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2007

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Correcting for effective area fished in fishery-dependent depletion estimates of abundance and capture efficiency

John F. Walter III, John M. Hoenig, and Todd Gedamke

Depletion methods are widely used to estimate capture efficiency and abundance. However, they are highly dependent on the depletion area assumed. In open-ocean depletion studies, it is difficult to determine the true area of depletion. Satellite vessel monitoring systems (VMS) offer the potential to determine the area effectively fished. Observer-collected catch-and-effort data from the 1999 Atlantic sea scallop fishery in Georges Bank Closed Area II were used to obtain spatially-explicit DeLury depletion estimates of dredge efficiency and abundance, with corrections for fished area made using VMS data. Non-area-corrected efficiency estimates often had theoretically impossible values, indicating that the naïvely assumed fished area was likely too big. Fine-scale spatial analyses on individual depletion cells confirmed this result. Corrected-area efficiency estimates exhibited reduced variability and more plausible efficiencies, with 70% of 289 individual depletion estimates falling between 20% and 55%, with a mean of 46%. Abundance estimates from individual depletion studies matched maps of abundance from a preseason survey. Results indicated a total abundance of ∼17 million pounds of scallop meat weight in the fished area, of which 6 million pounds were landed, providing an overall exploitation rate of 35%.

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Introduction

Depletion estimators are catch-effort methods widely used in fish and wildlife studies to estimate gear efficiency and population abundance (Seber, 2002). They assume a simple relationship between catch per unit effort (cpue) and cumulative effort (DeLury, 1947) or cumulative catch (Leslie and Davis, 1939). DeLury depletion models are formulated as linear regressions between the logarithm of the catch rate and cumulative effort. The slope of the regression estimates the negative of the catchability coefficient (q), which is the fraction of the population removed with one unit of effort (Ricker, 1940). Initial abundance can be obtained by exponentiating the intercept of the regression line and dividing by the catchability coefficient. Gear efficiency (E), or the fraction of the animals encountering the gear that is retained, can be calculated with knowledge of the area (a) sampled by a single unit of effort (e.g. a tow) and the total depletion area (A), as follows:

$$E = \frac{A}{a} \cdot q. \quad (1)$$

Both the catchability coefficient and the abundance are dependent on the depletion area. Initial abundance only has meaning with respect to a defined area, A, and the estimated catchability coefficient is, likewise, a function of A. At the initiation of a depletion study, one must assume an area over which the effort operates randomly. In many applications, A is relatively simple to obtain, e.g. in a depletion study in a pond where the entire area is fished (DeLury, 1947). In marine applications, where the study area is less well-defined, A is more difficult to obtain and misspecification can bias estimates of efficiency and initial abundance.

Vessel monitoring systems (VMS) and expanded placement of on-board observers present an opportunity to re-evaluate the application of depletion estimators to commercial fisheries data. Although the placement of VMS and observers on fishery vessels is primarily for enforcement purposes (Rago et al., 2000), they provide catch rates on the scale of a single unit of effort and similarly fine spatial and temporal records of total fishing effort (Gedamke et al., 2004). The complete accounting of all fishing effort provided by universal VMS coverage forms the basis for DeLury depletion estimates of abundance and capture efficiency (Gedamke et al., 2004) as well as for evaluating fishing intensity (Deng et al., 2005) and fleet behaviour (Gillis, 2003). VMS data provide additional information for depletion analyses in that they can be used to determine the actual locations fished. Thus, the portion (A_{eff}) of a nominal area (A) that is actually fished can be determined.

Here, we use VMS effort data and catch rates obtained by observers to obtain DeLury depletion estimates of sea scallop (Placopecten magellanicus) abundance and dredge efficiency. We

first follow the methodology of Gedamke *et al.* (2004) in defining a series of spatially explicit depletions centred on grid nodes of 1 nautical mile. However, we use data from standard fishery observers, whereas Gedamke *et al.* (2004) used data obtained from a designed study in which scientists were placed aboard vessels. We then use VMS data to correct these depletions for the effective area fished, compare the abundance estimates from the DeLury depletions with a preseason fishery-independent survey, and use depletion estimates to create geostatistical maps of abundance.

Methods

Fishery and observer data

Observed catches and the corresponding fishing effort in the North Atlantic scallop fishery in Georges Bank Closed Area II (Figure 1) were obtained from the National Marine Fisheries Service Northeast Fisheries Science Center (NMFS−NEFSC). The area encompasses 2020 square nautical miles of Georges Bank, with depths varying from 150 to 300 feet over predominantly sand or gravelly-sand seabed (Valentine and Lough, 1991). The entire area was closed to fishing in 1994 to protect groundfish stocks. In 1999, an area of 1120 square nautical miles was reopened for a limited-duration scallop fishery (Figure 1). During the opening, 30% of the vessels carried observers, producing 3831 observed catches from 35 vessels on a total of 40 trips from June through November 1999.

To obtain usable catch rates from the observer data, we eliminated tows of duration >2 h and tows of poor quality such as flipped, tangled, or lost dredges, or if it could not be determined whether the catch was from the port or starboard or both dredges. The catch was recorded in either whole weight or meat weight of retained and discarded scallops, or as the total number of bushel baskets of retained scallops. Tows for which these two measures did not correlate (the number of pounds landed should be a common multiple of the number of bushels) were removed. Of the 3831 observed tows, 2753 (72%) were of sufficient quality to be included in the analysis (Figure 2). We also removed 7 of the 2753 tows because they were recorded as zero bushels of
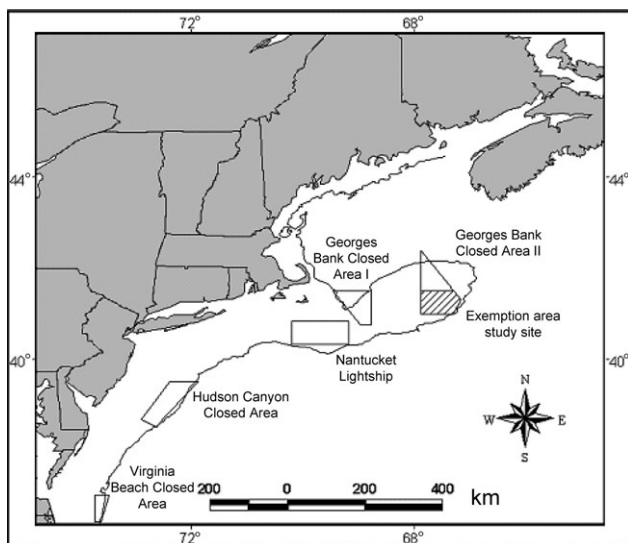

Figure 2. (a) Distribution of 90 944 VMS records for Georges Bank Closed Area II from 16 June to 12 November 1999, and (b) the midpoints of 2752 observed catches and individual depletion cell nodes. The expanded view in (b) shows a single depletion cell (number 254), divided into four quadrants. The dashed line is the area constrained for later predictions.

