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Georges Bank 'a' Scallop (*Placopecten magellanicus*) Annual Stock Assessment: Survey Design

Évaluation annuelle du stock de pétoncles « a » du banc Georges (*Placopecten magellanicus*) : conception du relevé

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ABSTRACT

This Research Document presents an evaluation of the current and alternative designs for the annual August survey of sea scallops (*Placopecten magellanicus*) on the Canadian portion of Georges Bank. This document was presented as a working paper as part of the advisory process for developing a new assessment framework for Georges Bank scallops so that decisions could be made on the design of future surveys.

The original design with stratification based on annual commercial catch rates had several disadvantages including strata boundaries that changed each year and inconsistent coverage that was tied to fishing patterns. This design also performed poorly in terms of precision when evaluated against a simple random sampling design.

Two alternative designs with fixed strata boundaries were proposed: stratification based on commercial catch rates from 1981-2007 and stratification based on the survey index from 1981-2007. Relative efficiency was used to evaluate designs by comparing the variance of the estimated number of scallops when a given design is imposed. A portion of the relative efficiency results from the allocation of tows and because this could not be controlled in this analysis, potential relative efficiency that would result if allocation was optimal was also examined. Both of these designs were found to be improvements over the original annual catch rate design and simple random sampling in terms of gains in realized and potential efficiency. However, the historical survey index (HSI) performed slightly better than the historical catch rate (HCR) in both realized (overall mean: 53% vs. 44%) and potential (overall mean: 69% vs. 64%) efficiency.

Other variables that could potentially be used to create strata boundaries were also evaluated including depth, scope for growth, and disturbance. These variable were found to be less predictive of scallop abundance than historical measures of abundance. Substrate type was not evaluated.

The recommendation from the framework meeting was to adopt the HSI design with a division between the north and south portion of the bank. The final design to be used in future will be the HSI design with the top 3 strata divided by the Northwest Atlantic Fisheries Organization (NAFO) line between areas 5Zej and 5Zem and the lowest strata common over the whole bank. This design provided further improvements in relative efficiency over the HSI design. Since strata boundaries remain the same for the northern and southern portions of the bank, any subsequent analysis could be conducted with or without a north/south division.

RÉSUMÉ

Ce document de recherche présente une évaluation des modèles de conception actuel et de remplacement pour le relevé annuel d'août sur le pétoncle géant (*Placopecten magellanicus*) dans la partie canadienne du banc Georges. Ce document a été présenté comme document de travail dans le cadre du processus de consultation visant à élaborer un nouveau cadre d'évaluation pour les pétoncles du banc Georges, et ce, en vue de prendre des décisions relativement à la conception des relevés à venir.

La conception initiale par stratification reposant sur le taux de captures commerciales comportait plusieurs inconvénients, y compris les limites des strates changeant chaque année et une couverture non uniforme associée aux modèles de pêche. Cette conception donnait aussi de mauvais résultats quant à la précision lorsque l'évaluation était faite par rapport à une conception d'échantillonnage aléatoire simple.

Deux conceptions de remplacement avec des limites de strates fixes ont été proposées : la stratification reposant sur le taux de captures commerciales de 1981 à 2007 et la stratification reposant sur l'indice de précision de 1981 à 2007. On a utilisé l'efficacité relative pour évaluer les conceptions, en comparant la variation du nombre estimé de pétoncles lorsqu'une conception donnée était imposée. Une partie de l'efficacité relative découle de l'allocation de traits, et comme ceci ne pouvait être contrôlé pour cette analyse, on a aussi examiné l'efficacité relative possible qui en découlerait si l'allocation était optimisée. On a constaté que chacune de ces conceptions représentait une amélioration par rapport à la conception initiale reposant sur le taux annuel de captures et l'échantillonnage aléatoire simple en ce qui concerne les gains pour l'efficacité possible et réalisée. Toutefois, l'indice historique de précision (IHP) a donné un rendement légèrement supérieur au taux historique de captures (THC) à la fois pour l'efficacité réalisée (moyenne globale : 53 % comparativement à 44 %) et possible (moyenne globale : 69 % comparativement à 64 %).

On a aussi évalué d'autres variables qui pourraient possiblement être utilisées pour créer les limites des strates, y compris la profondeur, les possibilités de croissance et la perturbation. On a constaté que ces variables donnaient moins de prévisions sur l'abondance des pétoncles que les mesures historiques sur l'abondance. Le type de substrat de croissance n'a pas été évalué.

Suivant la réunion sur le cadre de travail, il a été recommandé d'adopter la conception IHP, avec une division entre la partie nord et la partie sud du banc. La conception définitive à utiliser à l'avenir sera la conception IHP avec les trois strates supérieures divisées par la ligne de l'Organisation des pêches de l'Atlantique Nord-Ouest (OPANO) entre les zones 5Zej et 5Zem et la strate inférieure commune à tout le banc. Cette conception a entraîné d'autres améliorations pour l'efficacité relative par rapport à la conception IHP. Comme les limites des strates restent les mêmes pour les parties nord et sud du banc, toute analyse ultérieure pourrait être effectuée avec ou sans division nord-sud.

INTRODUCTION

The indices of fishable biomass derived from fishery surveys are the key ingredient in the models used for stock assessment of fisheries resources (Kimura and Somerton 2006). In order to estimate absolute abundance a reliable index of relative abundance is essential. Of the 3 main types of surveys - random, stratified random, and systematic, the stratified random design is the most precise when there is only one species of interest and detailed information is available on the abundance and variance of that species within strata (Kimura and Somerton 2006). This is the case for the sea scallop (*Placopecten magellanicus*) on Georges Bank, where it is the only target species of the survey and there is substantial past information on its abundance, distribution patterns and habitat associations.

Up to now, the assessment survey that takes place in August each year on Georges Bank has used a stratified random design. The strata were defined annually based on catch rates in the year prior to the survey. A previous evaluation of this design found that recent commercial catch rate data did not accurately represent the spatial variability in abundance at the time of the survey (Smith and Robert 1998). The annual catch rate design also has several other disadvantages such as not being independent of the fishery and, therefore, may be subject to all of the various factors affecting the fishery (e.g., market conditions, targeted fishing, seedboxes, etc.). As a result, annual changes in survey abundance may confound actual changes in abundance with changes in fishing pattern. Also, because strata change each year, they are not comparable over time, i.e., there can be no time series of individual strata. The area of the most concentrated fishing effort varies from year to year causing a change in where the higher catch rates are reported and results in the high and low catch rate strata changing location over time. The overall area covered by the survey changes over time as a function of the spatial distribution of fishing and, in some years, additional tows had to be assigned outside of the design to get sufficient coverage of the bank.

The purpose of a stratified design is to increase the precision of the estimates of population size (Cochran 1977; Gunderson 1993). This can be done by defining strata boundaries where the measured values within these boundaries are more similar to each other than to values in other strata, thereby, reducing the variance within each stratum (Gunderson 1993). Overall variance of the estimates can be further reduced by allocating more samples to strata with higher variances. Improving survey efficiency through better allocation may be possible when designing future surveys, but this Research Document will focus on defining the strata that will likely reduce overall variance in future surveys.

In this paper, the current survey design is evaluated, as well as alternative designs where the strata boundaries remain fixed and areas covered in the survey remain consistent from year to year. Stratifying variables will be examined to determine which will likely be the best predictor of abundance and most likely to improve survey efficiency. The variables examined include 2 direct measures of scallop abundance, historical commercial catch rate, and historical survey index of abundance, as well as 3 variables that may be correlated to scallop abundance, depth, scope for growth, and disturbance (DFO 2006). Substrate type is another potential stratifying variable known to be correlated with scallop abundance (Thouzeau et al. 1991; Kostylev et al. 2001), but these data were not available to be evaluated in this paper.

METHODS

The original annual catch rate design was completed by comparing it to a simple random design in order to see how well stratification improves the efficiency by reducing the variance (Var) of the estimated population numbers (P_{st}). The population estimate from a stratified random design is,

$$\hat{P}_{st} = \sum_{i=1}^{h} N_i \, \overline{C}_i \tag{1.1}$$

where,

N_i = A_i/a = number of towable units in stratum i, where A_i = area within stratum i and a = area of a towable unit

$\overline{C_i} = \sum_{j=1}^{n_i} C_{ij}$ = mean number of scallops per tow in stratum i, where n_i is the number of tows sampled in stratum i.

The variance of the population estimate from a stratified random design (ignoring the finite population correction) is,

$$Var\left(\hat{P}_{st}\right) = \sum_{i=1}^{h} N_i^{\,2}\, Var\left(\overline{C}_i\right) \tag{1.2}$$

Relative efficiency (RE) was calculated by comparing the variance of a stratified population estimate to the variance of a population estimate produced from simple random sampling (P_R)

$$RE = \frac{\left[Var(P_R) - Var(P_{st})\right] * 100}{Var(P_R)} \tag{1.3}$$

The simple random design variance can be estimated directly from data collected using a stratified random design (Sukhatme and Sukhatme 1970). A positive value for RE indicates that the stratified random design resulted in a smaller variance of the estimate and that the design contained useful information about the population being sampled. Relative efficiency breaks down into 2 components, one due the scheme used to allocate tows to strata and the other due to the stratification scheme (Smith and Gavaris 1993). The stratification component measures the contribution of the strata to the reduction in variance. The purpose of stratification is to obtain homogeneous groupings such that the mean within a stratum is very different from the mean over all strata. The larger this difference and the smaller the within stratum variance, then the larger the positive difference between the simple random sample variance and the stratified random variance. Tows can be allocated to strata arbitrarily, proportional to the stratum area, or proportional to some function of the stratum variance. The allocation term will be negative, zero, or positive for these 3 schemes, respectively. It is possible that a suboptimal allocation scheme could result in a negative value for this component that is large enough to cancel out any benefit that was obtained from the stratification scheme.

The efficiency of the new designs was compared relative to the original annual catch rate design. In this analysis, it is assumed that the probability of a tow being included in the survey was given by n_i/N_i as defined for the original catch rate strata. Tows assigned to the strata boundaries for the new designs may have come from more than one of the original annual catch rate strata and, hence, may have different probabilities of being included. As a result, estimates for the new designs need to be made using a domain estimator, which takes these differing probabilities into account (Särndal et al. 1992).

The allocation of tows to strata was based on the original annual catch rate stratification and, therefore, the allocation to the new strata may be quite suboptimal with respect to reducing variance. As a result, comparisons of the relative efficiency between the new and old designs may be confounded by these suboptimal allocations. To get around this issue, the potential relative efficiency was investigated by calculating the expected minimum variance had the allocation scheme been optimal. The expected minimum variance was calculated using the following equation from Cochran (1977).

$$Var_{\min} = \frac{1}{n}\left(\sum_{i=1}^{h}\frac{N_i}{N}S_i\right)^2 - \frac{1}{N}\sum_{i=1}^{h}\frac{N_i}{N}S_i^2 \qquad (1.4)$$

where, $N = \sum_i N_i$, $n = \sum_i n_i$ and S_i^2 is the variance for stratum i.

The stratum variance for the new designs was estimated for each stratum as the sample size times the variance of the mean.

Reconstruction of the Original Annual Catch Rate (ACR) Stratified Design

Stratum areas (A_i) in (1.2) are necessary to compare new design schemes to the original design scheme. Unfortunately, the areas and spatial boundaries of the strata from the original design are unavailable for many years. Therefore, we needed to reconstruct the original design, calculate the areas, and determine the original strata assignments for all of the existing tows.

The original strata were based upon spatial patterns in the catch rates prior to the survey. In the past, the catch rates were reported in the units kg/crhm (kilograms of scallop meat per number of crew members (cr) × hours fished (h) × the width (m) of gear used) for all fishing boats prior to the introduction of freezer trawlers and afterwards for the non-freezer trawler fleet (wet fishery) only. The reconstructed original design will use the units kg/hm (kilograms of scallop meat per hours fished × the width (m) of gear used). An analysis conducted as part of the process for designing the survey in 2008 indicated that when using the catch rate unit kg/hm, a standardization coefficient was unnecessary for combining catch rate data from both wet fishery and freezer trawler fleets (Jonsen et al. 2009). Linear models were fit to both catch rates in kg/crhm and in kg/hm to convert strata boundaries from kg/crhm to kg/hm. The bin sizes for the former units were set to <0.2, 0.2-0.5, 0.5-1, 1-2 and >2 kg/crhm, while they were <4, 4-8, 8-18, 18-36, and >36 kg/hm in the latter case.

In order to define the strata, catch rates were then contoured on the Georges Bank in each year of the survey. Past practice used fishery data from September of the previous year to June of the survey year for the contouring. The consequences of data spanning a period in time as opposed to being collected all at once at a particular moment in time are that one would expect a greater degree of variation between points sharing the same spatial position. For example, it would be quite likely that two fishing boats fishing the same place at different times in the season would have different catch rates. These differences could be driven by growth, recruitment, fishing, or natural mortality. To compensate for this temporal variation, catch rates were smoothed spatially over the bank.

The bank was divided into a grid of 1 nautical mile (3.43 km) and the catch rate was calculated using a Jackknife estimator (Smith 1980) from all reported catch and effort within each square. The Jackknife estimator was found to be a robust method for estimating catch rate and also provides the means for calculating confidence intervals.

$$CR_{-j} = n\left(\frac{C}{E}\right) - (n-1)R_{-j} \qquad (1.5)$$

where,

n = the number of records in a square
C = the sum of the catch in a square
E = the sum of the effort in a square

$R_{-j} = \left(\frac{\sum C_{ij}}{\sum E_{ij}}\right)$ with the jth observation removed

The value of the catch rate for a given square is the average of all CR_{-j} for that square.

For the purposes of assigning strata, catch rates were considered to be zero in cases where there were no data available for a particular square. The resulting smoothed data were then interpolated using a bilinear spline interpolation (Akima 1978) over a grid of 0.01 degrees of latitude (1.23 km^2) and plotted using the converted boundaries (e.g., Figure 1).

Original survey tows were assigned a stratum label based on the reconstructed strata definitions. Strata areas were calculated in standard towable units (1950.72 m^2) of which there are 634 per 0.01 degrees of latitude (1.23 km^2) square. Therefore, the number of towable units in each stratum is equal to the number of squares belonging to each stratum times 634 (Table 2).

Alternative Historic Catch Rate (HCR) Stratified Design

The HCR design differs from the ACR design in that catch rates are calculated from all catch and effort data on Georges Bank from 1981 to 2007. The HCR design spans a much greater period of time than the ACR design, so there is an even greater need for smoothing the data. As with the annual design, the catch rates were smoothed over a one nautical mile grid (3.43 km^2) by using a jackknife estimator from all reported catch and effort data for the period of 1981 to 2007 for each square of the grid. The HCR design uses the same methods as the annual design for interpolation, assigning catch rates and plotting the resulting strata with the exception that a bicubic spline interpolation (Akima 1996) was used for the spatial interpolation that produced the contours.

The optimal strata number and boundaries for increasing the efficiency of the survey were also investigated for the HCR design. Methods for determining the optimal number and boundaries for the strata can be found in Cochran (1977). The optimal number of strata is defined as the smallest number of strata where adding 1 more stratum does not substantially increase mean efficiency. Optimal strata boundaries are assigned by the cumulative $\sqrt{f(y)}$ rule, where $f(y)$ is the frequency function of the stratifying variable. Strata boundaries are then chosen such that the interval of the cumulative $\sqrt{f(y)}$ are approximately equal (Cochran 1977). For simplicity, strata boundaries were restricted to whole numbers.

The actual implementation of this type of design would probably consist of using the catch rate data from 1981 to the current survey year. Therefore, the performance and stability of this design was evaluated using the catch rate data prior to the survey and applying the design to the current and following years of the survey.

Alternative Historic Survey Index (HSI) Stratified Design

The HSI design is similar to the HCR design but uses the standardized number of scallops per tow for all survey stations on Georges Bank 'a' from 1981 to 2007 as a stratifying variable. These data spanned a long period of time and had to be smoothed over a 1 nautical mile grid by taking the median value found in each square of the grid. The smoothed data was interpolated using an inverse distance weighted interpolation (Pebesma 2004) over a grid of 0.01 degrees of latitude (1.23 km^2). The same methods for determining optimal number of strata and strata boundaries that were used in HCR design were used in this design as well. As with the HCR design, the HSI design must also be evaluated using data from a different time period as the proposed design. Past survey data are used to construct the strata and efficiencies for the HSI design are calculated that will better represent expected results if this design was implemented.

Other Alternative Stratified Designs

Other potential stratifying variables that were also investigated include depth, scope for growth and disturbance (DFO 2006). Depth data were obtained from the OLEX[1] database comprised of data collected from fishing and other vessels using their own echosounder and GPS and compiled with software designed to improve accuracy with repeated measures. Scope for growth is a dimensionless number from 0 to 1 generated by combining the following variables: food availability, annual bottom temperature, seasonal and interannual variability, oxygen, and salinity (Figure 2) (DFO 2006). Disturbance is defined as the log of the ratio of frictional velocity or bottom stress to the critical current required to move a given grain size (Figure 3) (DFO 2006). These data were acquired as raster files and assigned to each survey station as the mean of the values within a tow track (standard tow track = 800 m $\times$ 2.44 m). Tree regressions were used to determine which, if any, of these variables are correlated to abundance measures from the survey (Ripley 2007). Historic catch rate and historic survey index data collected from 1980 to 1998 were also fit as explanatory variables and the response variable in the model was the standardized total number of scallops for each tow from 1999 to present.

RESULTS

Although every reasonable effort was made to reproduce the original design given the available information, the reconstructed ACR design was not an exact reproduction of the original. When the new strata designations from the reconstructed ACR design are compared to the original strata designations, the strata designations generally do not match (Figure 4). The catch rates that were calculated in each nautical mile square using the jackknife estimator must have been

[1] www.olex.no

lower such that more tows tended to be assigned to new strata representing lower catch rates. For example, most tows that were originally strata 1 to 3 are now mostly strata 1; strata 4 are now mostly strata 2; and strata 5 are mostly strata 3 (Figure 4). When the contour plot used in the original design (Figure 5) is compared to a plot using the same data in the reconstructed design (Figure 1), it appears to support the premise that the reconstructed design seems to have produced lower catch rates even though the catch rates are given in different units.

