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Re-design of the Joint Industry-DFO Atlantic Halibut (*Hippoglossus Hippoglossus*) Survey off the Scotian Shelf and Grand Banks

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

The Industry-Fisheries and Oceans Canada (DFO) Atlantic Halibut Longline Fixed Station Survey is critical to the current management approach for Atlantic Halibut (*Hippoglossus hippoglossus*) on the Scotian Shelf and Grand Banks (Northwest Atlantic Fisheries Organization (NAFO) Divs. 3NOPs4VWX5Zc). The Atlantic Halibut Longline Survey indices are used as an index of abundance in the statistical catch-at-length stock assessment model and as a key input in the management procedure used to provide annual Total Allowable Catch (TAC) advice. The fixed-station survey design used from 1998-2016 has allocated more sampling in areas closer to port, areas along the shelf edge, and areas with historically high catch rates.

Alternative survey designs that achieve more representative and unbiased sampling coverage over the entire stock area are considered in this paper. Three alternative area-depth stratification options with a combination of 4 (4X5YZ, 4W, 4VnVs, 3NOPnPs) or 5 (4X5YZ, 4W, 4VnVs, 3PnPs, 3NO) NAFO area strata and 2 (30-250m, 251-750m) or 3 (30-130m, 131-250m, 251-750m) depth strata were evaluated. Bootstrap replicates were used to assess survey precision under different stratification options, sample sizes, and sampling allocation options. Bootstrap estimates of the average annual Coefficients of Variation (CV) of Catch Per Unit Effort (CPUE) were similar for all 3 stratification options and indicated that the greatest gains in survey precision were from improvements to sample allocations among the different strata. Sampling that was allocated in proportion to stratum area ('area-based allocation') or stratum area multiplied by stratum standard deviation ('optimal allocation') produced higher precision than the historical allocation of samples on the fixed station survey. All three stratification options produced similar CVs that were below the target 20% CV for n=150 annual samples, with bootstrap estimates of mean annual CVs ranging between 12.3-12.5% and 11.1-11.8% using area-based and optimal sampling allocations, respectively.

An implementation plan for the new survey using a calibration period, where the fixed station and the new Stratified Random Survey (StRS) will be run concurrently, was developed. Analysis of CPUE from subsets of the fixed stations (100, 150, Freq100, and Freq150) indicated that a subset of the most frequently surveyed stations can be used to calculate interim TACs during the transition period to the StRS. The fixed-stations subset will continue to be sampled each year along with 150 randomly selected stations from the StRS during the 3-4 year calibration period.

Refonte du relevé sur le flétan de l'Atlantique (Hippoglossus hippoglossus) mené conjointement par le MPO et l'industrie au large du plateau néo-écossaise et des Grands Bancs

RÉSUMÉ

Le relevé à la palangre aux stations fixes sur le flétan de l'Atlantique mené conjointement par l'industrie et Pêches et Océans Canada (MPO) est essentiel pour l'application de la méthode de gestion actuelle du flétan de l'Atlantique (*Hippoglossus hippoglossus*) au large du plateau néo-écossaise et des Grands Bancs (Organisation des pêches de l'Atlantique Nord-Ouest [OPANO], divisions 3NOPs4VWX5Zc). Les indices du relevé sur le flétan de l'Atlantique à la palangre servent d'indices de l'abondance dans le modèle d'évaluation statistique détaillé des prises selon la longueur et sont un élément essentiel des procédures de gestion utilisées pour obtenir un avis sur le total autorisé des captures (TAC) annuel. La conception du relevé aux stations fixes utilisé de 1998 à 2016 a attribué un échantillonnage plus important aux zones plus proches des ports, aux zones au bord du plateau et aux zones où les taux de prise sont historiquement élevés.

D'autres conceptions de relevés permettant une couverture d'échantillonnage plus représentative et moins biaisée de l'ensemble de la zone de stock sont examinées dans ce document. Trois autres options de stratification des zones en fonction de la profondeur examinant quatre (4X5YZ, 4W, 4VnVs, 3NOPnPs) ou cinq (4X5YZ, 4W, 4VnVs, 3PnPs, 3NO) strates des zones de l'OPANO et deux (30-250 m, 251-750 m) ou trois (30-130 m, 131-250 m, 251-750 m) profondeurs différentes ont été évaluées. Des répliques par auto-amorçage ont été utilisées pour évaluer la précision des relevés selon les différentes options de stratification, les tailles d'échantillons et les options de répartition de l'échantillonnage. Les estimations par auto-amorçage des coefficients annuels moyens de variation des prises par unité d'effort (CPUE) étaient similaires pour les trois options de stratification et indiquaient que les plus grands gains de précision des relevés provenaient des améliorations des allocations d'échantillonnage entre les différentes strates. L'échantillonnage qui a été attribué en fonction des zones de strate (allocation en fonction de la zone) ou de la zone de strate multipliée par l'écart-type de strate (allocation optimale) offrait une plus grande précision que l'allocation historique des échantillons des relevés à stations fixes. Les trois options de stratification donnaient des coefficients de variation similaires, sous la cible de 20 % pour les échantillons annuels n=150, avec des estimations par auto-amorçage des coefficients annuels moyens de variation entre 12,3 et 12,5 et 11,1 et 11,8 %, dans le cas de l'allocation par zone et de l'allocation optimale d'échantillons, respectivement.

Un plan de mise en œuvre des nouveaux relevés s'appuyant sur une période d'étalonnage, au cours de laquelle les relevés aux stations fixes et les nouveaux relevés aléatoires stratifiés seront menés simultanément, a été élaboré. L'analyse des CPUE des sous-ensembles des stations fixes (100, 150, Freq100 et Freq150) indiquait qu'un sous-ensemble des stations faisant le plus fréquemment l'objet de relevés peut être utilisé pour calculer les TAC intermédiaires pendant la période de transition vers les relevés aléatoires stratifiés. Le sous-ensemble de stations fixes continuera à faire l'objet d'un étalonnage chaque année, ainsi que 150 stations sélectionnées au hasard dans le cadre des relevés aléatoires stratifiés pendant une période d'étalonnage de 3 à 4 ans.

INTRODUCTION

The Atlantic Halibut (*Hippoglossus hippoglossus*) Longline Fixed Station Survey began in 1998 with the objective of developing an index of abundance for the exploitable Atlantic Halibut population (>81cm) on the Scotian Shelf and Grand Banks (Zwanenberg and Wilson 2000). The survey also collects information on bycatch, oceanographic conditions, and predator-prey relationships. These additional variables are seen as potentially important for ecosystem-based management of the Atlantic Halibut fishery, but secondary to providing a robust index of abundance for stock assessment and management (Zwanenberg and Wilson 2000). The original survey was a stratified random design, with strata defined using areas of low, medium, and high commercial Atlantic Halibut landings per trip during 1993-1997 (Zwanenburg et al. 2003). A total of 220 stratified random sets were allocated across the stock area at a ratio of 5:7:10, for a total of 50, 70, and 100 sets in areas of low (<49 kg), medium (50-249 kg), and high catch (>250 kg), respectively (Zwanenburg and Wilson 2000, Zwanenburg et al. 2003). The survey was subsequently modified to a fixed station design, and stations have been rearranged and added to achieve better coverage in the Bay of Fundy, Cape Breton, and Georges Bank (Trzcinski et al. 2011). Both the number of stations and the sampling protocol (e.g. soak time, number of hooks, etc.) varied from year to year, potentially adding variability to the Atlantic Halibut abundance index. Although standardization methods exist to adjust for such effects (Maunder and Punt 2004), fishery-independent surveys should strive for inter-annual consistency in the survey protocol.

Several options have been suggested for standardizing the Atlantic Halibut (*Hippoglossus hippoglossus*) Longline Fixed Station Survey data based on particular assumptions about the data and associated error distributions (Armsworthy et al. 2006, Trzcinski et al. 2009, Smith 2016). These solutions seek to account for features in the data that are otherwise ignored (e.g. skewness, zero-inflation, spatial correlation), as well as to improve the statistical attributes of the survey by shifting sampling effort among survey locations; however, the problem of survey design requires a broader perspective on the goals and intended use of the data. Fishery-independent surveys aim to provide an index of abundance (biomass or numbers) that is linearly proportional to the true stock size over the entire stock area (Hilborn and Walters 1992). This primary feature is needed to accurately represent stock trends and responses to management actions. Surveys designed to target areas of high abundance and fishery profitability typically do not meet this linear proportionality requirement. The current set of Atlantic Halibut Longline Fixed Station Survey locations targets higher sampling rates in areas closer to port, along the shelf edge, and in areas of historically high catch rates of mature Atlantic Halibut (Table 1, Figure 1). It is, therefore, important to consider alternative designs that can achieve representative, unbiased sampling coverage over the entire stock area.

The overarching goal of the survey re-design for Atlantic Halibut is to improve the representation and coverage of Atlantic Halibut habitat in a simple and cost-effective manner. Preliminary review and discussion by the survey review team (i.e., DFO, Atlantic Halibut Council, Landmark Fisheries Research) suggested that a new Stratified Random Survey (StRS) is likely required because it could be adjusted (i.e., "optimized") over time as information accumulates about the overall distribution of habitat and abundance. In this paper, alternative StRS design options are considered that extend the sampling distribution of the longline survey into areas and depths that are not well represented by the current survey.

The Atlantic Halibut Longline Fixed Station Survey is critical to the current management approach used for Atlantic Halibut on the Scotian Shelf and Grand Banks. It is used both as an index of abundance in the Statistical Catch-At-Length (SCAL) stock assessment model that is used in framework assessments every four years and as a key input to the interim procedure used to derive annual Total Allowable Catch (TAC) advice in the intervening years (DFO 2015). Changes in the survey design or switching to a new survey will directly affect management recommendations. A transition plan between the current fixed-station survey and a new StRS design is evaluated to understand the potential impact on management recommendations.

METHODS AND STUDY DESIGN

SURVEY DESIGN AND STRATIFICATION OPTIONS

The aim of stratification is to: (i) expand spatial coverage of the survey into depths and areas not currently sampled, and (ii) ensure a high survey precision each year. Throughout this paper, the term "coefficient of variation" (abbreviated CV) is used to represent survey precision (Smith and Gavaris 1993), i.e., $CV = \hat{s}/\bar{x}$ where $\hat{s}/\bar{x}$ are the standard error of the mean Catch Per Unit Effort (CPUE) and mean CPUE, respectively.

DATA SCREENING AND STANDARDIZING CPUE

The historical Atlantic Halibut Longline Fixed Station Survey catch rates were standardized to kg/1000 hooks and the commercial index sets were standardized to kg/1000 hooks/10 hours. Both data sets were filtered to exclude sets with soak times longer than 1250 minutes and less than 180 minutes, following Smith (2016), who found that soak times within this range encompassed the full range of Atlantic Halibut catches. Sets without a minimum hook count of 500 (den Heyer et al. 2015) and sets that did not have data for hook counts or soak times were similarly excluded. The data screening led to the removal of 2% of sets (67 out of 3,765) from the fixed-station survey and 25% of sets from the commercial index (3,206 out of 12,725).

The corresponding area-strata for each Atlantic Halibut Longline Fixed Station Survey set from 1998-2015 was determined using the estimated set midpoint location, assuming a straight line between the start and end deployment locations (Figure 2). Depth strata were assigned using the estimated depth at the set midpoint calculated as the average depth measurement between the start and end positions of set deployment locations. In cases where measured depths at deployment locations were not available (12 filtered sets from the fixed-station survey), depths were estimated using the corresponding General Bathymetric Chart of the Oceans (GEBCO) bathymetry at the set midpoint coordinates. After data screening, there were 9 sets between 1998-2012 in areas 4W, 4X, and 3P with estimated set midpoints deeper than the deep stratum boundary at depths between 754-919 m. These sets were included in the deep strata for the bootstrap analyses to provide larger sample sizes for bootstrap sampling. The depth at the first deployment location was used for all analyses of commercial index sets.

STRATA IDENTIFICATION

Area strata were based on aggregations of NAFO management zones that aim to ensure both coverage of the stock area and sufficient sample sizes for the bootstrap analyses. Two area-based options using either 4 or 5 NAFO combinations that differ only in the aggregation of the management zones east of the Laurentian Channel (NAFO areas 3N, 3O, 3Ps, 3Pn; Figure 2, Tables 2-4) were identified. The 5-area stratification identified a 3PsPn stratum and a 3NO stratum, whereas the 4-area stratification combines them all into one 3NOPsPn stratum. The 5-area stratification also yields strata of similar size, with areas 1-5 occupying 20%, 16%, 16%, 19%, and 29% of available sampling blocks, respectively (Table 4).

Depth strata were based on exploratory analyses of catch rates by depth using fixed-stations and commercial index sets from the Atlantic Halibut survey. Plots of log CPUE versus depth for different catch strata did not indicate a strong relationship between depth and catch rate

(Figure 3); however, the proportion of sets with zero Atlantic Halibut catch was higher in sets shallower than 250 m (Figure 4, Table 5).

The upper (30 m) and lower (750 m) depth stratum boundaries were chosen because they encompassed the majority of fishing sets and inferred Atlantic Halibut habitat. The choice of area and depth stratification was also influenced by a need to ensure stratum areas of reasonable size to permit pooling of existing survey sets for bootstrap analyses and random distribution of sampling units in the survey. For example, a stratification design with 5 area and 3 depth strata was initially considered but did not provide adequate sample sizes for stratified mean estimates and bootstrap analyses. Therefore the following 3 alternative area-depth stratification schemes were tested (Tables 2-4, Figure 5):

4A-2D: 4 area and 2 depth (30-250 m, 251-750 m);

4A-3D: 4 area and 3 depth (30-130 m, 131-250 m, 251-750 m); and

5A-2D: 5 area and 2 depth (30-250 m, 251-750 m).

The 4A-2D stratification allowed for a minimum of 2 survey sets in all years in each of the 8 area-depth strata and was used as the baseline stratification for bootstrap analyses. For practical reasons, the proposed survey re-design randomly samples 4x4 km blocks within each of the area-depth strata instead of specific locations.

Strata areas were calculated using the Canada Albers Equal Area Conic Projection (ESRI 102001). Depth strata were defined using bathymetry data obtained from the General Bathymetric Charts of the Oceans that was converted to rasters with 4x4 km grid cells using bilinear interpolation with the raster package in R (R Core Team 2014).

BOOTSTRAP EVALUATION OF CURRENT SURVEY SAMPLE ALLOCATION

The baseline 4A-2D stratification was used to evaluate the current sample allocation among strata. A total of 100 bootstrap replicates with replacement were sampled to assess the expected CVs for standardized annual catch rates from 1998-2015 using the 8 area-depth strata for the 4 areas and 2 depths. Each bootstrap comprised $n_{h,y}$ samples for $h = \{1,2,\ldots,8\}$ strata and $y = \{1998,1999,\ldots,2015\}$ years. Four scenarios for sampling effort were tested using different numbers of annual n_y samples per year to assess changes in CV for different sample sizes and to validate the bootstrap approach. Options for n_y included $n_{hist,y}$ (the historical number of samples that were actually taken in year *y*), as well as a fixed number of annual sets each year ($n = 50,150,250$). The proportion of $n_{h,y}$ in each bootstrap is equal to the proportion of the total fixed-station samples that historically occurred in $n_{h,y}$. This assumes that the fixed-station survey sets are representative of the population in each depth-area strata, and that bootstrapping can be used as a method to simulate randomly deployed sets in 4 x 4 km blocks in the strata.

Annual mean catch rates $\bar{y}_{h,y}$ and sampling variances $s^2_{h,y}$ for each stratum and year were used to calculate stratified means $\bar{y}_{str,y}$, variance $V(\bar{y}_{str,,y})$ and the CV of the stratified mean $CV(\bar{y}_{str,,y})$ for each bootstrap using standard Cochran (1977) estimators:

$$\bar{y}_{str,y} = \sum_{h=1}^{8} W_h \, \bar{y}_{h,y} \tag{1}$$

$$V(\bar{y}_{str,y}) = \sum_{h=1}^{8} W_h^{\ 2} \frac{s^2_{h,y}}{n_{h,y}} \left(1 - \frac{n_{h,y}}{N_h}\right) \quad (2)$$

$$s_{h,y}^2 = \sum_{i=1}^{n_{h,y}} \frac{(y_{h,y,i} - \bar{y}_{h,y})^2}{(n_{h,y} - 1)} \quad (3)$$

$$CV(\bar{y}_{str,y}) = \frac{\sqrt{V(\bar{y}_{str,y})}}{\bar{y}_{str,y}} \quad (4)$$

where $i = \{1, \dots, n_{h,y}\}$ are the individual sets in each strata and year. Stratified means and variances are weighted in proportion to the total N_h number of 4 x 4 km blocks in each h stratum relative to the number of 4 x 4 km blocks in the entire sampling space N, giving stratum weight $W_h = \frac{N_h}{N}$. The number of 4 x 4 km blocks and approximate areas for each stratum for different stratifications are shown in Tables 2-4. This same approach was used to evaluate 3 alternative allocation options and 2 different stratification schemes outlined below.

SURVEY ALLOCATION OPTIONS

Two options were tested for allocating samples among strata in proportion to either stratum area (Area-based), where $n_{h,y} = W \frac{N_h}{N}$, or stratum area times the standard deviation $n_{h,y} = \frac{W_h s_{h,y} n_y}{\sum W_h s_{h,y}}$ (Optimal). Area-based allocation is the easiest approach for improving survey precision (Smith and Gavaris 1993), while Optimal allocation minimizes expected variance (Cochran 1977). Optimal allocation requires an estimate of strata standard deviations, which can be obtained from previous surveys, pilot studies, or commercial fisheries data (Kimura and Somerton 2006). This analysis uses the observed survey strata standard deviations for year *y* in the Optimal allocation scheme and, therefore, under-represents the uncertainty associated with survey planning.

A minimum of 2 samples were allocated to every strata to ensure stratified mean and variance calculations would be possible for all bootstraps and years. Samples were added to achieve the minimum in cases where the strata allocations assigned 1 or 0 (e.g. if the allocation resulted in 1, it was assigned a sample size of 2; Table 2).

EVALUATION OF ALTERNATIVE STRATIFICATION OPTIONS

Stratification schemes 4A-3D and 5A-2D were evaluated under 4 scenarios for sampling effort ($n_{hist}, n = 50, n = 150, n = 250$), and 2 sample allocation options. Annual stratified means and CVs for each bootstrap were calculated for all years and strata with a minimum of 2 fixed-station survey sets. Due to realized sample sizes < 2 sets in certain year-strata combinations, the stratified means and CVs could not be estimated in 1998 and 2006 for the 4A-3D stratification and 1998, 2003, 2005, 2006 for the 5A-2D stratification. Strata with limited sample sizes were primarily in areas 4 and 5 (i.e., NAFO 3NOP), which received the lowest historical allocation of Atlantic Halibut Survey sets (Figure 1).

IMPLEMENTATION PLAN

Procedures for setting annual TACs during the transition from the current fixed-station survey to a new StRS design were evaluated to:

(i) test the potential management implications of the survey transition;

(ii) identify the number of years in which both surveys should be run concurrently; and

(iii) evaluate the impact of alternative sub-sampling schemes on the SCAL assessment model outputs.

Management implications were evaluated by assessing the utility of a new abundance index time series for setting interim TACs. The new index was derived from a subset of the historical fixed-station data (e.g. the “Golden Stations”) and calibrated to the Atlantic Halibut Survey Generalized Linear Model (GLM) predicted catch rates (DFO 2015). A case study from the British Columbia (BC) Sablefish fishery was used to examine how catchability estimates are affected during transition years and to identify the number of years over which both the old and new surveys should overlap. Finally, alternative sub-samples of the Atlantic Halibut survey over the 1998-2013 period were incorporated into the SCAL (DFO 2015) assessment model to determine how SCAL estimates of stock biomass and exploitation rates might be affected by sub-sampling during the transition period.

GOLDEN STATION CALIBRATION

There are 57 “Golden” stations in the fixed-station Atlantic Halibut survey that were regularly surveyed between 1998-2015 (Figure 6). The mean annual standardized catch rates (kg/1000 hooks) using only the Golden 57 stations were calculated to assess whether they could sufficiently represent the fixed station survey, and could be used to set TACs during the transition period. Following data screening and standardization, a minimum of 55 sets remained from the Golden 57 stations for each year from 1999-2015. Year 1998 had only 40 sets and was excluded from model fitting.