Figure 1. Scallop area closures on the east coast of North America. The hatched area is the study site on Closed Area II opened for fishing in 1999. The 50-fathom isobath is shown.
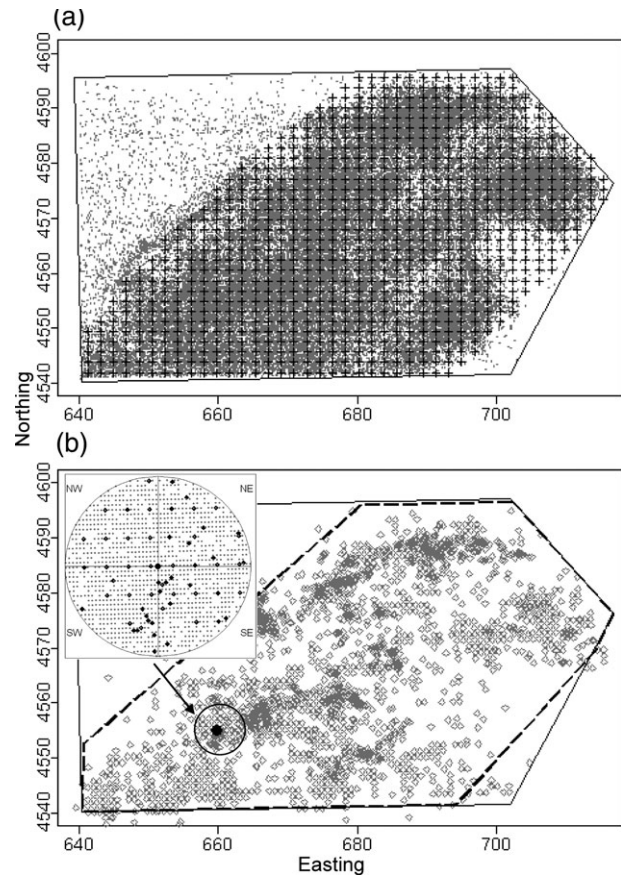
scallops, and it is unlikely that a commercial tow otherwise of good quality would have had zero scallops.

To georeference each tow, we used the midpoint of the start and end positions, and to obtain a towed distance, we used the product of the tow duration and an assumed average vessel speed of 5 knots (Gedamke *et al.*, 2004). We converted all positions to an equidistant scale in metres with a Universal Transverse Mercator projection in NAD 83, Zone 19.

We standardized scallop catches by converting the catch in total bushels of retained scallops to the numbers of scallops per nautical mile towed. We did not correct for selectivity in the scallop catches because 95% of the tows for which shell height was measured had mean shell heights >110 mm. This was well above the shell height of 100% selectivity (84 mm) for commercial dredge gear with 89 mm rings, which was used in the 1999 fishery (Serchuk and Smolowitz, 1980).

Processing VMS data

The US Atlantic sea scallop fishery has universal VMS equipment that records and transmits vessel positions. We obtained 90 944 individual VMS records, representing the total fishing effort from 16 June through 12 November 1999 in the exemption area of Closed Area II (Figure 2). Each record consisted of latitude

and longitude, time, date, and the time differential between the record and the previously recorded position for the vessel. The average straight-line velocity of the vessel (representing a minimum velocity, because the path may not have been straight) can be inferred from the distance between the current and the previous position divided by the elapsed time. We assumed that straight-line velocities of <5.5 knots implied that the vessels were fishing and used this criterion to compile fishing effort. For most records, the elapsed time was close to 1 h because the VMS was programmed to report vessel position approximately every hour. However, the actual time elapsed between successive reports varied slightly. In a small fraction (0.8%) of records, the elapsed times were greater than 3 h and were removed.

Effort obtained from the VMS data overestimates true fishing effort, because dredge deployment, retrieval, and emptying reduce the actual time that the gear is fishing. To account for gear handling, we reduced the recorded amount of fishing effort by 25%, according to estimates obtained during the fishery that vessels spent an average of 45 min of every hour with gear on the seabed (Gedamke et al., 2005). We refer to this scaled VMS effort as the FISHTIME.

Depletion model

The modern version of DeLury's (1947) depletion model assumes that the expected catch (C_i) for the ith time period is the expectation of a multinomial function:

$$E(C_i) = N_0(1 - p_1)(1 - p_2)\ldots(1 - p_{i-1})p_i$$
$$= N_0 e^{-q\sum_{j=1}^{i-1}f_j}(1 - e^{-qf_i}), \qquad (2)$$

where N_0 is the initial abundance, p_i the probability of capture in the ith period, f_i the effort in the ith period, and q the catchability coefficient (Seber, 2002). If it is assumed that all values of p_i are small, then using the approximation $p_i \approx qf_i$ and the approximate relationship $E[\ln(n_i/f_i)] \approx \ln[E(n_i/f_i)]$, we can divide by f_i, the effort during period i, and take logs of both sides to obtain the linear regression model:

$$\log_e(\text{cpue}_i) = \log_e(qN_0) - q\sum_{j=1}^{i-1}f_j. \qquad (3)$$

We did not use Braaten's (1969) correction for continuity because the VMS data provided cumulative fishing effort at the time of each tow rather than interval-censored values.

The absolute value of the slope of the regression estimates the catchability coefficient. Initial abundance (N_0) can be estimated by exponentiating the intercept of the regression line and dividing by the estimated catchability coefficient ($\hat{q}$):

$$\hat{N}_0 = \frac{\exp(\text{intercept})}{\hat{q}}. \qquad (4)$$

Capture efficiency (E) can be estimated with Equation (1) provided that the total area fished (A) and the area sampled by a tow (a) are known.

DeLury depletion estimators require the following assumptions (Seber, 2002): (i) the population is closed to additions from recruitment and immigration, and to losses from natural mortality and emigration during the depletion; (ii) individual units of effort are independent; (iii) all organisms have equal catchability; (iv) the catches used to track the depletion must not remove >2% of the population per tow; (v) there must be a substantial removal to create observable declines in catch rates; and (vi) effort is randomly placed in the depletion area. Additionally, the model requires the standard assumptions of a linear regression.

Obtaining individual depletions

An individual depletion represents a linear regression [Equation (3)] between the natural log of the catch of scallops per nautical mile and the cumulative within a given radius of a single grid node. Note that catch rate per nautical mile is the sum of the observed catch divided by the observed effort. Grid nodes were defined as a regular array of points spaced 1 nautical mile apart (Figure 2). We took two approaches to creating individual depletion experiments. The first part closely followed the methods of Gedamke et al. (2004) in defining a grid of nodes and selecting those that met suitability criteria for depletion analysis (Table 1). In the second part, we relaxed the strict requirements placed on individual grid cells, and used VMS data to correct the depletion area for the effective area fished.

The general methodology for creating individual depletion experiments was the same for both parts of the study (Figure 3). We accumulated catch data from the observed catches, and effort data from the accumulated VMS records within the depletion radius of each grid node. The grid nodes formed the centre of each depletion cell, and we assigned all observed catches for which the midpoint of the start and end locations fell within the

Table 1. List of model constants for the depletion studies using the full catch-and-effort criteria (Part I), then the relaxed criteria with variable effective area fished (Part II).

