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[Managment Brief]

Index-Removal Estimates of Dredge Efficiency for Sea Scallops on Georges Bank

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Abstract.—In June of 1999, fishermen were allowed access to the southern section of Georges Bank Closed Area II in the North Atlantic to harvest the large biomass of sea scallops *Placopecten magellanicus* that had accumulated during a 5-year multispecies fishing ban. Prior to the opening, managers conducted a fine-scale survey of the area and a catch quota was established as a fixed percentage of the estimated biomass. The estimate of biomass was uncertain because it was based on estimates of dredge efficiency that ranged from 16% to 40%. Because survey stations were reoccupied at the end of the fishery and significant removals had occurred, it was possible to use the index-removal method to obtain an estimate of gear efficiency. The estimate was 54% and ranged from 41% to 54% depending on model inputs. The 54% efficiency is believed to represent a maximal efficiency estimate.

In 1998, the fishery for sea scallops *Placopecten magellanicus* began lobbying for access to the Georges Bank closed areas in the North Atlantic to harvest the large biomass that had accumulated during a 5-year multispecies fishing ban. An industry–government partnership was initiated to provide a more detailed description of sea scallop abundance in the closed areas. As part of this cooperative program, a fine-scale grid survey of Georges Bank Closed Area II (GBCAII) (Figure 1) was conducted to quantify resource abundance and distribution during the summer of 1998.

The results of this survey provided managers with enough information to develop Framework Adjustment 11 to the Scallop Fishery Management Plan (FMP) and Framework Adjustment 29 to the Northeast Multispecies FMP. These framework adjustments allowed sea scallop fishermen access to the southern section (south of 41°30′N) of GBCAII as part of an experimental fishery program beginning on June 15, 1999.

Prior to the opening, indices of biomass were generated from both the 1998 cooperative survey and the annual sea scallop survey conducted by the National Marine Fisheries Service (NMFS) RV *Albatross*. However, the conversion of this information into absolute values was difficult. Three different models estimated 16–40% dredge efficiency and left managers with absolute biomass estimates that ranged from 25 million to 63 million lb and sea scallop total allowable catch (TAC) estimates that ranged from 6 million to 15 million lb.

A sea scallop TAC was set at approximately 10 million lb based on an assumed gear efficiency of 25%, and a bycatch TAC for yellowtail flounder *Limanda ferruginea* was set at 850,000 lb. In 5 months, nearly 6 million lb of large sea scallop meats were harvested before the yellowtail flounder TAC was reached on November 12, 1999. A study we conducted during the opening (Gedamke et al. 2004) and a review of data from the opening (NEFMC 2000) indicated that the 25% efficiency chosen in the final framework adjustment significantly overestimated stock size.

In this study, preseason survey stations were reoccupied during the last few weeks of the commercial fishery. Since total catch is known and a postfishing survey index is available, the gear efficiency can be estimated with the index-removal method (see Hoenig and Pollock 1998).

Methods

Study site and data collection.—The GBCAII is located along the Hague line in the easternmost U.S. portion of Georges Bank (Figure 1). It is approximately 200 nautical miles (nm) off the coast of Cape Cod, Massachusetts, and encompasses an area of 2,020 nm^2. Three different sources of information from GBCAII were used for this study: a 1998 cooperative fine-scale grid survey, vessel monitoring system (VMS) reports, and survey data collected onboard commercial vessels during the last few weeks of the opening.

The 1998 cooperative survey involved participants from the Center for Marine Science and Technology of the University of Massachusetts–Dartmouth, the Virginia Institute of Marine Science (VIMS) of the College of William and Mary,

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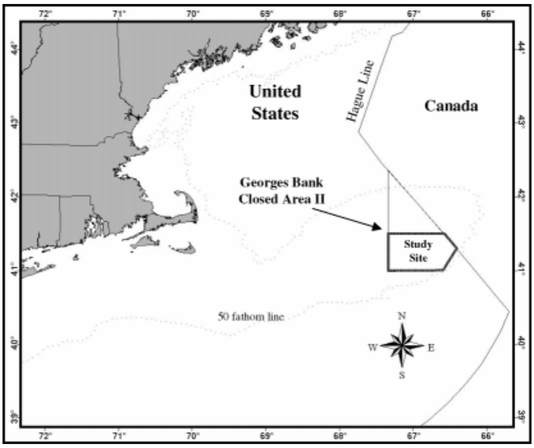

