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A Spatially Explicit Open-Ocean DeLury Analysis to Estimate Gear Efficiency in the Dredge Fishery for Sea Scallop *Placopecten magellanicus*

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Abstract.—The translation of survey data into estimates of absolute abundance hinges on the availability of an accurate estimate of gear efficiency. In many fisheries, however, a wide range of estimates exists and research directed at quantifying this critical parameter has focused on relatively small, fishery-independent data sets. In the present study, a technique was developed to utilize the copious amounts of data available from an open-ocean fishery for sea scallops *Placopecten magellanicus* in a spatially explicit depletion model. In June 1999, Georges Bank Closed Area II was opened to the commercial scallop fleet after a 5-year multispecies fishing ban. During the 5-month opening, the spatial distribution and magnitude of fishing effort was tracked through vessel monitoring systems, and a relatively small but still substantial number of catch observations were made aboard vessels from the commercial fleet. A spatial analysis of both catch and effort data was utilized to select areas consistent with the assumptions of a DeLury analysis. Maximum likelihood estimation was then used to generate a single estimate of the catchability coefficient (and thus efficiency), while simultaneously estimating the initial abundance in each area. The gear efficiency of the New England-style scallop dredge used during the fishing season was estimated to be 42.7%. A sensitivity analysis of model results shows a potential range of 35.5–52.5%, depending on model assumptions.

In fisheries management, survey data are routinely used to calculate the absolute abundance of stocks. Typically, catch indices from survey data are expanded to absolute values by the ratio of total survey area to the area sampled and also by the efficiency of the sampling gear. Unfortunately, in many fisheries, a single definitive and accepted gear efficiency estimate is not available, leading to uncertainty in biomass estimates and the overall stock assessment. In turn, managers have difficulty setting quotas to achieve specific exploitation levels chosen to maximize yield or net benefits from the resource.

These difficulties were evident as plans were being made for the 1999 fishery for sea scallop *Placopecten magellanicus* in Georges Bank Closed Area II (GBCAII). Following the National Marine Fisheries Service's (NMFS) annual sea scallop survey in 1998 and the discovery of high densities of large scallops, the area was resurveyed intensively by commercial vessels and gear over a fine-scale grid. Very similar indices of abundance were generated from the two surveys. The efficiency of the survey and commercial dredges is believed to be very similar, but estimates of this efficiency ranged from 16 to 40%. This left managers with total allowable catch (TAC) estimates that ranged from 6 to 15 million lb. Agreeing on a suitable efficiency estimate proved difficult, and an intermediate value of 25% was used to compute the TAC for the opening (NEFMC 1999). A preliminary look at the declines in catch per unit effort (CPUE), however, suggests that efficiency was underestimated and the resulting biomass estimates and TAC were too high (NEFMC 2000).

To resolve the question of gear efficiency, estimates can be made directly from photographic, video, or diver observations and indirectly from depletion estimators (e.g., Leslie–DeLury methods), mark–recapture studies, or change-in-ratio methods. Unlike fishery-independent data sets, which are typically limited in size and generated specifically for these analyses, fishery-dependent catch rate information is often copious and readily available and offers the potential to use depletion estimators. The basic logic was first introduced by Leslie and Davis (1939), and since then the methodology has been generalized for a variety of applications. The general approach, now known as depletion estimation, has been applied to both commercial and research data in terrestrial (Fletcher et al. 1990), marine (Lasta and Iribarne 1997; Currie and Parry 1999), and freshwater studies (Havey et al. 1981; Schnute 1983).

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Traditionally, the application of depletion estimators has been limited to the relatively small data sets from unique controlled settings for which detailed spatial information was available on catch and effort. The extensive amounts of open-ocean commercial data have rarely been used due to difficulties in meeting the assumptions of depletion estimators. The analysis and interpretation of data from commercial fishers is hindered by the lack of a proper sampling design (Ricker 1975) and spatial details on catch and effort (Paloheimo and Dickie 1964). The vessel monitoring systems (VMSs) now in place in many fisheries have created a new opportunity to utilize the huge amounts of available fishery-dependent data.

In this study, information from VMSs was used to disentangle the effects of nonrandom fishing patterns so that a depletion model could be applied. In addition, a comparatively small, yet nonetheless substantial amount of CPUE data were collected from commercial vessels during the 1999 sea scallop fishery in GBCAII and used along with the massive amounts of effort data from VMSs to estimate dredge efficiency. A spatial analysis was developed to select regions (and therefore subsets of the data) where the assumptions of a depletion estimator are met. Estimates of the catchability coefficient (q) and thus efficiency (E) could then be made from each area separately to explore the variability in estimates of E. If the estimates of E are similar in all suitable areas, a maximum likelihood estimator (MLE) can be used to analyze data from all areas simultaneously to estimate a single q (and thus E) and separate local abundances (N_0) for each area. This should result in a more precise estimate of E when E is more or less constant within the study area.

Methods

Study site and period of study.—Georges Bank Closed Area II is located in the easternmost U.S. portion of Georges Bank along the Hague line (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. Depths are generally between 150 and 300 ft with gravelly sand and gravel pavement in the north and large areas of sand and sand waves in the south (Valentine and Lough 1991). The area was closed to all mobile fishing gear in 1994 due to concerns about the low abundance of groundfish stocks, and by 1998 dramatic increases in sea scallop biomass were observed. Both industry and management recognized the potential benefits of redirecting effort from the heavily fished open areas, and the process to reopen the area to scallop fishermen began.

Both NMFS and commercial surveys identified high densities of large sea scallops (>120 mm [4.68 in]) in both the northern peak and along a southwest-to-northeast axis in the southern part of the region (NEFMC 1999). Using an efficiency estimate of 25% to generate a TAC of 9.4 million lb, NMFS opened the area south of 41°30′N to restricted fishing on June 15, 1999. The area was closed on November 12, 1999, when the allowable bycatch of yellowtail flounder *Pleuronectes ferrugineus* was exceeded and just over 6 million lb of scallop meats had been landed.

Data collection.—Data were collected on eight commercial scallop boat trips made from the opening of the GBCAII on June 15 until the closure of the area on November 12. During this time, two scientists from the College of William and Mary's Virginia Institute of Marine Science worked onboard seven of the larger (88–109-ft) and higher-horsepower (850–1,550) commercial vessels in the fleet, namely, FVs *Celtic, Tradition, Mary Anne, Alpha Omega II, Endeavor, Barbara Anne,* and *Heritage*. All of these vessels towed two 15-ft, New England-style scallop dredges fitted with 3.5-in rings and 10-in twine tops.

Trip length ranged from 4.5 to 12.8 d, for a total of 72 d at sea or 144 scientist days at sea. Vessels made an average of 140 tows per trip (range, 38–267 tows) and fished for an average of 8.9 d per trip (range, 2.8–11.1 d) to reach their trip possession limit of 13,000 lb. (Vessels participating in the research program were compensated with an exemption from the 10,000-lb limit and allowed to land 13,000 lb.) Position, catch, and swept-area information was obtained for 1,042 commercial tows on the eight research trips. Length-frequency distribution data were collected from 558 of these tows.