Constant	Full catch-and-effort criteria (Part I)	Relaxed catch-and-effort criteria (Part II)
Tow speed	5 knots (2–7 knots)	5 knots
Bottom time (min) per hour towed	45 min (20–60)	45 min
Depletion radius setting	1.9 nautical miles (0.8–3.2)	1.9 nautical miles
Minimum number of catches	30	10
Total effort in each cell	30 000 min	15 000 min
% of total effort that the samples must span	50%	Not applied
Depletion acceptance	Significant negative slope	Significant negative slope
Percentage of effort in each quadrant in each half of fishery	15–35%	Not applied
Depletion area (A)	38 899 054 m^2	Variable, see below
Effective depletion area (A_{eff})	Same as A, above	Scaled to actual fished area
Percentage of total effort used to determine A_{eff}	Not applied	90% (10–100%)

Values in parenthesis were used for sensitivity analysis. Slopes were considered significant if $p < 0.05$.
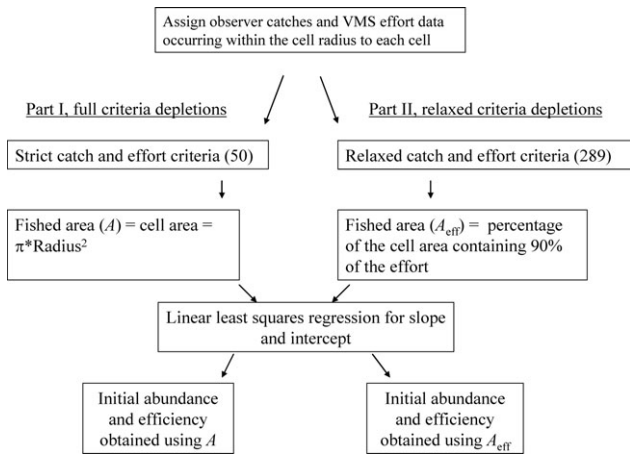
Figure 3. Diagram of the process of performing depletion analyses.

depletion radius to that cell (Figure 2). Similarly, to obtain total cumulative effort up to the time of each observed catch within a grid cell, we summed all prior FISHTIME records within the depletion radius. As a few observed catches were made before any VMS record, we offset the time of the VMS data by 2 h so that all observed catches occurred with some level of prior effort.

We obtained estimates of the slope and intercept of each regression through least squares regression. We used the estimated slope from each linear regression to obtain dredge efficiency estimates by rearranging Equation (1):

$$\hat{E} = \frac{\hat{q}A}{(\text{average tow speed} \times \text{average tow duration} \times \text{dredge width})}, \quad (5)$$

where the depletion area (A) is the area of a circle with the depletion radius (r). In the denominator, we have the area covered by a single unit of effort as the product of an assumed tow speed of 5 knots, a dredge width of 30 feet (two 15-foot dredges) and a mean tow duration of 55.6 min from the average duration of observed tows. Note that this mean tow duration differs from the VMS effort scaling of 45 min to an hour. Although tows average 55.6 min, time lost to gear handling eventually resulted in an average of 45 min of actual fishing per hour.

Part I: obtaining "good" depletions

To obtain depletion grid cells consistent with the assumptions of random fishing effort and to provide a direct comparison with the depletions obtained by Gedamke *et al.* (2005), we employed a similar set of restrictions to determine acceptable depletions. We partitioned each grid cell into four quadrants (Figure 2) and required that: (i) each quadrant had between 15% and 35% of the total observed fishing effort for each half of the season, subdivided on 1 September 1999; (ii) observed catches spanned at least 50% of the total fishing effort in the cell; (iii) the samples spanned at least 30 000 min of effort; and (iv) that at least 30 catches were observed for the entire depletion (Table 1). To meet the assumption of sufficient removal, we added one additional criterion that the depletions had a significant and negative slope. Applying these restrictions, we obtained 50 acceptable grid cells that we here refer to as the "good" cells (white centred points in Figure 4).

Part II: depletions with correction for effective area fished (A_{eff})

Individual depletion studies were set up as in Part I except that we relaxed the criteria for determining acceptable depletion cells by reducing the minimum number of observed tows to ten, the minimum effort to 15 000 min, and removing the quadrant and effort span requirements (Table 1). This produced a set of 289
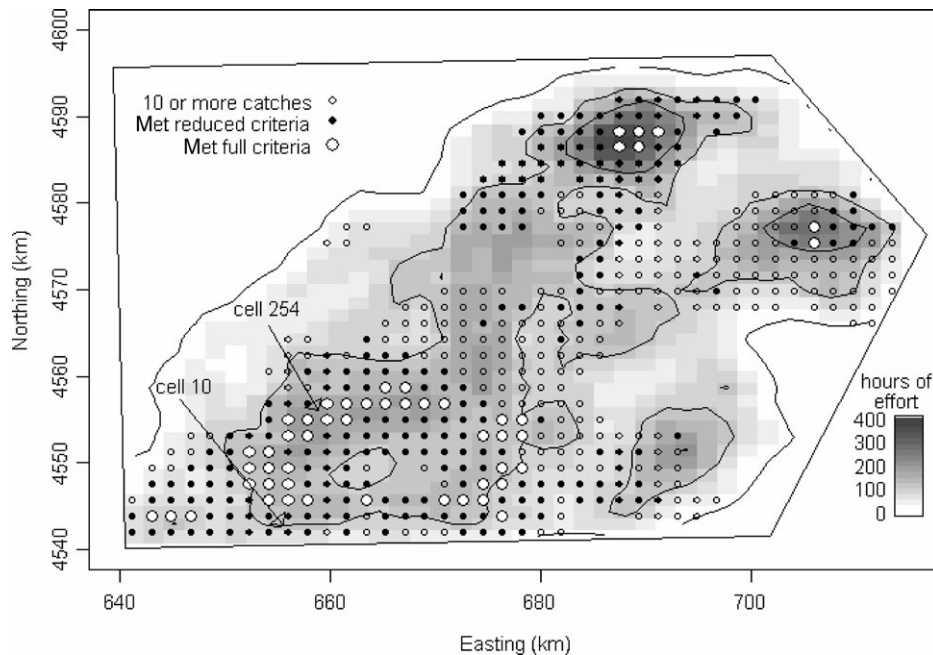

