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Model-based estimation of commercial-sized snow crab (*Chionoecetes opilio*) abundance in the southern Gulf of St. Lawrence, 1980-2013, using data from two bottom trawl surveys

H.P. Benoît[1] and N. Cadigan[2]

[1] Fisheries and Oceans Canada
Gulf Fisheries Centre
343 avenue université, P.O. Box 5030
Moncton (NB) E1C 9B6

[2] Centre for Fisheries Ecosystem Research
Fisheries and Marine Institute of Memorial University of Newfoundland
P.O. Box 4920
St. John's (NL) A1C 5R3

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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

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 to snow crab and has been conducted annually since 1988 (henceforth called the crab survey, CS). The second is a 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 and Cadigan (2013) presented a model-based estimation framework that integrates data from the two surveys to produce an annual standardized index of commercial-sized sGSL snow crab abundance for 1980-2012. Though the reliability of the framework still needs to be assessed using simulations, it was used here to update the standardized index using the most recent survey data collected in 2013 and to provide a preliminary estimate of the relative catchability (fishing efficiency) of the new vessel used in the CS in 2013. Two model variants were considered, one in which the catchability of the 2013 CS vessel was estimated separately from that of the other CS vessels, and a second in which the catchability of the two most recent CS vessels was constrained to be the same. The first model variant produced an estimate of 2013 crab abundance that was greater than the 2012 estimate, and estimated the relative catchability of the 2013 CS vessel to be among the lowest of the vessels used in that survey. In contrast, the second model variant estimates a slight decrease in abundance from 2012 to 2013. With a single year of data, we cannot rule out the possibility that a year effect in the RVS or CS in 2013 could have greatly influenced the model estimates of abundance for that year and the relative catchability of the 2013 CS vessel. With additional years of survey data involving this vessel and the RVS vessel, the reliability of the estimate of relative catchability will greatly improve. This situation highlights the importance of having some interannual consistency in the CS vessels in the absence of comparative fishing.

Estimation de l’abondance de crabe des neiges (*Chionoecetes opilio*) de taille commerciale dans le sud du Golfe du Saint Laurent, 1980-2013, basée sur un modèle ajusté aux données provenant de deux relevés au chalut de fond

RÉSUMÉ

Il y a deux relevés au chalut de fond indépendants des pêches qui fournissent des indices d'abondance relative sur le crabe des neiges dans le sud du golfe du Saint-Laurent. L'un d'eux est axé principalement sur le crabe des neiges et a lieu tous les ans depuis 1988 (appelé le relevé du crabe [RC]). L'autre est un relevé de chalut de fond effectué par un navire scientifique chaque année depuis 1971 (appelé le relevé par navire scientifique ou relevé NS). Au départ, il visait les poissons démersaux, mais il a permis de recueillir de l'information sur les prises de crabe des neiges depuis 1980. Benoît et Cadigan (2013) ont présenté un cadre d'estimation fondé sur un modèle qui intègre les données des deux relevés en vue de produire un indice annuel normalisé de l'abondance des crabes des neiges de taille commerciale dans le sud du golfe du Saint-Laurent de 1980 à 2012. Bien que la fiabilité de ce cadre doit encore être évaluée au moyen de simulations, il a tout de même servi à mettre à jour l'indice normalisé à partir des plus récentes données d'inventaire recueillies en 2013 et à fournir une estimation préliminaire de la capturabilité relative (efficacité de pêche) du nouveau navire utilisé pour le RC en 2013. Deux variantes de modèles ont été prises en compte, l'une dans laquelle la capturabilité du navire de RC de 2013 a été estimée séparément de celle des autres navires de RC, et l'autre dans laquelle la capturabilité des deux navires de RC les plus récents a été ajustée pour être la même. La première variante de modèle a généré une estimation de l'abondance du crabe pour 2013 plus élevée que celle de 2012, et la capturabilité relative du navire de RC de 2013 figure parmi les plus faibles des navires utilisés pour ce relevé. En comparaison, la deuxième variante de modèle a permis d'estimer une légère diminution de l'abondance de 2012 à 2013. Avec seulement une année de données, nous ne pouvons pas écarter la possibilité que l'effet d'une année dans le relevé du NS en 2013 ait eu une forte incidence sur les estimations de l'abondance du modèle pour cette année et sur la capturabilité relative du navire de RC en 2013. Lorsque nous disposerons d'autres années de données provenant de ce navire et du navire scientifique, la fiabilité de l'estimation de la capturabilité s'améliorera grandement. Cette situation met en évidence l'importance d'assurer une certaine uniformité au cours des années dans les navires de RC en l'absence de pêches comparatives.

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 to 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). However, both surveys also have inherent issues that could limit the reliability of the snow crab abundance indices produced by each individually.

First, the survey sampling frame for the CS has changed and generally increased over time, even as recently as 2006. The survey area was considerably smaller than the stock area in all years prior to 1997 and consequently the data for those years are presently not considered as part of the standardized stock-abundance series for the survey (DFO 2012). Second, there are presently no adjustments made for possible changes in catchability in the CS resulting from a change in the configuration of the fishing gear as of 1991, and from changes in survey vessels that occurred after 1998, 2002 and most recently 2012. Comparative fishing between the former and replacement vessels/gears to estimate their relative fishing efficiency (e.g., Pelletier 1998; Cadigan and Dowden 2010) was not undertaken prior to these changes. The changes in survey sampling frame and vessel/gear changes must be accounted for to avoid conflating them with actual changes in abundance. Third, prior to 2001 snow crab catches in the RVS were not sampled to determine the size-composition of crabs captured. The catch of commercial-sized male crabs, which is of interest for the assessment, has to be inferred using other information from the catches (Benoît and Cadigan 2013; details below). Fourth, although there has been comparative fishing that allows for the estimation of the relative catchability of most of the vessels used in the RVS (Benoît and Swain 2003a; Benoît 2006), an uncalibrated vessel was used in 2003 for the RVS.

Benoît and Cadigan (2013) presented a model-based estimation framework that integrates data from the RVS and CS to produce an annual standardized index of commercial-sized (≥ 95 mm carapace width) sGSL snow crab abundance for 1980-2012. The approach overcomes the individual shortcomings of the surveys, and provides estimates of the relative efficiencies of all of the vessels/gears involved in the surveys. Furthermore, uncertainty in key parameters such as the relative efficiency of different survey vessels is reflected in the uncertainty of the abundance estimates. Though the reliability of the framework still needs to be assessed using simulations, it was used here to update the standardized index using the most recent survey data collected in 2013 and to provide a preliminary estimate of the relative efficiency of the new vessel used in the CS in 2013.

2. METHODS

2.1 BACKGROUND AND DATA

2.1.1 The September multi-species RV survey

The RVS has been conducted each September since 1971. Sampling stations are selected according to a random-stratified design, with strata defined on the basis of depth and area (Fig. 1). The target fishing procedure is a 30-min. tow at 3.5 knots. Hurlbut and Clay (1990) provide more details on the survey methodology. For 2013, there were 122 valid RVS sets included in the analyses (Table 1).

Data from a common group of strata, sampled annually since 1971 and covering most of the southern Gulf of St. Lawrence (Northwest Atlantic Fishery Organization area 4T), were used in the analyses. There were a small number of strata in which there was no sampling in certain years (stratum 421 in 1983 and 1988, and strata 438 and 439 in 2003), though the model could address these gaps (described below).

Catches of snow crab (total numbers and mass per tow) have been recorded in the survey since 1980 (Tremblay 1997). Since 2001, captured crabs have also been measured and sexed, though maturity determination only began in 2012 (Benoît 2014).The number of commercial sized crabs (males ≥95 mm) in the RVS for 1980-2000 was inferred based on total catch numbers, the mean mass of crabs in a set catch (defined as the ratio of total catch mass and numbers) and a binomial generalized linear model that relates mean mass and the proportion of large males (PLM) in a set (Fig. 2; details in Benoît and Cadigan 2013). Presently, the PLM in each set for 1980-2000 is estimated prior to the fitting of the main model. In the future, the relationship between mean mass and the PLM will be estimated as part of the overall model fitting to ensure that its associated uncertainty is incorporated in the abundance index uncertainty. Since 2001 commercial-sized catch numbers are directly available from the RVS data and recourse to the estimation of PLM is not required.

In most years prior to 1991 there was a small proportion of sets for which catch numbers were recorded but mass was not because the mass was <1 kg (Table 1). In practice, catches close to 1 kg would have been rounded up to that value, so the absence of a mass value indicates even lighter catches. In these cases, we assumed that the catch of large snow crab (≥95 mm) was nil given the typical mass of large crabs (>500 g; see Fig. 2 in Cadigan 2012). This assumption may cause a slight underestimation of commercial-sized crab abundance during 1980-1990, though the magnitude of this bias is likely to be small because the proportion of affected sets is small and the number of large crabs implied by the low catch weights is also small. 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 1971, fishing during the RVS has been carried out by five different vessels and two different trawls have been used (Table 2). With the exception of the use of the CCGS *Wilfred Templeman* in 2003, comparative fishing involving side-by-side fishing by the former and replacement vessels/gear at a large number of sites was undertaken prior to switching to a new vessel/gear. The model utilizes the resulting comparative fishing data to estimate the relative efficiencies of all RVS vessels except the CCGS *Wilfred Templeman*, though the model uses other information in the data to also estimate the efficiency of this latter vessel (details below).