FIGURE 1.—Map showing the location of Georges Bank Closed Area II (GBCAII) in the North Atlantic. The study site was the southern section of GBCAII, which was reopened to fishing during 1999.

the Fisheries Survival Fund of New Bedford, Massachusetts, and the NMFS. Length-specific catch data were collected onboard six commercial fishing vessels that sampled both a fine-scale grid (stations approximately 2 nm apart) and also reoccupied stations from the 1998 NMFS annual stratified random survey. Stations (n = 497) that were located in and around the reopened southern section of GBCAII provided us with an extremely fine-scale description of resource abundance and composition prior to the opening (Figure 2). Survey tows were 10 min in length and were conducted with commercial gear in the same configuration (two 15-ft dredges fitted with 3.5-in rings and 10-in twine tops) that was used by most of the vessels during the opening.

During the last 4 weeks of the opening, 84 of the 497 stations from the 1998 surveys were reoccupied by cooperating commercial fisherman (Figure 3). The same sampling procedures employed in the preseason survey were utilized. Vessels participating in the research program were compensated with an exemption from the 10,000-lb possession limit and were allowed to possess a

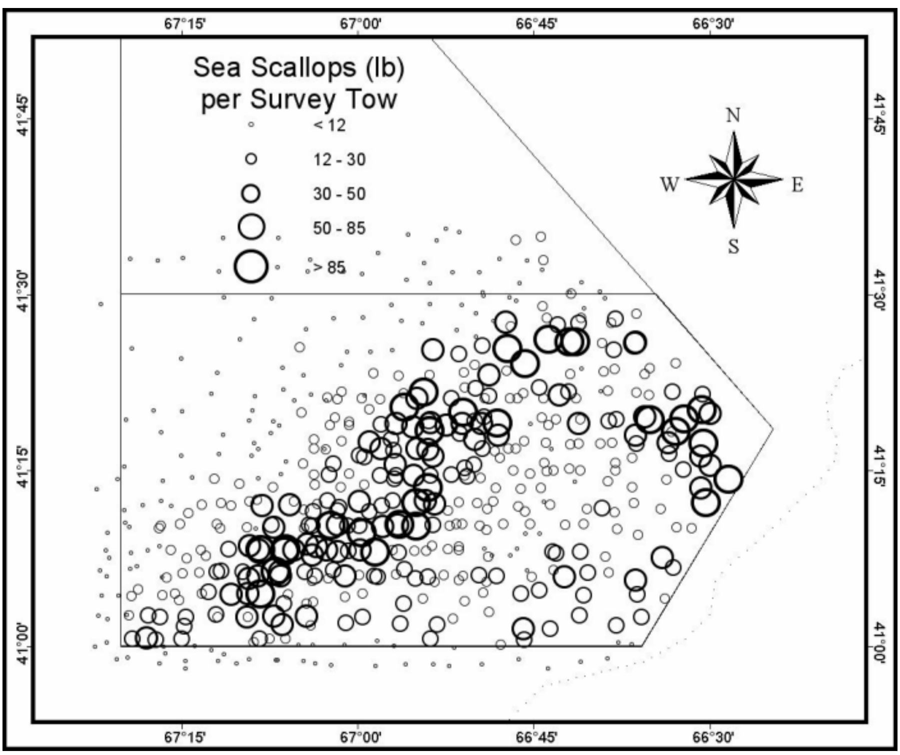

FIGURE 2.—Sea scallop catch at survey and grid stations in Georges Bank Closed Area II from the 1998 cooperative survey used for kriging analysis (n = 497). Catch weights reported are per 10-min survey tow; sea scallop data were advanced in time to June of 1999 to account for natural mortality and growth.

