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Research Document 2012/016

Newfoundland and Labrador Region

Document de recherche 2012/016

Région de Terre-Neuve-et-Labrador

Preliminary investigations into standardizing the 4T snow crab (*Chionoecetes opilio*) bottom-trawl survey index

Enquêtes préliminaires visant la normalisation de l'indice relatif au relevé au chalut de fond sur le crabe des neiges (*Chionoecetes opilio*) dans la division 4T

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ISSN 1499-3848 (Printed / Imprimé)
ISSN 1919-5044 (Online / En ligne)

Correct citation for this publication:

Cadigan, N.G. 2012. Preliminary investigations into standardizing the 4T snow crab (*Chionoecetes opilio*) bottom-trawl survey index. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/016. ii + 48 p.

ABSTRACT

The 4T snow crab survey has expanded since it was initiated, and total biomass estimates may not be comparable over the entire time-series because of changes in the area surveyed. In this paper a simple model is proposed to standardize the abundance and biomass time-series by extrapolating crab densities in areas not fished in some years. The model involves multiplicative mixed-effects, where year and spatial location are fixed effects, and year×spatial location are random effects. Trawl catches of crab are assumed to have a Negative Binomial distribution. The multiplicative mixed-effects model will be more appropriate when the spatial distribution of crab only changes randomly from year to year. The results indicate that 4T snow crab stock size is currently at a low level compared to most other years since 1988. The 2010 biomass estimate is the 4th lowest in the time-series, but improved compared to 2009 which was the 2nd lowest biomass estimate in the time-series.

RÉSUMÉ

Le relevé sur le crabe des neiges dans la division 4T a pris de l'ampleur depuis qu'il a été entrepris, et les estimations de la biomasse totale ne se comparent peut-être pas à l'ensemble de la série chronologique en raison des changements survenus dans la zone. Le présent document propose un modèle simple pour normaliser la série chronologique de l'abondance et de la biomasse en extrapolant les densités de crabe dans les zones non exploitées de certains relevés. Le modèle comprend des effets mixtes multiplicatifs, où l'année et l'emplacement spatial sont des effets fixes, et l'année×emplacement spatial sont des effets aléatoires. On assume que les captures de crabe par chalutage ont une distribution binomiale négative. Le modèle à effets mixtes multiplicatifs s'avérera plus utile lorsque la répartition spatiale du crabe ne variera que de façon aléatoire d'année en année. Selon les résultats, la taille du stock de crabe des neiges dans la division 4T est faible aujourd'hui comparativement à ce qu'elle a été la plupart des autres années depuis 1988. L'estimation de la biomasse pour 2010 est la quatrième plus faible de la série chronologique, mais montre une amélioration par rapport à l'année 2009, qui fut la deuxième plus faible estimation de la biomasse de la série chronologique.

1. INTRODUCTION

A bottom trawl survey for snow crab in the southern Gulf of St. Lawrence (NAFO Division 4T) was initiated in 1998 and has continued to 2011. The survey design is based on lattice sampling using grid squares of 10' X 10' dimensions and sampling at fixed stations within each square. Data are processed using geo-statisitical methods (Surette et al. 2007). The 4T snow crab survey has expanded since it was initiated and modifications over time are described by DFO (2006) and Moriyasu et al. (2008).

Changes and improvements in survey design are common; however, such changes can affect the year-to-year comparability of survey estimates of total stock size. This is certainty true when the survey area changes over time. If the total survey area increases over time for a survey that does not cover the entire stock area from inception, then trends in estimates of total survey biomass may not reflect the same trends in the stock. Some of the trends in survey estimates may reflect changes in survey area and not changes in stock size.

A common approach to deal with this problem is to select a portion of the survey area (i.e. the index area) that has been consistently sampled over time, and to base the stock size index on this index area only. This approach can be criticized from at least two aspects: (1) it ignores survey data outside of the index area, and (2) if the index area is too small then inferences about trends in stock size based on the survey index may be confounded by changes in the spatial distribution of the stock over time.

Rather than restricting the index area to a portion of the current survey area that has been consistently sampled over time, I propose that the survey index should be based on the maximal survey area and that the index be adjusted for years when there are gaps in survey coverage of the maximal area. I use a simple statistical model for this purpose, in which survey catches are assumed to be a stochastic function of fixed year and strata effects, and random year×strata interactions. These random interactions can be estimated even if there are no samples in a grid in some years, although each grid must be sampled at least once in the time-series. When there is no data in a grid then the estimate of the grid mean will be the estimated year plus grid effect; that is, the interaction term is zero. When there is data in a grid then the estimate of the grid mean will usually be similar to the sample mean, but there is some slight shrinkage of the interaction term towards zero.

The number of sampled grids currently used in the 4T snow crab survey is large (i.e. 277) for the purposes of this model. With 23 years of survey data this leads to 277×23 = 6400 year×grid interactions. To further simplify the analysis, I grouped grids into a smaller number (i.e. 30 or 50) of strata, and used the strata rather than the grids for modeling the spatial patterns in survey catches and how these change over time. This is described in the next section.

2. METHODS

2.1 THE DATA

The data used in this analysis are the catches of commercial-sized (number >= 95 mm carapace width) adult male crab of all carapace conditions as sampled from the dedicated snow crab bottom trawl survey of the southern Gulf. The weight of crab caught per tow were also available based on a standard length to weight relationship. Estimated swept area per tow was also provided. Details of the survey design, trawl, sampling protocols, and data collection are in Moriyasu et al. (2008).

2.2 THE MODEL

Let Y_{thi} denote the survey catch from the ith tow in year t and stratum h (h = 1, …, H), and let SA_{thi} denote the swept-area of the corresponding tow. I assume that $E(Y_{thi}) = \eta_{thi} = \mu_{th} \times SA_{thi}$ and that μ_{th} can be written as the product of year effects, stratum effects, and year×stratum interactions; that is, $\log(\mu_{th}) = \tau_t + \zeta_h + \delta_{th}$. For parameter identification purposes, I fix τ for the last year to be zero. Assumptions for δ_{th}'s are presented below. An important assumption in this stratum-effects model is that the catches are independent within a stratum and, apart from swept area differences, the means are constant with a stratum. The stratification scheme I used is described in Section 2.3.

I assume that the survey catches are realizations from a negative binomial (NB) distribution. This distribution is often suggested to be appropriate for modelling the variability in trawl survey catches (e.g. Gunderson 1993; Cadigan 2011). Survey catches typically have a variance that increases with the mean, and assuming constant variance is not appropriate and can lead to poor estimates of model parameters. If Y ~ NB(η,k) with probability distribution function

$$\Pr(Y = y) = \frac{\Gamma(y+k)}{\Gamma(y+1)\Gamma(k)}\left(\frac{\eta}{\eta+k}\right)^{y}\left(\frac{k}{\eta+k}\right)^{k}$$

then E(Y) = η and Var(Y) = η(1+ η/k). The NB variance is approximately Poisson in form (i.e. variance equals mean) when η << 1 or when k → ∞. When η is large the coefficient of variation for Y is approximately constant.

If the spatial distribution of the stock changes randomly from year to year, without distributional shifts, then the year×stratum interactions (i.e. δ_{th}'s), should vary about zero without trends. In this case it is reasonable to assume that the δ_{th}'s are independent $N(0,\sigma^2)$ random variables. These are then "integrated out" of the likelihood for inference about fixed effect parameters like the τ_t's. I used the AD Model Builder (Fournier et al. 2012) random effects module (ADMB-RE) to get the marginal likelihood. ADMB provides empirical Bayes predictions of the δ_{th}'s. If a strata has no data then the empirical Bayes prediction of δ_{th} is zero. Hence, the estimate of μ_{th} when there is no sampling in a stratum is:

$$\hat{\mu}_{th} = \exp(\hat{\tau}_t + \hat{\zeta}_h).$$

Otherwise, the estimate when there is sampling in a stratum is:

$$\hat{\mu}_{th} = \exp(\hat{\tau}_t + \hat{\zeta}_h + \hat{\delta}_{th}).$$

2.3 MODEL-BASED INDEX

I first standardized the swept area of the tows by dividing the recorded swept area by the average for the entire time series ($\overline{SW}$) which was 2,647 m². This analysis step was only for convenience, so that the τt and ζh parameters were more related to log catches of typical tows, and to facilitate estimation of mean number caught per tow (mnpt or $\hat{\mu}_t$).

The estimate of $\hat{\mu}_t$ is based on the usual stratum size-weighted average:

$$\hat{\mu}_t = \frac{\sum_{h=1}^{H} A_h \exp(\hat{\tau}_t + \hat{\zeta}_h + \hat{\delta}_{th})}{\sum_{h=1}^{H} A_h},$$

where A_h is the area of stratum h. Let w_{th} denote the average weight (kg) of crab caught in year t and stratum h. These are derived in Section 2.4. The estimate of mean biomass per tow ($\hat{b}_t$) is:

$$\hat{b}_t = \frac{\sum_{h=1}^{H} A_h w_{th} \exp(\hat{\tau}_t + \hat{\zeta}_h + \hat{\delta}_{th})}{\sum_{h=1}^{H} A_h}.$$

If A is the maximal survey area (in km^2) then the estimate of total biomass is:

$$\hat{B}_t = \frac{A \times 10^6}{10^3} \frac{\hat{b}_t}{\overline{SW}}.$$

Average biomass per m^2 is $\hat{b}_t / \overline{SW}$, which is multiplied by 10^6 to give average biomass per km^2, and then multiplied by A to give survey biomass (in kg). The division by 10^3 converts the result to metric tonnes.

The model is not run separately for mean number per tow ($\hat{\mu}_t$) and for biomass per tow. Inferences about survey biomass are derived from the model for numbers per tow, and annual stratified average weights per tow that are assumed to be fixed at estimated values.

ADMB automatically produces standard errors for derived quantities like mnpt and total biomass. By default it uses the delta method for standard errors. Confidence intervals were derived by exponentiating the 95% confidence intervals for the log of mnpt and total survey biomass. This approach usually better reflects the skewness in the distribution of the estimates.

2.4 STRATA

My goal was to stratify grids so that strata were spatially contiguous and covered similar depth ranges. The rationale for this is that snow crab have habitat preferences, and habitat is spatially correlated, which is why strata were selected to be spatially contiguous. Snow crab also have temperature preferences and temperature is highly dependent on depth (see Benoît 2012), which is why strata were selected to cover similar depth ranges.

There are many ways to construct strata – and perhaps the best way is for snow crab experts to examine the available habitat and bathymetry data to construct strata in which it is reasonable to assume that snow crab densities are homogeneous. For simplicity I clustered the sampling grids by latitude, longitude, and bottom depth. I simply averaged these variables for all tow records for each grid. I used the 'pam' (Maechler et al. 2011) clustering program in R (R 2011). I chose to cluster the grids into 30 strata. I felt this was a reasonable number of strata to account for spatial patterns in the data; however, other choices for the number of strata may also work well, and I conducted a sensitivity analysis using 50 strata. The R code for clustering is presented in Appendix a.

The "pam" clustering algorithm does not completely ensure that all strata are spatially contiguous. Although there are methods to do this, they require additional information about the spatial location of grids, such as the grid vertices or a matrix that describes which grids are adjacent to each other. However, the approach I used produced strata that were approximately spatially contiguous. This is a post-stratification of the survey design. Note however that I have not post-stratified the survey data because strata were not selected based on catches.

The associated stratum-effects model is reasonable if there is little or no spatial dependencies in model residuals (see Section 3). Ideally the minimum number of strata should be chosen to adequately account for spatial dependencies in snow crab catches.

2.5 WEIGHTS

Average individual weights per stratum and year (i.e. w_{th}) were estimated by regressing commercial weights on commercial counts with effects for year and stratum. A multiplicative model was used, with a Gaussian assumption for the model variability in weights. The R code for this is presented in the Appendix 1.

3. RESULTS

The results of the stratification scheme are shown in Figure 1. Not all strata are spatially contiguous; for example strata 2, 4, 5, 12, and 24. There are 277 grids shown in Figure 1. Note that the grid locations were based on the average latitude and longitude of all surveys sets in each grid, and this may not represent the mid-point of the grid.

The estimated annual weights of commercial-sized crab in these strata are shown in Figure 2 and other model output is shown in Table 1. Both the stratum and year effects were highly significant, with p-values < 1e-15. The deviance component for stratum was about 5 times as large as the deviance component for year.

Estimates of mnpt and total survey biomass are shown in Figures 3 and 5 and in Tables 2 and 3, respectively. It is remarkable how little the CV of estimates varies over the series, including in 1988 and 1989 when about 44% of the current grids were sampled. These CV's are based on the standard errors of the estimators of the year and strata fixed effects, as well as the predictions of the year×stratum random interaction terms. The standard errors of these predictions when there are no samples in a stratum are based directly on the estimate of the random effect variance (σ^2). When there are samples in a stratum then they also have an effect. It turns out that the standard errors of predictions of interaction terms when there are samples are only ~75% (see Figure 4) of the estimate of σ (i.e. 0.40). This is some of the reason why the CV's of mnpt and total biomass are so similar. The efficacy of these CV's requires further research.

The estimates of mnpt and total survey biomass are derived from estimates of the annual stratum means, μ_{th}, which are illustrated in Figures 6-11. The same color scheme is used in each figure. The plausibility of the estimated values for μ_{th}'s affect the plausibility of the estimates of mnpt and total survey biomass, although errors in the μ_{th}'s may cancel in the computations of mnpt and total survey biomass.

The 1996 biomass (51.3 Kt) is mostly an extrapolation because of incomplete survey coverage (Figure 14). The coefficient of variation (CV) for this year was 0.27. A similar biomass value (54.7 Kt) was estimated for 2008. This survey had full coverage and the CV (0.18) was 33% smaller than the value for 1996. This reflects the increased uncertainty due to the extrapolation.

Standardized residual plots are useful for assessing model fit. The NB standardized residual is:

$$e_{thi}^{(s)} = \frac{Y_{thi} - \hat{\eta}_{thi}}{\sqrt{\hat{\eta}_{thi}\left(1 - \hat{\eta}_{thi} / \hat{k}\right)}}.$$

Residuals are shown in Figures 12-17. They are scaled the same in each panel. In many years the residuals seem to have little spatial pattern overall, but there are some clusters of correlated residuals (e.g. Figure 17, 2010).

The overall mean of the raw residuals, $e_{thi} = Y_{thi} - \hat{\eta}_{thi}$, was 0.25 (see Figure 18) which is close to zero. Some summaries of the differences between observed catches and model predictions are given in Tables 4 and 5. The standardized residuals did not have an approximate normal distribution (Figures 19 and 20), which was unanticipated. If the NB variance model is appropriate then one expects that the standardized residuals should have an approximate normal distribution. This requires further investigation.

The NB variance model does provide a good description of how the variance in the raw residuals increases with the mean. This is illustrated in Figure 21. I first sorted all the predicted values for survey catches (for the entire time series) and then grouped the predictions into equal sized bins (size = 50). I computed the mean of the predictions in each bin, and the variance and standard deviations of the corresponding raw residuals for each bin. The standard deviations are plotted versus the bin mean predictions in Figure 21. The solid line is the square root of the NB variance model.

Accounting for deviations in the swept area of tows from the overall average did result in improved fit.

In the next section I increase the number of strata in an attempt to better model the spatial patterns in the survey catches.

3.1 SENSITIVITY TO THE NUMBER OF STRATA

I repeated the analyses with H=50 strata, in an attempt to better account for spatial patterns in the survey catches compared to the model with H=30. This choice of strata number resulted in a substantial improvement in model fit, although the standard errors of the predicted random interactions terms were larger (compare Figures 4 and 25) and of course there were more unsampled strata when H=50. The loglikelihood increased by 246.2 for an additional 20 mean parameters. Estimates of mnpt and total survey biomass (Tables 6 and 7; Figures 24 and 26) were similar to those when H=30 (i.e. Tables 2 and 3; Figures 3 and 5), although CV's were slightly smaller when H=50 due to more precise estimates of the fixed year-effects when H=50 compared to H=30. Of course there was more spatial variability in strata means (Figures 27-32) and somewhat less spatial pattern in residuals (Figures 33-38). The NB variance provided a good description of the raw residual variation (Figure 39), although standardized residuals still looked non-normal, similar to Figures 19 and 20.

4. DISCUSSION

The approach I propose can be used to “fill-in” for in-complete survey coverage in some years when estimating a time-series of average survey catch and total survey biomass. As such, the model can be used to standardize survey indices to a common survey area, which is the maximal survey area or some other choice. The approach I propose utilizes all survey data. However, the model is less appropriate when there has been a consistent change in the spatial distribution of the stock over time. This does not seem to be the case overall (although there have been some localized shifts in distribution) for 4T snow crab; however, this important assumption requires further testing.