The time series of mean number of scallops per tow calculated using the reconstructed ACR stratification are very similar to the mean number of scallops per tow ignoring the survey design (Figure 6). The standard errors of the means are also very similar; however, the relative errors show slightly less precision in the stratified means (Figure 6). This in turn results in relative efficiencies that are generally negative (Figure 7). Although a stratified design is expected to lower the variance of the mean, this was a post-stratification scheme with no control over the allocation of survey stations. Any gains in efficiency due to the stratification were offset by losses in efficiency due to poor allocation of survey stations to strata. Looking at the stratification efficiency for the ACR design relative to simple random sampling, relative allocation efficiency was mainly negative, and there were a few minor gains in efficiency due to stratification (Figure 7). The potential gains in efficiency for this design are fairly modest suggesting that the reconstructed ACR strata were not very effective for increasing the precision of the mean (Figure 7).

The HCR design was constructed using 5 strata as this was found to be an optimal number since increasing the number of strata further did not provide significant gains in efficiency (Figure 8). The strata boundaries arrived at using the cumulative $\sqrt{f(y)}$ rule were 1, 6, 8, 10, and 13 kg/hm. The resulting contour map (Figure 9) shows the expected trend that the strata representing higher abundances are found mainly on the northern portion of the bank. Areas where catch rates have historically been higher than 13 kg/hm (strata 5) are found mainly in the far northwest corner and centered around Lat. 42° N, Long. 66.5° W. Strata 3 and 4 (where catch rates have historically been higher than 8 kg/hm) are found mainly in the northern portion of the bank, particularly where the dominant sediment type is gravel (Figure 10, Kostylev et al. 2005), A few “hotspots” were found in the southern portion. Strata 1 and 2 represent areas where historic catch rates range from 1 to 8 kg/hm and are found mainly in the central part of the bank and from what may be marginal habitat in other areas. There were a few areas where historic catch rates were less than 1 kg/hm such as the middle of the bank near the international border and deeper waters in the south. In these areas, it is unlikely that any scallops would be captured in a survey tow, so they will be left out of the design and no stations would be assigned there.

The time series of the stratified mean number of scallops per standard tow produced from reassigning survey tows to the HCR strata is similar to both the time series of simple means and ACR stratified means (Figure 11). The standard and relative errors also appear similar; however, the relative efficiencies reveal some differences (Figure 12). Both the realized and potential efficiencies of the historical catch rate design compare favourably with the ACR design and simple random sampling when the strata are based on all available data (Figure 12). When only data prior to the survey were used, the efficiency relative to the ACR design was largely positive indicating an improved design (Figure 13). Potential relative efficiency shows that gains are possible in all years. The realized relative efficiencies are all positive for years later than 1999. This analysis also demonstrates that even when the data used to construct the strata were not from a recent period of time, the historical catch rate design provides substantial improvement over the reconstructed ACR design.

Gains in efficiency from increasing strata past 4 were minimal for the historic survey index (Figure 14); therefore, only 4 strata were used in this design. Optimal strata boundaries for the HSI design were 1, 105, 223, and 384 scallops per standard tow. The contour map of the historic survey index (Figure 15) demonstrates both similarities and differences with the map of the historic catch rate (Figure 9). The areas where no strata were assigned due to few or no scallops being caught were essentially the same for both designs. The areas assigned to the highest stratum in the catch rate design are also the highest stratum in the survey index design, but additional areas in the survey index design have also been given this designation. More areas of the high abundance are found in the southern portion of the bank, but this is less prominent with the catch rate data. As with the catch rate design, low abundances are found in the middle portion of the bank, which is predominantly stratum 1 in the survey index design. Overall, areas of higher abundance are more concentrated in the survey design map than the historical catch rate map, and it appears to more closely resemble the sediment type map (Figure 9) in the northern portion of the bank.

The stratified mean and standard errors produced by the survey index post-stratification scheme were lower than the means and standard errors produced by the ACR design and simple random sampling in most years (Figure 16). The realized relative efficiencies indicate that the historical survey index design is more efficient than the ACR design or simple random sampling despite the fact that there was no control over allocation. Considering optimal allocation, the potential relative efficiencies are even higher. The evaluation versions of the survey index design also support this as nearly all relative efficiencies were positive indicating improvement over the ACR design (Figure 17). As with the HCR design, the historical survey index provides improved precision over the ACR design even when data used to construct strata were collected over 16 year earlier (Figure 18).

By directly comparing the potential efficiency gains of the historical catch rate and historical survey index designs, it appears that the historical survey index strata have the greatest potential for improving the efficiency of the survey. A comparison of the difference in relative efficiencies of the evaluation versions of the 2 proposed designs when using data prior to 1998 indicates that the survey index design usually has a greater potential relative efficiency (Figure 19). The mean realized efficiency gains for the historical catch rate and historical survey index designs over all years in all break year analyses were 44% and 53%, respectively. The mean potential efficiency gains for the historical catch rate and historical survey index designs over all years in all break year analyses were 64% and 69%, respectively.

The tree regressions show that the historical survey index is clearly the most important variable in predicting the number of scallops per tow in future surveys (Figure 20). However, this is somewhat of a circular relationship and the regression was fitted again without historic survey index to see what explanatory power was possessed by the other variables. The result shows the most important variable was the historic catch rate, with some explanatory power being attributed to growth and disturbance.

DISCUSSION

The reproduction of the original ACR design reveals that this design did little to improve the precision of the estimated abundance from the survey. In most cases the stratified mean was less precise than the mean assuming simple random sampling. Although this poor performance was due mainly to poor allocation of survey stations, gains due to stratification and even potential efficiency given optimal allocation were substantially less than the other designs. It should be noted that the reconstructed strata of the annual design were not the same as the original strata that were assigned when the survey was conducted. However, a previous study of the original stratification found the same results: negative efficiency due to poor allocation and minimal gains in efficiency when strata were constructed from annual catch rate data (Smith and Robert 1998). These findings indicate that the old design likely does not provide any advantage over simple random sampling and, therefore, changing to a new design is warranted.

The HSI design provides the greatest gain in realized and potential efficiency, even when not including data from the same time period. However, it should not come as a surprise that the historical survey index is the best variable for predicting the more recent survey index. The historical catch rate designed strata also provide gains in efficiency as they too are a direct measure of abundance. The habitat variables, such as depth, growth, and disturbance are less direct measures of abundance and were not found to contribute as significantly in predicting the numbers of scallops found at each survey station. Despite this, they may still be contributing factors affecting abundance. A major factor affecting scallop abundance on Georges Bank that was not captured in these habitat variables is the fishery itself. The areas of preferential scallop habitat in the northern portion of the bank may provide the potential for high scallop abundances, but fishing effort is more highly concentrated in these areas. This means that areas that might otherwise have higher abundances are fished down until they more closely resemble areas of moderate abundance that have not experienced as much fishing pressure. This is evident from the comparison of the historical survey index contour map with the historical commercial catch rate contour map. The catch rate map shows data that were collected throughout the year and represents scallops that were removed from the bank, while the survey index is a snap shot in time of the concentrations that are currently there in a given year. The catch rate map correlates better with the environmental variables and indicates where the most scallops were and where they grow best. The survey index, which indicates where most scallops are at the time of the survey, shows relatively higher levels of abundance in the southern areas than would be expected by looking at environmental variables alone. For the purposes of reducing variance in survey estimates the historical survey index appears to be the best stratifying variable for predicting what abundances are expected at the time of the survey.

Direct abundance measures can change relatively quickly with time as they are subject to changing fishing pressure, as well as natural events. Variables such as depth, scope for growth, disturbance, and substrate change relatively little with time when compared to scallop abundance patterns. Analysis of the historic survey abundance and commercial catch rate designs indicates that the performance of a stratified design varies depending on what period the abundance data used to construct strata were collected. The efficiencies were generally lower when the time between the maximum year used for the design and the year of the actual survey increased. This suggests that a survey design based on historic abundance may lose some of its efficiency gains as time goes on. However, the variables tested (depth, growth, and disturbance) appear to be insufficient in explaining abundance. The distribution of juvenile scallops is likely determined by both physical processes during the larval stage and settlement success (Thouzeau et al. 1991). Settlement and subsequent success is dependent on the factors mentioned above (depth, growth, and disturbance), as well as habitat type, which has been shown to have strong associations with scallop populations (Kostylev et al. 2001). A map showing average grain size of the substrate on Georges Bank (Kostylev et al. 2005) demonstrates that, at least in the northern portion of the bank, the higher abundances in the historical survey index appear in areas dominated by gravel substrate. Environmental variables that include high resolution information regarding substrate composition may be an alternative to the historical survey design. These kinds of designs would remain relatively constant with time and ensure that different habitat types are represented in the estimates of total abundance.

Abundance indices were found to be lower when calculated using the stratification based on the historic survey index. Caution should be taken when interpreting these results as the original surveys stations were not properly allocated with these strata in mind. However, future surveys designed with proper allocation to new survey strata should be examined to see if there is a bias in the random design which may misrepresent a population that is aggregated (Kimura and Somerton 2006).

Adaptive allocation designs have been used for Georges Bank with success in the past (Robert et al. 2000) and may also be employed in future survey designs to increase precision. These designs allocate a portion of the total survey tows proportionally to the area of each stratum, and then once those tows have been completed allocate the remaining tows according to a specified decision rule (see Robert et al. 2000, Smith and Lundy 2006).

While a quantitative approach was preferred whenever possible, some of the methods used in constructing strata for the alternative designs were somewhat subjective. Different methods of spatial interpolation were used in the different designs because of the differing amount and distribution of data points. The annual catch rate data featured a large number of data points often concentrated in certain areas. On the other hand, the historical catch rate data featured even more data points spread out over the entire bank but also in large concentrations, while the survey index had relatively few data points spread more evenly throughout the bank. In order to achieve usable strata contours, the method of interpolation that best handled each case was chosen.

For the purposes of designing a survey that produces the most precise estimate of relative abundance, analysis suggests the appropriate choice would be the historical survey index design. However, the efficiency of the design could be improved by adding substrate information; this has shown promise where the incorporation of rudimentary habitat data as a covariate in the annual stratified design substantially improves the precision of the estimate (Smith and Robert 1998). A stratification scheme based on combined variables may be a better choice not only for improving the survey estimates but also for understanding changes in scallop abundance within their environment.

RECOMMENDATIONS AND FINAL DESIGN

This paper was tabled as a working paper at the advisory process meeting to develop a new assessment framework for Georges Bank scallop. The conclusion was reached that the HSI design should replace the ACR design for the August survey of Georges Bank (DFO 2009). For the final design, survey data from 2008 were included and 2 recommendations regarding survey design that were raised at the framework meeting were addressed: separation of northern and southern strata and a comparison of biomass versus abundance as a stratifying variable (DFO 2009). The separation of the strata by north and south was suggested because the fishery occurs mainly in the northern portion of the bank. Comparison of biomass index versus abundance was suggested because the original ACR design was stratified on biomass rather than abundance.

The separation of strata between north and south was achieved in 2 ways, by splitting the upper 3 strata of the HSI design into north and south strata (Figure 21), and calculating separate strata definitions for north and south effectively designing 2 separate surveys (Figure 22). To determine an appropriate division, 41.8°Lat. initially appeared to be reasonable given the pattern of historical abundance. However, because this is so close to the division between NAFO areas 5Zej and 5Zem (42° 50’), the NAFO line was chosen for consistency.

Both north/south divided HSI designs performed better than the original HSI design (Table 3). The time series of stratified mean and standard error for the split design was similar to the base HSI design with the exception of 1998 and 1999, where the means and error were substantially lower (Figure 16; Figure 23). Realized and potential efficiency gains were significant with this design and were even greater than the base HSI design in more recent years (Figure 17; Figure 24). The time series of stratified mean and standard error for the separate strata design was more similar to the base HSI design (Figure 16; Figure 25), while the potential relative efficiencies were generally higher (Figure 26). Although similar, the 3 strata split design performed slightly better in terms of realized efficiency and the separate strata design performed slightly better in terms of potential efficiency. The split design has the added advantage of being flexible because the strata boundaries are the same as the base HSI design, meaning the north and south strata could be recombined.

The design was also re-constructed stratifying by historical average total biomass per tow from the survey, and the results were similar to total abundance with only slightly lower efficiencies (Table 3). The final stratifying variable chosen was total abundance. Results do not indicate that it should be changed plus abundance is being measured directly in the survey, while biomass has to be calculated from the shell height frequency and the shell height/meat weight relationship derived from meat samples collected on the survey.

The final design for the August survey has strata constructed from the historical abundance index 1981-2008, with the top 3 strata divided by the NAFO areas 5Zej and 5Zem. The 3 strata split was selected as the final design because both designs added comparable gains in efficiency, but the split design had the advantage of being flexible. The lower limit for historical abundance was increased from 1 scallop per tow to 10 based on a suggestion from Industry. This had the effect of reducing the area surveyed where densities are too low to be commercially exploited.

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Table 1. Strata areas in towable units (1950.72 m^2) for annual catch rate design.

Year	Strata				
	1	2	3	4	5
1981	2072824	472249	328356	8874	0
1982	2152694	663684	61487	2536	634
1983	2394840	476052	10142	0	0
1984	2770738	110931	634	0	0
1985	2464569	417100	1268	0	0
1986	2290882	342935	235174	11410	634
1987	2104518	312508	456402	8874	0
1988	1903575	950837	27257	0	0
1989	2039228	796801	44372	634	0
1990	2032889	740385	108395	0	0
1991	1908646	595858	377799	0	0
1992	1847159	735948	299830	0	0
1993	1826874	491266	564797	0	0
1994	1780600	610437	491266	0	0
1995	2306096	569234	5705	0	0
1996	2418294	300464	141358	15847	1268
1997	2410688	178757	252289	39301	0
1998	2242707	438653	201577	0	0
1999	2299757	506479	69094	8241	0
2000	2585642	20918	41203	119172	112833
2001	2170443	155937	278278	251021	25990
2002	2443016	94450	129948	128046	88111
2003	2305462	134385	239611	175588	28525
2004	1993587	467178	416466	3169	0
2005	2385332	297929	200310	0	0
2006	2449355	227567	183828	22820	0
2007	2283276	350542	126778	94450	27891
2008	2368217	119172	221228	174954	0

Table 2. Strata areas in towable units (1950.72 m^2) for historical catch rate and survey index designs.

Design	Strata				
	1	2	3	4	5
historical catch rate	372094	850682	630722	400619	131215
historical survey index	1232284	632623	393012	316312	-

Table 3. Mean efficiency for historical survey index designs relative to annual catch rate design applied to survey index from 1981 to 2007. Values for the final design are in bold.

Design	Response variable	Realized efficiency (%)	Potential efficiency (%)
no North South split	total abundance	36.9	55.5
	total biomass	33.1	48.0
3 highest strata split by North and South, same boundaries	**total abundance**	**46.5**	**66.3**
	total biomass	36.1	58.4
separate designs for North and South	total abundance	39.4	68.1
	total biomass	31.8	62.4

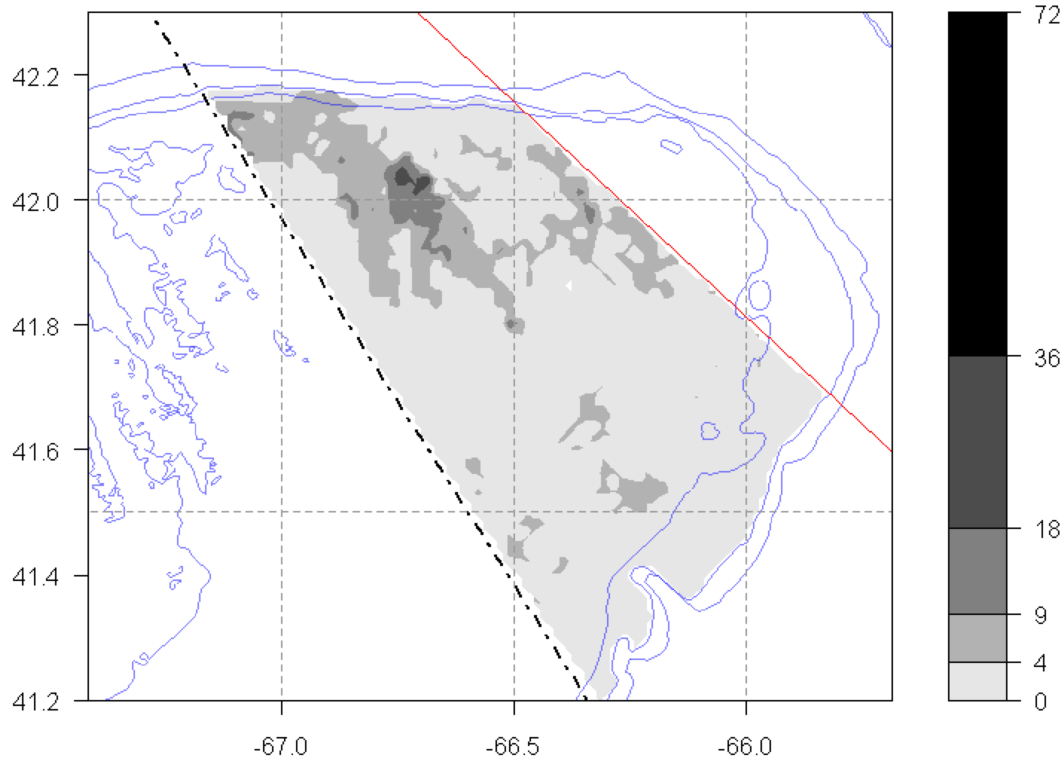

Figure 1. Contoured catch rates in kg/hm from the offshore sea scallop (Placopecten magellanicus) fishery on Georges Bank (Canadian side, management area 'a') from September 1998 to June 1999. The broken line indicates the international border between Canada and the United States and the red line indicates the division of management areas 'a' and 'b'.

