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2015 Eastern Scotian Shelf Shrimp (*Pandalus borealis*) Framework

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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 eastern Scotia Shelf Shrimp fishery has been ongoing since the early 1980s, although the fishery's contemporary history began with the introduction of the Nordmøre grate in 1991, which allowed the fishery to overcome bycatch limitations. Salient aspects of the species' and stock's biology and ecology are reviewed to support a detailed description of the diverse data streams that have been used in the provision of science following a multiple indicator Traffic Light Analysis for nearly a quarter-century. The details of the collaborative Fisheries and Oceans Canada (DFO)-Industry survey, which is entering its twentieth in 2015, are provided. This includes survey history and design, comparative fishing experiments, trawl mensuration methods for the estimation of total biomass and catch composition, which provides the data that are the basis of the many fishery-independent Traffic Light indicators. The details of the collection and analysis of commercial catch rate and catch composition data are also provided. The holistic manner in which these primary indicators of stock abundance and composition, as well as supporting ecosystem indicators, are analysed annually to provide science advice for adaptive Total Allowable Catch (TAC) adjustments in the new biennial assessment schedule are described. Despite its long track record of the provision of science advice for the highly successful co-management of this stock, the Traffic Light method has been subject to two important criticisms since its inception: the lack of defined quantitative outcomes based on the indicator values, and the lack of quantitative projections. These limitations are explored in detail and options are discussed to address them. The deterministic harvest control rule model discussed herein to provide a range of TAC advice yields relatively conservative quota advice that is generally consistent with the successful and conservative management history of this stock, except at high biomass, where it allows for higher exploitation than this conservative fishery has historically opted for. Its principle benefit is that it provides clear and conservative management guidance at low to moderate biomass levels (i.e. Critical and Cautious zones), where this fishery had very little contemporary experience. In addition to the higher (than historical) exploitation rates at high abundance resulting from this deterministic linkage of harvest advice to biomass indices, this method would risk losing the inclusivity and flexibility that has resulted in effective collaboration between science, management and stakeholders to guide this fishery towards a profitable and sustainable exploitation strategy for so long. Indicator weighting is necessary for deterministic harvest control rules and continues to be a serious and perhaps insurmountable problem with this approach. The results of a Bayesian state space biomass dynamic model is reviewed as a means to provide quantitative stock projections based on the relationship between variations in biomass as a function of previous biomass and other population specific parameters. All three biomass indicator series yield implausible biomass and parameters estimates, particularly those derived from a very low modelled carrying capacity (less than half of the historical survey biomass index values). The model assumptions, which this and most other shrimp stocks tend to seriously violate, are discussed. There has been no detectable influence of fishing mortality on biomass variation in the very conservatively exploited Scotian Shelf Shrimp stock. It is proposed that science advice for the eastern Scotian Shelf Shrimp fishery should continue to be provided by the holistic combination of qualitative and quantitative interpretations of data in the Traffic Light Analysis that has proven so successful. Quantitative analysis of biomass indicators, corroborated by a suite of other shrimp stock and ecosystem data, coupled with qualitative projections based tracking year classes in survey and commercial length frequencies now has a long track record of transparent and inclusive co-management of this stock, and there is no reason to change this. Future research efforts should focus on continued validation and refinement of the Traffic Light indicators rather than the identification of deterministic harvest control rules or quantitative projection methods.

Crevette nordique (*Pandalus borealis*) de l’est du plateau néo-écossais de 2015

RÉSUMÉ

On pêche la crevette nordique de l’est du plateau néo-écossais depuis les années 1980, bien que l’historique contemporain de la pêche ait débuté avec l’introduction de la grille Nordmore en 1991, ce qui a permis à la pêche de surmonter les limites des prises accessoires. Des aspects importants relatifs à la biologie et à l’écologie des espèces et des stocks sont examinés afin de contribuer à une description détaillée des flux de données divers qui ont servi à la transmission d’avis scientifiques à la suite d’une analyse des indicateurs multiples des feux de circulation depuis près d’un quart de siècle. On présente les détails de l’étude conjointe de Pêches et Océans Canada (MPO) avec l’industrie, qui entamait sa vingtième année en 2015. Ils comprennent l’historique et la conception de l’étude, des expériences de pêche comparatives, des méthodes et du dimensionnement des chaluts pour l’estimation de la composition totale de la biomasse et des prises, ce qui fournit les données sur lesquelles reposent de nombreux indicateurs de feux de circulation indépendants des pêches. On fournit également les détails relatifs à la collecte et à l’analyse des données sur le taux de prises commerciales et la composition des prises. La manière holistique avec laquelle ces indicateurs primaires de l’abondance et de la composition des stocks, et les indicateurs des écosystèmes à l’appui, sont analysés annuellement afin de fournir un avis scientifique pour les rajustements adaptatifs du total autorisé des captures (TAC) dans le nouveau calendrier d’évaluation biennal sont décrits. Malgré les longs antécédents de transmission d’avis scientifiques sur la cogestion très réussie de ce stock, la méthode des feux de circulation a fait l’objet de deux critiques importantes depuis ses débuts : le manque de résultats quantitatifs définis reposant sur les valeurs des indicateurs, et le manque de projections quantitatives. On explore ces limites en détail et discute des options en vue de les examiner. Le modèle déterministe de règle de contrôle de la capture dont il est question dans les présentes, dans le but de dispenser divers conseils sur le TAC, offre des conseils relativement conservateurs sur le quota qui concordent généralement avec l’historique de gestion réussi et conservateur de ce stock, sauf dans le cas d’une biomasse élevée, qui permet une plus vaste exploitation que cette pêche conservatrice a historiquement choisie. Son principal avantage vient du fait qu’il fournit des directives de gestion claires et conservatrices à des niveaux de biomasse qui varient de faibles à moyens (c.-à-d. des zones critiques et prudentes), dans lesquels cette pêche n’avait que peu d’expérience contemporaine. Outre les taux d’exploitation plus élevés (que les taux historiques) en période de grande abondance découlant de ce lien déterministe de l’avis sur la récolte des indices de la biomasse, cette méthode risquerait de perdre l’inclusivité et la flexibilité qui a abouti à la collaboration efficace de la science, de la gestion et des intervenants pour guider les pêches vers une stratégie d’exploitation rentable et durable depuis si longtemps. Le poids de l’indicateur est nécessaire pour obtenir des règles de contrôle des récoltes déterministes et continue de représenter un problème majeur, voire insurmontable, avec cette approche. On examine les résultats de la modélisation de la dynamique de la biomasse du modèle bayésien de type état-espace en tant que moyen de fournir des projections quantitatives sur les stocks qui reposent sur la relation entre les variations de la biomasse comme une fonction de la biomasse précédente et d’autres paramètres précis de la population. Les trois séries d’indicateurs de la biomasse donnent des estimations peu vraisemblables de la biomasse et des paramètres, particulièrement celles dérivées d’une très faible capacité de charge (moins de la moitié des valeurs historiques de l’indice de la biomasse exploitable). Nous discutons des hypothèses relatives au modèle, que ces stocks et la plupart des autres stocks de crevettes ont tendance à enfreindre gravement. Aucune influence de la mortalité de la pêche n’a été détectée sur la variation de la biomasse dans le stock de crevettes nordiques de l’est du plateau néo-écossais exploité de façon très conservatrice. Nous proposons l’apport continu d’avis scientifiques par la combinaison holistique d’interprétations qualitatives et quantitatives des

données dans l’analyse des feux de circulation qui se sont révélées un grand succès. Une analyse quantitative des indicateurs de la biomasse, corroborée par une série d’autres données sur le stock et l’écosystème de la crevette, jumelée à des projections qualitatives fondées sur la surveillance des classes d’âge dans les études et les fréquences des longueurs commerciales, a maintenant un long historique de cogestion transparente et inclusive de ce stock, et aucune raison ne justifierait un changement. Les efforts futurs déployés dans la recherche devront être axés sur la validation continue et le peaufinage des indicateurs de feux de circulation plutôt que sur la désignation de règles de contrôle de récolte déterministes ou de méthodes de projection quantitative.

INTRODUCTION

Science advice for the eastern Scotian Shelf (ESS) Shrimp stock is provided to set a new quota on an annual basis. A full stock assessment is performed every other year, generating a Research Document and Science Advisory Report. In the intervening years, interim advice is provided in the form of a Special Science Response at a smaller meeting. A framework meeting is scheduled to take place approximately every five years for this stock. The purpose of this framework is to thoroughly review and critically assess the background information and the stock assessment methodology for the ESS Shrimp stock.

BIOLOGY AND ECOLOGY

The biology of Northern (pink) Shrimp, *Pandalus borealis* (hereafter "shrimp"), is reviewed in Shumway et al. (1985) for various stocks world-wide, and by Koeller (1996, 2000, 2006) and Koeller et al. (2000a, 2003b) for the ESS stock. The above references provide a very thorough review. Salient points for this framework, which derive from the body of literature above, unless otherwise noted, are given below.

Shrimp have a discontinuous circumboreal distribution mostly north of the 46th parallel, depending mostly on temperature, salinity, substratum and depth. Shrimp are stenohaline, preferring high salinity, and are found at temperatures ranging from -1.6 to 12ºC, although most commonly from 0 to 5ºC. Extended periods of exposure to -1ºC or colder have resulted in mass mortality events. Shrimp prefer a soft mud or sand/silt bottom and their occurrence is strongly correlated with organic content of the bottom sediments. Depth preferences vary with latitude, with higher densities occurring at greater depths at higher latitudes than they do in southern parts of the species' range. Although they have been reported from water as deep as 1450 m, shrimp are most common between 50-500 m, especially on soft muddy bottoms from 10-300 m. Shrimp also undergo diurnal vertical migration, such that catch rates decrease with a bottom trawl at night and shrimp are sometimes seen at the surface at night. In general, female shrimp migrate inshore to release larvae, although this is less true on the ESS than in some other parts of the species' range (e.g. Gulf of Maine (GoM)).

Shrimp are protandrous hermaphrodites, and the interaction of habitat conditions, primarily temperature, with growth and the timing (age) of various life history transitions can have profound effects on the species' population dynamics. Sex transition to female generally takes place earlier in southern populations. In general, in warmer temperatures shrimp grow more quickly, undergo sex transition at a younger age (fewer years as males) and are less long-lived than in colder temperatures. However, density and total mortality are also thought to influence sex transition, with shrimp delaying changing sex when density is high (i.e. when there are lots of females, it is a good strategy to remain male) and changing sex at a younger age when adult mortality rates are high (i.e. when female abundance is declining, it is a good time to change sex to replace them).

Shrimp spawn in the summer or fall. They mate within 36 hours of moulting and fecundity, which is directly related to body size, ranges from 600-4900 eggs. Fertilized eggs remain attached to the female until they hatch in the spring. The occurrence of a pernidian parasite (known as "white eggs") can reduce fecundity. After hatching, larvae feed for 3-4 months in the water column before settling to the bottom. Recruitment processes have proven very difficult to define for shrimp, which has important implications for stock assessments and the provision of harvest advice.

Although there are no known direct methods for estimating natural mortality (M), it is thought to be generally high, especially that of females after spawning. Principle factors affecting M include predation by diverse fishes, temperature anomalies and food supply for juveniles. Important predators of shrimp include Cod, various flatfish, Silver Hake, Redfish and halibut.

Shrimp on the Scotian Shelf and in the GoM are at the southern extreme of the species' range (concentrated north of 46N), and by inference at the extreme of the species ecological and physiological limits (Koeller 1996). Although temperatures over a wide area of the Scotian Shelf are suitable for shrimp, smaller areas of suitable habitat on the ESS define the limits of the commercially important population. Most of the groundfish species on the ESS feed on crustaceans at some point in their lives, and shrimp have often been identified as important parts of the diets of Cod, Silver Hake, Greenland Halibut, Redfish and various flatfish (Shumway et al.1985). Koeller's (1996) analysis of environmental and ecological factors identified important differences between the GoM, western Scotian Shelf (WSS) and the ESS, including inshore areas of the Scotian Shelf where exploratory trap fisheries were ongoing. He found that the ESS contained by far a much higher proportion of preferred temperature and bottom habitat than the WSS, where generally unfavourable temperatures resulted in variable and short-lived commercially viable populations. Similarly marginally suitable temperatures were invoked to explain the relatively unstable stock in the GoM, which fluctuates a lot based on temperature anomalies and fluctuations in predator abundance. Overall, trends in shrimp stocks on the WSS track the GoM while the ESS shrimp stock is different. In particular, ESS shrimp are concentrated on relatively small areas of suitable habitat in a broad area of suitable temperatures, and so are less prone to temperature-induces crashes as seen in the GoM. Because temperatures are broadly suitable on the ESS, and depth is of lesser importance, predation appears to have a strong effect on shrimp abundance trends.

Shrimp migration patterns also differ significantly between stocks, mostly because of differences in temporal and spatial availability of suitable substrate and temperature combinations. For example, temperatures on deepwater habitats are perennially suitable for shrimp in Newfoundland, so inshore migrations are not observed. By contrast, in the GoM, deep water temperatures get too warm in the fall, so shrimp come inshore to spawn, and return to deep water in the spring. The same is true of the central and WSS, where deep water temperatures exceed the upper thermal limit for shrimp, resulting in a winter inshore migration similar to the GoM (e.g. between Roseway Basin and Mahone Bay). On the ESS, females and juveniles are found *both* inshore and offshore, suggesting that spawning takes place in both areas. This reflects the fact that ESS temperatures are near the shrimp's lower limit throughout the year, so stock components can stay inshore and offshore at high densities perennially. One exception to this is that it becomes too cold for shrimp in Chedabucto Bay in some years in the late winter/spring, so shrimp move offshore to deeper/warmer water in those instances. This difference is evident in winter trap fishery catches, with Mahone Bay experimental trappers catching mostly ovigerous females, while the ongoing commercial Chedabucto Bay trap fishery catches all life stages.

Several factors suggest that a high degree of precaution is warranted for the provision of sustainable harvest advice for ESS shrimp. First, the concentration of this stock on small areas of mud substrates makes local overfishing a potential concern. If this occurred, it is unlikely that the ESS could be reseeded from the next upstream stock in the Northern Gulf of St. Lawrence. Furthermore, the highly dynamic hydrogeographic regime, with horizontal tides and larval retention gyres larger than the area of suitable habitat, suggest that a high percentage of larvae settle on unsuitable habitat, or currents carry larvae from the ESS to unsuitable habitats to the west, which are not very far away. As a result, this stock may experience high larval mortality and be vulnerable to recruitment overfishing, in which case harvest strategies that maintain a higher Spawning Stock Biomass (SSB) would be prudent, relative to other stocks where reseeding from other stocks is more likely (e.g. Newfoundland).

Shrimp on the ESS are generally represented by six year classes – the first four as juveniles and males/transitionals followed by one primiparous female and one multiparous female year class (Koeller et al. 2000a). Under certain conditions, particularly when influenced by a particularly abundant year class, ESS shrimp appear to be able to live up for several more years (e.g. 2001 year class; Koeller et al. 2011).

Koeller (2006) reviewed available information on growth and stage structure in ESS shrimp. He found that only ages 2 and 3 are reliably identifiable length modes for many stock, despite living up to as much as 8 years. Although older age classes are difficult to differentiate based on length modes, they can be differentiated as being primiparous or multiparous based on sternal spines, which provides a useful means to roughly differentiate year classes (generally 5 and 6 year olds). Based on this work, Koeller found that size at sex transition and maximum size were largely determined by growth rate, rather than density, with faster growing shrimp in warm conditions changing sex earlier and reaching a smaller maximum size due to decreased longevity. When colder, and when density is high, they grow more slowly, change sex later and live longer, reaching a larger maximum size. Longevity was largely determined by the number of male age classes, achieved by protracting or abbreviating the male period before sex transition depending on growth rate, as determined by temperatures, metabolism and density effects.

Size at sex transition is an important life history parameter for stock assessment because of the demographic consequences of the relationship between body size and fecundity. While slow growing shrimp take longer to become female, they produce more eggs once they do. Conversely, although fast growing shrimp become female and begin producing eggs sooner, they are also less fecund. A further important consideration, especially for the provision of qualitative “projections” based on length-frequency tracking, is that only part of very large year classes will change sex each year.

