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Trends in the biomass, distribution, size composition and model-based estimates of commercial abundance of snow crab (*Chionoecetes opilio*) based on the multi-species bottom trawl survey of the southern Gulf of St. Lawrence, 1980-2014.

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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 research vessel bottom-trawl survey of the southern Gulf of St. Lawrence undertaken each September (RV survey) has been shown to provide reliable standardized indices of biomass, spatial distribution and habitat use of commercial-sized male snow crab (*Chionoecetes opilio*) for 2001-present and of all snow crab (aggregated index) for 1980-present. Furthermore, results from that survey have successfully been combined with data from a dedicated snow crab survey as part of model-based estimation of the abundance of commercial male snow crab. This document provides an update for biomass indices, spatial distribution, and size composition based on the results of the 2014 RV survey. Furthermore, the document provides an update of the model-based estimates of commercial crab abundance, as well as a presentation and discussion of a few changes that were made for that estimation since 2014. This information was provided in support of the regional snow crab assessment process that took place in Moncton, NB on January 27-29, 2015. Of particular note, the RV survey confirmed continued high biomasses of commercial-sized adult male snow crab since 2011 which were also estimated by the dedicated snow crab survey. Model-based estimates of commercial crab abundance in 2013 and 2014 were above the long-term average. The 2014 RV survey captured an unusually high number of small crabs (≤15 mm) in several areas of the southern Gulf of St. Lawrence. This is seemingly part of a general increase in small crab abundance since the early 2000s.

Tendances de la biomasse, de la distribution, de la composition des tailles et des estimations selon les modèles de l’abondance de crabe des neiges (*Chionoecetes opilio*) de taille commerciale basé sur le relevé au chalut de fond du crabe du neige et du relevé multi-espèces au chalut de fond du sud du Golfe du St.-Laurent, 1980 à 2014

RÉSUMÉ

Le relevé annuel au chalut de fond effectué en septembre par un navire de recherche (NR) dans le sud du golfe du Saint-Laurent (ci-après nommé relevé par NR) produit des indices normalisés fiables de biomasse, de répartition et d'utilisation de l'habitat pour le crabe des neiges (*Chionoecetes opilio*) mâle de taille commerciale depuis 2001, et pour tous les crabes des neiges (indice agrégé) depuis 1980. De plus, les résultats provenant de ce relevé ont été intégrés avec succès aux résultats provenant d’un relevé visant principalement le crabe des neiges dans le cadre d’une estimation basée sur un modèle de l’abondance de crabes commerciaux. Dans le présent document de recherche, une mise-à-jour des indices de biomasse, de distribution et de répartition des tailles du relevé par NR sont présentés basés sur les résultats du relevé de 2014. De plus, une mise-à-jour est présentée pour l’estimation basée sur un modèle de l’abondance de crabes commerciaux. Ces informations sont fournies en appui au processus d'évaluation régionale du crabe des neiges de 2015, lequel a eu à Moncton, au N.-B., du 27 au 29 janvier. En particulier, le relevé par NR confirme l’existence soutenue d’une biomasse élevée de crabes adultes de taille commerciale, qui a aussi été observée dans le cadre du relevé dédié au crabe des neiges. L’estimation de l’abondance de crabes commerciaux basée sur un modèle suggère que l’abondance se trouvait au delas de la moyenne à long terme en 2013 et 2014. En 2014, le relevé par NR a capturé un nombre anormalement élevé de petits crabs (≤15 mm) à plusieurs endroits dans le sud du golfe du Saint-Laurent. Ceci fait partie d’une tendance générale à la hausse qui a débutée au début des années 2000.

1. INTRODUCTION

There are two fishery-independent bottom-trawl surveys that provide relative abundance indices for snow crab in the southern Gulf of St. Lawrence (sGSL). One of the surveys is principally directed at snow crab and has been conducted annually since 1988 (henceforth called the crab survey, CS) (Hébert et al. 2014). The second is a multi-species research vessel bottom-trawl survey conducted annually since 1971 (henceforth called the research vessel survey, RVS), which was initially focused on demersal fish but which has provided information on snow crab in the catches since 1980 (Benoît 2014). Both surveys provide a coherent picture of the abundance, distribution, habitat preferences and demographic structure of sGSL snow crab (Benoît 2012).

This document provides an update for biomass indices, spatial distribution, and size composition of sGSL snow crab based on the results of the 2014 RVS. The document also provides an update for commercial snow crab abundance estimates derived from a model that integrates the data from the RVS and CS (Benoît and Cadigan 2014). This model addresses a number of shortcomings in the respective surveys to provide a standardized index of abundance for 1980-2014. These shortcomings include past changes in the sampling frame for the CS, uncalibrated changes in survey vessel and gear in the CS, and failure to disaggregate catches of snow crab in the RVS by sex and size prior to 2001 (details in Benoît and Cadigan 2013, 2014). Slight changes to the modelling approach made after the 2014 assessment for the stock are described in this document. Furthermore, the software used to fit the model changed. The consequences of these two changes are presented and discussed.

The information presented in this document was provided in support of the regional snow crab assessment process that took place in Moncton, NB from January 27-29, 2015.

2. METHODS

2.1 BACKGROUND AND DATA

2.1.1 The September multi-species RV survey

The RVS has been undertaken each September since 1971. It follows a random-stratified design, with strata defined on the basis of depth and area (Fig. 1) (see Hurlbut and Clay 1990 for details on the survey methodology). A common group of strata has been sampled annually since 1971, covering most of the southern Gulf of St. Lawrence (Northwest Atlantic Fishery Organization area 4T). Three inshore strata (strata 401, 402, and 403) were added to the survey in 1984. There are very few snow crab caught in these strata (Benoît and Cadigan 2013) and these strata and data are excluded from analyses that include years prior to 1984 so that the same set of strata are used in the time series analyzed. The target fishing procedure at each station during the survey is a 30-min. tow at a speed of 3.5 knots. The number of valid fishing sets completed annually has varied from approximately 70 during the early 1980s to 175 or more during much of the 1990s and 2000s. In 2014, 156 valid sets were completed (Table 1).

Catches of snow crab (numbers and mass per tow) have consistently been recorded in the survey since 1980 (Tremblay 1997). Prior to 1992, there was a small number of sets for which catch numbers were recorded but mass was not when the mass was <1 kg (Table 1). This was the consequence of the precision of the spring scales used at that time to weigh catches, and these cases were generally when catch per tow was ≤ 0.5 kg; amounts were generally rounded up to the nearest kg otherwise. For the calculation of an aggregated biomass index (kg/tow) the mass was assumed to be 0.5 kg in these cases, producing a very comparable result to that obtained using an estimated mean mass of crabs multiplied by the observed number in a set to estimate catch mass. For the model based estimates, such cases were assumed to reflect the absence of large snow crab (≥95 mm) in the catch (for an explanation see Benoît and Cadigan 2013). In most years prior to 2001 there was a small proportion of sets for which snow crab catch mass was recorded, but not catch numbers (Table 1). In these instances, the number caught was inferred using the stratum and year specific average catch mass per crab derived from sets with both catch and mass observations.

Since 2001, captured crabs have also been measured (carapace width) and sexed. Since 2012 all individual crabs were meant to be sexed, measured, weighed and their maturity determined based on the shape of the abdomen for females and based on measurements of chela height using the method of Conan and Comeau (1986) for males. In addition, any missing or regenerated appendages were meant to be noted. However, problems with the survey data entry system arising mid-way through the 2014 survey prevented the recording of chela height and appendage data. Consequently, the maturity of males could not be determined for the last 49 sets that caught males in 2014.

Fishing during the RV survey was carried out by the *E.E. Prince* from 1971 to 1985 using a Yankee-36 trawl. Since then, a number of different vessels have been used, each fishing a Western IIA trawl: the *Lady Hammond* (1985-1991), the *CCGS Alfred Needler* (1992-2002 and 2004-2005), the *CCGS Wilfred Templeman* (2003), and the *CCGS Teleost* (2004-present). Parameters for the trawls and vessels used in the RV survey are provided in Tables 2 and 3, respectively. Note that both trawls used in the survey are meant for fishing groundfish, though a liner is used in the codend to retain small animals.

Prior to the gear change and all but one of the vessel changes in the RVS (*CCGS Wilfred Templeman* used in 2003), paired tows involving the two vessels/gears at common sites were undertaken to estimate their relative catchabilities (Benoît and Swain 2003a; Benoît 2006). Based on these comparative fishing experiments, the *E.E. Prince* fishing the Yankee-36 was found to be less efficient at capturing snow crab compared to the *Lady Hammond* and *CCGS Alfred Needler*, and as a result corrections are applied to the *E.E. Prince* data prior to the calculation of indices for the RVS (Benoît and Swain 2003a; Benoît 2006). No corrections are applied for the CCGS Teleost (Benoît 2014). Note that in contrast to the approach used for the RVS indices, adjustments for differences in relative catchability between vessels are estimated and implemented directly in the model-based estimations (details below; Benoît and Cadigan 2014).