The efficacy of the variance estimates requires further research. For example, the 1996 biomass estimate was mostly an extrapolation and yet the CV for this year was only 50% greater than 2008 in which the survey had full coverage and the biomass estimate was similar to 1996. I expected a greater increase in CV for 1996. A possible cause for this is if the year×stratum random effect variance is smaller than the within-stratum variation of survey catches. In this case it will take several samples (I am not sure how many) to substantially reduce the standard errors of the predicted interaction terms and result in lower CV’s for total abundance and biomass estimates. The year×stratum random effect variance will be small when the spatial distribution of the stock is stable over time, and in this case it makes intuitive sense that it is possible to reliably adjust for un-sampled strata.

These statistical inferences are not based on the usual “design-based” framework in which catches are considered to be fixed responses and uncertainty arises only from the random selection of sites to sample The statistical framework I use includes variability in site selection (the survey design) and variability in catches (the NB model), although the first variance component is negligible if stock densities are homogeneous within strata. The approach is described in more detail in Smith (1990), Chen et al. (2004), and Cadigan (2011).

The model with H=50 strata resulted in a substantial improvement in fit compared to H=30. Estimates of mnpt and survey biomass were similar, but standard errors were smaller when H=50. This is consistent with survey literature which suggests that models do not have to be highly accurate to get design-unbiased estimates of population quantities (e.g. Särndal et al. 1992).The value of reliable models is improved precision for population totals. The choice of the number of strata requires further research, in addition to other approaches to model the spatial distribution of catches and to extrapolate densities when there are gaps in survey coverage over time. The H=50 stratum-effects model is highly parameterized, and more parsimonious smoothing methods may provide more reliable statistical inferences.

The NB standardized residuals did not look normally distributed, although the variability in raw residuals was well-described by the NB variance model. This requires further investigation. Also, residuals did not add to zero, and differences could be substantial in some years and strata. This could possibly indicate a bias in density estimates, and this requires further investigation.

The NB approach is not the only suitable one. A delta-lognormal approach may also be useful. In this approach, the probability of getting a positive catch is modeled separately from the positive catches. An advantage of the lognormal approach is that more common spatial models may be more efficiently used.

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Table 1. Estimated effects from the GLM model to estimate mean weight of crab.

	Estimate	Std. Error	t value	Pr(> |t|)
(Intercept)	-0.704	0.029	-24.083	0.000
fstratum2	0.128	0.013	10.056	0.000
fstratum3	0.091	0.014	6.560	0.000
fstratum4	0.104	0.023	4.476	0.000
fstratum5	0.053	0.016	3.361	0.001
fstratum6	0.083	0.013	6.455	0.000
fstratum7	0.030	0.013	2.297	0.022
fstratum8	0.128	0.078	1.642	0.101
fstratum9	0.222	0.011	19.645	0.000
fstratum10	0.017	0.010	1.653	0.098
fstratum11	0.122	0.013	9.597	0.000
fstratum12	0.407	0.854	0.477	0.634
fstratum13	0.408	0.017	23.320	0.000
fstratum14	0.152	0.009	16.459	0.000
fstratum15	0.051	0.010	5.038	0.000
fstratum16	0.146	0.022	6.663	0.000
fstratum17	0.127	0.017	7.350	0.000
fstratum18	0.160	0.013	12.752	0.000
fstratum19	0.279	0.014	19.743	0.000
fstratum20	0.202	0.010	20.508	0.000
fstratum21	0.031	0.011	2.753	0.006
fstratum22	0.114	0.012	9.513	0.000
fstratum23	0.281	0.027	10.472	0.000
fstratum24	0.308	0.011	29.092	0.000
fstratum25	0.204	0.013	15.743	0.000
fstratum26	0.234	0.012	20.271	0.000
fstratum27	0.268	0.010	26.549	0.000
fstratum28	0.277	0.038	7.258	0.000
fstratum29	0.411	0.010	39.300	0.000
fstratum30	0.428	0.027	15.859	0.000
fyear1989	-0.020	0.031	-0.628	0.530
fyear1990	-0.036	0.029	-1.235	0.217
fyear1991	0.002	0.029	0.077	0.938
fyear1992	-0.010	0.028	-0.352	0.725
fyear1993	0.003	0.028	0.120	0.905
fyear1994	0.024	0.028	0.859	0.391
fyear1995	0.082	0.028	2.893	0.004
fyear1996	0.017	0.035	0.484	0.628
fyear1997	0.066	0.029	2.232	0.026
fyear1998	0.001	0.029	0.047	0.963
fyear1999	-0.051	0.029	-1.735	0.083
fyear2000	0.011	0.030	0.363	0.716
fyear2001	-0.087	0.029	-2.998	0.003
fyear2002	-0.062	0.029	-2.150	0.032
fyear2003	-0.065	0.029	-2.254	0.024
fyear2004	-0.027	0.028	-0.953	0.341
fyear2005	0.009	0.029	0.322	0.747
fyear2006	0.095	0.029	3.313	0.001
fyear2007	0.066	0.029	2.265	0.024
fyear2008	0.078	0.030	2.640	0.008
fyear2009	0.048	0.031	1.525	0.127
fyear2010	0.019	0.031	0.621	0.535

Table 2. Mean number per tow (mnpt) estimates, with 95% confidence intervals for the model with h = 30 strata.

Year	n	Mean	SE	CV	L95	U95
1988	154	1.59	0.35	0.22	1.04	2.43
1989	155	2.81	0.59	0.21	1.86	4.25
1990	212	5.72	1.13	0.20	3.89	8.42
1991	215	6.77	1.34	0.20	4.60	9.97
1992	233	9.75	1.88	0.19	6.68	14.23
1993	208	11.31	2.33	0.21	7.55	16.95
1994	259	12.39	2.31	0.19	8.60	17.85
1995	261	8.57	1.60	0.19	5.94	12.37
1996	72	4.11	1.08	0.26	2.45	6.88
1997	259	5.36	1.01	0.19	3.71	7.76
1998	261	5.19	0.97	0.19	3.60	7.48
1999	277	5.20	0.96	0.18	3.63	7.46
2000	280	4.19	0.77	0.18	2.93	6.00
2001	292	5.36	0.99	0.18	3.74	7.69
2002	319	5.96	1.08	0.18	4.19	8.49
2003	317	7.13	1.29	0.18	5.01	10.17
2004	347	7.69	1.38	0.18	5.40	10.94
2005	355	6.30	1.12	0.18	4.44	8.93
2006	354	5.78	1.04	0.18	4.05	8.23
2007	355	5.17	0.91	0.18	3.67	7.30
2008	355	4.09	0.72	0.18	2.89	5.78
2009	355	2.35	0.42	0.18	1.65	3.34
2010	354	2.82	0.51	0.18	1.98	4.02

Table 3. Total annual biomass estimates (tonnes), with 95% confidence intervals, for the model with h = 30 strata.

Year	Mean	SE	CV	L95	U95
1988	19,639	4,255	0.22	12,845	30,029
1989	34,205	7,200	0.21	22,639	51,666
1990	69,015	13,623	0.20	46,870	101,608
1991	85,486	16,940	0.20	57,966	126,044
1992	119,040	22,965	0.19	81,543	173,705
1993	135,920	27,941	0.21	90,861	203,396
1994	151,930	28,195	0.19	105,585	218,541
1995	111,090	20,700	0.19	77,094	160,047
1996	51,299	13,613	0.27	30,482	86,260
1997	69,455	13,046	0.19	48,042	100,324
1998	64,342	11,987	0.19	44,660	92,703
1999	60,815	11,188	0.18	42,422	87,254
2000	52,627	9,638	0.18	36,756	75,354
2001	60,411	11,106	0.18	42,138	86,621
2002	69,253	12,503	0.18	48,636	98,703
2003	83,089	15,025	0.18	58,313	118,471
2004	92,130	16,574	0.18	64,757	131,085
2005	77,804	13,843	0.18	54,901	110,273
2006	77,579	13,990	0.18	54,477	110,466
2007	67,950	11,911	0.18	48,216	95,852
2008	54,650	9,651	0.18	38,673	77,274
2009	30,563	5,494	0.18	21,498	43,491
2010	35,881	6,475	0.18	25,193	51,108

Table 4. Total observed and predicted commercial counts, by stratum.

Stratum	Total Observed	Total Predicted	% Difference
1	689	677.1	1.8
2	55	48.7	12.9
3	647	608.6	6.3
4	1331	1306.7	1.9
5	679	674.6	0.6
6	2959	2909.4	1.7
7	1307	1145.8	14.1
8	3636	3670.4	-0.9
9	1715	1647.7	4.1
10	1319	1358.1	-2.9
11	1029	1004.9	2.4
12	190	187.4	1.4
13	185	141.7	30.5
14	277	201.1	37.7
15	1539	1549.5	-0.7
16	99	89.7	10.4
17	247	240.8	2.6
18	2396	2401.2	-0.2
19	1014	909.4	11.5
20	2054	2105.2	-2.4
21	2069	1804.9	14.6
22	1094	982.4	11.4
23	2036	2048.3	-0.6
24	1049	890.5	17.8
25	1	0.9	8.6
26	381	396.5	-3.9
27	6307	6094.1	3.5
28	3318	3170.8	4.6
29	313	297.0	5.4
30	1403	1239.2	13.2
All	41338	39802.5	3.9

Table 5. Total observed and predicted commercial counts, by year.

Year	Total Observed	Total Predicted	% Difference
1988	282	268.1	5.2
1989	535	488.9	9.4
1990	1,394	1,314.0	6.1
1991	1,702	1,634.6	4.1
1992	2,793	2,781.6	0.4
1993	3,281	2,873.2	14.2
1994	3,495	3,234.5	8.1
1995	2,341	2,139.3	9.4
1996	252	249.9	0.8
1997	1,335	1,274.4	4.8
1998	1,420	1,372.0	3.5
1999	1,472	1,465.0	0.5
2000	1,346	1,315.4	2.3
2001	1,744	1,706.2	2.2
2002	1,915	1,900.6	0.8
2003	2,682	2,687.6	-0.2
2004	3,321	3,118.8	6.5
2005	2,427	2,401.9	1.0
2006	2,302	2,245.2	2.5
2007	1,911	1,930.0	-1.0
2008	1,431	1,460.6	-2.0
2009	900	892.4	0.8
2010	1,057	1,048.4	0.8
All	41,338	39,802.5	3.9

Table 6. Mean number per tow (mnpt) estimates, with 95% confidence intervals for the model with h = 50 strata.

Year	n	Mean	SE	CV	L95	U95
1988	154	1.52	0.30	0.20	1.04	2.23
1989	155	2.62	0.51	0.19	1.80	3.83
1990	212	5.54	0.97	0.17	3.94	7.80
1991	215	6.60	1.17	0.18	4.67	9.33
1992	233	9.29	1.60	0.17	6.63	13.01
1993	208	10.62	1.93	0.18	7.43	15.17
1994	259	11.73	1.96	0.17	8.46	16.27
1995	261	8.07	1.35	0.17	5.81	11.21
1996	72	3.85	0.93	0.24	2.40	6.20
1997	259	5.27	0.87	0.16	3.82	7.28
1998	261	4.97	0.81	0.16	3.61	6.85
1999	277	5.07	0.82	0.16	3.70	6.95
2000	280	4.16	0.66	0.16	3.04	5.69
2001	292	5.29	0.84	0.16	3.88	7.22
2002	319	5.96	0.93	0.16	4.38	8.09
2003	317	7.02	1.10	0.16	5.17	9.55
2004	347	7.62	1.19	0.16	5.62	10.34
2005	355	6.25	0.97	0.15	4.61	8.46
2006	354	5.72	0.89	0.16	4.21	7.77
2007	355	5.21	0.80	0.15	3.86	7.05
2008	355	4.02	0.63	0.16	2.96	5.47
2009	355	2.37	0.37	0.16	1.74	3.22
2010	354	2.81	0.45	0.16	2.06	3.84

Table 7. Total annual biomass estimates (tonnes), with 95% confidence intervals, for the model with h = 50 strata.

Year	Total Biomass	SE	CV	L95	U95
1988	18,775	3,662	0.20	12,811	27,517
1989	31,818	6,138	0.19	21,806	46,447
1990	67,684	11,808	0.17	48,101	95,314
1991	83,484	14,856	0.18	58,878	118,276
1992	114,010	19,624	0.17	81,359	159,751
1993	128,510	23,237	0.18	90,182	183,216
1994	143,230	23,768	0.17	103,440	198,244
1995	104,110	17,359	0.17	75,073	144,319
1996	47,741	11,677	0.24	29,573	77,141
1997	68,731	11,232	0.16	49,896	94,684
1998	62,066	10,156	0.16	45,039	85,537
1999	59,174	9,527	0.16	43,150	81,109
2000	52,142	8,350	0.16	38,106	71,387
2001	58,888	9,349	0.16	43,124	80,351
2002	68,763	10,780	0.16	50,551	93,458
2003	81,414	12,780	0.16	59,834	110,711
2004	90,721	14,102	0.16	66,926	123,088
2005	77,049	11,906	0.15	56,905	104,282
2006	76,377	11,914	0.16	56,234	103,644
2007	68,269	10,481	0.15	50,518	92,218
2008	54,003	8,476	0.16	39,710	73,470
2009	30,708	4,848	0.16	22,529	41,833
2010	35,680	5,659	0.16	26,138	48,673

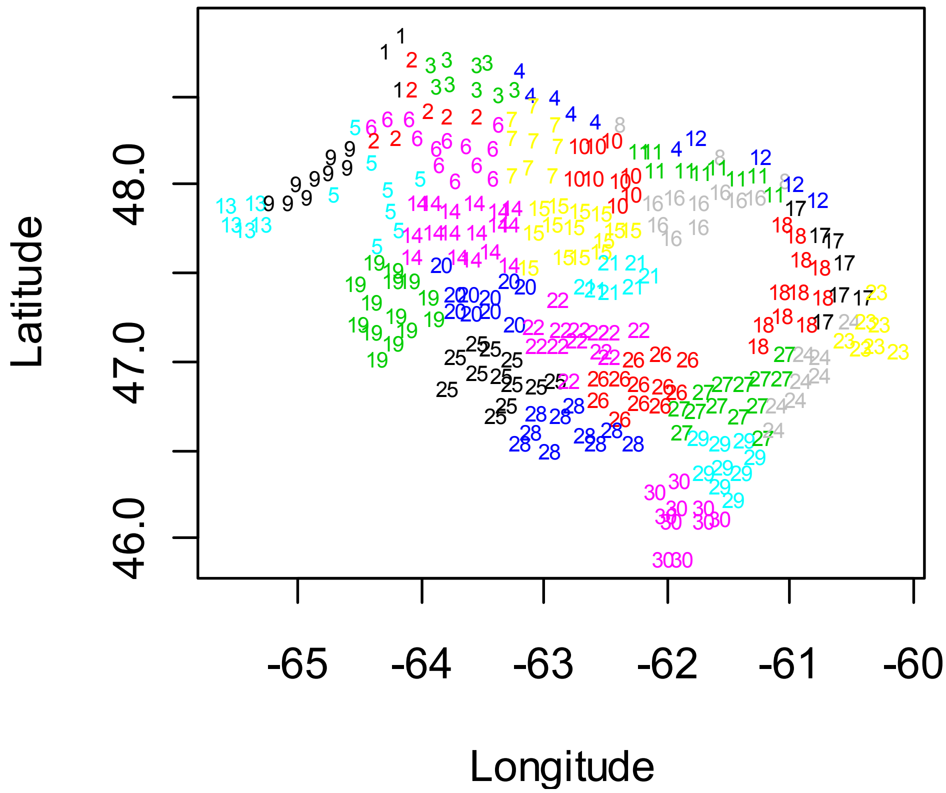

Figure 1. Assignment of grids into 30 strata. The location of each grid is plotted with its corresponding stratum number.