Koeller (2006) invoked these linkages between environment, growth rate, age/size at sex change, longevity and maximum size to explain the invariant nature of the ratio of size at sex transition and maximum size in ESS and other shrimp stocks (i.e. Charnov’s rule; Charnov and Skúladóttir 2000). When it is cold, growth slows, and *both* size at sex transition and maximum size increase. Conversely, when it is warm, growth is faster, and *both* size at sex transition and maximum size decrease. Because the environment affects the growth rates of all age classes, and because it is growth rate that determines size/age at sex transition, Charnov’s rule holds. Temperature is also relevant to shrimp population dynamics as a linkage between the ecosystem and shrimp life history. Koeller at al. (2009) showed that colder bottom temperatures increase egg incubation times resulting in later hatching times, which are closer to favourable spring growing conditions (warmer surface water and spring phytoplankton bloom).

FISHERY

Although there has been some shrimp fishing on the Scotian Shelf since the 1960s, the Nova Scotia fishery began to expand toward its full potential only when groundfish bycatch restrictions were overcome with the introduction of the Nordmøre grate in 1991 (Figure 1). The total allowable catch (TAC) was first reached in 1994, when individual Shrimp Fishing Area (SFAs) quotas were removed. The TAC was raised to 3600 mt for 1997 and to 3800 mt for 1998 in response to high biomass and good recruitment. The TAC was increased to 5000 mt in 1999 and to 5500 mt in 2000 due to the maintenance of high SSB and the recruitment of several large year classes (1993-1995) to the fishery. As those strong year classes completed their life cycle, survey biomass began to decrease, exploitation rates increased and the distribution of the resource began to change, triggering a TAC decrease to 5000 mt for 2001 and to 3000 mt for 2002 and 2003. Following the first survey index increase in 3 years during the 2003 survey, the TAC was raised to 3500 mt. Although the belly-bag index was still a relatively new data series at that point, the continuation of a detectable signal from the very strong 2001 year class suggested that the stock would continue to increase, and the 2004 survey biomass was the highest on record, so the TAC was raised to 5000 mt for 2005. The TAC was kept at 5000 mt for the 2006-2008 fisheries due to the maintenance of relatively high biomass, albeit gradually declining. The gradual declines in biomass were consistent with expectations that the 2001 year class was at or past normal life expectancy. This, coupled with below average recruitment from succeeding year classes and a large biomass decrease in Shrimp Fishing Area (SFA) 14, led to a TAC reduction to 3500 mt for 2009, despite the maintenance of relatively high commercial catch rates. A problem with the angle of attack of the Nordmøre grate in the survey trawl was discovered and rectified for the 2009 survey. The survey abundance index increased nearly 50% to the second highest value on record in 2009. The degree to which this increase, and the underestimation of the population in preceding years, can be attributed to the degeneration and refurbishment of the survey trawl is discussed in Koeller et al. (2011). In general, the increase in the survey index in 2009 can be attributed to both the increased catchability with the refurbished trawl and increased biomass, the latter due, in part, to the unexpected continued contribution of the 2001 year class beyond its expected lifespan. As a result, the TAC for 2010 was raised to 5000 mt, and a program of independent and professional survey trawl inspections was implemented. In response to a gradual decline in both survey and commercial catches beginning in 2010, TAC was reduced to 4600 mt (2011) and 3800 mt (2012). The precautionary TAC reductions until the full recruitment of the relatively strong 2007 and 2008 year classes to the SSB in 2013 helped to ensure a relatively abundant and evenly distributed resource on the ESS, so the TAC was raised to 4500 mt for 2014. Although survey catch rates declined in 2014, survey catch rates remained high and other indicators were generally favourable, so the TAC was once held at 4500 mt for 2015, once again with the proviso that immediate TAC reductions might be required for 2016 if the 2015 data showed signs that the 2007-2008 year classes that are currently supporting the fishery were reaching the end of the their life cycle, particularly given that succeeding year classes were known to be much less abundant.

Although approximately 25 indicators are considered in the provision of science advice for this stock, the quota history detailed above shows that TACs have generally been higher during periods of high survey total and SSB, and when large year classes are known to be recruiting to the fishery. The TAC has generally been reduced to maintain low exploitation rates when biomass indices and/or catch rates are decreasing, or are expected to decrease based on cohort tracking.

The SFAs on the ESS are shown in Figure 2 and Table 1. Table 2 gives licensing information for the recent period covered under sharing agreements between the Maritimes and Gulf fleets. It currently operates under an ‘evergreen’ Integrated Fisheries Management Plan. Because there are no discards of the target species, all shrimp removals are accounted for in the stock assessment.

Fishing effort is distributed clearly over the four “holes”, including the relatively concentrated shrimp habitat in Canso and Louisbourg holes, and the inshore area known as Bad Neighbours, as well as, the more diffuse habitat of Misaine Hole (Figure 3). Fishing takes place in all four areas in most years, except in some years in Louisbourg Hole (e.g. 2012, 2013) and very little trawling occurred in the inshore areas until 1998. The annual temporal distribution of effort changes over time, although in recent years effort has generally been broadly distributed in the spring, becoming more sparse and scattered in the summer when shrimp are moulting, and then concentrated in the inshore in the fall (since fishing began there in 1998). Prior to 1998, most fall fishing effort took place in Misaine Hole. Catch rates over 400 kg/h were infrequent until the stock increased in the early 2000s. Since then, such high catch rates have generally been achieved in all areas except in Louisbourg Hole, where abundance appears more cyclically variable.

Of all the experimental trap fishing that has been undertaken since the mid-1990s, only the Chedabucto Bay fishery has become established (Figure 4). The experimental trap fishery was not under quota management from 1995-1998 except for a 500 mt precautionary “cap”. As a result, the total catch tended to exceed the TAC due to the trap fishery. When the trap fishery in Chedabucto Bay was made permanent in 1999, a trap quota was set at 10% of the total TAC, e.g. 500 tons of the 5000 mt TAC. The reallocation of any uncaught portion of the trap quota late in the year resulted in some fishers being unable to take advantage of the additional quota. This often contributed to an overall catch lower than the TAC. In an attempt to avoid reallocations, in 2004, only 300 mt were allocated to this fishery, which was closer to its capacity. The trap allocation was reduced to 8% in 2005 and trap fishing effort and catch were very low during 2005-2010 due to poor market conditions. Market conditions improved in recent years. Total trap landings were 224 mt for 2013, and 122 mt (of 360 mt quota allocation) were landed as of November 17, 2014.

BYCATCH

The introduction of the Nordmøre grate in 1991 reduced bycatch and allowed the fishery to expand to its present size. Bycatch data from 2004-2014 was derived from observer coverage of 29 commercial mobile shrimp trips (404 tows) on the shrimp grounds of the ESS (Table 3). In most years, observer coverage is a good representation of the spatial distribution of the fishery (Figure 5). Between 0.01-0.03% of total reported fishing hours are covered by observers annually.

Both log book data and observer data are reported by tow allowing for a comparison of shrimp landed to the shrimp catch as estimated by the observer. The weight of shrimp landed (MARFIS), rather than shrimp estimated by the observer, is used in determining the proportion of bycatch by weight. Shrimp account for between 97.2-99.5% of the total catch by weight on observed trips over the past decade (average 98.2%). The three most common bycatch species, on average are Atlantic Herring (0.41%), Silver Hake (0.33%) and Witch Flounder (0.23%). On average, bycatch is slightly higher in the fall (2.7%) than in the spring (1.7%) fishing period, particularly for Atlantic Herring and Silver Hake (Table 4). Overall, bycatch information from observed fishing trips suggests that the fleet’s trawl configurations including the use of the Nordmøre grate continue to ensure low total bycatch. It is noteworthy that this value is very likely over-estimated due to the minimum 1 kg weight recorded by the observers (e.g. a single Sand Lance would be recorded as 1 kg despite weighing only a few grams.

FISHERIES AND OCEANS CANADA (DFO)-INDUSTRY COOPERATIVE TRAWL SURVEY

Although Fisheries and Oceans Canada (DFO) groundfish (ecosystem) surveys on the ESS have been ongoing since 1970, shrimp catchability in groundfish gear without a cod end liner neither precisely nor accurately represent trends in shrimp abundance. Although groundfish survey records have been applied to questions of shrimp distribution, only shrimp-specific surveys are considered for quantification of this stock. These include a biannual research survey carried out from 1982-1988 using the Fisheries Research Vessel (FRV) the *EE Prince* (Etter and Mohn 1989), an industry survey in 1993 carried using commercial vessels/trawls (Roddick 1994) and the ongoing contemporary DFO-Industry collaborative survey (1995-present), which uses a commercial vessel and a standard survey trawl (DFO 2015 and below). This data series includes periods of both low (1982-1988) and high (1995-present) shrimp abundance. Although the entire range of data are included in order to provide a broad range of indicator values, comparative fishing experiments were not done to directly intercalibrate the surveys from the two abundance periods. Catch rates between the two periods have only been adjusted to account for the difference in the wingspread of the trawls used in 1982-1988 (trawl specifications) versus the ongoing modern survey (actual trawl mensuration). Size selectivity of the trawls in the two times series is assumed to be identical because the cod end mesh was 40 mm in all cases.

SURVEY DESIGN

The contemporary survey follows a mixed stratified random/fixed station design. There are four survey strata, the nomenclature of which has been a source of confusion between *survey strata* and *shrimp fishing areas* (SFAs). The “inshore” stratum 17 includes portions of SFAs 13-15 (Louisbourg, Misaine and Canso holes, respectively). Strata 13-15 are the parts of SFAs 13-15 that are not captured in stratum 17 (Figure 2). To further confuse the issue, the “inshore line” on Figure 2 delineates the management boundary for the Chedabucto Bay trap fishery, within which the trawler are not permitted to fish, and is not relevant to the inshore *stratum* (17). Survey stations in strata 13 and 15 are randomly stratified at depths >100 fathoms. Stations in stratum 14 are fixed due to difficulty finding trawlable bottom. The fixed stations in stratum 14 are assumed to be representative of shrimp abundance throughout the stratum. Stations in stratum 17 are randomly selected at all depths having a bottom type identified as LaHave clay on Atlantic Geosciences surficial geology maps. This survey does not extend beyond the boundaries of the stock distribution, focusing instead only on the main concentrations in the shrimp “holes”. Shrimp distributions on the ESS are strongly correlated with organic mud habitats in the survey area (Koeller 2000) and their abundance therein is considered to be representative of the abundance of the stock as a whole. To extend this survey beyond the stock range while maintaining suitable coverage within the holes would be prohibitively expensive for this small industry, relative to the benefits gained. As a result, the swept area abundance estimate is generally referred to as an abundance *index*, and it is explicitly acknowledged that it underestimates true stock abundance, perhaps by as much as 25%. This fact is considered to represent an additional measure of precaution in the consideration of relative exploitation indices/fishing mortality (i.e. that there are “bonus shrimp” unaccounted for in the periphery). However, the fact that the earliest signs of stock decline are likely to occur at the peripheries of the species’ range, where this survey might not detect them, should not be overlooked.

The annual survey consists of 15 survey stations in each of the 4 strata. Each station consists of a 30 minute tow at a vessel speed of 2.5 knots. Because shrimp are known to be mostly densely aggregated near the bottom during daytime, survey stations are only conducted between 0500 and 2000, beginning on June 1st as or soon as possible thereafter as weather conditions permit (but not earlier). The survey generally takes about 8-12 days of fishing, depending mostly on weather conditions and is generally completely by June 20th at the latest. Stations are not carried out in very rough weather for safety reasons and to ensure consistent trawl performance/catchability. The clock on the computer is synchronized with the temperature/depth recorders, vessel Global Positioning System (GPS) and Netmind system at the start of fishing every day for the purposes of determining bottom time for trawl mensuration (below). Science staff and the vessel skipper monitor the Netmind trawl mensuration data during each tow, and inspect the gear and catch when the trawl and catch are brought aboard before deciding if the set is “good” or not. If there are any problems or doubts about the representativeness of the catch the problem is rectified and the station is repeated.

SURVEY HISTORY

The cooperative DFO-Industry trawl survey began in 1995, and all surveys since 1997, have been conducted using a standard trawl (Gourock #1126 2-bridle shrimp trawl and #9 Bison doors). The chronology of survey vessels, gear changes and comparative fishing experiments are summarized in Table 5. Trawl mensuration (headline height and trawl wingspread) were made in all survey sets using SCANMAR or Netmind sensors. The current sensors (Netmind) are beginning to become problematic, as the technology has become obsolete. The Netmind system is no longer supported, is not upgradeable and the sensors are no longer holding their charge very well. These problems have recently be exacerbated by the fact that VEMCO has ceased production of their MINILOG temperature/pressure sensors that have been used to aid in the verification/determination of bottom time for the trawl mensuration process. In 2015, the assessment team acquired a complete set of eSonar trawl mensuration equipment, which will be installed and used from 2015 onwards. This system is fully supported, works on a digital signal (which is superior to analogue in quality and accuracy). Furthermore, the eSonar system has temperature and depth logging capabilities, which will alleviate the loss of MINILOG sensors. The manufacturers (eSonar) are working to develop bottom contact sensors, which can be added to the new system once developed and would further improve trawl mensuration.

2013 COMPARATIVE FISHING

Previous comparative fishing experiments are discussed in Koeller et al. (1997). The most recent comparative fishing work took place during an interim year in 2013 (i.e. no research document) and so has not previously been documented. The survey trawl was most recently replaced in 2011. A small modification was made in 2011 to correct an error in trawl construction – the chafer was sewn too low on the cod end. The sets done on the first trip of the 2011 survey before the chafer problem was detected were redone once the trawl was up to specifications. In 2012, in the course of some deep water sets in particular strong currents, the skipper of the survey vessel noted that the trawl did not seem to be “taking bottom” very well. He pointed out that the gear was coming up too clean and that the bridles were more tarnished than would be expected if they were rubbing the bottom firmly throughout the sets (they should be shiny). Some possible reasons for this were cumulative effects of rust-loss on footgear chains and doors, trawl knot looseness or some other intangible aspect of the new trawl construction or attachment to the gear. He proposed adding weight to the doors and to the footgear during the 2012 survey, but it was decided not to change the trawl mid-survey. It was decided to proceed with the addition of weight to the trawl for the 2013 survey, and to conduct a small comparative fishing experiment during the 2013 survey to test the effect of the added weight at various depths and current situations.

Methods

In 2013, approximately 35 kg (each) purpose-built door weights were added to the survey doors and approximately 20 kg of chain (5 kg per section) was added to the footgear using hammer locks. Four sets in each stratum were repeated without the additional weight at a variety of depths (Table 6). Two stations were repeated on any given day (consecutive stations to minimize the amount of work required adding and removing additional weight). Station selection was non-random; the first station of the day after 0900 hrs and the one following that were repeated to avoid crepuscular periods when shrimp may be less “settled” on the bottom. No stations were repeated without gear changes. The repeated station was carried out to be as close and as similar as possible to the first set, but not so close as to be expected to be influenced by the preceding set (e.g. depletion, herding or other disruptions).

Results and Discussion

The weighted trawl caught from 46% to 194% as much weight of shrimp as the unweighted trawl, after having accounted for differences in trawl mensuration (Table 6). On average, the weighted trawl caught approximately 9% more shrimp (271.8 kg) relative to the unweighted trawl (253.8 kg). This difference was not statistically significant (paired t-test, $P>0.5$) and correlation coefficient between the two catch series was 93% (Figure 6). Although there was no significant relationship between trawl performance (weighted/unweighted ratio) and average depth ($R^2 = -0.0171$, $P=0.4$), the weighted trawl caught more shrimp in both the main trawl and the belly-bag at the only two stations (station 47, 48) for which notably strong currents were recorded on the decksheets. This last result provides some support for the conclusions that unweighted trawl performance was indeed being negatively affected by currents in 2011 and 2012, although with so few data, this conclusion cannot be unequivocally made. However, other subjective indicators of trawl performance, including the amount of mud in the trawl and doors, increased shine on the bridles, and skipper feedback (i.e. “feel” and RPM versus vessel speed) suggested that the trawl was indeed performing closer to specifications than it did without the weight. Given that the added weight did not appear to influence catch rates in most conditions except possibly when the current was very strong, it was concluded that the survey could continue with the added weight on this trawl, as it did in 2014, and that no adjustments were needed to the data. Due to very low catches of juvenile shrimp in the belly-bag in 2013 (i.e. “0” catches at many stations; Table 6), any effect of trawl weighting on juvenile catch rates are impossible to detect in such a limited comparative experiment, except to note that catches were approximately twice as high in the weighted trawl belly-bag at the two stations where notably strong current was observed and where higher main trawl catches were also observed in the weighted trawl.