The spatial and temporal distribution of fishing effort for the entire fleet during the opening was determined from satellite positions obtained from VMS data provided by the NMFS. Vessel monitoring systems have been in place since 1998 and provide a time-stamped position and vessel-identifying number for every vessel in the fleet. The NMFS provided us with a data set that contained position, date, time, vessel speed, and time elapsed since the last transmission. From this information, we were able to eliminate data from vessels that were steaming in and out of the area (based on a vessel speed of greater than 5.5 knots) and also potentially faulty information from vessels that

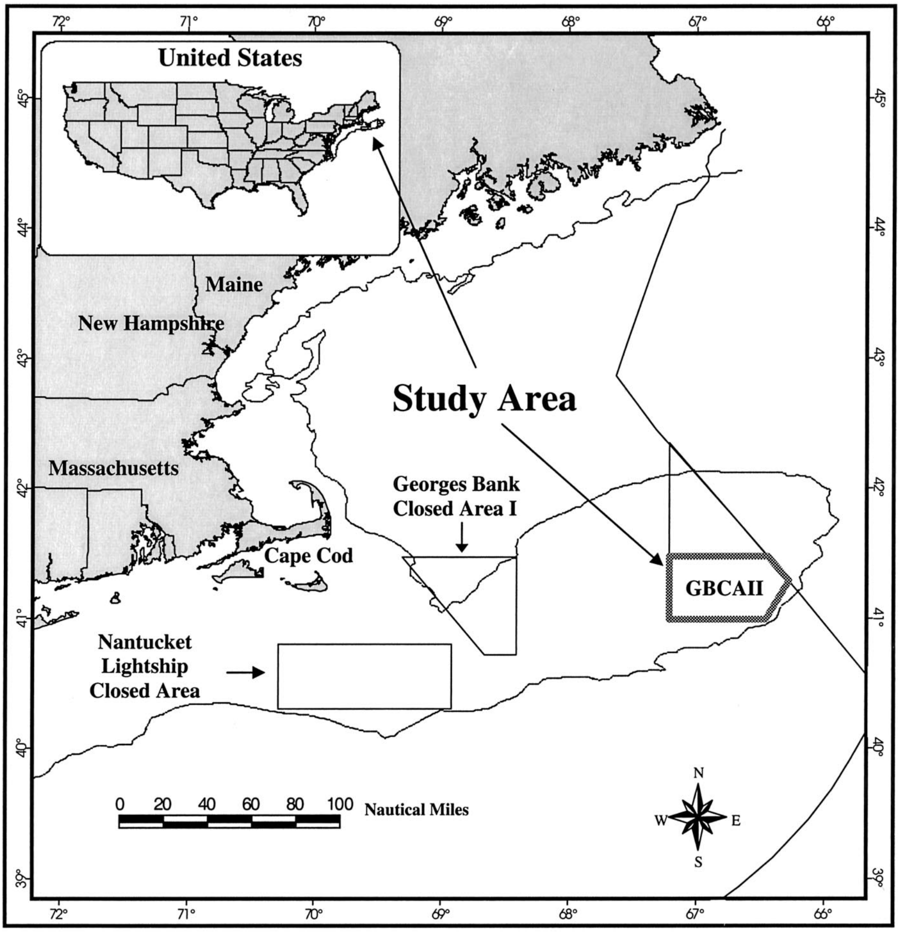

FIGURE 1.—Map showing the locations of Georges Bank closed areas. The southern section of Georges Bank Closed Area II (GBCAII), which was reopened to fishing, has been indicated.

had not reported a position for over 12 h. All data manipulation and additional analysis were done with SAS (SAS Institute 1999).

Standardizing raw data and defining units of effort.—Catch rates were calculated from each dredge on each tow and only successful tows were included in the analysis (i.e., data from flipped or damaged dredges were removed). Length-frequency data from subsampled bushels were collected to calculate the average size and number of individuals per bushel. An estimated total number of individuals caught and retained for each tow was then calculated by applying the average number of individuals per bushel to total bushel counts. All catch data were then standardized to the number of individuals captured per minute of gear time on the bottom.

The spatial and temporal distribution of fishing effort provided by the VMS represents total fishing time and needs to be scaled to represent actual minutes of gear time on the bottom. On seven of the eight trips sampled for this study, vessels had gear on the bottom for a mean of 45 min/h of fishing. Under normal fishing operations, raw VMS data were scaled down by the bottom time constant (i.e., 0.75 for 45 min of bottom time per hour of fishing); however, at the extremely high catch rates observed on one sampling trip the actual bottom time was constrained by production capabilities and a correction had to be applied (see Application section for specifics).

Model overview.—The opening of GBCAII provided a semicontrolled environment with which to investigate dredge efficiency and develop a spatially explicit DeLury model. A spatial and temporal analysis of the distribution of fishing effort

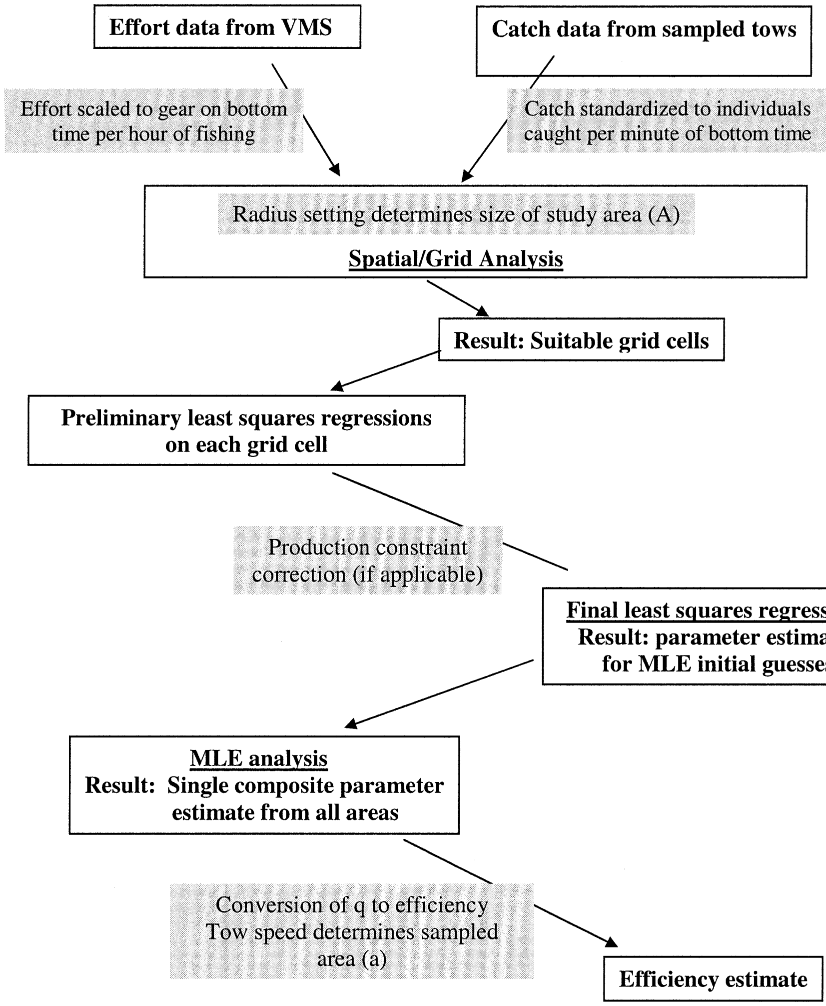

FIGURE 2.—Conceptual diagram of the model design for analysis of declines in commercial sea scallop catch per unit effort (CPUE). All variable inputs and model options are highlighted in gray; VMS refers to vessel monitoring system data, MLE to maximum likelihood estimation, and q to the catchability coefficient or slope of the decline.

and CPUE observations was used to select subsets of the data for which the assumptions of a depletion analysis were met. Declines in CPUE were then evaluated through linear least-squares regressions and corrected for production constraints; finally, a single efficiency estimate was generated through maximum likelihood estimation (Figure 2). A sensitivity analysis was performed to determine the effects of model assumptions on parameter estimates.