Figure 4. Plot of cumulated VMS effort (in h) and grid nodes of all depletion cells with ten or more observed samples, with the set of 50 good depletion cells and the set of 289 relaxed criteria cells.
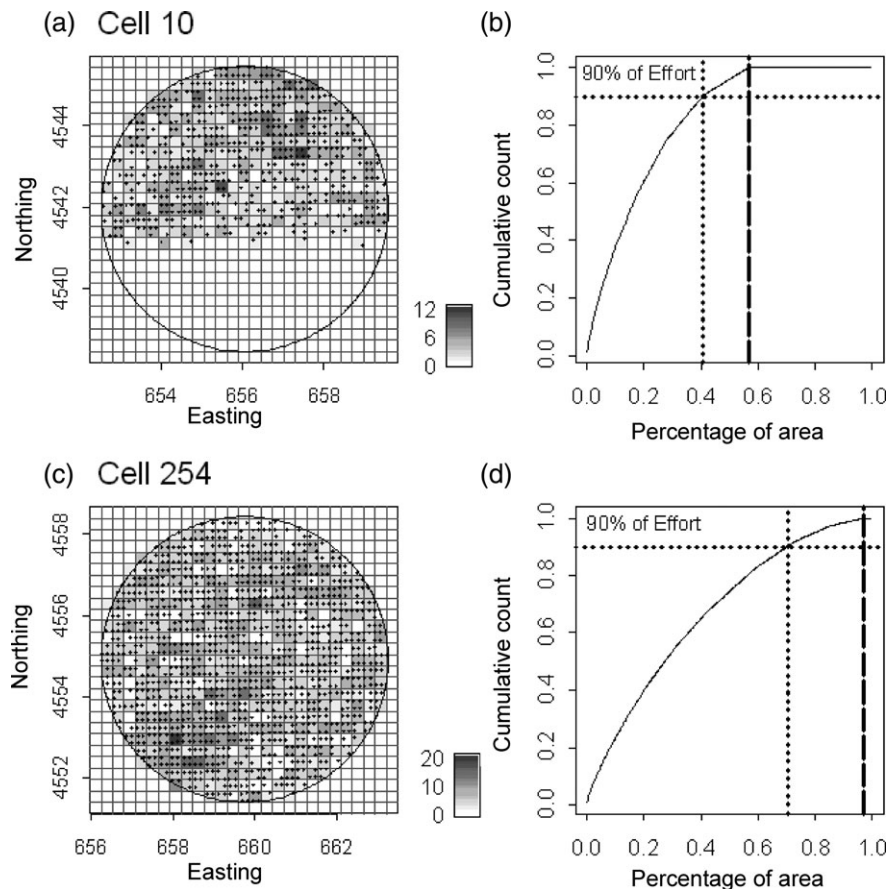
Figure 5. Accumulated fishing effort for cells 10 (panels a, b) and 254 (panels c, d). In (a) and (c), each point is an individual VMS reporting location. In (b) and (d), the cumulative percentage of effort is plotted against the cumulative area (percentage of bins), starting with the bin with the highest number of records, and progressing to the bin with the least effort. The intersection of the dotted lines depicts the percentage area in which 90% of the total effort occurred. The dashed line indicates the percentage area in which 100% of the effort occurred.

depletion cells which we refer to as the relaxed criteria cells (Figure 4).

Combining duration, speed (5 knots), and dredge width (2 dredges each 15 feet wide), we obtained an estimate of the average swept area of all observed tows in each depletion radius. During the 1999 fishery, the VMS system recorded vessel position each hour, so each VMS record represented one hour of fishing, or with the bottom time constraints, 45 min of actual fishing. We placed a set of square bins over the spatial extent of each cell (Figure 5a and c), removed bins that fell outside the depletion radius, then added the number of VMS records in each bin, essentially creating a two-dimensional histogram of fishing effort. We then sorted the counts of effort and plotted the cumulative frequency distribution of effort against the percentage of bins occupied (Figure 5b and c).

For depletion cell 254, where effort was relatively evenly distributed over the entire cell, the plot of accumulated effort against area fished asymptoted at close to 98% of the area, whereas for cell 10 where effort was unevenly distributed, the plot asymptoted at 58% of the total area (Figure 5). As effort in most depletion cells was unevenly distributed, we defined our cut-off of effective area fished (A_{eff}) to be the area over which 90% of the total effort was observed (intersection of the dotted lines in Figure 5b and d). As this is an arbitrary cut-off, we conducted a sensitivity analysis

in which we varied this restriction between 20% and 100% of total effort. We estimated A_{eff} for each of the 289 relaxed cells and used this in Equations (1) and (5) to determine area-corrected efficiencies and initial abundances.

Geostatistical prediction of scallop abundance and dredge efficiency

Individual depletion profiles provide an estimate of scallop abundance at the location of each grid node. We used geostatistical methods to incorporate these into spatial estimates and maps of abundance for the entire study area. Geostatistics involves a two-step process in which a model of spatial autocorrelation, the variogram, is obtained, then used to predict abundance by kriging and to create maps (Cressie, 1993; Petitgas, 1993). Using the estimated scallop abundance or dredge efficiency on each depletion grid node, we obtained empirical variograms using the robust method of Cressie and Hawkins (1980). We then fitted either spherical or exponential variograms (Figure 6), and obtained kriged predictions of bushels of scallops per nautical mile and dredge efficiency on a grid covering the fished section of Closed Area II. We chose functional forms of the variograms based on the weighted least-square estimator of Cressie (1993). We restricted the predictions to a polygon encompassing 99% of the catches observed (dashed line in Figure 2).
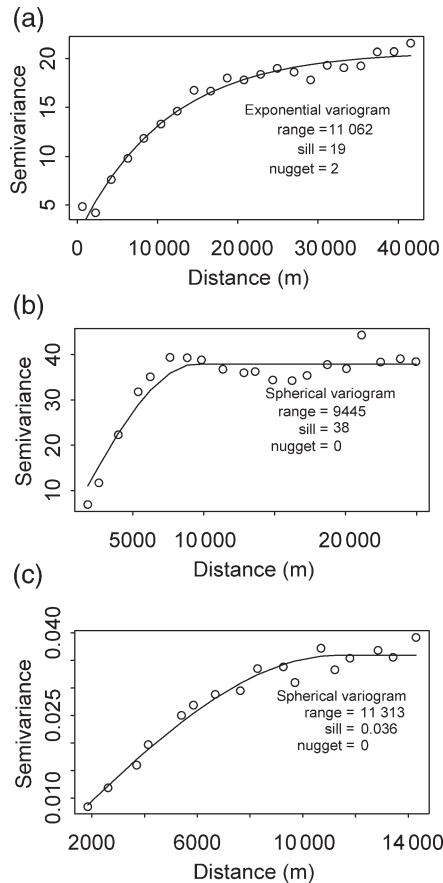
Figure 6. (a) Exponential variogram for 1998 cooperative survey relative abundance data in bushels of scallops per nautical mile towed, and spherical variograms of DeLury estimates of (b) scallop absolute abundance and (c) efficiency. Fitted lines are theoretical variograms chosen on the basis of the best objective fit as measured by Cressie's (1993) weighted least squares function.

Comparison with fishery-independent survey

We compared estimates of abundance obtained from the individual depletions with a fishery-independent survey of Closed Area II conducted between July and October 1998, before the fishery opening. Termed the cooperative survey, this joint effort between the scallop industry and the scientific community consisted of 531 samples from random and systematic grid locations. The samples were collected on six commercial scallop vessels using gear similar to that used in the 1999 fishery (4.57 m dredges fitted with 8.89 cm rings and 25.4 cm twine tops). However, tows were 10-min straight-line tows at ∼5 knots.

For direct comparison with the observer-recorded catches in 1999, we converted numbers of scallops in 1998 to numbers of scallops in 1999 by incrementing for recruitment and decrementing for mortality. All scallops were measured and assigned to 5-mm shell-height bins, then adjusted for size selectivity using the selectivity curve of DuPaul *et al.* (1989). The size at the midpoint of each bin was converted to an age using a von Bertalanffy growth model obtained from NMFS surveys of Georges Bank in 1998 (shell height = $L_{inf}(1 - \exp(-k(\text{age}_t - t_0)))$; $L_{inf} = 162$ mm, $k = 0.3374$ year^{-1}, $t_0 = 1.00$ years; NMFS, NEFSC). This age was advanced 1 year and a shell height after 1 year of growth was obtained. The number of scallops was

decremented for 1 year of natural mortality ($M = 0.1$ year^{-1}; Merrill and Posgay, 1964), then adjusted using the selectivity curve to reflect the expected catch of scallops at length in 1999. The number of scallops in each size bin was then converted into bushels using the shell height for the midpoint of each bin, and a regression was obtained from the 1998 survey of the number of scallops of a given shell height per bushel (number of scallops per bushel = 10^8 shell height$^{-2.84}$; $r^2 = 0.77$, d.f. = 1034). Total bushels of scallops of all sizes per tow were then obtained as the sum of the bushels of scallops across all size bins. We kriged the cooperative survey data and obtained predictions on the same locations as the depletion estimates to provide a set of fishery-independent pointwise comparisons of abundance.