TRAWL MENSURATION

The vessel’s GPS system feeds directly into the Netmind trawl mensuration software. Synchronizing the science computer clock to the vessel’s GPS at the start of each workday ensures that all files are consistently time-stamped, which is important for the trawl mensuration process. The Netmind file includes data, time, latitude, longitude, wingspread, headline height and vessel speed at 2-second intervals. Time-stamped temperature data downloaded from the Minilog are combined with the Netmind file to create a chart (e.g. Figure 7). When the trawl reaches the bottom, it is not considered to be fishing effectively until the headline “settles out”. Invariably, the headline signal (which is being monitored in real-time by science staff and the Captain) spikes to a high value before “settling out” at a value of approximately 6 m. For trawl mensuration data calculations, the time at which the set is considered to have begun is visually determined at the time when the headline has stabilized. Mean bottom temperature, vessel speed, headline height and wingspread are calculated from that time until the vessel speed drops of, which is the beginning of haulback (when the winches are engaged) and the end of the set time. For the example in Figure 7, the average temperature is 3ºC, average speed is 2.5 knots, average headline height is 5.9 m and average wingspread is 17.3 m. In the event that the Netmind signal is dropped, as is evident in the artificial spike the wingspread signal in Figure 7 around 6:00:00 (detected and corrected visually/manually), these values are excluded from the calculation of average wingspread used in the calculation of swept-area.

The distance trawled in nautical miles is calculated based on latitude and longitude at the times corresponding to the beginning (warp “all out”; LATs & LONs) and end (vessel speed drops off – haul back begins; LATe and LONe) of the set as follows:

$$\begin{aligned} Distance = {} & acos(cos(rad(90 - LATs)\ \text{x}\ cos\left(rad(90 - LATe)\right. \\ & + sin\left(rad(90 - LATs)\right)\text{x}\ sin\left(rad(90 - LATe)\right)\text{x}\ cos\left(rad(LONGs\right. \\ & \left.\left. - LONGe)\right)\right)\ \text{x}\ 3440.065 \end{aligned}$$

The actual catch at each survey station is estimated by weighing each bag of shrimp on a spring scale for catches totaling less than 15 bags. In rough conditions, the speed of the vessel is reduced to improve the accuracy of the weights. For catches of more than 15 bags, an average bag weight is calculated by weighing 6 bags taken from different parts of the catch, and then multiplying the average of the 6 bags by the bag count, plus any part (final) bag. The actual catch at each survey station is standardised (17.4 m x 1.25 nm) by the average measured wingspread and the actual distance travelled (Table 7). The average standardized survey catch in each stratum is raised to the total number of trawlable units in that stratum and the four stratum totals are combined to estimate the survey biomass index (Halliday and Koeller 1981). Confidence intervals are estimated using the BIOSurvey package in R (Smith 1997).

COMMERCIAL AND SURVEY SAMPLE ANALYSIS

Samples have been collected from shrimp surveys in 1982-1988; 1993; 1995-2014. One main-trawl (entire series) and one belly-bag (since 2002) sample are collected from each survey set as follows. Approximately 5 kg of shrimp are collected immediately when the trawl is emptied (before any shrimp are removed) by scooping from several different parts of the catch into a standard 20-lb fish pan. A similar 5 kg sample of shrimp is collected from the last set of each commercial trip (collected during the fishery in all areas from all fleet components including vessels <65' landing mainly in Louisbourg and vessels >65' landing mainly in Arichat), and frozen.

The belly-bag is emptied into a large bucket with a mesh bottom and rinsed with saltwater if necessary. Any bycatch and debris is removed except for mysids and other small crustaceans and the belly-bag contents are transferred to a labelled bag. Both samples are immediately frozen onboard.

Trap samples are collected twice monthly from varying Chedabucto Bay trap vessels during periods of active commercial fishing. The sample is a pseudo-random selection of shrimp from one vessel obtained by scooping a few pounds from 3 or 4 different traps from the same string. All samples collected are analysed. This can range from 0 -16 per season depending on fishing activity. Sampling generally reflects the temporal distribution of effort, which occurs for a variable period, depending on market conditions and catch rates, between September and April.

Three hundred shrimp (*P. borealis* only) are analysed from every survey trawl, commercial mobile trawl and trap sample using the same protocol. Prior to 2006, 500 shrimp were analysed. The data collected for each individual includes: sex (nine stages), egg development stage (nine stages) and sternal spine condition (four stages). Each individual is also weighed, measured for carapace length and inspected for parasites, egg disease and other unusual conditions. These data, along with associated vessel (boat code), fishing date, latitude, longitude and gear type are uploaded to the Scotian Shelf Shrimp Database after in-house quality assurance and quality control.

All 60 survey trawl samples, all 60 survey belly-bag samples, and all trap samples are analysed every year, but only 50 of the many commercial trawl samples are analysed. These 50 samples are selected in a manner to reflect the spatial and temporal distribution of the fishery between the two fleets (Gulf and Maritimes). Once the Monitoring Document data has been entered into the DFO MARFIS database, the monthly catch by SFA by fleet (Maritimes or Gulf based vessel) are used to estimate the percentage of the quota caught in each SFA by month and the proportional number of samples per fleet per month is selected for detailed analysis. The 50 trawl samples, of which 75% are from Maritimes-based vessel and 25% from Gulf-based vessels, are selected to reflect these proportions.

The population length frequency is estimated from the carapace lengths of the 300 shrimp measured in each of the 60 main-trawl survey samples, then raised to an estimate of the total number of shrimp of each length class via the swept area method for the number of trawlable units in each stratum, summed over the entire survey area. The total population estimate is subdivided into length frequencies of multiparous and primiparous/transitional shrimp by multiplying the total population estimate of each length bin by the percentage of multiparous and primiparous/transitional shrimp in the samples, respectively. The male population length frequency is obtained by subtracting the multiparous and primiparous/transitional estimates for each length bin from the population totals.

The commercial catch length frequency is estimated from the carapace lengths of the 300 shrimp measured in each of the 50 commercial samples each year. The sample length frequencies are raised to the total catch for that year in each SFA and a length-weight relationship for this stock is used to generate a total commercial catch length frequency.

COMMERCIAL FISHERY LOGBOOK DATA

Commercial catch and effort data from both the mobile and trap monitoring documents are downloaded from the Maritime Fishery Information System database. Checks and adjustments are done in Excel using the filter feature to identify suspected errors. Corrections are made only after errors or omissions are confirmed through manual checks of the scanned monitoring document, contact with Commercial Data Division or the vessel Captain directly. Once corrections are completed, data is uploaded to the Science Shrimp Database.

Errors can include but are not limited to data entry typos and misinterpretation of the written entry or missing values in a document field. For example, the last tow of the trip is sometimes missing estimated catch weight which, once the catch weights are prorated to actual offload weight, artificially inflates the CPUE for the entire trip.

Checks conducted include:

- Confirmation of a monitoring document for every hail in.
- Cases where effort (hours fished) is null, less than 1 or greater than 8 hours for mobile logs, and is less than 24 or greater than 72 hours for trap.
- Cases where estimate weight is anomalous (null, very high or low).
- Cases where a large discrepancy exists between tow catch estimate and actual weight/tow (approximately 1000 lbs).
- Cases where a large discrepancy exists between hail in and offload weights.
- Confirmation that positions are within reasonable proximity to the fishing grounds (e.g. 48 degrees latitude should be 43 degrees latitude).
- Examination of CPUE (kg/hr towed) outliers that could indicate incorrect tow time or estimated weight.

TRAFFIC LIGHT ANALYSIS

“Traffic Light Approach” (TLA) was first coined by Caddy (1998) to describe a precautionary assessment framework for fisheries assessment in data-poor situations. He proposed that the state of a fishery and ecosystem could be summarised using red (poor), yellow (neutral) and green (good) lights to characterize the status of multiple indicators. The TLA was viewed as a way to focus scientific attention on the biology of the resource and its interactions with the ecosystem and the environment to provide a broader and sounder basis than approaches based simply on an accounting for population changes. The TLA also provides more opportunity for the integration of industry experiences and knowledge, and allowed results to be presented in a manner that promoted a broad understanding of the results by all stakeholders in a simple and transparent way. At the time of its inception, the TLA was viewed as an alternative to Maximum Sustainable Yield (MSY) methods to apply the Precautionary Approach (PA) in a manner that would help to overcome some of the limitations of MSY based references points. These limitations included that MSY approaches: assume that a relationship between recruitment and spawning stock size is exists and is understood, require lots of data, base decision rules on only biomass and fishing mortality, and consider the dynamics of only a single species in environmental and ecological stasis.

A TLA has been used to assess the status of the ESS shrimp stock for the provision of science advice since 1999 (Koeller et al. 2000b, Mohn et al. 2001, Halliday et al. 2001). This holistic multiple indicator approach considers the current value of each indicator relative to its time series and summarises individual indicators into four “characteristics”, as well as in an overall stock summary value. Indicators always represent summary data for the entire area (i.e. all SFAs combined, according to the current practice of managing the fishery as one stock). Where appropriate, the interpretation of the indicator time series themselves are supplemented by other data. For example, individual SFA data often replicate the area-wise indicator trends and thus substantiate them. Supporting data may be quite independent from the data used to derive the main indicator. For example, if catch rates in the shrimp trap fishery supported the apparent increasing shrimp aggregation shown by the survey and Catch Per Unit Effort (CPUE) data; anecdotal reports of large numbers of Age 1 shrimp found on Cape Breton beaches in 2002 supported survey data indicating a strong 2001 year class, etc. This additional information may be used in the interpretation of indicator trends, but it is not used in the summary traffic light “scores.” The TLA is currently seen simply as a tool for displaying, summarising and synthesising a large number of relevant yet disparate data sources into a consensus opinion on the health of the stock. To date, such scoring has not been intended to be translated directly into management action (e.g. in the form of rules linked to summary scores), although that possibility is discussed herein.

TRAFFIC LIGHT INDICATORS

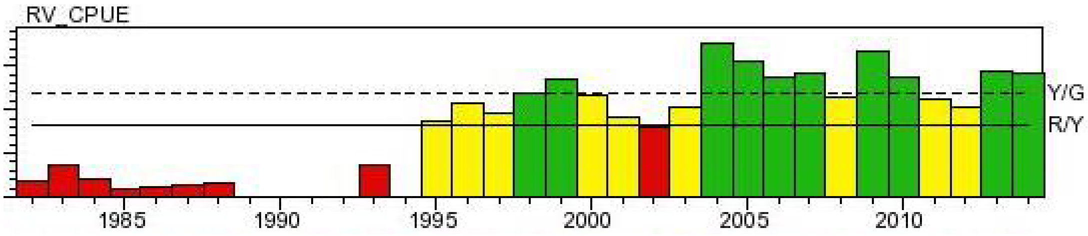
Ideally, Traffic Light indicators are easily and precisely measureable, clearly interpretable, and sensitive to changes in the status of the stock (Halliday et al. 2001). Default boundaries between traffic lights for individual indicators, i.e. transition from green to yellow and from yellow to red, were arbitrarily taken as the 0.66 and 0.33 percentiles, respectively, of the data in the series, unless an increase was considered bad for stock health, in which case these are reversed (Table 8). Data series vary in length from 13-33 years depending on the availability of data for each indicator. The 24 indicators are grouped into Abundance, Production, Fishing Effects and Ecosystem characteristics (which are themselves assigned a Traffic Light colour, as is the overall Traffic Light summary of all indicators). Indicator summaries are achieved by assigning a value according to the indicator colour, i.e. green = 3, yellow = 2, and red = 1, and an average is calculated. Regardless of whether or not an indicator time series is presented in an independent figure in the assessment documents, a red-yellow-green bar graph is presented depicting the relative values of each indicator, characteristic or overall summary over time.

Table 9 shows a correlation matrix of all indicators relative to each other. It should be noted that the correlation coefficients given therein do not necessarily inform whether or not there exists a biologically significant correlation between a given pair of indicators, because potential factors such as non-linear relationships, complex interactions between multiple indicators and the expectations of time lags are not accounted for.

ABUNDANCE CHARACTERISTIC

The survey (Figures 8-9), Gulf and standardised CPUE indices generally track one another, and particularly close attention is paid to possible explanation in years when they do not. Because the vessels and gear differ somewhat between the three series, each of the indicator series were normalized to one (divided by the mean of the series) and the mean of the three indicators series (Figure 10) was taken. Although it has previously been suggested that a single standardised CPUE index should be adopted (DFO 2013), the assessment team has supported the maintenance of the three separate CPUE indicator series by virtue of the diagnostic benefits of corroborative (or contradictory) catch rate indices, and for comparative value of fishery dependent versus fishery independent catch rates to detect clumping of a declining stock. Nonetheless, normalizing the three CPUE indicators to their respective means will be helpful for comparing them more robustly to each other, and the mean normalized CPUE index provides an informative summary of shrimp catch rates as a measure of abundance for discussion purposes, even though the three CPUE indicator series will be retained in the TLA.

Survey Abundance Index

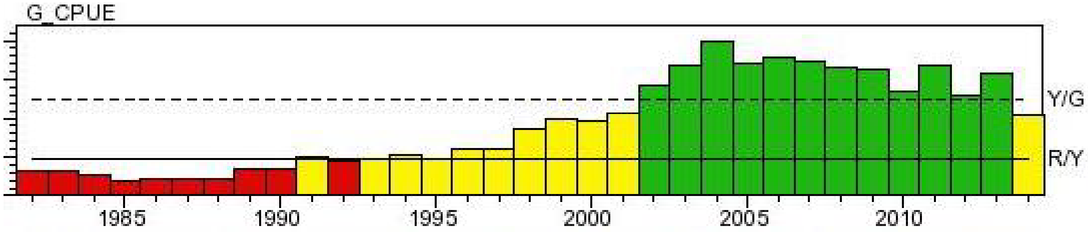


The Research Vessel (RV) Survey Abundance Index provides a generally robust, fishery independent metric of shrimp abundance trends in the ESS SFA (Figures 8-9). Coupled with commercial catch rate indices, with which it is generally strongly correlated (Figure 10, Table 9), and the modal analysis of sample length-frequencies, the survey abundance index forms the basis of the most important data considered in the assessment of this stock. Many other indices, including SSB, Age 2 and Age 4 Abundance, Total. and Female Exploitation, derive at least in part from this index. As discussed earlier, the derivation of biomass and exploitation indices from survey coverage that is restricted to the shrimp fishing grounds (rather than exceeding the stock boundaries as survey design theory would recommend) is generally viewed as an extra measure of precaution in the management of this fishery (i.e. uncounted shrimp outside of the survey area are “bonus shrimp”). However, the fact that this survey design would not detect peripheral range retractions until they effect aggregations in central/optimal habitat in the shrimp holes is an important proviso.

In general, the three CPUE-based indicators follow similar trends (Figure 10, Figure 11 – top panel). There have been three notable divergences between commercial CPUEs and the shrimp survey (*i.e.* high commercial CPUEs in the face of declining survey CPUE in 2000-2003 and 2005-2008, and declining commercial CPUEs in the face of a high/stable survey CPUE in 2014; Figure 10, Figure 11 – top panel). The first divergence was attributed to distributional changes associated with the demise of the large 1995 year class. The second divergence appears to be, at least in part, due to problems with the survey trawl (Koeller et al. 2011). Most recently, the commercial CPUEs declined (Figure 10) due to a decline in the incidents (Figure 12) and area (Figure 13) of highest catch rates. This may also have been due to some vessels reportedly targeting aggregations of larger shrimp despite lower catch rates. The results of comparative fishing discussed above, coupled with the fact that the three catch rate trends were consistent in 2013, suggests that the use of the trawl weights for the 2014 survey do not account for the divergence of the survey from the commercial catch rate trends.

The total (all SFAs) abundance index is evaluated in the context of what was expected based on the ongoing qualitative tracking of year classes, which starts in some cases with the belly-bag index (Figure 14) and following on through the modal analysis of the survey (Figure 15) and commercial (Figure 16) sample length frequency distributions, both quantitatively (formal modal analysis, below) and qualitatively/visually. The trend in survey abundance estimate is expected to corroborate these qualitative “projections” from cohort tracking, especially when a particularly strong year class or group of year classes is expected to be entering or leaving the fishable biomass. A divergence from this expectation necessitates closes examination to differentiate survey coverage or catchability problems from unexpected changes in biomass. Similarly, survey biomass trends are considered most robust when they are consistent with commercial catch rates, which they generally are. If they are not, the divergence between survey and commercial catch rates is further examined in the context of indices of dispersion (e.g. survey coefficient of variation, commercial fishing area), to try to identify instances whereby high catch rates are maintained by fishing aggregations of a declining stock. In that case, the survey coefficient of variation would be expected to be high, and the commercial fishing area index would be expected to indicate declining areas of high catch rates. Lastly, the total survey abundance index is evaluated in the context of abundance trends in each SFA, even though the stock is not managed at that level. As is the case with several other indices in the TLA, this is done based on the principle of evaluating whether or not trends in individual SFAs corroborate the index trend across the entire survey area. Furthermore, doing so can help to clarify some divergences between survey and commercial catch rates, especially in years when fishing effort is particularly unevenly spatially or temporally distributed among SFAs. For example, there can sometimes be very little fishing effort in the relatively remote Louisbourg Hole (SFA 13) until biomass and/or shrimp size reach a commercially viable threshold, at which point effort increases. The estimation of abundance within SFAs also allows the assessment team to monitor SFA-specific exploitation rates (Table 10).