Fishing in the RVS was restricted to daylight hours (07:00-19:00) from 1971 to 1984 but has been conducted 24 hours per day since 1985. Because fishing efficiency (catchability) can vary by time of day as a result of species and size specific diel behaviours such as hiding and trawl avoidance, the effect of time of day needs to be accounted for in analyses of the RVS that span 1984 and in analyses that include the CS, which is only conducted during the day. There are two sources of information utilized by the model to estimate the diel catchability effect for the RVS: catches during the day and the night in common strata and years, and in a small number of instances, at common sites and years.

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, often 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, across 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 2013, there were 351 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). 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 such that 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-present (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-present. Survey data for 1988-1996 are not presently 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) models the survey catches of commercial snow crab as a function of the RVS strata (Fig. 1), in which 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 ABUNDANCE INDEX ESTIMATION MODEL

The basic model is conceptually simple and 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. This count-data distribution is often considered to be suitable for modeling trawl catches (Cadigan 2011).

Let R be a random variable for a survey catch. In addition to stratum and year, other important factors are survey vessel and associated fishing protocols (denoted as v), day or night (denoted as $dn = 0$ or 1, respectively), and site i in a stratum. In some years there are repeat samples at some sites in the RVS due to comparative fishing or other reasons (394 of 12,130 sites over all years for the combined RVS and CS data), and these repeat samples are indicated with a j

subscript. In 22 of those instances there were three or more repeat sets at a site in a year, though only the first two repeat sets were used here.

Let R_{syvij} denote the catch from the *j*'th tow in stratum *s* and year *y* for survey vessel *v* at site *i*. Let λ_{syij} denote stock density at site *i,j* in stratum *s* and year *y*. The motivation for the *i,j* subscripts will be described shortly. The catch depends on trawl catchability (*q*) and the density of snow crab at the site. This density is assumed to be the product of a fixed stratum and year effect (λ_{sy}), a random site effect (γ_{syi}) and a random repeat tow effect (γ_{syij}) at site *i*; that is, $\lambda_{syij} = \lambda_{sy}\gamma_{syi}\gamma_{syij}$. The random effects are assumed to have means equal to one, $E(\gamma_{syi}) = E(\gamma_{syij}) = 1$, and $E(\lambda_{syij}) = \lambda_{sy}$. Fixed effects parameters (e.g λ_{sy}), denoted collectively as the parameter vector θ, are estimated via maximum likelihood (MLE) based on the marginal likelihood, $L(\theta)$, in which random effects, denoted collectively as γ, are "integrated out". The marginal likelihood is

$$L(\theta) = \int\int\int_{\gamma} f_{\theta}(data \mid \theta, \gamma) g_{\theta}(\gamma) \partial\gamma \tag{1}$$

where $f_{\theta}(data \mid \theta, \gamma)$ is the joint probability mass function (pmf) of the survey data conditional on γ and $g_{\theta}(\gamma)$ is the joint probability density function (pdf) for γ. The γ's are not required for inferences about trends in stock size.Conditional on λ_{syij}, R_{syvij} is assumed to Poisson distributed with mean $\mu_{syvij}. = q_{vdy}\lambda_{syij}$. The survey catchability parameters (q's) are described later.

The γ_{syij}'s are assumed to be independent and identically distributed (iid) Gamma random variables with mean 1 and variance $1/k_p$. A gamma random variable is strictly positive and seems appropriate for modeling variation in species density. The *p* notation indicates pair because most repeat tows are due to paired vessel comparisons. It is well known (e.g., Cadigan 2011) that if $R_{syvij} \mid \gamma_{syi}\gamma_{syij} \sim \text{Poisson}(\mu_{syvij})$ then the marginal distribution (with respect to γ_{syij}) of $R_{syvij}|\gamma_{syi}$ ~ NB with mean $\mu_{syvi} = q_{vdy}\lambda_{sy}\gamma_{syi}$ and variance $\mu_{syvi} + \mu_{syvi}^2 / k_p$. The pmf is

$$\Pr(R_{syvij} = y \mid \gamma_{syi}) = \frac{\Gamma(y+k_p)}{\Gamma(y+1)\Gamma(k_p)} \left(\frac{\mu_{syvi}}{\mu_{syvi}+k_p}\right)^y \left(\frac{k_p}{\mu_{syvi}+k_p}\right)^{k_p}.$$

However, the marginal distribution (with respect to γ_{syi}) of R_{syvij} is not NB. If the γ_{syi}'s are iid Gamma random variables with mean 1 and variance $1/k$ then the marginal distribution of R_{si} is

$$\Pr(R_{syvij} = y) = \int\int \Pr(R_{syvij} = y \mid \gamma_{syi}, \gamma_{syij}) \Pr(\gamma_{syi}) \Pr(\gamma_{syij}) \partial\gamma_{syi} \partial\gamma_{syij}$$

$$= \frac{k^k k_p^{kp} \mu_s^y \Gamma(k+y)}{\Gamma(k)\Gamma(k_p)} \int_0^{\infty} \frac{e^{-k_p t} t^{y+k_p-1}}{(\mu_{sy} t + k)^{y+k}} \partial t \tag{2}$$

The ∂t integral in equation (2) does not have a closed form but this can be evaluated numerically. Note that we expect the between-site variability of crab density to be greater than the within-site variability during repeat tows, i.e., $Var(\gamma_{syi}) > Var(\gamma_{syij})$ such that $k < k_p$. It can be shown that $E(R_{syvij}) = \mu_{syv}$ and $Var(R_{syvij}) = \mu_{syv} + \mu_{syv}^2 / k_c$, where $k_c = kk_p/(1 + k + k_p)$. Note that the over-dispersion, $1/k_c$, is the sum of the site and pair over-dispersion plus their product, $1/k_c = 1/k + 1/k_p + 1/kk_p$. To simplify estimation, the marginal distribution R_{syvij} is approximated as NB with over-dispersion parameter k_c when there is only a single tow at a site.

Repeat tows at a site have marginal correlation because there is a common γ_{syi} random effect in their distribution. Consider the situation where there is only a pair of tows at a site. The marginal probability of the pair R_{syvi1}, R_{syvi2} is the integral of two NB probabilities:

$$\Pr(R_{syvi1} = y_1, R_{syvi2} = y2) =$$

$$\frac{\Gamma(y_1 + k_p)\Gamma(y_2 + k_p)k^k}{\Gamma(y_1+1)\Gamma(y_2+1)\Gamma(k)\Gamma^2(k_p)} \int \left(\frac{\mu_{syv1}t}{\mu_{syv1}t + k_p}\right)^{y_1} \left(\frac{k_p}{\mu_{syv1}t + k_p}\right)^{k_p} \left(\frac{\mu_{syv2}t}{\mu_{syv2}t + k_p}\right)^{y_2} \left(\frac{k_p}{\mu_{syv2}t + k_p}\right)^{k_p} t^{k-1}e^{-kt}\partial t. \quad (3)$$

The ∂t integral in equation 3 does not have a closed form but this can be evaluated numerically. Note that the means for R_{syvij} may depend on j because of vessel effects or day/night effects (see below). The marginal variance of R_{syvij} is $Var(R_{syvij}) = \mu_{syvj} + \mu_{syvj}^2 / k_c$ and $Cov(R_{syvi1}, R_{syvi2}) = \mu_{syv1}\mu_{syv2} / k_c$ indicating positive correlation of paired tows. Unlike the single tow case, the marginal distribution of repeat tows cannot be approximated using a NB pmf.

The mean $\mu_{syvj} = q_{vyj}\lambda_{sy}$ is a product of catchability (q) and density (λ). The λ_{sy}'s are treated as fixed parameters. There are great many of these, one for each of 24 strata and 34 years, plus some additional strata effects for comparative fishing tows from August 1992 that were not part of the RV survey. Note that these August 1992 tows contribute information about q but not information about λ for the index. There are a total of 829 λ_{sy} parameters; however, λ_{sy} was fixed at a small value, exp(-10), for any stratum in which all survey catches were null. The MLE of λ_{sy} tends towards zero in this case, but λ must be greater than zero and a lower bound of exp(-10) was used. This reduced the number of λ_{sy} parameters to estimate to 687.

Benoît and Cadigan (2013) found that relative catchability in the CS did not vary with time of day. However, diel differences in relative catchability were observed for the RVS. While the changes were continuous in time, the authors concluded that the effect could reliably be treated as a single factor effect (i.e., catches at night, 19:00-7:00, relative to those during the day). Furthermore, the authors concluded that this diel effect was not vessel specific and therefore defined it as:

$$\delta_j = \begin{cases} 1, & j \text{ is a day tow} \\ \delta_, & j \text{ is a night tow} \end{cases}$$

The catchability parameters further depend on the vessel used in a survey (see Fig. 3 for a summary of the vessels used as a function of year). Note that vessel effects can reflect not only the fishing efficiency for a given swept area, but also how swept area is assessed. This latter consideration is relevant for the CS vessels because swept area is estimated for each tow and is used to standardize catches.