Results

The 2753 observer records provided 538 depletion grid cells with >10 catches, 289 cells that met the relaxed criteria, and 50 that met the full catch-and-effort criteria (Figure 4). Only 61 of the 538 cells (11%) with 10 or more observed catches had positive slopes, indicative of a lack of depletion. Linear least-squares regressions for cells 10 and 254, and for seven other cells randomly selected from the good 50 depletion cells, are provided in Figure 7. The 50 grid cells meeting the full catch-and-effort criteria (Figure 4) had values of r^2 ranging from 5% to 63%, efficiency estimates from 17.6% to 94.7% (Figure 8a), and a median efficiency of 45.5% (mean of 47.3%).

Depletions with correction for effective area fished (A_{eff})

Above, the majority of cells deemed unacceptable failed the criterion of similar effort in the four quadrants. Many of those cells indicated strong depletions, with slopes and intercepts that were similar to the accepted cells, but because of heterogeneous spatial effort, the depletion was only to a portion of the individual cell, so overestimating efficiency and, in some cases, providing estimates >1 (Figure 8b). Although the estimated efficiencies >1 are theoretically impossible, they are entirely probable with fished area underestimated.

We applied area corrections to each of the 289 relaxed criterion cells. Depletion cells far from the locations with the greatest effort generally had smaller effective fished areas than cells closer to the high-effort areas. Note that every cell received some area correction owing to our decision to restrain the area to that which received 90% of the effort. Although this decision was arbitrary, we felt that it was appropriate given that, for most cells, most depletion would have been in the areas receiving 90% of the effort. By extending the fished area to the last 10%, we included areas that were only lightly fished, so incorporating greater spatial heterogeneity in fishing effort.

When corrected for A_{eff}, the depletion estimates of dredge efficiency for the 50 good depletions decreased from a mean of 47.3% to a mean of 32%, and the standard deviation of these estimates was reduced from 0.15 to 0.10 (Figure 8c). Moreover, no efficiency estimate was greater than 70%. For the relaxed criteria depletion cells, the mean efficiency estimate of the 289 area-corrected depletions decreased from 72% to 44%, and 70% of the 289 area-corrected depletion estimates fell between 20% and 55%. Also, just 8 of the 289 efficiency estimates (2.8%) were >1, so most of the predicted efficiencies were theoretically possible.

We obtained a kriged map of dredge efficiency using the spherical variogram shown in Figure 6c. The map of dredge
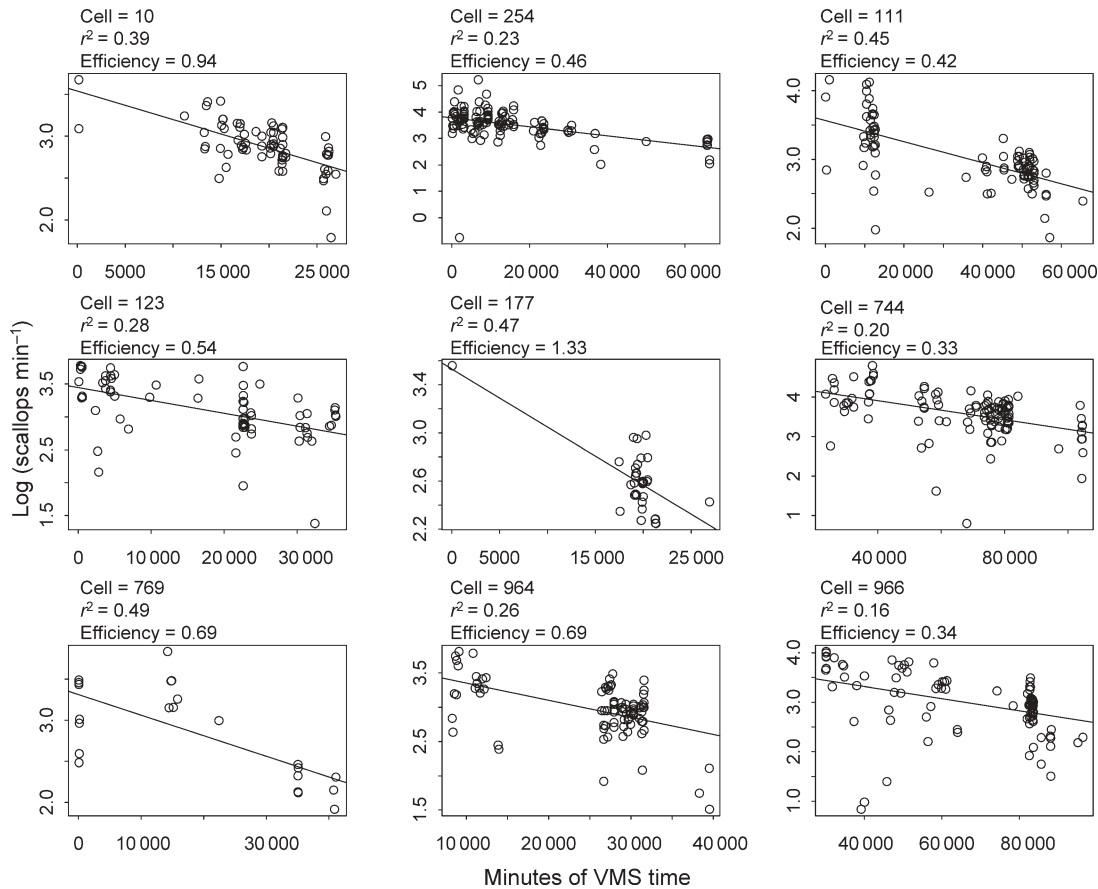
Figure 7. Linear least-squares regressions and DeLury depletion parameter estimates for cells 10 and 254, and for seven other randomly selected depletion cells.

efficiency showed a tendency for higher efficiencies on the edges of the areas with greater effort (cf. Figures 4 and 9). In areas where there were large numbers of depletion cells and high effort, efficiency estimates were consistently between 20% and 50%. Efficiency estimates were greatest and theoretically impossible in isolated areas with little fishing effort and few catches. Three areas, indicated by the black-and-white dashed contours, possessed anomalous efficiencies >1 and were spurious, because in two of the cases, a single very-low catch caused the estimated slopes to be very steep (Figure 9). We discuss these problems later.