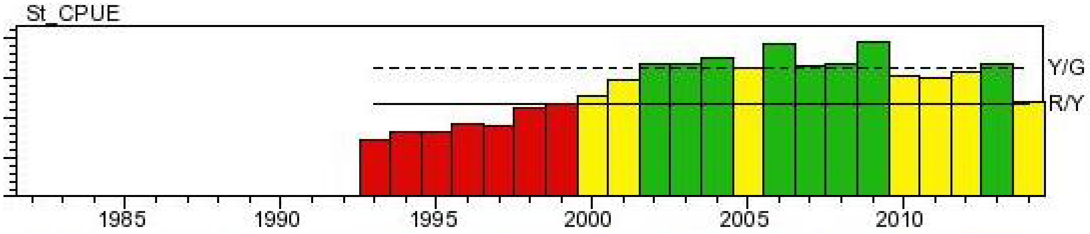
Gulf Vessels Catch Per Unit Effort



The Gulf Region vessels are the largest vessels in the fleet (>65’, compared to the <65’ Maritimes Region fleet). Catch data from this time series are particularly valuable because they include periods of both low (preceding groundfish collapse) and high shrimp abundance on the ESS. However, the introduction of the Nordmøre grate in 1991 coincides approximately with the beginning of the increase to the contemporary period of high abundance of this stock, and so the difference in this index between those two periods should be interpreted cautiously. This catch rate data from, which this index derives, also tends to be temporally and sometimes spatially different from the Maritimes fleet data, because the Gulf vessels typically fish most of their quota very early in the year, generally returning in the late fall only in the event of transfer of trap quota back to the mobile fleet from the trap fleet. The Gulf fleet is also more likely to fish, or at least try fishing, in Louisbourg Hole. The fact that the Gulf index tends to track the Standardised Index quite closely (Figures 10-11) despite these spatio-temporal differences in effort make both indices more compelling.

This and the Standardised Index (below) are interpreted similarly to the Survey Abundance Index in the sense that all three indices are expected to yield consistent results. When they do not, the underlying data, as well as the trends in other indices (as described above), are examined to attempt to reveal whether survey results are thought to be robust that year and whether the unexpected divergence of catch rate trends might be explained by high commercial catch rate on a declining and highly aggregated resource (clumping). As a result of this possibility, the “polarity” of the default boundary for both commercial catch rate series should be considered in conjunction other indicators for certain years. For example, increased CPUE series coupled with increased aggregation and decreased survey abundance would be viewed as a negative development.

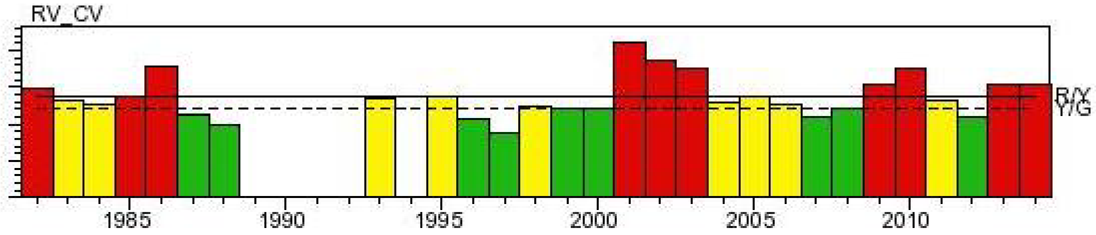
Commercial Trawler Standardised Catch Per Unit Effort



Although the unstandardised CPUE time series overall and by SFA are presented annually as supporting material for discussion (e.g. Figure 11 – bottom panel), the Traffic Light Index for the standardised Maritimes vessel CPUE time series includes only vessels <65’ that have fished for at least 7 years in the time-series (1994-present), including the present year. Only data from April-July inclusive, the months when the bulk of the TAC is generally caught, are used. A generalised linear model is used to standardise commercial CPUEs with year, month, area, and vessel as categorical components. Predicted standardised CPUE values and confidence limits for a reference vessel, month, and area are then calculated for each year using the package predict.glm (R Development Core Team 2005). The data fit best to a Gaussian distribution (lowest Akaike information criterion value). The time series is standarised to the month of June, the high liner of the fleet in the current year and to SFA 14.

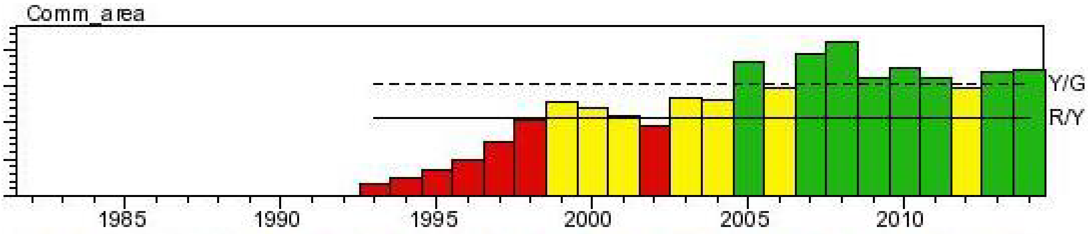
The standardised Commercial CPUE index is interpreted alongside the Gulf and Survey catch rates as discussed above. Here also, divergences among catch rate time series are evaluated in the context of other indices of stock dispersion and predicted changes based on previous years’ length-frequency distributions.

Survey Coefficient of Variation



This measure of shrimp stock dispersion (Figure 17), along with the Commercial Fishing Area index (below), is used to interpret changes in biomass indices, particularly in cases where survey biomass is declining while commercial catch rates stay high. In that case, an increase in this index would warrant consideration that the fishery may be maintaining high catch rates on remaining high-density aggregations of a declining resource, while the survey is revealing patchiness in the distribution of shrimp. This trend would be even more worrisome if the Commercial Fishing Area index declined, indicating that the area within which high catch rates are being achieved is smaller as the stock clumps in these areas. It should be noted that other factors, such as anomalous temperature conditions during the survey affecting shrimp distribution (Figure 9) or availability to survey gear, or the dominance of a small number of year classes in the biomass (e.g. large shrimp tend to aggregate at the southern ends of the shrimp holes), can also result in high survey coefficient of variation for reasons unrelated to a declining stock. High survey abundance despite a high coefficient of variation can lessen concerns about this index, as was the case in 2013 and 2014.

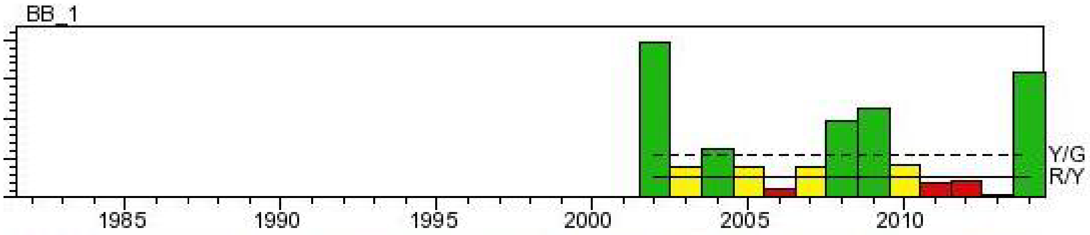
Commercial Fishing Area



As discussed above, this measure of dispersion is particularly important when survey indices are decreasing while commercial catch rates continue to increase, particularly if the survey index of dispersion is also high. Although the trend in the area of commercial catch rates >250 kg/h are used for the Commercial Fishing Area index, trends in the area of several other ranges of catch rates are also presented for discussion and to contextualize the interpretation of this index (Figure 13). For example, although the areas of catch rates >250 kg/h (this index) remained favourably high in 2014, declines in all commercial CPUE indices while the survey catches remained high warranted a closer examination of the dispersion of commercial catches. Industry feedback suggested that while no-one was achieving the extremely high catch rates of recent years, most were achieving consistently high catch rates throughout the fishing area. This was supported by the evaluation of other trends, which showed that the highest catch rates (>450 kg/h) had declined after the passage of the 2001 year class, and then increased as the 2007-2008 year classes recruited to the fishery, were now declining again as these more recent dominant year classes began to reach the end of their lifespan. Although the spatial distribution of effort does not link directly to any of the traffic light indices in this assessment, it is presented annually, in comparison to the previous year, and can be useful in the interpretation of the temporal trends in the distribution of areas where various ranges of CPUEs are achieved (e.g. Figures 18-19).

PRODUCTION CHARACTERISTIC

Belly-bag Abundance at Age 1

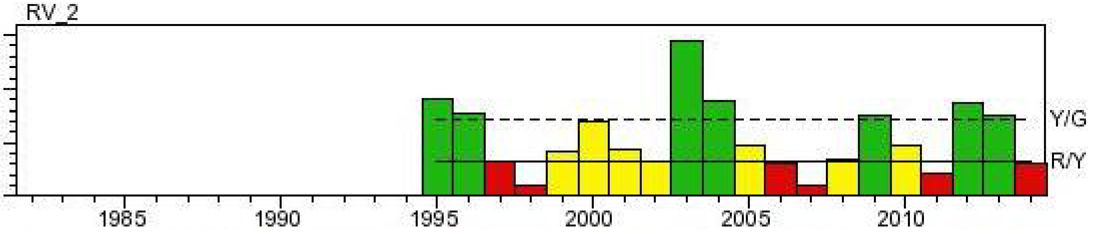


The need to develop an early index of recruitment of ESS shrimp was identified as a research priority in the late 1990s (DFO 2000). Juvenile surveys using small-mesh beam trawls in February proved less efficient than the addition of a small-mesh “belly-bag” to the footgear of the survey trawl (Koeller et al. 2003a). As a result, the latter method was chosen to provide the data for an index of recruitment for this stock, and has been used since 2002. The belly-bag is a small mesh bag 1 m wide that is attached to the footrope and belly between the two middle rollers. A belly-bag sample is obtained from each survey station, which is analysed to obtain a swept area index estimate of shrimp of each carapace length class of 11 mm and shorter. The belly-bag index of recruitment is the sum of this index for all SFAs for all carapace lengths <12 mm, which are interpreted as the carapace lengths in June that corresponding to the preceding year’s cohort.

This index shows considerable dynamic range. It correctly predicted the strength of the 2001, 2007 and 2008 year classes, two years before these began to show up in commercial catches, and as many as five years before they were fully recruited to the fishery (Figures 14-15, Table 11). The belly-bag index of Age 1 abundance was the second highest on record in 2014 (Table 11, Figure 14), which is consistent with a third recruitment pulse derived from a successful spawning event by the mature 2007-2008 year classes in 2013. Although there is a positive correlation between the belly-bag index and the time lagged Age 2 (1 year) and Age 4 (3 year) indicators series, these relationships collapse if the very large 2001 year class is removed from the series (Figure 20). The 2013 year class, which was observed in the 2014 survey at very nearly the same level as the 2001 year class, will be monitored closely for its contributions to the Age 2 indicator in 2015 and to future biomass thereafter.

These three recruitment pulses since the modern fishery began, i.e. strong year classes associated with the maturation of the 1994-1995, 2001, and now 2007-2008 year classes provide evidence of recruitment cycles that approximately equal the species' life-span. The appearance of recruitment cycles provides evidence that some form of a stock recruitment relationship exists (i.e. strong year classes result in large spawning stocks, thus resulting in strong year classes); although no classic stock recruitment relationship is immediately evident in the data (Figure 21). The lack of a stock recruitment relationship for ESS shrimp is consistent with numerous sources of evidence supporting that shrimp recruitment is most strongly influenced by environmental factors rather than by SSB.

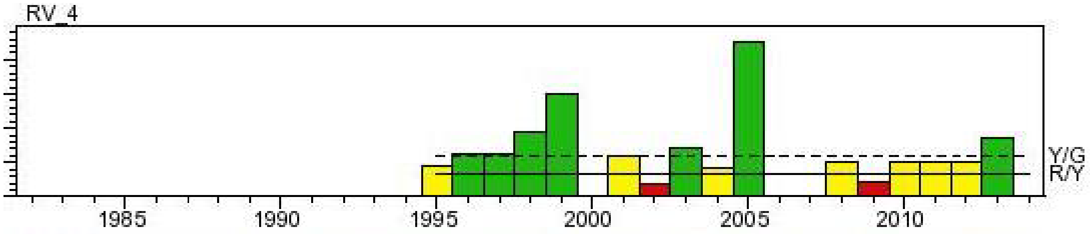
Survey Abundance at Age 2



Survey Age 2 and Age 4 abundance indices for the TLA, as well as survey population estimates of all ages (e.g. Table 11) are estimated from the detailed analysis of survey samples (described above). The number of shrimp of each length caught in each survey stratum is standardised and multiplied by the number of trawlable units in that stratum as per the swept area method to estimate the total number of shrimp in each stratum and summed over the survey area. Survey population estimates by age group are estimated by separating total population at length estimates from the swept area method into inferred age groups using modal analysis ("mixdist" in R; Macdonald and Pitcher 1979). The data are usually assigned to seven age bins, which are interpreted as corresponding to ages 1-7, although in some years the use of six bins for ages 1-6 provides a more highly significant fit to the length frequency. Although this is verified annually and the most significant fit is presented, modes corresponding to older ages are binned together as 5+ (Table 11) because the assignment of ages would be highly subjective for ages 6 and older.

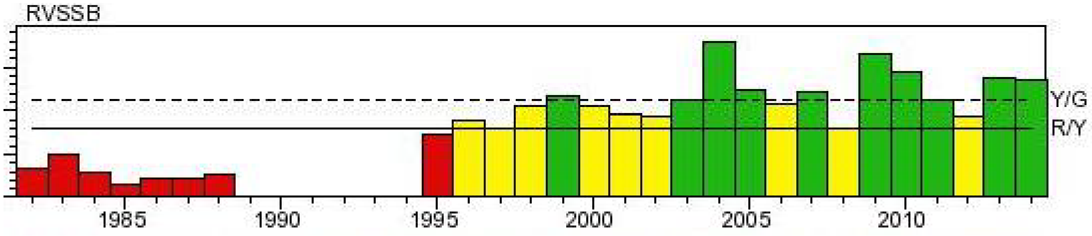
Although the length frequency modal analysis tends to clearly define the Age 2 mode, it is possible that this size of shrimp is not well (quantitatively) sampled by the main survey trawl. It is perhaps for this reason that concordance between indices of Age 1 and Age 2 abundance have been somewhat equivocal (i.e. changes in the Age 1 index are not always followed by concomitant changes in the Age 2 indicator the following year, Table 11, Figure 20).

Survey Abundance at Age 4



The abundance of Age 4 shrimp is calculated as per Age 2 above; from survey population at length estimates from swept area and modal analysis. On the Scotian Shelf, most Age 4 shrimp are in their final year as males. This group represents shrimp that will breed as males during the survey year and will change sex the following year. Since females comprise most of the catch, the last-year males are a measure of recruitment to the fishery. In some years, the Age 4 mode is indistinguishable from the large modes of older shrimp from very strong year classes. This has occurred in the past (2000, 2006, 2007, 2014) when the mode representing Age 4 shrimp could not be distinguished from the large 1995, 2001 and 2007-08 year classes (Table 11, Figure 15). In several cases, this index has reflected recruitment pulses first seen in the belly-bag four years before (e.g. 1995 year class in 1999 Age 4 index, 2001 year class in 2002 belly-bag and 2005 Age 4 index, and 2007-08 year classes in 2008-09 belly-bag and 2011-12 Age 4 index; Table 11, Figure 20).