Time series of mean catch rates from the Golden 57 stations (G) were compared with mean catch rates generated using all stations, and the Atlantic Halibut survey GLM-predicted catch rates (HS). A linear regression was used to evaluate the relationship between G and HS:

$$HS = \beta_0 G^{\beta_1} e^{\nu} \quad (5)$$

$$\log(HS) = \log(\beta_0) + \beta_1 \times \log(G) + \nu \quad (6)$$

where $\nu \sim N(0, \sigma^2)$. The management implications of using the Golden 57 stations to provide harvest advice during the transition period were investigated by comparing a trajectory of TACs obtained using the Golden 57 stations only with a reference trajectory that uses the actual HS GLM index (*HS*). The Golden 57 TACs are obtained using Equations 6-8:

$$B_t' = \left(\frac{HS'_t + HS'_{t-1} + HS'_{t-2}}{3} \right) \times \frac{1}{q_{HS}} \quad (7)$$

$$TAC_{t+1}' = \left(1 - e^{-F}\right) B_t' \quad (8)$$

where *HS'* is the HS index predicted from Golden 57 station data *G* in 1999-2015, q_{HS} = 0.00479 is the SCAL catchability estimate (DFO 2015), B_t' is the estimated survey biomass using the 3-year average of *HS'*, TAC_{t+1}' is the total allowable catch for year *t+1,* and *F* is the target fishing mortality rate (F=0.125). Reference TACs were calculated using *HS* for *t*=1999-2014 and Equations 7-8 (See Table 6 for list of parameters in Harvest Control Rules).

CATCHABILITY ESTIMATES DURING TRANSITION PERIOD

The British Columbia (BC) Sablefish stock assessment model (Cox et al. 2011) was used to investigate how the calibration period for simultaneously running a fixed station standardized survey (Std; 45 stations) and a new StRS (90 random stations) affects catchability estimated for the new survey. The BC Sablefish assessment uses multiple abundance index data sets similar to the Atlantic Halibut framework assessment. Catchability was evaluated because the current Harvest Control Rule for Atlantic Halibut assumes known survey catchability in setting annual TACs.

The Sablefish stock assessment model was fit to combinations of Std and StRS data from 2003 to 2009 and compared model estimates of biomass and catchability. For each year, the model was fit to (*i*) Std and StRS (i.e., a calibration year) and (*ii*) the new StRS point alone (a full implementation year) and compared performance using the mean squared error statistic computed using the two estimated biomass time-series. Catchability estimates were calculated for each year to show how they evolved over the 6-year transition period.

SCAL OUTPUTS FOR ALTERNATIVE HS SURVEY SUB-SAMPLES

Catch rates for sub-samples of the existing HS stations over 1998-2013 provided by DFO were: (1) Base stations – the full HS survey; (2) Golden 57 stations as described above, (3) Freq100 – the 100 most frequently sampled stations; (4) Freq150 – the 150 most frequently sampled stations; and (5) Opt150 – the 150 stations selected via optimal stratification of the existing HS survey. For each sub-sampling scheme, only the Atlantic Halibut survey index of biomass component to the SCAL assessment model input was changed; length composition data for the HS survey were not updated to reflect the sub-sampling scheme.

SCAL outputs were summarized via the estimated survey CV (a measure of how well SCAL fit the new survey series), average age-1 recruitment, unfished spawning stock biomass, spawning biomass in 2013, legal biomass in 2013, and the proportional exploitation rate in 2013.

RESULTS

SURVEY DESIGN

Bootstrap Model Validation – Baseline Stratification

The results of the 4 bootstrap scenarios using the historical sampling allocation and different n_y sampling scenarios are shown in Figures 7, 8, and 9. The bootstrap CV estimates for historical sample size align well with those from the original data (“realCV”), and show the expected increase in precision (lower CV) as sample sizes increase. There are occasional outliers due to very low sample sizes and sample populations with high proportions of zeros for $n_{h,y}$ strata (e.g. compare n=50 sampling with realCV in Area 4 shallow and deep stratum in 1998). The n_{hist} bootstrap scenario, which uses the historical number of samples that were actually taken in year *y,* and the $n_y = 150{,}250$ can accurately replicate the actual CV for most $n_{h,y}$. The $n_y = 50$ scenario yields the highest CV in nearly all years and strata evaluated.

The bootstrap analysis reflects the concentration of historical sampling effort in the shallow (30-250 m) depth stratum in Areas 1 and 2. These areas should therefore achieve the best survey precision (lowest CV), but only Area 1 achieves CVs that are consistently below the target

(CV < 0.20) and are relatively insensitive to sampling effort within the historical range of $n_y = 150{,}250$. The realized (true) and bootstrap estimates of CV in all other survey strata vary from year to year, but are generally higher than the target. Increasing sampling effort through more bootstrap samples increases the precision of mean CPUE estimates (e.g. lower CV) across the strata and years that were examined (Figures 8 and 9).

With the possible exception of the Area 2 deep (250-750m) stratum, Atlantic Halibut catch rates have increased throughout all survey strata since 2005 (Figures 8 and 9), and corresponding survey CVs have tended to decrease and stabilize since 2009 (for example, see Area 1 deep stratum, Figure 9). Decreasing CV in recent years of the survey may be attributed to a decrease in the number of sets returning zero Atlantic Halibut catch. For example, the proportion of sets with no Atlantic Halibut catch throughout the survey strata was as high as 90% in 1998, and dropped to 30% by 2015 (Table 5).

Allocation Options – Baseline Stratification

Tables 7 and 8 present the effect of changing the allocation scheme across the 8 survey strata for 4A-2D stratification using both allocation options; the historical allocation is included as a reference case. Mean annual CVs for each allocation scheme given the sampling effort n_{hist}, n=250, n=150, and n=50 are shown in Figure 10. Across all sample sizes, the historical sample allocation achieves the worst precision (highest mean CV) relative to the 2 alternative allocation options. As expected, Optimal allocation achieved the highest precision (Figure 10). Increasing sample sizes improved survey precision and with the exception of n=50, all sample allocation schemes met or exceeded the required CV < 0.20 on average (Table 9)

Performance of Alternative Stratification Schemes

Mean CVs for 1998-2015 (excluding 1998, 2003, 2005, 2006 due to insufficient samples) of stratified mean catch rates are provided in Table 10 for 4A-3D and 5A-2D stratification schemes. Similar to the baseline 4A-2D stratification, the Optimal allocation achieves the best precision. Increasing sample sizes improved survey precision and, with the exception of n=50 for the Area-based allocation option, both allocation options met the required CV < 0.20 on average for all levels of sampling effort. There is essentially no difference in survey precision estimates due to the different stratification schemes (Table 10). The largest difference between survey precision estimates was for the n=50 sampling scenario under the optimal allocation where the 4A-3D stratification produced the lowest CV (18.6%), followed by the 5A-2D stratification (18.9%) and the baseline 4A-2D stratification (20.3%). Plots are provided for reference in Appendix A (Figures A.4-A.7) of mean annual CVs from bootstrap analyses for each of the 4 sampling scenarios.

IMPLEMENTATION PLAN

Golden 57 Station Calibration

Standardized mean catch rates from the Golden 57 stations are higher on average and less precise than the catch rates generated using data from all stations (Figure 11). This observation is expected given the Golden 57 stations have fewer survey stations in the low catch stratum, which translates into higher mean catch rates for these data (Table 11; Figure 11). The linear regression model suggests that log-transformed Golden 57 station CPUE is a good predictor of log-transformed Atlantic Halibut survey GLM-predicted catch rates (Figure 12) with the exception of outlier years 2007 and 2009.

There is no consistent bias (i.e. over or under-estimation) between TACs (TAC') computed with the Golden 57 station-generated Atlantic Halibut survey index (HS') and TACs computed using the Atlantic Halibut Survey GLM-predicted catch rates (HS) for calculations using the target fishing mortality of F=0.125 between 2000 and 2014 (Table 12, Figure 13). However, the time series do not agree exactly with differences in predicted allowable catches ranging between 165 to 226 mt.

SCAL Outputs for Alternative HS Survey Sub-samples

Quantities estimated from the SCAL framework assessment using station sub-samples and percentage differences from the base case (i.e., all stations) are presented in the following table.

Survey	obsErrCV	avgRec	SSB0	SSB_2013	legalB_2013	explRate_2013
Base	0.19	668,945	79,573	6,650	23,480	0.103
Golden 57	0.21	679,132 (1.52%)	80,785 (1.52%)	7,385 (11%)	25,402 (8.18%)	0.095 (-7.78%)
Freq 100	0.18	670,721 (0.26%)	79,784 (0.26%)	6,754 (1.56%)	23,823 (1.46%)	0.101 (-1.94%)
Freq 150	0.23	669,579 (0.094%)	79,648 (0.094%)	6,636 (-0.21%)	23,623 (0.61%)	0.102 (-0.97%)
Opt 150	0.23	675,525 (0.98%)	80,355 (0.98%)	7,059 (6.15%)	24,750 (5.41%)	0.098 (-4.85%)

In general, estimated biomass and recruitment were greater for all sub-sampling schemes compared to the full HS survey (Base) dataset. The only exception was 2013 spawning stock biomass under Freq150 sampling, which was estimated lower than the Base sample. The Golden 57 stations over-estimated 2013 spawning biomass by 11% compared to the Base data, which is consistent with the slight non-linear relationship between the Base and Golden 57 stations shown in Figure 12.

Although the Opt150 scheme would be optimal in a statistical sense given the underlying stratification, it also produced relatively high biases compared to the Base data set. This is also not surprising given that the original stratification was aimed toward better fish locations; therefore, optimal stratification reinforces the bias associated with selectively sampling good fishing locations.

Overall, either of the Freq100 or Freq150 sub-sampling schemes should produce similar SCAL outputs given the data up to 2013.

DISCUSSION

SURVEY DESIGN

The goals of this study were to: (i) identify alternative survey designs that achieve broader sampling coverage of the Atlantic Halibut stock, and (ii) recommend a process for transitioning between the old and new surveys. The survey design involved identification of: (i) sampling strata, (ii) an appropriate plan for allocating samples between strata, and (iii) recommendations for number of samples required to achieve a CV of ≤ 0.2.

Three separate stratification schemes for the new survey design that included 8 strata (4A-2D; 4 NAFO area x 2 depth), 12 strata (4A-3D; 4 NAFO area x 3 depth), and 10 strata (5A-2D; 5 NAFO area x 2 depth) were evaluated. The evaluation was restricted to these three options, as previous studies found the largest improvements in precision resulted from improved allocation of sampling effort among strata, rather than improved identification of strata based on appropriate geographical area (Smith and Gavaris 1993). Cochran (1977) similarly noted only modest gains in survey precision from geographic stratification, and emphasized sample allocation over continued refinement of strata boundaries. The depth strata used in this analysis were selected based on an evaluation of the relationship between survey CPUE and depth, and previous studies that found areas of highest Atlantic Halibut catches are concentrated at the shelf edge, along the upper continental slope, and in channels between offshore banks (McCracken 1958, Bowering 1986, Zwanenburg and Wilson 2000, Trzcinski et al. 2009). These regions correspond with the deep depth stratum (251-750 m) presented here.

The 4A-2D stratification was used as a baseline for bootstrap evaluation of the current Atlantic Halibut survey. Results confirmed that the shallow depths in Area 1 had the highest number of samples available for the bootstrap, and achieved the required statistical precision over the historical time series. The Area 3 deep stratum achieved similarly good historical performance, largely because of a low percentage of sets with zero Atlantic Halibut catch. Performance of the survey generally improved in all areas after 2009, concurrent with an increase in Atlantic Halibut CPUE and a reduction in sets with zero Atlantic Halibut catch. The bootstrap serves as a useful guide for planning the survey, clearly demonstrating that a sample size of 50 is too small to adequately survey the stock in any strata, even when sampling is biased toward areas of highest catch.

Alternative Area-based and Optimal sample allocation options both drew sampling effort away from NAFO 4X5YZ and 4W and into NAFO 3NOPnPs, and are expected to result in a large improvement in the sampling coverage of the Atlantic Halibut stock. The choice between the Area-based and Optimal allocation options may therefore hinge more on feasibility and logistics than statistical performance alone. Although Optimal allocation achieved the best precision under all scenarios tested, Area-based allocation performed nearly as well and is simpler to implement. Recall that Optimal allocation uses the true SD for each stratum in a given year for allocating the bootstrap samples for that same year. In practice, the stratum SD is not known prior to sampling and Optimal allocation strategies typically use observed variance from previous years (Smith and Gavaris 1993). The variance across strata was similar for most years and on average there are not major differences in the number of samples allocated to each strata using the Optimal or Area-based allocation options (Tables 7-8). The exception is the shallow strata in area 1 (NAFO area 4X5YZ), which has lower variance since this area has received a much larger sampling effort than the other regions. Any allocation scheme could be re-evaluated after a few years of data have accumulated, particularly if large variances are observed in any stratum. For example, Smith and Gavaris (1993) found large improvements in the relative efficiencies for improved precision in abundance estimates of Atlantic Cod from an optimal allocation strategy, using strata variance from previous years data and stratum area, over an area-based allocation strategy based solely on stratum area.

Minor differences were noted in the mean annual CV between the examined stratification schemes, but their relative performance depends on the sample allocation approach. For instance, 5A-2D stratification achieved the lowest CV at all sample sizes for Area-based allocation, 4A-3D stratification achieved the lowest CV for Optimal allocation, and 4A-2D achieved the highest CV across all allocation options and sample sizes examined. Nevertheless, all stratification schemes remained well under the CV target of 20% for sample sizes greater than 50.

The 5A-2D stratification divides each area stratum into areas of similar size and separates areas 3P and 3NO into 2 distinct strata. There may be logistical reasons to consider these as separate strata, given some of the distinct features in those two regions. For example, Area 3P borders the Gulf of St. Lawrence stock boundary and contains the deep Laurentian channel, while area 3NO borders the Newfoundland-Labrador stock boundary and contains productive fishing areas around the Southern Grand Banks. However, given the similarity in performance of the 3 stratification options, there appears to be little statistical support for further refining strata boundaries.

Implementation Considerations

Given the random distribution of sampling locations among strata, the distance between nearest sampling locations is variable and will affect the number of sets that can be performed per day. The distance between nearest neighbouring sampling locations using Area-based allocation are expected to range from 4 km to 99 km (mean = 29 km) for 150 annual sample blocks and from 4 km to 83 km (mean = 22 km) for 250 annual sample blocks (statistics for different stratification schemes shown in Table A-2). Larger distances between nearest sampling units reduce the potential for spatial correlation between sampling blocks (Kimura and Somerton 2006). Appendix A Figures A-8, A-9, A-10, and A-11 provide maps of randomly generated sample locations using Area-based allocation along with histograms of the distances between nearest sampling locations for each of the 3 stratification schemes.

Limitations of the Survey Design

This study did not consider spatial differences in movement patterns, growth rates, and age/size composition that have been observed for Atlantic Halibut in the Gulf of St Lawrence, Gulf of Maine, Grand Banks, Newfoundland and Labrador (Stobo et al. 1988, Neilson et al. 1993, Sigourney et al. 2006, Trzcinski et al. 2011). Due to a greater abundance of immature Atlantic Halibut in the southwest, it has been speculated that some areas on the Scotian Shelf (e.g. Sable Island Gully and Browns Bank) contain spawning or nursery habitats and that as Atlantic Halibut mature they move towards the northeast (Stobo et al. 1988, Neilson et al. 1993, Zwanenburg et al. 1997). Local environmental conditions (e.g. water temperatures, food availability, currents) that may also affect Atlantic Halibut abundance may be less variable within specific areas. Precision might be improved in the future by using different stratification characteristics that are more indicative of habitat suitability (e.g. bottom type or temperature) and are highly correlated with the spatial distribution of Atlantic Halibut. The high spatial resolution data needed for stratification by bottom substrate or temperature is currently not available; however, the depth stratification can provide a proxy for temperature as well as some bottom habitat information (e.g. continental shelf vs. slope). For example, Smith (2016) found that depth and temperature variables are strongly correlated for depths deeper than 280 m for sets in NAFO areas 4VWX.

Expected Halibut CPUE computed from the bootstrap samples probably do not accurately reflect the true underlying relative abundance in each stratum and should therefore be treated with caution until new data accumulate. The bootstrap analysis assumes that when the historical fixed-station survey samples are pooled for the different area-depth strata, that they are representative of the subpopulations in each strata. The strata in 4VWX5YZ NAFO areas have higher densities of fixed stations that are more likely to provide a better representation of the subpopulations for those regions than the 3NOP NAFO areas that have a much lower density of fixed stations (Figure 1). The low density of fixed stations in area 3NOP combined with a large 41% weighting (Table 7) for the stratified mean and variance in the shallow depth strata make this area more vulnerable to bias in mean estimates of CPUE in bootstrap results. Furthermore, under Area-based or Optimal allocation strategies, there will be a large increase in the number of samples allocated to areas within 3NOP than have been historically allocated in the fixed station survey. For example, under 4A-2D-stratification, Area-based allocation, and an n=150 sampling scenario, there are 62 sets allocated to the 30-249 m depth strata in area 4 (NAFO 3NOP), yet only 22-25 sets from 2009-2015 used for bootstrap sampling with replacement. Similar situations exist for shallow strata in NAFO areas 3NOP under the 4A-3D and 5A-2D stratification schemes (See Appendix A Figures A-1, A-2, A-3).

For similar reasons, a new survey is also likely to exhibit a higher proportion of sets with zero Atlantic Halibut catch relative to recent years, which may lead to greater variability in comparison to the bootstrap CV estimates. This is expected because the stratum areas also have different proportions of fixed stations with low, medium and high catch stratum. The area 1 stratum (NAFO area 4X5YZ) has 78, 59, and 6 fixed stations with low, medium and high catch stratum, respectively (Table 1). Stratum areas in 4W and 4VnVs have fixed stations with primarily medium and high catch rates, while areas in 3NOP have fixed stations that are mostly in the high catch rate stratum. Since the new survey design does not select set locations based on areas with historical fishing success, it is possible that there will be sets in 3NOP areas with lower catch rates than is currently represented in the fixed station data.

IMPLEMENTATION PLAN

International best practices for addressing changes in survey gear, vessels, and designs emphasize the need for calibration to understand the relationship between the catchability of the two time series, and procedural standards that ensure use of common gear and procedures across years and vessels (Bagley et al. 2015). The goal is to maintain temporal continuity of survey time series when vessels or technologies change. Calibration methodologies range from benchmarking (e.g. fishing side by side) to modelling approaches such as data transformations, treatment of zero catches, and stock assessment models used to fit the time series and develop conversion factors (Pelletier 1998). However, calibration experiments are expensive and time-consuming, and they can generate imprecise correction factors if not properly designed and implemented (Bagley et al 2015). Thus, while widely recognized to be best practice, logistics and costs generally limit the use of calibration approaches in fisheries surveys (Bagley et al. 2015).

Experience with Pacific Herring and Sablefish in British Columbia show two contrasting approaches to survey calibration. For Pacific Herring, DFO made an abrupt switch in 1986 from surface to dive survey methods for estimating Herring egg density (Martell et al. 2011). No overlapping calibration period was used. Lack of an overlapping calibration period continues to create challenges for scaling the egg deposition estimates to population biomass. For Sablefish, DFO and the Canadian Sablefish Association concurrently operated a historical fixed station Std survey (45 stations) and a new StRS (90 random stations) from 2003 to 2009 before finally discontinuing the fixed station survey. The choice to discontinue was made based on a management strategy evaluation process in which future management performance was tested with and without the fixed station survey. Simulations showed that similar conservation performance could be achieved based on the more precise (8% CV) StRS alone. Between 2010 and 2013, the stratification scheme was adjusted to improve overall precision and currently uses 110 sets per year.

Based on the retrospective analysis of the Sablefish stock assessment model fits using both Std and StRS data (Figure 14), a calibration period of at least 3-4 years for the Atlantic Halibut Survey is suggested, where both the fixed station and random stratified surveys will be run concurrently. Anything less than 3 years is not feasible because the Atlantic Halibut harvest control rule uses a 3-year moving average of the survey. Based on the sablefish model, 3 years may be enough to establish a reasonable catchability estimate; however, the Atlantic Halibut situation may require a longer period for at least two reasons. First, all 3 sablefish abundance indices are derived from targeted fisheries/surveys and both fishery-independent surveys >95% Sablefish in the survey catch. Second, the new StRS survey is reasonably precise with CV approximately 8%, which may be lower than the new Atlantic Halibut survey (Figure 10, Tables 9-10). The randomization of sampling blocks in the new Atlantic Halibut survey will also lead to more sample locations in areas with few historical Atlantic Halibut landings and potentially increase the number of sets with zero Atlantic Halibut catch relative to recent years. Thus, the bootstrap estimates of CVs are likely biased low and do not account for increased variability from random sampling.