In the course of this research, it was necessary to make certain assumptions about model structure and the nature of the model data. Because there are two distinct views in the literature about the efficiency of the dredge, we deliberately made decisions that would tend to bias results towards a lower efficiency. In this way, if the estimated efficiency were higher than indicated by the early studies, the conclusion of higher efficiency would be robust. On the other hand, if the efficiency in the current study were estimated to be low, we would need to repeat the analyses with choices made so as to bias the estimates upwards. If the estimated efficiency remained low, we would then have confidence that the conclusion was robust to the assumptions. For the purposes of this paper, we refer to assumptions or choices that tend to minimize the estimated efficiency as conservative.

Model Development

Theoretical Framework–DeLury Analysis

DeLury (1947) developed a depletion estimator based on declines in catch rate with cumulative fishing effort. This is of interest in the present study because spatially and temporally specific effort data were available from the VMS. The DeLury relationship is linearized by plotting the natural logarithm of CPUE against cumulative effort:

$$\log_e(CPUE_t) = \log_e(q \cdot N_0) - q \cdot \mathrm{f}_{cum,t}, \quad (1)$$

where CPUE_t = the catch rate (catch per unit effort) at time t, N_0 = initial abundance, $f_{\mathrm{cum},t}$ = cumulative effort at time t, and q = the catchability coefficient.

The catchability coefficient is a constant defined as the fraction of the population that is taken by one unit of fishing effort, provided that the fraction is small. It is based on the probability that an individual in the population will be encountered by fishing gear and the probability of capture given encounter by gear (Ricker 1975). The catchability coefficient is related to gear efficiency, E, by the relationship

$$q = \frac{a}{A} \cdot E, \quad (2)$$

where E = the fraction of animals encountering the gear that is retained by the gear, a = the area covered by the gear in one unit of fishing effort, and A = the total area of the population or study site.

Thus, estimates of q can be converted into estimates of E. Note that to apply this model it is necessary to have time-specific records of all effort in the study area but that CPUE records do not have to be available for all points in time. In addition, Braaten's (1969) modification is not necessary in the present study because the VMS provides cumulative fishing effort for each point in time rather than interval-censored values of commercial effort.

DeLury-type depletion models assume that during the study (1) the population in the study area is closed except for the removals (i.e., there is no immigration, emigration, recruitment, or natural mortality); (2) removal results in a significant reduction of the population size; (3) catchability is constant; and (4) all of the fishing effort expended is known (Omand 1951; Ricker 1975). The challenge of any study using DeLury depletion models is to avoid violating these assumptions.

Spatial Analysis

Historically, one of the most problematic issues in using fishery- dependant data for depletion analysis has been the violation of the assumption of constant catchability due to the nonrandom spatial distribution of effort. Populations are not generally uniformly distributed, and this results in the nonrandom distribution of effort. Paloheimo and Dickie (1964) state that if fish are not randomly distributed, ‘‘additional information on [the] distribution of fish and the operations of fishing vessels’’ is necessary or CPUE cannot provide valid parameter estimates. It appears that many of the sources of bias from nonrandom distribution will result in the underestimation of abundance (Mohn and Elner 1987; Miller and Mohn 1993) and overestimation of gear efficiency.

These issues have to be addressed when fishing effort follows the pattern described by Beverton and Holt's (1957) ‘‘limiting distribution of fishing effort’’ theory, where vessels focus on the densest patches first and then spread out as catch rates decline. Virtually all open-ocean commercial fishing fleets operate in this fashion and result in data sets that are not suitable for a standard depletion analysis. One of the most common ways to deal with this type of nonrandomness is to ‘‘group data over small statistical area and time units’’ (Sanders and Morgan 1976), which will hopefully be nearly random on that scale (Caddy 1975).

For this study, a spatial analysis was used to detect small regions within the fishing grounds that are most likely to be consistent with the assumptions of the DeLury model (i.e., where the spatial distribution of fishing effort is random over the course of the fishing season). A 1-nm × 1-nm grid was generated covering the entire fishing grounds in the southern portion of GBCAII (Figure 3). Catch and effort data from within a certain radius of each grid point, hereinafter referred to as a cell, could then be evaluated for spatial and temporal distributions. Each cell was divided into four quadrants, and the degree of uniformity of effort data from the VMS was evaluated for the first half and the second half of the opening separately (see Application section for specifics). By this procedure, cells in which the fishing effort noticeably switched quadrants as the season progressed could be eliminated from further consideration.

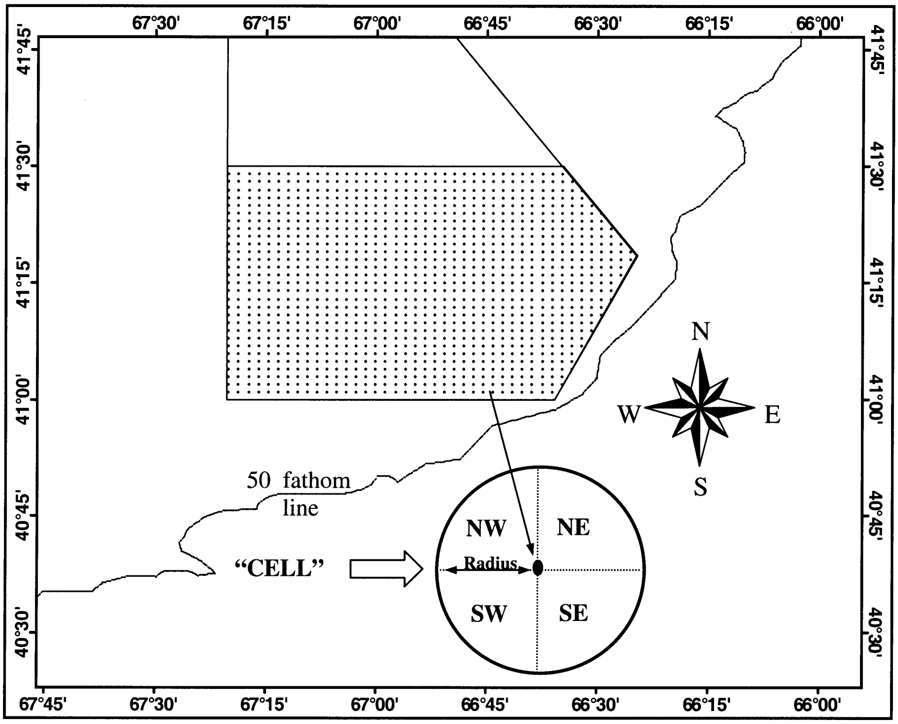

FIGURE 3.—Schematic of grid analysis. A 1-nautical-mile × 1-nautical-mile grid was placed over GBCAII and data were analyzed from cells within a specified distance of each grid point. Quadrants (NW, NE, SW, and SE) were used to evaluate the spatial distribution of effort in each half of the opening.