Survey Spawning Stock Biomass (Females)



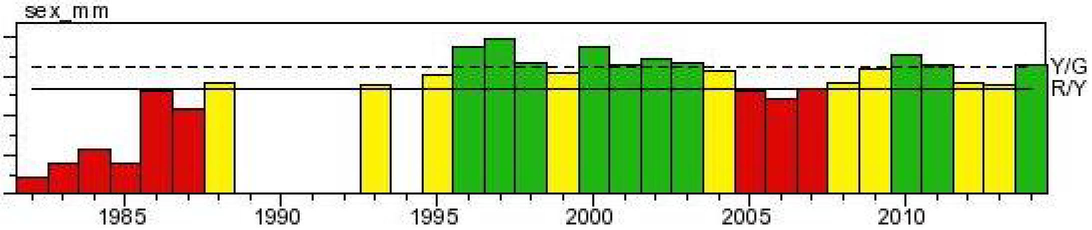
A clear stock-recruitment relationship has not yet been described for Scotian Shelf Shrimp (Figure 21), although it has been for some other pandalid stocks (Hannah 1995, Boutillier and Bond 2000). The limited amount of good shrimp habitat on the ESS and the nature of currents as they pertain to shrimp settlement/colonization, suggest that a more precautionary approach is needed for this stock in terms of maintaining a high SSB relative to areas like Newfoundland (Koeller 2000). For this reason, because of evidence of recruitment cycles following high SSB, and because the fishery targets mostly females, the SSB Index is used to define biomass reference points for this stock (see Precautionary Approach section, below).

The SSB, or total weight of females in the population, is calculated with the swept area method from the weight of females in each set, determined by identifying females (including transitionals) and their lengths in the detailed sample, the total catch weight, and a length-weight relationship. Transitionals are included because on the ESS, all transitionals are expected to complete sex change during the summer and extrude eggs during the late summer, contributing to the SSB that year.

Beginning in the late 1980s, SSBs increased from approximately 4300 mt to values nearly 3-fold higher by the mid-1990s. However, these increases occurred under specific environmental conditions (cold water temperatures and decreasing natural mortality due to predation) and negligible fishing mortalities, so 4300 mt should be considered the very lowest that the stock should be allowed to decline, and a more conservative value (5459 mt) is used as the Limit Reference Point (LRP) for this stock. By itself, SSB is not a measure of reproductive capacity.

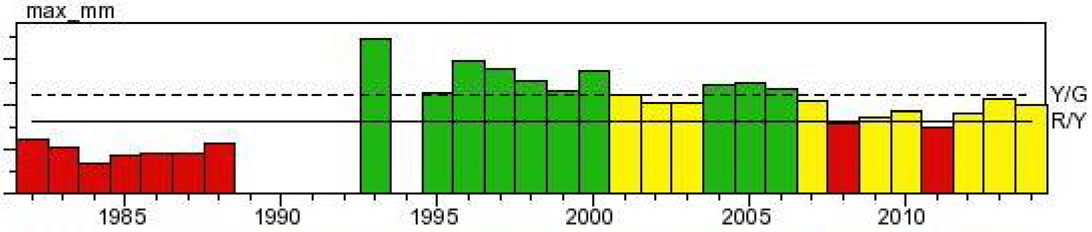
Since fecundity is directly related to size, it should be considered in conjunction with the shrimp size indicators. In addition, multiparous females tend not to spawn every year.

Average Size at Sex Transition (L_t)



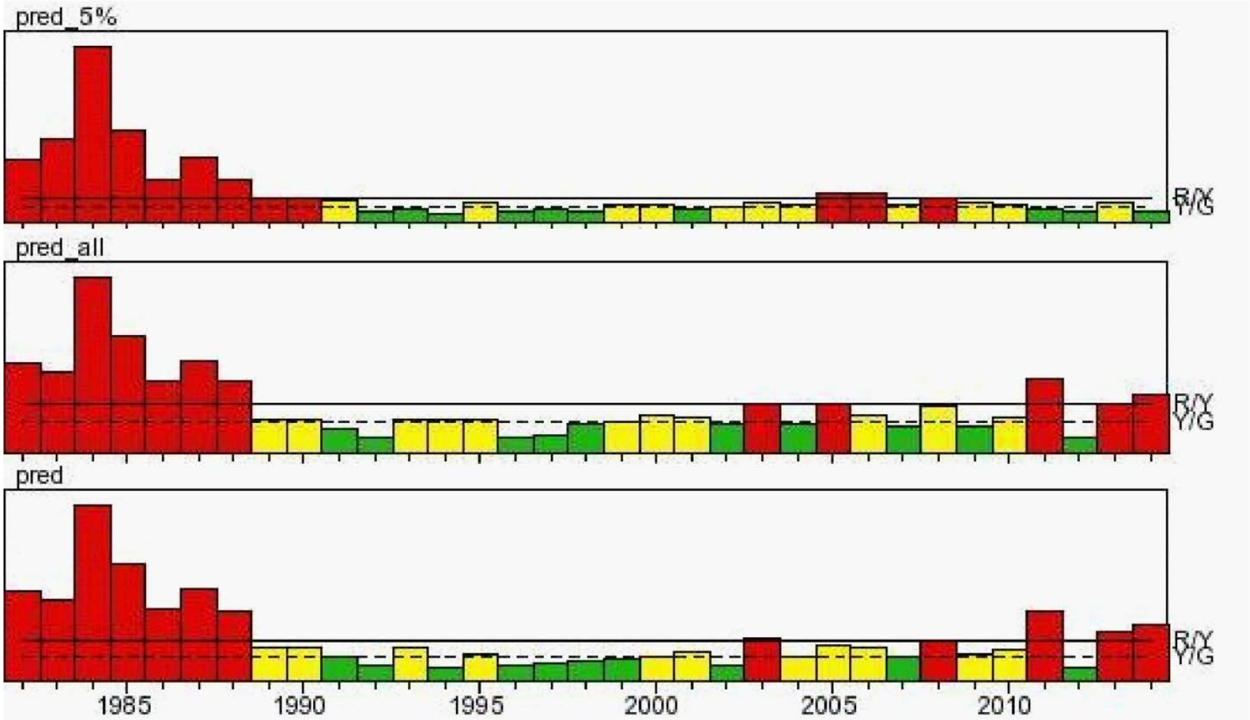
Size indices, of which four are included in the TLA, provide important information about shrimp stocks given that environmental (temperature) and demographic (density) factors influence shrimp growth and life history in ways that can have profound effects on the stock. Koeller et al. (2003b) and Koeller (2006) show that size at transition is related to growth rate. It is hypothesised that an increase in growth rate, due to density dependent effects or temperature increases (Koeller et al. 2000a), results in decreases in the size at transition, maximum size, longevity, and fecundity, followed by a population decline. By contrast, during cooler periods, shrimp grow more slowly, undergo sex transition at a larger size and older age, and live longer. Furthermore, delayed sex transition occurs during periods of high population density and results in extra years of growth, which in turn results in the production of larger females. Because of the relationship between female shrimp size and fecundity, a stock composed of larger females is potentially much more productive. The increased longevity of particularly abundant year classes (e.g. 2001) can have important implications for the qualitative projections (based on length frequency tracking) used to evaluate the potential exploitation rates resulting from different TACs. Although the 2007-2008 year classes were expected to be at or near the end of their lifespan (6-7 years), science advice in 2014 considered the high likelihood that these year classes were expected to live longer than year classes from periods of lower abundance, and so cautious maintenance of a relatively high TAC was advised with the proviso that immediate TAC reductions would be required as soon as the stock began to show signs of the expected decline (DFO 2015).

Average Maximum Size (L_{max})



The ratio of size at sex transition to maximum size was hypothesised to be constant (invariant) at about 0.8-0.9 for all stocks of *P. borealis* (Charnov and Skúladóttir 2000). This rule was shown to apply to the Scotian Shelf (Koeller et al. 2003b, Koeller 2006). Consequently, maximum size attained in the population is an indicator of growth, i.e. change in maximum size is probably indicative of a change in growth rate. The relationship between L_t or L_{max} to changes in growth rate is complex due to the influence of other factors including concurrent changes in longevity and natural mortality (e.g. slower growing shrimp tend to live longer). Overall though, when the biggest shrimp are particularly big, this is likely because they are slow growing and long-lived, as they tend to be during periods of high abundance and slow growth due to cool temperatures. A large maximum size is, therefore, indicative of favourable environmental and stock conditions. The indicator declined gradually since the early-1990s, and although interannual variation and uncertainty in the estimate make it difficult to discern short-term trends, it appears to have stabilized or even be increasing again since 2006 (Figure 22B).

Predation



The predation index is an index of natural mortality. Most groundfish feed on crustaceans at some time in their life history. Groundfish abundance is negatively correlated with shrimp abundance on the Scotian Shelf and in most other SFAs. Shrimp are an important component of the diets of several important commercial groundfish species that comprise most of the biomass on the ESS, including Atlantic Cod, Silver Hake, Greenland Halibut and various flatfish species (Koeller 2000). Shrimp populations on the Scotian Shelf are influenced by predation, temperatures and habitat availability. However, on the ESS specifically, temperatures are more broadly suitable and depth is of lesser importance. Here, shrimp are concentrated on small areas of suitable habitat, and are less prone to temperature induced crashes as seen in the GoM, so predation appears to have a relatively strong influence on ESS shrimp abundance (Koeller 2000).

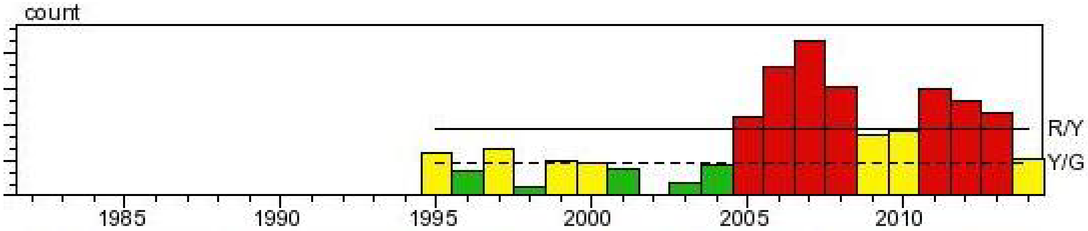
This index derives from the mean stratified catch per tow on the annual ecosystem survey (previously known as the “groundfish” survey) of all groundfish in strata coinciding with known areas of shrimp distribution (i.e. strata 443-445 and 459), and it is assumed to be proportional to predation pressure. Here, “groundfish” refers to all species with species codes less than 1000 in the ecosystem survey database, and it includes a broad range of species (Table 12). As a result, in recent shrimp assessments, the term ‘finfish’ has been used rather than groundfish to reflect this fact.

This index does not reflect whether or not the species considered are confirmed to eat shrimp on the ESS and, if so, how much. Despite this, the unrefined index is still very likely a suitable index of predation. However, it overlooks the availability of the necessary data from the stomach contents analysis of a subsample of the fish collected during summer surveys on the ESS. Reviewers at past assessments have pointed out that this would be a useful improvement in this index. In response to this, the following options are proposed.

Stomach contents data from the ecosystem survey on the Scotian Shelf from 2000-2010 were used to obtain a list of all fish species observed to have shrimp in their stomachs, and the percentage of shrimp in their diet was quantified, as well as the frequency of shrimp found in the stomachs of individuals of that species (Table 12). The list of confirmed shrimp predators is somewhat shorter than the previously used list of species derived from species code <1000 (Table 12). However, the traffic light series generated based on the list of confirmed shrimp predators ("pred_all" series, above) did not differ greatly from the original indicator series ("pred" above and Figure 23). Further limiting the selection of shrimp predators to those observed with shrimp in their stomach >5% of the time (Table 12) generates a different time series ("pred_5% above and Figure 23). In particular, the >5% predation series is less variable, which is mostly because of the exclusion of haddock data. As a result, the >5% predation index is less likely than the other series to result in a red traffic light due to large fluctuations in biomass of species that are not common shrimp predators. Figure 23 shows that the negative correlation between predator and shrimp abundance indices occurs on a broad scale (i.e. pre-1990 versus mid-1990s to present). Compelling negative correlations between shrimp and predator abundance indices using any of the predator criteria are driven by the pre-1990s data of high groundfish and low shrimp abundance (Figure 24). The shrimp assessment will proceed using an index of all known shrimp predators while the stomach contents database is explored in more detail to ensure species that are known to be important shrimp predators but that may not show up in the database due to eviscerated stomachs (e.g. Redfish) are included.

FISHING IMPACTS CHARACTERISTIC

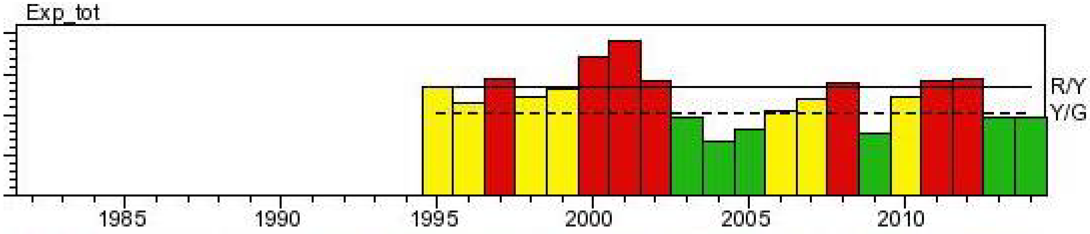
Commercial Counts



Fishers determine the number of shrimp per pound (the "count") in their catches soon after they are brought aboard in order to determine the price that they will obtain from buyers, and adjust fishing practices (especially location) accordingly. This information is of economic importance and is often conveyed to other fishers or buyers before landing, so care is usually taken in obtaining and recording it. The methodology used is basic (number of shrimp in a fixed volume, often a tobacco can, that weighs about 1 lb) but generally agrees with more rigorous methods used by buyers. The index used here is the simple arithmetic average of all counts reported in log books for the year.

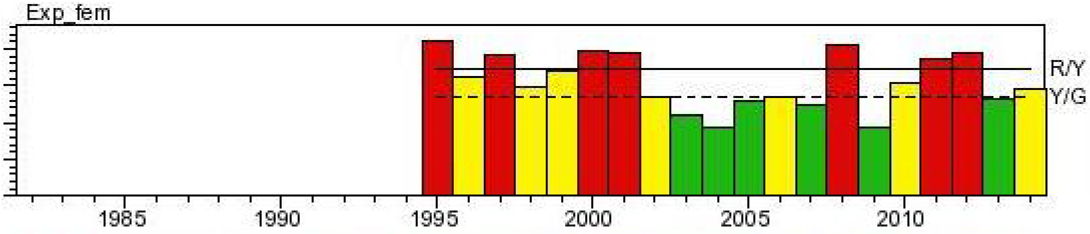
Although in general, low counts are characteristic of a slow-growing population of late-maturing, large, long lived and highly fecund shrimp, the interpretation of this indicator should take into account the possibility that the polarity may need to be reversed. For example, an increase in the count could indicate that (a) recruitment is good and there are so many small shrimp it is difficult to avoid them or (b) the population of larger shrimp is declining, or a combination of (a) and (b). Moreover, an increase in this indicator can be considered good (increased recruitment) or bad (growth overfishing) depending on whether it is placed in the production or fishing effects characteristic. Consequently, this indicator must be considered with others including abundance indices of the different age categories. Note that counts also change considerably during the fishing season, usually starting relatively high, decreasing to a minimum in July, and increasing thereafter, probably due to size specific changes in vertical and\or geographic distribution associated with changes in day length. The Commercial Counts index can also be useful to corroborate the interpretation of year class strengths from length frequencies. For example, the 2014 counts were at their lowest level in the past decade, reflecting the high biomass of large female shrimp from the 2007-2008 year classes and very little representation of the less abundant subsequent year classes (Figure 22).

Exploitation Index



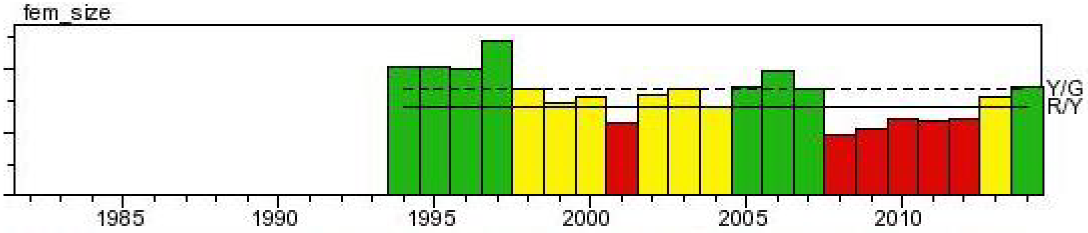
An overall index of exploitation rate is calculated as the total catch weight divided by the RV biomass estimated using the swept area method. The survey biomass estimate has been shown to be underestimated by as much as 25% because of lack of coverage in shallow areas surrounding the shrimp holes; consequently, the exploitation rate is probably overestimated. This indicator is, therefore, considered an *index* of exploitation. Since the survey uses a common commercial trawl with a Nordmøre grate, its selectivity is similar to commercial gear. The biomass used to estimate exploitation can be considered an estimate of "fishable biomass". At the time of the annual provision of science advice (November or December), the exploitation index is provided based on the assumption that all or nearly all of the TAC will be caught, and is adjusted if necessary thereafter. Although shrimp stock are generally thought to be quite robust to overfishing, and exploitation projections for the ESS shrimp stock in the 1980s suggested that up to 35% of the biomass could be taken sustainably, other stocks have collapsed at lower exploitation rates. Furthermore, larval settlement patterns and the low likelihood of "rescue" from adjacent stocks to reseed the ESS have been invoked to suggest that a more conservative exploitation strategy is required here (Koeller 2000). The total exploitation index for this stock averages about 12% and is generally very conservative, having never exceeded 20% (Table 10, Figure 25 top panel).