Vessel effects (q_v) were defined as

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

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. There was no direct comparative fishing between the *EE Prince* or the *Lady Hammond* and the *CCGS Teleost* and these conversions were inferred stepwise, e.g. $q_{EP \to T} = q_{EP \to LH} q_{LH \to AN} q_{AN \to T}$. Hence, in addition to the stratum density parameters, there were nine vessel *q* parameters, one day/night δ parameter, and two NB over-dispersion parameters (k and k_p). We refer to this model hereafter as the unconstrained model. A variant of this model, termed the constrained model hereafter, was also fit assuming that the 2013 CS vessel had equal catchability to the vessel used in 2003-2012 (i.e., the vessel effect for 2013 was assumed to be $q_{SCS4 \to T}$ and only eight vessel *q* parameters were estimated). This was done to look at the sensitivity of model results to the assumption that the 2013 CS vessel had different catchability, given that there was only a year's worth of data to estimate that effect.

Standardization for variations in swept area was applied directly to the models. For the CS, we defined:

$$\mathrm{E}(R_{syvij}) = \mu_{syvij} = q_v \delta_{vj} \lambda_{sy} a_{syvij}$$

where a_{syvij} is the swept area for the *j*'th tow. Hence, the model for expected catch was:

$$\log(\mu_{syvj}) = \beta_0 + \log(q_v) + \log(\delta_{vj}) + \log(\lambda_{sy}) + Z_{syvij}, \tag{4}$$

where Z_{syvij} is often referred to as an offset and for the CS is equal to $\log(a_{syvij})$.

Standardization of the RVS data involved adjustment for the actual tow distance (d_{syvij}) relative to the nominal tow distance (d_o=1.75 NM), the area swept by a nominal standard *CCGS Teleost* tow (0.0405028 Km^2), and adjustments for occasional subsampling of catches (*ratio*). Consequently the offsets for the RVS data as of 2001 were defined as

$$Z_{syvij} = log(d_{syvij}/d_o) + log(ratio_{syvij}) + log(0.0405028).$$

Adjustment of total RV survey catches prior to 2001 to correspond to catches of commercial-sized males were also incorporated this way. Rather than multiplying catches by the proportion of commercial-sized males (PLM), this proportion was divided into *E(R)*; that is, the offsets for RV survey total catches prior to 2001 were

$$Z_{syvij} = log(d_{syvij}/d_o) + log(ratio_{syvij}) + log(0.0405028) - log(PLM).$$

The estimated PLM sometimes varied substantially among sets in a stratum. If the proportion was very small for sets with low catch weights then the offset could be large. If there were other larger catches in a stratum then the few sets with large offsets produced large predicted catches when observed catches were near zero. The only way to get predictions closer to observations was if λ_{sy} was estimated to be close to zero, but this resulted in poor fits to the sets with larger catches. With the NB model, because the variance increases with the square of the mean, over-predicting a small catch is a smaller error (i.e. the variance is high in this case) than under-predicting a large catch (i.e. the variance is low in this case). This situation led to estimation problems. As a remedy, a catch-weighted average proportion for each stratum was used. With this approach the mean total catch divided by the average proportion is identical to the average of the estimated catch of large males obtained by applying tow-specific proportions to the total catches. That is, if there are n_s catches in some stratum s and if $\bar{p}_s = \sum_{i=1}^{n_s} r_i p_i \Big/ \sum_{i=1}^{n_s} r_i$ then

$$\bar{r}_s \bar{p}_s = \sum_{i=1}^{n_s} r_i p_i \Big/ n_s \ .$$

AD Model Builder (ADMB; Fournier et al. 2012) was used to implement the model. The joint pmf (Equation 3) for the likelihood function of repeat survey catches was computed using the numerical integration function adromb(). The pmf for single catches was based on the NB approximation with over-dispersion parameter k_c. The stock size index is defined as

$$\lambda_y = \frac{\sum_{s \in S} W_s \lambda_{sy}}{\sum_{s \in S} W_s} ,$$

where W_s is the size of stratum s and S is the set of all strata. ADMB automatically provides standard errors for λ_y and these standard errors include uncertainty due to changes in survey protocols (i.e. vessels and gears). Stratum 421 was not sampled by either survey in 1983 and 1988, and therefore λ_{sy} was assigned a small value, exp(-10), in those years. The median catch in this stratum for all other years combined was 0 so this assumption seems reasonable.

2.3 PRELIMINARY ANALYSIS OF THE TEMPORAL STABILITY OF ESTIMATED VESSEL EFFECTS

The use of a new vessel for the CS in 2013 raised the question of how many years of data might be required to obtain a reliable estimate of relative catchability for an otherwise uncalibrated vessel. A preliminary examination of this question was accomplished by examining the stability of the estimates of $q_{SCS4 \rightarrow T}$ in a retrospective analysis of the existing data. Parameter estimates were obtained by fitting the model repeatedly, successively adding years to produce estimates based on 1980-2005, 1980-2006, to 1980-2012. The data for 1980-2005 contain two years of survey data for the SCS4 vessel, while 1980-2012 contains nine years of data for this vessel. A retrospective analysis for 1980-2004 is not presented because eliminating 2005 results in the loss of a large number of comparative fishing sets in the RVS, which in turn affects the estimates of $q_{AN \rightarrow T}$ and the numerous other parameters that depend on $q_{AN \rightarrow T}$, complicating comparisons of results with other retrospective periods.

3. RESULTS

The estimates of snow crab abundance from both the unconstrained and constrained models were nearly identical for all years except 2013 (Fig. 4). Though both models estimate numbers that are at or above the long term average since 2011, the unconstrained model (i.e., in which $q_{SCS5 \rightarrow T}$ was estimated) produces an increase in abundance from 2012 (Table 3) while the constrained model estimates a slight decrease (Fig. 4B). The former result is driven by the value of $q_{SCS5 \rightarrow T}$, which is estimated to be one of the lowest relative catchabilities of the vessel/gear combinations used in the CS since 1988 (Fig. 5A). This in turns follows from the fact that the RVS caught much more commercial sized snow crab in 2013 compared to 2012 (Benoît 2014), while average densities in the CS were lower in 2013 compared to 2012 (Hébert et al. 2014). Constraining the 2013 CS vessel to have the same catchability as the former vessel results in an estimate of $q_{SCS4 \rightarrow T}$ that is nearly identical to the estimate obtained for the unconstrained model (Fig. 5).

The unconstrained model (negative log-likelihood [NLL] = 35,796.1) provided a slightly better fit to the data compared to the constrained model (NLL=35,799.5). The difference in fit was statistically significant based on a likelihood-ratio test (p=0.0091). The patterns in residuals from both models were nearly identical overall (Fig. 6). The dispersion in residuals from 2013 predictions for the *Teleost* (panels labelled T in Fig. 6) is slightly less for the unconstrained model compared to the constrained model, consistent with a slightly better fit. However the dispersion in residuals from the constrained model for 2013 is certainly in line with other years, which suggests that assuming a constant CS catchability for 2003-2013 does not produce a poor model fit.

The parameter estimates for RVS vessel catchabilities and the diel effect (Table 4) were very similar to those obtained previously and are consistent with literature values (details in Benoît and Cadigan 2013). The estimates for the within-site and between-site over-dispersion parameters, k *and* k_p, are different from the values reported previously. This is a result of an error discovered after the 2013 regional assessment process (RAP) in the ADMB computer code used to numerically integrate Equation (3). This error affected estimates of k *and* k_p but had little effect on other model estimates.

Benoît and Cadigan (2013) presented a number of diagnostic plots of model residuals to evaluate the suitability of the approach. These plots have been updated for the new model fits and are presented in the Appendix but are only briefly interpreted here (note that only the plots for the unconstrained model are presented given the strong similarity with the results for the other model). As was found previously, the NB variance model provided a good description of how the variance in the raw residuals increased with the mean (Appendix Figures A1 and A2). Generally, there were no major time trends in residuals indicating major differences in survey trends (Appendix Figure A3). There was a close correspondence between stratum-average catches and model predictions for the snow crab survey (Appendix Figure A4), the RV survey (Appendix Figure A5) and the two combined (Appendix Figure A6).

The retrospective analyses suggest that after only two years of data for the SCS4, estimates of $q_{SCS4 \rightarrow T}$ were similar to estimates based on a larger number of years (Table 5). However, the relative uncertainty in the estimates of $q_{SCS4 \rightarrow T}$ declined as data from greater number of years were included in the analysis. The value of the coefficient of variation after nine years of SCS4 data was half the value after only two years of data. This analysis should be considered as preliminary and only indicative of the relationship between relative catchability parameter estimates and vessel years-in-service as it represents just one realization of this relationship.