The absence of comparative fishing with the *CCGS Wilfred Templeman* used in 2003 precludes the direct estimation of catchability relative to other RVS vessels. Though the model of Benoît and Cadigan (2013, 2014) does provide an estimate for commercial-sized crabs (details below), it does not provide an estimate for size-aggregated catches and still needs to be validated with simulation testing. Consequently, results of the indices based exclusively on the RVS for 2003 are not presented in this report.

From 1971 to 1984, fishing in the RVS survey was restricted to daylight hours (07:00-19:00). Since 1985, fishing has been conducted 24 hours per day. Because fishing efficiency can vary by time of day, survey catches were standardized post-hoc for the calculation of indices from the RVS, based on the results of analyses of survey catches and comparative fishing over the diel cycle (Benoît and Swain 2003b; details in Benoît 2014). Note again that in contrast to the approach used for the RVS indices, adjustments for diel differences in relative catchability are estimated and implemented directly in the model-based estimations (details below; Benoît and Cadigan 2014).

The estimation model of Benoît and Cadigan (2014) is based in part on the abundance of commercial sized crabs (males ≥95 mm) in the RVS. Those values are directly available since 2001 but not for the 1980-2000 period. For the 1980-2000 time period, an empirical relationship between the mean mass of crabs in a survey set and the proportion of large males (*PLM*) in that set is used to predict the catches of commercial sized males based on length aggregated catches (details in Benoît and Cadigan 2013, 2014). In the past that estimation step was done externally to the model and was applied as part of an offset term during model fitting. In this document we provide results from a new version of the model in which this estimation is integrated into the model fitting (details below). This was done so that this source of uncertainty is included in uncertainty estimates for snow crab abundance.

2.1.2 The snow crab survey

The snow crab survey has been conducted annually since 1988, though survey coverage was very limited in 1996; details are available in Moriyasu et al. (2008). The survey has generally been conducted following the commercial fishery, generally beginning in July and ending in late September or early October, though the start and duration have varied between years. The survey follows a systematic random sampling design in which, for most years, stations were largely fixed once chosen. The survey gear is a Nephrops trawl (20 m Bigouden trawl net) and the target fishing procedure at each site is a 4-6 minute tow at an average speed of approximately 2 knots. Trawl mounted sensors are used to quantify the swept area of tows, which is used to standardize the catches. Each individual crab captured in the snow crab survey is sampled with respect to their biological characteristics. Here we consider only the catches of commercial sized-males. For 2014, there were 353 valid CS sets included in the analyses (Table 1).

Four chartered vessels have been used to conduct the survey since 1988: the side trawler *Emy-Serge* (1988-1998), and the stern trawlers, *Den C Martin* (1999-2002), *Marco-Michel* (2003-2012) and *Jean-Mathieu* (2013-2014). There has not been any comparative fishing between these vessels to estimate their relative fishing efficiency. In addition to the change in vessels, the survey gear was modified after 1990. Specifically, a chain that had been attached to the trawl footgear was subsequently wrapped around the footgear to increase gear-handling safety and fishing efficiency, based on the advice of experienced harvesters. There has been no comparative fishing with respect to the gear modification.

The snow crab survey sampling frame has changed considerably from 1988 to 2014 (Moriyasu et al. 2008; Benoît and Cadigan 2013). With the notable exception of 1996, the area covered generally increased over time though the area was largely constant from 1997-2005 and from 2006 to present. Survey data for 1988-1996 are not used in the stock assessment because of gaps in survey coverage with respect to the target sGSL snow crab assessment area (DFO 2012).

The approach of Benoît and Cadigan (2013; 2014) models the survey catches of commercial snow crab as a function of the RVS strata (Fig. 1). Stratum 417 was modified slightly to include a small area consistently sampled by the CS. Sets from the snow crab survey were attributed to the strata based on their respective geographic positions using the ‘point.in.polygon’ function in the ‘sp’ package for R (Bivand et al. 2008). The estimation domain for the model was strata 415-439, including the adjustment to stratum 417.

2.2 ANALYSIS

2.2.1 Multi-species RV survey indices

Trawlable biomass (kg) of commercial male snow crab in year t (RV_t), was calculated as:

$$RV_t = Padult_t \sum_{l=1}^{L} \frac{U_l}{n_{l,t}} \sum_{i=1}^{n_{l,t}} \sum_{j=95}^{J} y_{i,j,t}\, \alpha\, j^{\beta} \quad (1)$$

for t = 2001 to 2014 (excluding 2003),

where $Padult_t$ is the proportion of snow crab ≥95mm that were adults in year t,

U_l is the number of trawlable units in stratum l (i.e., surface area / area swept by a standard tow),

$n_{l,t}$ is the number of survey tows in stratum l and year t,

$y_{i,j,t}$ is the standardized number of male crab of carapace width j caught in tow i in year t, and

α = 2.665E-7 and β = 3.089 are parameters for the relationship between carapace width (in mm) and mass (in g) (Hébert et al. 2014).

The values for $Padult_t$ were taken from the dedicated snow crab survey for all years for reasons of consistency (Hébert et al. 2014; Hébert pers. comm. for 2014 value). Confidence intervals were calculated using the standard estimator for standard error based on stratified random sampling (Krebs 1989) and using a Satterthwaite approximation for the degrees of freedom for the t-value.

An aggregated biomass index for snow crab per standard 1.75 NM tow (mean kg/tow, B_t ; all sizes and sexes) was calculated as:

$$B_t = \sum_{l=1}^{L} \frac{U_l}{U \cdot n_{l,t}} \sum_{i=1}^{n_{l,t}} b_{i,t} \quad (2)$$

for t = 1980 to 2014 (excluding 2003),

where U is the total number of trawlable units in the survey domain and

$b_{i,t}$ is the observed biomass (kg) of snow crab in set i of year t.

Analyses for B_t were undertaken for two geographic areas of inference: the current snow crab assessment area representing 57,840 km^2, and the RV survey area for strata 415-439 (Fig. 1) representing 70,061 km^2. To approximate the snow crab assessment area, strata 401-403, 420, 421, 428, 432, and 435 were excluded from the analysis. Analyses for RV_t were only undertaken for the geographic area equivalent to the current snow crab assessment area because the values of $Padult_t$ are pertinent to this area.

Annual survey-weighted proportions ($P_{j,s,t}$) of sGSL crab as a function of each mm carapace diameter j, and each sex (for 2001-2011) or sex and maturity stage (2012-2014) s, were calculated as:

$$P_{j,s,t} = \sum_{i} \left(w_{i,t} \cdot y_{i,j,s,t} \right) \Big/ \sum_{s} \sum_{j_s} \sum_{i} \left(w_{i,t} \cdot y_{i,j_s,s,t} \right) \quad (3)$$

Where $w_{i,t} = \dfrac{U_l}{U \cdot n_{l,t}}$.

These values were used to produce annual histograms for the RV survey catches.

Catch rates as numbers per tow of commercial-sized adult male snow crab in the RV survey were mapped using inverse distance weighted gradient interpolation. The contour levels for plotting were defined as the 10th, 25th, 50th, 75th, and 90th percentiles of non-zero catches over the period of interest, 2001-2014 (excluding 2003). Catch rates of small crab (≤15 mm) were likewise mapped to illustrate their spatial distribution given an observed high relative abundance since 2012.

2.2.2 Integrated abundance index estimation model

Here we provide a summary of the estimation model (see Benoît and Cadigan (2014) for additional details).

The basic model assumes that crab density is stochastically constant within strata, i.e., density varies randomly within a stratum with a constant mean. Density is assumed to be independent from site to site within strata, and crab densities are modeled separately for each stratum and for each year. The index of stock size is based on the strata size-weighted average of the strata densities. Trawl catches are basically assumed to Negative Binomial (NB) random variables, which is considered suitable for modeling trawl catches (Cadigan 2011). Trawl catches are assumed to be a function of the underlying density, catchability of commercial snow crab to the surveys, and the area swept by survey tows.

The model contains parameters that account for factors that affect the catchability of crab within and between surveys. First, there is a parameter that accounts for different catchability between day (7:00-19:00) and night tows in the RVS. Information to estimate this parameter comes from the contrasts between day and night catches in the RVS within common strata and years and for repeated (paired) tows conducted day and night at the same sites, typically within 24 hrs. No diel adjustment is required for the CS (Benoît and Cadigan 2013).