Comparison with cooperative survey

To provide direct comparisons with DeLury depletion estimates of abundance, we obtained kriged predictions of scallop abundance using the cooperative survey on the location of each depletion grid node. Regressions of the kriged cooperative survey estimates of abundance against the DeLury estimates of bushels of scallops per nautical mile towed were significant and positive, with an r^2 value of 43%, a slope of 0.41 ($p < 0.001$), and an intercept of 2.29 ($p < 0.001$) (Figure 10). Because the DeLury depletion estimates were absolute, and the survey estimates only relative, the DeLury estimates would be expected to be higher and, if both are unbiased, the ratio of the two should give the survey efficiency. To determine this ratio, we fitted a regression with zero intercept to the data ($r^2 = 38.1\%$, slope = 0.523, $p < 0.001$; Figure 10).

The spatial distribution of abundance from the 289 depletion studies closely matched that of the cooperative survey (Figure 11a and b). The peaks of abundance in the northern and eastern regions were well defined on both maps, as was the diagonal ridge of abundance running from the southwest to northeast. Further, there is evidence in both analyses of the central area of low abundance. The kriged mean abundance for the cooperative survey was 6.7 bushels per nautical mile towed, and the kriged mean of the DeLury depletion abundances was 13.3 bushels per nautical mile.

Sensitivity analysis of efficiency estimates based on the 289 DeLury depletions vs. the percentage of the total effort used to determine the effective area fished (Figure 12a) indicated that using a larger percentage of the area increased the efficiency estimate. Using the full depletion cell area resulted in many estimates above the theoretical limit of 1. The greatest marginal increase in median efficiency was between 90% and 100% (39.5–54%), indicating that allowing the area possessing the last 10% of effort resulted in a disproportionately greater increase in efficiency.

As the percentage of the total effort used to determine the effective area fished increased, the estimated abundance per unit area decreased (Figure 12b). The DeLury regression parameters remained unchanged, but the exponentiated intercept of Equation (4) is divided by a larger area, resulting in less abundance per unit area.
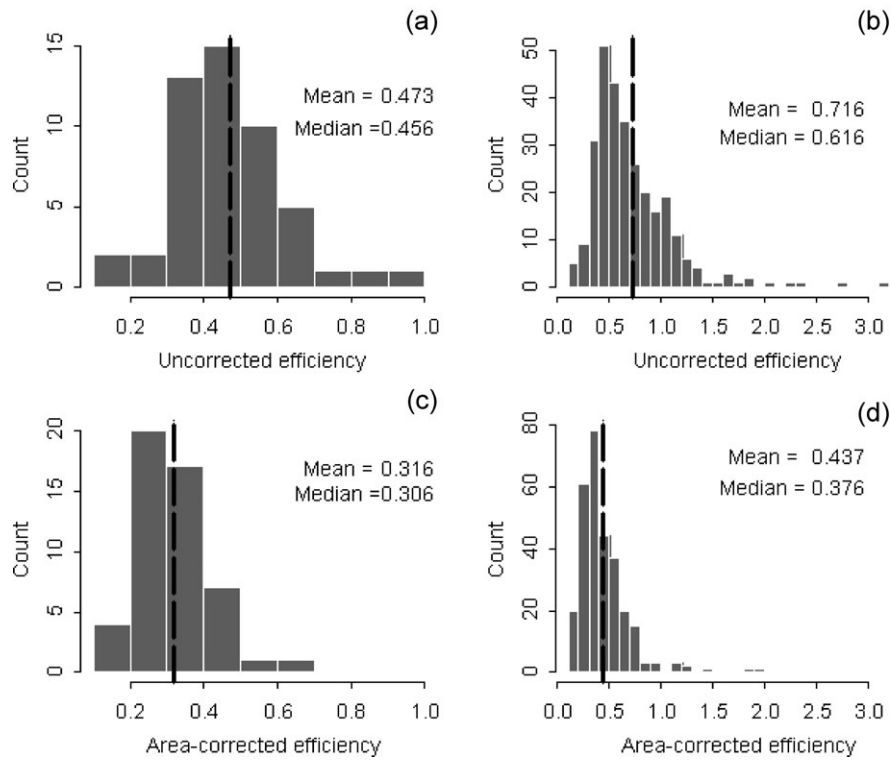
Figure 8. (a) Uncorrected and (c) area-corrected efficiencies for the 50 good depletions, and (b) uncorrected and (d) area-corrected efficiencies for the 289 relaxed criteria cells. Vertical dashed lines show the means graphically.
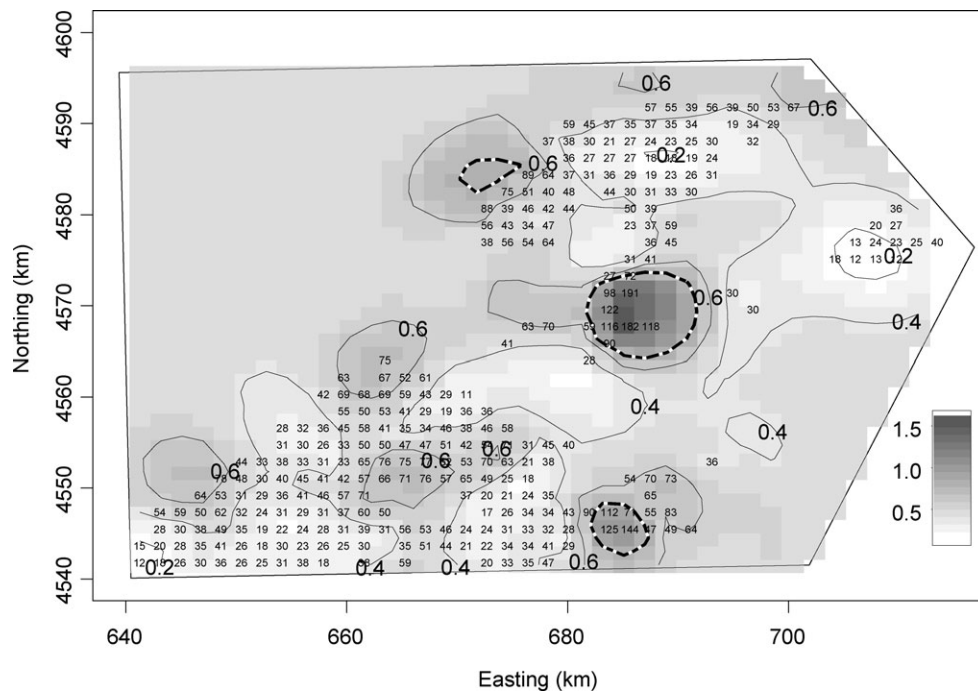

Figure 9. Kriged dredge efficiency based on estimates of efficiency from the 289 depletion studies. Small numbers are the real DeLury-derived estimates of efficiency. Contour lines of dredge efficiency are shown, the dashed ones identifying unrealistic efficiencies >80%.
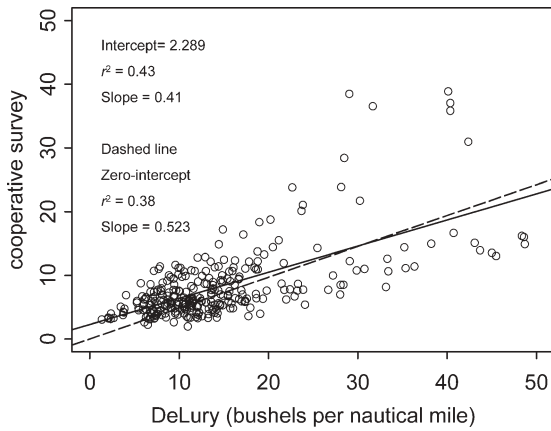
Figure 10. Linear regression of cooperative survey kriged predictions plotted against DeLury scallop abundance in bushels per nautical mile at the same locations. The dashed line is the zero-intercept regression.