There was statistical support for using Golden 57 station CPUE time series for predicting the Atlantic Halibut survey GLM index from 1999-2014, which is used in the harvest control rule. Time series of TACs from 2002-2014 generated using the true Atlantic Halibut survey GLM index were generally similar with those generated using the Golden 57 station index with the difference in annual TACs ranging from -165 to 226 mt for calculations using a target fishing mortality of F=0.125 (Table 12).

Although the Golden 57 station CPUE and implied TACs were significantly correlated with the full HS dataset, SCAL framework assessment model estimates of biomass, recruitment, and exploitation rates were more optimistic using these stations compared to the full data set. Alternative sub-sampling schemes such as Freq100 and Freq150 would probably produce more consistent and robust TACs.

The +/- 15% change limit on annual TAC also restricts the extent that the TAC can change from one year to the next (DFO 2015). This limit will further restrict changes in TAC over the transition period.

RECOMMENDATIONS

Analysis of CPUE from alternative sub-sets of HS survey stations indicates that a Freq100 or Freq150 subset of fixed stations can be used to calculate interim TACs during the transition period to the new random stratified survey. It is anticipated that sampling these fixed stations will need to continue for at least 3-4 years while the new StRS is initiated, during which time the assessment model can be calibrated to the new time series.

The bootstrap analyses indicate that sample sizes greater than 50 can achieve the target 20% CV for the stratified mean catch rates using either the Area-based or Optimal allocation schemes. However, the bootstrap analyses do not account for increased variation that is expected from random sampling and this cannot be determined from the existing fixed station data. There was very little difference in the bootstrapped CV estimates between the 3 different stratification schemes, and all stratification options are expected to perform similarly.

The new StRS design will lead to major changes in the distribution of sampling effort across NAFO areas. There will be increases in sampling effort for areas 3NOP and a reduction in sampling effort for areas 4XW5YZ. It is recommended that 100-150 sampling blocks be used in the first year of the random stratified survey, and that the annual sampling effort be adjusted upward or downward in subsequent years to achieve the desired level of precision. Bootstrap analyses indicated only minor gains (approximately 1% improvements to CV) from the Optimal allocation strategy; therefore, Area-based allocation of samples to survey strata is recommended during the first 1-2 years after which the potential for precision gains from an Optimal allocation strategy can be re-assessed once data collected from random sampling are available for each stratum. Further stratification, such as 5 areas and 3 depths (i.e., 5A-3D, see Appendix B) were not possible to evaluate here, but may be warranted given that the new survey will occur in previously un-sampled areas and depths where Atlantic Halibut catch rates may be unacceptably low.

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TABLES

Table 1. Historical distribution of fixed stations with low (<49 kg), medium (50-249 kg) and high (>250 kg) catch rate stratum from 1998-2015 that are within aggregated NAFO areas strata for the new random stratified survey design.

	Historical Distribution of Fixed Stations						
	Numbers				Percentage		
NAFO Areas	low	medium	high	total	low	medium	high
4X5YZ	78	59	6	143	55%	41%	4%
4W	11	30	40	81	14%	37%	49%
4VnVs	14	20	32	66	21%	30%	48%
3PnPs	2	3	18	23	9%	13%	78%
3NO	3	7	25	35	9%	20%	71%
All Areas	108	119	121	348	31%	34%	35%

Table 2. Number of 4 km x 4 km sampling blocks and area for 4A-2D baseline stratification.

Strata Number	Area Strata	NAFO Areas	Depth Strata (m)	Number of Blocks (N_h)	Approx. Area km^2	Proportional Allocation by Area (W_h)	Allocation for n=150 Sets
1	1	4X5YZ	30-250	4,772	76,352	18%	27
2	1	4X5YZ	251-750	360	5,760	1%	2
3	2	4W	30-250	3,877	62,032	15%	23
4	2	4W	251-750	216	3,456	1%	2
5	3	4VnVs	30-250	2,889	46,224	11%	17
6	3	4VnVs	251-750	1,357	21,712	5%	8
7	4	3NOPnPs	30-250	10,783	172,528	41%	62
8	4	3NOPnPs	251-750	1,995	31,920	8%	12

Table 3. Number of 4 km x 4 km sampling blocks and area for 4A-3D stratification.

Strata Number	Area Strata	NAFO Areas	Depth Strata (m)	Number of Blocks (N_h)	Approx. Area km^2	Proportional Allocation by Area (W_h)	Allocation for n=150 Sets
1	1	4X5YZ	30-130	2,846	45,536	11%	16
2	1	4X5YZ	131-250	1,926	30,816	7%	11
3	1	4X5YZ	251-750	360	5,760	1%	2
4	2	4W	30-130	2,661	42,576	10%	15
5	2	4W	131-250	1,216	19,456	5%	7
6	2	4W	251-750	216	3,456	1%	2
7	3	4VnVs	30-130	1,938	31,008	7%	11
8	3	4VnVs	131-250	951	15,216	4%	5
9	3	4VnVs	251-750	1,357	21,712	5%	8
10	4	3NOPnPs	30-130	8,956	143,296	34%	51
11	4	3NOPnPs	131-250	1,827	29,232	7%	10
12	4	3NOPnPs	251-750	1,995	31,920	8%	11

Table 4. Number of 4 km x 4 km sampling blocks and area for 5A-2D stratification.

Strata Number	Area Strata	NAFO Areas	Depth Strata (m)	Number of Blocks (N_h)	Approx. Area km^2	Proportional Allocation by Area (W_h)	Allocation for n=150 Sets
1	1	4X5YZ	30-250	4,772	76,352	18%	27
2	1	4X5YZ	251-750	360	5,760	1%	2
3	2	4W	30-250	3,877	62,032	15%	22
4	2	4W	251-750	216	3,456	1%	2
5	3	4VnVs	30-250	2,889	46,224	11%	17
6	3	4VnVs	251-750	1,357	21,712	5%	8
7	4	3PnPs	30-250	3,659	58,544	14%	21
8	4	3PnPs	251-750	1,457	23,312	6%	8
9	5	3NO	30-250	7,124	113,984	27%	41
10	5	3NO	251-750	538	8,608	2%	3

Table 5. Percentage of survey sets with zero Atlantic Halibut catch by area stratum, depth stratum and year for 4A-2D stratification.

	Stratum							
	Area 1 - 4X5YZ		Area 2 - 4W		Area 3 - 4VnVs		Area 4 - 3NOPnPs	
Year	Shallow	Deep	Shallow	Deep	Shallow	Deep	Shallow	Deep
1998	72	50	48	36	74	12	90	0
1999	39	33	62	8	47	8	57	22
2000	42	0	50	0	46	18	47	13
2001	38	60	45	14	47	7	46	8
2002	38	88	69	14	61	0	40	11
2003	51	43	73	0	58	26	42	20
2004	35	70	55	8	73	29	48	13
2005	28	50	63	11	73	6	62	0
2006	18	60	49	15	36	7	25	20
2007	51	47	29	36	46	15	64	14
2008	35	67	35	9	50	19	35	27
2009	22	0	14	8	37	10	28	0
2010	21	0	30	10	42	14	36	25
2011	16	0	29	0	31	15	27	0
2012	15	0	27	10	33	17	64	7
2013	16	0	29	0	39	11	27	6
2014	23	20	30	10	50	5	38	0
2015	10	22	30	0	30	5	25	0

Table 6. Symbol definitions for parameters in Harvest Control Rules.

Symbol	TAC
G_t	Mean standardized catch rates for Golden 57 stations for year t
HS_t	Atlantic Halibut survey GLM index for year t
HS_t'	Predicted Atlantic Halibut survey GLM index for year t using G
q_{HS}	Catchability estimate for Atlantic Halibut survey GLM index
F	Fishing mortality rate
B_t	Estimated survey biomass estimates for year t using HS_t
B_t'	Estimated survey biomass estimates for year t using HS_t'
TAC_t	Total allowable harvest using B_t
TAC_t'	Total allowable harvest using B_t'

Table 7. Average allocation of sets by area and depth strata (shallow stratum = 30-250 m, deep stratum = 251-750 m) in bootstrap analyses for 4A-2D stratification from 1998-2015 for different allocation options with n=150 samples per year.

Allocation Option	Area 1 - 4X5YZ		Area 2 - 4W		Area 3 - 4VnVs		Area 4 - 3NOPnPs		
	Shallow	Deep	Shallow	Deep	Shallow	Deep	Shallow	Deep	Total
Historical	32%	4%	22%	6%	12%	9%	10%	5%	100%
Area	18%	1%	15%	1%	11%	5%	41%	7%	100%
Optimal	11%	1%	17%	1%	12%	6%	41%	10%	100%

Table 8. Example allocation of sets for different strata for n=150 sets per year using average annual allocation from bootstrap analyses in Table 7.

Allocation Option	Area 1 - 4X5YZ		Area 2 - 4W		Area 3 - 4VnVs		Area 4 - 3NOPnPs		
	Shallow	Deep	Shallow	Deep	Shallow	Deep	Shallow	Deep	Total
Historical	48	6	33	9	17	14	15	8	150
Area	27	2	22	2	17	8	62	11	151
Optimal	17	2	26	2	17	9	62	15	150

Table 9. Mean CV (%) of annual stratified mean catch rates from 1998-2015 for the 4 allocation options and 4 sampling scenarios tested using the baseline 4A-2D stratification.

Allocation Option	**CV (%) for Different Sampling Scenarios (n)**			
	50	**150**	n_{hist}	**250**
Historical	28.6	17.9	15.6	14.1
Area	21.2	12.7	11.0	9.8
Optimal	20.1	11.7	10.1	9.1

Table 10. Sensitivity of CV (%) to 2 allocation options, 3 stratification schemes, and 4 sample size scenarios for comparable years from 1998-2015 (excluding 1998, 2003, 2005, 2006).

		Mean Annual CV (%) for Stratified Means			
Allocation	**Stratification**	**n = 50**	**n = 150**	n_{hist}	**n = 250**
Area	4A-2D	21.0	12.5	10.5	9.6
	4A-3D	21.0	12.6	10.5	9.8
	5A-2D	20.5	12.3	10.4	9.5
Optimal	4A-2D	20.3	11.8	9.9	9.2
	4A-3D	18.6	11.0	9.2	8.5
	5A-2D	18.9	11.1	9.3	8.6

Table 11. Mean annual percentage of sets from survey stations in different catch strata for CPUE indices derived from the Golden 57 stations and all stations from 1999-2015.

Catch Stratum	**All Stations**	**Golden 57**
Low	28	21
Medium	36	46
High	36	33

Table 12. Total allowable catches (TAC) (mt) calculated from Atlantic Halibut Survey GLM predicted catch rates (TAC) and Golden 57 station-generated Atlantic Halibut Survey Index (TAC') for 2001-2015 for a fishing mortality of F=0.125.

Year	TAC	TAC'	TAC - TAC'
2002	1,012	954	59
2003	1,025	1,017	8
2004	799	962	-163
2005	843	1,008	-165
2006	928	940	-12
2007	1,061	967	93
2008	1,126	1,232	-106
2009	1,272	1,436	-164
2010	1,529	1,537	-8
2011	1,758	1,583	175
2012	2,178	1,974	203
2013	2,352	2,312	39
2014	2,643	2,416	226
2015	2,610	2,462	148

FIGURES

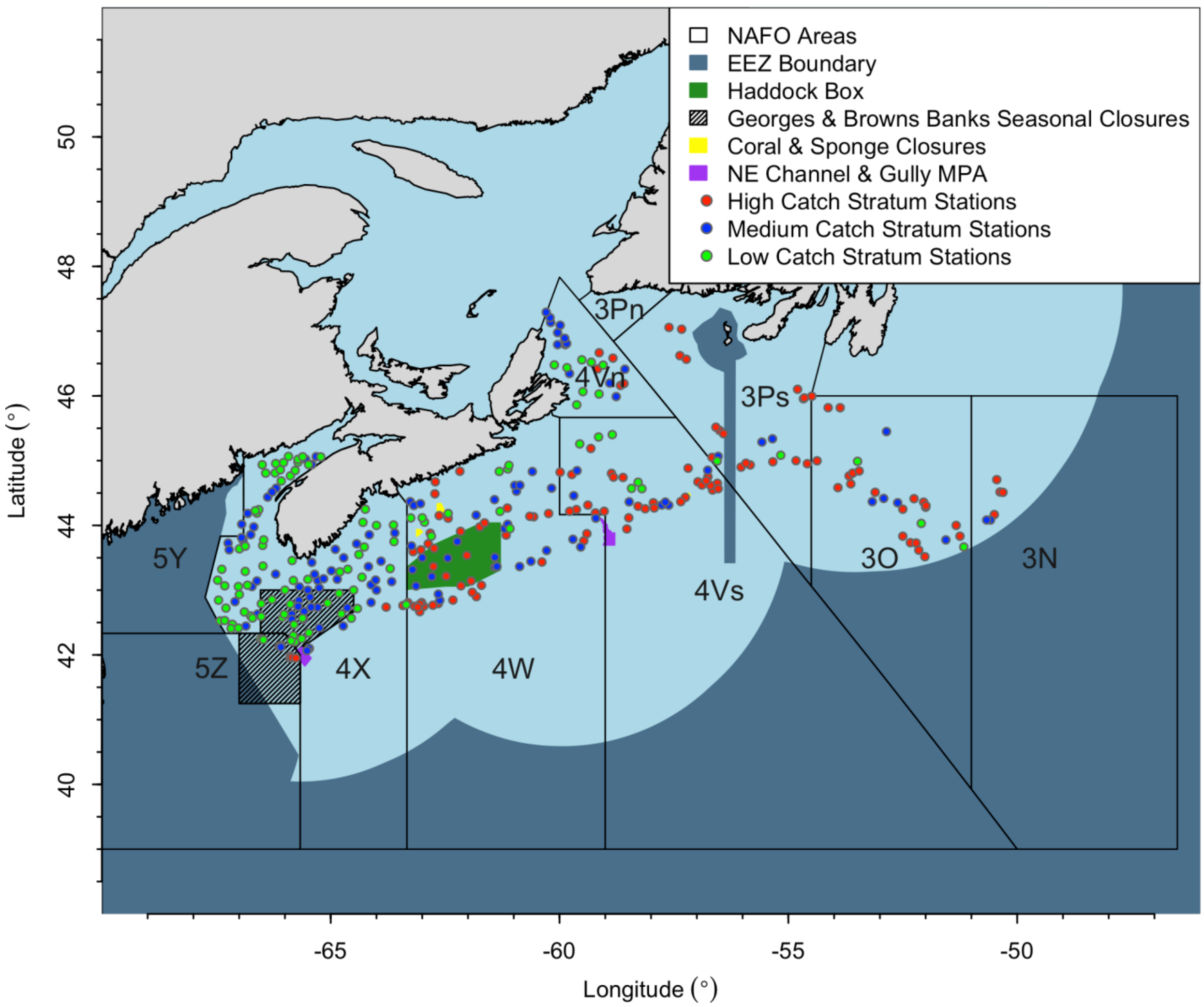

Figure 1. NAFO management areas and area closures with Atlantic Halibut survey fixed stations from 1998-2015 for different catch stratum.

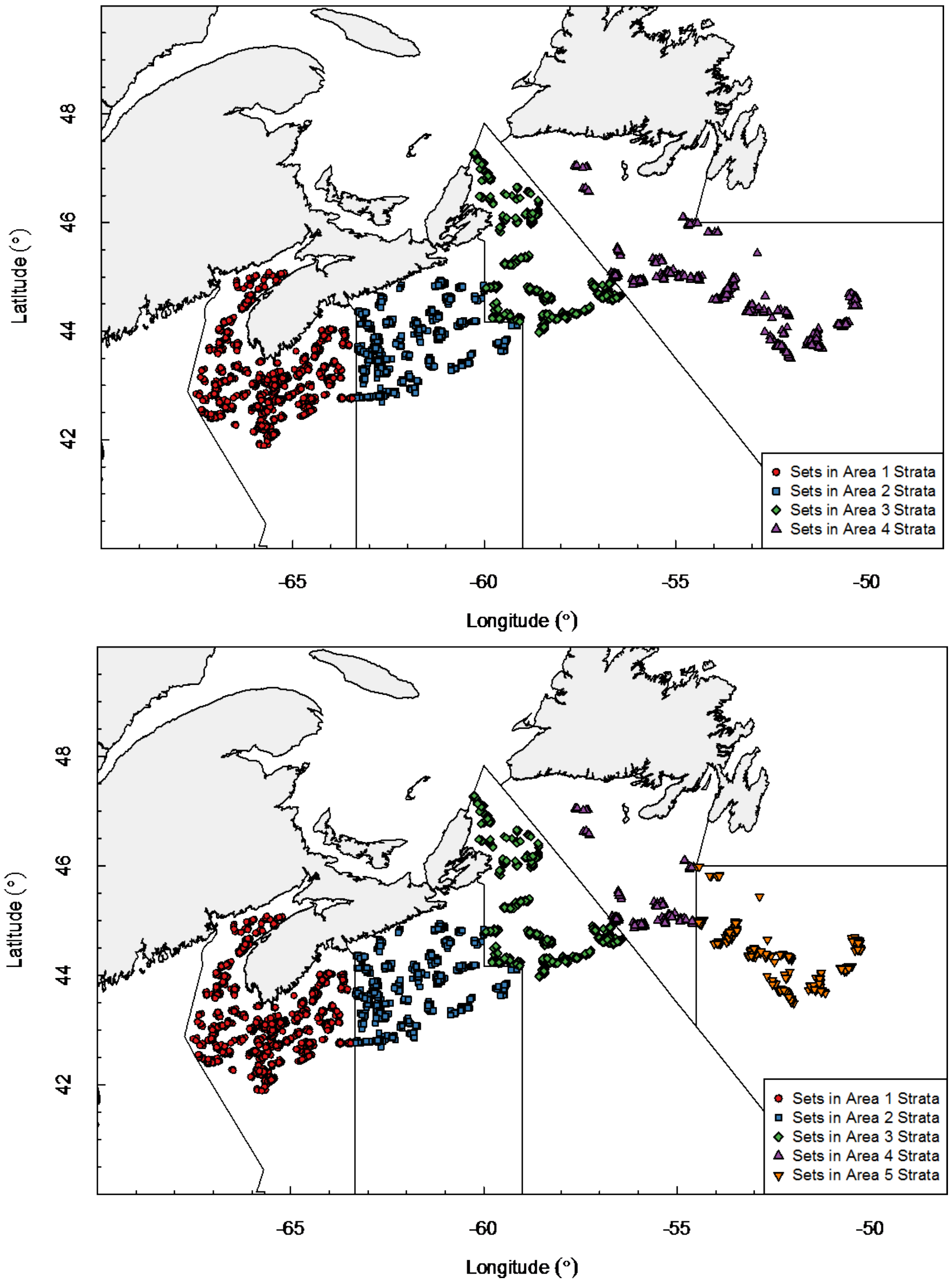

Figure 2. Area stratification and historical distribution of Atlantic Halibut survey set midpoints used for bootstrapping analysis for evaluating survey designs with 4 (top) and 5 (bottom) area strata. There are three 698 midpoints plotted from 1998-2015 fixed-station sets used in the analysis with substantial overlap since sets are from 346 fixed stations.