Second, there is a suite of parameters to account for catchability differences between vessels used for the surveys (q_v; see Figure 2 for a summary of which vessels were used in each year):

$$q_v = \begin{cases} 1, & v = Teleost, & 2004-2014, \\ q_{WT\to T}, & v = Wilfred\ Templeman, & 2003, \\ q_{AN\to T}, & v = Alfred\ Needler, & 1992-2005,\ not\ 2003, \\ q_{LH\to T} = q_{LH\to AN}q_{AN\to T}, & v = Lady\ Hammond, & 1985-1992, \\ q_{EP\to T} = q_{EP\to LH}q_{LH\to AN}q_{AN\to T}, & v = EE\ Prince, & 1980-1985, \\ q_{SCS1\to T}, & gear\ used\ in\ SCS1, & 1988-1990, \\ q_{SCS2\to T}, & gear\ used\ in\ SCS2, & 1991-1998, \\ q_{SCS3\to T}, & v\ in\ SCS3, & 1999-2002, \\ q_{SCS4\to T}, & v\ in\ SCS4, & 2003-2012. \\ q_{SCS5\to T}, & v\ in\ SCS5, & 2013,\ 2014 \end{cases}$$

The notation $q_{a\to b}$ indicates the catchability of vessel *a* relative to vessel *b*. The catchability of the *CCGS Teleost* was fixed at one and *CCGS Teleost* was the reference vessel. Information to estimate the catchabilities for all RVS vessels except the *Wilfred Templeman* comes almost exclusively from the paired-tow comparative fishing data (within-pair catch contrast). Because there was no direct comparative fishing between the *EE Prince* or the *Lady Hammond* and the *CCGS Teleost*, these conversions were inferred stepwise, e.g. $q_{EP\to T} = q_{EP\to LH}q_{LH\to AN}q_{AN\to T}$. Information to estimate the catchabilities for the remaining vessels (*Wilfred Templeman* and the five CS vessels, SCS1-SCS5) comes from contrasts in catches between surveys, within strata and years.

Third there are two parameters that determine the NB over-dispersion; one for between-site variability of crab density (k) and one for within pair over-dispersion (k_p).

The model was originally implemented in AD Model Builder (ADMB; Fournier et al. 2012). The model has recently also been implemented in Template Model Builder (TMB; Kristensen 2013), a new model fitting environment that provides considerably more efficient and rapid estimation of random effects, as are used here to model the NB over-dispersion and to address within pair correlations. Though the estimates obtained using both modelling environments are expected to be very similar, they are nonetheless compared here to confirm that this is the case.

A second change to the model compared to the 2014 assessment concerns the estimation of the proportion of large males (*PLM*) for RVS catches for 1980-2000. Whereas *PLM* was estimated outside the model for the 2013 and 2014 assessment documents (Benoît and Cadigan 2013; 2014), for the present analyses the estimation was integrated directly in the model fitting. In this manner, the uncertainty inherent in the *PLM* estimation is integrated in the uncertainty of annual abundance estimates. We compare the results obtained using both approaches.

The comparisons of model results between model fitting environments and for internal versus external estimation of *PLM* were completed before the 2014 survey results were available. Those comparisons were therefore based on the data for 1980 to 2013.

3. RESULTS AND DISCUSSION

3.1 MULTI-SPECIES RV SURVEY INDICES

The biomass of commercial-sized adult male snow crab increased from a relatively low level in 2001, to a relatively high level mid-decade, declining to the lowest levels of the 2000s in 2010 (Fig. 3). Since then, the index has increased, reaching a level in 2013 and 2014 that is comparable to that of the mid-2000s.

The RV survey aggregated biomass index (all sizes, both sexes) provides a longer-term perspective of snow crab population dynamics in the sGSL (Fig. 4). Trends in this index during the 2000s generally match those observed for large male crab (Fig. 3) because the large males typically comprise the bulk of the biomass in the catches. The exception was in 2013, when the aggregated index reached its highest value since the early 1990s (Fig. 4). The value for 2014 was above the long-term average of 6.0 kg/tow.

The size-frequency distributions of crabs in the RV survey are shown in Figure 5. Generally, the late 2000s were characterized by a higher proportion of snow crab <30 mm, relative to the early 2000s. In particular, a very high proportion of small crab (≤15 mm) was observed in the 2012-2014 surveys. Crabs of this size were captured at higher abundances and in more locations in 2013 and 2014 compared to surveys in 2001-2011 (Fig. 6). In fact, high densities of small crabs were caught throughout most of the survey area. These crabs may represent a very early signal of strong incoming recruitment that will hopefully be tracked over the coming years. Higher proportions of such small crabs are expected in the RV survey compared to the dedicated crab survey because of a smaller mesh size in the RV survey trawl codend (19 mm in RV survey compared to 40 mm in the snow crab survey). This may explain why abundance of crabs ≤15 mm has not appeared particularly elevated in the dedicated crab survey in 2012 and 2013.

The relative composition of commercial-sized adult male crab in 2014 was comparable to the levels seen in 2007, 2008 and 2011-2013 (Fig. 5). As in 2012 and 2013, the proportion of crab larger than 110 mm remained small and at a level comparable to that observed during the relatively low abundance years of 2001 and 2009. Densities of commercial-sized adult male snow crab over the Magdalen shallows and the west of Cape Breton Island in the 2014 RV survey were similar to those observed in 2012-2013 (Fig. 7).

3.2 INTEGRATED ABUNDANCE INDEX ESTIMATION MODEL

Very similar trends in estimated snow crab abundance were obtained from the models with external versus internal estimation of the proportion of large males, *PLM* (Fig. 8). Internal estimation resulted in slightly greater uncertainty for the abundance estimates for the 1980 to 2000 period (Fig. 9B) compared to results from the model with external estimation (Fig. 9A). This result was expected given that uncertainty in the *PLM* estimation is desirably reflected in the overall uncertainty of model parameter estimates when that estimation is done internally. This is also evident in the slightly larger confidence intervals for the vessel/gear catchability parameters (Fig 10). Though the estimates for those parameters did differ a little between internal and external *PLM* estimation, particularly for vessels that were in service prior to 2001, the respective confidence intervals obtained for external versus internal estimation overlapped for each of the parameters.

There were very few differences in the results obtained for the model with internal estimation of *PLM*, whether it was estimated in ADMB or TMB (Fig. 11 and 12). There were a few instances of larger residuals from the model fit in ADMB compared to TMB (Fig. 13). This is the result of a difference in the treatment of random effects between environments. In TMB, the Laplace approximation was used directly to obtain the marginal likelihood by integrating out the random effects for replicate tows at a site. In ADMB, the Laplace approximation approach was very slow and the integration had to be coded and then implemented with a special function (adromb function).

Based on the advantages of TMB over ADMB and the pertinence of including the *PLM* estimation directly in the model, these two changes were made for the model estimation for the 1980 to 2014 period. The 2014 CS was the second year in which the vessel Jean-Matthieu (SCS5) was used to complete the survey. The estimated catchability coefficient for that vessel increased relative to last year’s estimate, resulting in a value that was closer to those for the other CS vessels (Fig. 14). The confidence intervals for that estimate were also narrower. The parameter attenuation and increased precision with an additional year of data are expected statistically and were predicted in 2014 based on a quick retrospective analysis of the data for the SCS4 vessel, Marco Michel (see Table 5 in Benoît and Cadigan 2014). Further additional years of data are likely to result in smaller changes in the estimated parameter and more modest improvements in precision.

The change in the q_v value for SCS5 resulted in a decrease in the estimated abundance of commercial snow crab for 2013 compared to estimates derived from the data series excluding the 2014 surveys (Fig. 15). The estimated abundance for 2014 is slightly greater than the estimate for 2013, both values are at an elevated level relative to estimates for years after 1995, and both are above the long-term average of around 105 crabs/km2. The similar fits provided to the model for the 1980-2013 versus 1980-2014 data were also reflected in very similar residual patterns (Fig. 16).

As was found previously, the NB variance model provided a good description of the variance in the raw residuals with respect to the mean (Fig. 17).

Overall, the conclusions of Benoît and Cadigan (2013; 2014) remain valid with the addition of the 2014 values and the other slight changes to the model and model fitting. The model provides a useful method for integrating the available data on snow crab abundance in the sGSL, making the best use of available data. The model draws strength from both the RV and crab surveys to estimate relative catchability parameters that would otherwise be difficult to estimate (SCS1-SCS5 and $q_{WT \rightarrow T}$). Furthermore, the model provides a useful framework in which to efficiently estimate relative catchability coefficients for the RV survey vessels and for a diel effect by drawing simultaneously on information from samples that are grouped at the site level and at the stratum level (S. Wang, N.G. Cadigan, and H.P. Benoît. Inference about regression parameters using highly stratified survey count data with over-dispersion and repeated measurements. Unpublished report submitted to Journal of Applied Statistics). By estimating these parameters within a common modeling framework, their associated uncertainties are reflected in the estimated abundance index, as was shown here by the inclusion of the *PLM* estimation directly in the model.

The switch to TMB for estimation brought a considerable improvement in estimation speed. This has effectively removed a barrier that restricted our ability to conduct simulation testing of the model to ensure its statistical reliability.

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TABLES

Table 1. Annual summary of the number of sets from the research vessel (RVS) and snow crab (CS) surveys used to estimate the abundance index. The summary for the RVS sets is further broken down to indicate the number of sets for which both catch mass and numbers were recorded and sets for which values of only one of the two variables was recorded.