4. DISCUSSION

The results obtained by comparing the unconstrained and constrained models suggest that it may be pre-mature to establish that the relative catchability of the 2013 CS vessel is indeed amongst the lowest of the vessels used in the CS since 1988. With a single year of data, we cannot rule out the possibility that the relatively elevated catches in the RVS may have been the result of a year effect which in turn greatly influenced the estimate of $q_{SCS5 \rightarrow T}$. With additional years of survey data involving the *Jean-Mathieu* for the CS and the *CCGS Teleost* for the RVS, the reliability of the estimate of $q_{SCS5 \rightarrow T}$ will greatly improve. The retrospective analysis suggests that this can occur after two years, though if there are year effects in the data for either survey, this period is likely to be longer. Furthermore, uncertainty in the estimates will decline with additional years of data. This situation highlights the importance of having some interannual consistency in the CS vessels, given the absence of comparative fishing.

More generally, the conclusions of Benoît and Cadigan (2013) remain valid with the addition of the 2013 values and the other slight changes to the model. The model provides a useful method for integrating the available data on snow crab abundance in the sGSL, making the best use of data that are costly to obtain. The model draws strength from both the RV and crab surveys to estimate relative catchability parameters that would otherwise be difficult to estimate (SCS1-SCS4 and $q_{WT \rightarrow T}$). Furthermore, the model provides a useful framework in which to efficiently estimate relative catchability coefficients for the RV survey for 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. By estimating these parameters within a common modeling framework, their associated uncertainties are reflected in the estimated abundance index.

It is well-known that maximum likelihood estimates of variance parameters such as the NB over-dispersion parameters are biased when the number of mean parameters in a model is large (e.g. Cadigan and Tobin 2010). Maximum likelihood estimators of variance parameters do not make adjustments for model degrees of freedom, i.e. n-p, where p is the number of model parameters. Hence, variance parameter estimates may be too low when the degree of freedom is small relative to n. If the bias is substantial then it can result in underestimated parameter standard errors, confidence intervals that are too narrow and an underestimated p-value for the likelihood ratio test used to compare the constrained and unconstrained models. Although our survey model has many stratum-effect parameters the total sample size is large so we do not feel this bias problem will be large for k and k_p. Nonetheless, we have begun work aimed at improving the reliability of the dispersion parameter estimates. Likewise, future versions of this model will include uncertainty in the estimation of PLM as part of the estimation. The main activity ahead is to test the overall reliability of the model estimations using simulations.

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We wish to thank Gérald Chaput for his helpful review of a draft of this research document.

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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	na
1981	70	57	13	0	na
1982	65	47	17	1	na
1983	67	48	14	5	na
1984	102	85	12	5	na
1985	209	162	41	6	na
1986	164	156	0	8	na
1987	152	128	13	11	na
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

Table 2. Summary of the vessels and gear used in the research vessel survey.

Vessel	Trawl	Years in service	Comparative fishing data available
E.E. Prince	Yankee 36	1971-1985	Yes
Lady Hammond	Western IIA	1985-1991	Yes
CCGS *Alfred Needler*	Western IIA	1992-2002; 2004-2005	Yes
CCGS *Wilfred Templeman*	Western IIA	2003	No
CCGS *Teleost*	Western IIA	2004-ongoing	Yes

Table 3. Estimated annual density (number per km^2; mean, coefficient of variation (CV) and 95% confidence intervals) of 4T snow crab abundance for the model that assumed a separate catchability for the 2013 CS vessel.

Year	*Estimate*	*CV*	*Lower*	*Upper*
1980	79.660	0.36	39.283	161.547
1981	84.943	0.41	38.333	188.234
1982	151.060	0.36	75.184	303.526
1983	157.060	0.37	75.741	325.669
1984	69.328	0.30	38.821	123.821
1985	37.518	0.21	25.077	56.128
1986	56.716	0.21	37.675	85.388
1987	56.163	0.23	35.684	88.384
1988	77.961	0.28	44.982	135.115
1989	76.900	0.17	54.910	107.695
1990	208.300	0.16	151.061	287.240
1991	124.630	0.13	96.652	160.724
1992	134.150	0.12	106.128	169.551
1993	172.320	0.13	134.331	221.029
1994	199.690	0.12	156.494	254.826
1995	134.360	0.12	105.776	170.694
1996	53.678	0.14	40.543	71.067
1997	73.816	0.12	58.594	92.997
1998	87.612	0.12	69.406	110.589
1999	56.464	0.12	44.438	71.744
2000	51.081	0.12	40.294	64.754
2001	57.138	0.13	44.471	73.417
2002	72.388	0.12	56.917	92.057
2003	141.190	0.10	116.443	171.193
2004	150.150	0.08	127.347	177.024
2005	133.610	0.08	114.011	156.570
2006	114.770	0.08	97.952	134.467
2007	96.306	0.08	83.099	111.605
2008	82.067	0.08	70.843	95.062
2009	51.606	0.08	43.785	60.820
2010	52.260	0.08	44.537	61.319
2011	99.408	0.08	85.213	115.960
2012	108.980	0.08	92.903	127.823
2013	144.220	0.14	110.408	188.410

Table 4. Estimates (mean, CV, and 95% confidence interval) of some snow crab model parameters for the model that assumed a separate catchability for the 2013 SC vessel. The negative loglikelihood totals 35,796

Year	*Estimate*	*CV*	*Lower*	*Upper*
$q_{AN \to T}$	1.035	0.09	0.870	1.231
$q_{LH \to AN}$	1.347	0.10	1.115	1.626
$q_{EP \to LH}$	0.412	0.14	0.316	0.537
$q_{WT \to T}$	0.616	0.19	0.422	0.901
$q_{SCS1 \to T}$	11.938	0.17	8.574	16.622
$q_{SCS2 \to T}$	23.362	0.11	18.976	28.761
$q_{SCS3 \to T}$	30.726	0.12	24.498	38.537
$q_{SCS4 \to T}$	17.740	0.05	15.976	19.698
$q_{SCS5 \to T}$	11.830	0.15	8.781	15.936
δ (day/night)	1.332	0.04	1.231	1.442
k	1.055	0.04	0.978	1.138
k_p	3.847	0.08	3.259	4.542

Table 5. Estimates of the relative catchability of SCS4 ($q_{SCS4 \to T}$), and associated coefficient of variation, as a function of the last year included in the retrospective analysis (e.g., terminal year 2008 indicates the results for the model fit to the data for 1980-2008).

Year	$q_{SCS4 \to T}$	*CV*
2005	17.805	0.10
2006	16.651	0.08
2007	17.181	0.07
2008	16.760	0.07
2009	16.281	0.06
2010	16.991	0.06
2011	16.742	0.06
2012	17.740	0.05

FIGURES

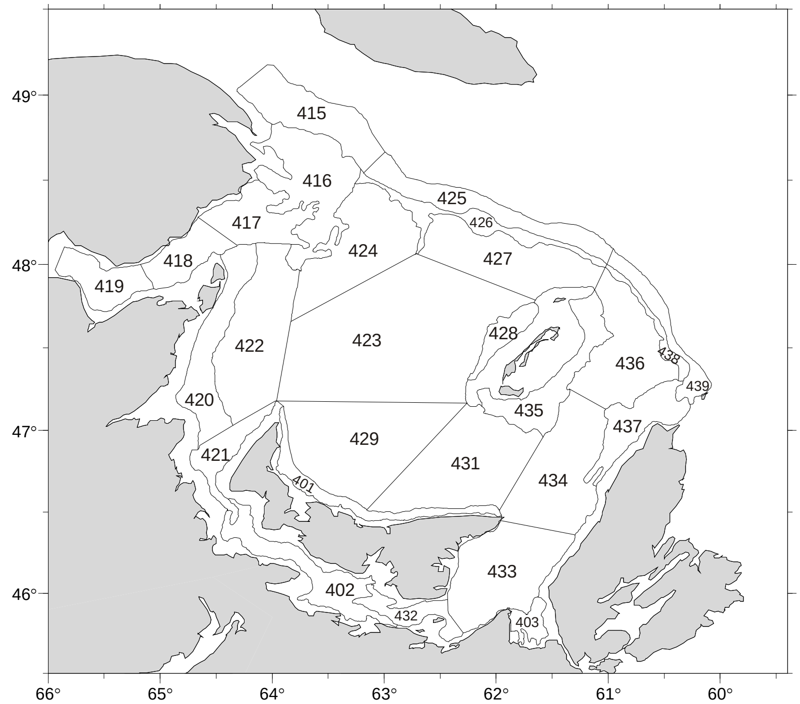


Figure. 1. Stratum boundaries for the southern Gulf of St. Lawrence September RV survey.

