004
3	normal	0.04	0.0391	0.0046	0.119	−0.0009
3	normal	0.06	0.0591	0.0067	0.113	−0.0009
3	normal	0.08	0.0781	0.0090	0.115	−0.0019
3	normal	0.10	0.0979	0.0096	0.098	−0.0021
3	uniform	0.02	0.0200	0.0049	0.244	−0.0000[a]
3	uniform	0.04	0.0396	0.0081	0.205	−0.0004
3	uniform	0.06	0.0597	0.0096	0.161	−0.0003
3	uniform	0.08	0.0787	0.0105	0.134	−0.0013
3	uniform	0.10	0.0987	0.0133	0.135	−0.0013
4	normal	0.02	0.0207	0.0043	0.209	0.0007
4	normal	0.04	0.0417	0.0081	0.194	0.0017
4	normal	0.06	0.0622	0.0103	0.166	0.0022
4	normal	0.08	0.0837	0.0147	0.176	0.0037
4	normal	0.10	0.1029	0.0179	0.174	0.0029
4	uniform	0.02	0.0194	0.0067	0.347	−0.0006
4	uniform	0.04	0.0395	0.0113	0.286	−0.0005
4	uniform	0.06	0.0586	0.0147	0.252	−0.0014
4	uniform	0.08	0.0770	0.0183	0.238	−0.0030
4	uniform	0.10	0.0986	0.0223	0.226	−0.0014

Densities are in fish/unit^2 (CV = coefficient of variation)

[a]Bias < 0

estimator employed in the data analysis provide accurate estimates of fish densities. The biases for the grid-pattern density estimates are not statistically significant and vary due to random error introduced by the simulation process (Table 2). The CVs for the density estimates vary by population density, school configuration, and distribution. With the exception of school 4 drawn from the uniform distribution, CVs for the grid-pattern method decrease with increasing population density (Table 2, Fig. 5). Higher population densities increase the probability a grid-method transect will detect fish, resulting in less variability in transect densities. Lower mean CVs are found for school 1 (mean CV = 0.124) and school 3 (mean CV = 0.157) relative to school 2 (mean CV = 0.179) and school 4 (mean CV = 0.183). School 1 and school 3 configurations allow every grid-pattern transect to potentially contact some part of the school resulting in few transects with zero detections, where grid-pattern transects crossing schools 2 and 4 are more likely to have zero detections resulting in estimates with higher variability (Fig. 2).

At first the star-pattern method, like the grid-pattern method, is treated as a line transect survey, but the geometry of the transect placement requires additional data weighting. Previous uses of the star-pattern method (see Josse et al. 1999, Doonan et al. 2003) involve echo integration and the analytical methods are not appropriate for individual-fish data employed in this study. Previously it was shown by Yule (2000) that a fish's contribution to the density of a 1 unit wide transect is a function of its depth based on the geometry of the acoustic cone. Creating an empirical model for sampling intensity allows the creation of linear model to weight the contribution of a fish to a transect density as a function of its distance to the survey star's center, similar to the depth adjustment. The sampling intensity data are used to create a model to correct for bias resulting in a simple linear function that, when scaled properly, provides the necessary bias correction for the contributions of individual fish to transect fish densities. Depending on the school configuration, the adjusted star-pattern method estimates of mean density compare favorably to those obtained using the grid-pattern methods (Tables 2 and 4). For the adjusted star-pattern method no significant bias is observed and differences by school configuration, population density, and distribution are likely due to randomness in the simulation process. Similar to the grid-pattern results, CVs for the adjusted star-pattern method generally decrease with increasing population density for the same reason (Table 4, Fig. 5). Lower mean CVs are found for school 1 (mean CV = 0.132) and school 2 (mean CV = 0.129) relative to school 3 (mean CV = 0.158) and school 4 (mean CV = 0.227). This is expected as schools 1 and 2 are by design located around the simulation space center and all five star transects will contact these schools in a similar way. School 4 exhibits the largest mean CV since few star transects are likely to actually cross schools in this configuration

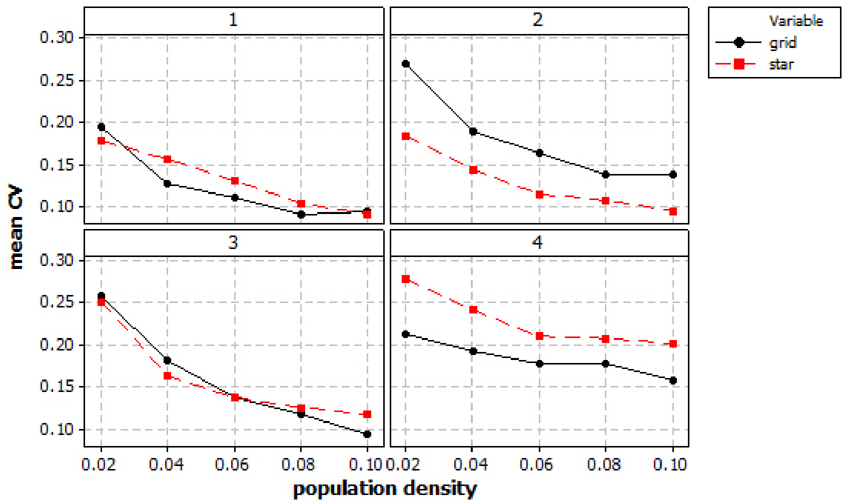

Figure 5. Plots of mean CV versus population density for the grid and adjusted-star survey methods and four school configurations.

resulting in multiple transects with zero densities leading to greater variation in density estimates.

As mentioned previously, CVs are similar for both survey patterns and show a consistent decrease with increasing population density. What differences in CVs exist between the two survey methods indicate that, besides population density, school configuration also affects the magnitude of CVs. Averaging the CVs from each distribution gives the mean CV by population density, survey method, and school configuration (Fig. 5). From this perspective the survey method with the smaller CV is preferable to the other for a given school configuration. For school 1 the grid method has slightly lower CVs, which might be expected given the diffuse nature of the fish distribution. School 2, however, is clearly better sampled by the adjusted star method. This school is purposely located at the center of the simulation space as an analog of a rockfish school associated with a pinnacle, the circumstance the star method is designed to sample. The performance of the two methods is nearly identical for school 3. A school of this configuration in a field situation would likely be surveyed using the grid method given its elongate form with transects parallel to the longer axis. Overall, the mean CVs indicate the grid method is preferable to the star method for school 4. In a field situation a rockfish school with this configuration would be surveyed using the star method centered on the school rather than the simulation space.

The data acquisition and analyses used in acoustic rockfish surveys appear to provide reasonably unbiased estimates of rockfish density regardless of the characteristics of the rockfish schools being surveyed. The grid-pattern method, as expected, provides unbiased estimates without any modification of analyses used. The star-pattern method requires some adjustment to the data analysis based on a fish's distance to the center of the star-pattern transects, but once this adjustment is made unbiased estimates are reliably obtained.

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