Year	RVS total valid sets	RVS sets with numbers and mass	RVS sets with numbers only	RVS sets with mass only	CS valid sets
1980	70	47	2	21	-
1981	70	57	13	0	-
1982	65	47	17	1	-
1983	67	48	14	5	-
1984	102	85	12	5	-
1985	209	162	41	6	-
1986	164	156	0	8	-
1987	152	128	13	11	-
1988	147	121	19	7	154
1989	166	143	14	9	155
1990	141	134	6	1	212
1991	188	184	0	4	215
1992	162	154	0	8	233
1993	183	176	0	7	208
1994	154	150	0	4	259
1995	175	168	0	7	260
1996	194	189	0	5	72
1997	202	185	0	17	259
1998	192	145	0	47	261
1999	180	175	0	5	277
2000	182	181	0	1	280
2001	141	141	0	0	290
2002	173	173	0	0	319
2003	78	78	0	0	317
2004	212	212	0	0	347
2005	231	231	0	0	355
2006	165	165	0	0	354
2007	163	163	0	0	355
2008	177	177	0	0	355
2009	148	148	0	0	355
2010	137	137	0	0	354
2011	126	126	0	0	353
2012	142	142	0	0	321
2013	122	122	0	0	351
2014	156	156	0	0	353

Table 2. Parameters for the two trawls used in the RV survey of the southern Gulf of St. Lawrence.

Characteristics	Yankee 36	Western IIA
Years in operation	1971-1984	1985-present
Footrope	7 inch (outer sections) and 14 inch (inner sections) rubber disc spacers + 17 lb. iron spacers	21 inch (outer) and 18 inch (inner) rubber bobbins and 6.75 inch diameter 7 inch long rubber spacers
Footrope length (ft)	80	106
Headline length (ft)	60	75
Headline height (ft)	9	15
Wingspread (ft)	35	41
Door type	Steel bound wood	Portuguese (all steel)
Door weight (lbs)	1,000	1,800
Lengthening piece liner (inches)	1.25	1.25
Codend liner (inches)	0.25 inches	0.75 inches

Table 3. Parameters for the vessels used in the RV survey of the southern Gulf of St. Lawrence for the years presented in this report.

Characteristics	*E.E. Prince*	*Lady Hammond*	*CCGS Alfred Needler*	*CCGS Teleost*
Vessel type	Stern trawler	Stern trawler	Stern trawler	Stern trawler
Tonnage	406	897	959	2,405
Length (m)	40	58	50	63

FIGURES

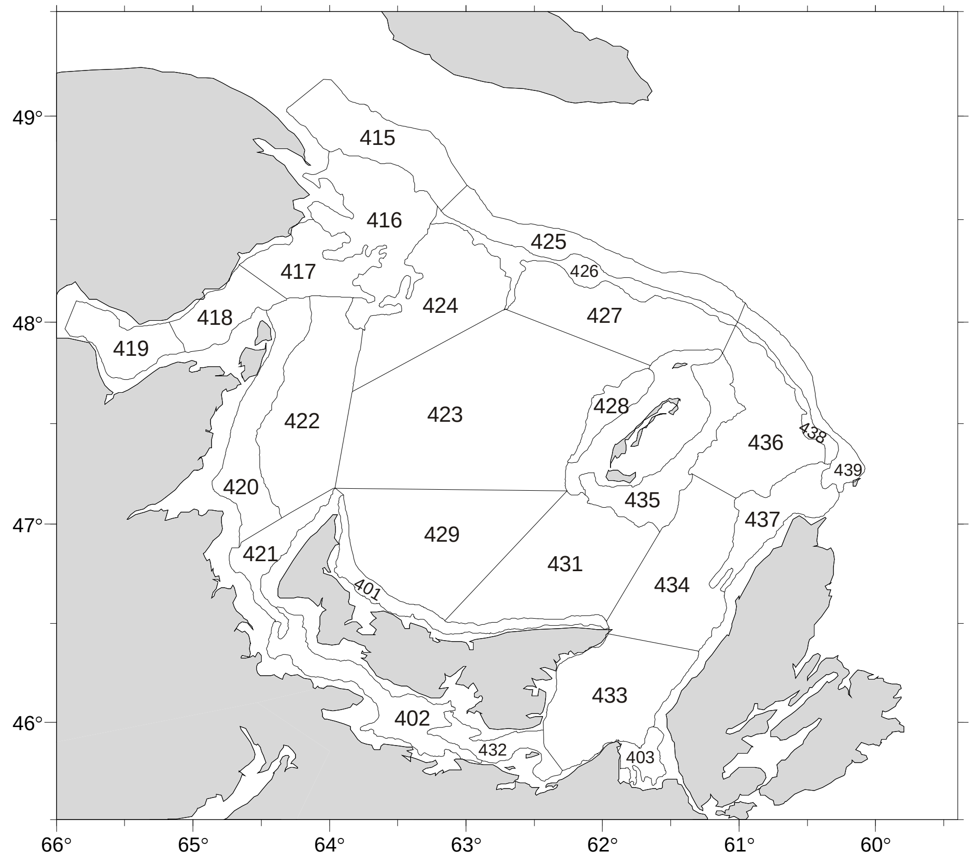

Figure. 1. Stratum boundaries for the southern Gulf of St. Lawrence September RV survey.

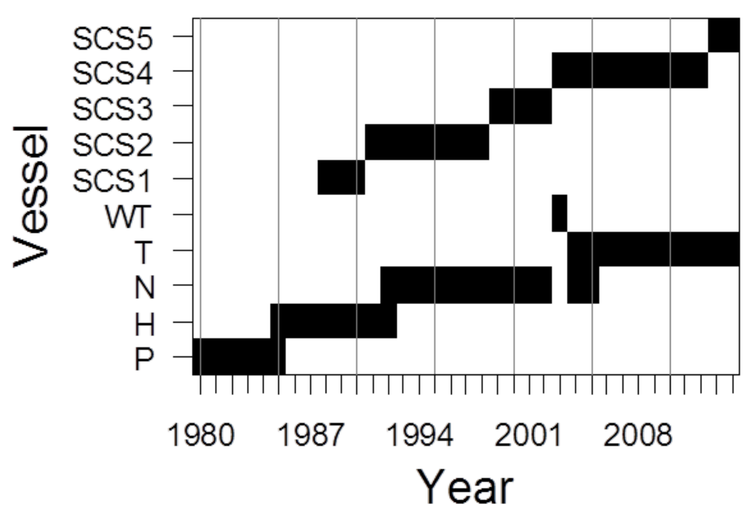

Figure 2. Summary of the survey vessels used in the snow crab surveys (SC) and research vessel survey (RVS) as a function of year for 1980-2014

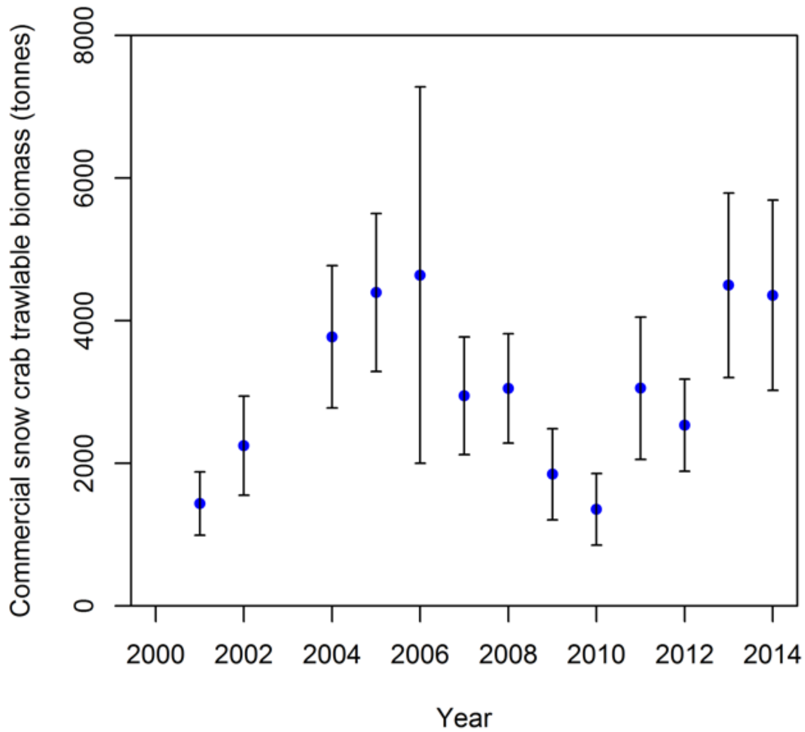

Figure 3. Estimated trawlable biomass (tonnes; mean ± 95% confidence interval) of commercial-sized adult male snow crab in the RV survey, 2001-2014, for a geographic area comparable to that used for the current snow crab assessment.