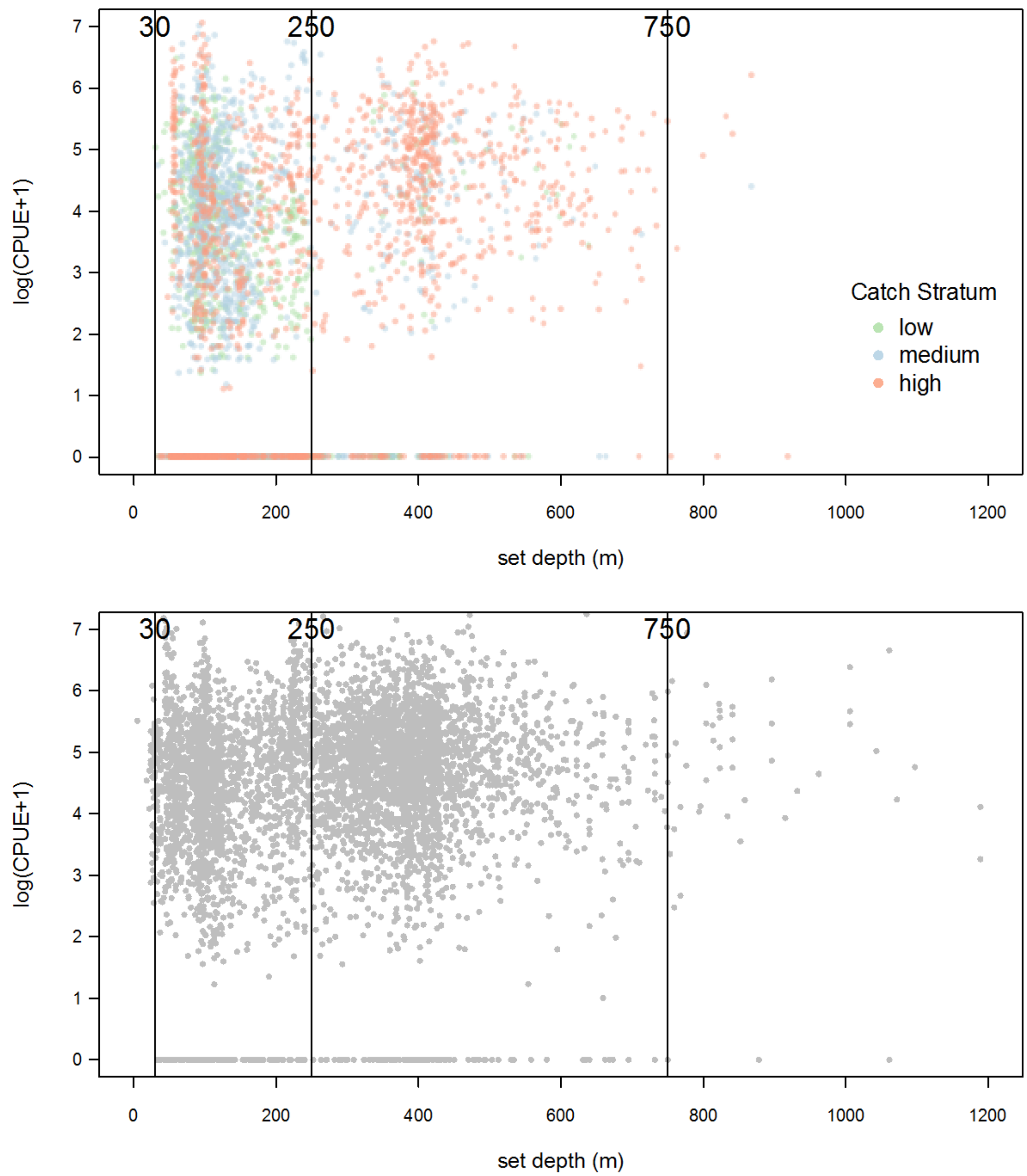

Figure 3. Log-transformed standardized catch rates from the fixed-station longline survey (top) and commercial index (bottom) plotted by depth. The catch strata are low (<49kg), medium (50-249kg), and high (>250kg) based on Zwanenburg et al. (2003). Fixed Station CPUE is standaridized as kg/1000 hooks and commercial index CPUE is standardized as kg/1000 hooks/10 hours.

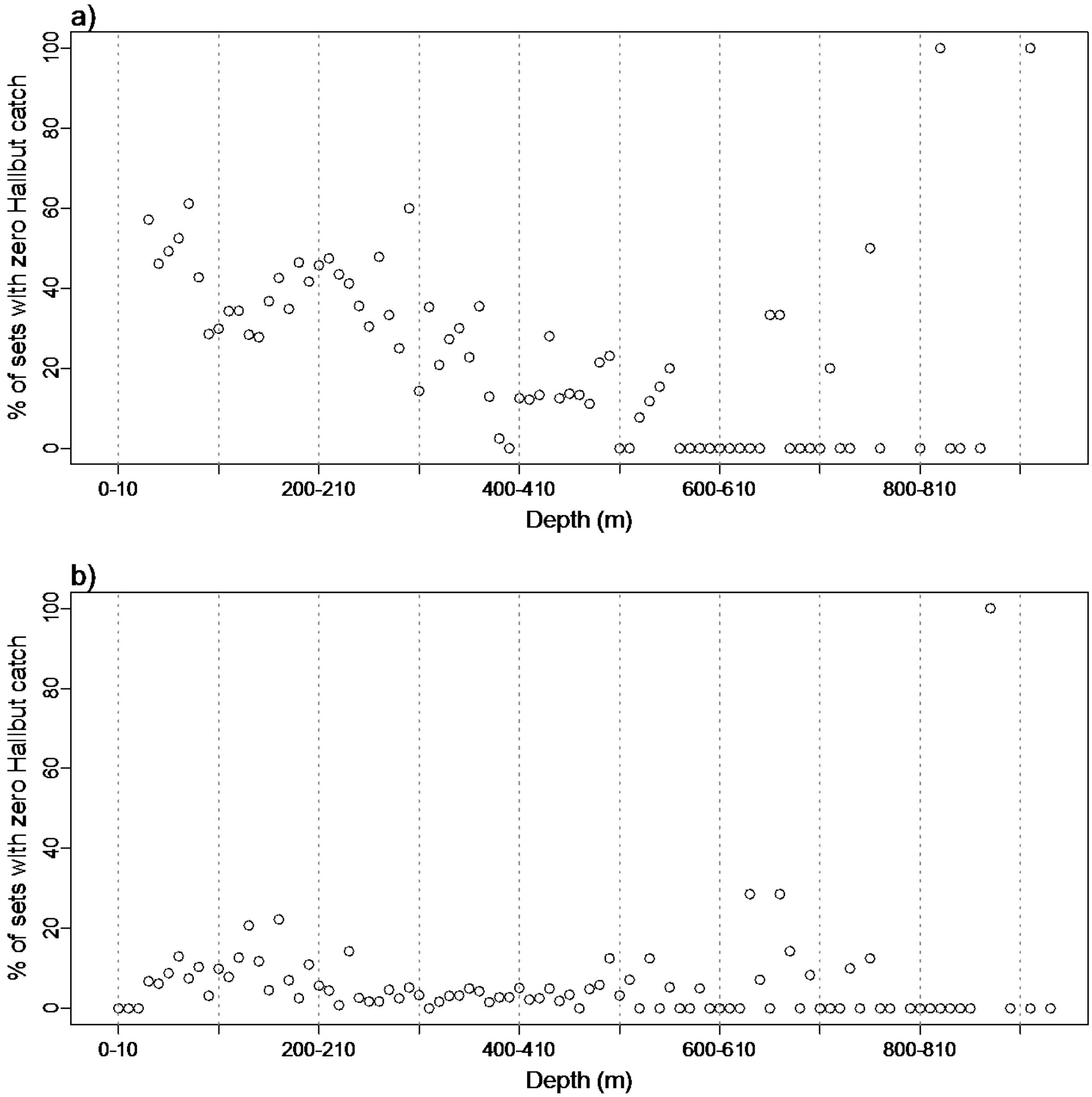

Figure 4. Percentage of sets from 1998-2015 (after data screening) with zero Atlantic Halibut catch for 10 m depth intervals for Atlantic Halibut survey fixed-stations (n=3 698) (top) and commercial index sets (n=5 272) (bottom).

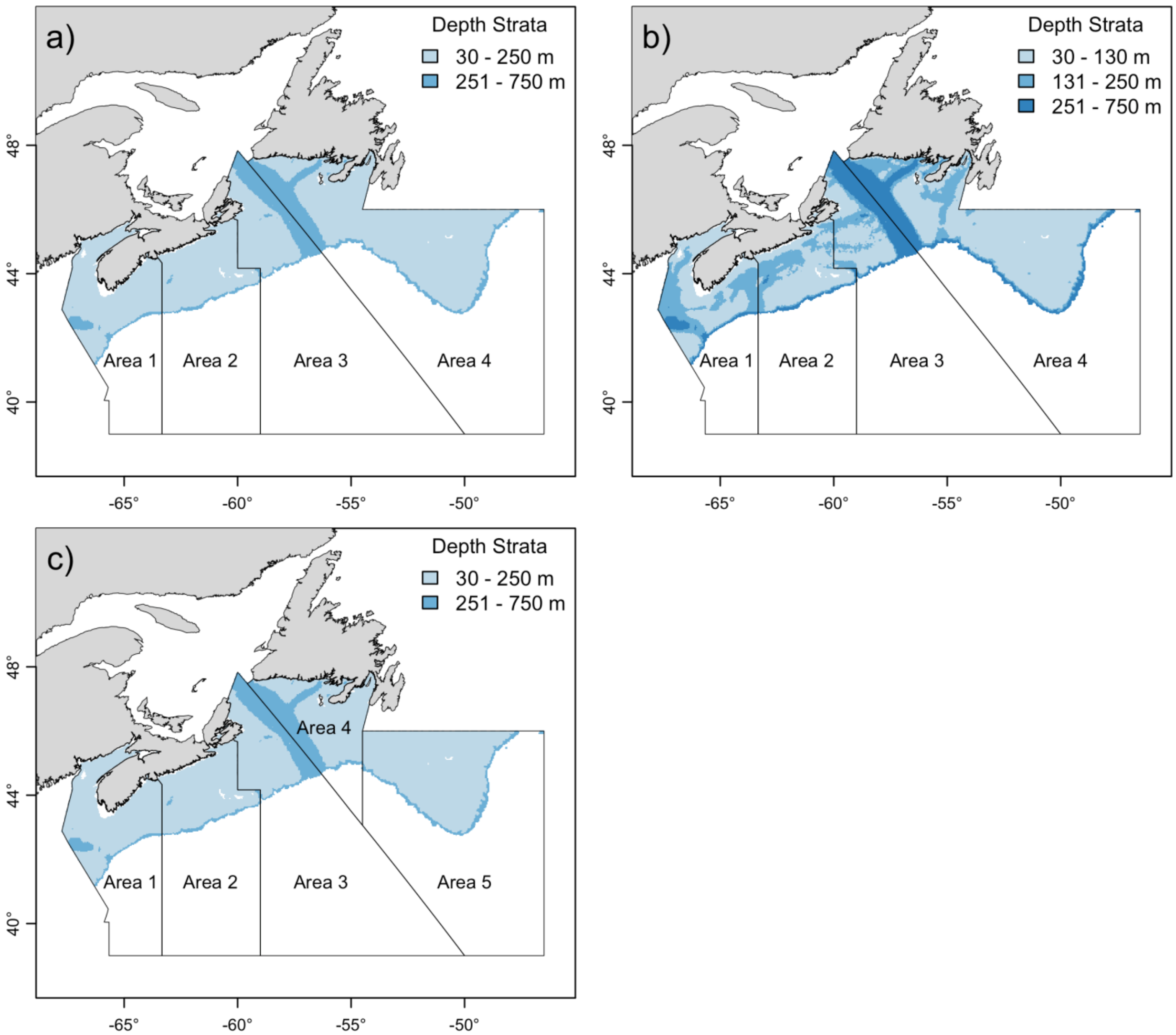

Figure 5. Area and depth strata for 3 different stratification schemes tested in bootstrap evaluations of survey designs: a) 4A-2D stratification, b) 4A-3D stratification, and c) 5A-2D stratification.

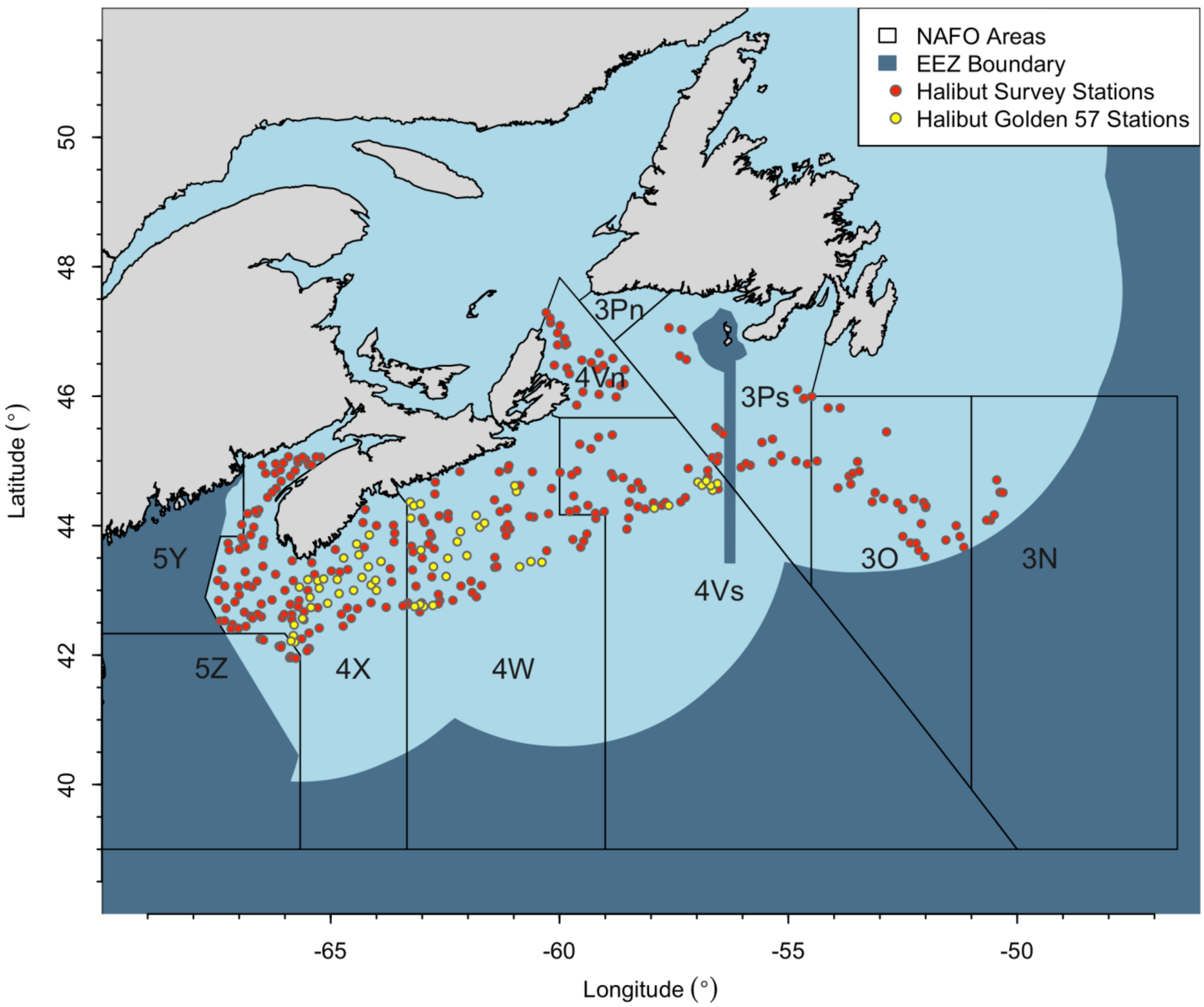

Figure 6. NAFO management areas with all Atlantic Halibut survey stations and the Golden 57 stations from 1998-2015.

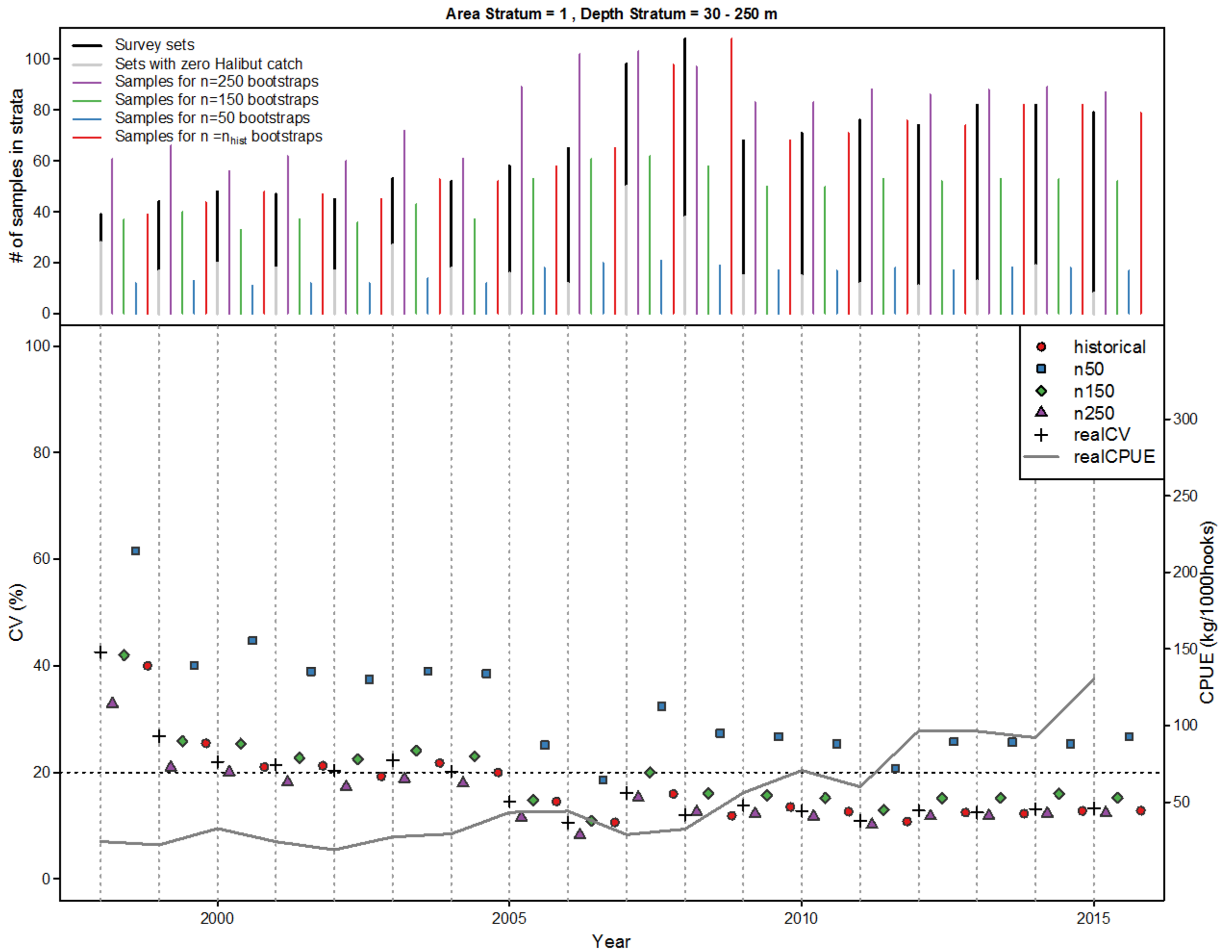

Figure 7. Annual sample sizes, mean CPUE, and coefficients of variation (%) for mean CPUE from 1998-2015 for survey stations and bootstrap sampling in area 1 and shallow depth (30-250 m) strata for 4A-2D stratification. Upper panel displays the number of survey sets and the number of bootstrap samples under different n_y sampling scenarios with samples allocated in the same proportions to the historical survey set distribution. Lower panel displays standardized mean catch rates for the strata from fixed-station survey data as well as coefficients of variation (%) from bootstrap sampling with different sample sizes. This figure serves as a guide for the multi-panel plots in Figures 8 and 9.