Maximum Likelihood Estimation

Once suitable cells were chosen and similar estimates of catchability were obtained from all cells, a single gear efficiency estimate could be calculated using a maximum likelihood estimator, as suggested in much of the recent literature (Seber 1973; Gould and Pollock 1996; Wang and Loneragan 1996). This technique allows the use of data from all usable grid cells simultaneously on the assumption that q is constant over all cells (although abundance will vary from cell to cell). The probability density function, f, of a normally distributed random variable is

$$f(x;\, \mu, \sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} \cdot \exp\left[\frac{-\frac{1}{2}\cdot(x-\mu)^2}{\sigma^2}\right], \quad (3)$$

where x is a random variable having a mean of μ and a variance of σ^2. The product likelihood function (Λ) results by substituting DeLury equation (1) for x. Thus,

$$\Lambda = \prod_{i=1}^{n}\prod_{j=1}^{m_i}\frac{1}{\sqrt{2\pi\sigma^2}} \times \exp\left\{\left[-\frac{1}{2}\cdot\{\log_e(\mathrm{CPUE}_{ij}) - [\log_e(q\cdot N_{0i}) - q\cdot f_{\mathrm{cum},ij}]\}^2\right] \div \sigma^2\right\}, \quad (4)$$

where i indexes the n cells and j indexes the m_i tows within a cell. The kernel of the log-likelihood is thus

$$L = -\sum_{i=1}^{n} m_i(\log_e\sigma) - \frac{1}{2\sigma^2}\sum_{i=1}^{n}\sum_{j=1}^{m_i}[\log_e(\mathrm{CPUE}_{ij}) - \log_e(q\cdot N_{0i}) + q\cdot f_{\mathrm{cum},ij}]^2. \quad (5)$$

This equation can then be maximized to estimate parameters. The catchability coefficient is assumed

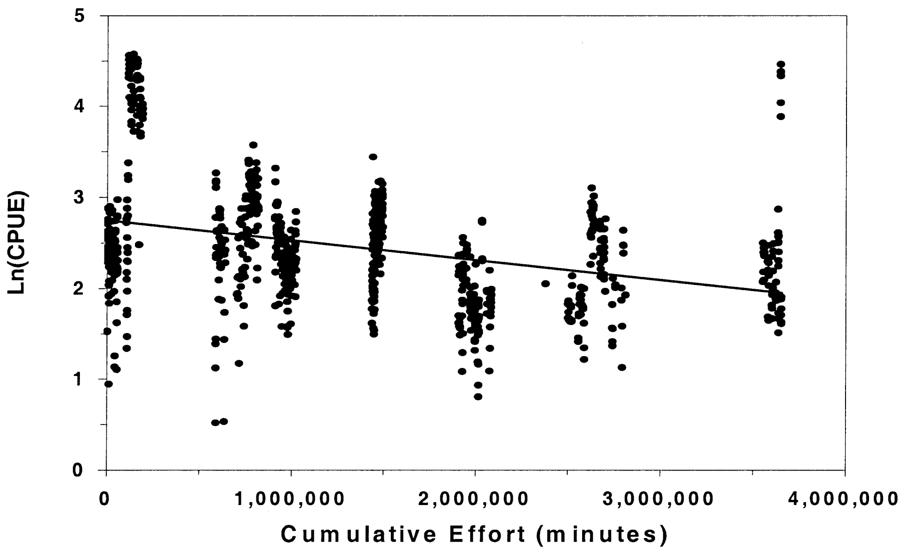

FIGURE 4.—Composite DeLury model for the entire reopened area of GBCAII. All of the CPUE and vessel monitoring system (VMS) effort data collected for this study are included. Raw VMS data were scaled downward by a factor of 0.75 to allow for 45 min of bottom time per hour of fishing. Each data point consists of a catch per standardized unit of effort plotted against the cumulative commercial fishing effort.

to be constant for all areas, so that for n grid cells $n + 2$ parameter estimates are made. For example, if five grid cells are being used in the analysis, the initial populations in each cell (N_1–N_5) and the variance (σ^2) are estimated in addition to q.

The catchability coefficient was then converted to an efficiency estimate from the relationship in equation (2) which is equivalent to

$$E = q \cdot \frac{\pi \cdot (\text{radius of grid cell})^2}{\text{tow speed} \times \text{tow duration} \times \text{gear width}}. \tag{6}$$

Application to the Sea Scallop Fishery

Plotting a composite of all of the catch rate data recorded during the 1999 opening of GBCAII against cumulative effort showed CPUE declines of approximately 50% (Figure 4). The relatively high catch rates recorded at the beginning were from a small, high-density patch of large sea scallops found in the northeastern corner of the area. The relatively high catch rates recorded at the end were from higher-density pockets of smaller scallops in the far eastern part that were fished only as a last resort to reach the possession limit. Parameter estimates from a DeLury analysis of this composite decline, calculated on the basis of the total area re-opened to fishing and assuming that vessels had gear on the bottom for 45 min/h, would give an estimate of efficiency of approximately 60%.

As previously discussed, the validity of parameter estimates from the composite analysis of the CPUE declines presented in Figure 4 is undermined by the spatial heterogeneity of the resource, effort, and sampling. The observed 50% decline, however, suggests that although fishermen are searching for pockets of higher abundance to keep catch rates as high as possible, removals were great enough (at least in some places) to meet assumption 2 of a depletion model.

Spatial Grid Analysis

To avoid violating the assumption of constant catchability, it was necessary to find suitable subunits of the fishing grounds. Eliminating regions where fishers switched areas as they caused local depletion was the next step in our analysis. Vessel monitoring system data were evaluated for the first half of the opening (prior to September 1, 1999) and the second half (after September 1) separately. Each cell was divided into four quadrants (northeast, northwest, southwest, and southeast) (Figure 3), and the percentage of effort in each quadrant was calculated. Standard model settings (Table 1) required that for each half of the opening 15–35% of the total effort occur in each quadrant and that there be a minimum of 10,000 min of effort in the

TABLE 1.—Standard model settings for analysis of gear efficiency in the sea scallop fishery. Data were obtained for a previously closed area of Georges Bank that was opened to commercial fishing from June 15 to November 12, 1999. Separate evaluations were done for the first and second halves of the open period (before and after September 1, 1999, respectively). The abbreviation nm stands for nautical mile.

Variable	Setting
Grid size	1 nm × 1 nm
Radius of analysis cell	1.9 nm
Percentage of effort in each cell quadrant for each half of the open period	15–35%
Minimum amount of effort in each half of the open period	10,000 min
Minimum number of sampled tows	40
Minimum amount of effort spanned by the sampling	30,000 min
Minimum ratio of effort spanned by the sampling to total effort	70%
Bottom time per hour of total fishing	45 min
Tow speed	5 knots

cell for each half of the season. The 10,000-min minimum effort requirement insured that there was a temporal distribution of effort, while the quadrant requirements insured that there was a suitable spatial distribution of effort for each half of the opening.

For the catch data, whole cells were evaluated over the entire opening, requiring that at least 40 tows be sampled. In addition, we required that samples span at least a total of 30,000 min of effort and that at least 70% of the total effort be sampled in each cell. This insured that for the entire opening both significant amounts of effort were expended in the area and that we sampled over a substantial portion of the decline.

Using a radius of 1.9 nm, the grid analysis identified 12 areas that were most likely to be consistent with the model assumptions (Figure 5). The majority of the cells that met both sets of selection criteria fall into two distinct areas in the northeast and southwest. This occurred in virtually all analyses when selection criteria were varied. These two regions contained dense patches of sea scallops prior to the opening and received concentrated levels of effort early in the opening.

Production Constraints

A production constraint correction was necessary if initial catch rates were so high that crews were unable to process the catch as quickly as it was caught. In this situation, vessels ceased fishing so the catch on deck could be processed. As a result, the raw VMS data needed to be scaled differentially to reflect the reduced time on the bottom before declines in suitable cells could be analyzed. Unfortunately, there is limited information on the production capabilities of scallop vessels and the relationship between catch rates and actual fishing time.