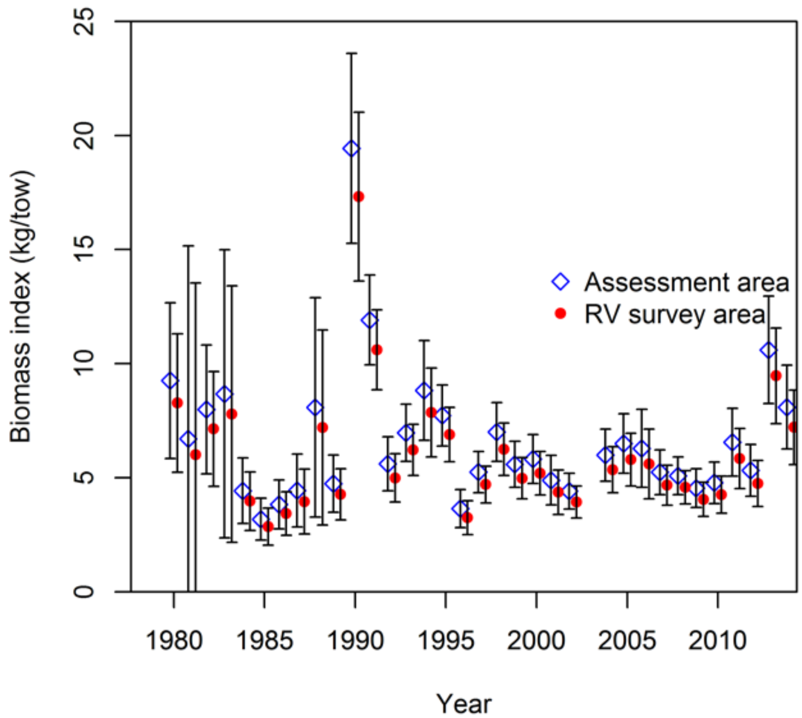

Figure 4. Biomass index (kg/tow; mean ± 95% confidence interval) for all snow crab (male and female) in the RV survey, 1980-2014, for a geographic area comparable to that used for the current snow crab assessment (open blue diamond) and for the entire RV survey area (solid red circle).

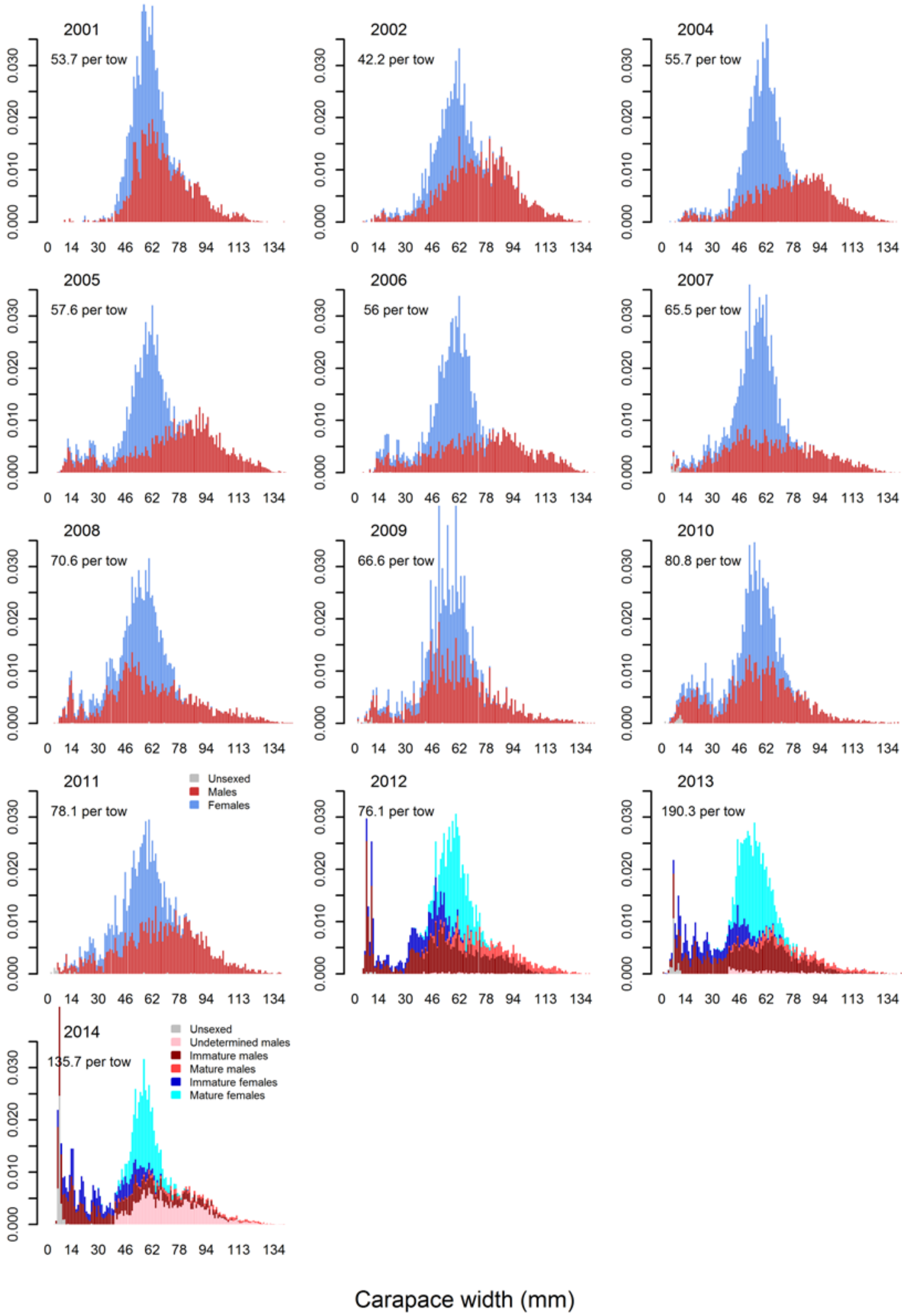

Figure 5. Annual survey-weighted relative frequency distributions (expressed as proportions) of snow crab by carapace width (mm) as a function of sex (for 2001-2011) or sex and maturity stage (2012-2014). The numbers in each panel indicate the value of the annual abundance index (numbers per tow) for snow crab (all sizes and sexes). The data for 2003 are not shown because that survey was incomplete.

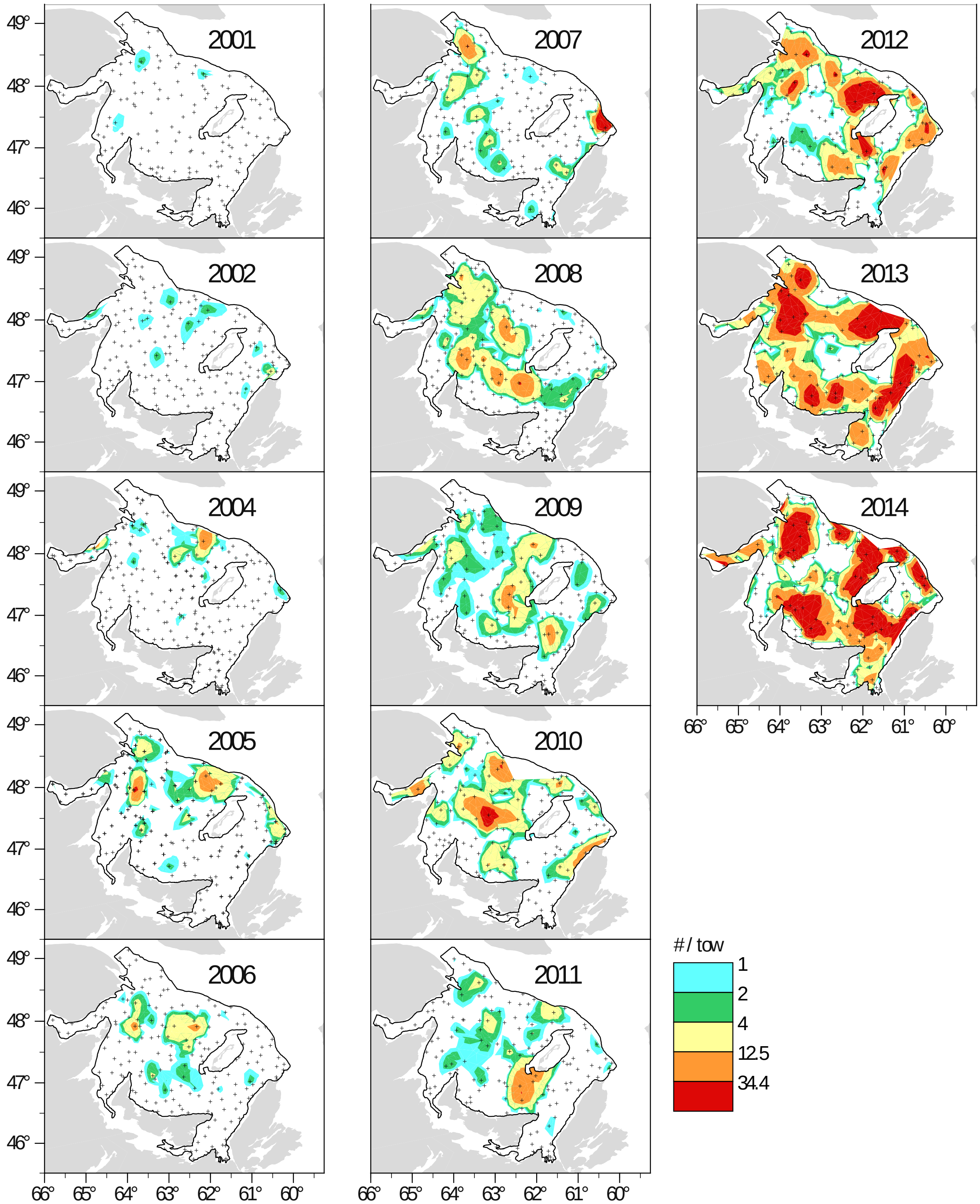

Figure 6. Annual geographic distribution of catch rates (number of crabs per tow) of small snow crab (≤15 mm) in the September RV survey, 2001-2014 (excluding 2003). The small crosses indicate the set locations. The contour levels represent the 10th, 25th, 50th, 75th and 90th percentiles of non-zero catches for the entire period.