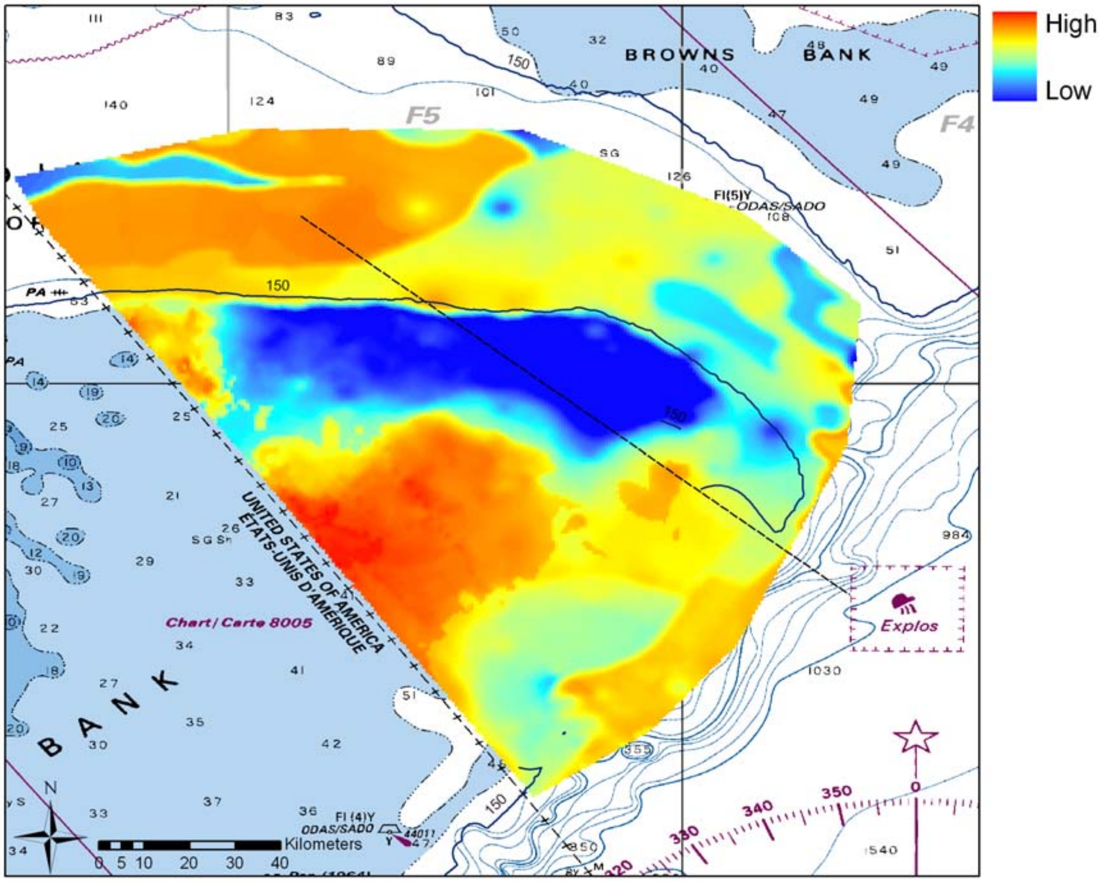

Figure 2. Index of disturbance defined as frictional velocity divided by current velocity required moving a given grain size for Canadian portion of Georges Bank.

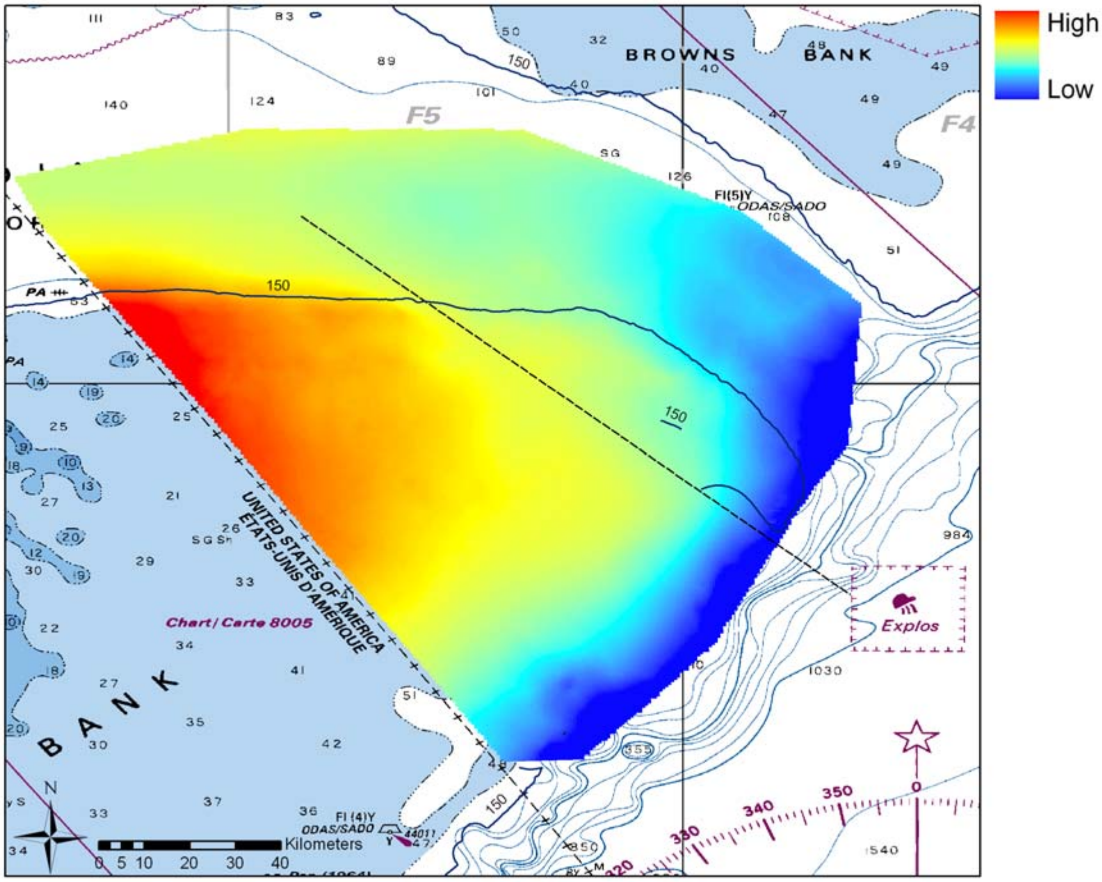

Figure 3. Scope for growth generated by combining the following variables: food availability, annual bottom temperature, seasonal and interannual temperature variability, oxygen, and salinity on the Canadian portion of Georges Bank.

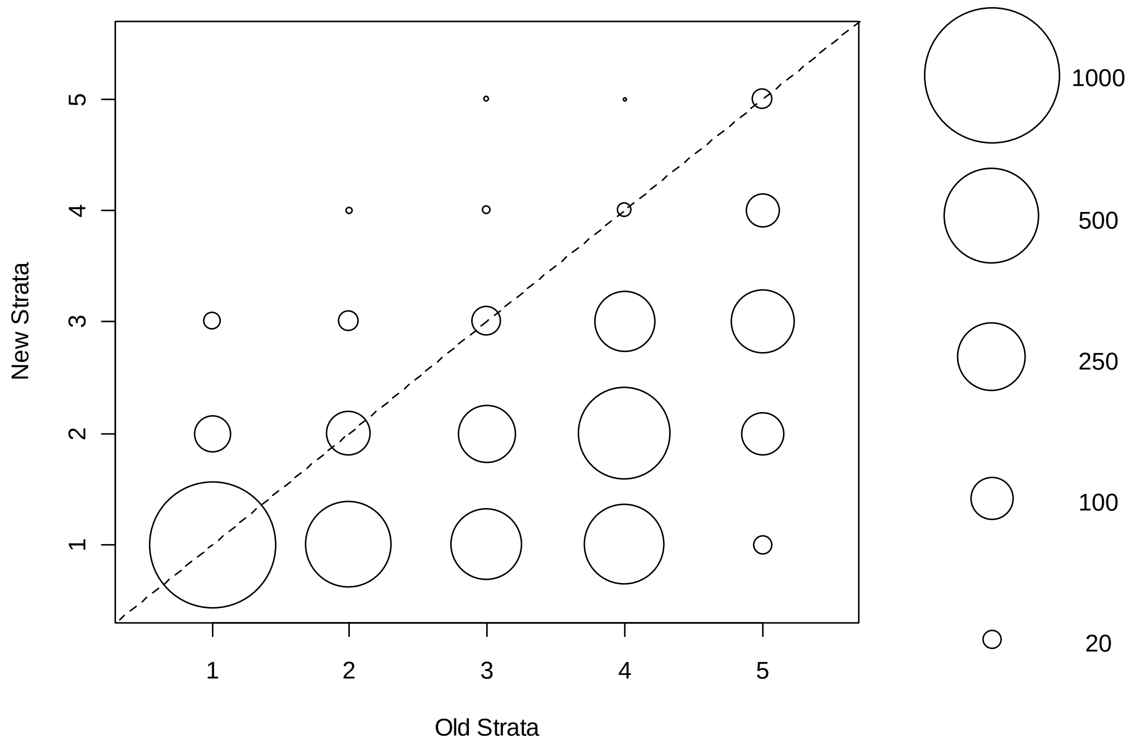

Figure 4. Comparison of original annual catch rate strata (old strata) and the new strata from the post stratification based on reconstructed annual catch rate contours. Bubble size indicates the number of tows in each old strata - new strata combination.

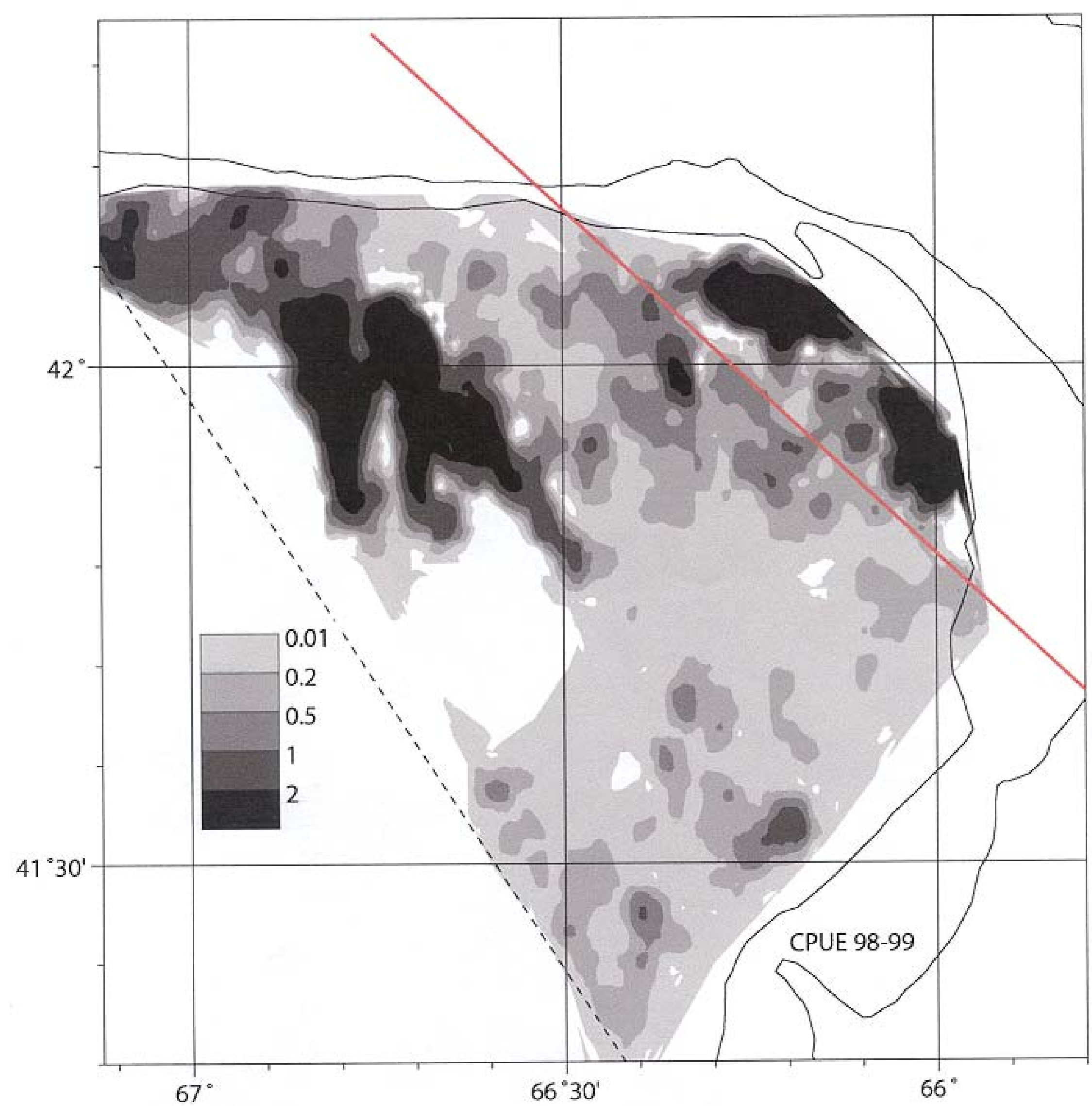

Figure 5. Contoured catch rates in kg/crhm form the offshore sea scallop (Placopecten magellanicus) fishery on Georges Bank from September 1998 to June 1999. The broken line indicates the international border between Canada and the United States and the red line indicates the division of management areas ‘a’ and ‘b’. Figure representing the original contours from Robert et al. (2000).

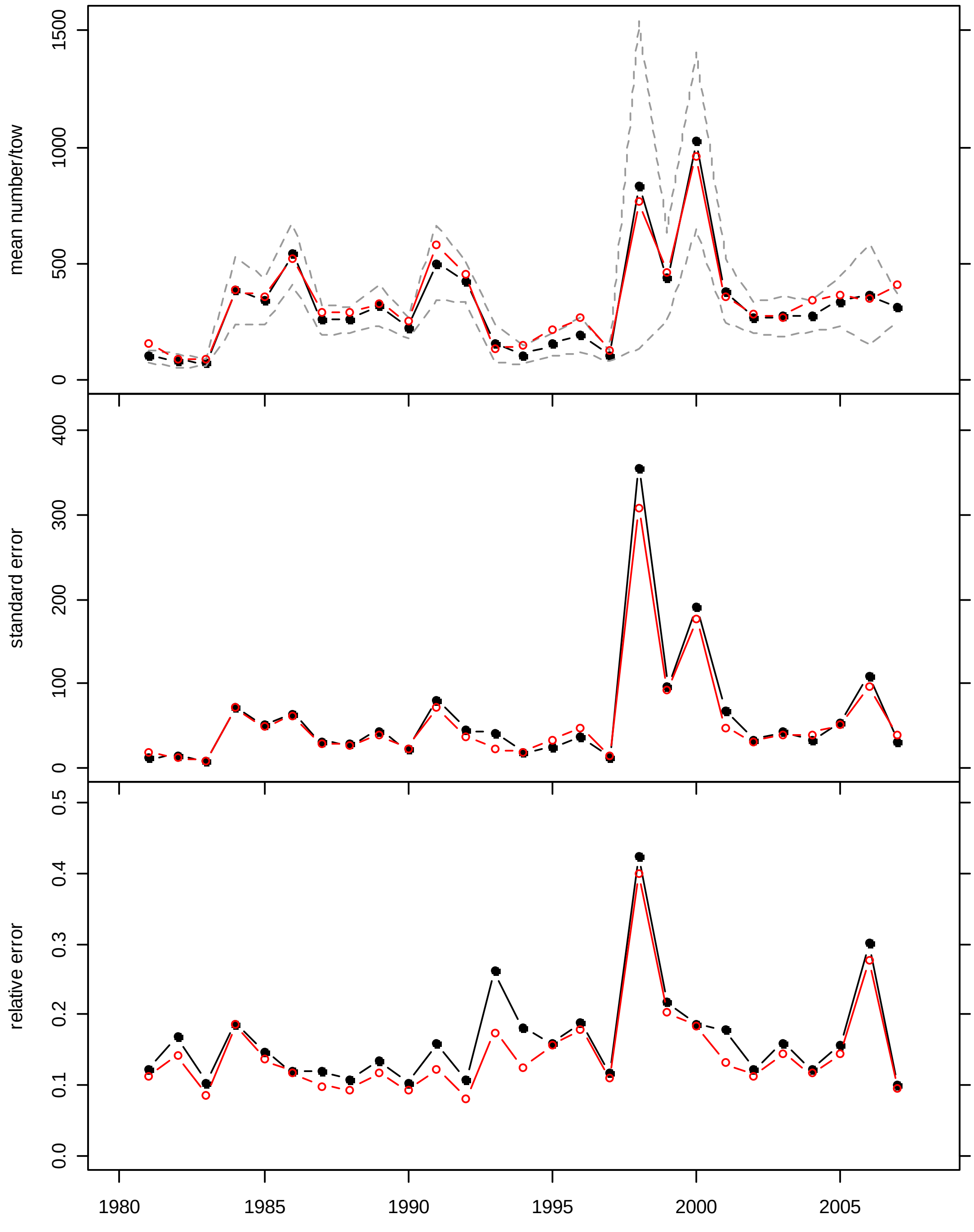

Figure 6. Comparison of the means (upper panel), standard errors (middle panel), and relative errors (lower panel) from the annual catch rate stratified design (•) and from a simple random design (◦) for the abundance index of sea scallops (Placopecten magellanicus) on Georges Bank (management area 'a'). Confidence intervals (---) are given for the stratified mean.