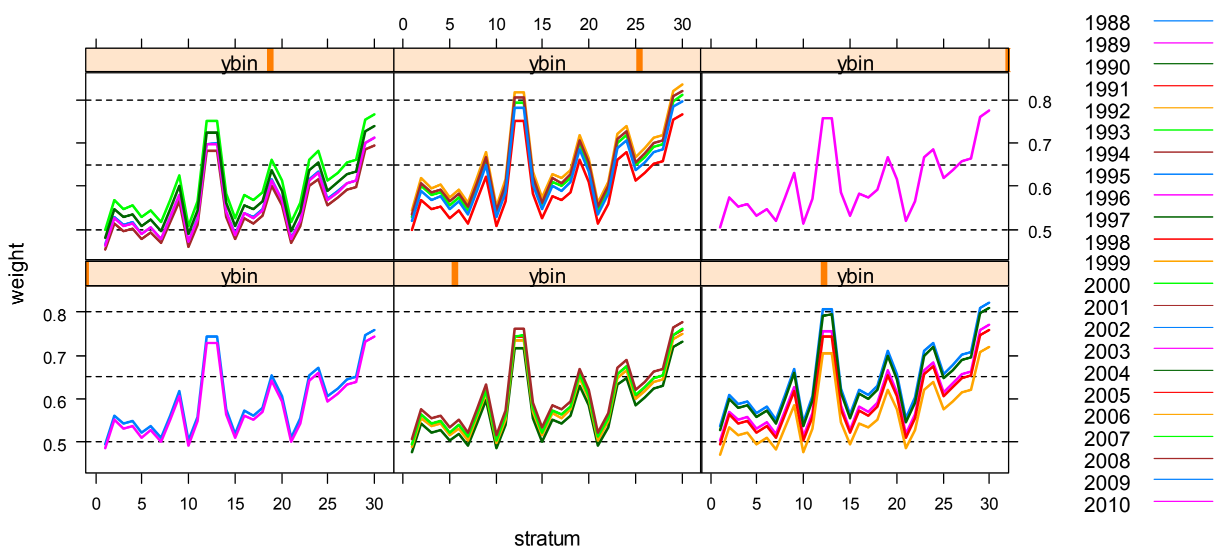

Figure 2. Estimated weights by stratum (H=30) and year. Each panel shows weights for groups of years: 1) 1988-89, 2) 1990-1994, 3) 1995-1999, 4) 2000-2004, 5) 2005-2009, 6) 2010.

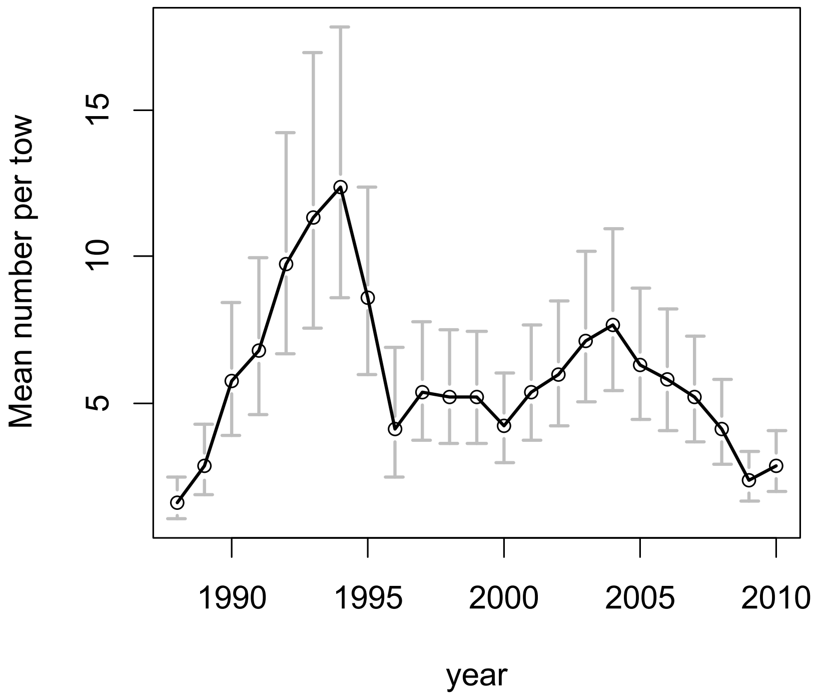

Figure 3. Estimates of mean number per tow for 4T snow crab, with 95% confidence intervals (grey vertical lines). H=30 strata.

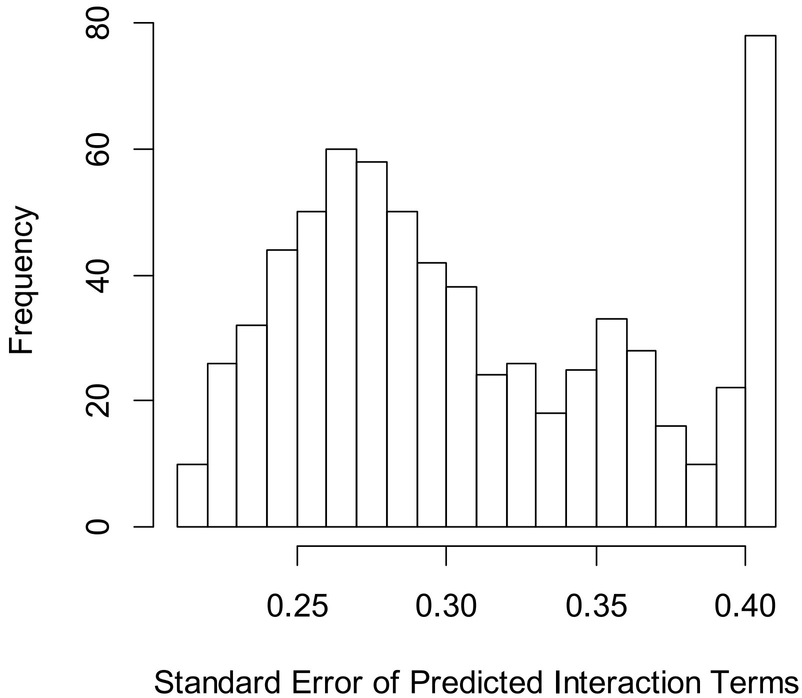

Figure 4. A histogram of the standard errors of the predicted random interaction terms for all years. The "spike" on the right-hand side reflects the standard errors un-sampled for strata. H=30 strata.

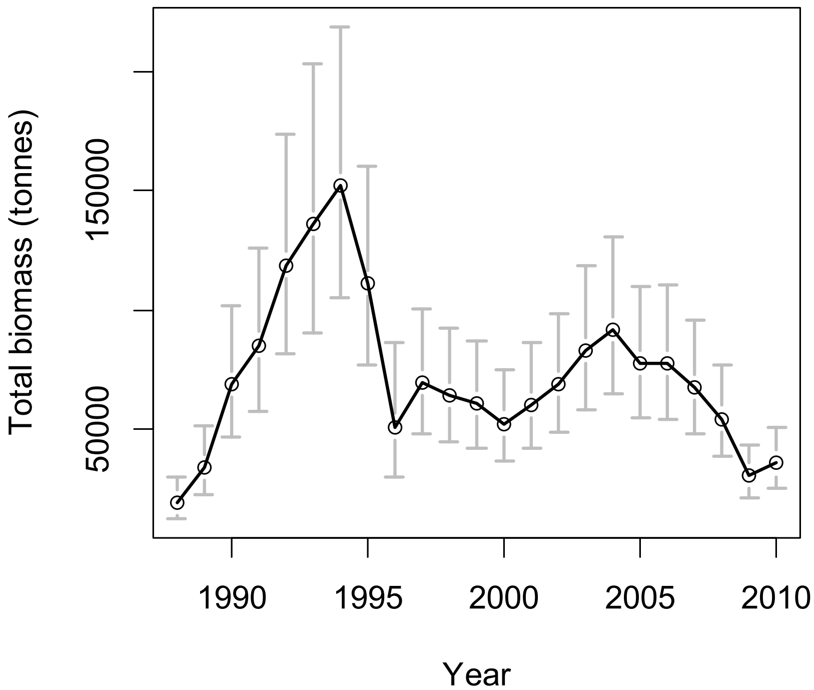

Figure 5. Estimates of total survey biomass for 4T snow crab, with 95% confidence intervals (grey vertical lines). H=30 strata.

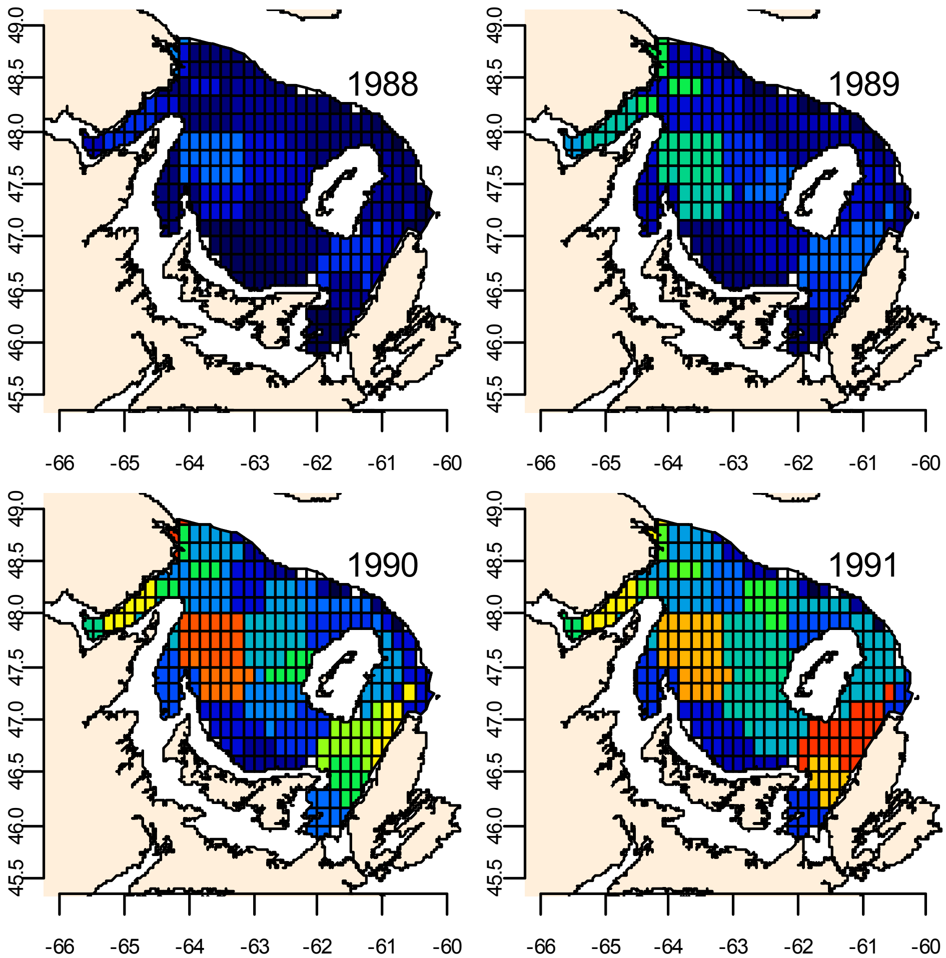

Figure 6. Annual estimates of the density of snow crab (number per tow) in each stratum for 1988-1991. The color scheme is low (dark blue) to high (red). The number of strata is 30.

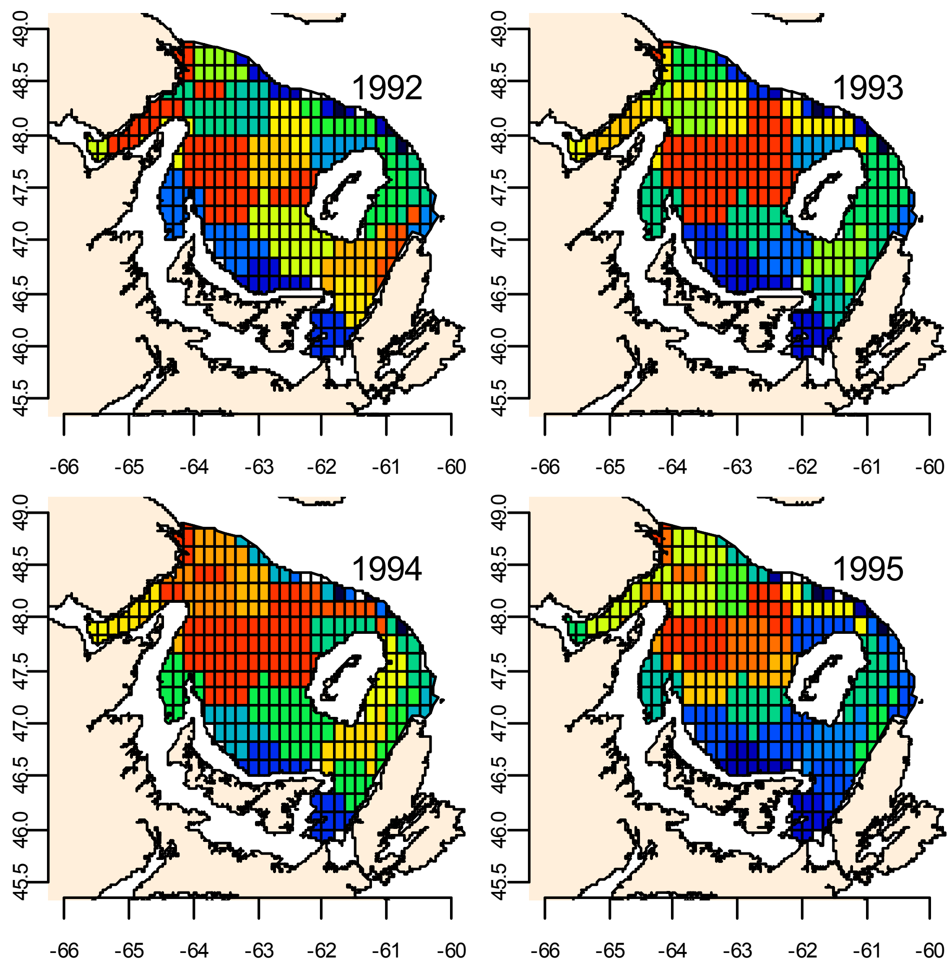

Figure 7. Annual estimates of the density of snow crab (number per tow) in each stratum for 1992-1995. The color scheme is low (dark blue) to high (red). The number of strata is 30.

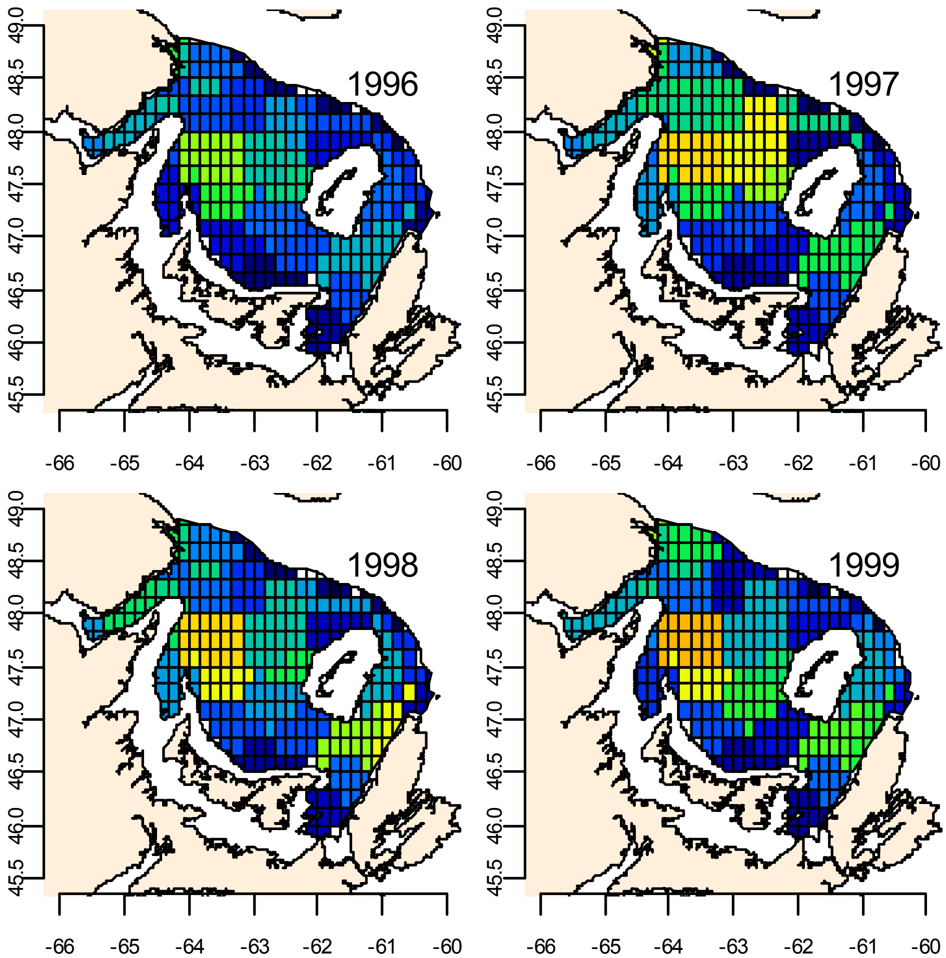

Figure 8. Annual estimates of the density of snow crab (number per tow) in each stratum for 1996-1999. The color scheme is low (dark blue) to high (red). The number of strata is 30.