Female Exploitation Rate



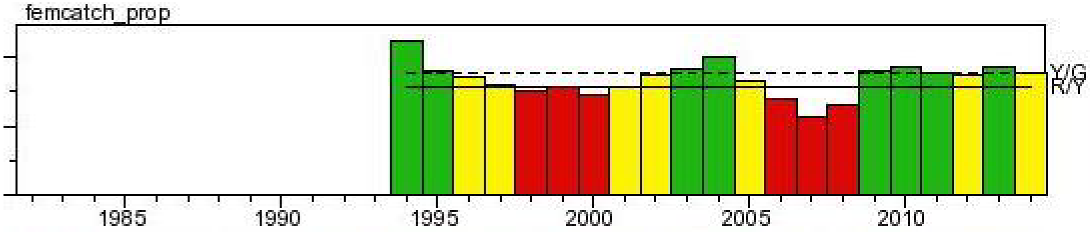
Female exploitation is of interest because the shrimp fishery is selective for the larger females. It can be considered an important measure of the impact of fishing on the reproductive potential of the stock, and it is for this reason that it is used as the removal reference for the Precautionary Approach for this stock (Smith et al. 2012). This is calculated as the estimated weight of females in the catch divided by the weight of females in the population from the survey, i.e. SSB. The catch composition is determined from the detailed analysis of commercial samples as discussed above. As is the case for the total exploitation index, the female exploitation index is also quite conservative, rarely exceeding 20%, which is the removal reference (which management decisions avoid exceeding when the stock is in the Healthy Zone; Figure 25 bottom panel, Figure 26).

Mean Size of Females in Catch



A decrease in this indicator could indicate a decrease in the number of larger shrimp in the population due to fishing removals and an increased reliance on smaller animals, i.e. possible growth overfishing and/or recruitment overfishing. The average size of females in the catch has decreased from the early years of the fishery as the larger animals were selectively and continually removed from the population. During periods of high biomass, when growth slows, sex transition is delayed, and the longevity of large females increase (i.e. maturation of the 2001 and now 2007-2008 year classes) this index tends to increases (Figure 22C). The trend in this index tends to be similar to the Commercial Counts index, given that it derives from port samples that are selected to approximate the spatio-temporal distribution of fishing effort, and that counts are going to be low when the female shrimp that make up the bulk of that catch are large.

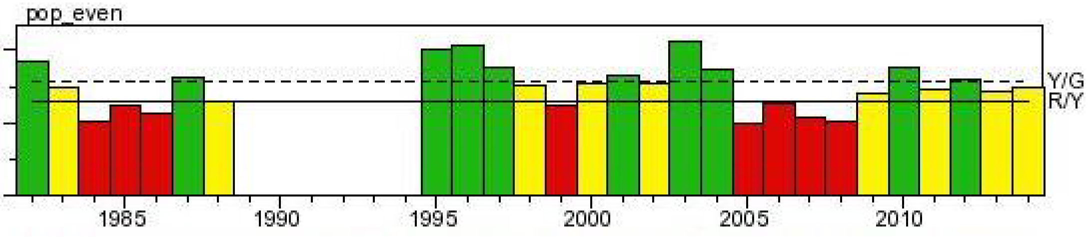
Proportion of Females in Catch



A decrease in this indicator could indicate a decrease in the number of larger shrimp in the population due to fishing removals and an increased reliance on smaller animals, *i.e.* possible growth overfishing and/or recruitment overfishing. It is calculated based on the data obtained from the analysis of commercial samples (described above) using the lengths and individual weights of shrimp identified as female, relative to the total catch weight. It should be interpreted cautiously and in combination with other indicators, since it could also indicate good recruitment conditions and difficulty in avoiding young shrimp. For example, the proportion of females in the catch decreased between 2004 and 2006 due to the increase in the proportion of 2001 year class males, so the negative traffic light was an artefact of a positive development in the stock. The increase in 2007-2010 was due to the sex change and recruitment to the female population of this year class, and the delayed sex-transition of abundant 4+ males observed in 2009. The proportion of females in the catch has been relatively stable at a high value since 2009, which reflects the fact that the population is currently dominated by older shrimp, mostly female, with relatively poor succeeding year classes (fewer males), which is also apparent in survey and commercial length frequency distributions (Figures 14-16).

ECOSYSTEM CHARACTERISTIC

Population Age-length Evenness



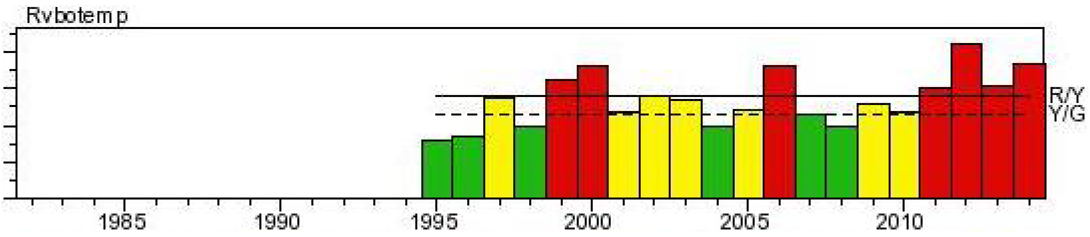
This indicator is based on the assumption that a population that is spread evenly across length or age classes is more resilient to environmental or fishing perturbations than one where the population is concentrated in fewer length or age classes. It is calculated from the survey population-at-length estimate as Shannon's equitability index, E_H, which is obtained from Shannon's diversity index, H. The latter is calculated from the proportion (p) of the population in each of the total number of length groups (S).

$$H = -\sum_{i=1}^{S} p_i \ln p_i$$

This indicator is placed under the ecosystem characteristic assuming that evenness is related to the population's robustness or resiliency to various perturbations within the ecosystem, but it could also have been placed under fishing effects, since fishing will remove the largest/oldest length/age classes, or production, since an even length/age distribution implies stable recruitment. On the other hand, this index will also respond to the passage of an exceptional year class through the population, which may not be a negative development if the abundance of other year classes remains relatively stable.

Population evenness was high at the beginning of the survey series in 1995 when the fishery was relatively new (it first attained the TAC only in 1994). It declined in the late 1990s as the large 1994-1995 year classes dominated the population, and was very low once again in 2003-2006 as the 2001 year class dominated. Since the end of the long-lived 2001 year class in 2009, the index has been fluctuating around a relatively high value.

Bottom Temperatures



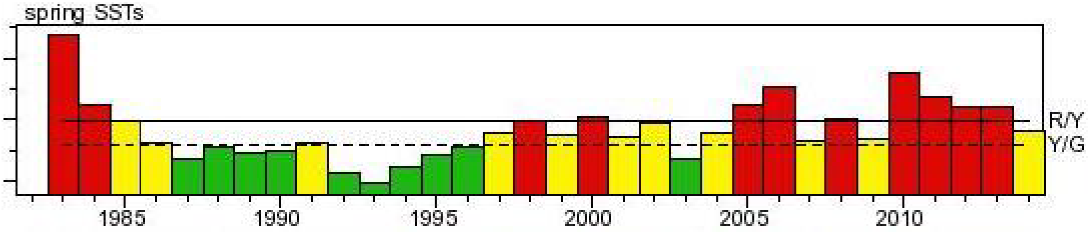
For some Northern Shrimp stocks near the southern limits of the species' range, abundance is negatively correlated with water temperatures (Appolonio et al. 1986). It is hypothesized that warmer water temperatures have a negative influence on shrimp populations because of the decreased fecundity associated with increased growth rates, decreased size at transition, and decreased maximum size as described above. Recent work also indicates that colder bottom temperatures increase egg incubation times resulting in later hatching times, which are closer to favourable spring growing conditions (warmer surface water and the spring phytoplankton bloom (Koeller et al. 2009). On the ESS, the large population increase that occurred from the mid-1980s to the mid-1990s is associated with colder surface and bottom water temperatures

(Figures 27-28). However, relative to the GoM and the rest of the Scotian Shelf, the ESS shrimp grounds are known to more broadly and perennially remain near the shrimp's lower thermal limit, so small scale temperature anomalies may have a less severe impact on ESS shrimp.

Bottom temperatures on the shrimp grounds were relatively warm during the 1980s, when the shrimp population was low, and they were colder during the population increase of the 1990s (Figure 28). Colder temperatures in 2007-2008 may have helped larval survival, as measured by belly-bag results, by increasing the incubation period, bringing hatching times closer to the spring bloom and vernal warming of surface waters, which are conditions favourable for larval growth and survival. Similarly, the warmer temperatures in 2005, 2006 and 2009 are consistent with the low belly-bag index results in 2006, 2007 and 2010, respectively. However, despite warm bottom and spring Sea Surface Temperatures (SSTs) in 2013, the belly-bag index result from 2014 was very high (Figure 28, Table 11). Bottom temperatures during the shrimp survey have been high for the past four years and increased in 2014 relative to 2013 (Figures 27-28).

Shrimp survey bottom temperatures are determined throughout each shrimp survey set with a continuous temperature recorder (Vemco Ltd.) attached to the headline of the trawl and are generally consistent with temperatures from the groundfish survey (Figure 29). In the past, this index was calculated from July groundfish survey data as the mean bottom temperatures at depths >100 m in sampling strata (443, 444, 445, and 459) on the ESS that encompass the shrimp grounds (because it provided a longer data series). However, given inconsistencies in groundfish survey temperature recording methods and the fact that that shrimp survey temperature data series now covers 20 years, the latter is now used.

Spring Sea Surface Temperatures

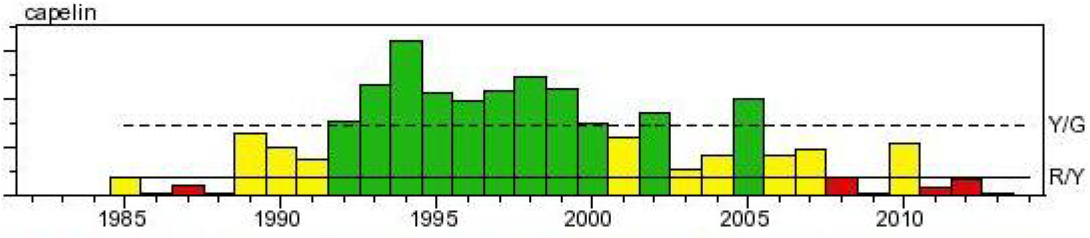


Negative correlations between spring SST and lagged population estimates (four to five years in GoM) are common for the southern *P. borealis* stocks (Appolonio et al. 1986). This may be related to water-column stability and the match-mismatch of resulting phytoplankton bloom conditions with hatching times as hypothesised by Ouellet et al. (2007). Accordingly, SSTs used were averages for a period encompassing average hatching times on the Scotian Shelf (mid-February to mid-March). Sea surface temperatures are calculated from satellite data as average temperatures within defined rectangles encompassing the shrimp holes.

On the Scotian Shelf, the below average temperatures prevalent during the late 1980s and early 1990s may have facilitated the high abundances in the mid to late 1990s associated with the strong 1994-1995 year classes. However, at least one exceptional recruitment event occurred recently (2001) despite relatively high SSTs, and the same appears to be true for the 2013 year class.

Similarly to the bottom temperature index, SST on the ESS only appears negatively correlated with shrimp abundance on a broad scale (pre- versus post-1990), whether lagged (four years) or not (Figure 30). Since the early 1990s, SST has been gradually warming, with significant interannual variability, during a period when shrimp abundance was also rising. In fact, neither the 4-year lagged nor unlagged SST index series appear negatively correlated with shrimp abundance (Figure 31) at an annual scale, so this indicator series appears only to be relevant to shrimp abundance at a broad scale. Once again, this may be due to the fact that temperatures on the ESS are cooler overall than other in areas where such negative correlations exist (e.g. GoM).

Capelin Abundance

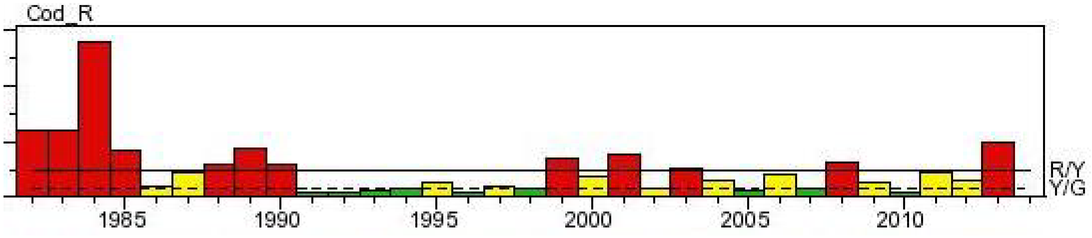


Capelin is among the most common bycatch species, both in the ESS shrimp fishery (Table 4) and the June shrimp survey. They have been shown to increase in abundance during cold periods, which are also favourable for shrimp recruitment, and so can be considered a sympatric species (e.g. Frank et al. 1994). Their presence has, therefore, been considered an indicator of conditions favourable to the production of shrimp.

During the last 10 years, Capelin abundance has been lower on average than the relatively high values between 1993 and 1999, and was especially low (near those of the 1980s when shrimp abundance was low) in 2008-2009. Capelin abundance in 2014 was the lowest on record, while shrimp abundance indices continue to oscillate around relatively high values.

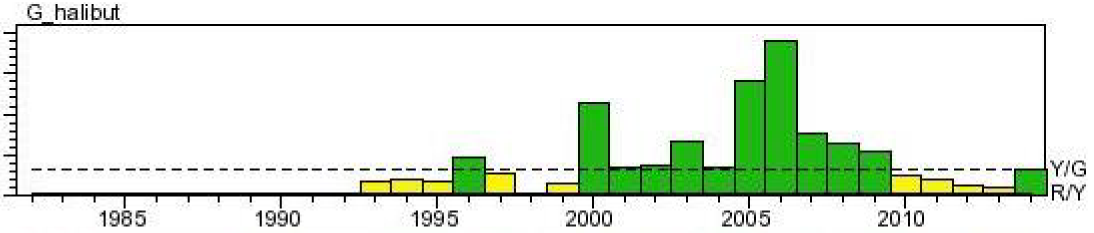
Overall, there is no significant correlation between the Capelin abundance and any of the CPUE indices of abundance used in this analysis, and abundance index trends between shrimp indicators and the Capelin index appear to be generally correlated until approximately 1998 (Figure 32). Whether or not the divergence of shrimp and Capelin abundance index trends over the past 15 years or so reflects differential sensitivity to gradually warming temperatures or to changes in ESS groundfish abundance or species composition, or both, or some other combination of factors, is beyond the scope of this work. However, the lack of concordance between these indices over the past 15 years suggests that Capelin abundance may no longer provide a meaningful predictor of suitable conditions for shrimp on the ESS. The Capelin index will no longer be considered in the assessment of the ESS shrimp stock.