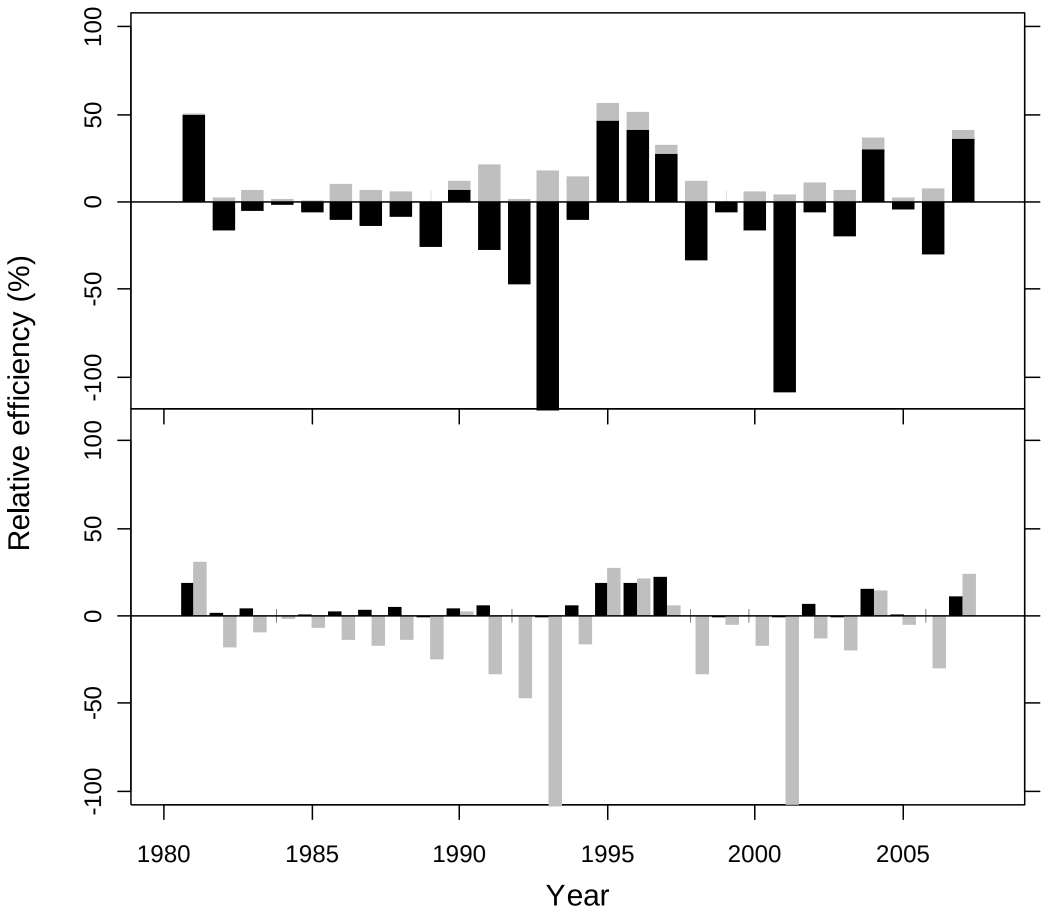

Figure 7. Efficiency of the reconstructed annual catch rate design relative to a simple random design for the survey of sea scallops (Placopecten magellanicus) on Georges Bank (management area 'a').The upper panel shows the realized (■) relative efficiencies and the potential (■) relative efficiencies given optimal allocation. The lower panel is a break down of realized relative efficiencies into strata (■) and allocation (■) components.

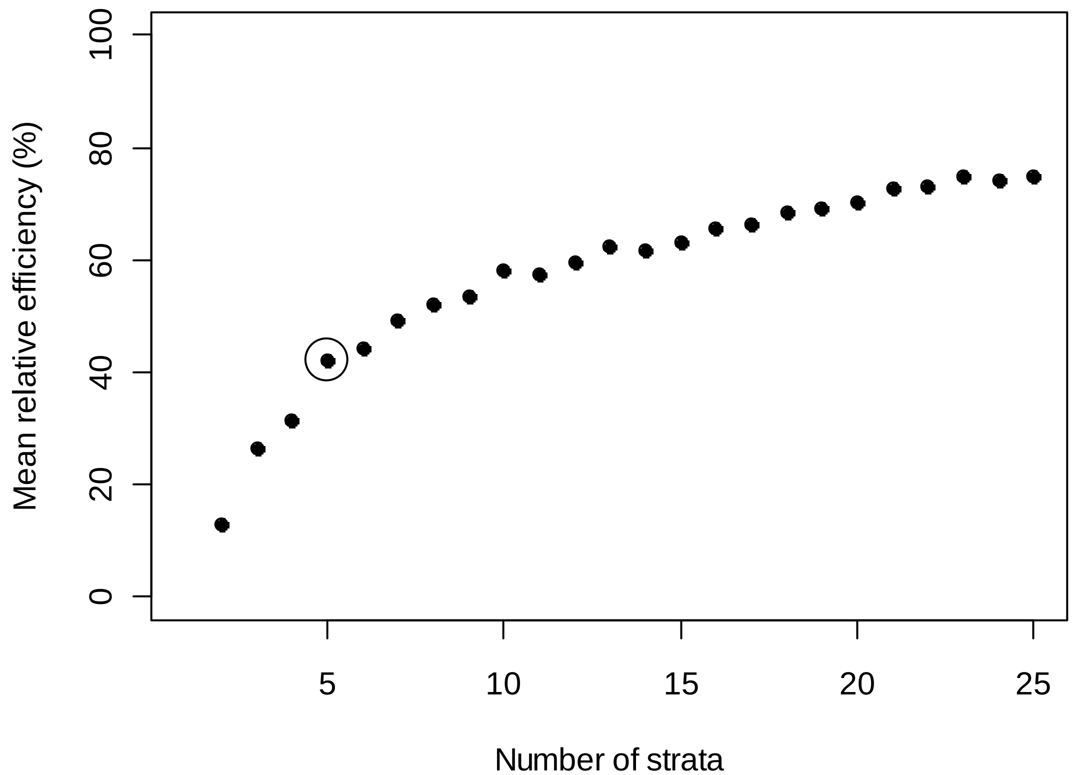

Figure 8. The gain in relative efficiency assuming optimal allocation for different numbers of strata based on commercial catch rates of sea scallops (Placopecten magellanicus) on Georges Bank (management area 'a') from 1981 to 2007. The circled point indicates that no further appreciable gain in efficiency is achieved be increasing the number of strata past 5.

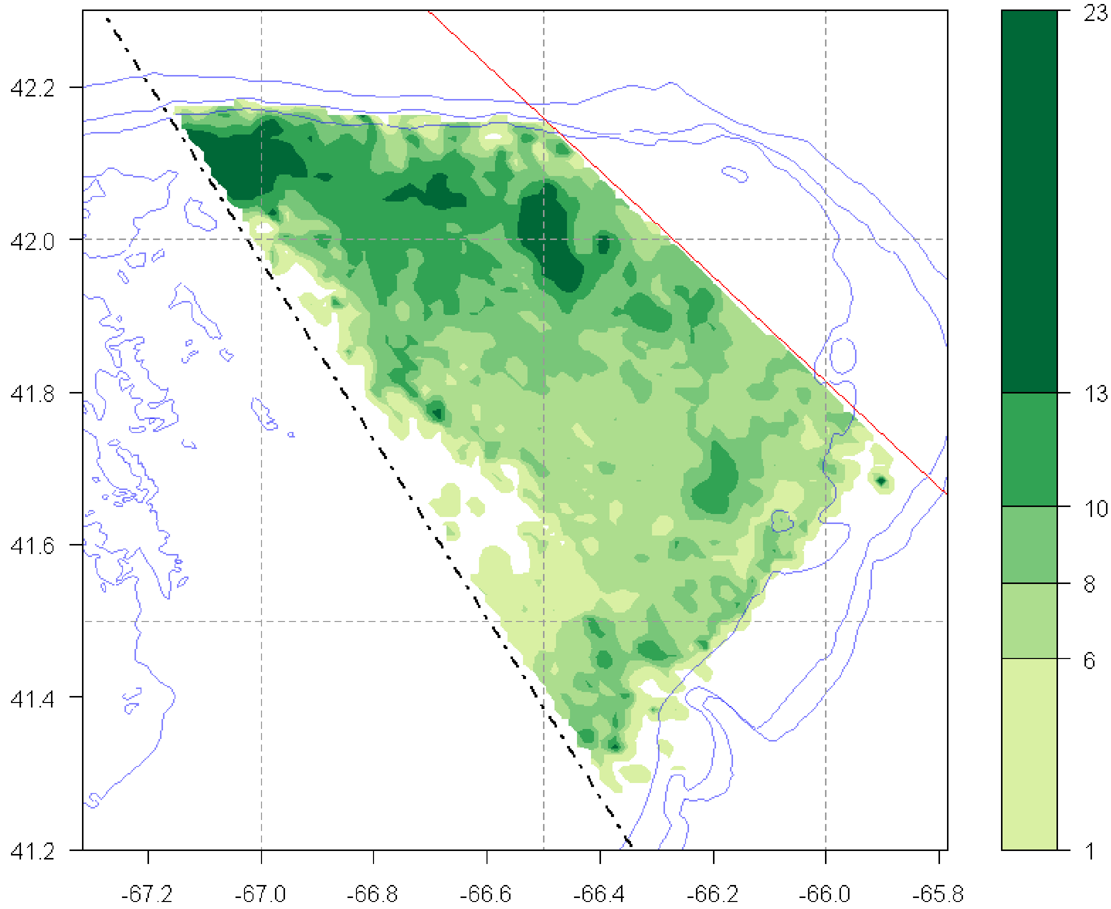

Figure 9. Contoured catch rates in kg/hm from the offshore sea scallops (Placopecten magellanicus) fishery on Georges Bank (Canadian side, management area 'a') from 1981 to 2007. The broken line indicates the international border between Canada and the United States and the red line indicates the division of management areas 'a' and 'b'.

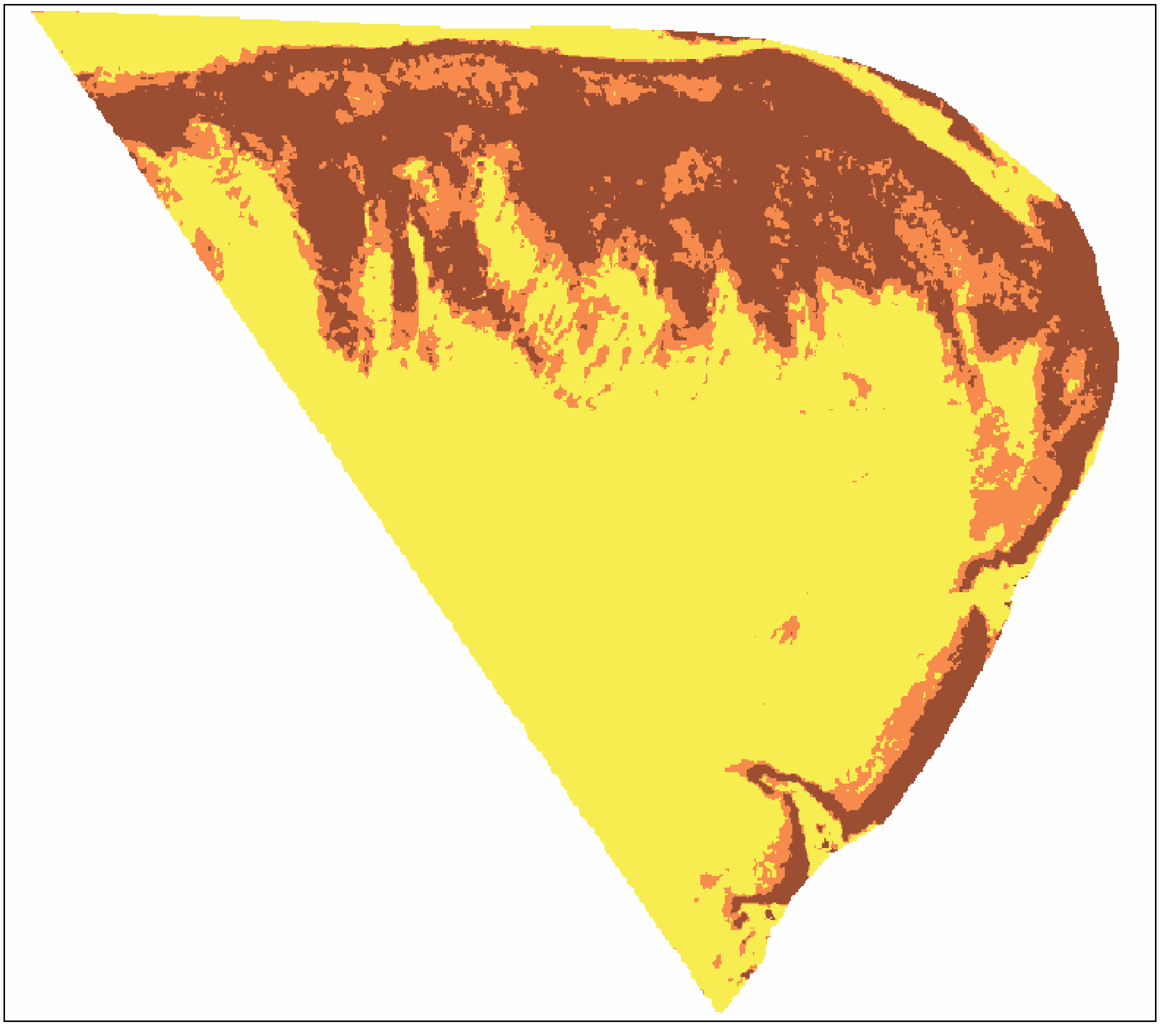

Figure 10. Reclassified backscatter map showing dominant sediment type based on the relationship of gain size and backscatter. Areas with greater than 70% gravel are classified as gravel (■); areas with greater than 70% sand and finer sediments are classified as sand (■). The area classified as mixed sediments (■) is where both gravel and sand are represented equally (from Kostylev et al. 2005).

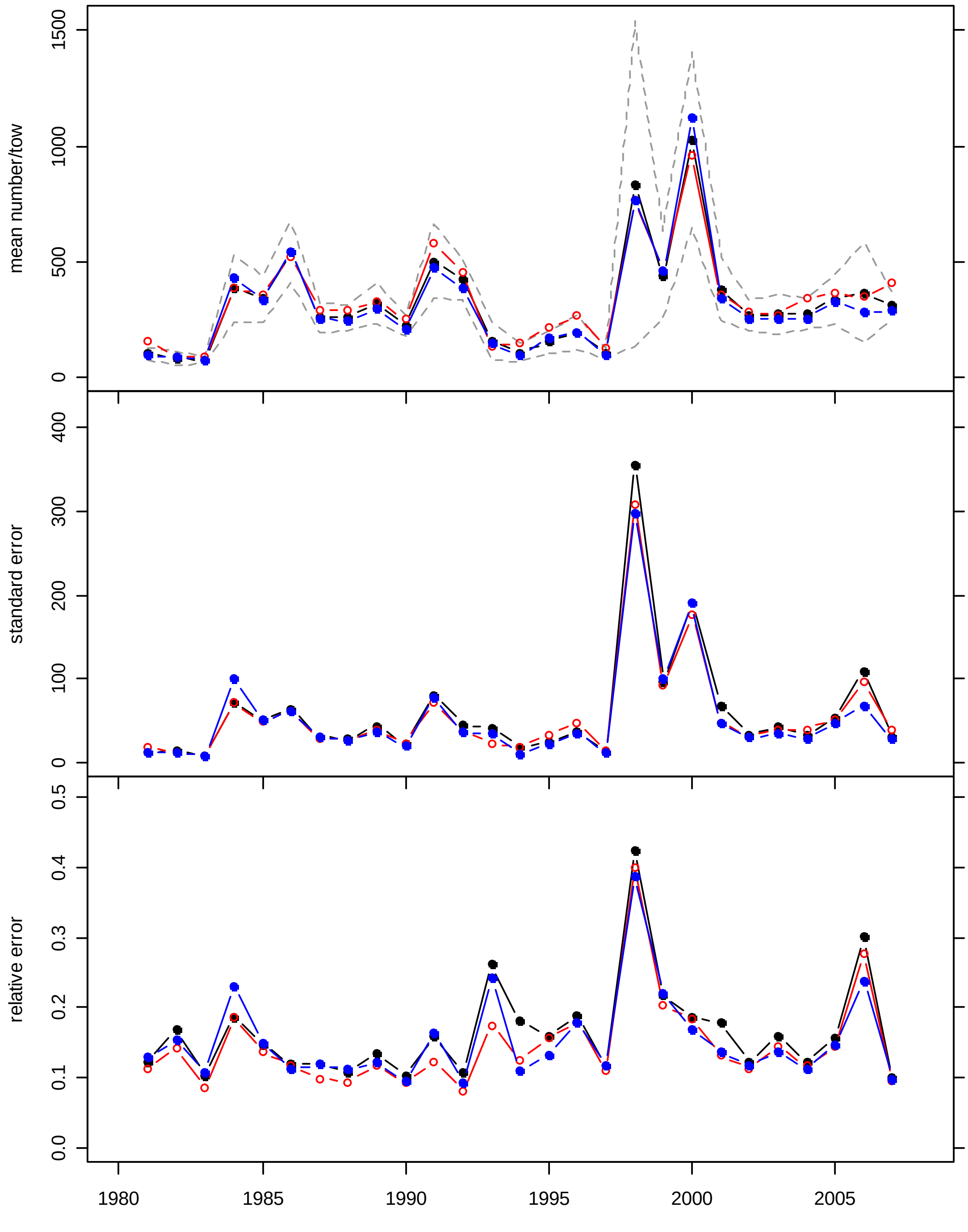

Figure 11. Comparison of the means (upper panel), standard errors (middle panel), and relative errors (lower panel) from the historic catch rate stratified design (●), the original annual catch rate stratified design (●) and from a simple random design (○) for the abundance index of sea scallops (Placopecten magellanicus) on Georges Bank (management area 'a'). Confidence intervals (---) are given for the annual catch rate stratified mean.