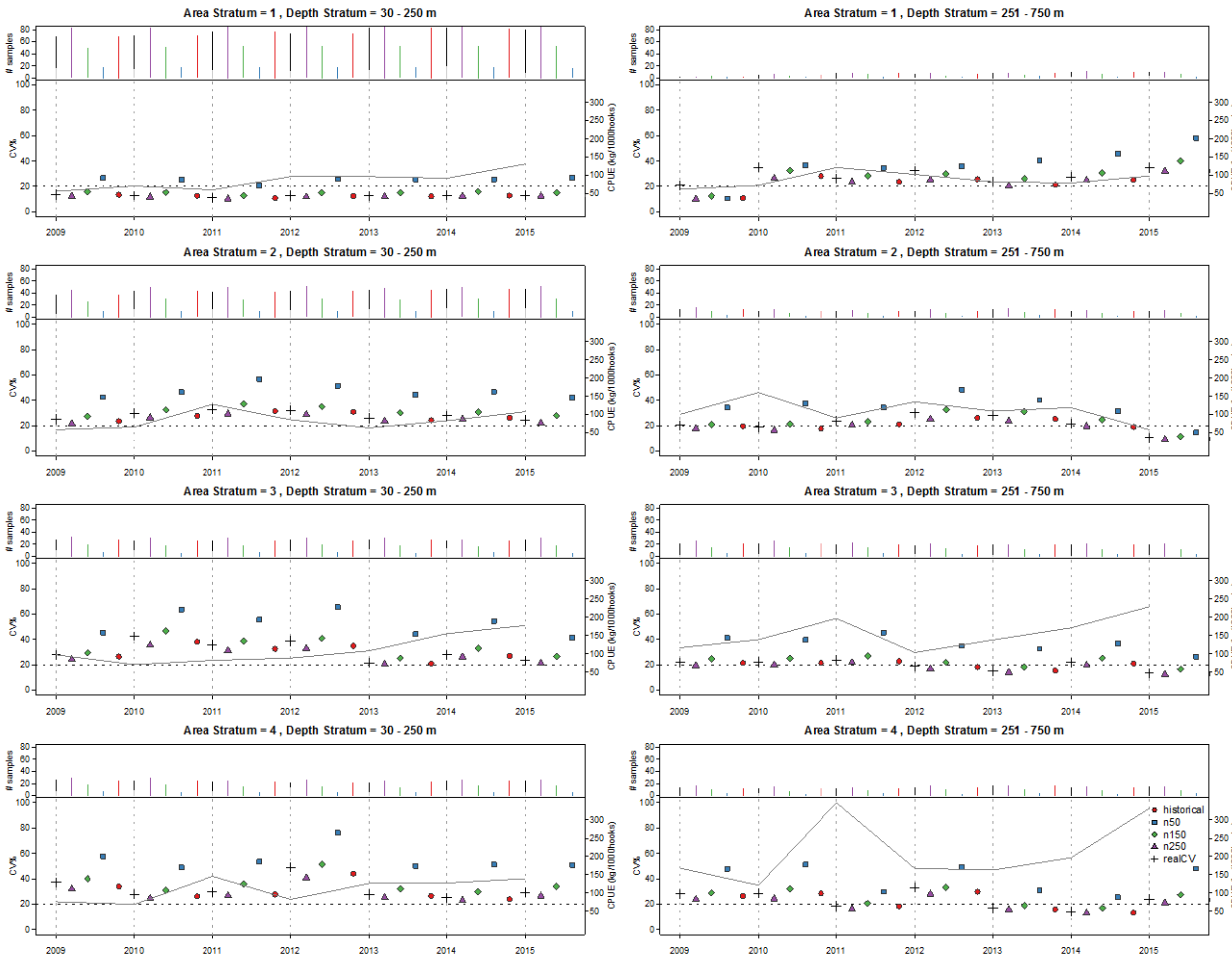

Figure 8. Sample sizes, mean catch rates, and coefficients of variation (%) for each strata in 4A-2D stratification from 2009-2015 for fixed-station data and bootstrap samples allocated in same proportions to historical annual set distribution. Black vertical bars in top panel represent annual sample sizes from fixed-station surveys and grey bars indicate sets with zero catch. Colored vertical bars indicate the number of bootstrap samples in each strata for different n_y sampling scenarios. Solid grey line in lower panel is the true mean catch rate (kg/1000 hooks) from fixed-station survey data.

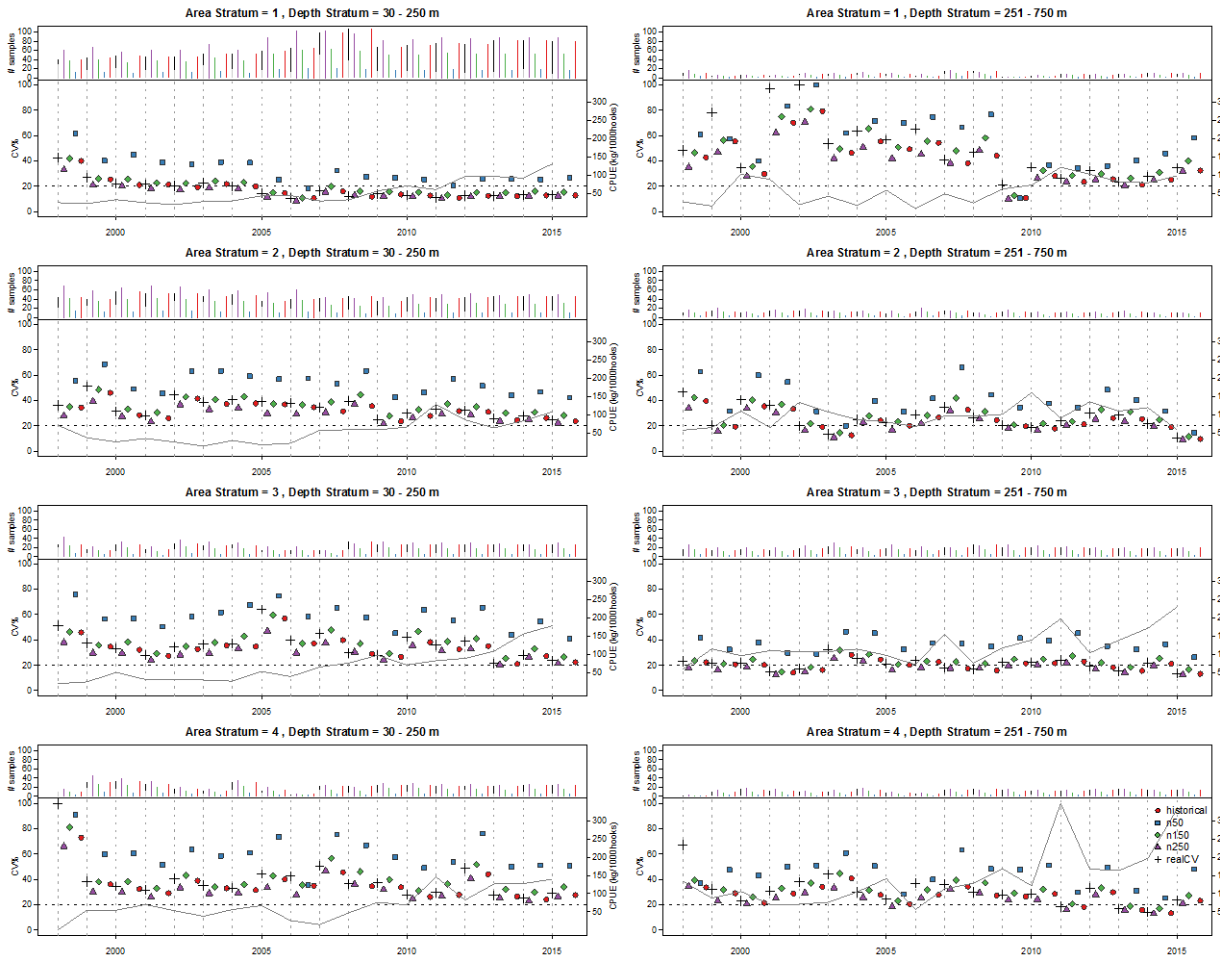

Figure 9. Sample sizes, mean catch rates and coefficients of variation (%) for each strata in 4A-2D stratification from 1998-2015 for fixed-station data and bootstrap samples allocated in same proportions to historical annual set distribution. Black vertical bars in top panel represent annual sample sizes from fixed-station surveys and grey bars indicate sets with zero catch. Colored vertical bars indicate the number of bootstrap samples in each strata for different n_y sampling scenarios. Solid grey line in lower panel is the true mean catch rate (kg/1000 hooks) from fixed-station survey data.

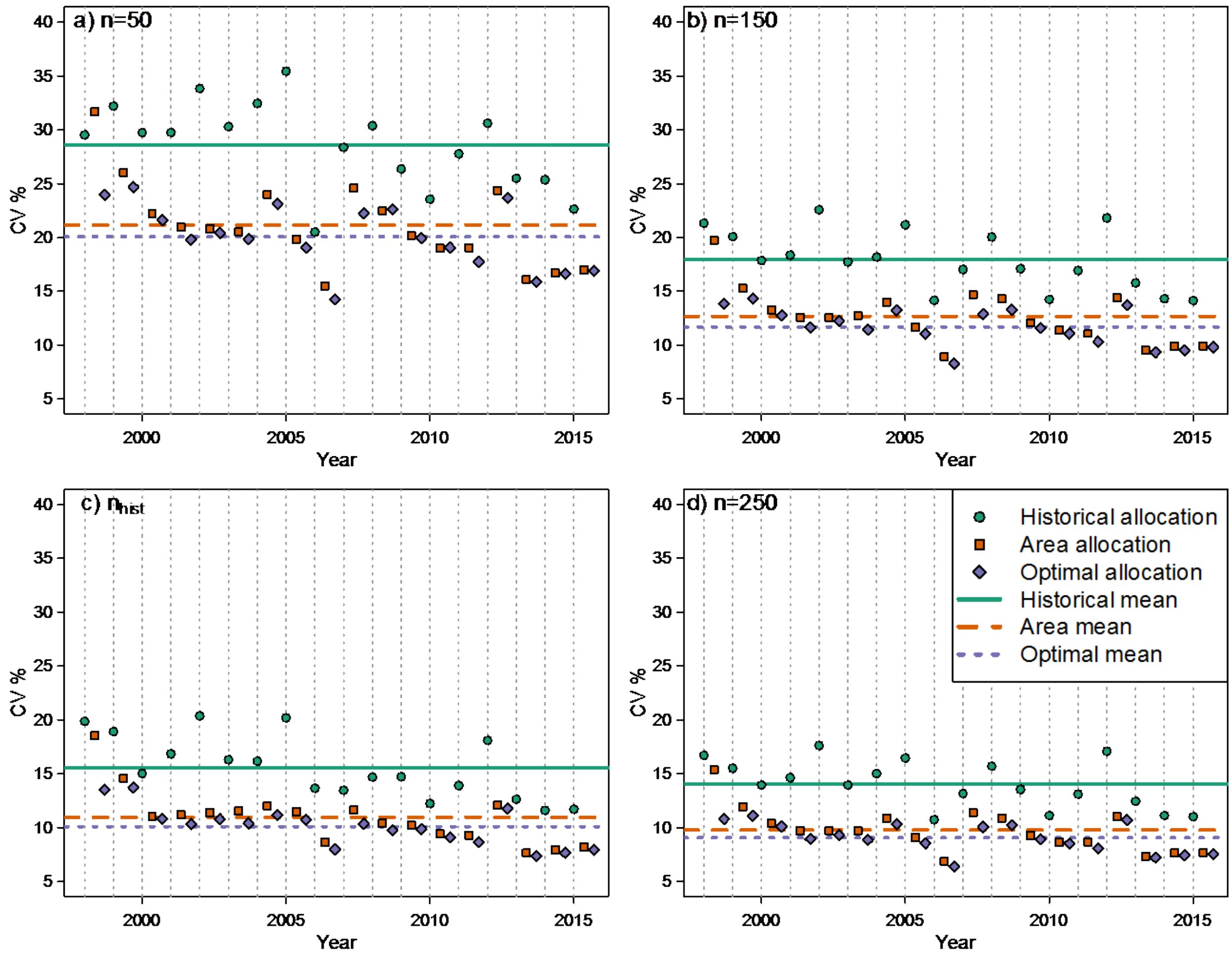

Figure 10. Mean annual coefficients of variation (%) and means across all years (1998-2015) for stratified mean catch rates from bootstrap analyses using 3 different allocation options and 4 different n_y sampling scenarios: a) n=50; b) n=150; c) n_{hist}, where annual sets are approximately equal to the historical number of annual sets in the fixed station survey; and d) n=250 samples per year.

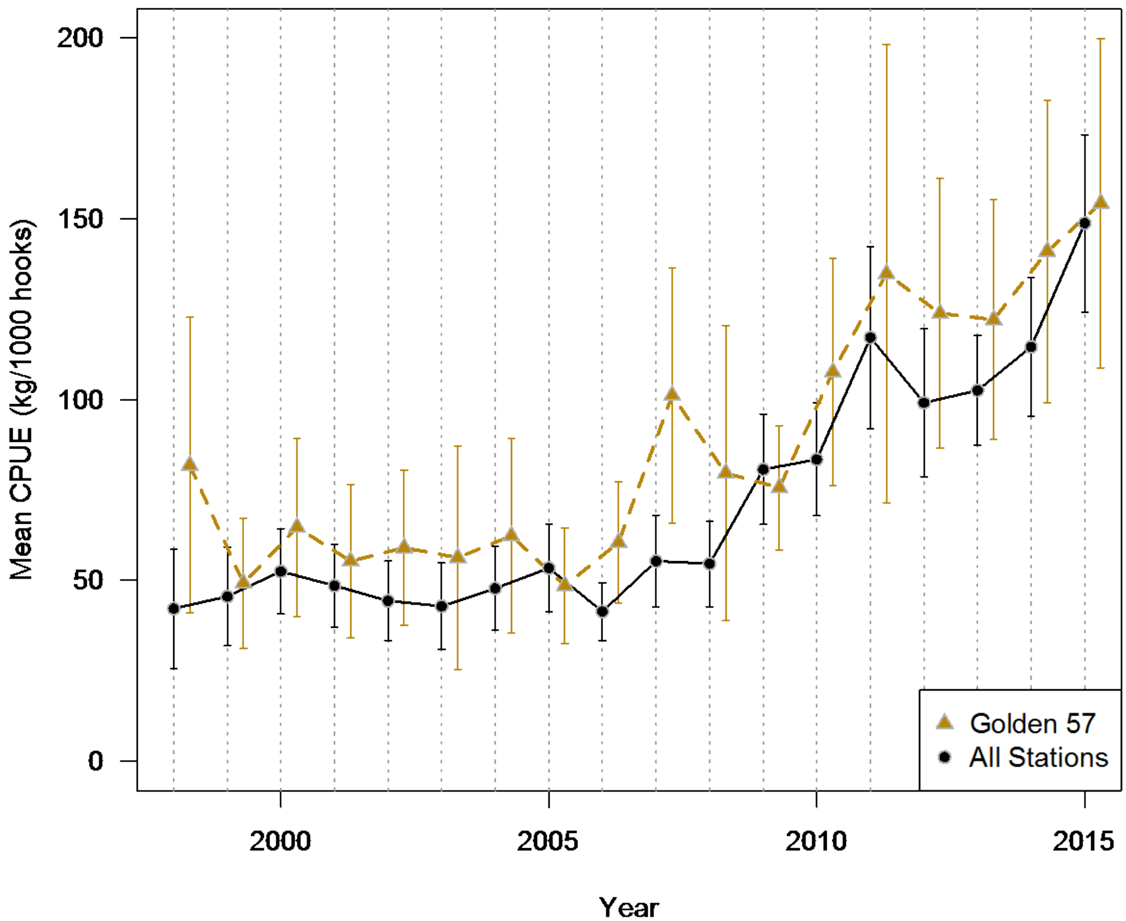

Figure 11. Annual mean standardized catch rates (+/- 2SE) calculated using all Atlantic Halibut survey fixed stations and using only Golden 57 stations from 1998-2015.

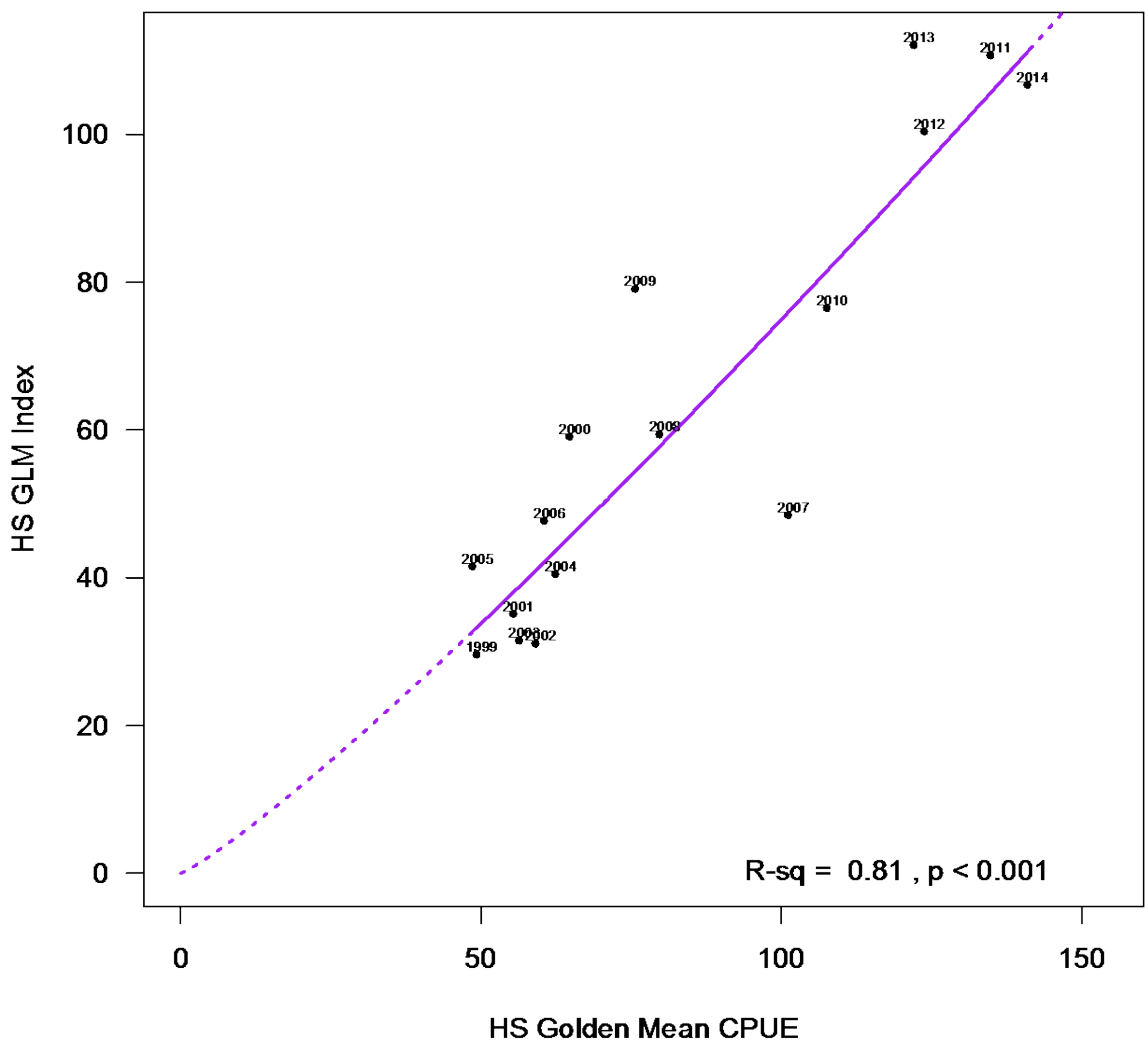

Figure 12. Back-transformed relationship between Atlantic Halibut survey GLM index (HS) and Golden 57 station CPUE index (G), where $S = \beta_0 G^{\beta_1} e^{v}$. The parameters were estimated as $log(\beta_o) = -0.97$ and $\beta_1 = 1.15$ using a linear regression model fit on the log-log scale with log-transformed Golden 57 CPUE index (G) as predictor variable and log-transformed Atlantic Halibut survey GLM predicted catch rates (HS) as response variable using 1999-2014 data, where $log(HS) = log(\beta_0) + \beta_1 \, x \, log(G) + v$.