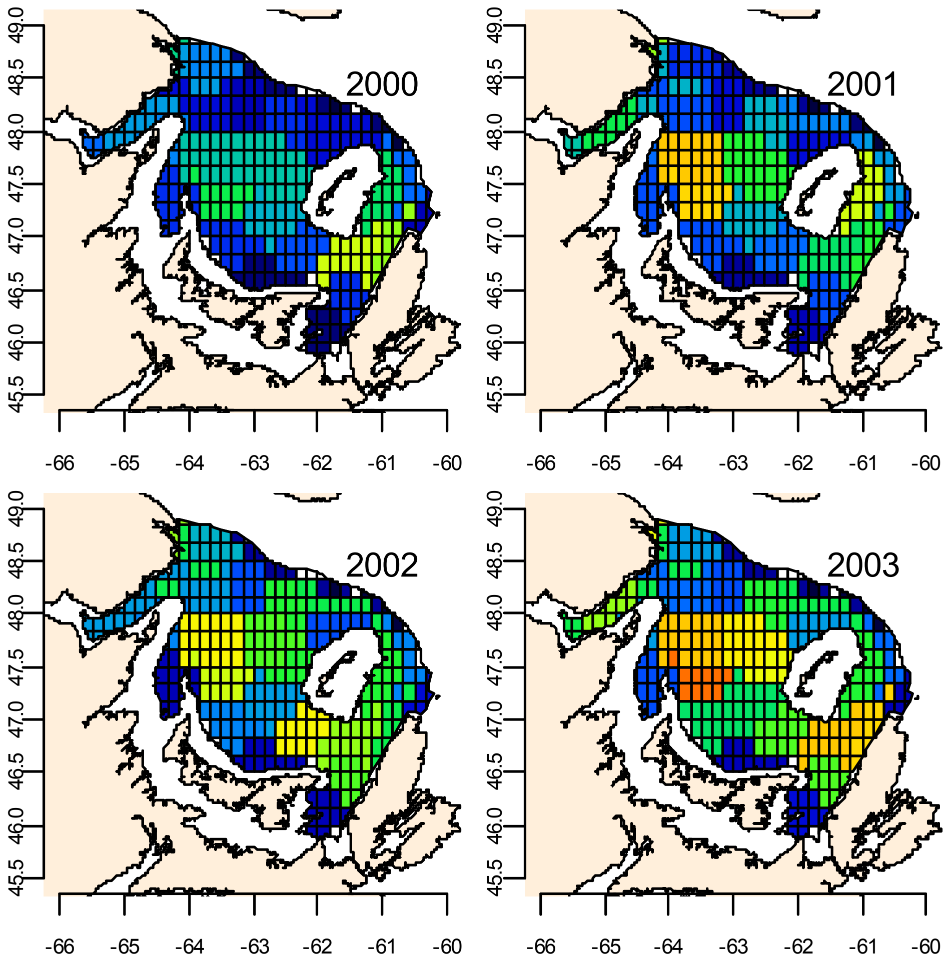

Figure 9. Annual estimates of the density of snow crab (number per tow) in each stratum for 2000-2003. The color scheme is low (dark blue) to high (red). The number of strata is 30.

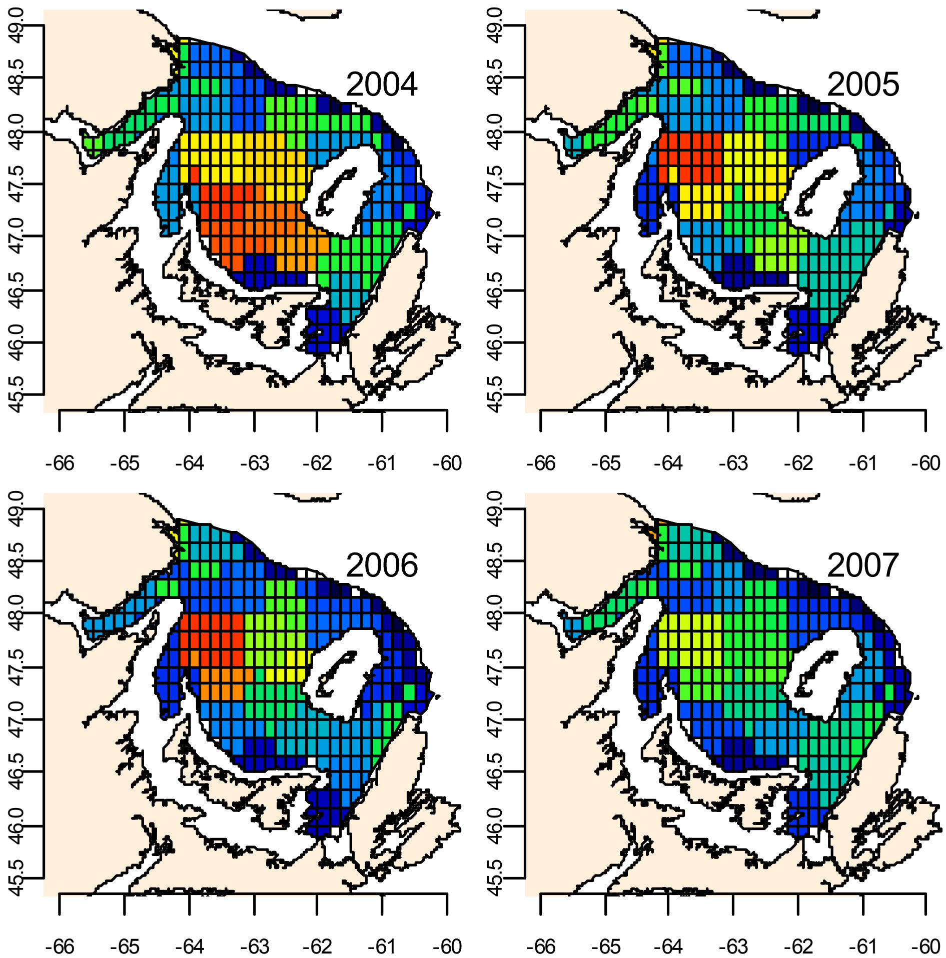

Figure 10. Annual estimates of the density of snow crab (number per tow) in each stratum for 2004-2007. The color scheme is low (dark blue) to high (red). The number of strata is 30.

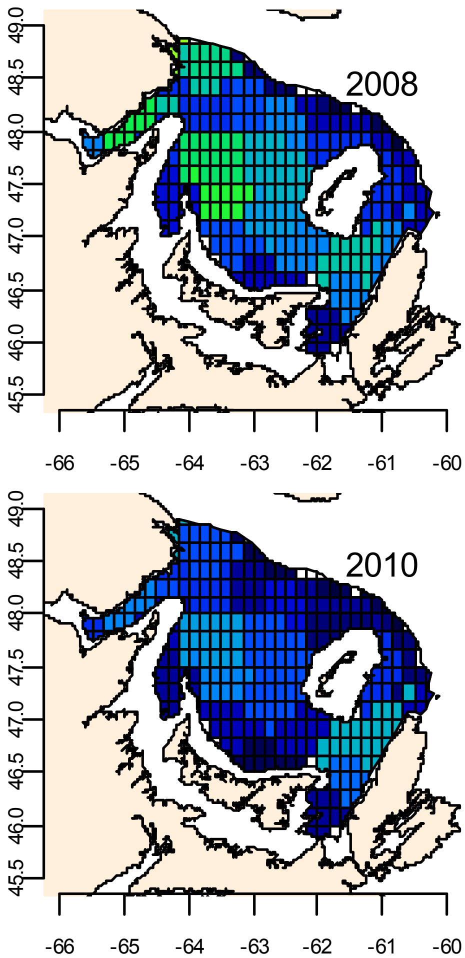

Figure 11. Annual estimates of the density of snow crab (number per tow) in each stratum for 2008-2010. The color scheme is low (dark blue) to high (red). The number of strata is 30.

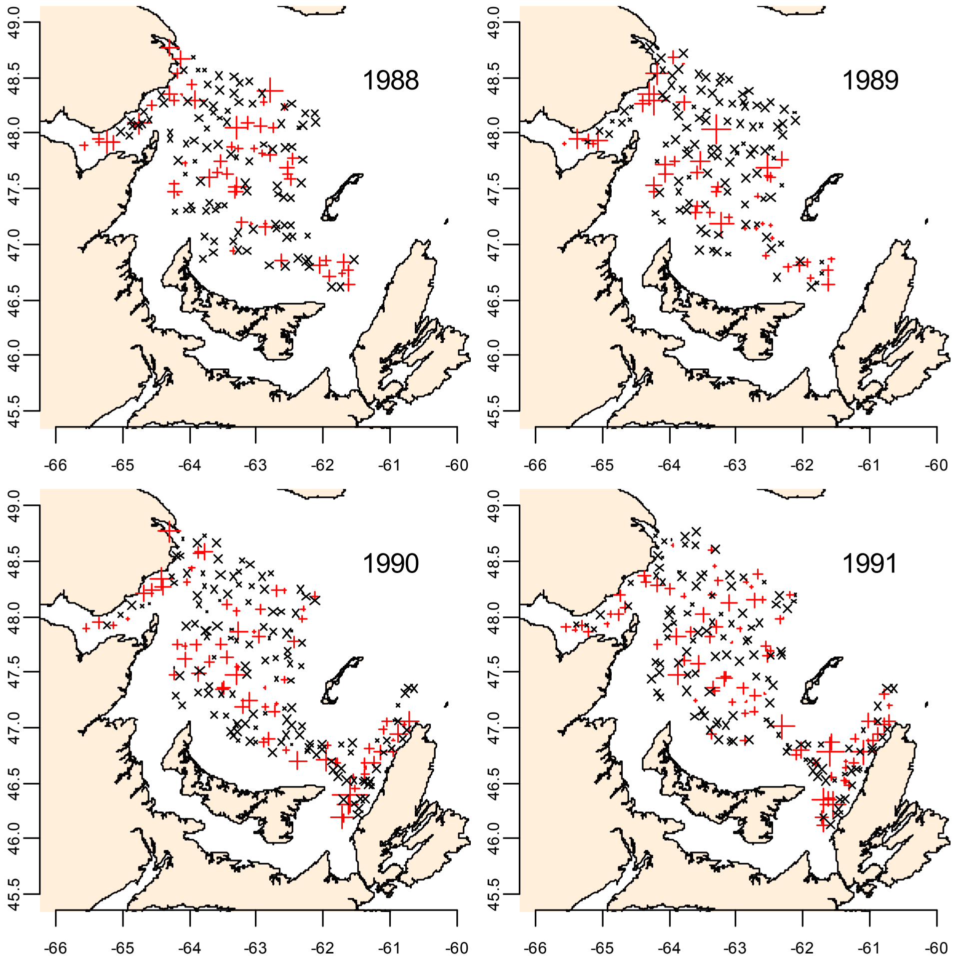

Figure 12. Standardized NB residuals for 1988-1991. The size of the plotting symbol is proportional to the square root of the absolute residual. A red **+** *indicates a positive residual, and a black* **×** *indicates a negative residual. H = 30 strata.*

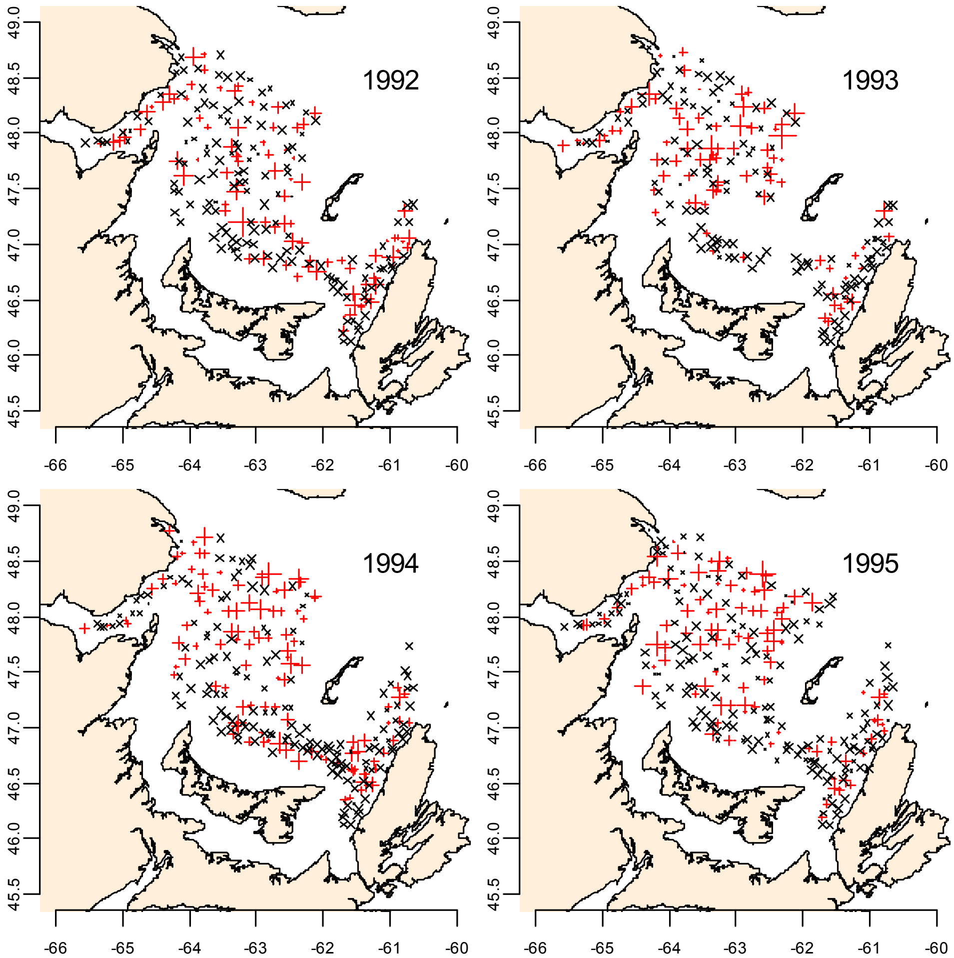

Figure 13. Standardized NB residuals for 1992-1995. The size of the plotting symbol is proportional to the square root of the absolute residual. A red **+** *indicates a positive residual, and a black* **×** *indicates a negative residual. H = 30 strata.*

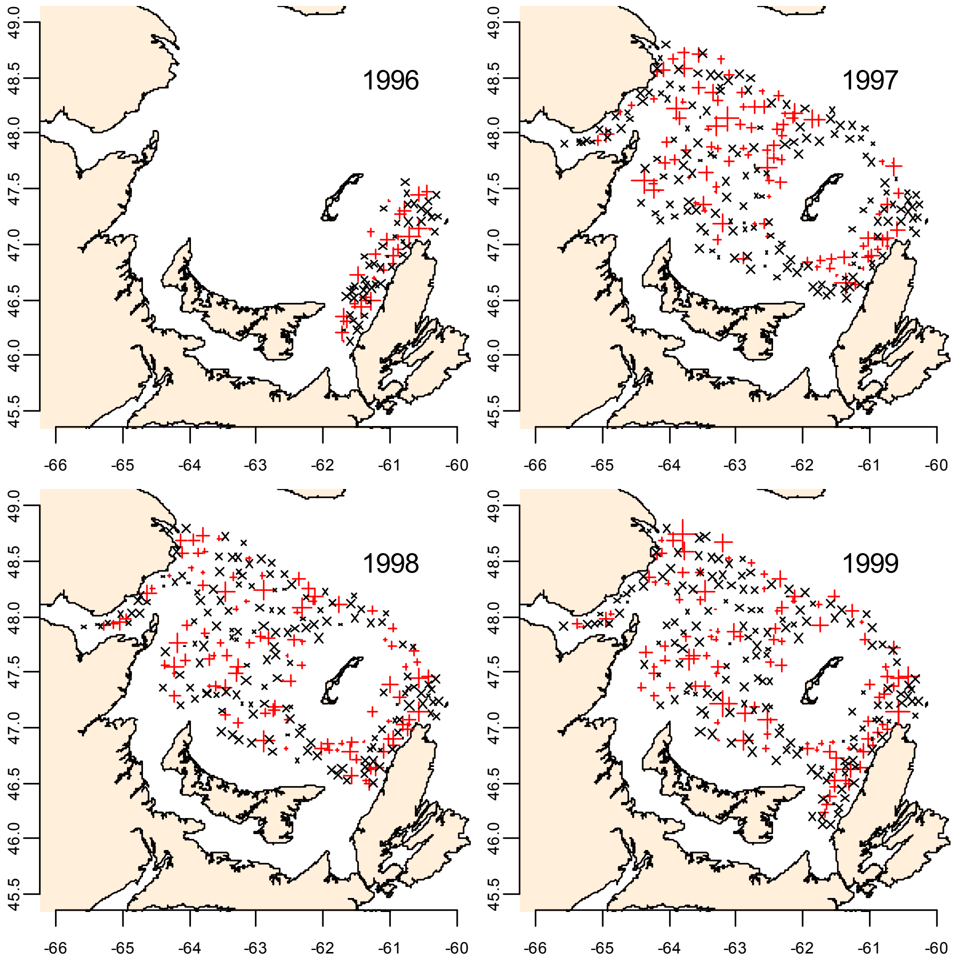

Figure 14. Standardized NB residuals for 1996-1999. The size of the plotting symbol is proportional to the square root of the absolute residual. A red **+** *indicates a positive residual, and a black* **×** *indicates a negative residual. H = 30 strata.*