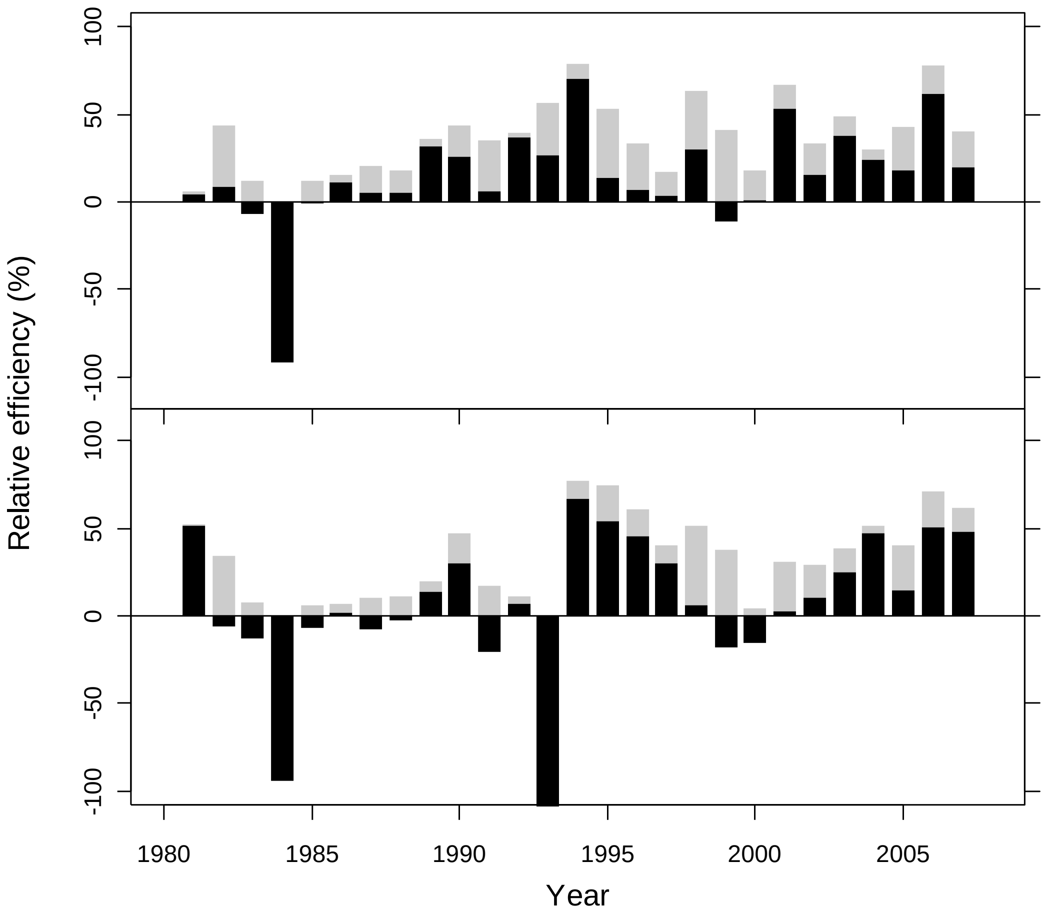

Figure 12. Realized (■) and potential (■) relative efficiencies of the historical catch rate design for the survey of sea scallops (Placopecten magellanicus) on Georges Bank (management area 'a').The upper panel shows the efficiencies relative to the annual catch rate design and the lower panel shows the efficiencies relative to simple random sampling.

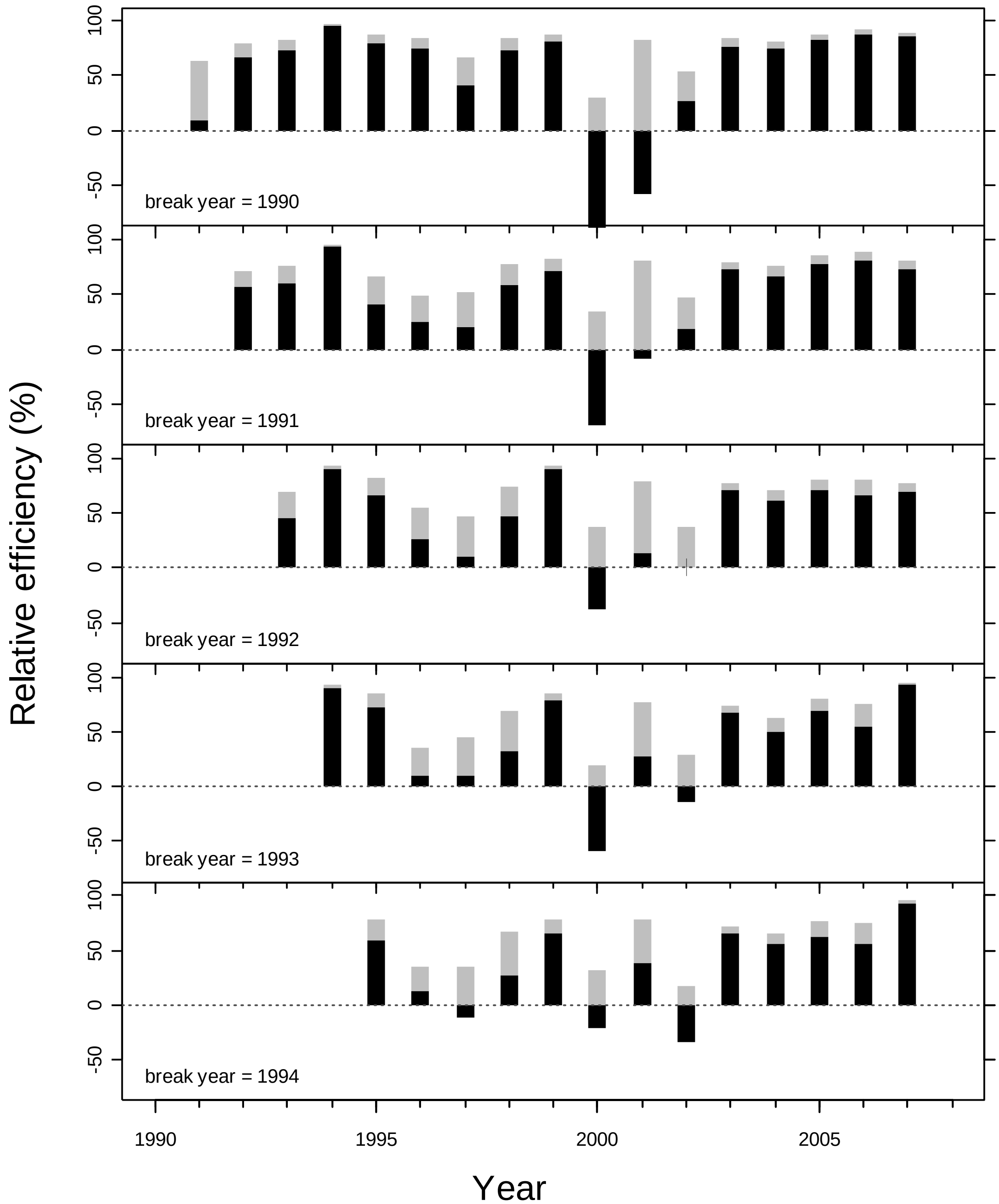

Figure 13. Realized (■) and potential (■) efficiencies of the historic catch rate design relative to the original annual catch rate design. Potential efficiency is the maximum efficiency achievable with a given set of strata when the allocation is optimal. The historic catch rate design is based on catch rates from the period 1981 to the break year in each panel. Relative efficiencies were calculated for surveys following the break year.

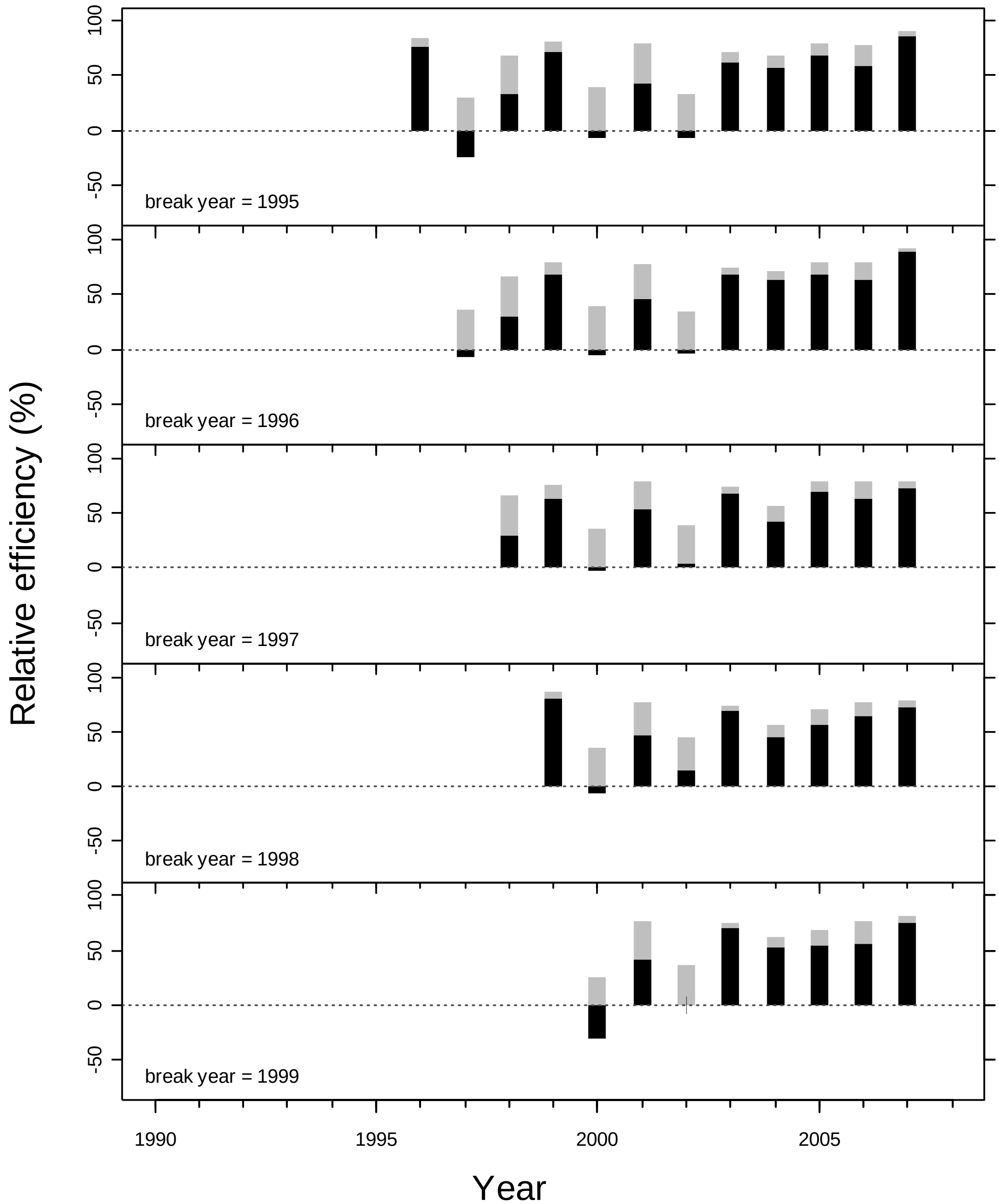

Figure 13 continued. Realized (■) and potential (■) efficiencies of the historic catch rate design relative to the original annual catch rate design. Potential efficiency is the maximum efficiency achievable with a given set of strata when the allocation is optimal. The historic catch rate design is based on catch rates from the period 1981 to the break year in each panel. Relative efficiencies were calculated for surveys following the break year.

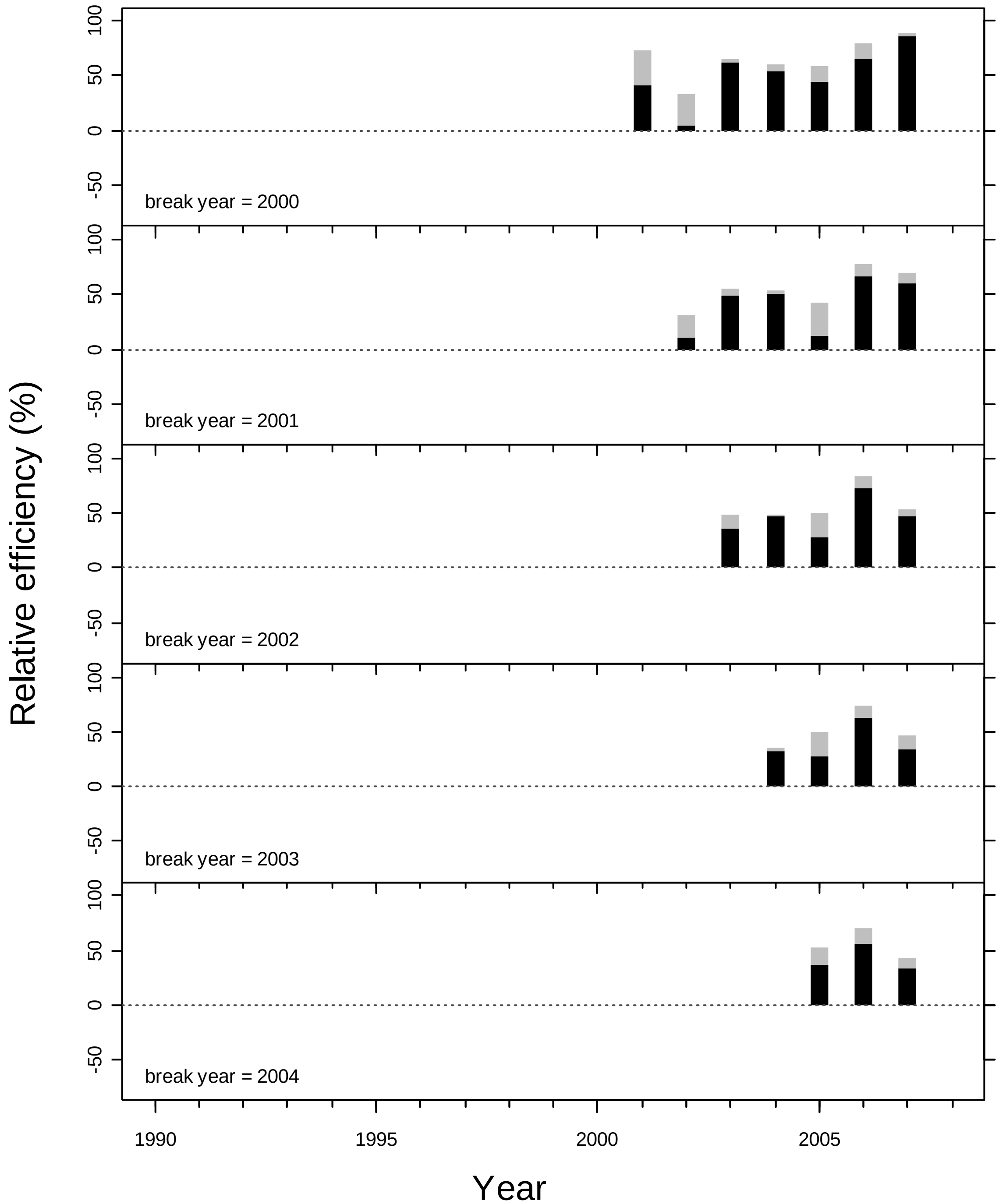

Figure 13 continued. Realized (■) and potential (■) efficiencies of the historic catch rate design relative to the original annual catch rate design. Potential efficiency is the maximum efficiency achievable with a given set of strata when the allocation is optimal. The historic catch rate design is based on catch rates from the period 1981 to the break year in each panel. Relative efficiencies were calculated for surveys following the break year.

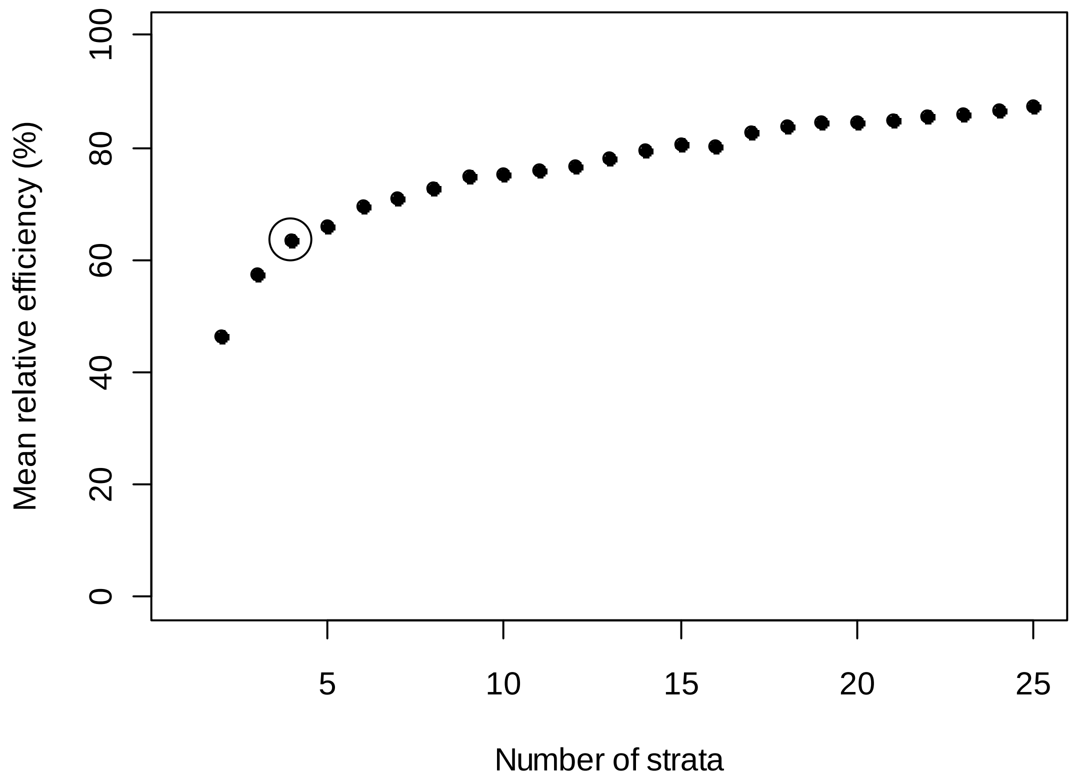

Figure 14. The gain in relative efficiency due to stratification for different numbers of strata based on commercial catch rates of sea scallops (Placopecten magellanicus) on Georges Bank (management area 'a') from 1981 to 2007. The circled point indicates that no further appreciable gain in efficiency is achieved be increasing the number of strata past 4.