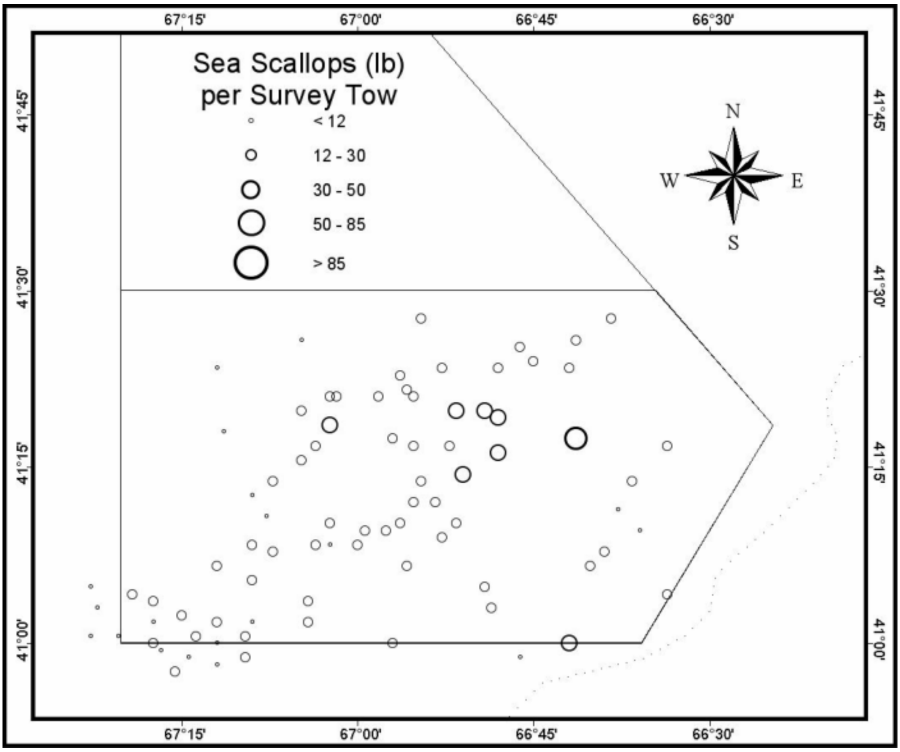

FIGURE 3.—Sea scallop catch from the Georges Bank Closed Area II cooperative survey stations that were reoccupied at the end of the 1999 opening (n = 84). Catch weights reported are per 10-min survey tow.

total of 13,000 lb. Sixty-four of these stations were sampled onboard the same vessel (FV *Celtic*) that conducted the original industry survey. Basic descriptive statistics on individual variables and regressions between correlated data were used as an auditing tool to ensure the integrity of our data and to correct shipboard recording and data entry errors.

The spatial and temporal distribution of fishing effort during the opening was determined from VMS data obtained from the NMFS. The VMS has been in place since 1998 and provides time-referenced positions for every vessel in the fleet. The speed of vessels was calculated from successive positions, and vessels traveling less than 5.5 knots were assumed to be fishing. A 95% kernel analysis was conducted on the cumulative VMS data in ArcView (animal movement extension) to determine the effective area fished (Silverman 1986; ArcView 1999; Hooge et al. 1999). For the remainder of this paper, this 95% kernel of effort will be referred to as the effective area fished (Figure 4).

We used the selectivity curve of DuPaul et al. (1989) to correct raw catch data from both surveys for gear selectivity. Data from the cooperative 1998 survey were then corrected for growth and natural mortality by use of growth parameters from Serchuk et al. (1979) (k [the growth coefficient] = 0.3374 per year, t_0 [the theoretical age when length = 0] = 1.4544 per year, L_∞ [the maximum length] = 152.46 mm) and an assumed natural mortality of 0.1 per year. This procedure projected the biomass ahead by 10 months to the start of the opening of GBCAII on June 15, 1999, and accounted for the error potential arising from recruitment during the period prior to the opening. Only animals that were, or were projected to be, greater than 3.15 in (80 mm) during the fishery were included in the analysis. Finally, the size frequency composition of the catch was used to convert catch data to biomass by means of the shell height–meat weight relationship:

$$W = \exp(a + b \cdot \log_e[s]), \qquad (1)$$

where W is the meat weight (g; 1 g = 0.0353 oz) of a sea scallop of shell height s (mm; 1 mm = 0.0394 in), a = −11.4403, and b = 3.0734 (NEFMC 2000).