During the GBCAII opening sea scallops were larger than normal and we obtained data from only one production-constrained vessel, so a technique to derive a conservative estimate had to be developed (Gedamke 2002). In the early part of the season, when scallop abundance was extremely high, it was assumed that vessels in the fleet would be production constrained, and VMS observations were converted into estimates of fishing effort by using a bottom time of 30 min for each hour of VMS fishing time. This scaled the VMS data to the mean of the fully production-constrained operations observed at the beginning of the opening and that of normal operations after the production threshold was crossed.

The transition from applying a 30-min to a 45-min VMS scaling factor was specified as follows. First, the 30-min value was used to scale all of the VMS data and CPUE was regressed against the scaled data. Then the value of the scaled VMS data at which the CPUE declined to the threshold of 50,000 individuals per day (approximately 5,000 lb) was calculated and converted to a date. This date was then used to separate the VMS data into early season (when the production constraint applied) and late season data (when no production constraint applied). Although this is not an unbiased procedure for determining the transition date, it is conservative in the sense of underestimating the date at which the production threshold is reached by initially overestimating gear efficiency. This insured that the correction underestimated the actual effect of production constraints on model estimates. In practice, the correction never significantly altered the final efficiency estimate, and a sensitivity analysis was performed to quantify its likely effect.

Results and Sensitivity Analysis

In all grid cells that met the criteria for effort and catch data, the CPUE declines were analyzed

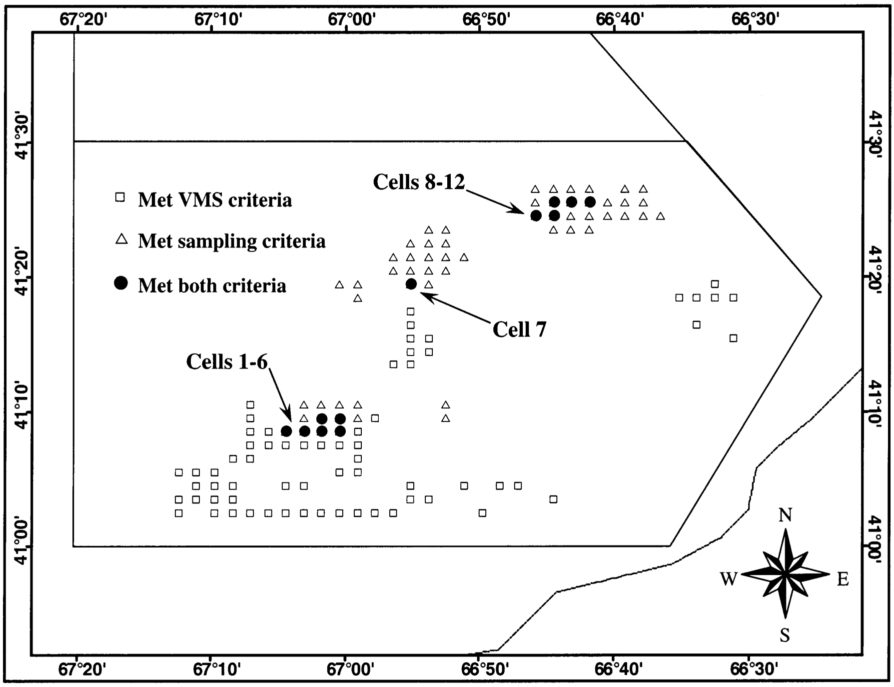

FIGURE 5.—Grid analysis cells in GBCAII meeting the criteria for effort with respect to vessel monitoring system data (squares), CPUE from sampled tows (triangles), and both (circles).

and produced efficiencies that ranged from 26.9% to 63.5% (Figure 6; Table 2). A production constraint correction was then applied to cells 8–12 due to extremely high initial catch rates. This reduced estimates of N_0 slightly in each of these cells and raised efficiency estimates by 1.2–2.5 percentage points (Table 2). An MLE analysis on all cells then estimated dredge efficiency at 42.7%. Confidence intervals (95%) for the efficiency estimates were calculated by both the Wald and likelihood ratio methods in SAS and were never greater than ±0.5% of the estimate (SAS Institute 1999). These confidence intervals are misleading in that they reflect the accuracy of the MLE procedure and not the accuracy of the overall efficiency estimate or model as a whole. Valid standard errors and confidence intervals are impossible to calculate due to the limited information available for certain model inputs (such as bottom time per hour of fishing). Instead, a sensitivity analysis was performed to quantify the potential uncertainty of our final estimate owing to both variable inputs and the overall design of the model.

One of the more critical variables to evaluate in a DeLury analysis—and the first main input to our model—is the designation of the study area. The effect of changing radius settings within the range 1.3–2.8 nm (5.31–24.63 nm^2) resulted in efficiency estimates that ranged from 37.7% to 43.7% (Figure 7). Grid selection criteria (i.e., the percentage of effort required in each quadrant) had to be relaxed for radii less than 1.3 nm and more than 2.8 nm in order to produce grid cells for analysis; estimates began to fluctuate unpredictably at extreme values of the study area radius. Within the 1.3–2.8-nm range, however, there was a decreasing trend in estimates as the radius increased. Investigation revealed that as the radius increased the relative number of cells included in the analysis from the southwestern part of the study area also increased. A radius setting of 1.9 nm provided nearly equal amounts of information from the southwestern and northeastern areas as well as information from one additional, centrally located cell.

With the radius of the study area set to 1.9 nm, the effect of the grid selection criteria was evaluated. Standard model settings—the percentage of effort in each quadrant, minimum effort, minimum number of sampled tows, and minimum range of effort over which samples were obtained—were changed to result in different numbers and locations of grid cells to analyze. In 20 runs of the model, between 5 and 49 grid cells met the criteria