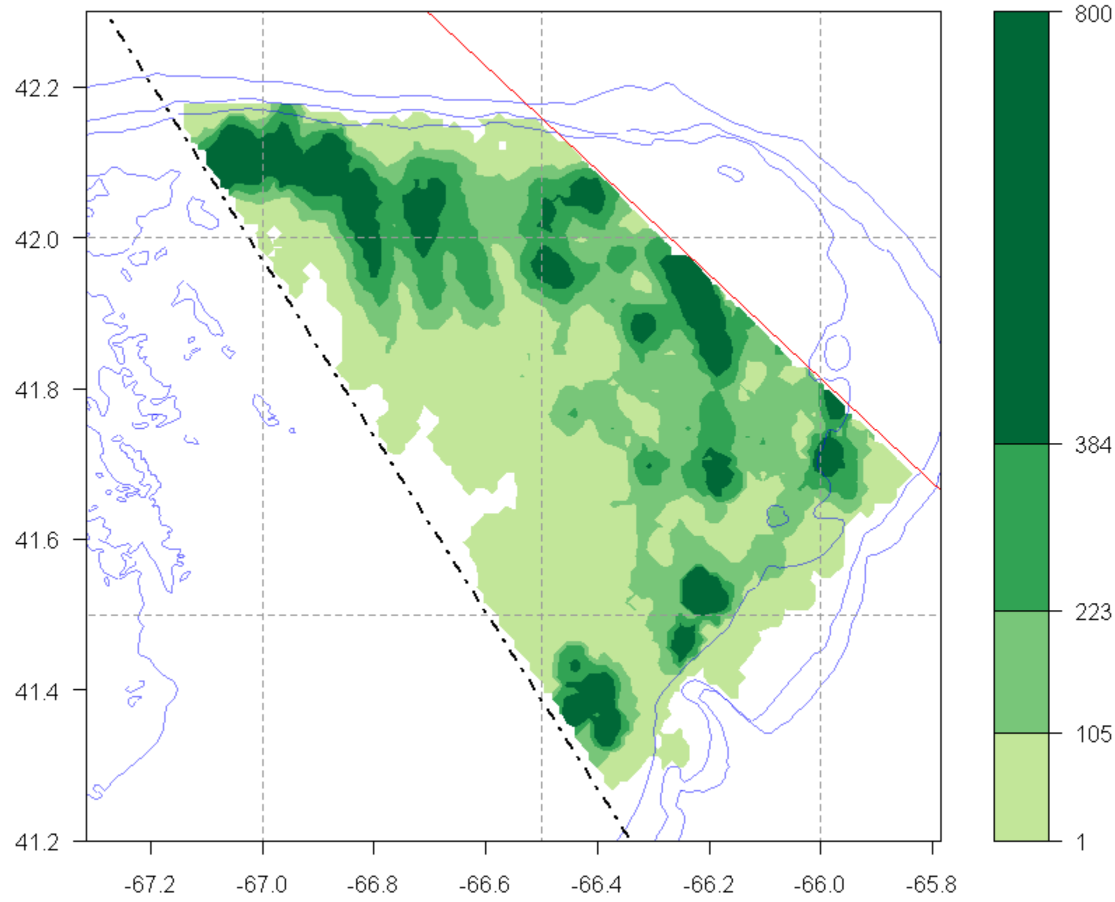

Figure 15. Contoured number of scallops per standard tow from the August survey stations on the Canadian side of Georges Bank (management area 'a') from 1981 to 2007. The broken line indicates the international border between Canada and the United States and the red line indicates the division of management areas 'a' and 'b'.

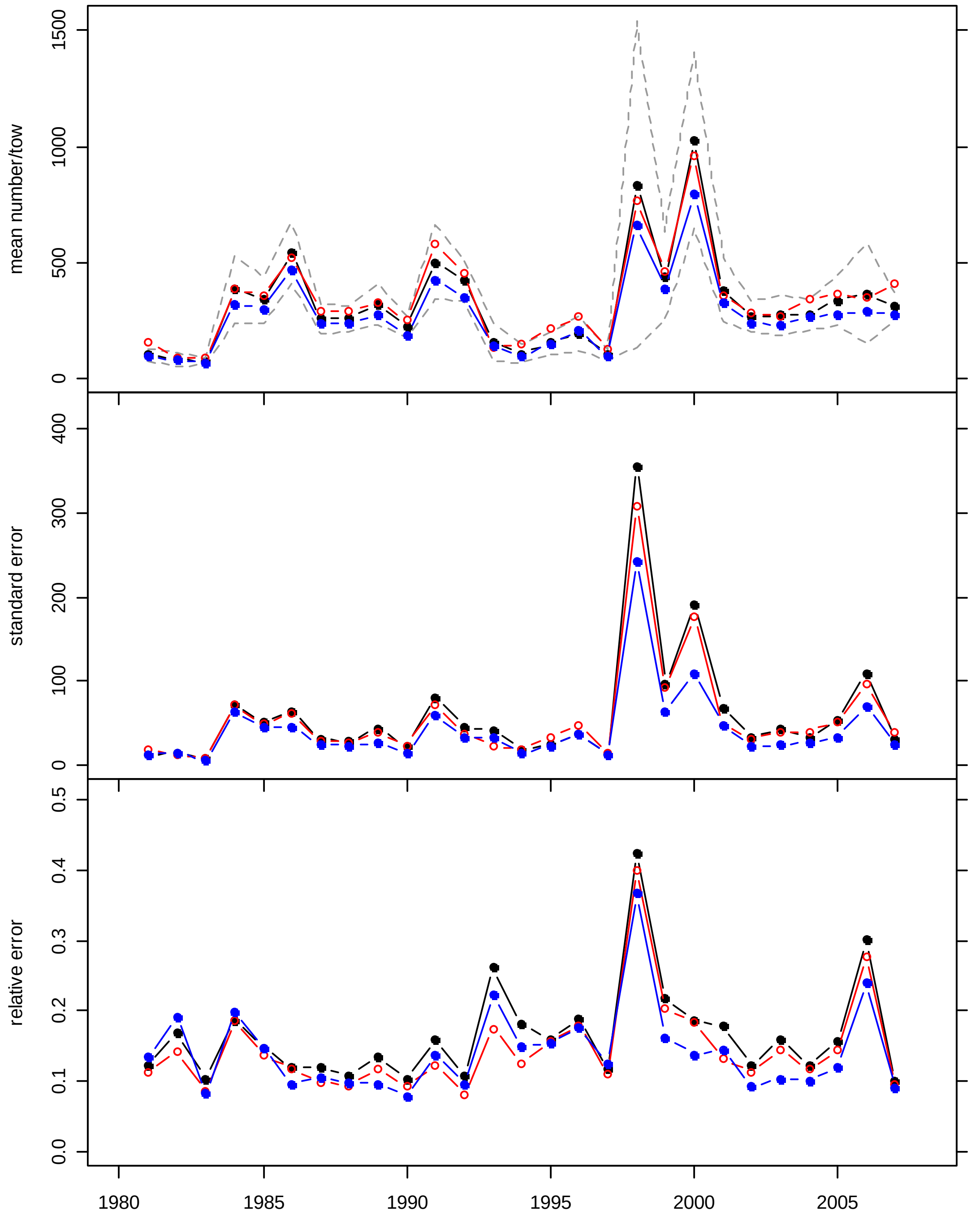

Figure 16. Comparison of the means (upper panel), standard errors (middle panel), and relative errors (lower panel) from the historic survey index stratified design (●), the original annual catch rate stratified design (●) and from simple random sampling (○) for the abundance index of sea scallops (Placopecten magellanicus) on Georges Bank (management area 'a'). Confidence intervals (---) are given for the annual catch rate stratified mean.

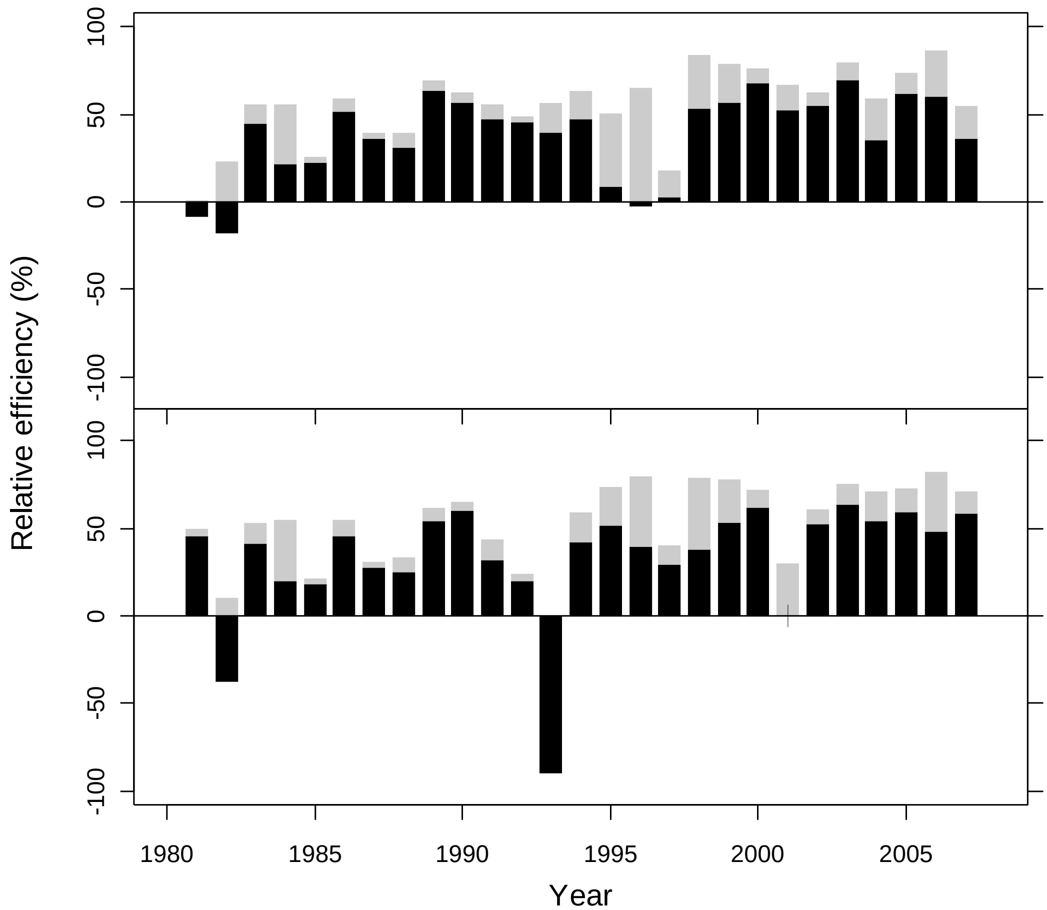

Figure 17. Realized (■) and potential (■) relative efficiencies of the historical survey index design for the survey of sea scallops (Placopecten magellanicus) on Georges Bank (management area 'a'). The upper panel shows the efficiencies relative to the annual catch rate design and the lower panel shows the efficiencies relative to simple random sampling.

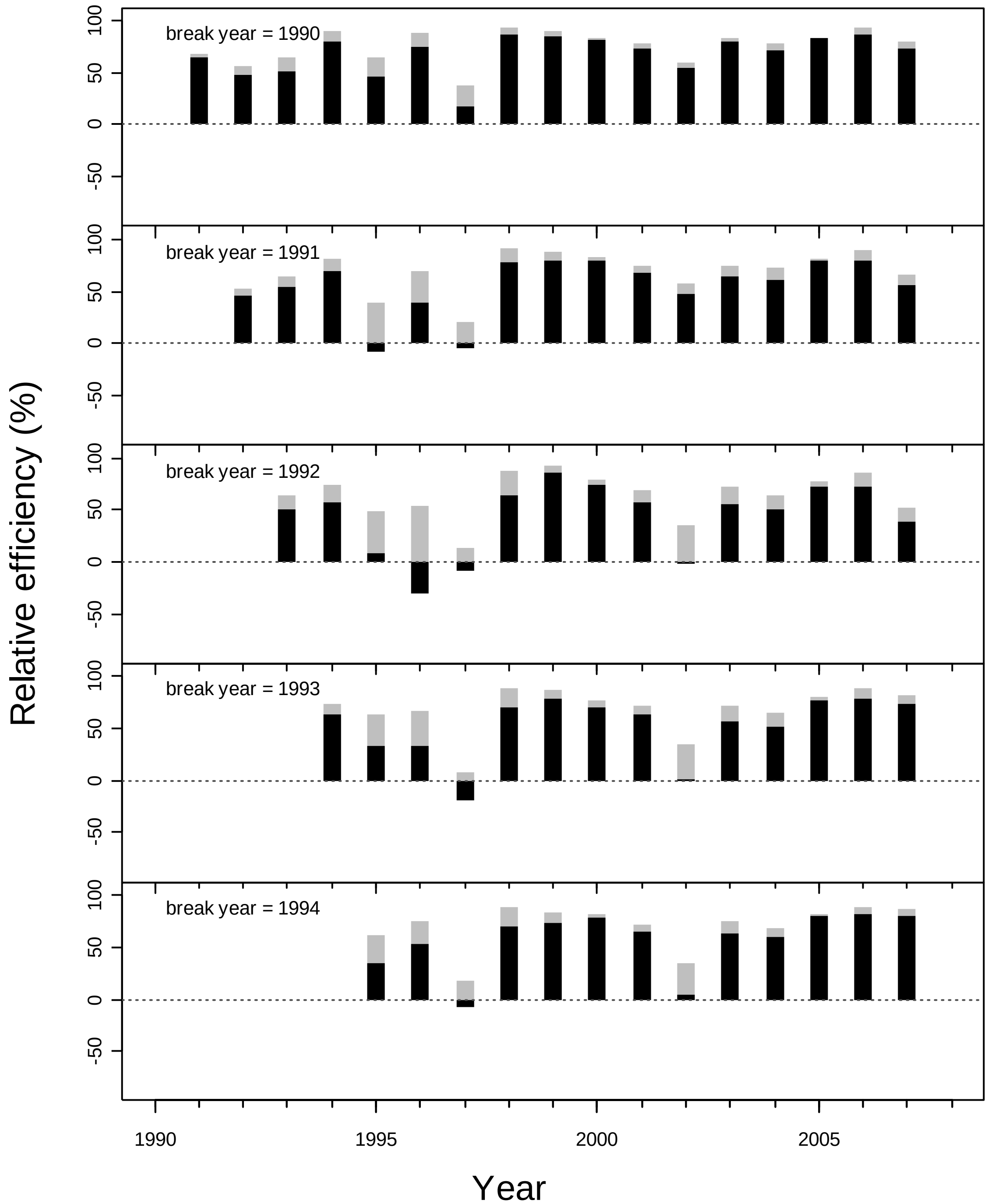

Figure 18. Realized (■) and potential (■) efficiencies of the historic survey index design relative to the original annual catch rate design. Potential efficiency is the maximum efficiency achievable with a given set of strata when the allocation is optimal. The historic survey index design is based on survey abundance estimates from the period 1981 to the break year in each panel. Relative efficiencies were calculated for surveys following the break year.

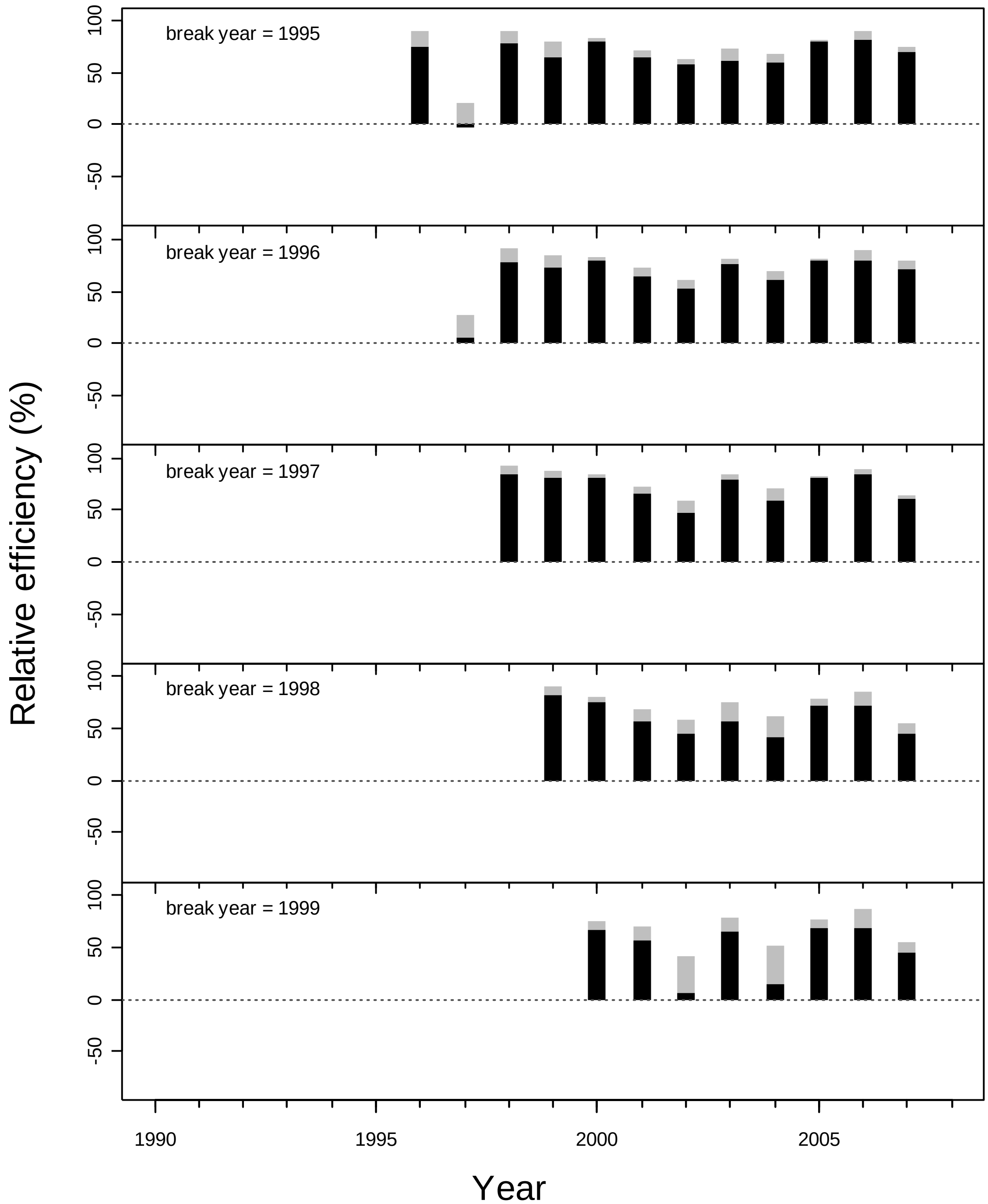

Figure 18 continued. Realized (■) and potential (■) efficiencies of the historic survey index design relative to the original annual catch rate design. Potential efficiency is the maximum efficiency achievable with a given set of strata when the allocation is optimal. The historic survey index design is based on survey abundance estimates from the period 1981 to the break year in each panel. Relative efficiencies were calculated for surveys following the break year.