Discussion

Satisfying the assumptions

Given the near-sessile nature of sea scallops and the limited duration of the fishery (6 months), the assumption of a closed

system is unlikely to be violated. Although *P. magellanicus* can swim, animals >100 mm have greatly reduced swimming capability (Caddy, 1968) and movement is primarily an escape response (Posgay, 1981).

Random fishing effort within the uncorrected depletion areas was, however, violated (Figure 5). Reducing the area to just the actual area fished greatly increased the potential that fishing is random or at least representative within the reduced area. This follows DeLury's (1951) comment that through "stratification" (DeLury's emphasis), it may be possible to create subpopulations which, although not strictly random, are reasonably representative to be treated as such. With the fine-scale resolution of VMS and observer catch data, we appear to approach such a stratification.

Violating the assumption of random fishing effort within the area-corrected depletion areas remained a potential problem. It is not straightforward to determine how non-random fishing effort would affect depletion estimates, because it could result in observed hyperdepletion or hyperstability in catch rates, depending on when in the fishery the observations were made (Miller and Mohn, 1999). Nevertheless, constraining the depletion area to just the fished area mitigated this problem to the extent that areas with no fishing effort were not included in the total estimates of depletion area. The assumption of constant catchability is also a
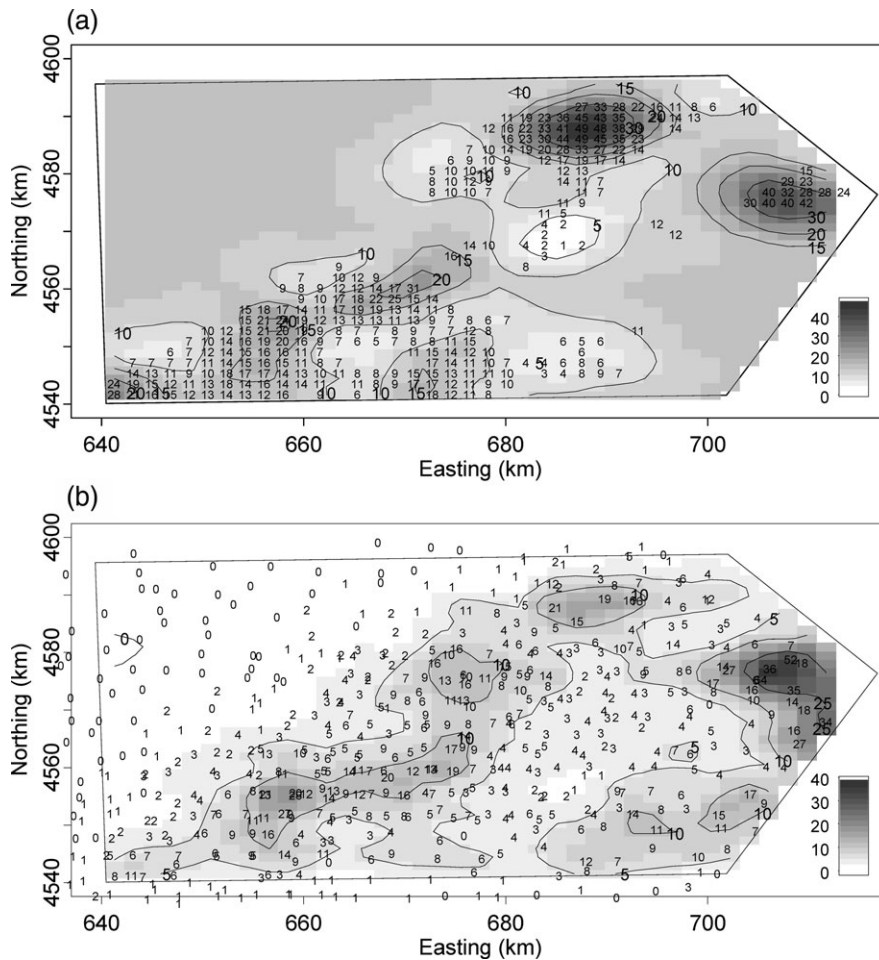

Figure 11. Kriged (a) scallop abundance in bushels per nautical mile towed from the 289 depletion studies, and (b) scallop relative abundance from the preseason cooperative survey (numbers are the actual DeLury estimates or survey values).
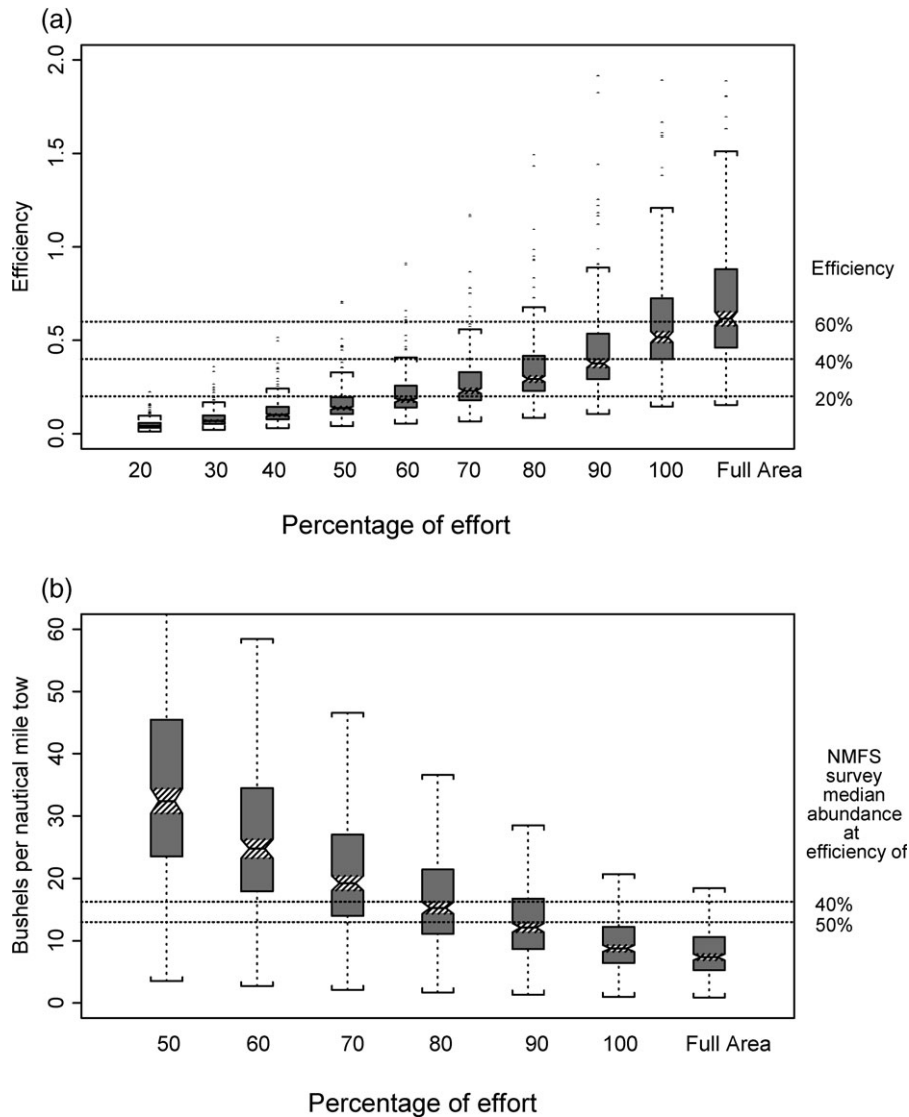
Figure 12. Boxplots of sensitivity of DeLury estimates of (a) efficiency, and (b) bushels per nautical mile towed to variation in the percentage of total effort used to determine the effective area fished. In (a), the lines represent efficiencies; and in (b), the lines are the median kriged values of the cooperative survey for 40% and 50% efficiency. The notched areas are 95% confidence intervals based on quantiles.

potential problem. The spatial variation in efficiency may be due to differences in depth, substratum, or scallop abundance. However, without further exploration, this statement is purely speculative.