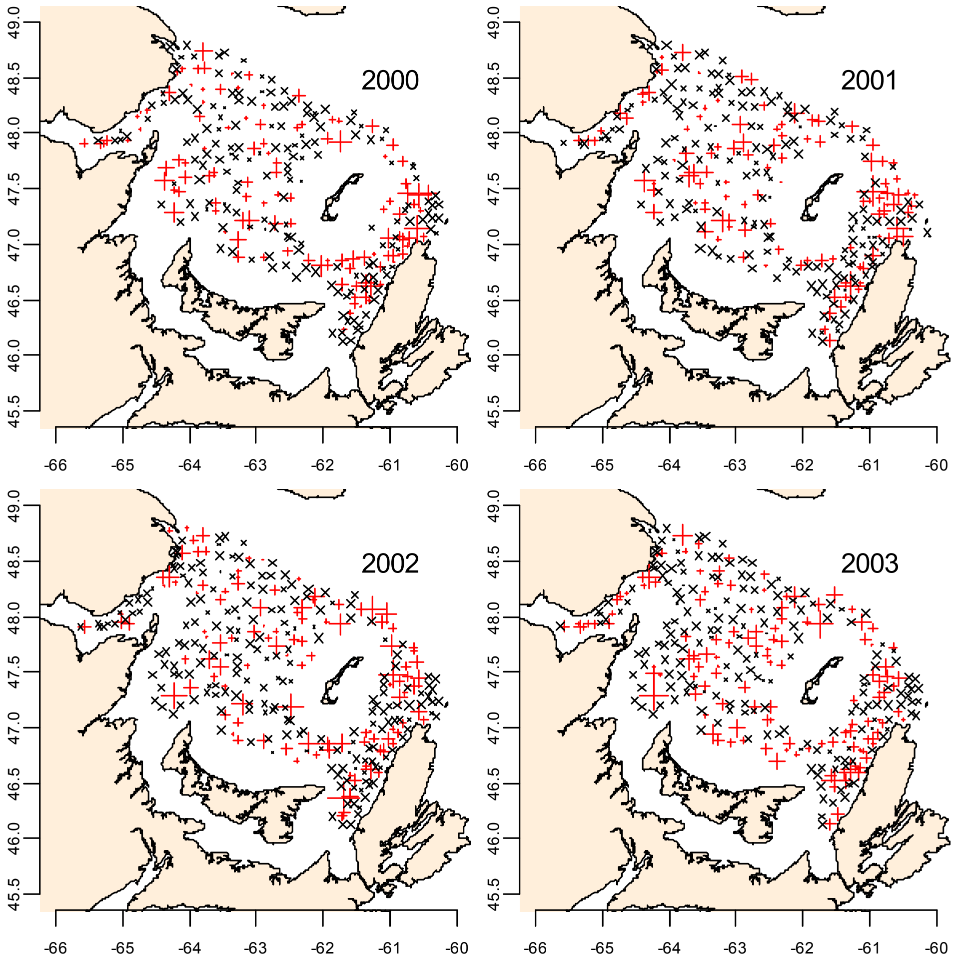

Figure 15. Standardized NB residuals for 2000-2003. The size of the plotting symbol is proportional to the square root of the absolute residual. A red **+** *indicates a positive residual, and a black* **×** *indicates a negative residual. H = 30 strata.*

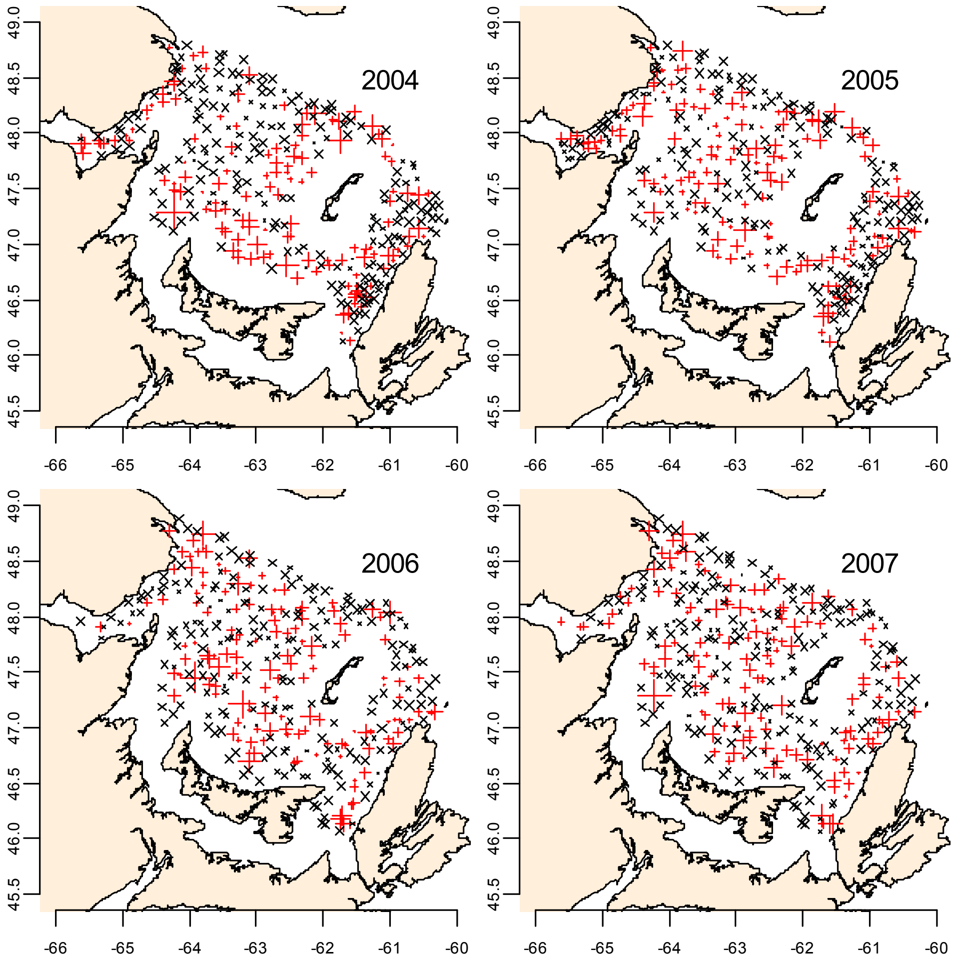

*Figure 16. Standardized NB residuals for 2004-2007. The size of the plotting symbol is proportional to the square root of the absolute residual. A red **+** indicates a positive residual, and a black **×** indicates a negative residual. H = 30 strata.*

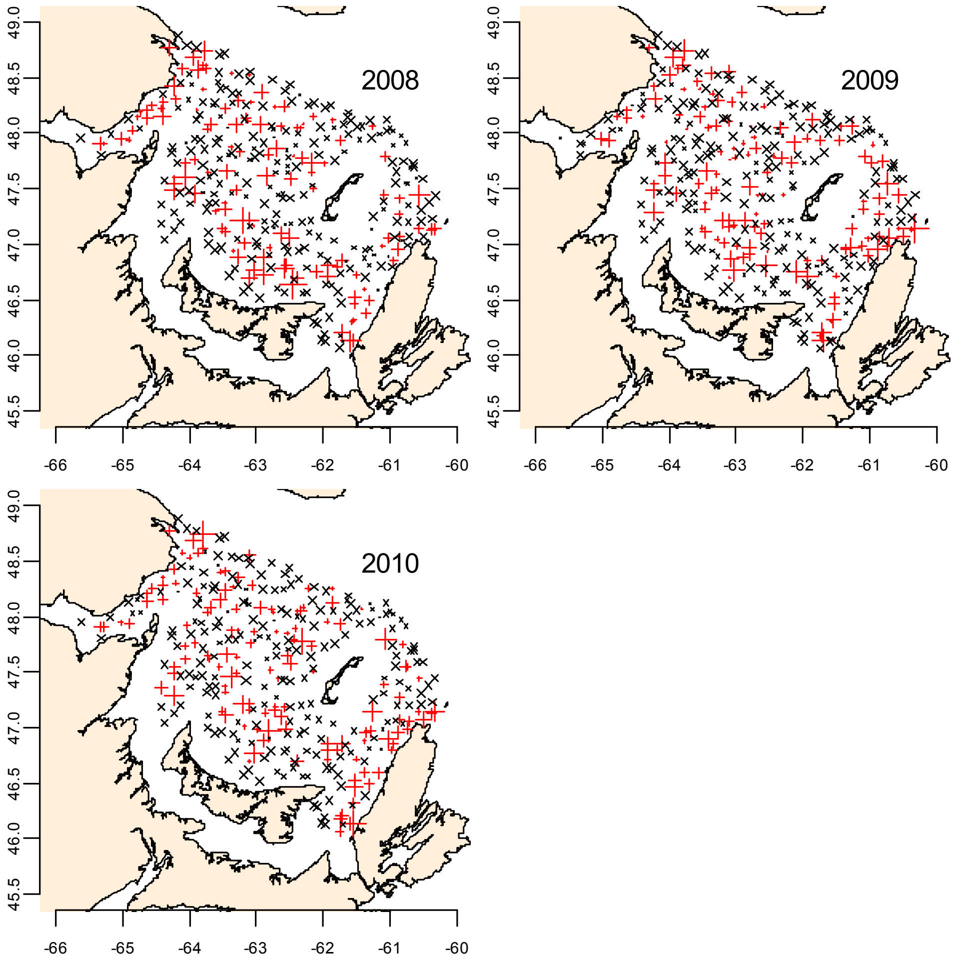

Figure 17. Standardized NB residuals for 2008-2010. The size of the plotting symbol is proportional to the square root of the absolute residual. A red **+** *indicates a positive residual, and a black* **×** *indicates a negative residual. H = 30 strata.*

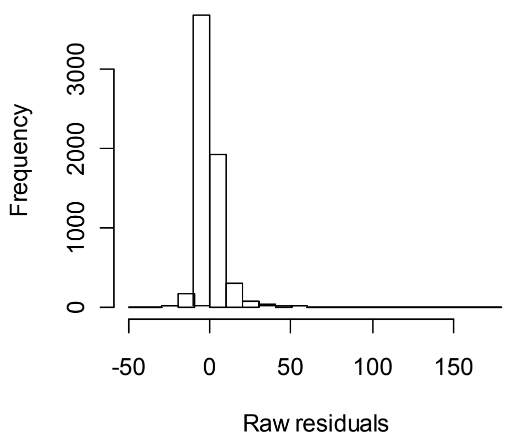

Figure 18. Histogram of raw residuals, for the model with H=30.

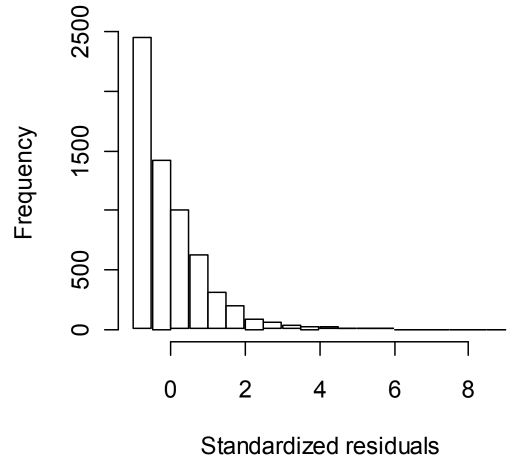

Figure 19. Histogram of standardized residuals, for the model with H=30.

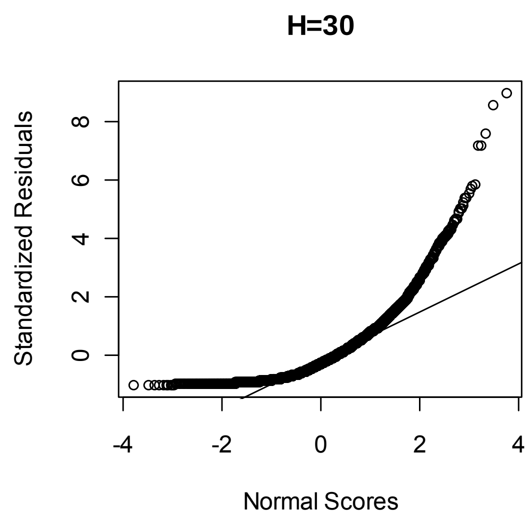

Figure 20. Normal probability plot of the standardized residuals, for the model with H=30.

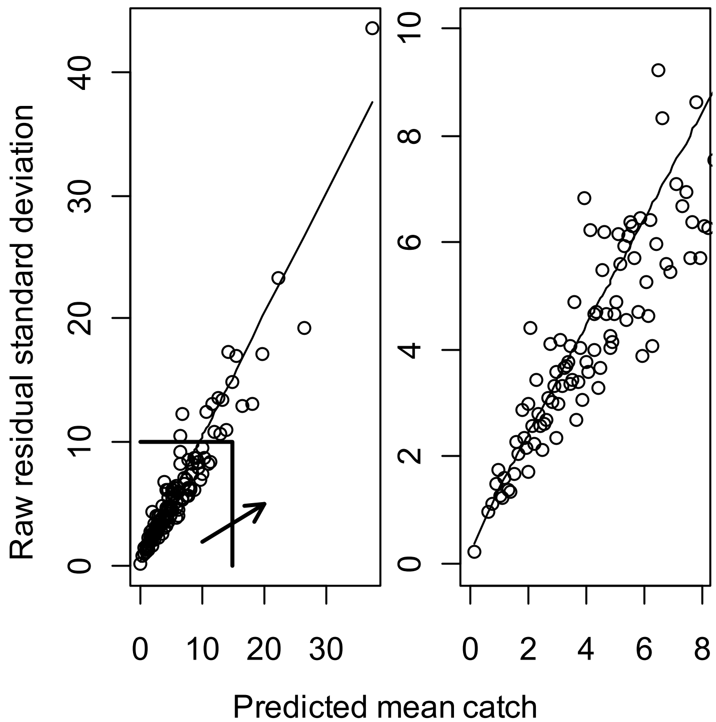

Figure 21. Standard deviations (sd's) of the binned raw residuals, for the model with H=30. The solid line is the NB prediction of the raw residual sd, {predicted(1 + predicted/k)}$^{1/2}$.

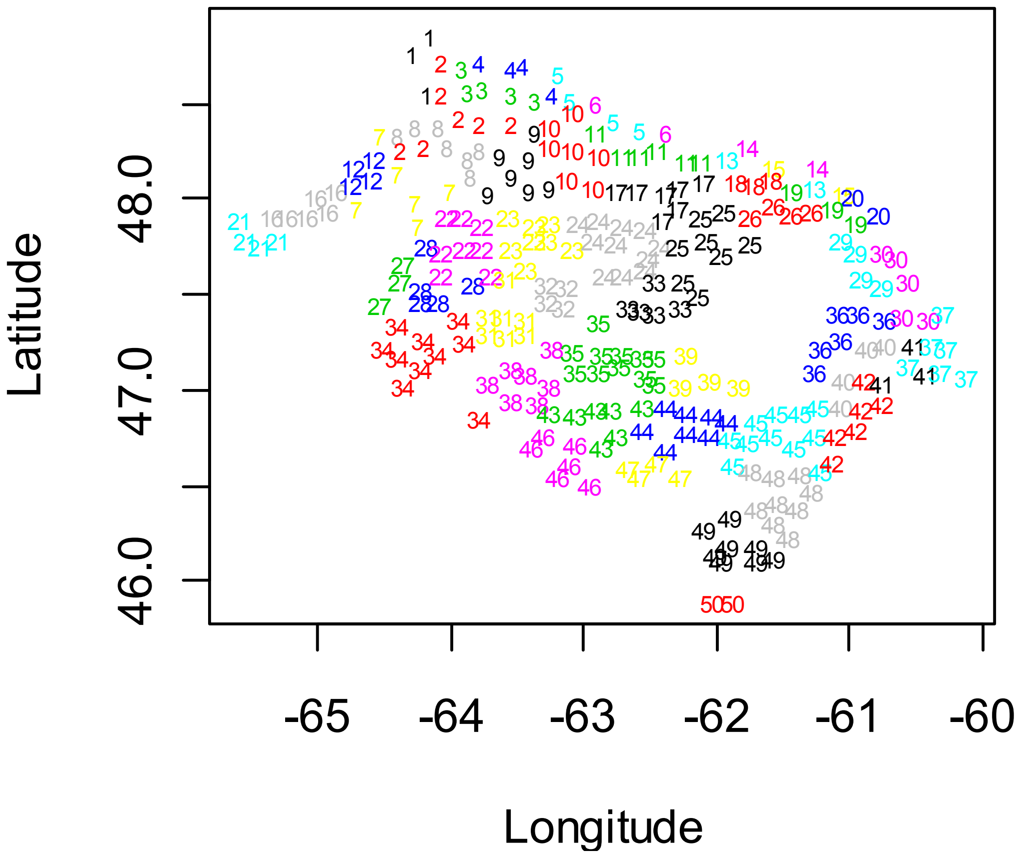

Figure 22. Assignment of grids into 50 strata. The location of each grid is plotted with its corresponding strata number.