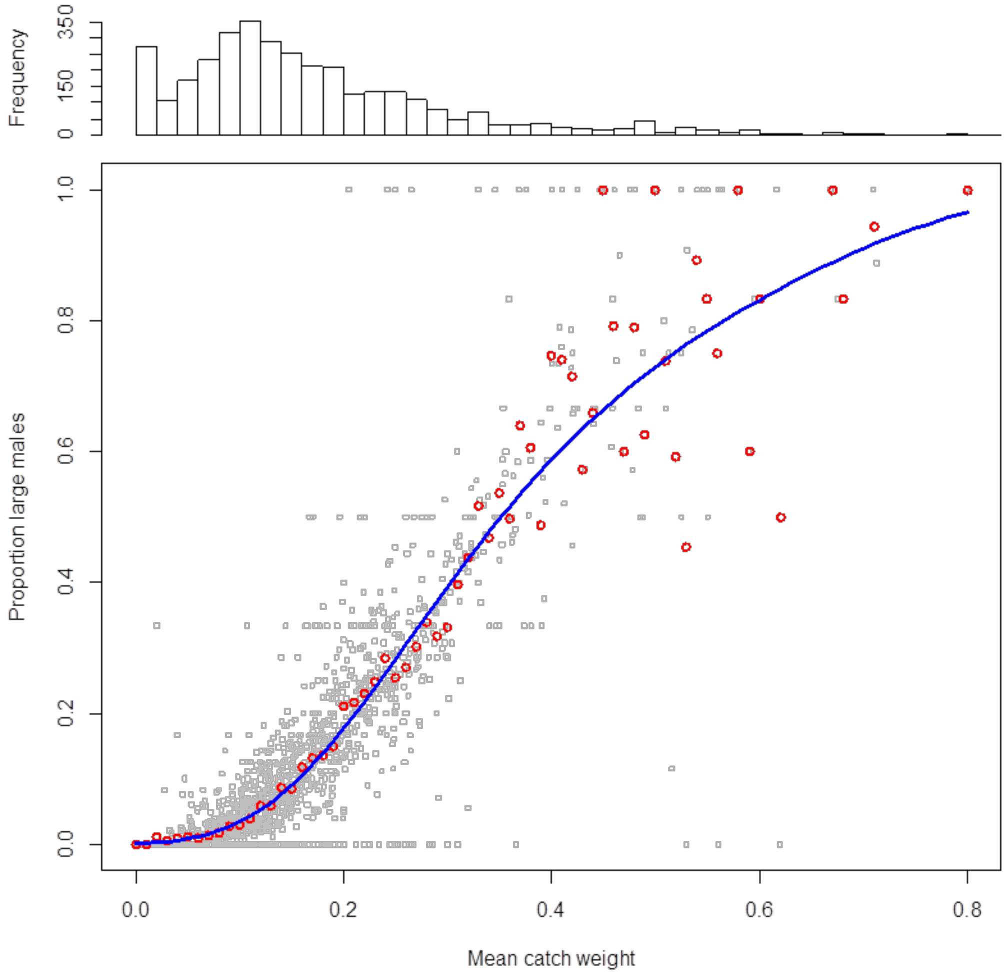


Figure 2. The main panel shows the proportion, by numbers, of the catch in a RV survey set that is comprised of large males (PLM; 95+ mm), as a function of the mean mass (mean catch weight) of individuals in the set. Grey squares represent values for individual RV survey sets (2001-2012), red circles represent the average proportion summarized in mean mass bins of 0.01 kg, and the blue line is the fit of the best model. The top panel shows a histogram of the mean mass of individuals for RV survey sets from 1980 to 2000, showing the distribution of values for which inferences are required.

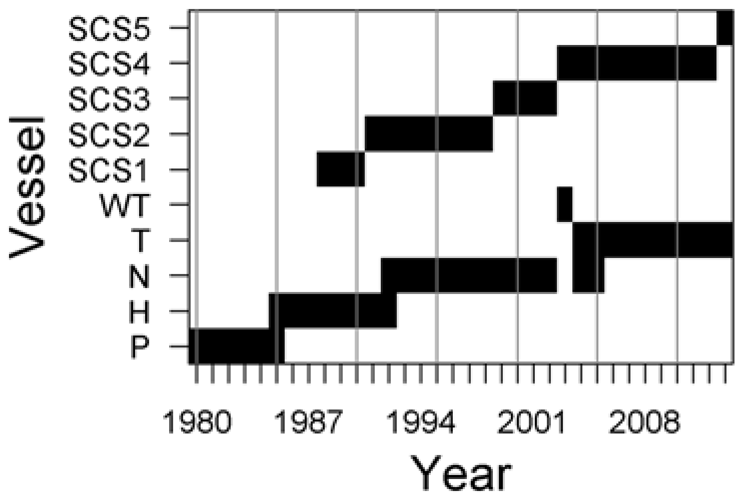


Figure 3. Summary of the survey vessels used in the snow crab surveys (SC) and research vessel survey (RVS) as a function of year for 1980-2013.

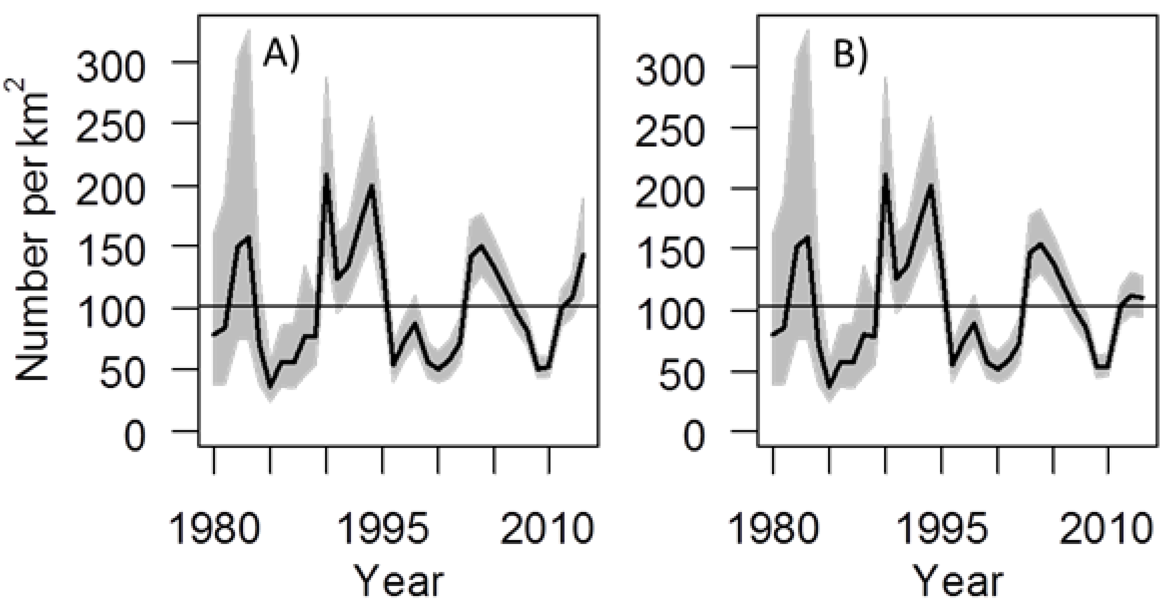


Figure 4. Annual estimated densities (number per km²) of southern Gulf commercial male snow crab, 1980 to 2013. The horizontal line indicates the series average and the shaded region indicates the 95% confidence interval range. The results for the model that estimated a separate catchability for the 2013 SCS vessel are shown in panel A (left) and the results for the model that constrained the 2003-2012 and 2013 vessels to have the same catchability are shown in panel B (right).

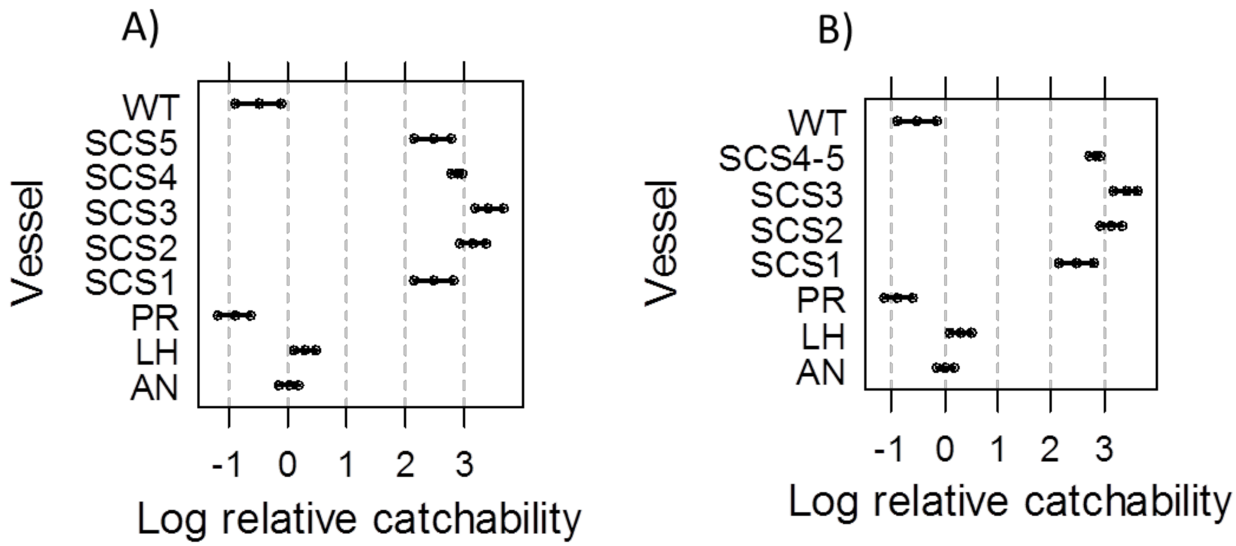


Figure 5. Estimates (middle points) of survey vessel/gear relative catchabilities, log(q) with 95% confidence intervals for the model that estimated a separate catchability for the 2013 SCS vessel (panel A; left) and for the model that constrained the 2003-2012 and 2013 vessels to have the same catchability (panel B; right). The catchability comparisons are annotated as follows: WT is CCGS Wilfred Templeman → CCGS Teleost, PR is EE Prince → Lady Hammond, LH is Lady Hammond → CCGS Alfred Needler, and AN is 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,SCS5 – vessel for 2013 and SCS4-5 – vessels for 2003-2013.