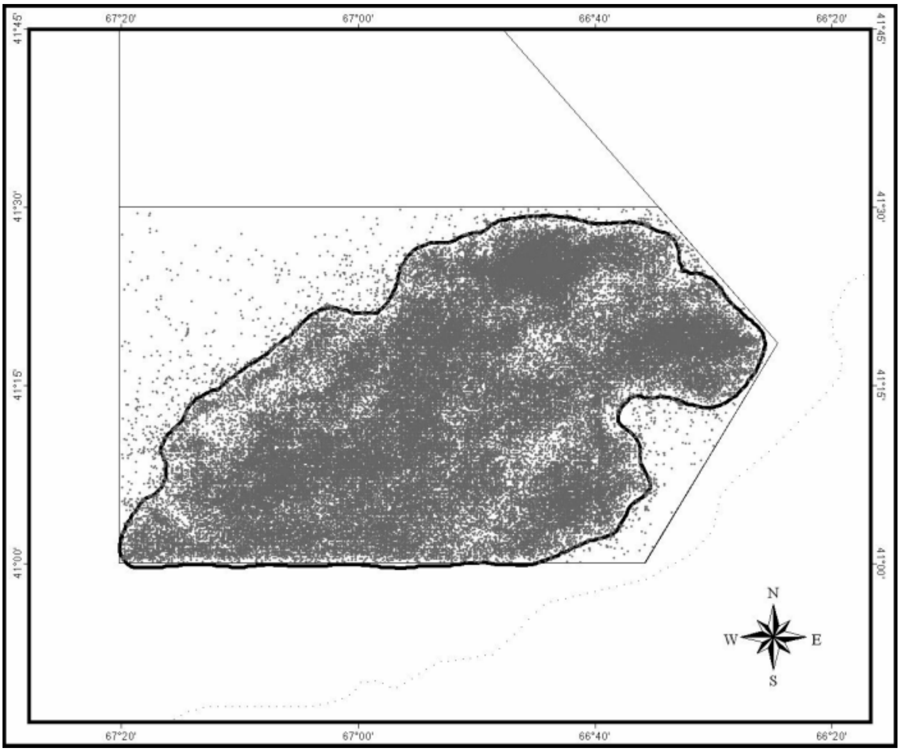

FIGURE 4.—Effective area fished, as determined by a 95% kernel analysis of all vessel monitoring system (VMS) data observed during the entire opening of Georges Bank Closed Area II in 1999. Each point in the plot represents a single report from the VMS system. Vessels effectively fished 68% of the total reopened area.

We then used ordinary kriging to calculate indices of abundance from survey data. Kriging requires the assumptions that (1) there is no spatial trend in the data and (2) the pattern of spatial autocorrelation is isotropic or the same in all directions (Webster and Oliver 2001). The data were evaluated for spatial trends by examining the plots of the data against both latitude and longitude. The data were also examined for anisotropy through directional variograms. Slight trend and departure from isotropy were observed but did not appear to be important enough to warrant action to detrend the data or correct for anisotropy. An empirical semivariogram was generated from the 1998 survey stations and was fit to a spherical model by weighted least squares in SPLUS (Kaluzny et al. 1997). A spherical variogram model was chosen because it provided a good fit to the data and was observed by Warren (1998) to be applicable to sea scallops. Kriging estimates were then calculated on a 0.125-nm grid by use of the theoretical variogram and the PROC KRIG2D procedure in the Statistical Analysis System (SAS 1999). Mean catch indices were then calculated from the grid points within both the effective area fished and the entire southern GBCAII section that was reopened to fishing. As reported in Framework 11, a nominal survey tow length of 1 nm was used to determine swept area sampled (NEFMC 1999a).

Index-removal method.—The theoretical framework for the index-removal method was introduced by Petrides (1949) and has been built upon by Seber (1973), Routledge (1989), Dawe et al. (1993), and Chen et al. (1998) (see Hoenig and Pollock 1998 for a review). We assume that

(1) the population is closed except for the known removals (i.e., immigration, emigration, recruitment, and natural mortality are negligible);
(2) all animals have the same probability of capture in the surveys, and this probability does not vary from survey to survey; and
(3) the fraction of the population taken in the surveys (compared to total removals) is negligible.