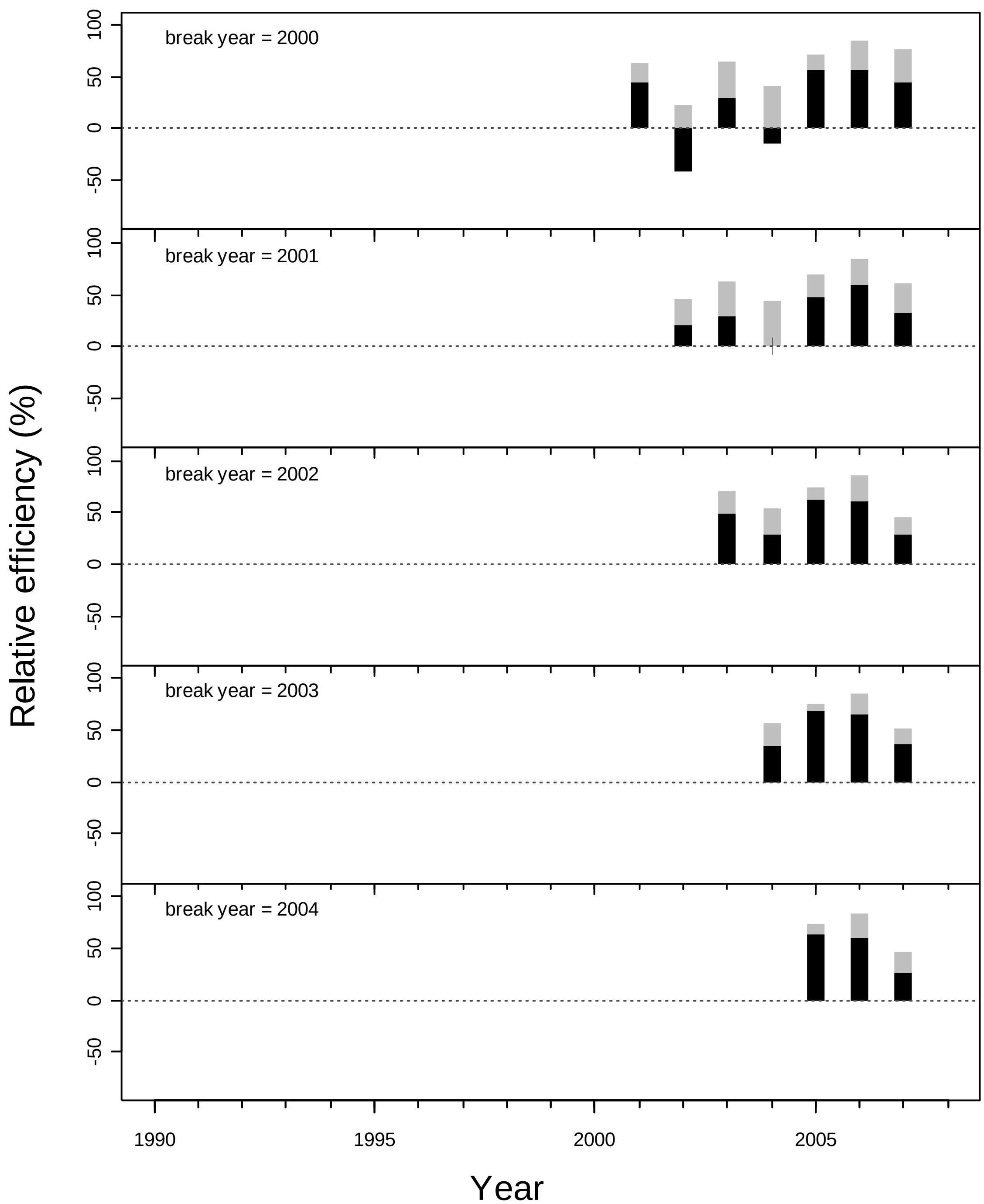

Figure 18 continued. Realized (■) and potential (■) efficiencies of the historic survey index design relative to the original annual catch rate design. Potential efficiency is the maximum efficiency achievable with a given set of strata when the allocation is optimal. The historic survey index design is based on survey abundance estimates from the period 1981 to the break year in each panel. Relative efficiencies were calculated for surveys following the break year.

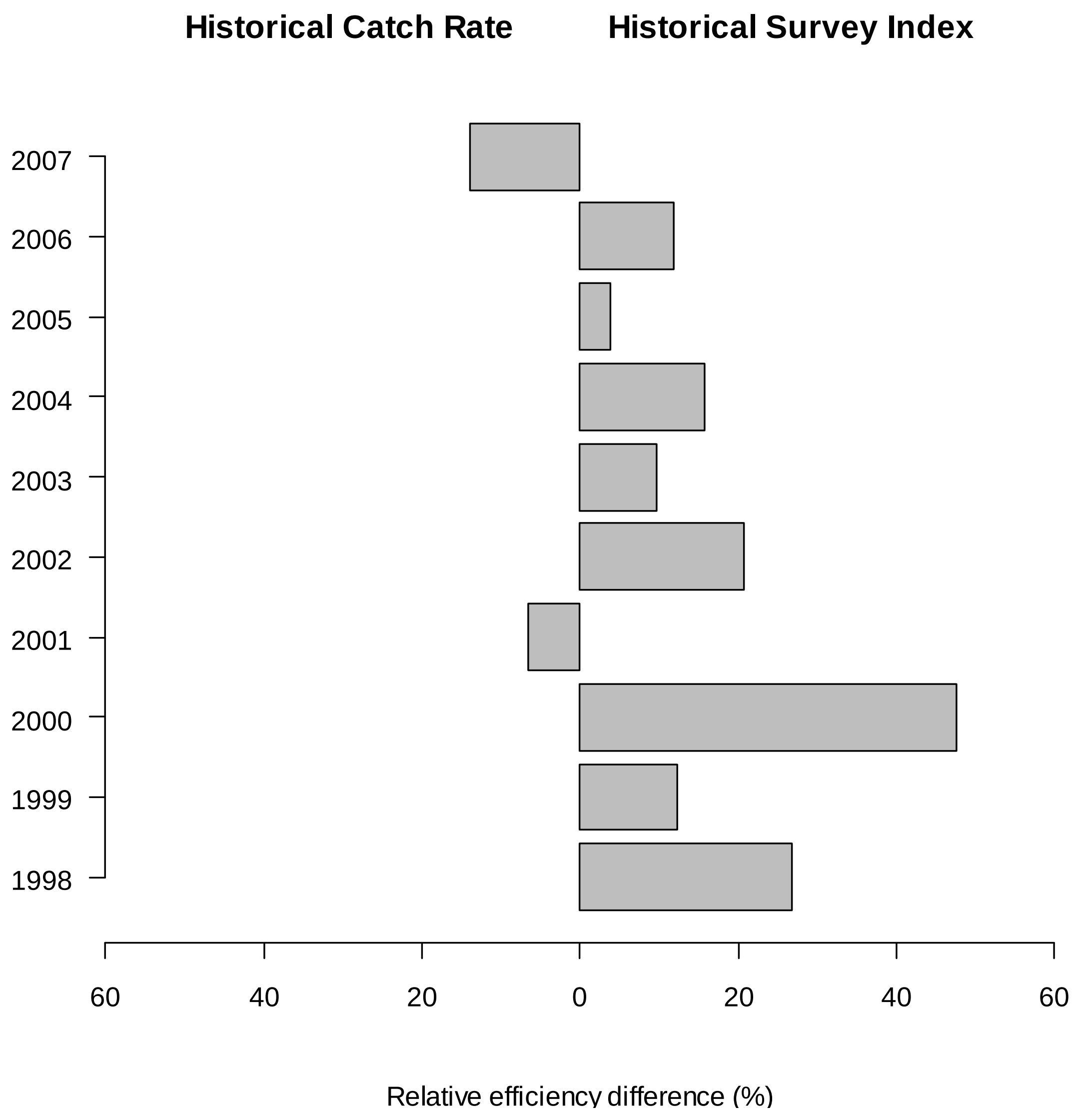

Figure 19. The difference in potential efficiency gains relative to the original annual catch rate design between the 2 new proposed designs, historical catch rate and historical survey index. For example, in 2002, the potential efficiency gains over the annual catch rate design are greater in the historical survey index design by 20 percentage points. The strata for the designs were constructed from data prior to 1998 and the response variable, number of scallops per tow, was taken from surveys since 1998.

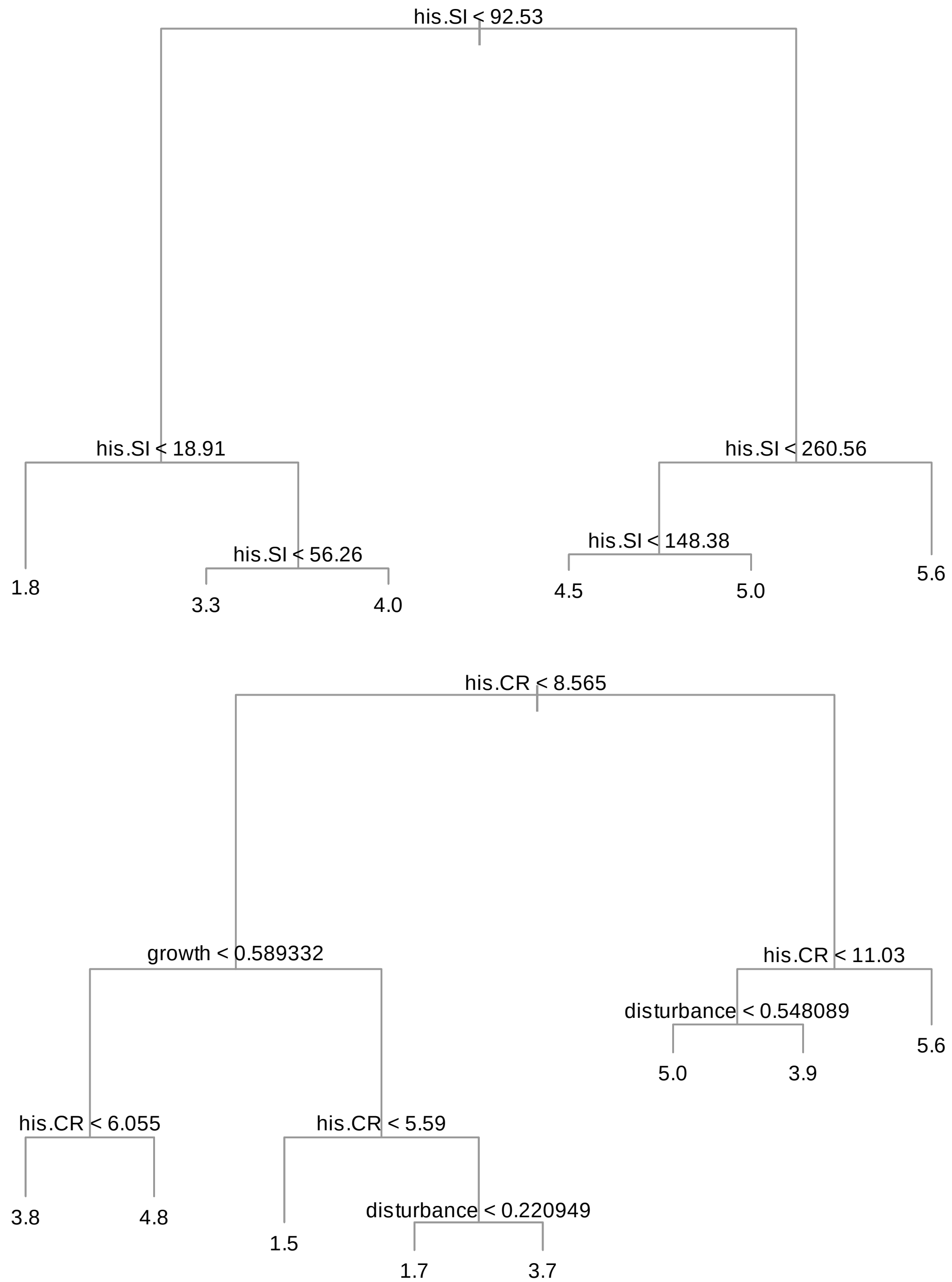

Figure 20. Regression trees showing the relative importance of stratifying variables for predicting the number of scallops in a survey tow. Upper tree includes all stratifying variables and lower tree excludes the historical survey index strata. Historical survey index and catch rate strata were constructed from data prior to 1998 and the response variable, number of scallops per tow, was taken from surveys since 1998.

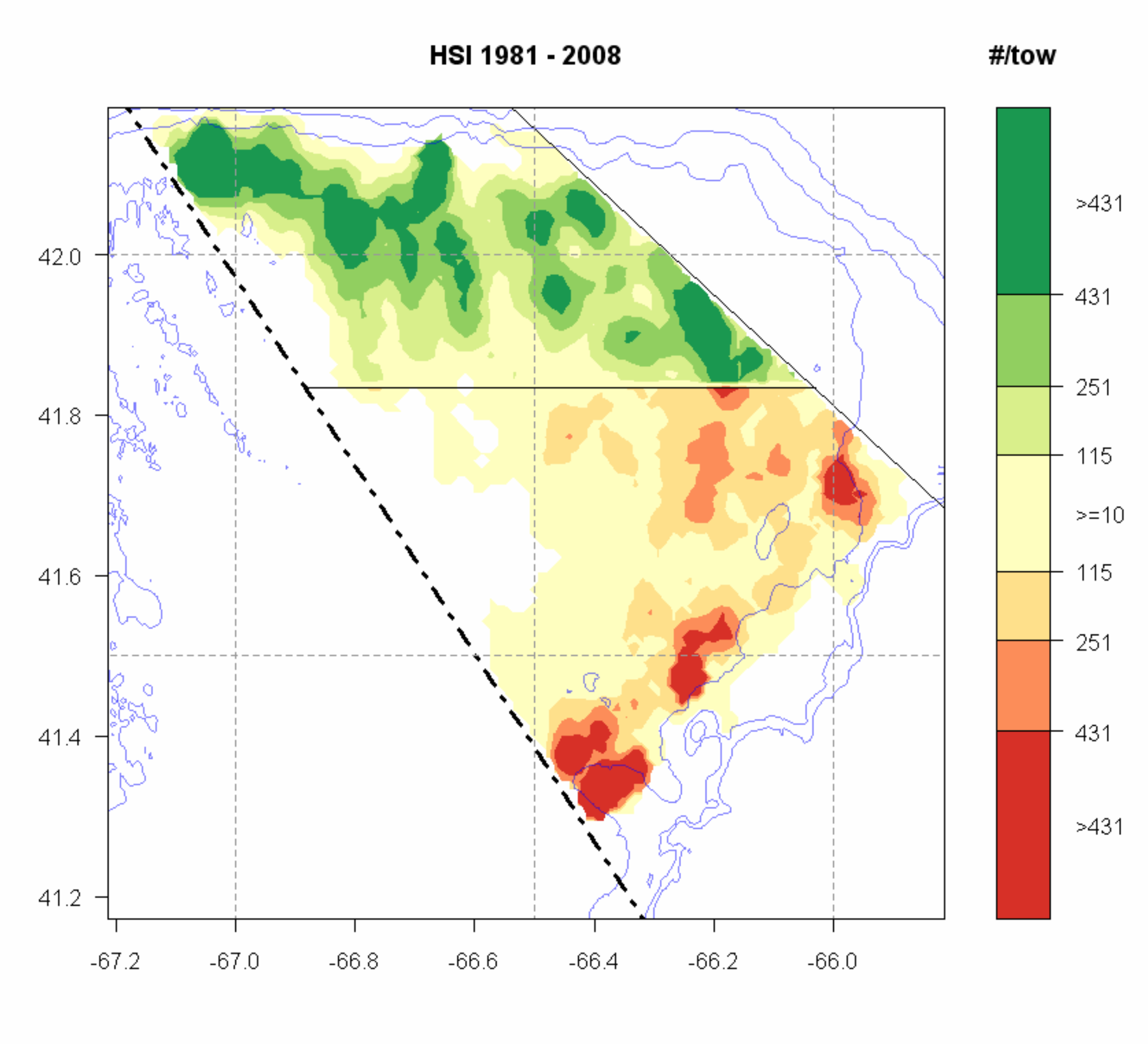

Figure 21. Contoured number of scallops per standard tow from the August survey stations on the Canadian side of Georges Bank (management area ‘a’) from 1981 to 2008. The upper 3 strata are divided between northern (green) and southern (red) portions of the bank, while the lowest strata (yellow) is common to both portions. The broken line indicates the international border between Canada and the United States and the solid lines indicate the division of management areas ‘a’ and ‘b’ and Northwest Atlantic Fisheries Organization (NAFO) areas 5Zej and 5Zem.