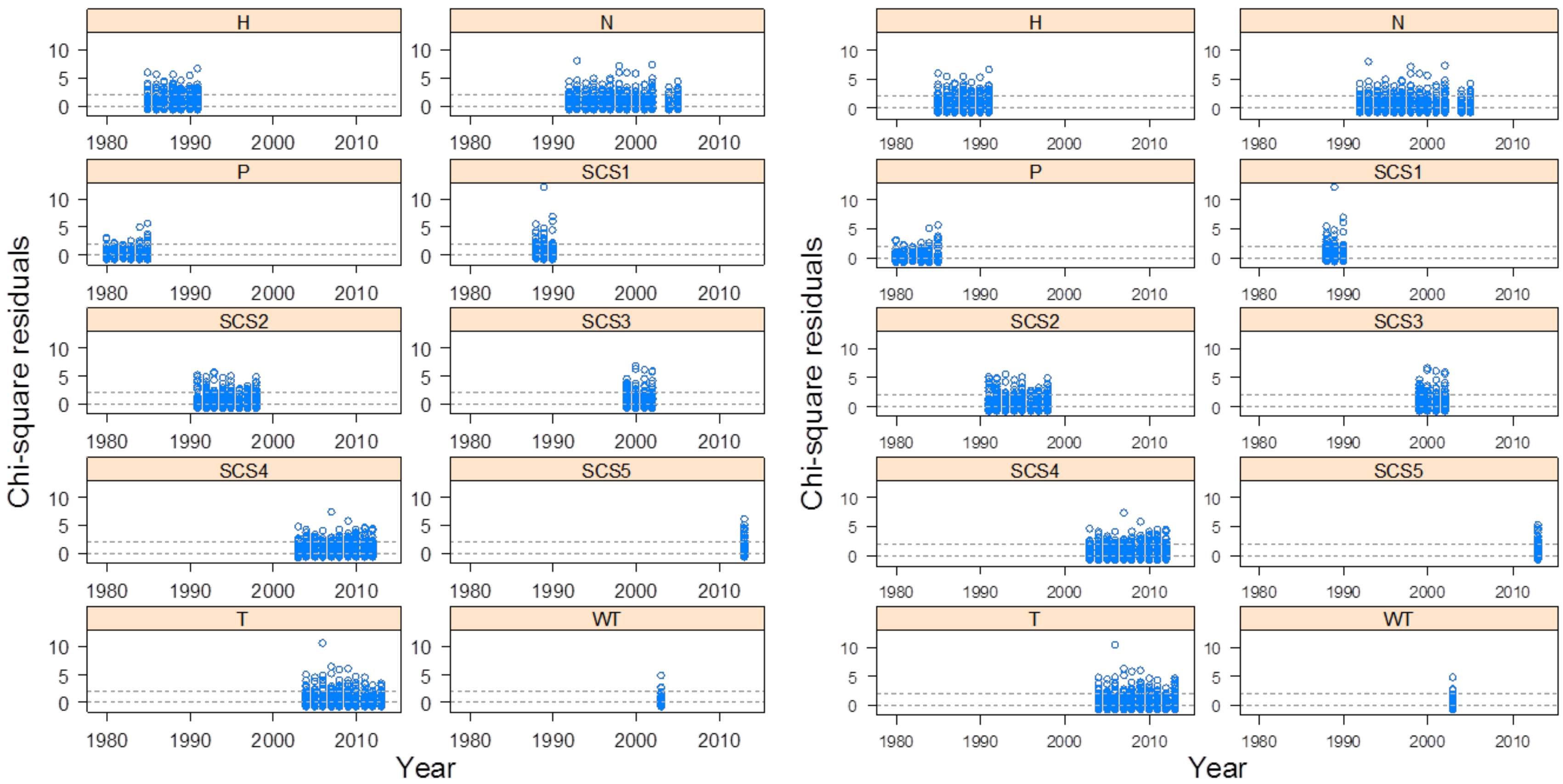
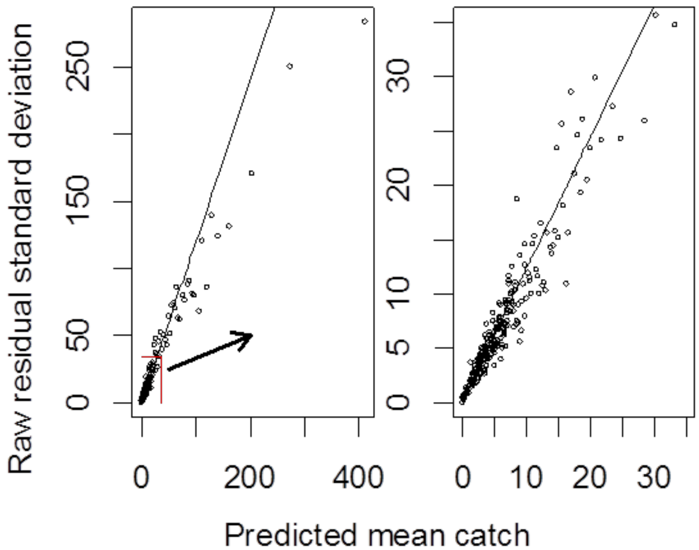
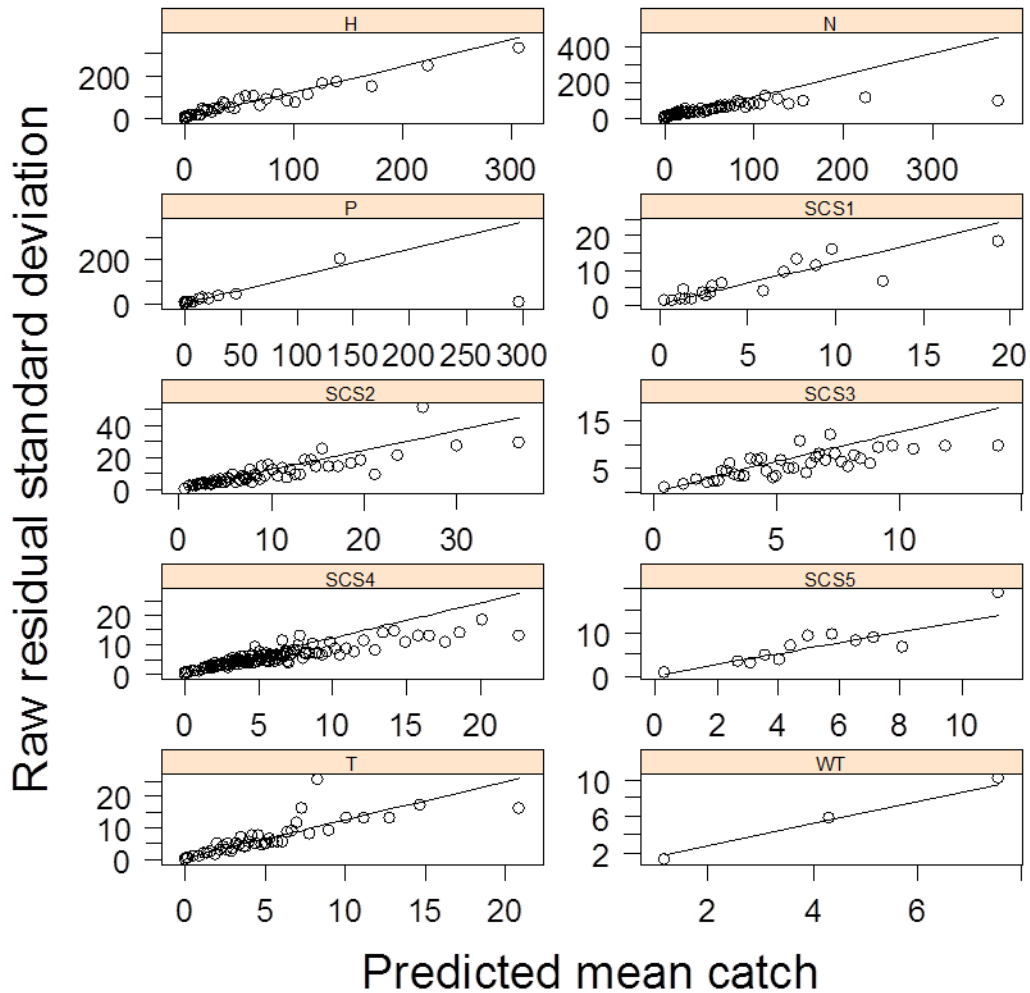


Figure 6. Model residuals by year (x-axes) and vessel (panels). For the left panel, the residuals are from the model that estimated a separate catchability for the 2013 SCS vessel. For the right panel, the residuals are for the model that constrained the 2003-2012 and 2013 vessels to have the same catchability.