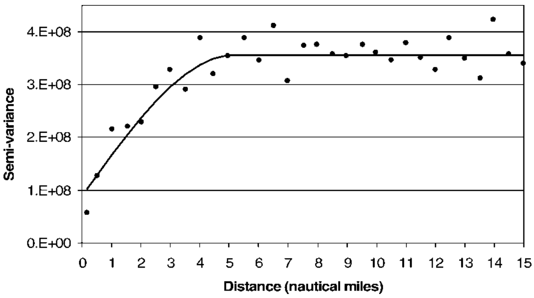

FIGURE 5.—Semivariogram generated from the 1998 Georges Bank Closed Area II cooperative survey stations. The dark line indicates the spherical model used in the analysis (range = 5.2 nm, sill = 3.5 × 10^8 nm^2, nugget = 8.9 × 10^7).

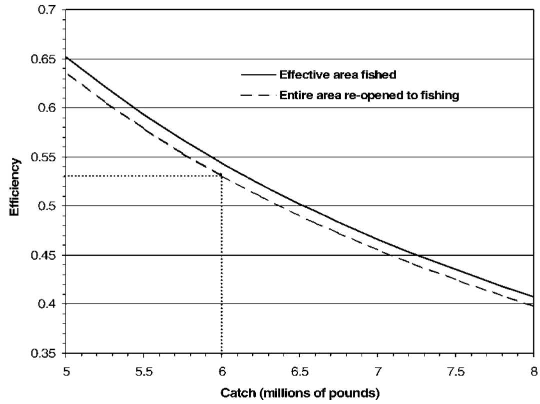

FIGURE 6.—Response of dredge efficiency estimates to total sea scallop catch (or total removals) input to the model for the Georges Bank Closed Area II. The total reported landings and the corresponding efficiency estimate are indicated by the dashed line. To illustrate the sensitivity of the model, removals as low as 5 million lb are included.

Given these assumptions, we can determine the following:

$$\text{prefishing population} = N_1 = \frac{(I_1 \cdot A/a)}{E} \qquad (2)$$

$$\text{postfishing population} = N_2 = \frac{(I_2 \cdot A/a)}{E} \qquad (3)$$

$$\text{catch} = N_1 - N_2$$

or, equivalently,

$$N_2 = N_1 - C, \qquad (4)$$

where I_1 and I_2 are the expected values of pre- and postremoval catch indices, respectively; A is the total study area; a is the area sampled (swept area of survey dredge); E is dredge efficiency; and C is total commercial catch. By substitution, I_1 and I_2 are related to total catch by the following equation:

$$\text{catch} = C = \frac{(I_1 \cdot A/a)}{E} - \frac{(I_2 \cdot A/a)}{E}. \qquad (5)$$

Equation (5) is equivalent to

$$E = \frac{(A/a) \cdot (I_1 - I_2)}{C}. \qquad (6)$$

An efficiency estimate made by the method of moments is obtained by replacing the expected values of the indices with survey estimates. This is also the maximum likelihood estimate.

These results were then used to solve equation (6) for efficiency based on a known catch of 5,996,110 lb.

Results

The fitted spherical experimental semivariogram (Figure 5) produced from the 1998 cooperative survey showed a range of 5.2 nm, a sill of 3.5 × 10^8 nm^2, and a nugget value of 8.9 × 10^7. Kriged estimates of preseason survey catch data projected forward in time from 1998 based on these fitted variogram parameter values had a mean of 33.6 lb/tow over the entire reopened area, while the estimate from the effective area fished (95% kernel) was 41.6 lb/tow.

A very different picture was generated from the survey stations resampled after the fishing season (Figure 3). Kriged estimates for the entire reopened area from the 1999 postseason survey stations showed a considerable reduction of the mean catch to 20.0 lb/tow. The effective area fished had a postseason mean of 21.0 lb/tow. Using the mean catch indices from both surveys and a total catch of 5,996,110 lb, we solved equation (6) to obtain efficiency estimates of 53.1% for the entire reopened area and 54.4% for the effective area fished. The model's sensitivity to total catch estimates was then evaluated. If total catch had actually been 7 million lb instead of 6 million lb, efficiency estimates would have been reduced to 45.5% for the entire reopened area and 46.6% for the effective area fished (Figure 6).

Discussion

Dredge efficiency was estimated to be 53.1% and 54.4% by applying the index-removal method to survey data collected before and after the opening of GBCAII. Although survey stations were resampled identically and Chen et al. (1998) found this to increase the precision of results in this type of analysis, a random selection of stations was not used, so a traditional approach to data analysis was not applicable. Kriging represents one approach that does not have the assumption of randomness and is suitable for both the systematic grid conducted in 1998 and the resampled survey data collected at the end of the opening (Petitgas 1993; Webster and Oliver 2001).