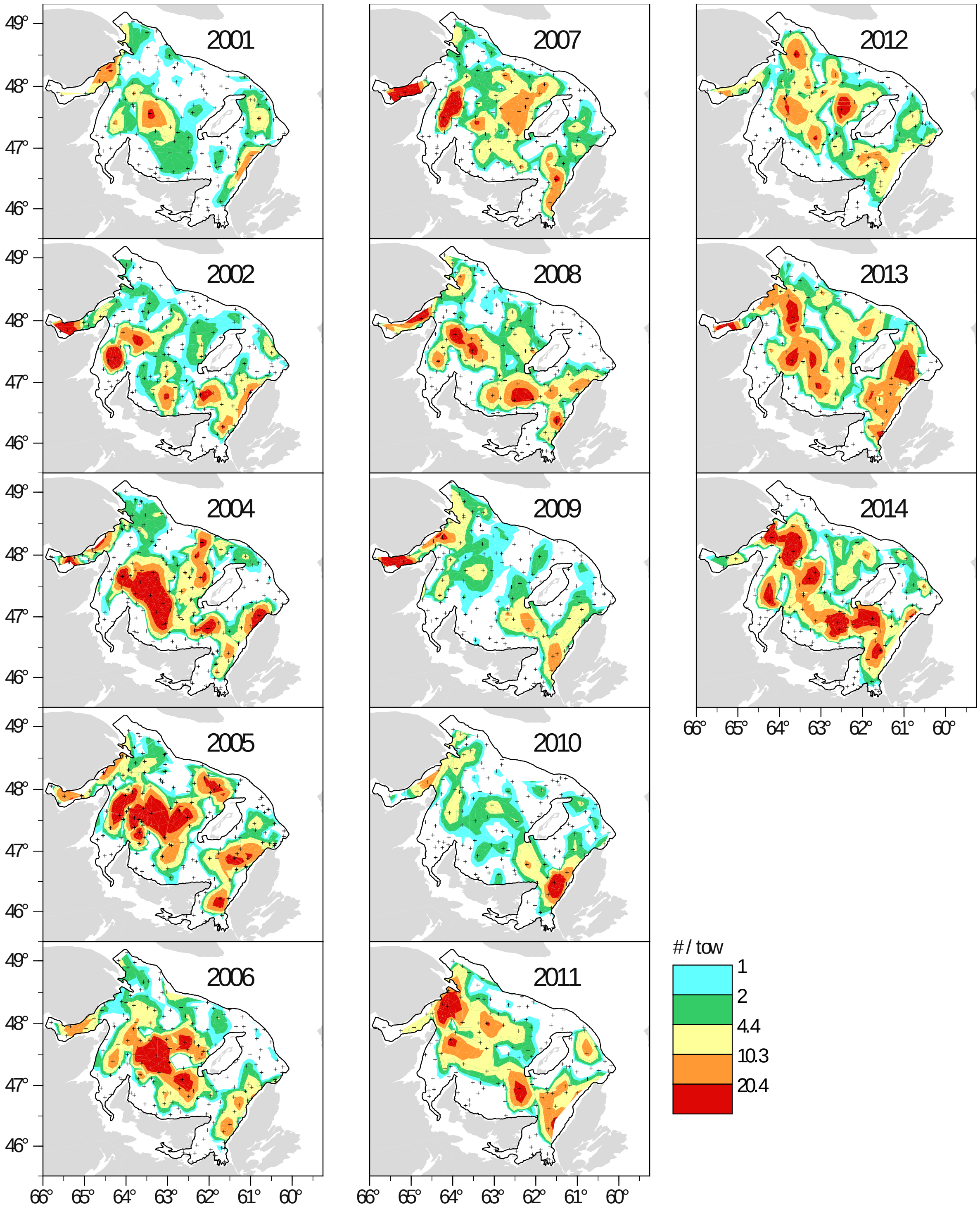

Figure 7. Annual geographic distribution of snow crab catch rates (number of crabs per tow; males ≥95 mm) in the September RV survey, 2001-2014 (excluding 2003). The small crosses indicate the set locations. The contour levels represent the 10th, 25th, 50th, 75th and 90th percentiles of non-zero catches for the entire period.

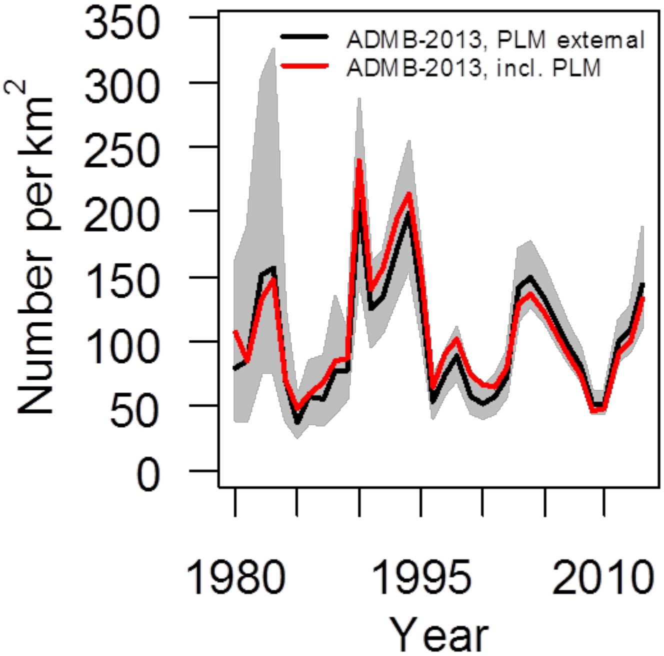

Figure 8. Annual estimated densities (number per km²) of southern Gulf commercial male snow crab, 1980 to 2013 for the model estimated in ADMB with the proportion of large males (PLM) estimation done externally (black line) and internally (red line) to the model. The shaded region indicates the 95% confidence interval range for the model with external estimation.

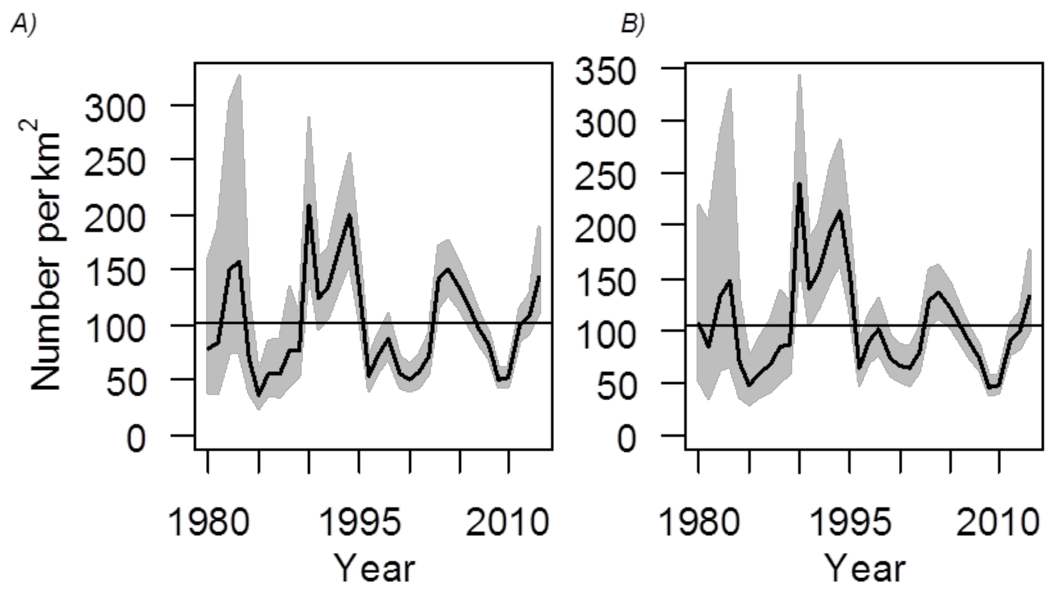

Figure 9. Annual estimated densities (number per km²) of southern Gulf commercial male snow crab, 1980 to 2013. The horizontal lines indicate the series average and the shaded regions indicates the 95% confidence interval ranges. The results for the model for which the proportion of large males (PLM) estimation was done externally to the model are shown in panel A (left) and the results for the model that integrated the PLM estimation are shown in panel B (right).