Cod Recruitment



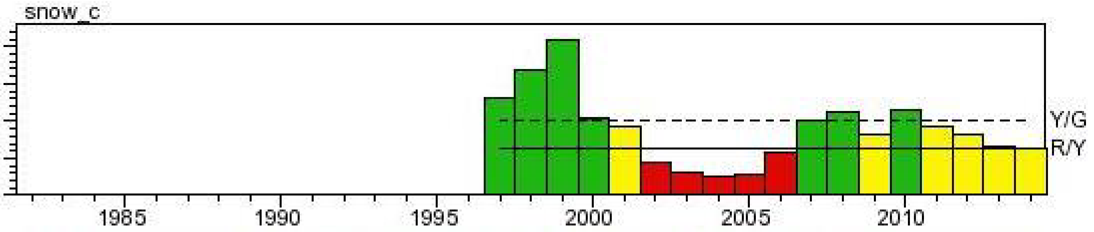
This is an index of natural mortality due to predation, which reflects the fact that Cod abundance is generally negatively correlated with shrimp abundance for most north Atlantic stocks, including the Scotian Shelf (Berenboim et al. 2000, Ingibjörg et al. 2012). This is probably partly due to large scale environmental influences, such as temperature, which appear to have opposite effects on Cod and shrimp population dynamics, as well as a trophic effect of Cod predation on shrimp via predation (Lilly et al. 2000, Worm and Myers 2003). With few exceptions, the Cod recruitment index (<30 cm) has remained very low since the early 1990s, which is interpreted that natural morality of shrimp due to Cod predation is likely to remain low. Cod are among the species that are found to contain shrimp >5% of the time that their stomachs have been examined (Table 12), and their abundance index approximately mirrors that of shrimp on the ESS (Figure 33).

Greenland Halibut Recruitment



Greenland Halibut is a cold water species whose abundance is often positively correlated to shrimp abundance (Figure 34). This is among the most common bycatch species, both in the ESS shrimp fishery (Table 4) and the June shrimp survey. Although Greenland halibut are also known predators of shrimp (Table 12), this species was rarely found during the warmer period of the 1980s when shrimp and Capelin were also low in abundance. Greenland halibut <30 cm increased in the 1990s and early 2000s in general concordance with increases in shrimp abundance on the ESS (Figure 34). Restricting this indicator to juvenile halibut (<30 cm) decreases the influence of predation and may have more predictive value for shrimp abundance. Retaining this indicator at this time is recommended, as is monitoring the downward trend of the past 5 years in comparison to shrimp abundance trajectories, in the event that more influential factors than those shared with shrimp are acting to depress Greenland Halibut abundance, as appears to be the case for Capelin.

Snow Crab Recruitment



The Snow Crab recruitment index, as described in Hardie et al. (2013), is now shifted forward by 1 year in the TLA (e.g. 2013 value used for 2014 Traffic Light Value) to solve the problem that the current-year value is generally not available in time for the shrimp assessment. This is an index of immature male snow crabs (<56 mm carapace length), which would be 1-3 years pre-fishable biomass and about 6-8 years post-settlement.

Snow Crab abundance, as with Greenland Halibut and Capelin, are thought to track shrimp abundance in the long-term; however, Snow Crab have considerably longer longevities and population cycles. These life history differences make it difficult to interpret how the trends are expected to be correlated, depending especially on what time-lag would be appropriate for their comparison (Figure 35). The snow crab recruitment index has been relatively strongly correlated with the shrimp abundance indices for the past decade, although earlier values were discordant.

TRAFFIC LIGHT SUMMARY

Traffic Light indices are summarised (Figure 36) for each of the four characteristics and as a single overall summary traffic light colour. These summaries are not emphasized in the provision of advice because they are derived by a simple averaging process that does not account for complex interactions between indicators that may be occurring. Figure 36 simply ties all the individual indicator values into a single picture where stakeholders can review the status and trends of all the indicators, and be reminded to which characteristics of stock and ecosystem health they pertain. It is worth remembering that the polarity of some indicators should be considered reversed in some years (but doing so in Figure 36 would reverse the value for all other years as well), and the placement of indicators within characteristics is also open to interpretation, as discussed above.

Generally, a simple statement is made about the Traffic Light summary, in reference to the trends in the summary characteristics. For example, for 2014: the summary Traffic Light indicator for 2014 improved to green for the first time in four years. In general, while indices of Abundance declined, Ecosystem indices improved and Fishing Effects and Production indices remained relatively stable (Figure 36).

Similarly, each of the summary characteristics are very briefly discussed to remind readers of which individual indicators provided particularly meaningful or influential signals to explain the summary characteristic values. For example, for 2014: the Abundance characteristic for 2014 declined to yellow for the first time in a decade due to declines in the Gulf and Standardised CPUE indices. The Production characteristic remained yellow in 2014. The negative influence of declines in the abundance of young shrimp associated with poor juvenile recruitment over the past four years were offset by the positive influence of a very strong recruitment signal of the 2013 year class in the 2014 belly-bag and the maintenance of high SSB. The Fishing Effects characteristic remained green for 2014, after having improved greatly from red values for 2011 and 2012. This is due mostly to relatively low total and female exploitation indices and a high proportion of large females in the catch. The 2014 Ecosystem characteristic improved to yellow after three years as red. This improvement is accounted for by a decrease in spring sea surface temperature (good juvenile recruitment conditions), a very low Cod recruitment index (expectation of low predation by Cod) and an increase in Greenland halibut recruitment (sympatric coldwater species) (Figure 37).

Overall, it is in the holistic and inclusive analysis and discussion of the individual indicators that the “meat” of the science advice is provided. The TLA returns to the overall and characteristic traffic light summaries simply as a means to provide a concise image of the complex data and to put the conclusions in context.

PRECAUTIONARY APPROACH

A PA using reference points and control rules within the framework of the TLA was first reviewed during the DFO Maritimes 2009 Regional Science Advisory Process. That approach has since been modified and included in the new Integrated Fisheries Management Plan in 2011 and was reviewed at a Regional Science Advisory Process in 2012 (Smith et al. 2012). In general, the precautionary application of reference points for ESS shrimp (Figure 26) includes the following.

Limit Reference Point (LRP): 30% of the average SSB (5459 mt) maintained during the modern fishery (2000-2010[1]). The LRP is approximately equal to the average SSB during the

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[1] The reference points are set based on data from 2000-2010 to avoid a scenario whereby reference points based on a moving average would become *less* conservative during a period of a biomass downturn. This action does not negate the need to be vigilant for signs of a shift away from the current high productivity regime towards a lower productivity regime in which these reference points may no longer be suitable.

low-productivity (pre-1990) period for this stock, characterised by low shrimp abundance, high groundfish abundance and relatively warm temperatures. The Scotian Shelf shrimp population previously increased from a low level (approximately 4300 mt) during the transition from low- to high-productivity, so the working assumption is that shrimp could once again recover from this level given appropriate environmental conditions and fishing pressure (i.e. $B_{recover}$ proxy). Secondly, given the important role of shrimp in the Scotian Shelf ecosystem, particularly as prey for groundfish, this LRP is set to avoid a decrease in shrimp abundance below the level at which it was previously able to fulfill its ecosystem roles under a situation of high groundfish abundance (i.e. to avoid a scenario in which low shrimp abundance could act as a limiting factor in groundfish non-recovery). At SSB levels below the LRP the fishery is closed.

Upper Stock Reference (USR): 80% of the average SSB (14,558 mt) maintained during the modern fishery (2000-2010[1]). The USR has been selected at the default value (80%) and to maintain a sufficient gap between the LRP and USR to account for uncertainty in the stock and removal reference values, and to provide sufficient time for biological changes in the population to be expressed, detected and acted upon.

Removal Reference Point: The removal reference for Scotian Shelf shrimp is 20% female exploitation (actual female catch/SSB) when above the USR. This exploitation rate has rarely been exceeded during the modern fishery (2000-present), a period during which high CPUE and SSB have been maintained. Additionally, given that shrimp survive for approximately 3-4 years after their recruitment to the fishery, it can be approximated that on the order of 25-33% of the fishable biomass would be subject to natural mortality in any given year. As a result, the removal reference of 20% for shrimp is on the conservative side of this simplistic estimation of natural mortality (25-33%). Although exploitation scenarios in which fishing mortality equals natural mortality may result in optimal yield (e.g. Gulland 1971), this may be an overly risky exploitation strategy. As a result, the maximum removal reference of 20% for shrimp is on the conservative side of the simplistic approximate range of natural mortality (25-33%).

It is worth reiterating that SSB by itself is not a measure of reproductive capacity. Because the relationship between fecundity and size, and the dynamic range of shrimp size in response to fluctuations in density, temperature and growth rate, it is important to carefully consider the "Auxiliary Data" provided by the Traffic Light indicators when interpreting the biomass and removal reference points. A suite of approximately 20 secondary indicators of shrimp abundance and production, fishing effects and environmental conditions provide a scientific interpretation of holistic data to inform the way in which science advises responding to the stock status and removal relative to reference points.

BIENNIAL INTERIM SCIENCE ADVICE

Although the TAC is set annually at the Advisory Committee meeting early in the calendar year, science advice for this stock adopted a multi-year assessment approach in 2013. Full assessments are provided biennially, with interim advice provided in alternate years. The DFO-Industry survey is completed annually.

In "Full Assessment" years, advice is provided as it has been throughout the recent history of this fishery. Once the assessment has been completed, the assessment team attends the Atlantic Canadian Shrimp Association (ACSA) Annual General Meeting (AGM) to present the results of the analysis and to obtain industry feedback, as well as discussing any other business. Shortly thereafter, a Regional Advisory Process (RAP) meeting is held, with simultaneous translation provided, in which a Research Document and Science Advisory Report (SAR) is presented by the assessment team and reviewed by expert reviewers. This meeting is attended by all stakeholders. The SAR is finalized shortly thereafter and translated in time for the Advisory Committee meeting, when the TAC is discussed and decided (e.g. DFO 2014).

In “Interim” years, the same complete analysis of all data is carried out as per a full assessment. The assessment team once again attends the ACSA AGM, but no RAP is held. Instead, the assessment team prepares a much shorter Special Science Response (SSR), which is presented at a meeting attended only by DFO Science, CSAS and expert reviewers. The SSR is finalized at this meeting and is translated in time for the Advisory Committee meeting, when the TAC is discussed and decided.

In the 2013 SSR, the results for all TLA indices and characteristics were presented in the form of the TLA summary (Figure 36), which shows only changes in the colour of the traffic light for each index (without the bar graphs showing relatives changes within colours). Key indices that are emphasized every year were presented, including the PA figure (SSB and Female Exploitation, Figure 26), as well survey, Gulf and Standardised CPUE indices, the swept area biomass estimate and survey length frequencies (differentiating total, transitional/primiparous, multiparous shrimp). Results from other indices were discussed if notable or if relevant to the interpretation of other indices (DFO 2014).

The main strengths of this approach are that both forms of science advice are provided based on complete analysis of the data on an annual basis. The continuation of the survey and complete TLA data analysis on an annual basis enable for TAC adjustments in a manner that is consisted with the PA for a species/stock that has a short life-span and for which abundance can change quite rapidly. The TLA lends itself particular well to the production of an SSR because the key indices can be summarized, along with any of the secondary indicators that show particularly notable changes or trends in that year, and these can be succinctly discussed in a relatively concise document.

The main weaknesses of this approach include the removal of industry and other stakeholders from the science review process, and the minimal time-savings for the assessment team (relative to multi-year assessment schema in which no analysis or less analysis is carried out in interim years). The lack of other stakeholders means that science reviewers and industry representatives do not review the assessment at the same time (the former at the SSR meeting, and the latter at the AGM and Advisory Committee meeting), which limits the often productive discussion based on the respective perspectives if each and expertise that tend to take place at RAP meetings in full assessment years. Although the complete analysis of all data in interim years minimizes the time savings for the assessment team, the efficiencies realized by not having to produce and edit the long Research Document and SAR should not be overlooked. Given the long-standing, highly productive and cooperative relationship between this industry and DFO, options to include a small number of industry representatives in the SSR review process should be explored, so that their important perspectives can be considered during the review process. One example in which this was particularly important occurred in 2014 (which fortunately was a full assessment year). Industry representatives were able to provide a very important perspective on the interpretation of a decline in CPUE trends that were inconsistent with the maintenance of high survey catch rates. Had this occurred in an interim year, this would not have been possible. One minimal option would be to include the Skipper of the survey vessel in the SSR review process in interim years.

Given that the full analysis of data is completed every year for this assessment, and the time between full assessments is short (biannual), it is perhaps less imperative to define triggers for initiating full assessments in what would otherwise be an interim year than it would be for stocks that have set multiyear TACs, reduced analyses for interim years, or set longer periods between full assessments. Furthermore, given that the assessment team presents and receives industry feedback on the full analysis at the Industry AGM annually, the only benefits of full assessments are the more thorough science review of the assessment in those years and the opportunity for science reviewers and industry to overlap. The principle situation in which this would be particularly important is when commercial and survey CPUE indices provide discordant results that are likely to affect the science advice, or if abundance indices are inconsistent with expectations based on qualitative and quantitative interpretation of length frequencies the preceding year.

QUANTITATIVE HARVEST CONTROL RULES

WEIGHTING AND QUANTIFYING TRAFFIC LIGHT SCORES

At its inception, the TLA was to include a set of harvest control rules (HCRs) to define actions to be taken depending on the number of lights of each colour, with increasingly restrictive measures as the proportion of reds increased. By incorporating such rules, Halliday et al. (2001) suggested that the TLA could provide a single framework within which DFO could provide management advice in a manner compliant with the Precautionary Approach, and that the TLA could be used to assess the status of diverse stocks, whether rich or poor in data. In principle, the development of HCRs to trigger pre-agreed conservation and management actions in response to estimated or perceived stock conditions would allow for rational, objective and farsighted decision making. However, the translation of biological information on stock status directly into catch limits has proven difficult. In a broad sense, doing so tends to oversimplify biological inputs that form the basis of stock status determination by not taking into account the full range of information in setting the TAC (e.g. biological, environmental, ecological but also socioeconomic, compliance, etc.). Deterministic HCRs for co-managed fisheries also tend to overlook that the *science* perspective should be emphasized when the stock is in an unstable or depressed state, whereas *industry* and *management* perspectives should be emphasized when it is stable and abundant. Specifically, though, the principle crux of applying HCRs to the TLA is that it cannot be achieved quantitatively without explicit consideration of weighting of the indices, which has generally been very problematic.

Theoretically speaking, weighting should reflect:

- the degree of independence of indices when derived from the same data,
- the availability of multiple indicators for the same stock attribute,
- the degree to which the index is a true measure of the stock attribute, and
- the precision of the indicator estimation, among other things.

Practically speaking, understanding and accounting for the non-independence of indicators has proven very difficult. In addition, indices can be over-represented when the time series/trend is interpreted in the provision of advice (rather than just the value of that index in the current year) such that the status of the index was already used to adjust the TAC the previous year(s), and that TAC forms the basis from which quotas are adjusted the following year. Furthermore, the relevance and extent to which an indicator provides a true measure of the stock attribute is often not amenable to statistical quantification.

The strength of the TLA is its ability to bring together a broad spectrum of information, qualitative and quantitative, which might be relevant to the issue in question. Weighting has tended to generate intense, prolonged and highly technical debate while adding little the accuracy of the overall result (Halliday et al. 2001). The Proceedings from ESS shrimp stock assessments using the TLA reveal a record of discussion about whether or not the indicators could or should be weighted to reflect that some are clearly more strongly emphasized than others, with a view towards developing quantitative decision rules. Overall, the assessment team continued to defend the qualitative application of the TLA, without weighting individual indices, as a holistic framework for the discussion and interpretation of diverse indices of shrimp abundance, productivity, fishery and ecosystem condition as a means to inform decisions for adaptive TAC adjustments. Furthermore, industry feedback suggested that they preferred traffic lights as a visual representation for a fluid and truly cooperative discussion rather than having them directly resulting in a TAC, which would functionally exclude them from the co-management process. Quantitative HCRs were also viewed as problematic because the TLA is meant to be a composite of many factors used in decision making. To use the TLA score against just one indicator (biomass) to develop the TAC was viewed as contrary to the holistic philosophy of the TLA. Quantitative HCRs force a large quantitative leap to be taken at the last step, after a qualitative discussion of the other indices. Shrimp assessment proceedings from the early-mid 2000s provide a record of this philosophical difference of opinion on the value of the TLA as a holistic discussion framework for adaptive co-management versus several reiterations of the view that deterministic HCRs (which necessitate indicator weighting) were essential to the defensible application of the TLA for the provision of science advice. Since the mid-2000s, however, the TLA has been used in the former sense – without weighting or deterministic interpretation, as a means to take into account a variety of different factors and to facilitate discussion. Although it would be naïve to discount the innate high productivity of shrimp during this period as an important factor, the *status quo* approach of using adaptive TAC adjustments based on a holistic discussion of diverse shrimp stock, fishery and ecosystem considerations as guided by the TLA have clearly provided one of the best examples of a truly cooperative assessment and adaptive management framework.