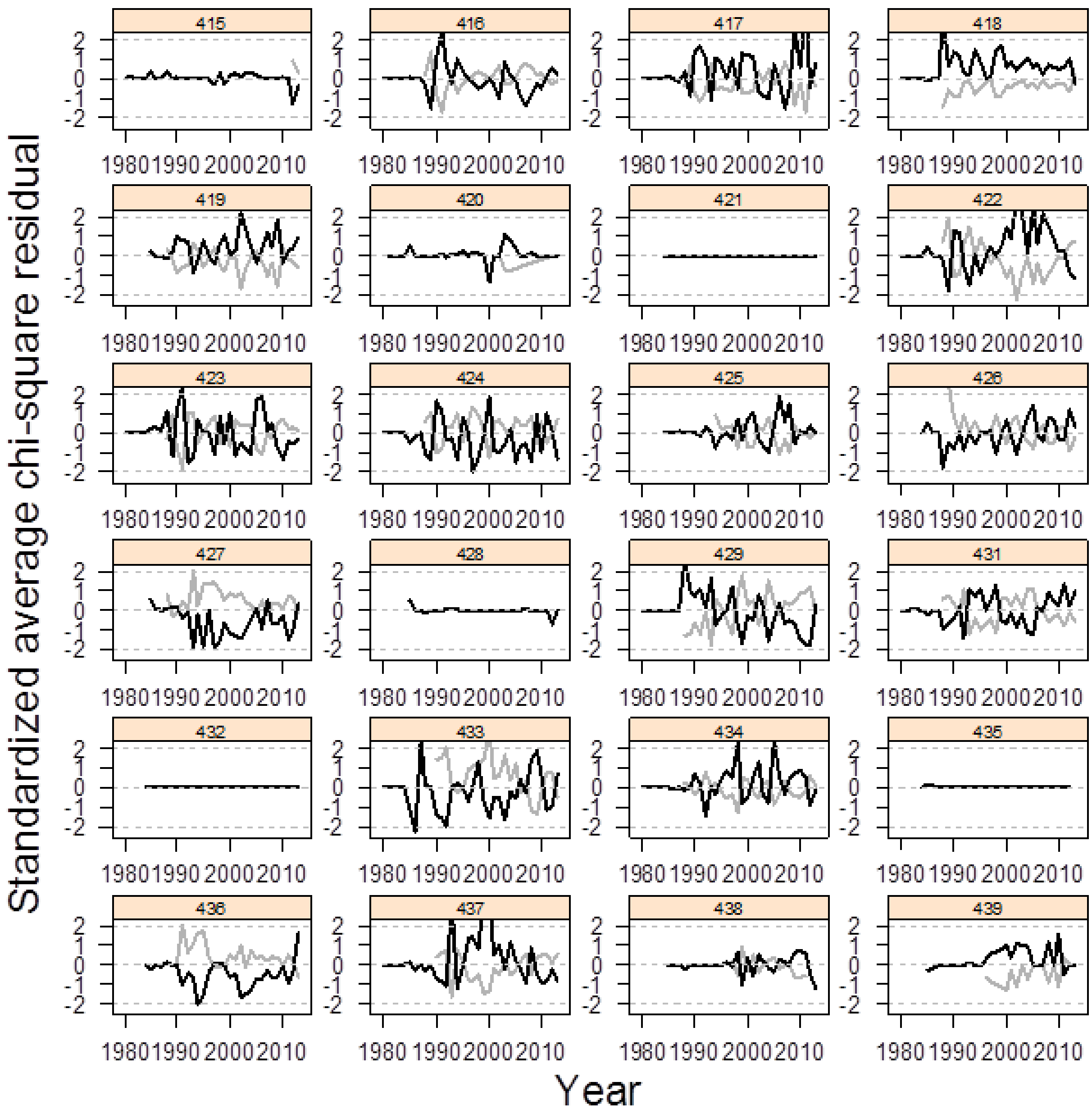
APPENDIX



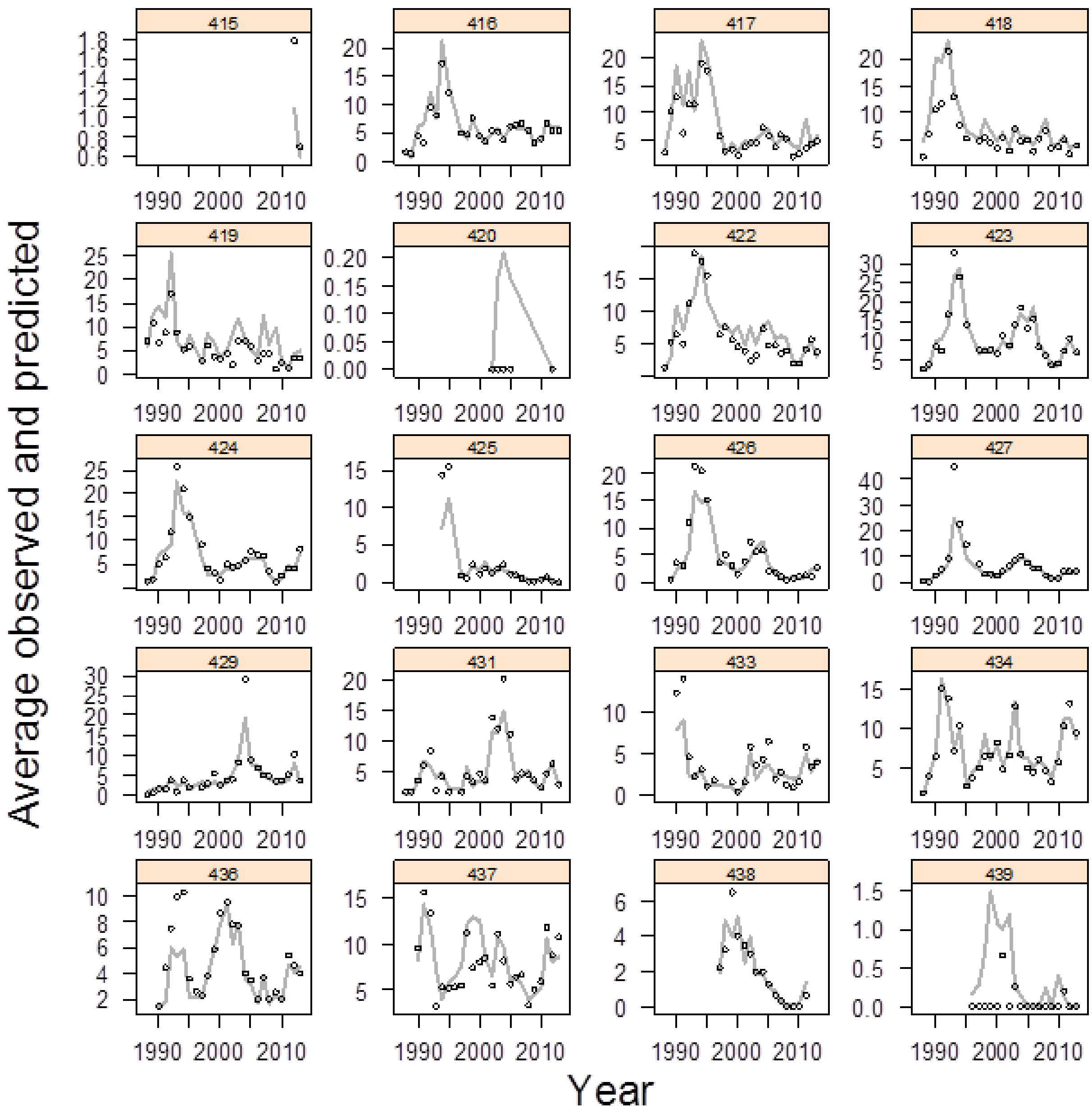
Appendix Figure 1. Standard deviations (sd's) of the binned raw residuals for the model that estimated a separate catchability for the 2013 SCS vessel. The solid line is the NB prediction of the raw residual sd (sqrt[predicted + predicted^2/k]). The right panel is the same as the left panel but using a narrower range on both the x and y axes.