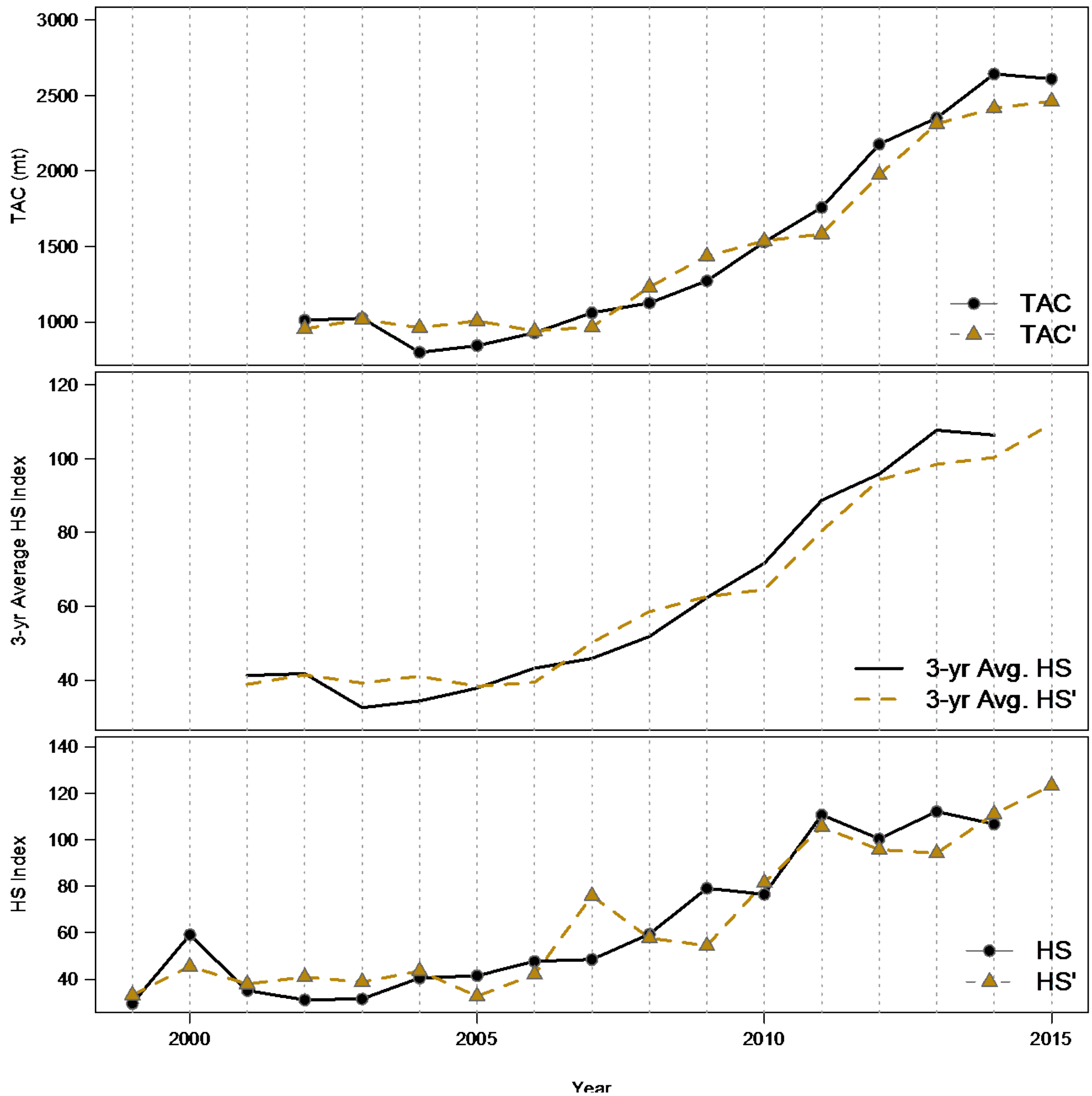

Figure 13. Time series of total allowable catch (TAC) using F=0.125, calculated using Atlantic Halibut survey GLM predicted catch rates (HS) and interim total allowable catch (TAC') from index generated using Golden 57 stations (HS'). TAC is calculated from 2002-2015 using Atlantic Halibut Survey GLM data from 1999-2014 and TAC' is calculated from 2002-2016 using Golden 57 station CPUE from 1999-2015. Note TAC calculations do not apply +/-15% annual change limit for TAC (DFO 2015).

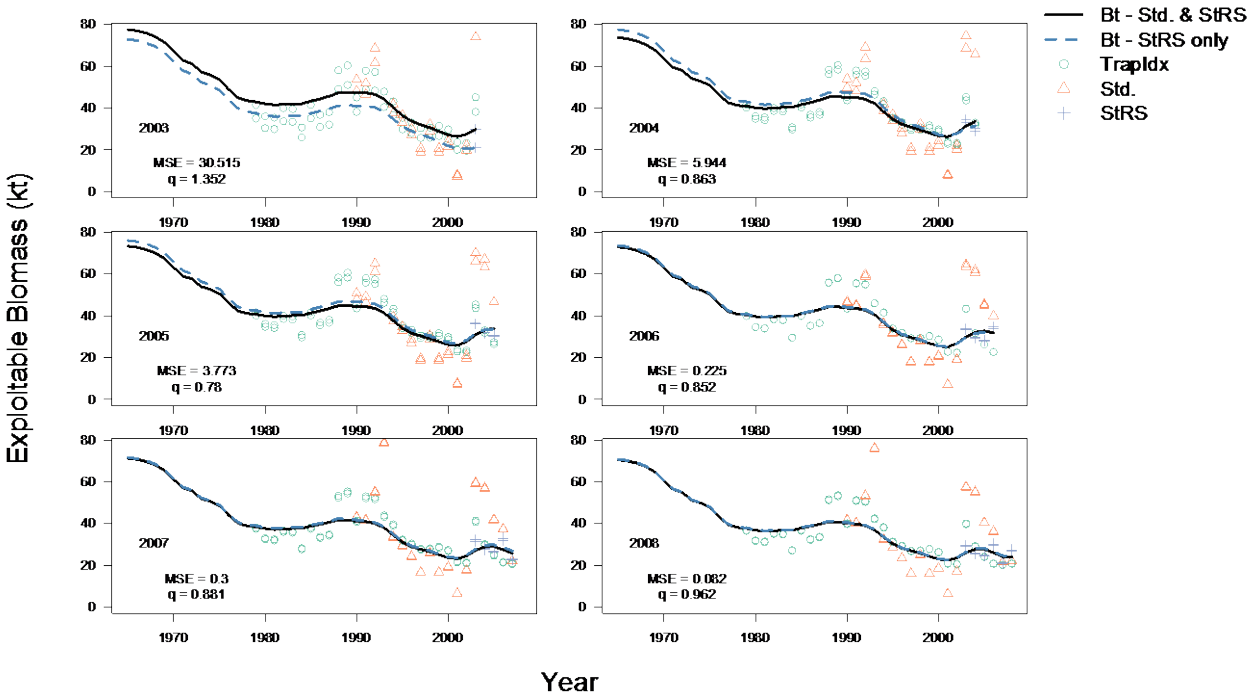

Figure 14. Evolution of biomass and catchability estimates for BC Sablefish over the 6-year transition period from the Std survey to a new StRS. The assessment model also uses a fishery CPUE dataset (TrapIdx) that spans all years. Mean square error statistics (between the two estimated biomass time-series) and catchability estimates are provided within each plot.

APPENDICES

APPENDIX A. SUPPLEMENTARY TABLES AND FIGURES

This appendix contains supplementary tables and figures from bootstraps evaluating survey performance for different stratification options, sample sizes and sampling allocations. It includes annual bootstrap sample sizes for each 4A-2D strata under different allocation options (Table A-1), the 2009-2015 time series of bootstrapped CVs by strata for different stratifications (Figures A-1, A-2 and A-3), and the results of the sensitivity analyses comparing annual CVs for the 4A-2D, 4A-3D and 5A-2D stratifications for each year (Figures A-4, A-5, A-6 and A-7).

This appendix also includes maps with example sample locations for an area-based allocation of n=150 and n=250 annual samples for 4A-2D, 4A-3D and 5A-2D stratifications (Figures A-8, A-9 and A-10). The distances between nearest sample sites for different sample sizes and stratifications are shown in Table A-2 and Figure A-11.

Table A-1. Bootstrap allocations by strata for $n_{hist,y}$ scenarios using the 4 allocation options for the 4A-2D stratification.

		Area 1		Area2		Area 3		Area 4		
Year	**Allocation Option**	**Shallow**	**Deep**	**Shallow**	**Deep**	**Shallow**	**Deep**	**Shallow**	**Deep**	**Total**
1998	Historical	39	10	44	11	27	17	10	2	160
	Area	29	2	24	2	18	8	66	12	161
	SD	17	11	45	23	13	15	2	34	160
	SD x Area	33	2	69	2	15	8	5	27	161
1999	Historical	44	3	39	13	15	13	30	9	166
	Area	30	2	25	2	18	9	68	13	167
	SD	12	6	35	15	11	27	35	26	167
	SD x Area	14	2	33	2	7	9	90	12	169
2000	Historical	48	6	56	11	28	17	34	15	215
	Area	39	3	32	2	24	11	88	16	215
	SD	15	26	18	44	26	25	33	28	215
	SD x Area	23	3	22	3	24	11	112	18	216
2001	Historical	47	5	53	14	17	15	26	13	190
	Area	35	3	28	2	21	10	78	14	191
	SD	10	54	20	25	10	18	32	22	191
	SD x Area	16	6	25	2	9	8	110	14	190
2002	Historical	45	8	51	14	28	19	15	9	189
	Area	34	3	28	2	21	10	78	14	190
	SD	9	18	27	34	18	27	29	28	190
	SD x Area	13	2	32	2	16	11	95	17	188
2003	Historical	53	7	45	11	24	23	12	10	185
	Area	34	3	27	2	20	10	76	14	186
	SD	15	20	12	16	17	55	15	35	185
	SD x Area	27	3	18	2	19	29	62	27	187
2004	Historical	52	10	49	13	26	17	31	15	213

		Area 1		Area2		Area 3		Area 4		
Year	**Allocation Option**	**Shallow**	**Deep**	**Shallow**	**Deep**	**Shallow**	**Deep**	**Shallow**	**Deep**	**Total**
	Area	39	3	31	2	23	11	87	16	212
	SD	14	12	28	26	16	40	35	41	212
	SD x Area	20	2	31	2	14	15	108	23	215
2005	Historical	58	8	35	9	15	18	13	7	163
	Area	30	2	24	2	18	8	67	12	163
	SD	12	24	10	14	33	22	27	23	165
	SD x Area	17	2	11	2	27	8	83	13	163
2006	Historical	65	5	39	13	14	15	4	5	160
	Area	29	2	24	2	18	8	66	12	161
	SD	17	5	23	31	25	29	10	21	161
	SD x Area	29	2	32	2	27	14	39	15	160
2007	Historical	98	15	41	14	13	20	22	14	237
	Area	43	3	35	2	26	12	97	18	236
	SD	14	23	37	38	31	37	11	46	237
	SD x Area	27	3	60	3	37	21	47	38	236
2008	Historical	108	15	46	11	34	27	23	15	279
	Area	51	4	41	2	31	14	115	21	279
	SD	15	16	58	31	48	24	31	55	278
	SD x Area	22	2	68	2	42	10	100	33	279
2009	Historical	68	2	36	13	27	21	25	13	205
	Area	37	3	30	2	23	11	84	16	206
	SD	16	5	22	19	35	30	36	43	206
	SD x Area	20	2	22	2	27	11	101	22	207
2010	Historical	71	5	43	10	26	21	25	12	213
	Area	39	3	31	2	23	11	87	16	212
	SD	19	14	32	24	37	35	24	29	214
	SD x Area	28	2	38	2	33	15	78	18	214
2011	Historical	76	8	42	10	26	20	22	12	216
	Area	39	3	32	2	24	11	89	16	216
	SD	10	15	46	12	25	36	34	38	216
	SD x Area	13	2	48	2	20	13	100	20	218
2012	Historical	74	6	44	10	27	18	22	14	215
	Area	39	3	32	2	24	11	88	16	215
	SD	20	15	34	24	33	15	35	39	215
	SD x Area	25	2	35	2	25	6	101	20	216
2013	Historical	82	8	45	13	28	19	22	16	233
	Area	42	3	34	2	26	12	96	18	233
	SD	29	15	29	30	33	25	44	29	234
	SD x Area	35	2	29	2	24	9	119	15	235

		Area 1		Area2		Area 3		Area 4		
Year	**Allocation Option**	**Shallow**	**Deep**	**Shallow**	**Deep**	**Shallow**	**Deep**	**Shallow**	**Deep**	**Total**
2014	Historical	82	10	46	10	26	19	24	14	231
	Area	42	3	34	2	25	12	95	18	231
	SD	24	15	34	18	48	35	34	23	231
	SD x Area	31	2	36	2	38	13	99	12	233
2015	Historical	79	9	46	10	27	19	24	14	228
	Area	41	3	34	2	25	12	94	17	228
	SD	27	18	31	3	38	24	35	52	228
	SD x Area	33	2	31	2	29	8	98	27	230

Table A-2. Summary statistics for nearest distances between sampling locations for 100 different sets of randomly generated sample locations using area-based proportional allocation for different stratifications and sample sizes.

Samples	Stratification	Mean	Median	SD	Max.	Min.
150	4A-2D	29	26	16	98	4
	4A-3D	29	27	17	99	4
	5A-2D	29	27	16	97	5
250	4A-2D	22	20	12	81	4
	4A-3D	22	20	12	82	4
	5A-2D	22	20	12	83	4

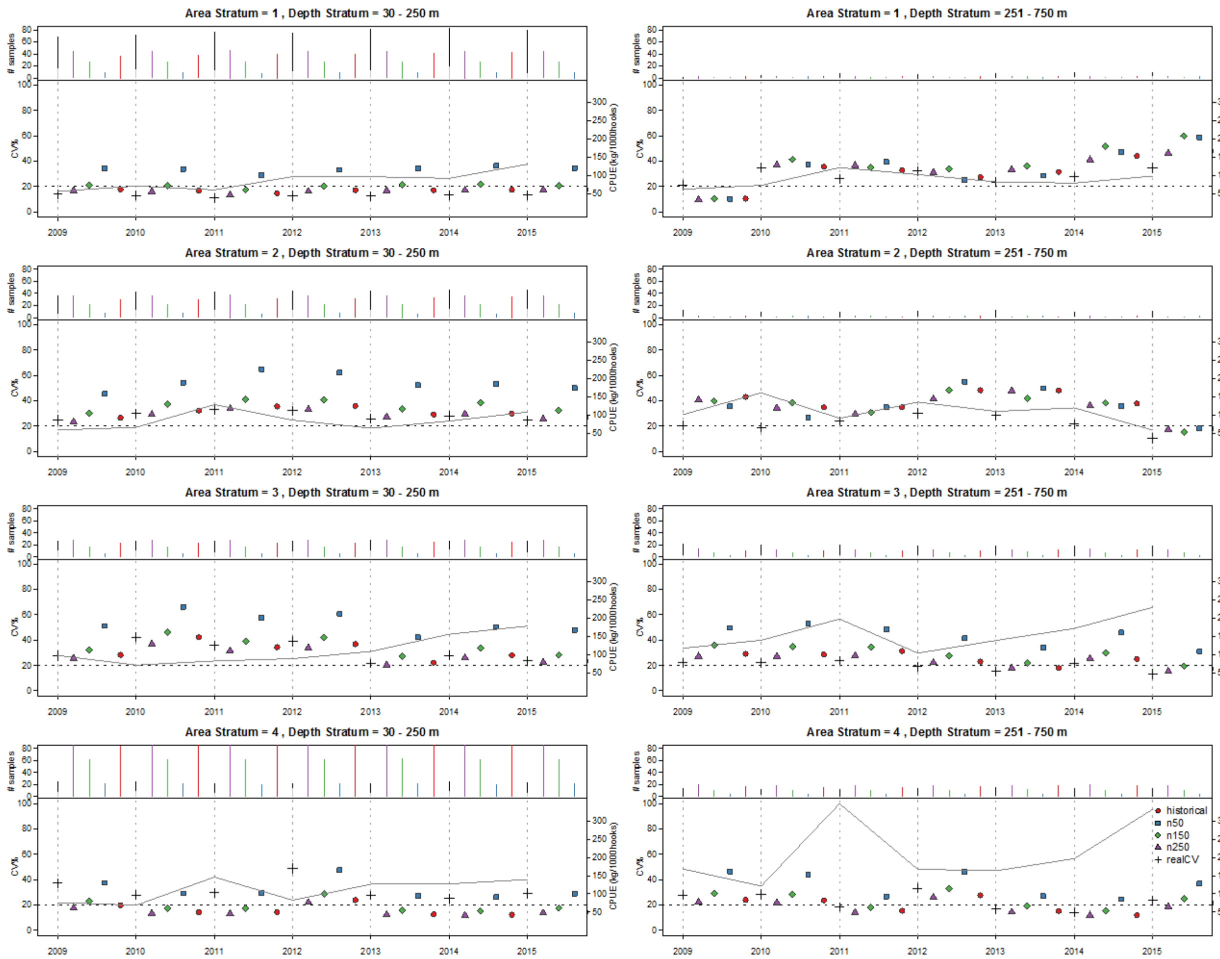

Figure A-1. Standardized mean catch rates and coefficients of variation (%) for 8 strata for baseline 4A-2D stratification from 2009-2015 for fixed-station data and bootstrap samples under area-based allocation. Black vertical bars in top panel represent annual sample sizes from fixed-station surveys and grey bars indicate sets with zero catch. Colored vertical bars indicate the number of bootstrap samples in each strata for different n_y scenarios.

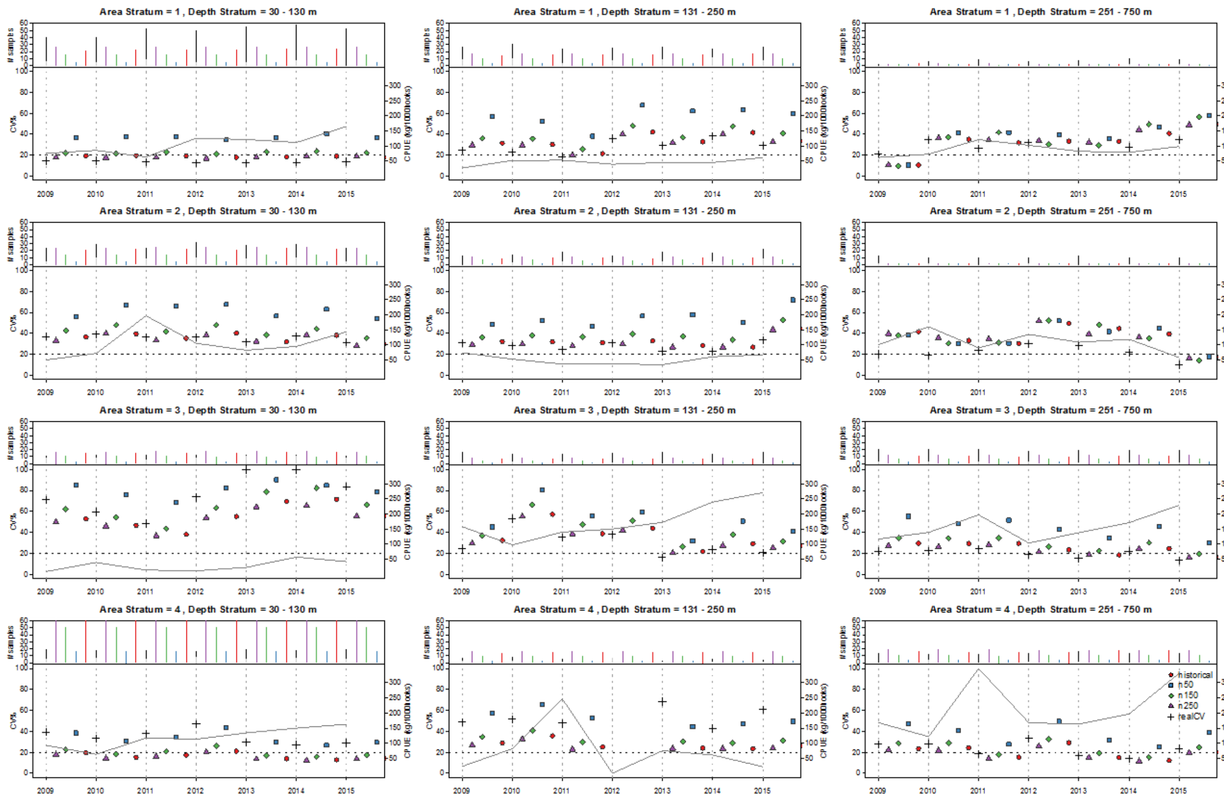

Figure A-2. Standardized mean catch rates and coefficients of variation (%) for 12 strata for 4A-3D stratification from 2009-2015 for fixed-station data and bootstrap samples under area-based allocation. Black vertical bars in top panel represent annual sample sizes from fixed-station surveys and grey bars indicate sets with zero catch. Colored vertical bars indicate the number of bootstrap samples in each strata for different n_y scenarios.