Interest in kriging arose from attempts to utilize the spatial patterns of populations and the spatial correlation between samples in the analysis. Previous applications for the assessment of marine species have been conducted primarily on relatively sedentary animals (Simard et al. 1992; González-Gurriarán et al. 1993), including sea scallops (Ecker and Heltshe 1994; Warren 1998). Advocates of kriging suggest that results from this technique are more accurate because of a smaller standard error; however, due to fundamental differences in the techniques, variance estimates from kriging and traditional analysis methods cannot be compared (Brus and De Gruijter 1993, 1997; Warren 1998).

Although we omitted variance estimates here because of this conceptual problem, the reliability of the results is supported by the fact that the mean catch indices generated from our analysis were consistent with those generated from the NMFS stratified random survey. Catch indices for the southern half of GBCAII from the 1998 survey, advanced forward in time to represent predicted values for the opening, were approximately 33.1 lb/survey tow for the NMFS calculations and 33.6 lb/survey tow from the kriging technique (NEFMC 1999a). Although fewer stations were sampled postseason, large amounts of fishing effort had selectively targeted the highest density areas, significantly reducing the overall variance of the population (Langton and Robinson 1990). Thus, the chance of errors stemming from the spatial distribution of the resource was greatly reduced.

The efficiency estimates calculated with the index-removal method were made by assuming that the population was closed and that all removals were known. The documented landings during the opening of GBCAII were 5,996,110 lb, and this value was used as the total removal parameter in our model. Even if every landed sea scallop meat was reported, the actual total losses from the area are likely to be greater than the total reported catch. For example, the shell height–meat weight relationship used to convert size-specific catch data to biomass can be altered by a number of factors, including meat weight gains due to freshwater absorption (DuPaul et al. 1990), variable commercial shucking yields (Kirkley and DuPaul 1990), and postspawning meat weight losses (NEFMC 1999b). In addition, minor removals of additional sea scallops would have occurred on vessels that processed catches and discarded animals while steaming home. These factors probably led to a modest understatement of the total removals. As a result, it is likely that efficiency was overestimated.

Additional losses are also likely from natural, discard, and noncatch mortality. Although the effects of an assumed natural mortality rate of 0.1 per year were probably not important over the 5-month opening, recent studies suggest that the incidental mortality of sea scallops may be as high as 15% of the catch (Caddy 1973; NEFSC 2001). In addition, sea scallops caught and then discarded would have been subjected to some additional level of mortality that would have resulted in greater overall removals. A summary of these factors in the 2000 Scallop FMP Stock Assessment and Fishery Evaluation Report suggested that actual removals were closer to 30% greater than the documented landings (NEFMC 2000). If actual removals were between 10% and 20% of the documented landings, an additional 0.6 million to 1.2 million lb would have been lost to these processes and our efficiency estimates would range from 44.2% to 49.4%. If we assume that total nonharvest losses from all causes were no greater than 30% of the documented landings, our efficiency estimates would range from 40.8% to 54.4%.

The efficiency estimates presented in this study support the results of recent comparable studies, which suggest that the 16–40% range used in Framework Adjustment 11 was too low. As we summarized in a prior study (Gedamke et al. 2004), early studies by Caddy (1968, 1971) estimated efficiency in the range of 8.3–16.9%, while recent research points toward efficiencies of over 40%. A modified depletion model that was applied during the 1998 survey of GBCAII estimated efficiency at 41% (NEFMC 1999a). We (Gedamke et al. 2004) applied a spatially explicit DeLury analysis to commercial catch data collected during the opening and estimated a minimal efficiency of 42.7%. It should be noted, however, that Caddy's (1968, 1971) lower estimates resulted from very different resource and operational conditions than those of this study and that gear efficiency is likely to be strongly tied to bottom type, resource conditions, and fishing behavior.

If we assume that 54% represents an upper-limit estimate of efficiency, while the result of 43% in our prior study (Gedamke et al. 2004) represents a minimal estimate, then the actual gear efficiency in GBCAII is probably within the 45–50% range. The approach presented in this study provides a relatively easy way to calibrate regional efficiency estimates and could be applied to any situation where pre- and postseason indices of abundance can be related to a known harvest.

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