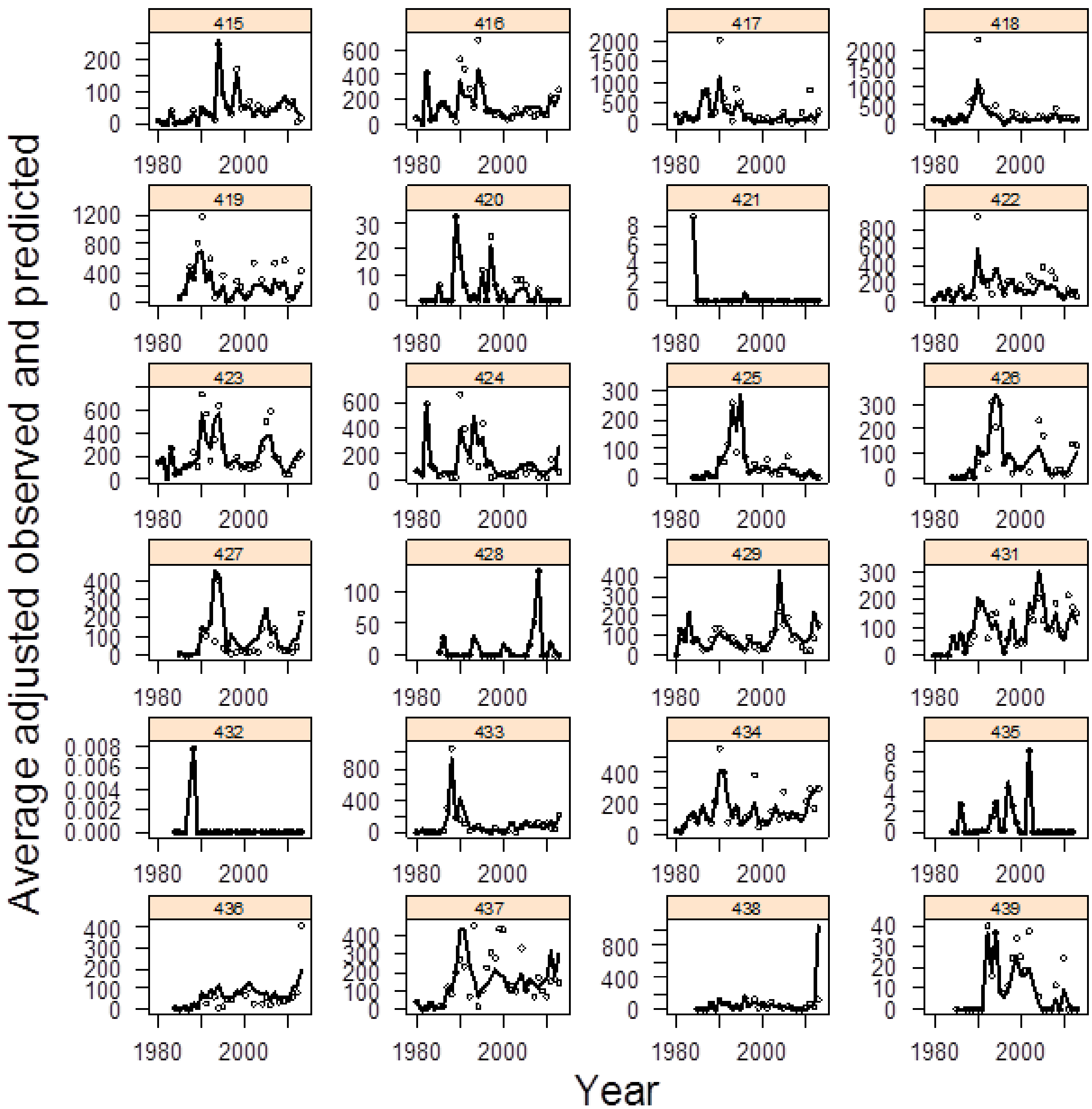
Appendix Figure 2. Standard deviations (sd's) of the binned raw residuals for survey vessel/gears for the model that estimated a separate catchability for the 2013 SCS vessel. The solid line is the NB prediction of the raw residual sd, (sqrt[predicted + predicted^2/k]). The panel labels are as follows: WT - CCGS Wilfred Templeman, T - CCGS Teleost, P - EE Prince, H – Lady Hammond, N – CCGS Alfred Needler. SCS1 – Snow crab survey gear for 1988-1990, SCS2 – vessel for 1991-1998, SCS3 – vessel for 1999-2002, and SCS4 – vessel for 2003-2012.



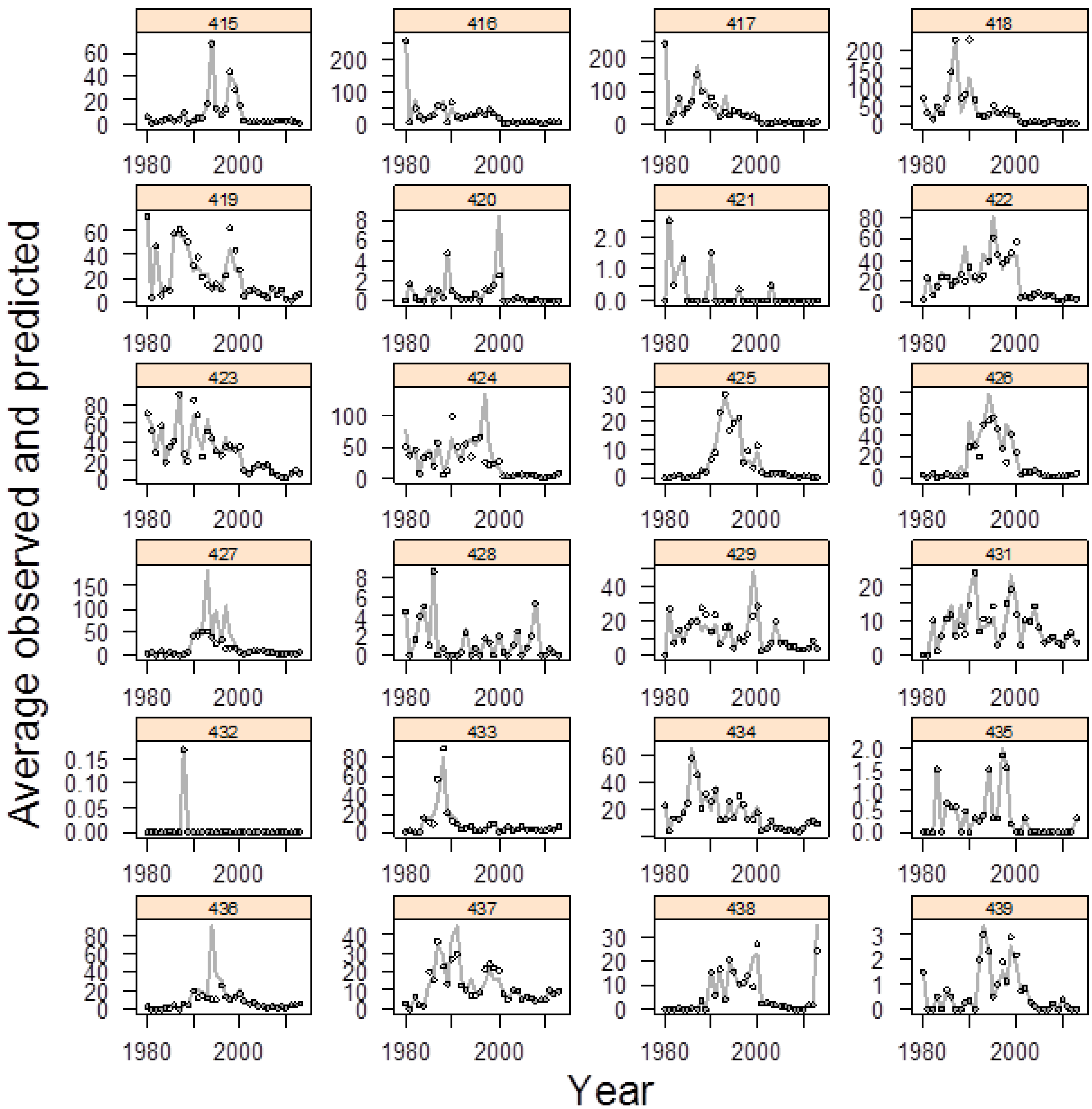
Appendix Figure 3. Annual stratum-average chi-square residuals for the RV survey (black) and the snow crab survey (grey) for the model that estimated a separate catchability for the 2013 SC vessel. A dashed reference line at 0 is shown. Stratum number is listed at the top of each panel. Only averages based on more than two observations are shown. Note that residuals are very small for strata with very low crab densities and in which the snow crab survey does not sample.



Appendix Figure 4. Annual stratum-average observed (points) versus predicted (lines) snow crab survey catches (number of commercial-sized adult male crab per tow). The predictions are those for the model that estimated a separate catchability for the 2013 SC vessel. Stratum number is listed at the top of each panel. Only averages based on more than two observations are shown. Note the different y-axis scales among the strata panels.



Appendix Figure 5. Annual stratum-average adjusted observed (points) versus predicted (lines) RV survey catches (number of commercial-sized adult male crab per km²). Predictions are those for the model that estimated a separate catchability for the 2013 SC vessel. Stratum number is listed at the top of each panel. Only averages based on more than two observations are shown. Note the different y-axis scales among the strata panels.



Appendix Figure 6. Annual stratum-average observed (points) versus predicted (lines) catches per tow, based on aggregated catches for both surveys. Stratum number is listed at the top of each panel. Only averages based on more than two observations are shown. Note the different y-axis scales among the strata panels.