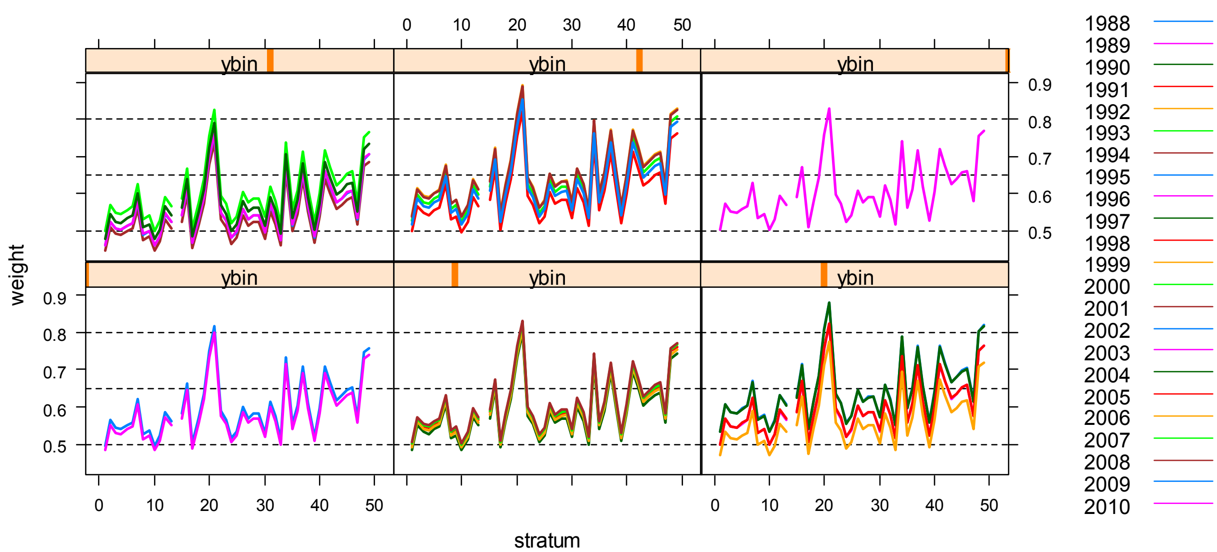

Figure 23. Estimated weights by stratum (H=50) and year. Each panel shows weights for groups of years: 1) 1988-89, 2) 1990-1994, 3) 1995-1999, 4) 2000-2004, 5) 2005-2009, 6) 2010.

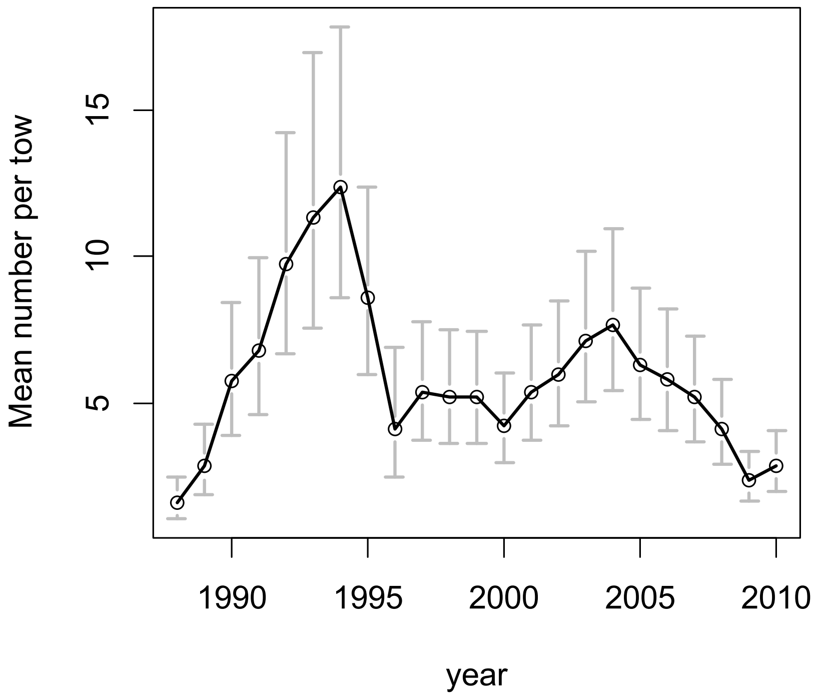

Figure 24. Estimates of mean number per tow for 4T snow crab based on a model with H=50 strata. Grey vertical lines indicate 95% confidence intervals.

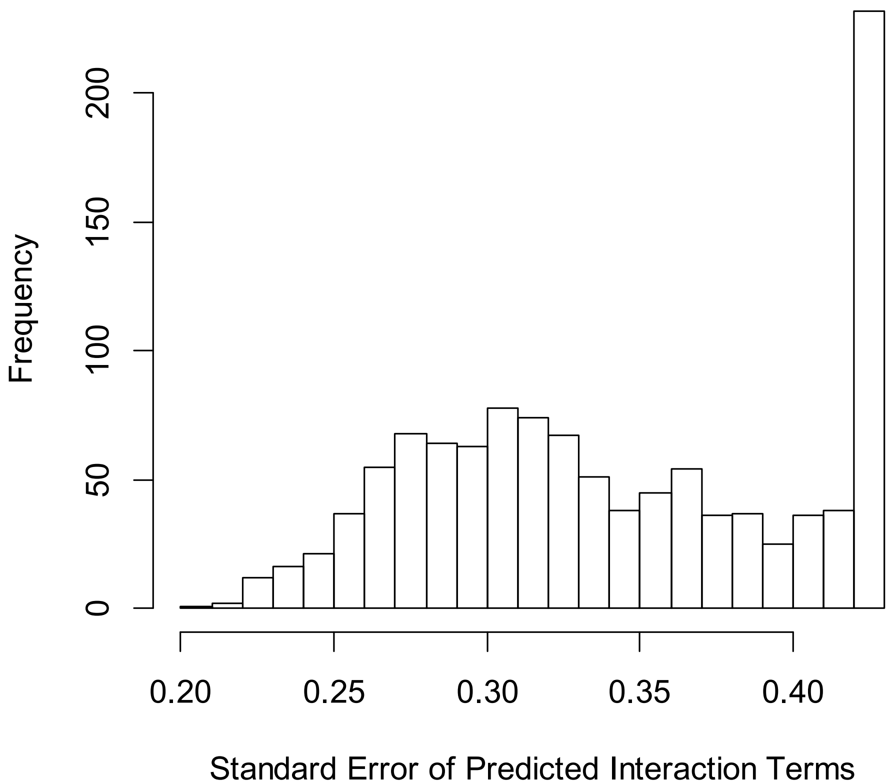

Figure 25. A histogram of the standard errors of the predicted random interaction terms for all years. The "spike" on the right-hand side reflects the standard errors un-sampled for strata. H=50 strata.

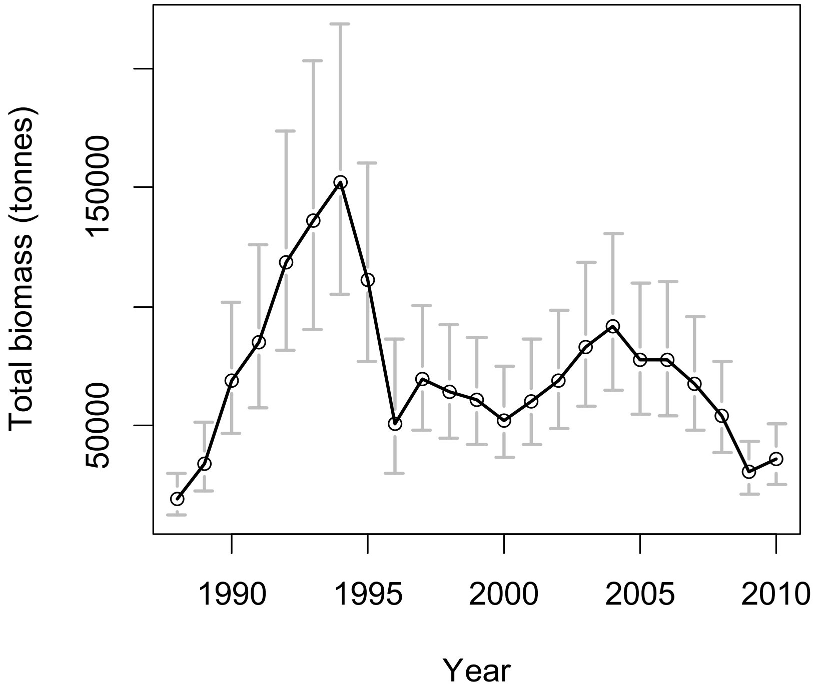

Figure 26. Estimates of total survey biomass for 4T snow crab based on a model with H=50 strata. Grey vertical lines indicate 95% confidence intervals.

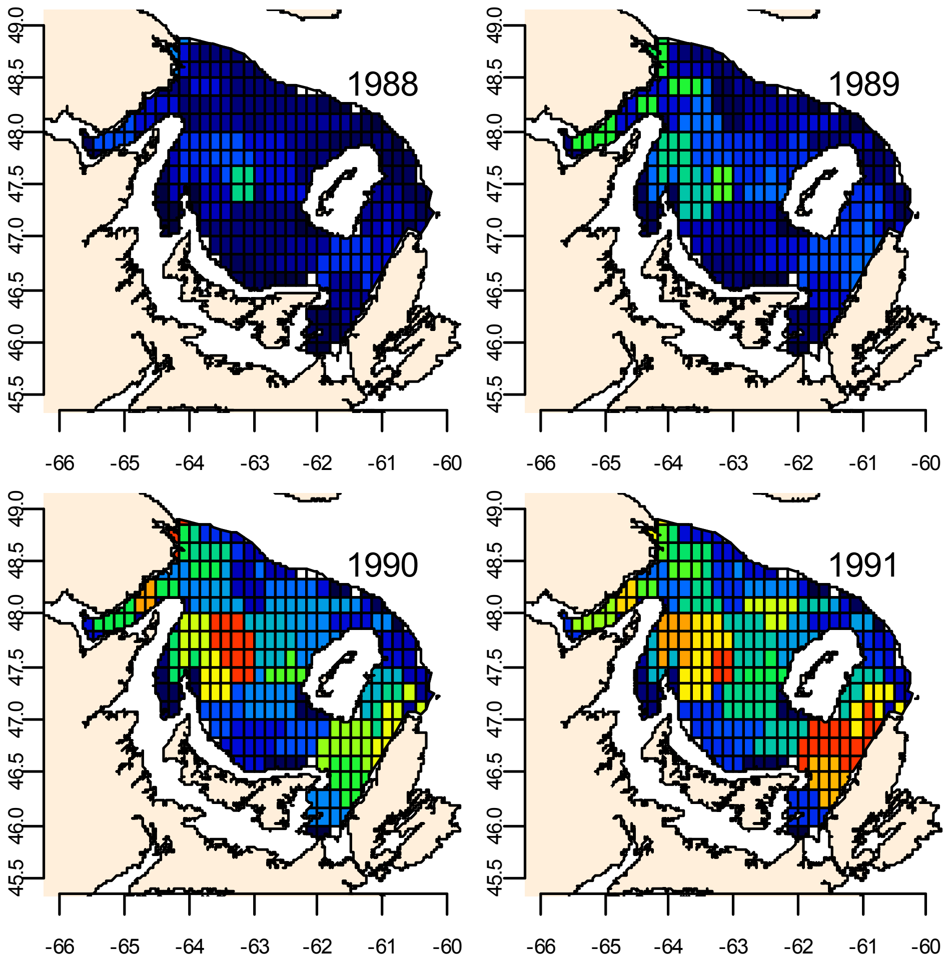

Figure 27. Annual estimates of the density of snow crab (number per tow) in each stratum for 1988-1991. The color scheme is low (dark blue) to high (red). The number of strata is 50.

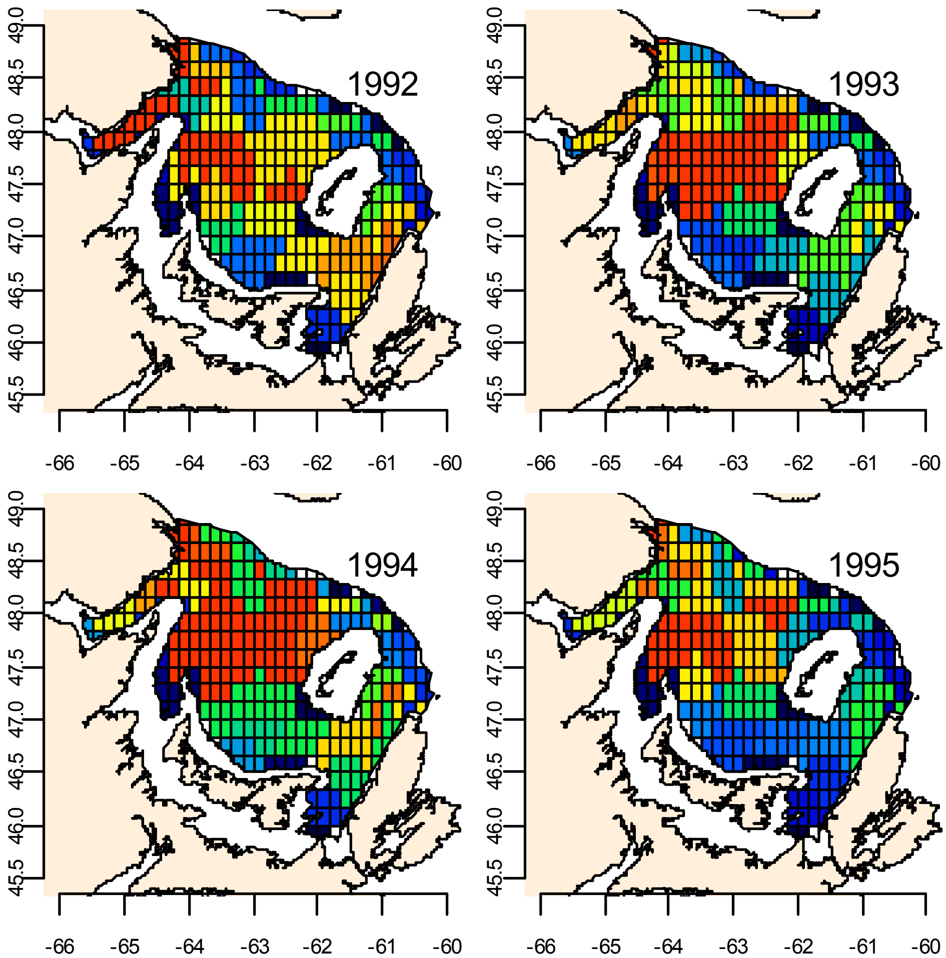

Figure 28. Annual estimates of the density of snow crab (number per tow) in each stratum for 1992-1995. The color scheme is low (dark blue) to high (red). The number of strata is 50.