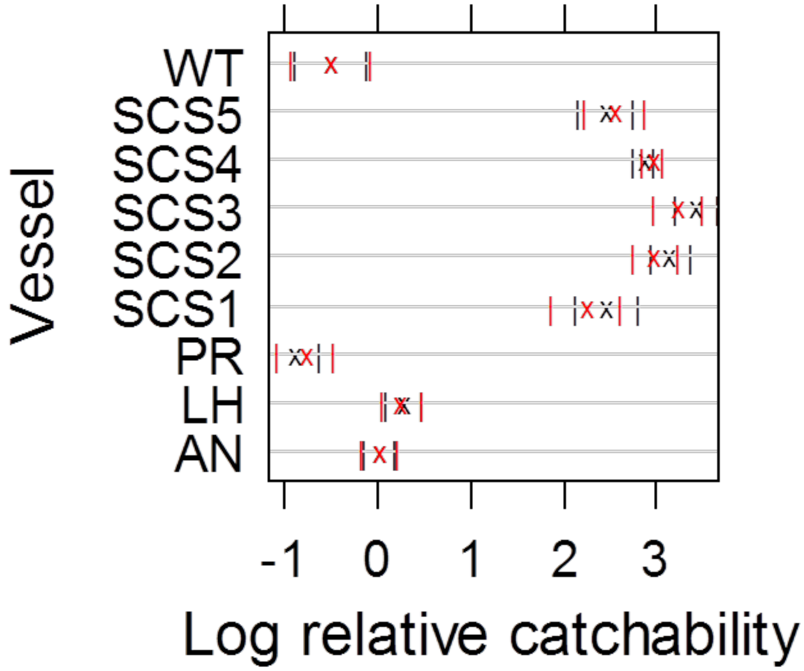

Figure 10. Estimates (crosses) of survey vessel/gear relative catchabilities, log(qv), with 95% confidence intervals (bars) for the model estimated in ADMB with the proportion of large males (PLM) estimation done externally (black) and internally (red) to the model. The catchability comparisons are annotated as follows: WT= CCGS Wilfred Templeman → CCGS Teleost, PR = EE Prince → Lady Hammond, LH = Lady Hammond → CCGS Alfred Needler, and AN = CCGS Alfred Needler → CCGS Teleost. The entries SCS are for the catchability of the snow crab survey vessel/gear, relative to the Teleost: SCS1 – Snow crab survey gear for 1988-1990, SCS2 – vessel for 1991-1998, SCS3 – vessel for 1999-2002, SCS4 – vessel for 2003-2012,and SCS5 – vessel for 2013-2014.

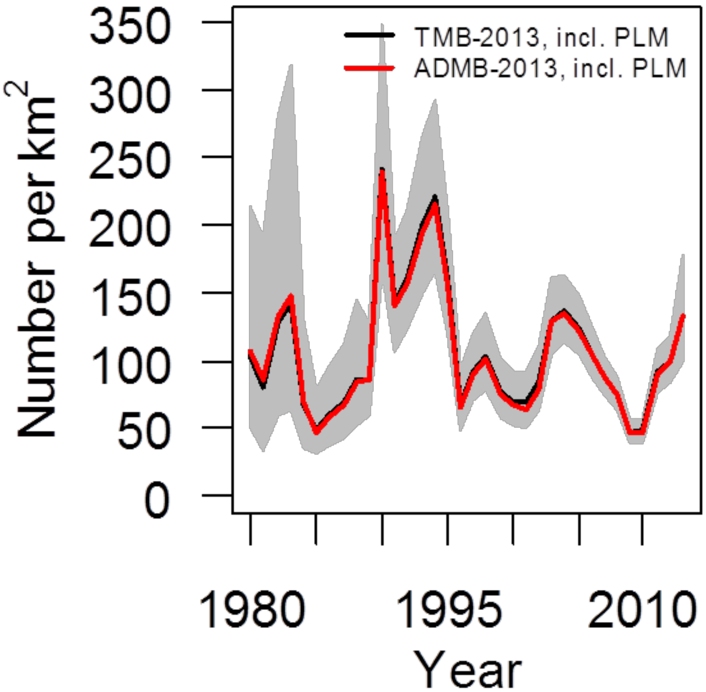

Figure 11. Annual densities (number per km²) of southern Gulf commercial male snow crab, 1980 to 2013, estimated in TMB (black line) and in ADMB (red line), in both cases with internal estimation of the proportion of large males. The shaded region indicates the 95% confidence interval range for the model estimated in TMB.

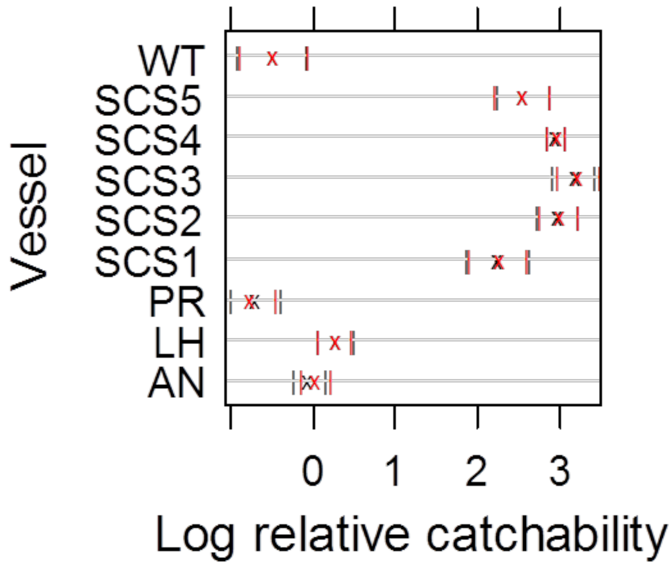

Figure 12. Estimates (crosses) of survey vessel/gear relative catchabilities, log(qv), with 95% confidence intervals (bars), obtained from the model fit TMB (black) and in ADMB (red), in both cases with internal estimation of the proportion of large males.The catchability comparisons are annotated as follows: WT = CCGS Wilfred Templeman → CCGS Teleost, PR = EE Prince → Lady Hammond, LH = Lady Hammond → CCGS Alfred Needler, and AN = CCGS Alfred Needler → CCGS Teleost. The entries SCS are for the catchability of the snow crab survey vessel/gear, relative to the Teleost: SCS1 – Snow crab survey gear for 1988-1990, SCS2 – vessel for 1991-1998, SCS3 – vessel for 1999-2002, SCS4 – vessel for 2003-2012,and SCS5 – vessel for 2013-2014.

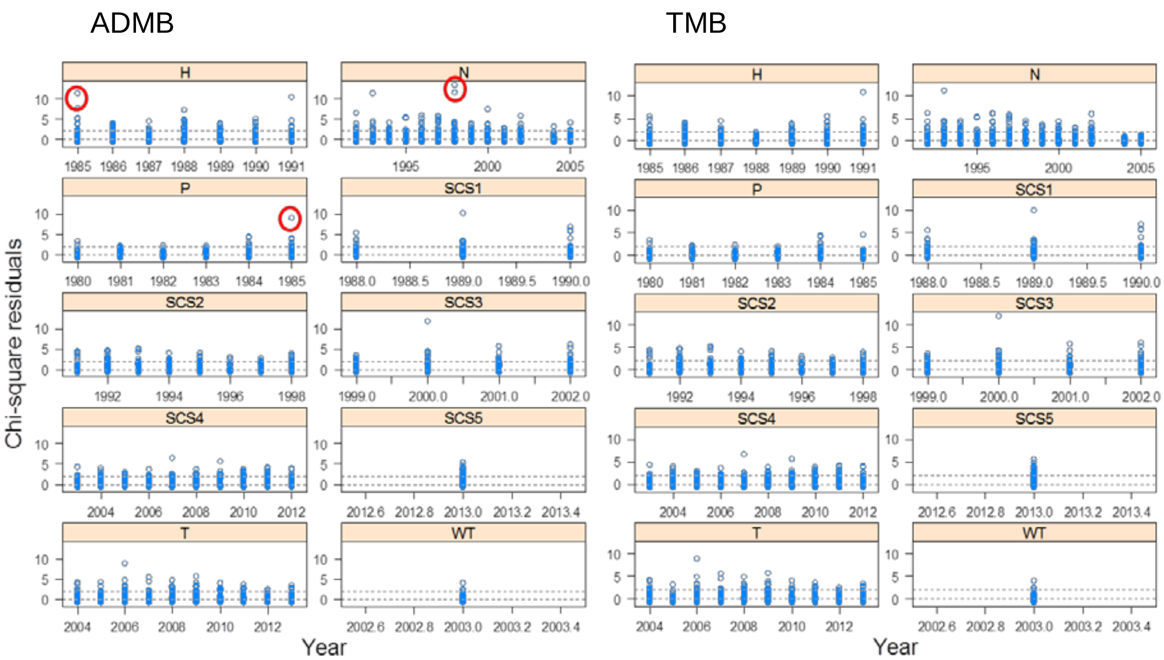

Figure 13. Model residuals by year (x-axes) and vessel (panels),from the model fit in ADMB (left panel) and in TMB (right panel), in both cases with internal estimation of the proportion of large males.Notable differences in residuals between ADMB and TMB are indicated using red circles.