For our method of correcting for effective area fished, we make an additional assumption that vessels spent 45 min of every hour of VMS time with gear on the seabed. Although we made this assumption based on observations in Gedamke *et al.* (2004), and rough estimates could also be obtained from observer databases, this is a critical parameter for depletion analyses and for the use of VMS effort data for any fishery-monitoring purpose. Potentially, VMS recorders could be programmed to transmit whether a vessel is fishing actively.

Although not presented here, Walter (2006) found that tow speeds within the range of the most probable speeds for vessels in the fleet (4.5–5.5 knots) had little effect on estimates of efficiency. At tow speeds <3.5 knots, many efficiencies were

unrealistically estimated to be above the theoretical limit of 100%. As tow speeds were not available in the observer database for 1999, we assumed a tow speed of 5 knots but, given the sensitivity of efficiency estimates to low vessel speeds, we recommend that this observation be carefully recorded in future. We also chose a depletion radius of 1.9 nautical miles, a distance considered appropriate by Gedamke *et al.* (2004). Walter (2006) also found 1.9 nautical miles to be the most appropriate radius by examining the effects of varying the radius of individual depletion cells from 0.8 to 3.2 nautical miles.

We also assumed that the area in which 90% of the effort occurred represented the effective area fished, A_{eff}. Further exploration of the VMS and observer datasets may allow this value to be refined and perhaps to be variable, depending on the spatial distribution of effort. Although our choice of an area possessing 90% of total effort was arbitrary, the cooperative-survey-predicted abundances provided some guidance

on appropriate upper and lower cut-off bounds. If we assume survey efficiencies between 40% and 50% (NEFMC, 1999; Gedamke *et al.*, 2004, 2005), then an effort cut-off between 80% and 90% gives similar abundances (Figure 12b). At the full area and 100% effort cut-offs, the DeLury-predicted abundances were substantially less than cooperative survey estimates, indicating that assuming that the entire area is fished tends to underestimate abundance. In contrast, at cut-offs at very low percentage effort, the DeLury abundances increased to unlikely levels. It appears that, if survey efficiency is between 40% and 50%, effort cut-offs of 80–90% provide the most appropriate measure of effective area fished.

Reliability of the estimates

Here, the large number of records (2753), together with the requirement that tows met certain quality requirements, provided protection from the influence of erroneous observations. Unfortunately, parcelling the data into a series of 289 depletion studies meant that outlier or erroneous data points had greater potential to influence single depletions. As depletions with over-lapping depletion radii can share catches, a single outlier catch could affect several depletions. Such a case exists, in fact, for all nine of the depletions with efficiencies between 91% and 124% in the centre of Figure 9. Although we have no objective reason to remove the offending data point (other than that its removal reduces each of the efficiency estimates to legitimate values), it does illustrate a limitation of the method, particularly when sample sizes are low. Given the potential effects of outliers on the unweighted linear regressions, it is reassuring to record that just 10 of the 289 depletions (3.5%) had estimated efficiencies >1. Further refinements of the model could include a likelihood-based approach for estimating overall efficiency or for estimating initial abundance (Gould and Pollock, 1997). Maximum likelihood estimation might provide less variable results given the potential error and variability in catch-and-effort measurements (Gould *et al.*, 1997) and the ability to borrow inferential power from all cells (Gould and Pollock, 1997).

Comparisons with other estimates of efficiency and abundance

The estimates of efficiency for this study were comparable with recent studies that estimated commercial dredge efficiencies of 24–57% with a mean of 40% (NEFMC, 1999) and between 35.5% and 52% (Gedamke *et al.*, 2004, 2005). Without the fished-area correction, many of the 289 depletions possessed estimated efficiencies >100% and were non-informative. Efficiency estimates from the current study and Gedamke *et al.* (2004, 2005) are, however, much higher than previous estimates (Bourne, 1966; Caddy, 1971), suggesting either spatial differences in dredge efficiency attributable to water depth, bottom type, scallop size, or scallop abundance, or that dredge efficiency may have increased over time.

Although the purpose of this study was to demonstrate the utility of area-corrected depletion estimators derived from commercial catch data, the estimates of abundance warrant comparison with other estimates. The estimated kriged abundances closely match the cooperative survey estimates if a survey efficiency of 50% is assumed. Total abundance estimated from the kriged DeLury predictions over the prediction area (842 nautical miles^2 of the total 1200 nautical miles^2 of the exemption area of Closed Area II; Figure 2) and using an estimate of 7.5 pounds of scallop meat per bushel would be 17 million pounds. Kriged cooperative survey abundance in the same area using the same conversions is between 17.2 and 21.5 million pounds, with efficiencies of 50% and 40%, respectively. A harvest of 6 million pounds of scallop meat weight and an initial abundance of 17 million pounds gives an overall exploitation rate of 35% in the area fished inside Closed Area II.

In contrast, if the efficiency estimate (25%) used to determine the preseason quota in 1999 is assumed, then the depletions underestimate abundance by about half. However, the ratio of the cooperative survey abundances to the DeLury depletion abundances is 0.523, indicating a survey efficiency of 52.3%, so survey dredge efficiency would be closer to 50% than 25% (Figure 10). We would not, however, suggest that abundance estimates derived from commercial catch data be used exclusively to set quotas, because the vagaries of the spatial and temporal distribution of observed catches may not provide catch information in all fished areas. In such a case, the broad spatial coverage provides kriged abundances similar to that of the preseason cooperative survey. However, reduced observer coverage would limit the ability to produce kriged maps of overall abundance and greatly reduce the number of adequate depletions.

Conclusions

Few depletion studies have evaluated critically whether the assumed area of the depletion corresponds with the effective depletion area. It is, however, a crucial issue for any depletion study whether the study is based on the assumption of random catch and effort within an area (DeLury, 1951) or in studies designed to target the exact same area. Only with the recent advent of precise vessel positioning systems does the potential exist to determine effective area fished for research surveys (Joll and Penn, 1990) and, with the placement of VMS tracking systems, for commercial depletion studies. Without correcting for the actual area fished, the vast majority of catches observed in this study produced spuriously high efficiency estimates. Correcting for fished area provided 289 individual depletions and estimates of dredge efficiency and scallop abundance close to estimates obtained in other studies.

Acknowledgements

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