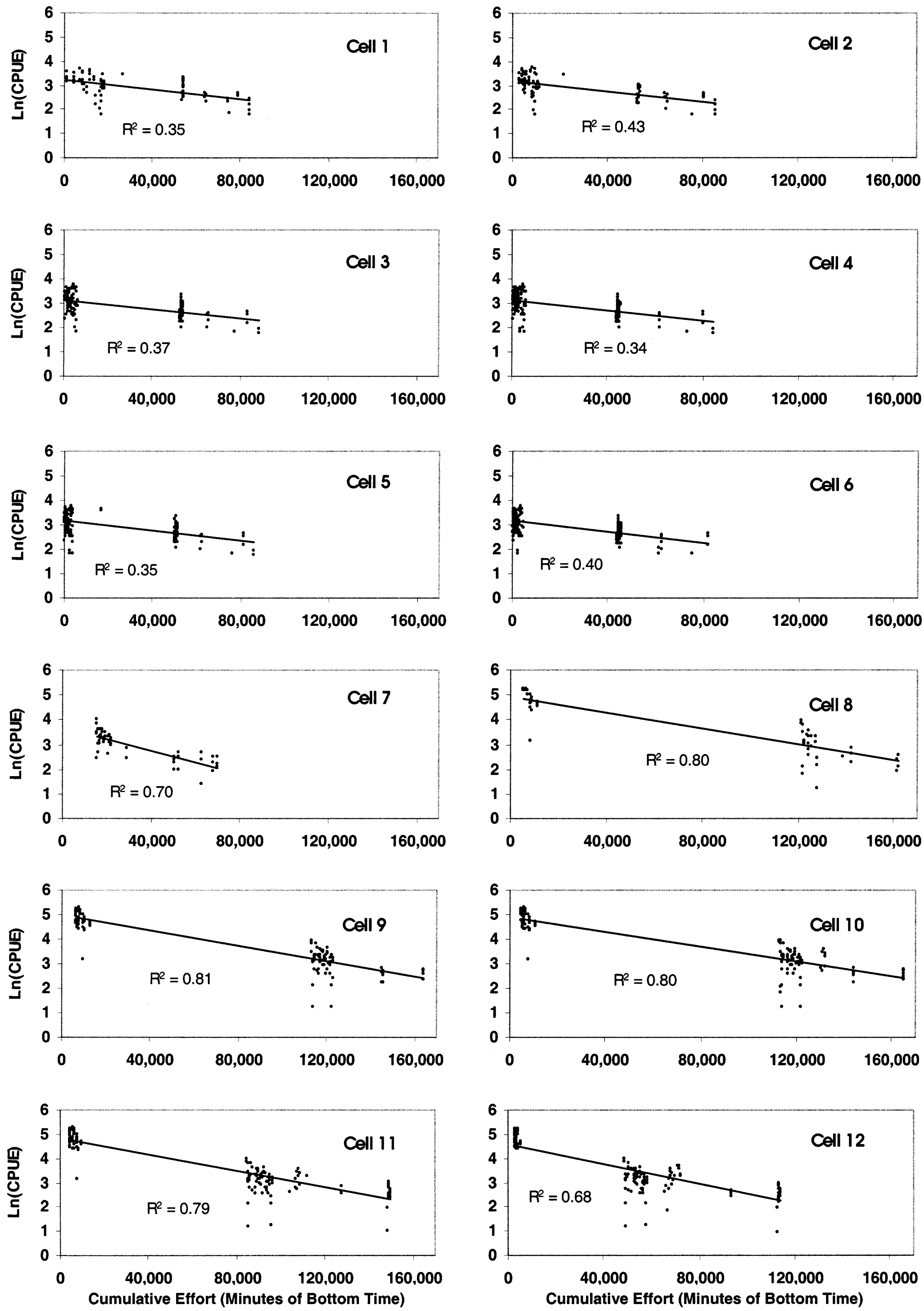

FIGURE 6.—CPUE declines relative to cumulative effort prior to production constraint correction for each cell analyzed. See Figure 5 for cell locations.

TABLE 2.—Linear least-squares parameter estimates for DeLury models for each cell. Estimates in parentheses have been corrected for production constraints (see text); q is the catchability coefficient and N_0 is the initial population in each cell.

Cell	Degrees of freedom	Intercept ($\mathrm{Log}_e[q \cdot N_0]$)	Slope of $-q \cdot 10^{-5}$	R^2 (%)	Efficiency (%)	Exploitation rate (%)
1	75	3.22	1.00	34.9	27.7	57.1
2	106	3.21	1.10	42.8	30.2	60.9
3	144	3.14	0.97	37.1	26.9	57.8
4	160	3.13	1.09	34.1	29.9	60.0
5	144	3.16	1.03	35.1	28.3	58.8
6	156	3.17	1.14	40.3	31.5	60.9
7	58	3.66	2.30	69.9	63.5	80.1
8	58	4.94 (4.86)	1.60 (1.68)	80.0 (79.9)	44.2 (46.2)	92.6 (92.1)
9	126	4.95 (4.87)	1.54 (1.63)	81.0 (80.9)	42.5 (44.9)	92.0 (91.6)
10	135	4.92 (4.85)	1.51 (1.61)	79.9 (79.6)	41.7 (44.2)	91.8 (91.5)
11	162	4.82 (4.74)	1.67 (1.74)	78.7 (77.9)	46.0 (47.9)	91.8 (91.3)
12	145	4.56 (4.48)	2.04 (2.09)	67.6 (66.2)	56.3 (57.5)	90.2 (89.5)

and were analyzed. Most of the areas selected were still located in the northeastern and southwestern pockets. Efficiency estimates were relatively stable, with a mean of 41.4% and a standard error of 0.73%. Regardless of the selection criteria, all results were within 3.1% of the mean and the fluctuations reflected the regional distribution of selected cells as in Figure 7.

The model is fairly sensitive to the scaling of total effort to bottom time, and at standard settings it begins to break down ($E > 100\%$) at less than 20 min of bottom time per hour. On the eight cruises conducted for this study, mean bottom time per hour of fishing was 44.8 min/h (with cruise ranges of 38.0–49.2 min for non-production-constrained trips). Based on our observed mean, general observations during the opening, and information from over 1,000 additional tows recorded by captains on nonobserved trips, the fleetwide mean is confidently estimated to be between 40 and 50 min/h. With this range of input values and all other standard settings, the resulting efficiency estimates ranged from 39.0% to 47.2% (Figure 8).

Within this range of potential bottom times and with standard model settings, the effect of applying production constraint corrections was evaluated. At 45 min/h of bottom time our estimate was raised by 1.3%, and as expected, production constraint corrections had a greater impact at 50 min/h (+1.8%) than at 40 min/h(+0.7%).

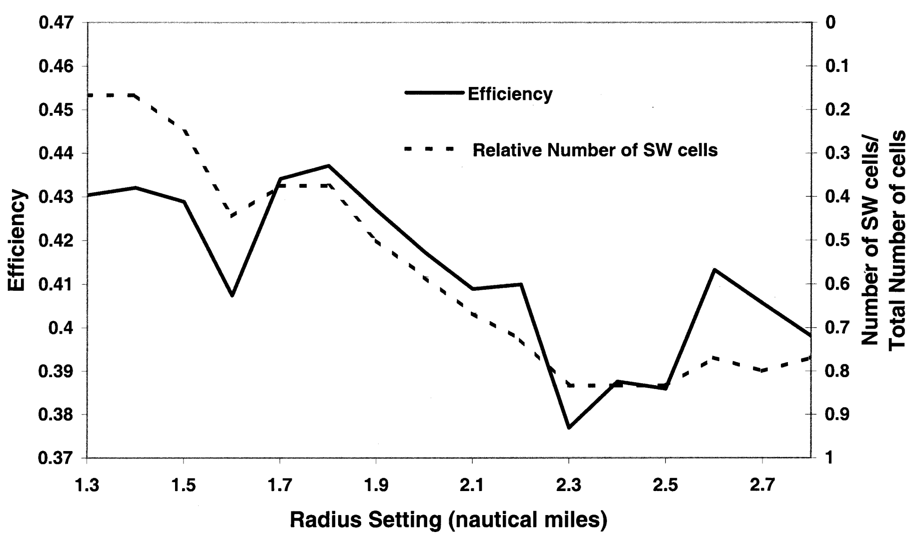

FIGURE 7.—Response of gear efficiency estimates (%) and regional distribution of selected cells to model radius settings. All cells were located in either the SW or NE areas (see Figure 5) except for radius settings of 1.5, 1.9, 2.0, 2.1, and 2.8 nautical miles, for which one additional cell was selected from the central region of the area.