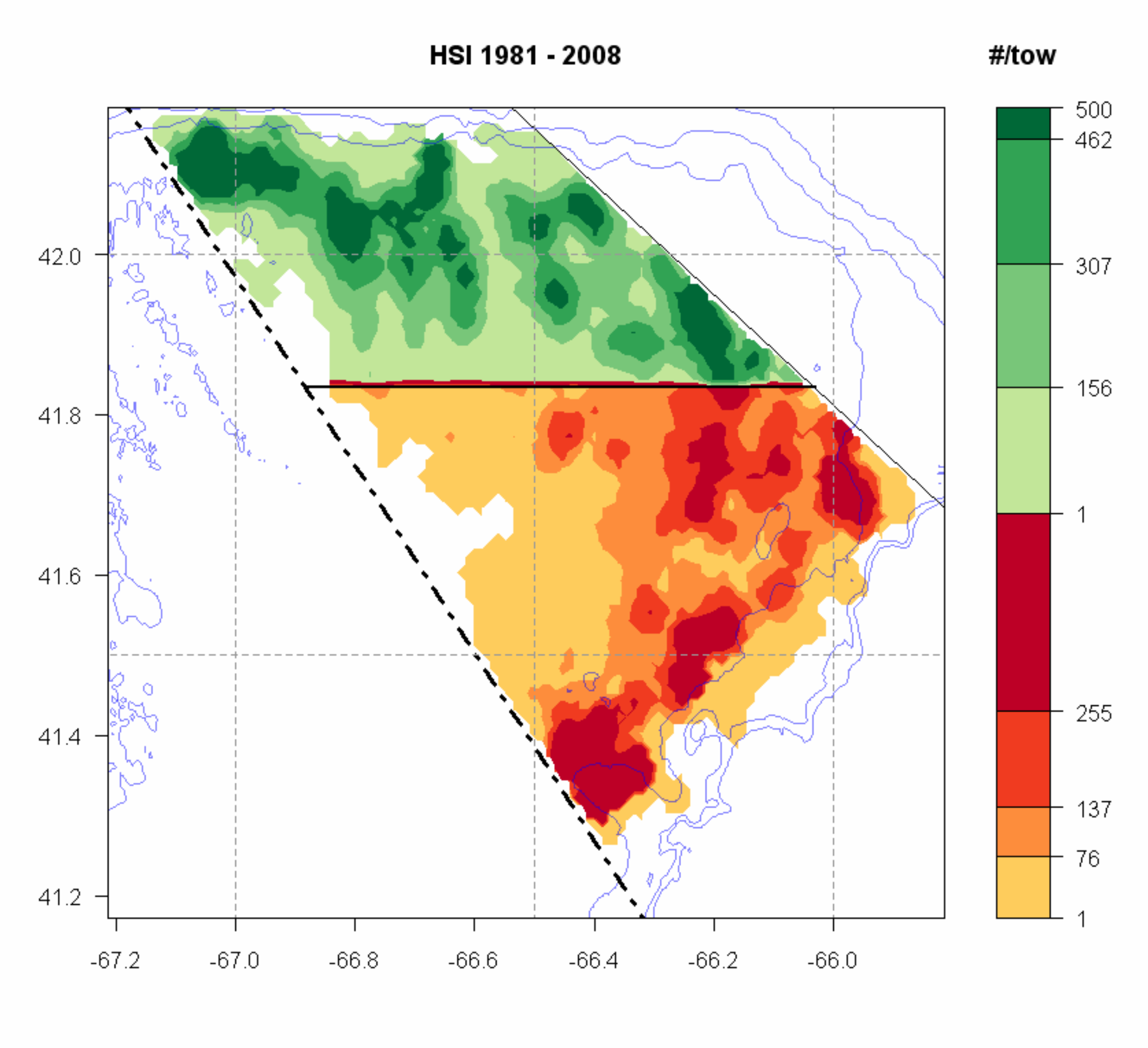

Figure 22. Contoured number of scallops per standard tow from the August survey stations on the Canadian side of Georges Bank (management area 'a') from 1981 to 2008. Strata definitions were calculated for the northern (green) and southern (red) portions of the bank separately. The broken line indicates the international border between Canada and the United States and the solid lines indicate the division of management areas 'a' and 'b' and Northwest Atlantic Fisheries Organization (NAFO) areas 5Zej and 5Zem.

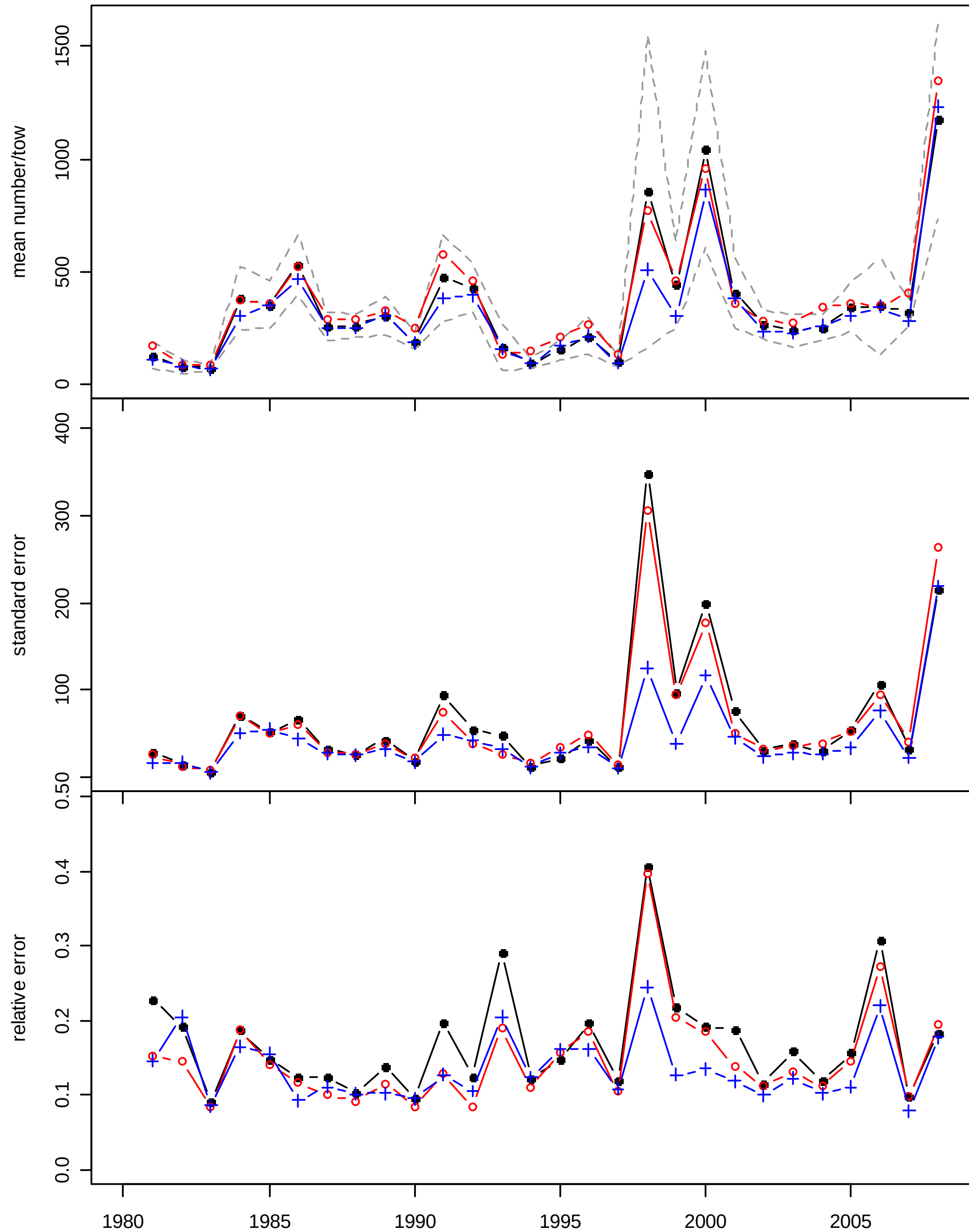

Figure 23. Comparison of the means (upper panel), standard errors (middle panel), and relative errors (lower panel) from the historic survey index stratified design with a north/south split (+), the original annual catch rate stratified design (●) and from simple random sampling (○) for the abundance index of sea scallops (Placopecten magellanicus) on Georges Bank (management area 'a'). Confidence intervals (---) are given for the annual catch rate stratified mean.

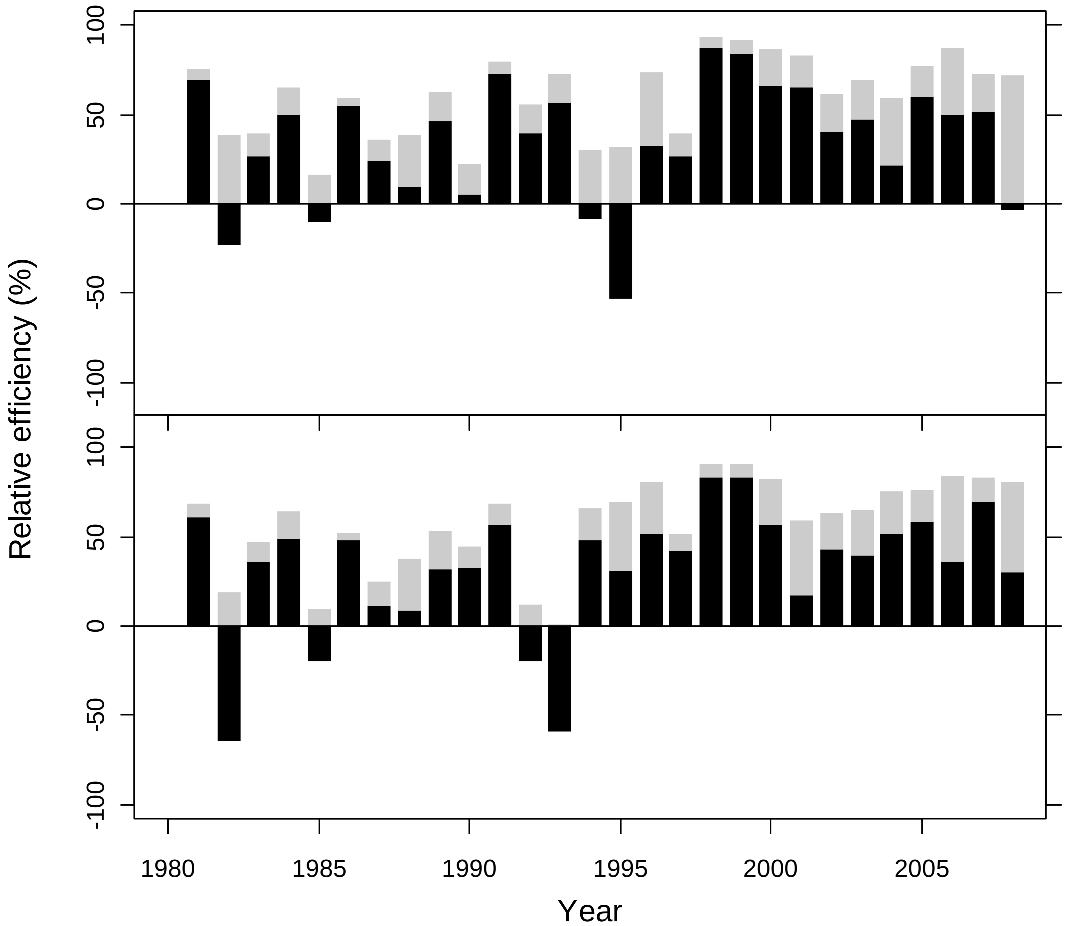

Figure 24. Realized (■) and potential (■) relative efficiencies of the historical survey index design with a north/south split for the survey of sea scallops (Placopecten magellanicus) on Georges Bank (management area 'a').The upper panel shows the efficiencies relative to the annual catch rate design and the lower panel shows the efficiencies relative to simple random sampling.

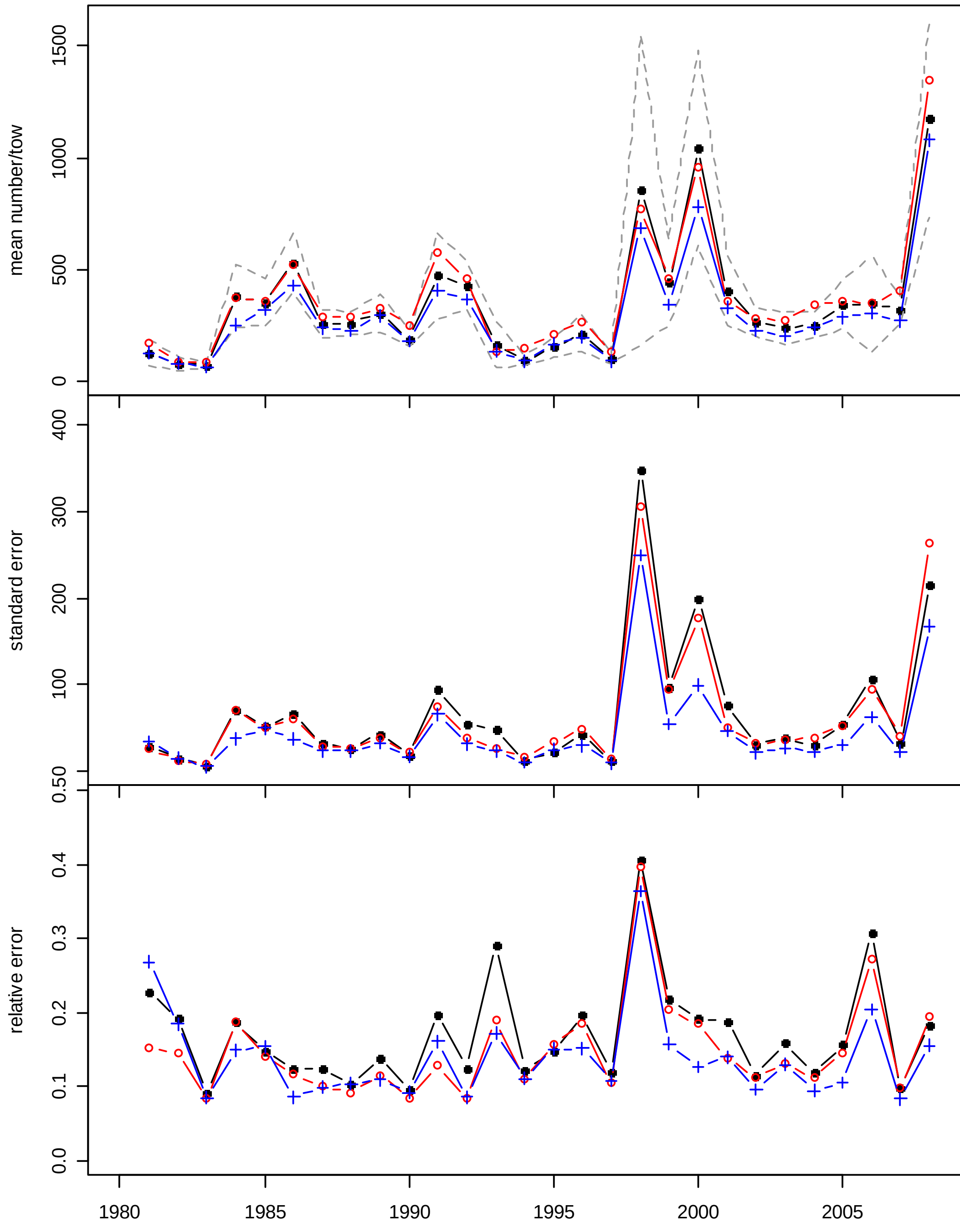

Figure 25. Comparison of the means (upper panel), standard errors (middle panel), and relative errors (lower panel) from the historic survey index stratified design with separate strata definitions for north and south (+), the original annual catch rate stratified design (●) and from simple random sampling (○) for the abundance index of sea scallops (Placopecten magellanicus) on Georges Bank (management area 'a'). Confidence intervals (---) are given for the annual catch rate stratified mean.

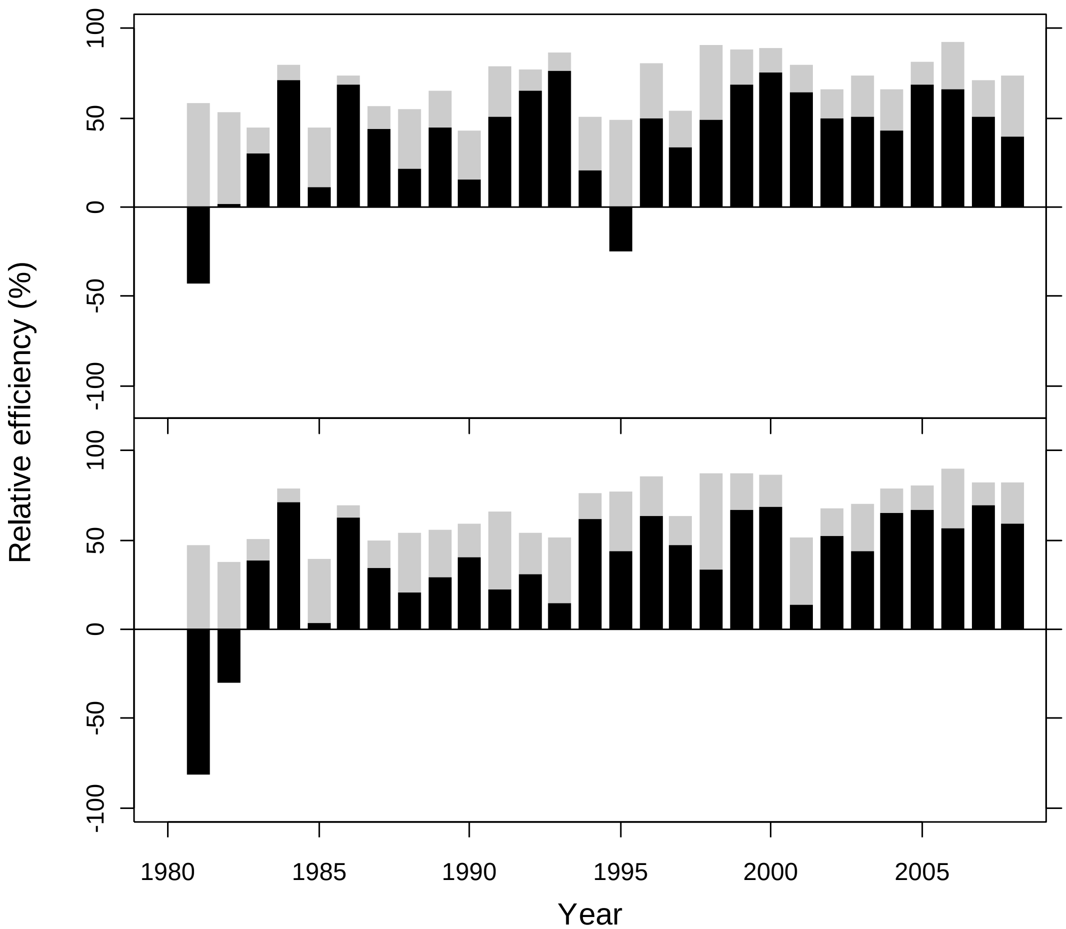

Figure 26. Realized (■) and potential (■) relative efficiencies of the historical survey index design with separate strata definitions for north and south for the survey of sea scallops (Placopecten magellanicus) on Georges Bank (management area 'a').The upper panel shows the efficiencies relative to the annual catch rate design and the lower panel shows the efficiencies relative to simple random sampling.