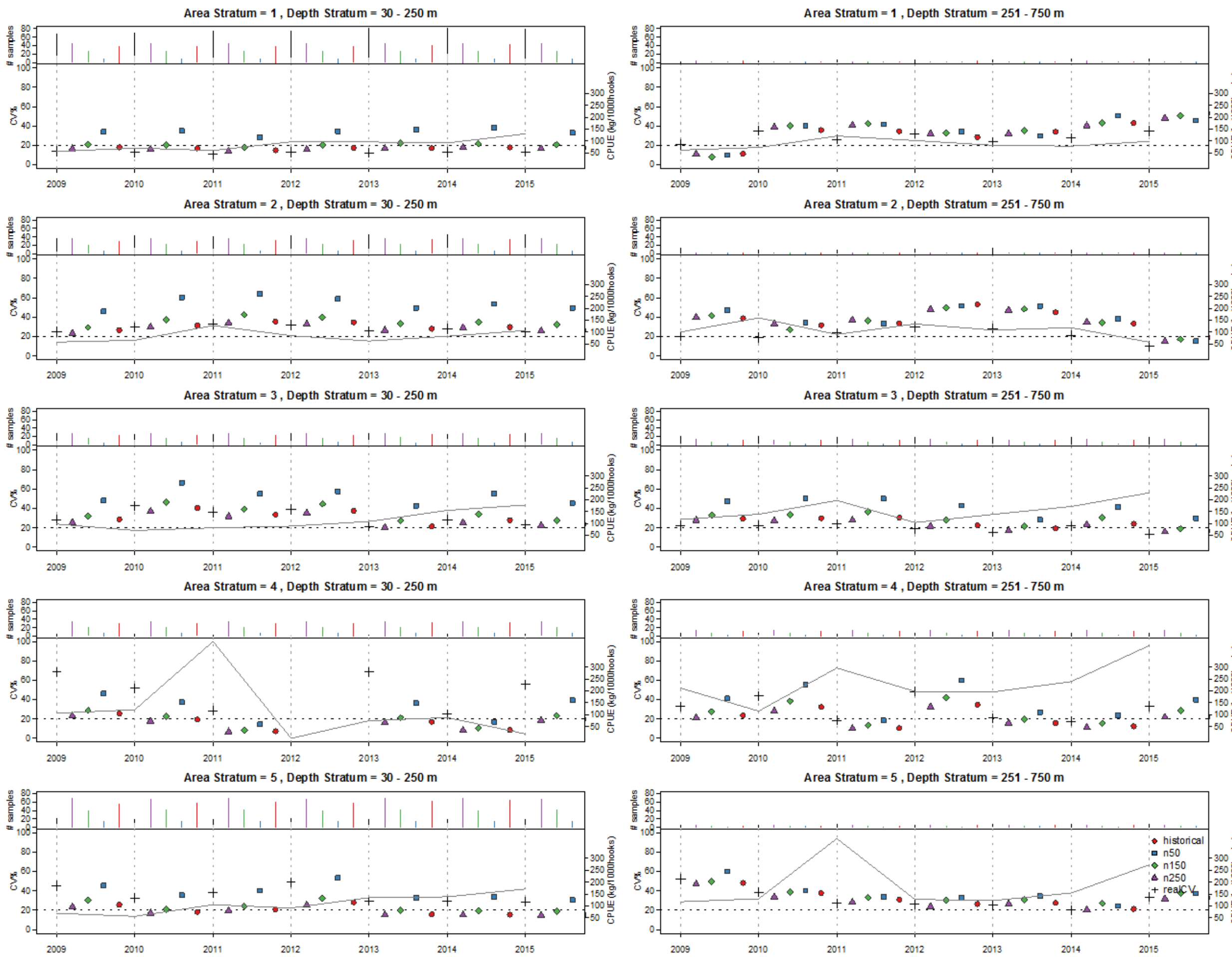

Figure A-3. Standardized mean catch rates and coefficients of variation (%) for 10 strata for 5A-2D stratification from 2009-2015 for fixed-station data and bootstrap samples under area-based allocation. Black vertical bars in top panel represent annual sample sizes from fixed-station surveys and grey bars indicate sets with zero catch. Colored vertical bars indicate the number of bootstrap samples in each strata for different n_y scenarios.

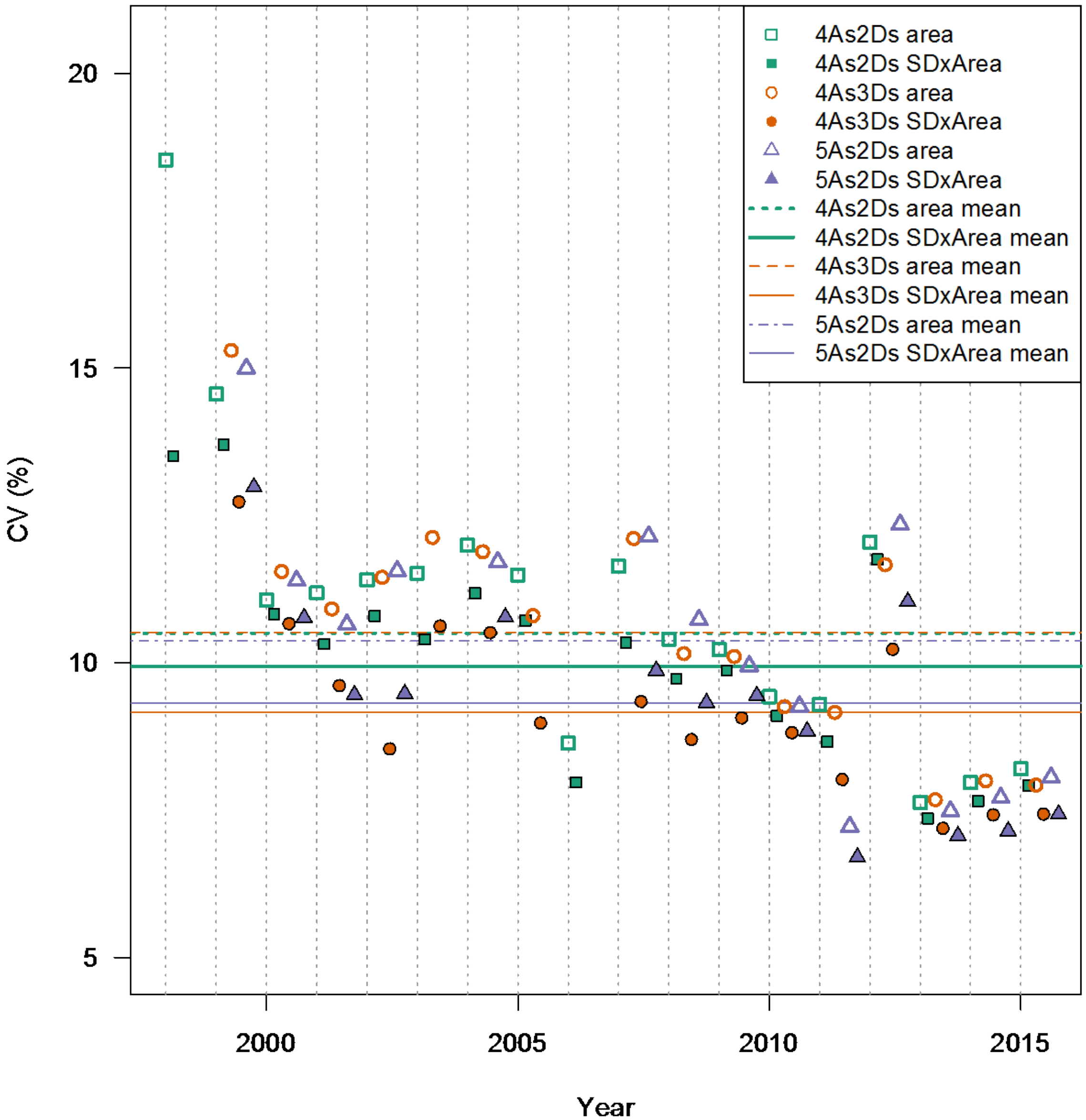

Figure A-4. Mean annual coefficients of variation (%) and means across comparable years (e.g. excluding 1998, 2003, 2005, 2006) for estimated stratified catch rates from bootstrap analyses for n_{hist} where annual sets are approximately equal to the historical number of sets in the fixed station survey. Analyses are compared from for 3 different stratification schemes (4A-2D, 4A-3D, 5A-2D) with area-based and optimal (SDxArea) allocation.

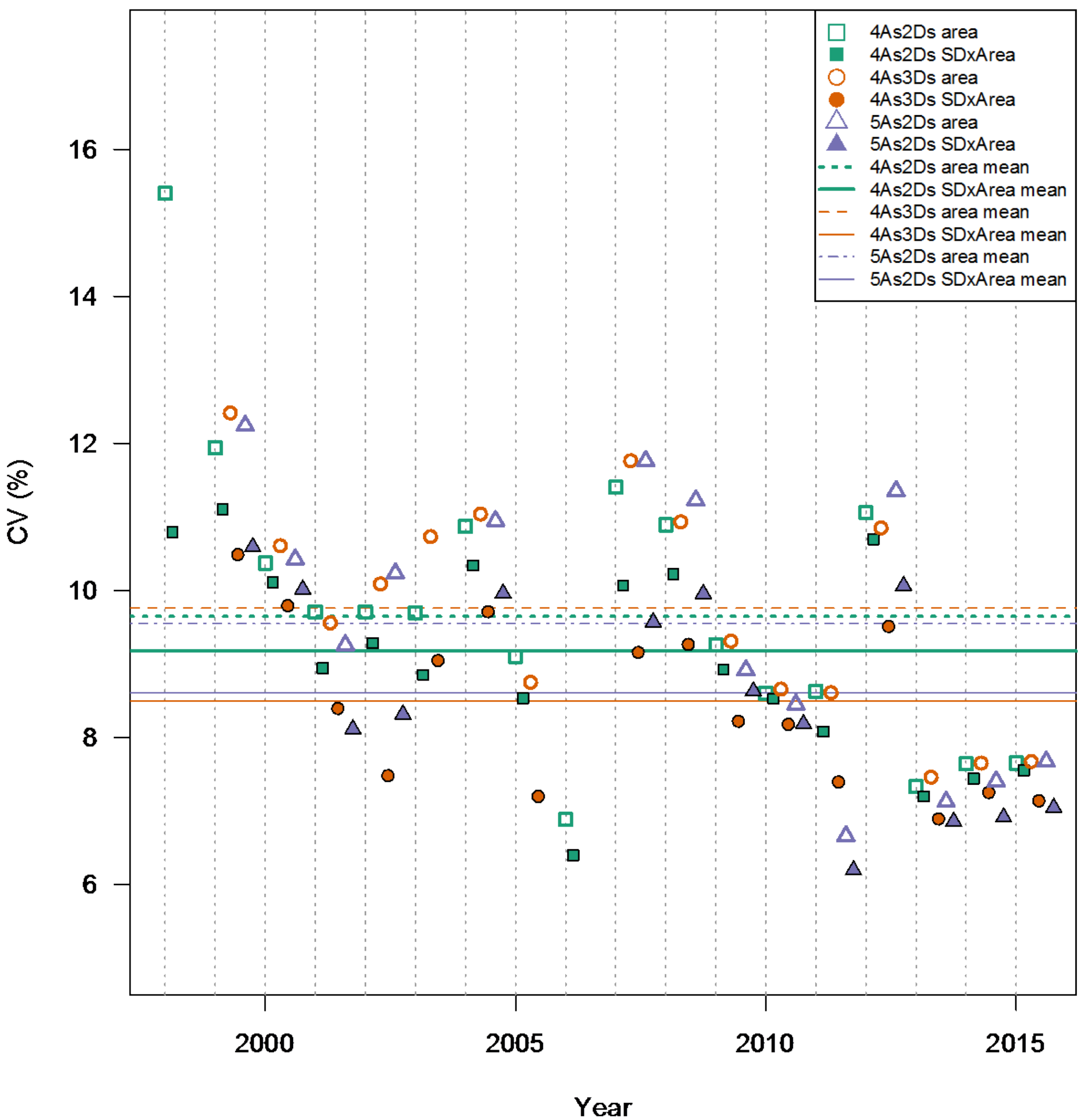

Figure A-5. Mean annual coefficients of variation (%) and means across comparable years (e.g. excluding 1998, 2003, 2005, 2006) for estimated stratifed catch rates from bootstrap analyses for n=250. Analyses are compared from for 3 different stratification schemes (4A-2D, 4A-3D, 5A-2D) with area-based and optimal (SDxArea) allocation.

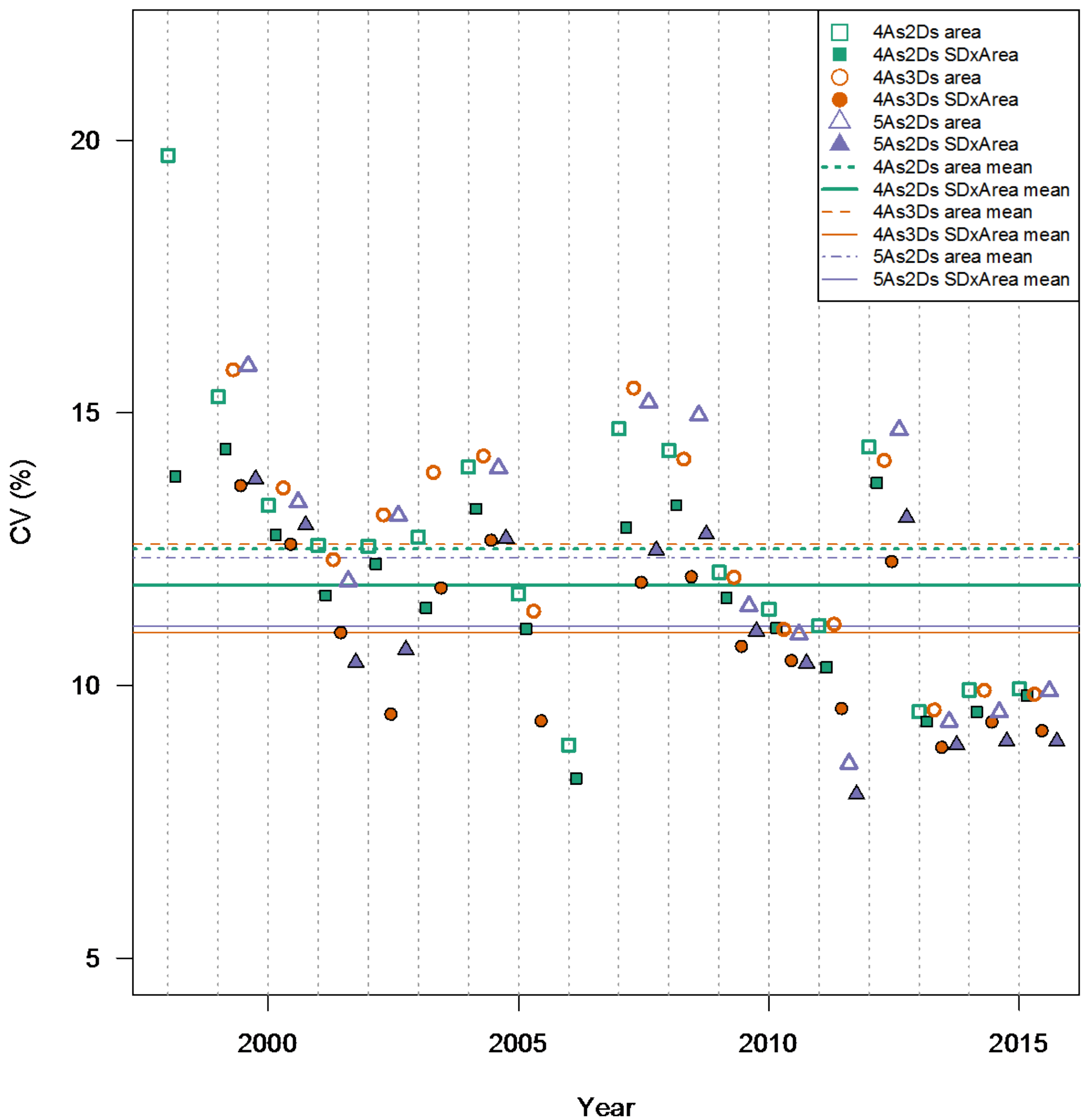

Figure A-6. Mean annual coefficients of variation (%) and means across comparable years (e.g. excluding 1998, 2003, 2005, 2006) for estimated stratifed catch rates from bootstrap analyses for n=150. Analyses are compared from for 3 different stratification schemes (4A-2D, 4A-3D, 5A-2D) with area-based and optimal (SDxArea) allocation.

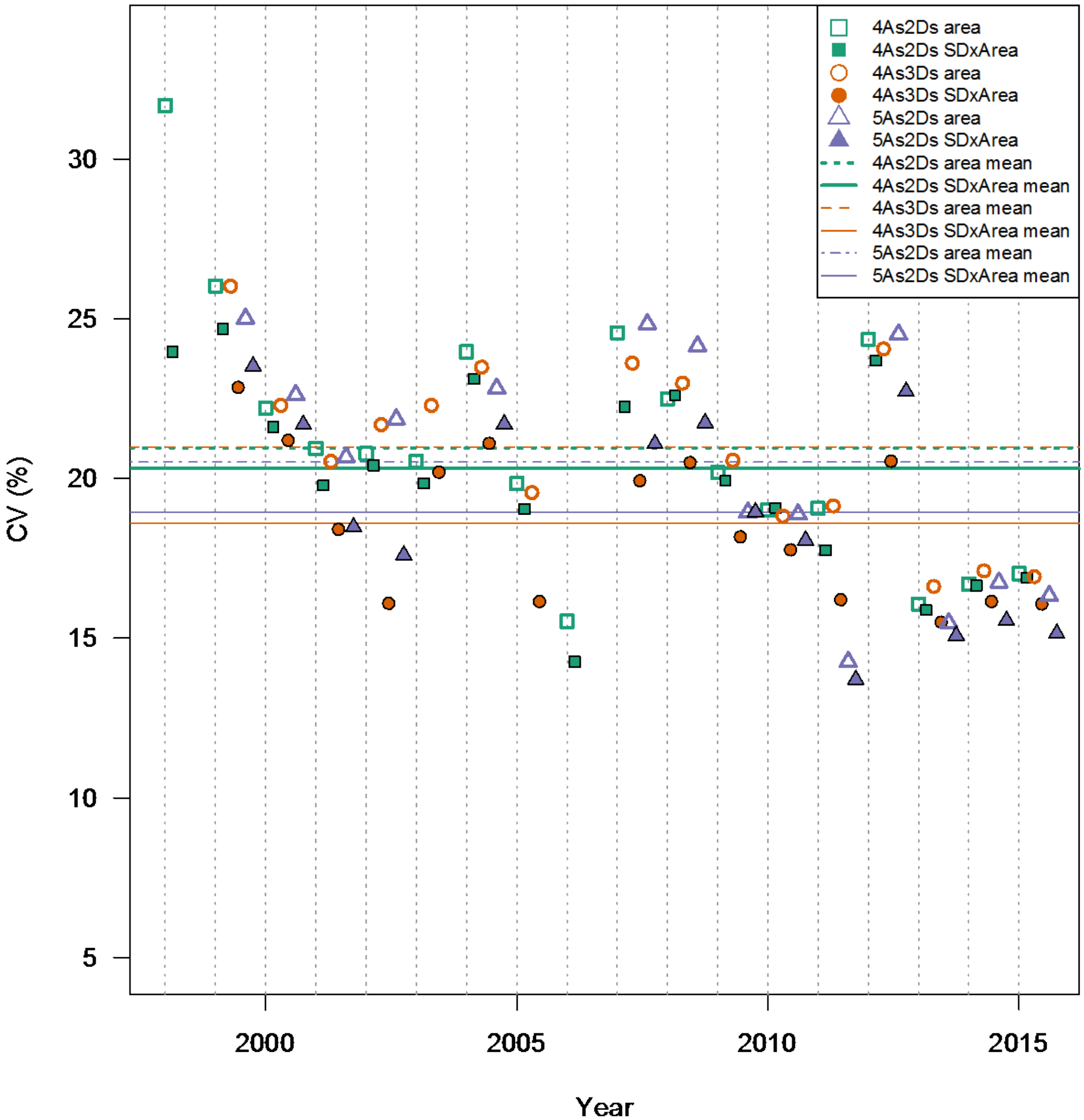

Figure A-7. Mean annual coefficients of variation (%) and means across comparable years (e.g. excluding 1998, 2003, 2005, 2006) for estimated stratifed catch rates from bootstrap analyses for n=50. Analyses are compared from for 3 different stratification schemes (4A-2D, 4A-3D, 5A-2D) with area-based and optimal (SDxArea) allocation.