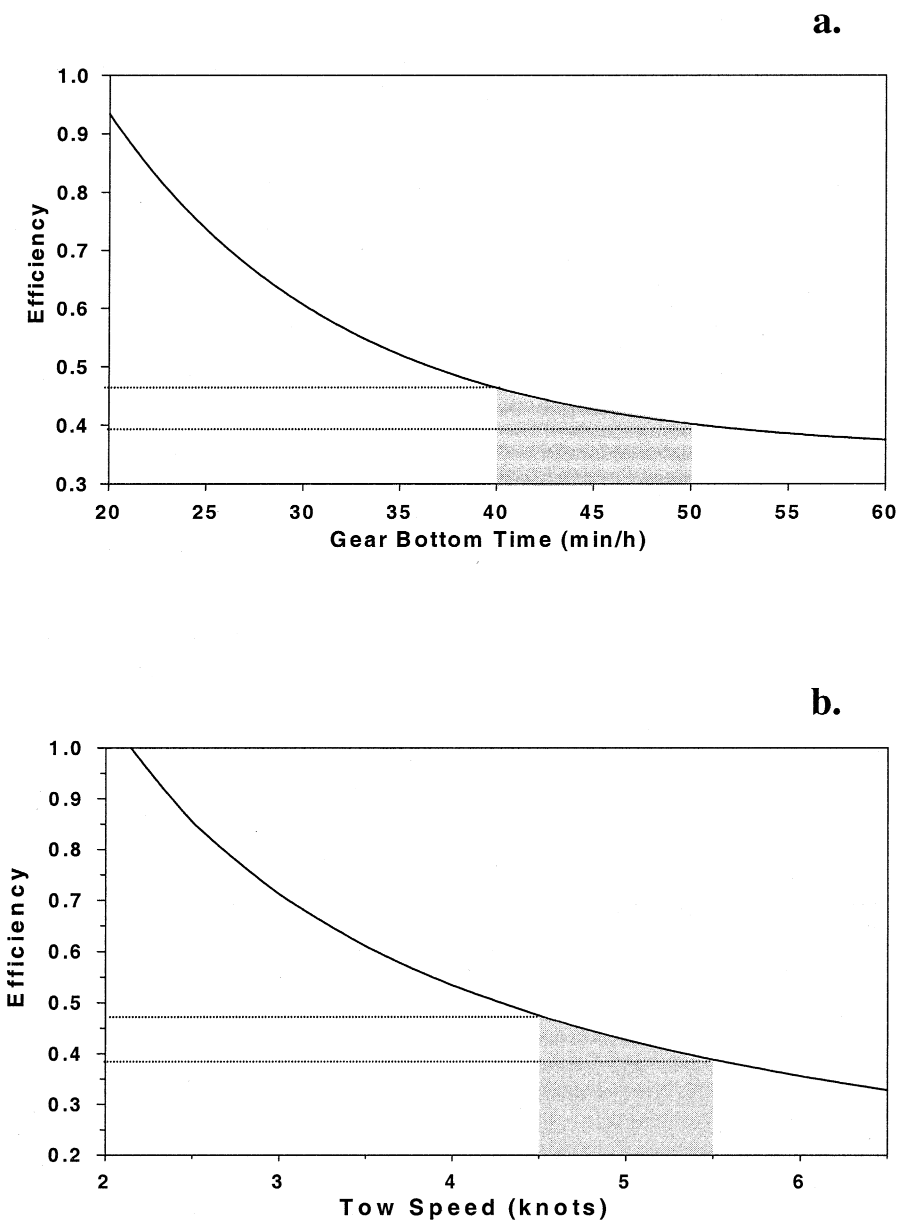

FIGURE 8.—Response of gear efficiency estimates (%) to estimates of two aspects of fleet behavior: **(a)** gear time on the bottom and **(b)** tow speed. The reasonable ranges of the estimates for fleet behavior are indicated in the shaded areas.

Once the grid cells were selected and the total effort had been appropriately scaled to bottom time, a common catchability coefficient and initial populations for each area (N_1, N_2, . . . , N_n) were generated through MLE. The conversion of the estimated q to efficiency, however, is determined by the ratio of sampled area to the total study area, as shown in equation (6). Since dredge width and tow time are fixed, tow speed is the only variable that will affect the area sampled by one unit of effort. As a result, the conversion of q to E is sensitive to this input. With all other standard settings, tow speeds just below 2 knots resulted in efficiency estimates of over 100%. On the eight cruises conducted for this study, the mean tow speed was 4.9 knots (with cruise means ranging from 4.3 to 5.4 knots). Based on our observed mean, bridge logs from additional vessels, and general observations during the opening, the fleet-wide mean is confidently estimated to be between 4.5 and 5.5 knots. Using this range of inputs, the efficiency estimates ranged from 38.8% to 47.4% (Figure 8).

Since the model is sensitive to both tow speed and average time on the bottom per hour of fishing, the interaction between these two variables was evaluated. Individually each variable could alter the final efficiency estimates by approximately 4–5%, but combined they could raise estimates by 9.8% or lower them by 7.2%. The mean efficiency estimate of 42.7% could thus range from 35.5% to 52.5% if fleetwide averages of bottom time and vessel speed are significantly different from our results and at the extreme ends of plausible values.

Discussion

Satisfying Model Assumptions

The first two assumptions of a DeLury model—a closed population and a significant reduction of that population—were met due to the nature of the target species and the magnitude of the removals from the area. Large immigration, emigration, or recruitment events are unlikely for a relatively sessile species during the 5-month opening, and the accepted natural mortality of 0.1/year is negligible in light of the massive fishing mortality and the relatively short duration of fishing.

The failure of many studies to meet the third assumption of a DeLury model, constant catchability, is the most commonly cited reason for biases in or faulty interpretation of depletion studies (Ricker 1975; Schnute 1983). Although a number of researchers, including Winters and Wheeler (1985), Polovina (1986), Crittenden (1983), Swain and Sinclair (1994) and Wang and Loneragan (1996), have suggested modifications to the original model, this issue remains problematic. Changes in catchability over time often introduce systematic errors (Ricker 1975) and can be caused by a number of density-dependent behavioral processes, including changes in feeding (Fletcher et al. 1990), contraction of the home range (Winters and Wheeler 1985), and such things as the capture of the most vulnerable fish first (Ricker 1975; Hilborn and Walters 1992). For this study, density-dependent behavioral processes are not a complicating factor due to the largely sedentary nature of the target species. However, potential problems still exist and warrant further discussion.

One possible reason for trends or variations in catchability is that gear efficiency itself is a function of density. In this study, efficiency estimates from the southwestern section of GBCAII were consistently lower than estimates from the higher-density areas in the northeast. The relationship was extremely noisy but suggested that density dependence plays a role. On the other hand, regional differences in *q* due to differences in bottom type could have the same effect. A slight curvilinear trend was also observed in the residuals for some of the northeastern plots, which supports the possibility of density dependence. Previous studies that have noted similar trends in the data have suggested modifying the basic relationship between CPUE and abundance to a power function (Winters and Wheeler 1985; Hutchings and Myers 1994). Application of this model to other areas over a wide range of densities and bottom types will allow this to be investigated further.

The grid analysis was designed to avoid violating the assumption of constant catchability and was needed to account for the commercial fleet's ability to sense differences in resource abundance and change fishing behavior. During the first 2 weeks of the opening, effort focused on areas as small as 19.6 nm^2 (circular areas with radii of 2.5 nm). Multiple vessels covering distances between 4 and 5 nm on a single tow were essentially fishing randomly in these areas, and under this heavy fishing pressure the small-scale, contagious distribution of sea scallops would be expected to become random (Langton and Robinson 1990).

The resolution of the grid analysis was consistent with this and fine enough to select cells of essentially randomly distributed effort within these patches. This was evident in the relationship between the cell radius and geographic locations of selected cells. As the radius size increased, more cells from the northeast were excluded owing to the small sizes of the high-density patches found in that region. Cells still met the selection criteria in the southwest, however, as there were larger regions of scallop beds of similar density (and therefore more randomly distributed effort) in that area. The use of VMS data provided the fine-scale, detailed information on the spatial distribution of effort that is usually lacking for the successful application of a DeLury model to open-ocean commercial fishing events.

Although the VMS data provided the spatial information necessary to select the regions most suitable to the DeLury model, the scaling of raw VMS data to our independent variable—actual gear time on the bottom—was more problematic. In addition to determining the appropriate tow speed and production constraint corrections, quantifying this relationship is necessary to meet assumption 4 and requires mean values from entire fleet operations. With precise data from only 8 of the 644 trips taken during the opening, careful consideration of vessel operations as a whole needed to be taken into account and conservative estimates had to be made for these model inputs.