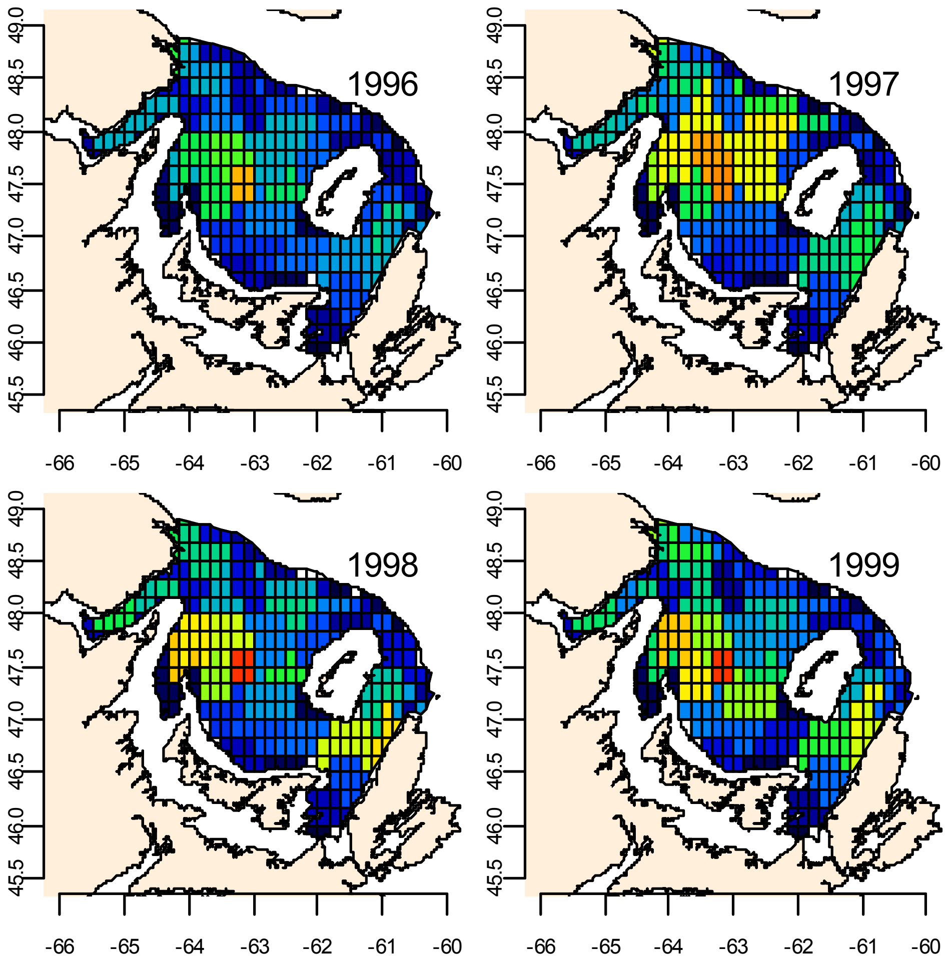

Figure 29. Annual estimates of the density of snow crab (number per tow) in each stratum for 1996-1999. The color scheme is low (dark blue) to high (red). The number of strata is 50.

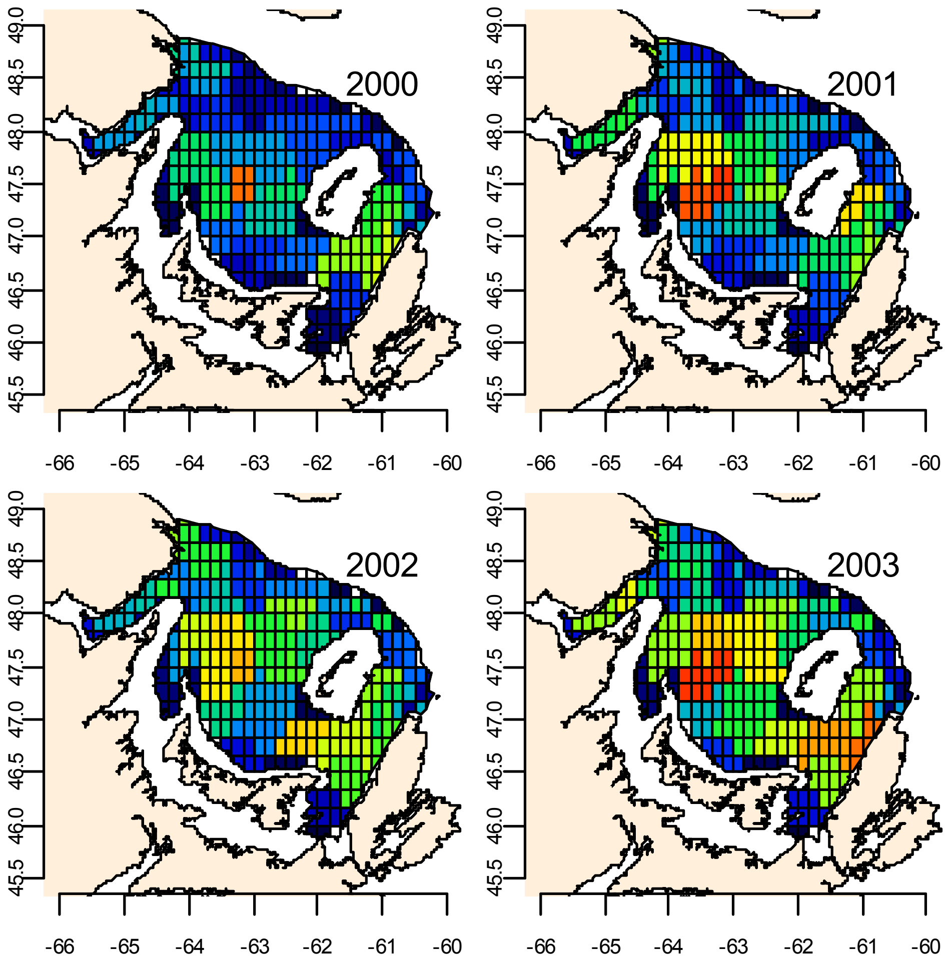

Figure 30. Annual estimates of the density of snow crab (number per tow) in each stratum for 2000-2003. The color scheme is low (dark blue) to high (red). The number of strata is 50.

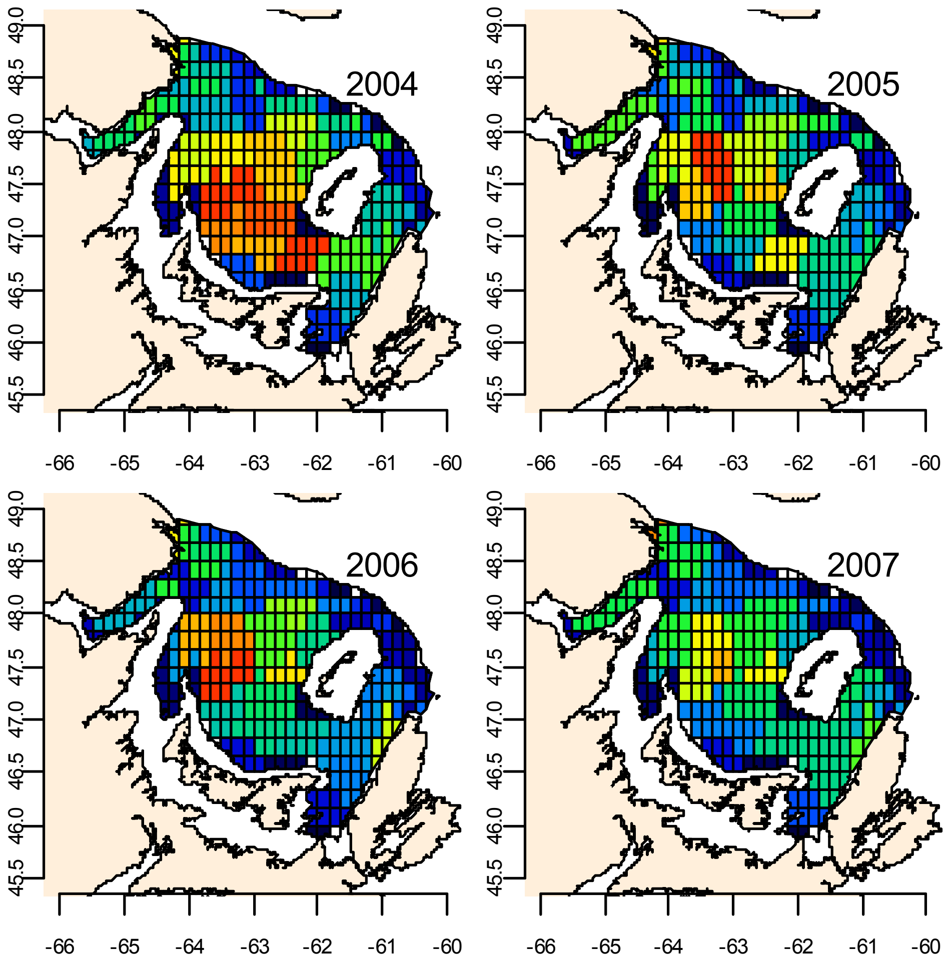

Figure 31. Annual estimates of the density of snow crab (number per tow) in each stratum for 2004-2007. The color scheme is low (dark blue) to high (red). The number of strata is 50.

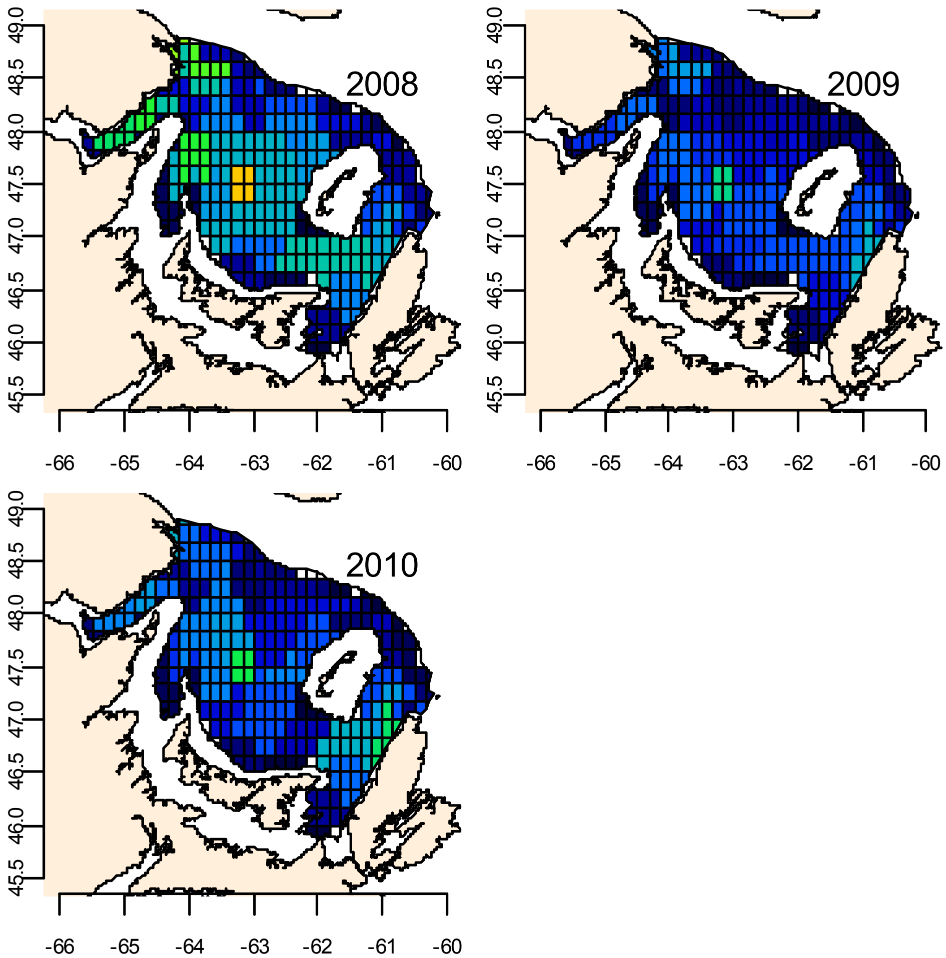

Figure32. Annual estimates of the density of snow crab (number per tow) in each stratum for 2008-2011. The color scheme is low (dark blue) to high (red). The number of strata is 50.

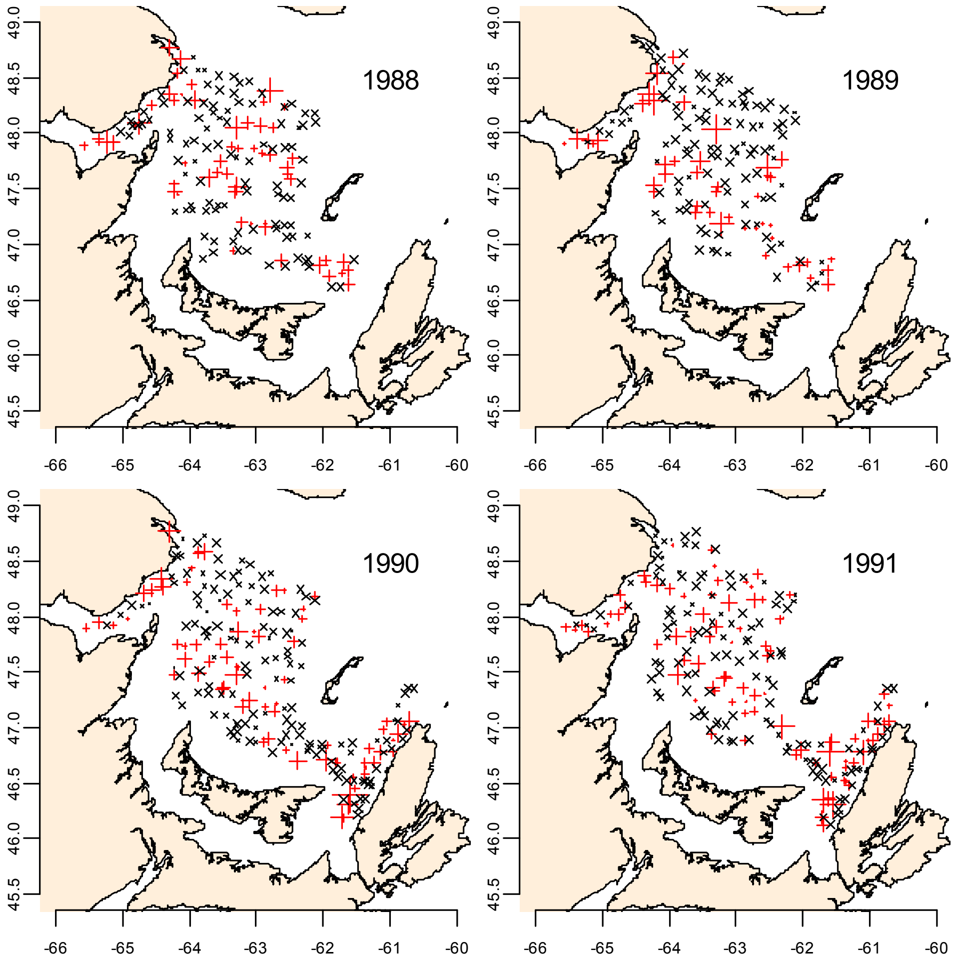

Figure 33. Standardized NB residuals for 1988-1991. The size of the plotting symbol is proportional to the square root of the absolute residual. A red **+** *indicates a positive residual, and a black* **×** *indicates a negative residual. H = 50 strata*

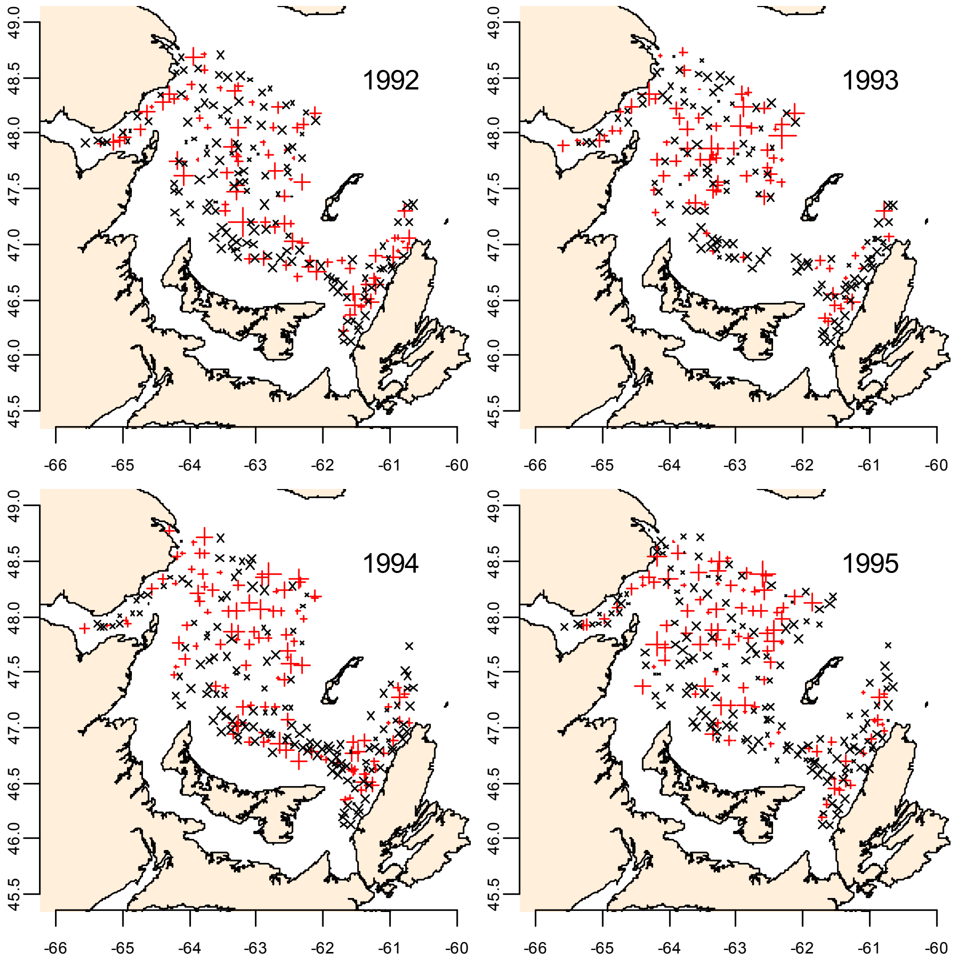

*Figure 34. Standardized NB residuals for 1992-1995. The size of the plotting symbol is proportional to the square root of the absolute residual. A red **+** indicates a positive residual, and a black **×** indicates a negative residual. H = 50 strata.*