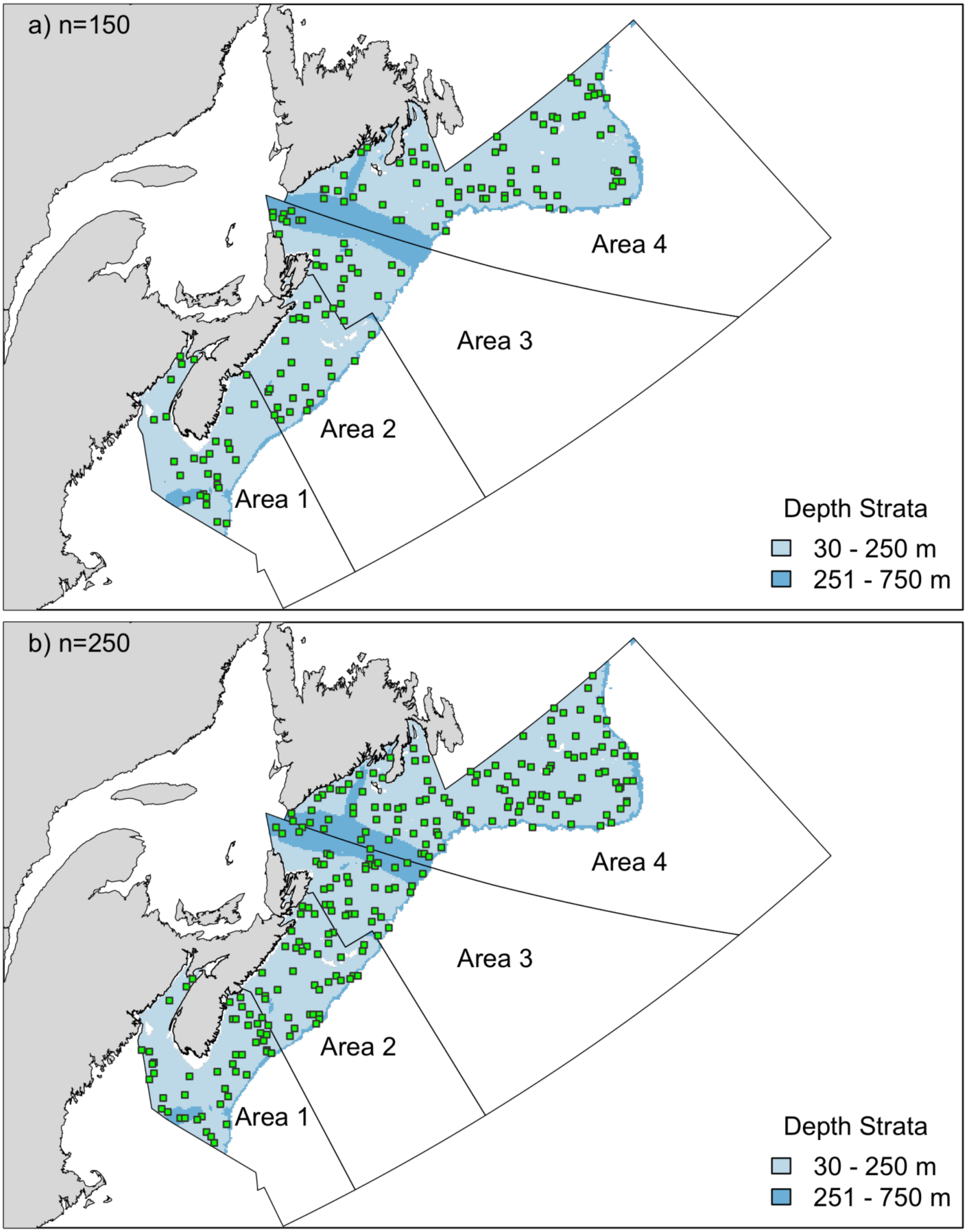

Figure A-8. Randomly generated sample locations in 4 km x 4 km blocks (green sample blocks not to scale) for 4A-2D stratification using area allocation for a) n=150 and b) n=250 samples.

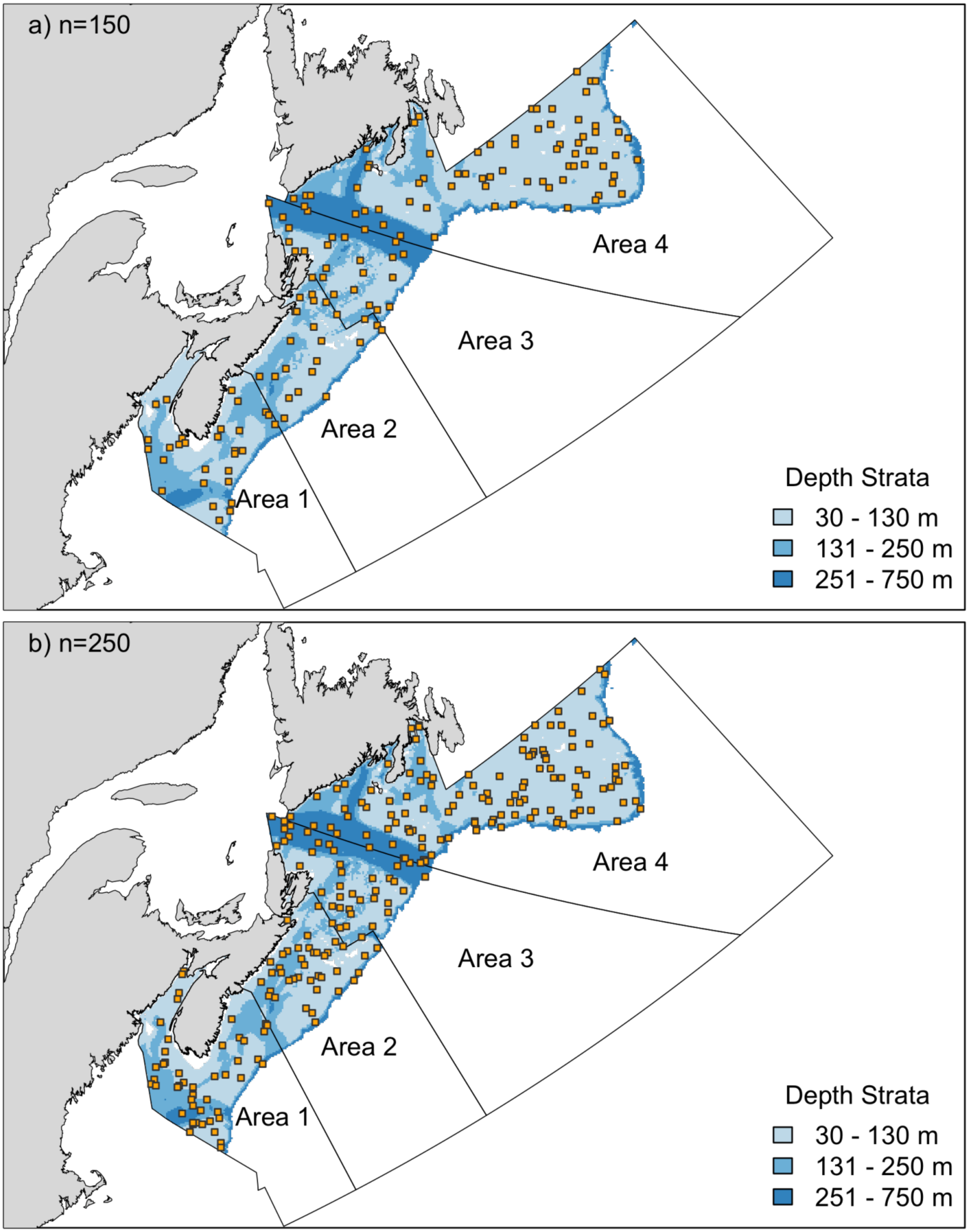

Figure A-9. Randomly generated sample locations in 4 km x 4 km blocks (orange sample blocks not too scale) for 4A-3D stratification using area allocation for a) n=150 and b) n=250 samples.

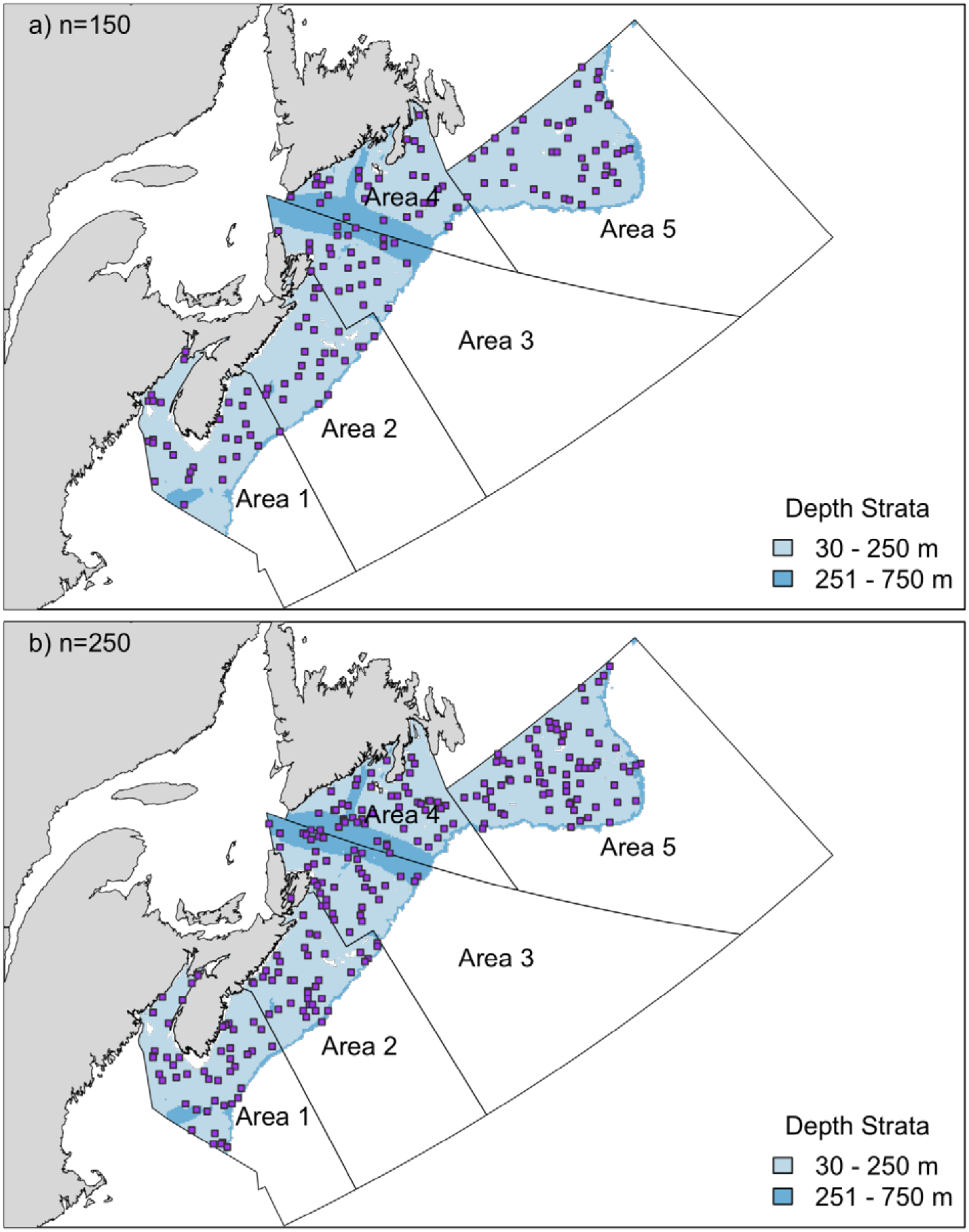

Figure A-10. Randomly generated sample locations in 4 km x 4 km blocks (purple sample blocks not too scale) for 5A-2D stratification using area allocation for a) n=150 and b) n=250 samples.

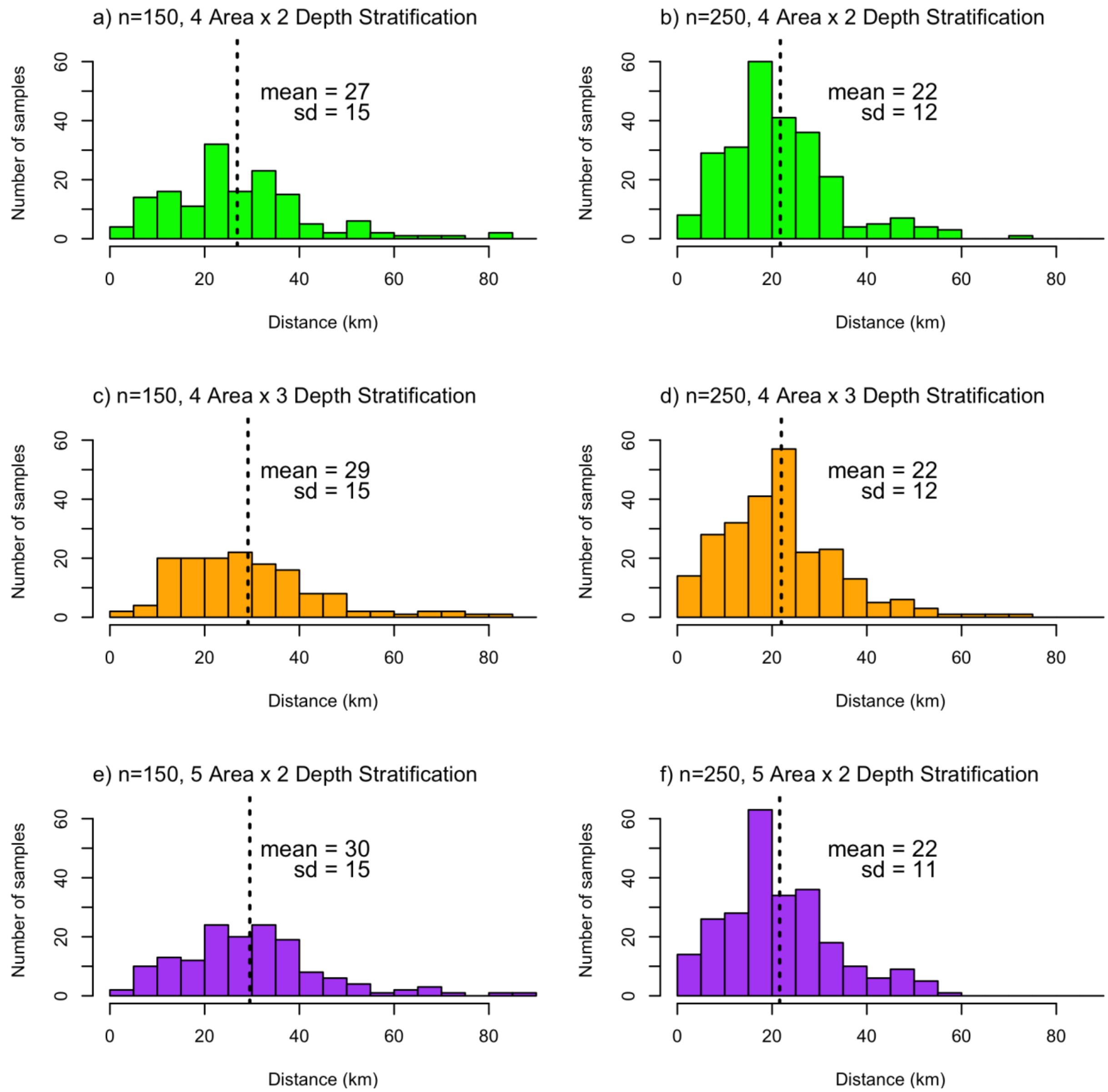

Figure A-11. Distibution of nearest distances between neighbouring sample locations for the randomly generated 4 km x 4 km sample blocks in Fig A-8, A-9, and A.10. Distance is measured as straight line between the centres of sampling blocks.

APPENDIX B. SAMPLING LOCATIONS FOR ATLANTIC HALIBUT 5A-3D STRATIFIED RANDOM SURVEY

This appendix provides the specifications for a 5A-3D StRS as discussed in post-CSAS review meetings of this paper. It is included to document the origin of the new stratified random Atlantic Halibut survey as of 2017.

The file *5A3D_5yrPlan_150sites.csv* (provided along with maps to DFO (N. den Heyer) and industry collaborators (B. Chapman, K. Vascotto) on 21 March 2017 via email) provides the coordinates and relevant details (Table B-1) for sampling locations in the newly designed Atlantic Halibut StRS for a 5-year period from 2017-2021. There are n=150 sampling blocks selected for each year with the number of samples allocated in proportion to the total area in each strata for a 5 area and 3 depth (5A-3D) stratification design (Table B-2). Sampling blocks within each stratum are randomly selected without replacement in each year.

There are three options (A, B, C) provided for each sample site in case a location cannot be fished. If option A is unfishable, then option B should be attempted and then C. Only one option per site number should be fished each year (e.g. only one of site numbers 1A, 1B or 1C). The same letter option does not have to be fished at each site.

Table B-1. Description of column names in 5A3D_5yrPlan_150sites.csv

Column Name	Description
year	Survey year
siteNum	Unique identifier for StRS sample site in given year
option	Options A, B, and C for each site number
as	area strata code: 1 = area 1, NAFO regions 4X5YZ 2 = area 2, NAFO regions 4W 3 = area 3, NAFO regions 4VnVs 4 = area 4, NAFO regions 3PnPs 5 = area 5, NAFO regions 3NO
ds	depth strata code: 1 = 30 - 130m 2 = 131 - 250 m 3 = 251 - 750 m
s.id	Unique strata ID where the first number is the area strata code and the number after the decimal is the depth strata code
gridNum	Unique grid cell number for raster cells in 5A-3D stratification raster (Raster filename: *depthStrata_5As3Ds.grd*)
xAEAm	x coordinates (m) using Canada Albers Equal Area Conic Projection (ESRI 102001, resources.arcgis.com).

Column Name	Description
yAEAm	y coordinates (m) using Canada Albers Equal Area Conic Projection (ESRI 102001, resources.arcgis.com).
lon.DecDeg	Longitude in Decimal Degrees
lat.DecDeg	Latitude in Decimal Degrees
lon.Deg	Longitude Degrees
lon.Min	Longitude Minutes
lon.Sec	Longitude Seconds
lat.Deg	Latitude Degrees
lat.Min	Latitude Minutes
lat.Sec	Latitude Seconds
blockMidDepth_m	Estimated depth (m) for the centre of 4 km x 4 km raster cells. Raw GEBCO bathymetry data for 30 arc-second intervals was aggregated to 4 km^2 cells through bilinear interpolation of nearest neighbouring cells using the R raster package.
blockID	Unique ID for each of the 25,290 4 km x 4 km blocks available for sampling
nearestSiteNum	The sample site number and option letter (e.g. 2A) of the next closest StRS sampling location with the same option letter in that year (excluding alternates and Freq100 stations)
nearestBlockID	The block ID of the next closest sampling location with same option letter in that year (excluding alternates and Freq100 stations)
minDist_km	Distance to the next closest sampling location with same option letter in that year

Table B-2. Number of 4 km x 4 km blocks in each strata layer for 5A-3D stratification (including blocks in closed areas) and allocation for n=150 samples.

Strata ID	Area Strata	Depth Strata (m)	NAFO Areas	Number of Blocks	Approx. Area km^2	Proportional Allocation by Area	Allocation for n=150 Sets
1.1	1	30-130	4X5YZ	2,846	45,536	10.8%	16
1.2	1	131-250	4X5YZ	1,926	30,816	7.3%	11
1.3	1	251-750	4X5YZ	360	5,760	1.4%	2
2.1	2	30-130	4W	2,661	42,576	10.1%	15
2.2	2	131-250	4W	1,216	19,456	4.6%	7
2.3	2	251-750	4W	216	3,456	0.8%	2
3.1	3	30-130	4VnVs	1,938	31,008	7.4%	11
3.2	3	131-250	4VnVs	951	15,216	3.6%	5
3.3	3	251-750	4VnVs	1,357	21,712	5.2%	8
4.1	4	30-130	3PnPs	2,214	35,424	8.4%	13
4.2	4	131-250	3PnPs	1,445	23,120	5.5%	8
4.3	4	251-750	3PnPs	1,457	23,312	5.6%	8
5.1	5	30-130	3NO	6,742	107,872	25.7%	39
5.2	5	131-250	3NO	382	6,112	1.5%	2
5.3	5	251-750	3NO	527	8,432	2.0%	3