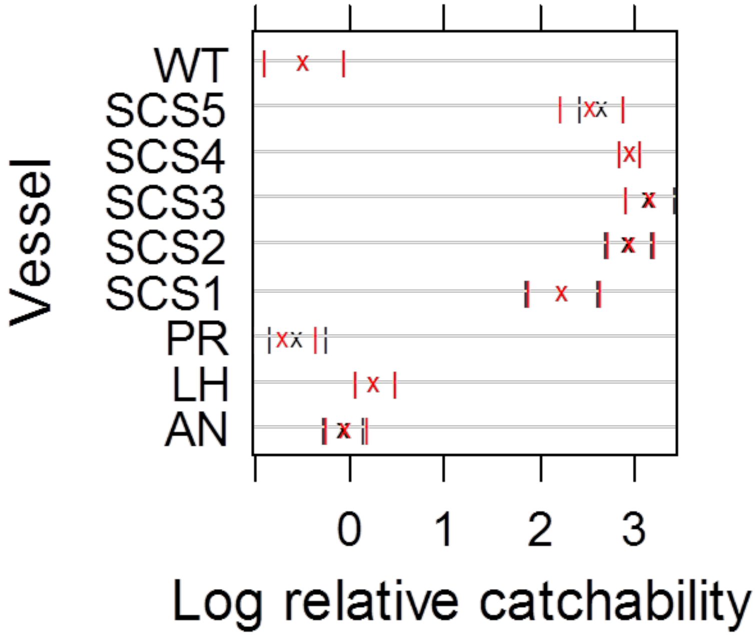

Figure 14. Estimates (crosses) of survey vessel/gear relative catchabilities, log(qv), with 95% confidence intervals (bars), obtained from the model fit inTemplate Model Builder for 1980-2014 (black) and 1980-2013 (red), in both cases with internal estimation of the proportion of large males. The catchability comparisons are annotated as follows: WT = CCGS Wilfred Templeman → CCGS Teleost, PR = EE Prince → Lady Hammond, LH = Lady Hammond → CCGS Alfred Needler, and AN = CCGS Alfred Needler → CCGS Teleost. The entries SCS are for the catchability of the snow crab survey vessel/gear, relative to the Teleost: SCS1 – Snow crab survey gear for 1988-1990, SCS2 – vessel for 1991-1998, SCS3 – vessel for 1999-2002, SCS4 – vessel for 2003-2012,and SCS5 – vessel for 2013-2014.

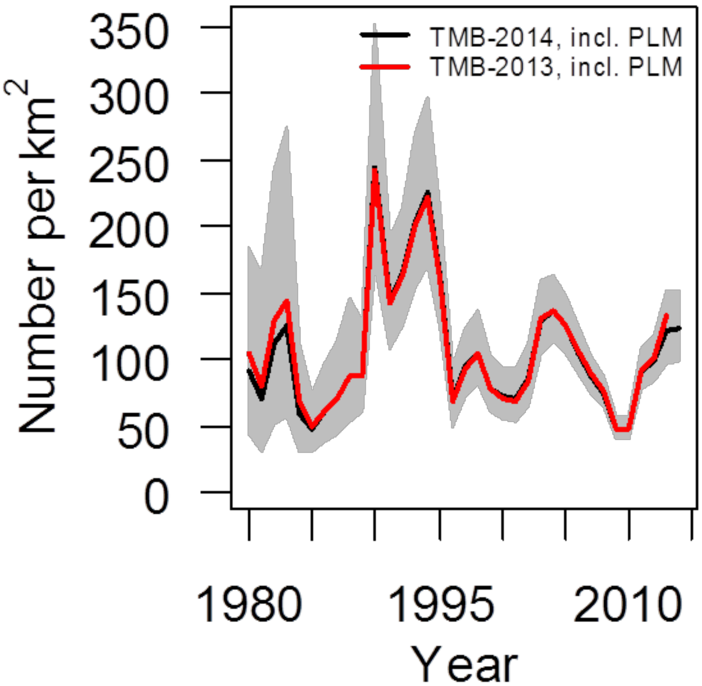

Figure 15. Annual densities (number per km²) of southern Gulf commercial male snow crab, 1980 to 2013 (red) or 1980 to 2014 (black), estimated in Template Model Builder with internal estimation of the proportion of large males. The shaded region indicates the 95% confidence interval range for 1980-2014 estimation.

A) B)

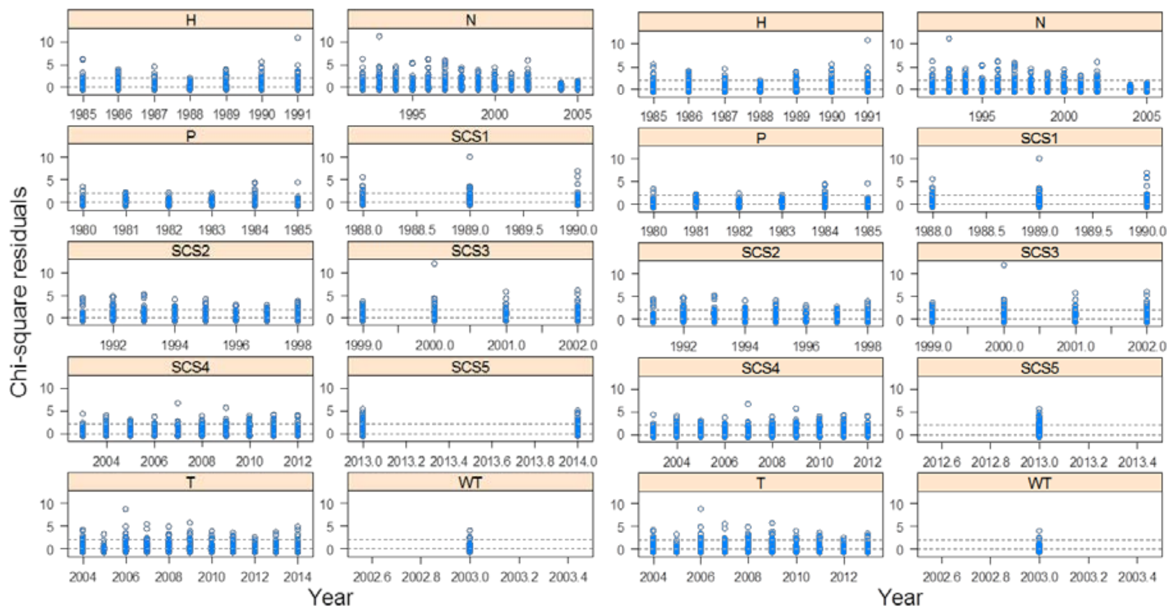

Figure 16. Model residuals by year (x-axes) and vessel (panels), for the model fit in TMB for A) 1980-2014 and B) 1980-2013.

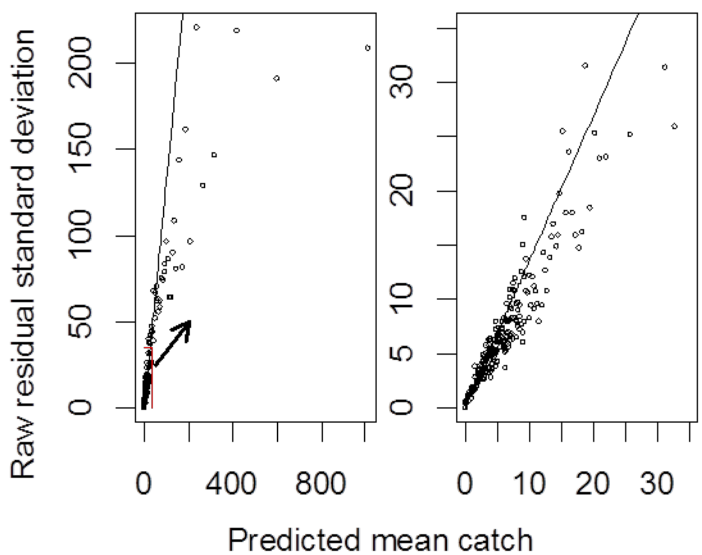

Figure 17. Standard deviations (sd's) of the binned raw residuals for the final model fit in TMB with internal estimation of the proportion of large males. The solid line is the NB prediction of the raw residual sd, sqrt (predicted + predicted2 /k). The right panel is the same as the left panel but using a narrower range on both the x and y axes.