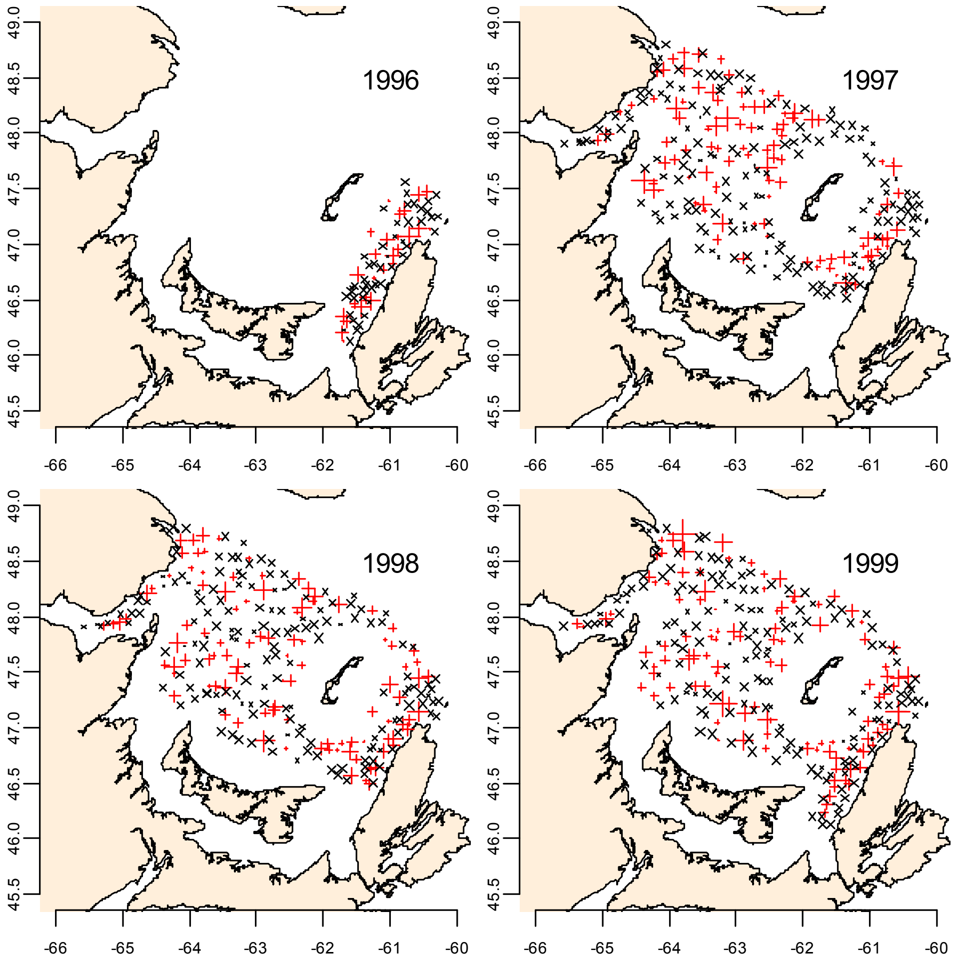

Figure 35. Standardized NB residuals for 1996-1999. The size of the plotting symbol is proportional to the square root of the absolute residual. A red **+** *indicates a positive residual, and a black* **×** *indicates a negative residual. H = 50 strata.*

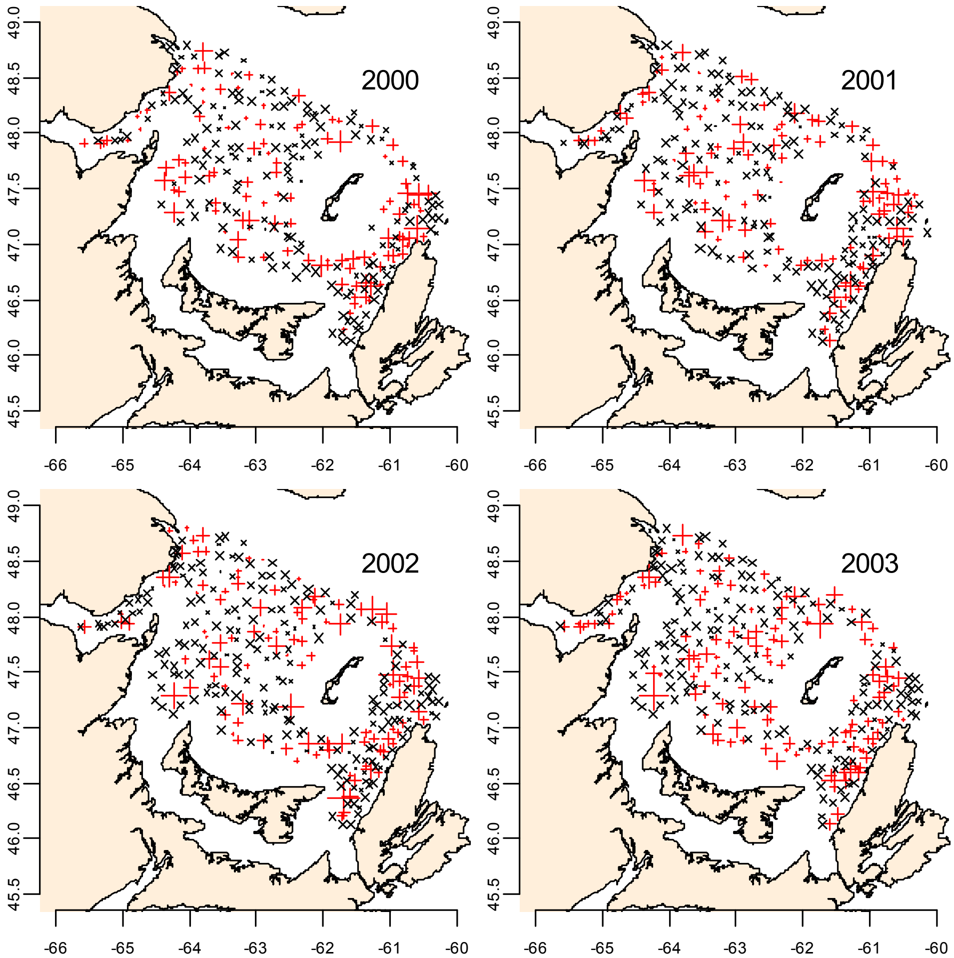

Figure 36. Standardized NB residuals for 2000-2003. The size of the plotting symbol is proportional to the square root of the absolute residual. A red **+** *indicates a positive residual, and a black* **×** *indicates a negative residual. H = 50 strata.*

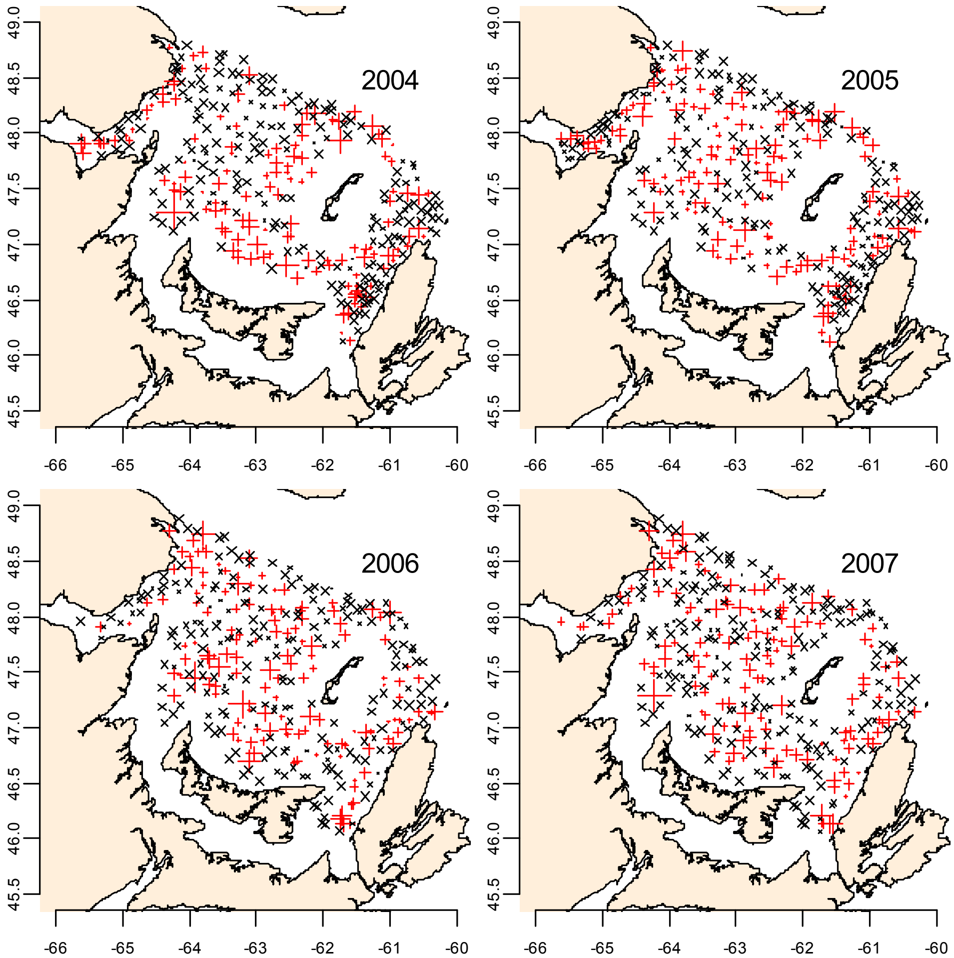

Figure 37. Standardized NB residuals for 2004-2007. The size of the plotting symbol is proportional to the square root of the absolute residual. A red **+** *indicates a positive residual, and a black* **×** *indicates a negative residual. H = 50 strata.*

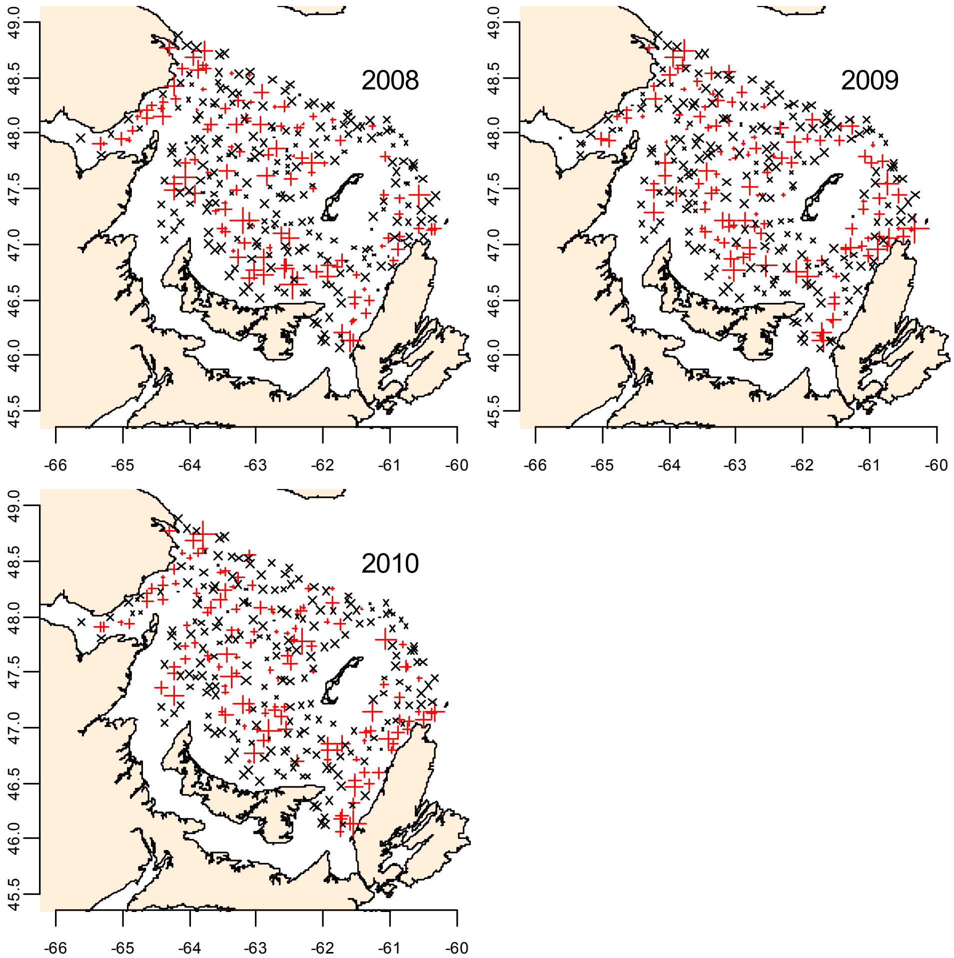

Figure 38. Standardized NB residuals for 2008-2010. The size of the plotting symbol is proportional to the square root of the absolute residual. A red **+** *indicates a positive residual, and a black* **×** *indicates a negative residual. H = 50 strata.*

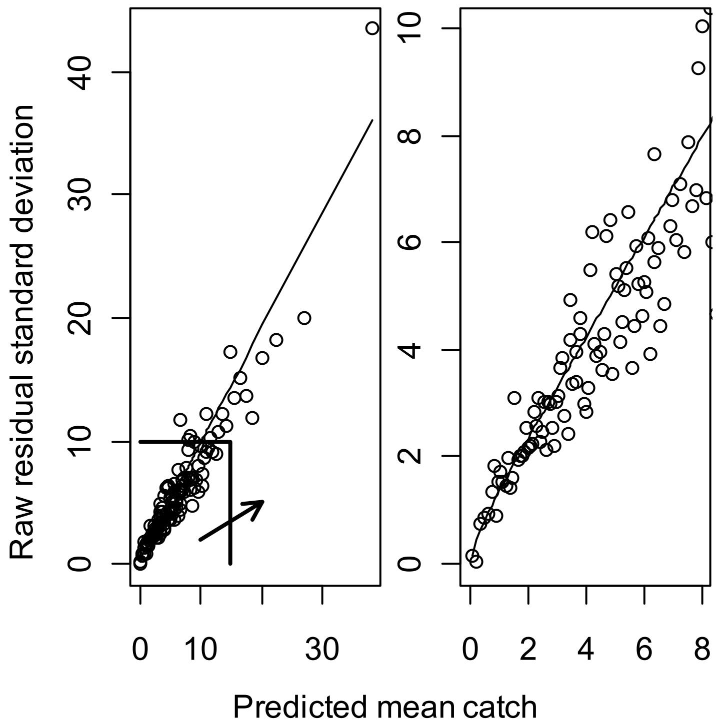

Figure 39. Standard deviations (sd's) of the binned raw residuals, for the model with H=50. The solid line is the NB prediction of the raw residual sd, {predicted(1 + predicted/k)}$^{1/2}$.

APPENDIX 1. R CODE

Clustering

```
dpth = tapply(data$Depth,data$grid,mean,na.rm=T)
dpth[is.na(dpth)]=52.5
lat = tapply(data$Lat,data$grid,mean,na.rm=T)
lon = tapply(data$Lon,data$grid,mean,na.rm=T)
cdata=data.frame(depth=dpth,lat=lat,lon=lon)
scdata=scale(cdata)
n.stratum=30
fit <- pam(scdata, n.stratum)
stratum = unlist(fit$clustering)
```

Weights

```
data$fstratum = as.factor(data$stratum)
data$fyear = as.factor(data$Year)
fit1 = glm(Commercial.weight ~ fstratum + fyear,family=gaussian(link = "log"),
      offset = log(Commercial.count),data=data,subset = Commercial.count>0)
uyear = unique(data$Year)
stratum = sort(unique(data$stratum))
ppoints = data.frame(fyear = as.factor(rep(uyear,each=n.stratum)),
  fstratum = as.factor(rep(stratum,length(uyear))))
ppoints$Commercial.count=1
weight.predict = exp(predict(fit1,ppoints))
wdata = data.frame(year = rep(uyear,each=n.stratum),
  stratum = rep(stratum,length(uyear)),weight=weight.predict)

wdata$ybin = wdata$year - wdata$year%%5
xyplot(weight ~ stratum|ybin,groups=year,data=wdata,type='l',auto.key =
      list(space = "right", points = FALSE, lines = TRUE,lwd=2),lwd=2,
      panel = function(...) {
         panel.abline(h = c(0.5,0.65,0.8), lty = 2)
         panel.xyplot(...)
      })
```