Satisfying Statistical Assumptions

The use of the VMS data avoids a common statistical error that can occur in the application of the DeLury model. In many cases both catch and effort data are collected from the same vessels, leading to the nonindependence of the dependant and independent variables. In our case, this problem does not exist because the catch and effort data were collected from different sources. Although all nominal fishing effort is recorded by the VMS systems and thus avoids the problem of nonindependence, these data must be converted into actual gear time on the bottom, which leads to another potential problem. The fraction of the nominal fishing time during which fishing gear is in contact with the bottom is variable from tow to tow. Therefore, converting nominal effort to actual effort by applying a correction factor results in some error in the independent variable (cumulative effort) used in the analysis.

A Monte Carlo simulation was performed as follows to demonstrate the impact of random errors in cumulative effort: First, we calculated the mean and sample variance for the tow durations and intertow times observed during this study. Although these tows were not randomly selected from the entire fleet's fishing activity, we assumed that they give an approximate indication of the variability in vessel operations. We defined a fishing event to be the duration of a tow plus the time elapsed until the next tow (the intertow time), and we computed the mean time of the events observed (76.6 min). Next, the nominal amount of fleet fishing effort (from the VMS system) between our research tows was converted to the number of fishing events by dividing the nominal effort by the average event time. Also, the nominal effort was multiplied by 0.75 (45 min/h) to obtain the expected gear time on the bottom. To this, a normally distributed random error was added with expectation 0 and variance equal to the number of events times the variance of the observed tow times (232.9 min^2). The simulated data set was then analyzed by regression for each area individually and through the MLE procedure for the composite data set. The simulation was run 1,500 times with only trivial differences in the new parameter estimates. The simulated results had the same mean as the original data set, an overall range of only 0.5%, and 95% confidence intervals of $\pm$0.004%.

A final concern about the DeLury formulation is that the logarithmic transformation could result in an inappropriate error structure (i.e., heteroscedasticity). Because our multisite model is linear, the parameter estimates will remain unbiased; however, the standard error estimates will be biased if the variance structure is specified incorrectly. An examination of the residuals for each area shows no appreciable trend in variance over the range of the independent variable, suggesting this is not a problem in our analysis.

Model Inputs and Sensitivity

The appropriate scaling of VMS data required a mean bottom time per hour of fishing for all vessels in each region. On the trips sampled for this study, vessels fished for a mean of 47 min/h during optimal conditions and 45 min/h when time lost to equipment failure or weather was included. Considering that hand-picked vessels were used for this study, it is unlikely that the true mean for the fleet is greater than the 47 min observed under optimal conditions, and thus the potential variability in model results should only be due to actual bottom times being lower than this value. If we assume that the true mean is greater than 42 min/h, the realistic range for efficiency estimates becomes a modest 41.1–45.3%.

A conservative production constraint correction was calculated using a cutoff of 50,000 individuals (~5,000 lb) per day, which is almost double the value (2,660 lb) used in the original calculations made before the opening of GBCAII (NEFMC 1999). As a result, the insignificant 1–2% positive shift in efficiency estimates that resulted from the use of production constraints would be expected to represent no more than one-half of the true effect. As better information is obtained on fleet operations, a more accurate production constraint relationship can be developed that will include the crew size, length of trip, and mean shell heights.

The final calculation, converting q into E, should also result in conservative efficiency estimates. Data were collected from some of the larger vessels in the fleet, and as a result our observed tow speeds and dredge width model inputs should be slightly greater than the actual mean for the fleet.

Some of the smaller, lower-horsepower vessels were using dredges less than 15 ft across and could not maintain the same fishing speeds as the larger vessels in high-density or bad weather conditions. This resulted in a high estimate for the area fished by one unit of effort (*a*) and therefore a low estimate of gear efficiency. Although a power correction may be appropriate to adjust for these differences (Gulland 1969; Sanders and Morgan 1976), specific information on the fishing behavior and gear used by individual vessels was not used in this study.

Previous Estimates of Efficiency

Early studies on the New England-style dredge suggested efficiencies much lower than those of this study. Caddy's (1968, 1971, 1973) work is the most comprehensive and was done primarily by direct observations. In his 1968 study, survey transects were made in an area that had been previously surveyed by divers, and efficiency was estimated at 8.3% for sea scallops larger than 100 mm (3.74 in). His study was conducted in shallow water at dredge speeds of only 2 knots. His follow-up study (1971), conducted on Georges Bank, used cameras mounted to the front of the dredge. Efficiency was then estimated at 16.9% for scallops larger than 100 mm.

More recent studies, however, suggest that efficiency is actually much higher than previously reported. The results of an application of the patch model, which was developed by Paul Rago (NEFMC 1999) during the 1998 NMFS survey of GBCAII, are the most comparable to ours. Rago reparameterized a Leslie–DeLury model to incorporate the spatial aspect of sampling and applied it to 10 sets of depletion tows conducted during the survey. Since his study was conducted in the same area and with the same basic tow methodology as ours, the depth, tow speed, size of sea scallops, and bottom type were virtually identical. Rago's efficiency estimates were very similar to ours, ranging from 25% to 57%, with an overall average of 41%.

Other recent studies on comparable dredge equipment also suggest that the efficiency of this type of heavy dredge may be higher than earlier estimates. Hall-Spencer et al. (1999) suggested an efficiency of 44% for the Rapido trawl (a 9.8-ft-wide steel frame with a 3.15-in mesh weighing approximately 375 lb) on the St. James scallop *Pecten jacobaeus* for soft, sandy bottom types similar to that of the southern GBCAII. Currie and Parry (1999) found comparable estimates for the Peninsula dredge (a 10.2-ft-wide frame with a 2.76-in × 1.77-in mesh towed at 5.5–6 knots) in southeastern Australia. Their dredge efficiency estimates ranged from 51% to 56% in soft, flat, muddy bottoms and from 38% to 44% in firm, sandy sediments.

Conclusions

The success of our study and our confidence in the resulting range of parameter estimates can be attributed to our careful consideration of data sources, our use of VMS data for fine-scale spatial analysis, and the unique situation that evolved with the opening of GBCAII. The extremely high densities that resulted from the 5-year closure generated exploitation rates of over 90% in some areas. With depletions of this magnitude, the effects of sampling errors are reduced and the potential to produce valid estimates heightened (Gould and Pollock 1997; Gould et al. 1997).

The results of our study strongly suggest that the 25% efficiency used in the calculations made before the opening of GBCAII overestimated the absolute abundance in the region. Our efficiency estimate of 42.7% should represent a minimal estimate of the true efficiency considering the deliberate underestimation of both the required production constraint correction and fleetwide behavior parameters utilized in our study. If an efficiency of 45–50% had been used in the calculations made prior to the opening of GBCAII, an absolute biomass estimate of approximately 20 million lb and a TAC of close to 5 million lb would have resulted. These values are substantially different from the original calculations, which gave an absolute abundance of 25–63 million lb and TACs of 6–15 million lb. The TAC suggested in this study was landed by early October, just following the authorization of additional trips into the area.

Unfortunately, the decision to allow these additional trips had to be made with little new supporting scientific information. With the widespread use of VMS systems, the opportunity now exists to collect a relatively small amount of CPUE data from commercial vessels and successfully apply a depletion model to an open-ocean commercial fishing event. For future openings of closed areas, the analysis developed in this study could act as one means of monitoring the opening, evaluating the original biomass estimates, and estimating gear efficiency for the different regions or closed areas.

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