Nonetheless, the recent implementation of a multi-year assessment schedule for shrimp provides the opportunity to revisit ideas during the Framework meetings. Here, presented *for discussion*, is a model that qualitatively links the annual values of weighted Traffic Light indicators to the provision of a range of TACs for the following year as a proportion of the survey biomass index from the preceding year. The model discussed herein does not circumvent the limitations and complications of weighting indices and of the use of deterministic HCRs from the TLA that are outlined above. Rather, it embraces, or at least acknowledges them, effectively “taking the bulls by the horns” to examine: what quantitative HCRs might look like, what outcomes are produced, how outcomes compare retrospectively to history, and what steps, if any, can be taken to mitigate some philosophical and practical issues that have been identified with such steps.

THE HARVEST CONTROL RULE TRAFFIC LIGHT ANALYSIS MODEL

Methods

The model presented for discussion herein builds on the SSB-based biomass reference points that have been adopted for this stock (Smith et al. 2012 and discussed above). Historically, TAC recommendations for year *t+1* have ranged from 10% – 16% of the survey biomass estimate in year *t* (average13%). Notably, TACs representing the highest proportion of the biomass index have resulted from assessments when SSB (and survey biomass) were low, with TACs representing lower exploitation rates derived from years of higher SSB. When the SSB Traffic Light index was red, historic TACs represented, on average, 14% exploitation of the preceding year survey biomass index; 14.5% when SSB index was yellow, and only 12% when it was green. Higher relative exploitations during periods of lower stock abundance may seem counter-intuitive to conservative management practices; however, this is not the case here. In fact, this trend reflects the fact that the current application of the TLA is functioning effectively to ensure that *other* aspects of stock, fishery and ecosystem condition are being considered when the TAC is set, not just shrimp biomass. The Advisory Committee generally seeks quite modest increases in the TAC from within the range advised by science, even when biomass has increased significantly (i.e. less than proportional TAC increases). This fact alone, as will be seen below, flags the possibility that applying deterministic HCRs based on a biomass index could result in a less precautionary quota setting process than the *status quo* holistic TLA in an adaptive co-management framework.

For the HCR model, the base TAC (baseTAC) is a proportion of the preceding year's swept area biomass estimate, depending where in the biomass reference zone current SSB is, to a maximum of 10% when SSB is above the USR. Further proportions of the preceding year's swept area biomass estimate are added to baseTAC depending on the value of the other Traffic Light indices (tlaTAC), which are weighted based on the historic emphasis that has been places on the various indices and characteristics, to a maximum of 8%, as described below.

As outlined above, the TLA for the ESS has never formally employed quantitative weighting of indicators. Nonetheless, there has been a natural emphasis on certain core indicators in every annual assessment. Other indicators are routinely less strongly emphasized, unless a particularly notable trend occurs, or unless the information from those "secondary" indicators helps to inform the interpretation of one of the "core" indicators. Certainly, survey and commercial catch rate indices (survey, Gulf and standardised CPUE) and indices linked to length frequency distributions and analysis (belly-bag, SSB, Age 2 and Age 4 abundance) have generally been strongly emphasised in annual assessments. Environmental indices such as temperature and Cod recruitment, which are known to be important determinants of shrimp population dynamics, are generally given more consideration than, for example, abundance trends in conspecific species such as Capelin, Greenland Halibut, or Snow Crab. Here, a weighting system has been applied to all the indicators except for SSB (which is already very heavily weighted as the basis for baseTAC) based on a subjective review of the summary bullets in Science Advisory Reports and of discussions as recorded in meeting Proceedings, to see which indicators have tended to be most strongly emphasised in the provision of past science advice. Importantly, this makes the assumption that the provision of past science advice has been correct. Ironically, this assignment of quantitative weights undertaken by a subjective leap of faith by the assessment team is precisely what the application of deterministic HCRs strives to get away from (subjectivity). Nonetheless, indicators are weighted here on this subjective basis to allow a working model to be discussed. No additional rules are applied for the purposes of this exercise (e.g. limiting maximum relative TAC changes, limiting maximum TAC). In the event that a deterministic approach is adopted for this stock, the question of weighting indicators will surely need to be revisited by an expert panel, as will the issue of whether additional rules are needed to constrain the HCR model.

Currently, the only formal HCR is that the fishery is closed when the stock is below the LRP (5459 mt SSB), which is 30% of the mean SSB during a high productivity period truncated to 2000-2010 inclusive (see Precautionary Approach section above). For the purposes of this model, mean SSB is further divided into 10% increments from 30% to 100% of the mean 2000-2010 SSB, and a baseTAC has been assigned to each of these 10% mean SSB intervals as shown in Table 13. The sum of baseTAC and tlaTAC are the total Harvest Control Rule TAC (hcrTAC), expressed for the quota for year *t* as a percentage of the survey swept area biomass estimate B_s from year *t-1*. It is worth reiterating that SSB is simply an indicator that had been assigned a higher significance by virtue of its adoption as the basis of the PA. Similarly, in this context it has functionally been very heavily weighted as the basis for baseTAC (Table 14). Before accounting for any other indicators, SSB_t determines $baseTAC_{t+1}$ as 0% to 10% of B_s, increasing stepwise in an approximately sigmoidal fashion throughout the 10% stepwise increases in SSB_t (Table 13, Figure 38). At an absolute maximum, baseTAC (10% at or above USR) and tlaTAC (8% if all indicators are at their highest values on record -100th percentile) combine for a total exploitation rate of 18% of the preceding year's swept area biomass. The mean characteristic tlaTACs for each characteristic are multiplied by 4% for the Abundance characteristic, 2% for the Productivity characteristic, and 1% each for the Fishing Effects and Ecosystem characteristics. The weighting of both indicators and characteristics results in cumulative weights shown in the last column of Table 14. These cumulative weights do not account for the sometimes high degree of correlation of indicators, particularly those that derive from the same data (Table 9).

The tlaTAC was calculated for each characteristic, as follows:

$$\boldsymbol{tlaTACabund} = 3 * rvcpue + 2 * gcpue + 2 * stcpue + rvcv + area/9$$

$$\boldsymbol{tlaTACprod} = (2 * bb + 2 * rv2 + 2 * rv4 + sexmm + maxmm + 2 * pred)/10$$

$$\boldsymbol{tlaTACfish} = (count + 2 * exp + 2 * femexp + femprop + femsize)/7$$

$$\boldsymbol{tlaTACeco} = (popeven + 2 * botemp + 2 * surtemp + 0.5 * capelin + cod + 0.5 * turbot + 0.5 * crab)/7.5$$

Characteristic tlaTACs were added to baseTAC and combined to reflect weighting of the characteristics as follows:

$$\boldsymbol{hcrTAC} = baseTAC + 4(tlaTACabund) + 2(tlaTACprod + tlaTACfish + tlaTACeco)$$

The bounds of the minimum (10% of B_s) and maximum (18% of B_s) hcrTACs possible using this method contain 75% of the values of historical 1-year lagged exploitation rates ($TAC_t / B_{s(t-1)}$) (Figure 38). The range provided around the proposed hcrTAC is simply the annually derived 95% confidence interval in the survey biomass estimate, proportionally applied to the hcrTAC to reflect the uncertainty in the biomass estimate and to provide flexibility for continued co-management of the fishery in a way that reflects industry, socio-economic and management concerns as well as science advice.

Results

The retrospective application of the HCR model results in significantly higher (5003 mt) average hcrTACs (5003 mt) than average historical quotas (4342 mt) (Figure 39, paired t-test for means, $p<0.05$). However, several of the highest hcrTACs over 6000 mt would be unlikely to be supported by the Advisory Committee, based on the conservative history of co-management of this stock. Historic TACs falls within the proposed range of the hcrTACs in 8 of the 19 year series. The result that some hcrTACs, especially when SSB is in the Healthy Zone, would have exceeded management history was predictable based on the fact that some historical quotas are lower than the *minimum* baseTAC (Figure 38). As discussed above, relatively low quotas at high stock abundance levels reflect the history of generally cautious increases in targeted exploitation when the stock increased and the careful consideration of the all indicators (other than abundance). However, under periods of lower abundance around the USR, the HCR method more closely simulates management history (Figure 38).

The ESS shrimp stock has been relatively abundant throughout the period captured by the contemporary survey data series (1996-present) in Figures 38-39. As a result, Figure 39 provides accurate predictions of the results of the HCR model for these years, for which both B_s and SSB data exist, but the actual TAC predictions (tonnage) for lower abundance period remain obscure. For example, the HCR model tells us that in the lowest part of the Cautious Zone (between 30-40% of the PA SSB index) the hcrTAC would range between 0-8% of B_s depending on the tlaTAC (because baseTAC is 0%). Because the data do not include contemporary survey or SSB estimates for such low abundance, this question cannot be easily answered (i.e. it is not known what B_s is; it is likely to be at low SSB). In order to approximate the possible ranges of TACs for hypothetical low-SSB situations, a regression equation between B_s and SSB was used. The relationship is auto-correlated given that survey CPUE data are used to calculate both indices (SSB simply accounts for the proportion of females and transitionals in the catch), so is used here only for the purposes of approximating the B_s values at low SSB to estimate hypothetical hcrTACs in low PA zones for which there is no robust data. Table 15 shows minimum (baseTAC) and maximum (maxTAC) values as percentages of hypothetical Bs values extrapolated from the regression of Bs on SSB from 1996-present data. It is important to note that maximum TAC values are largely theoretical, especially at low SSB, because they represent the situation where every indicator is at 100th percentile of the entire data range. This is unlikely in any case, but it is impossible at low abundance. While the maximum TAC column makes relatively high TACs (e.g. 1244 mt when only just above the LRP) seem possible, the low Traffic Light values of most indicators when the biomass is so low would result in hcrTACs much closer to baseTAC than to maximum TAC near the LRP. Quotas closer to maximum hcrTAC are increasingly likely the higher the stock abundance.

Conclusions

In general, the HCR model achieves the goal of providing a quantitative means of interpreting Traffic Light indicators and Characteristics in a manner that is consistent with the PA. However, as was stated above, there remain serious concerns and limitations with a deterministic interpretation of the TLA that this model does not resolve. Although the earliest proposals of the TLA purported that HCRs triggering pre-agreed conservation and management actions were necessary for the TLA to be compliant with the PA, the ESS shrimp assessment gradually moved away from this deterministic interpretation. So it should be reiterated that, right at the outset, this exercise is a philosophical departure from the much more qualitative interpretation of the TLA as a holistic means to summarize and discuss diverse information to arrive at adaptive quota decisions in a cooperative manner with various stakeholders. Another important issue with the HCR model is that it ties the lion's share of the TAC annual adjustments to variability in biomass indicators, which favours as a management strategy that "chases the biomass".

Probably the most serious and difficult to overcome problem with the HCR model is the issue of weighting. The way in which weights were applied in this exercise (subjectively interpreting the emphasis placed on different indicators and characteristics throughout stock history) is inconsistent with the spirit of the approach to reduce subjectivity in the TLA. Certainly, there are means to improve this, such as a canonical correspondence analysis of indicator values when quotas were increased or decreased (i.e. quantifying which indicators were "greener" when the quota was increased in the past, which indicators were "redder" when the quota was reduced, and weighting those accordingly). This makes the important assumption (as has been made here) that the past quota adjustments have been the correct ones. Making this assumption then begs the important question: if the past management actions have been correct, then why change things? Another approach is for an expert panel to rigorously quantify the evidence for a biological basis of each indicator, and to apply weights accordingly. But the biological and statistical complexity of the correlations between indicators, and the interactions of other factors on the index values, would surely make this approach prohibitively complex so as to no longer be useful. Such an undertaking risks confusing the obscure with the profound, putting us once again completely at odds with the philosophy of the TLA. Overall, the problem of weighting in the deterministic application of the TLA may be insurmountable.

The retrospective analysis shows that the hcrTACs tend to be more conservative than historical TACs at lower abundance, but less conservative at higher abundance. On the one hand, this is consistent with a conservative approach, although the very high hcrTACs when abundance is high are beyond what this fishery has experienced, so there are some unknowns (e.g. market conditions, fleet capacity, local depletion, etc.). When considering the possibility of a more directly proportional link between exploitation rate and biomass that would result from the HCR model, it is worth reiterating that the ESS shrimp survey covers the stock distribution in a rather limited way, and there is considerable uncertainly in the biomass indices that derive from it. If a deterministic approach such as the HCR model is taken, some precautionary caps might be advisable until the outcomes over higher TACs are better understood. Given that the ESS shrimp TAC has undergone annual changes of up to 43% in recent years (both increases and decreases), it would be difficult to justify a supplemental rule limiting the permissible relative annual change in TAC. Such decisive TAC changes in response to science advice underly the success of the adaptive co-management of this stock. There is, of course, no true lower limit on the TAC using any method for the provision of advice; the Advisory Committee can always decide on a lower quota than the science advice.

Under the current PA, conservative management actions are well defined within the Critical Zone (close the fishery) and the Healthy Zone (set TACs to try remain below 20% exploitation). However, management actions are much less well defined within the Cautious Zone, and the fishery has been there infrequently enough so as not to have developed much experience with it. The HCR model does provide some potential benefit here, where the current management guidelines fall somewhere between the vastly different Critical and Healthy Zone rules. Overall, the sigmoidal changes in the baseTAC within the Cautious Zone ensure increasingly conservative decreases in the TAC the closer the stock gets to the LRP, and the supplemental tlaTAC that is added to the sigmoidal baseTAC are likely to also be very conservative, particularly given how many indicators are derived from abundance metrics, and these tend to be more heavily weighted.

The proportional application of the confidence intervals from the swept-area biomass estimate to the hcrTACs is a rather blunt way to provide a range of quota advice. However, in addition to reflecting uncertainty in the survey biomass data that is used for many indicators, it also helps to overcome one of the previous concerns expressed by industry: that a deterministic interpretation of the TLA would tend to exclude them from the interpretation of the data. The relatively large range of the hcrTAC advice leaves room for input by industry and other stakeholders in the interpretation of science advice. Furthermore, it provides flexibility in the science advice itself, in the event that there are nuances in the data that are not adequately captured in the HCR model (e.g. the loss of the ability to interpret an indicator differently based on trends in other indicator(s)).

In summary, although the HCR model does appear to provide harvest advice following a quantitative analysis of the Traffic Light indicators and characteristics in a manner consistent with the PA, weighting remains a problem that will be difficult or impossible to overcome, as it always has been. Despite some perceived benefits of a more prescriptive interpretation, particularly in the Cautious Zone where appropriate management actions are currently poorly defined, this approach appears to be in conflict with the two-decade long proven track record of the interpretation of the TLA as a way to summarize diverse information about stock health in a way that engenders fluid and open discussion by industry, management, science and other stakeholders to achieve precautionary TACs via adaptive co-management.

QUANTITATIVE STOCK ASSESSMENT MODELS

Quantitative stock assessment models have often proven difficult to apply to shrimp populations. Uncertainties concerning age, growth and mortality, difficulties in judging year class strength, and particularly the failure to adequately define widely variable and environmentally determined recruitment processes have prevented quantitative projections of shrimp biomass. As a result, catch recommendations have generally been decided based on changes in CPUE, biomass estimates and tracking changed in length-frequencies (Shumway et al. 1985). Shrimp assessment methods do not normally employ biological reference points, tending to be more descriptive in nature, monitoring changes in commercial and survey data and samples to make TAC decisions without making a formal link between population structure and recruitment (Koeller et al. 2000). Stock collapses in shrimp are relatively rare compared to highly parameterized models and management regimes in many finfish stocks.

A surplus production model (SPM) was explored in 2009 (Koeller et al. 2011). The SPM is a class of model using undifferentiated aggregated biomass to circumvent the lack of age information, as is the case for shrimp. This approach assumes that the population produces more offspring than necessary to replenish itself and that fisheries can harvest this surplus indefinitely. Other SPM assumptions include:

- that abundance indices are proportional to true abundance,
- that the population has stabilized to the current rate of fishing,
- that all losses other than fishing are natural mortality,
- that fishing mortality is density independent,
- that the stock reacts instantaneously to fishing mortality, and
- that the environment is constant and has no effect on biomass trajectory.

Clearly, many of these assumptions are problematic for shrimp, perhaps most notably the last two. Fitting a SPM generally requires a wide range of dynamic values as the time series of inputs.

Koeller et al. (2009) used ASPIC (*A Stock Production Model Incorporating Covariates*) in the NOAA Fisheries Toolbox to fit ESS shrimp data to Shaefer's (logistic) and generalized SPMs. They used survey, Gulf and Standardised Maritimes CPUE indices to simulate stock dynamic during different periods of stock productivity. Modelled values of carrying capacity (K), MSY and equilibrium yield for 2010 were substantially different among the three data series. Given uncertainties between the Gulf vessel catch rates during periods of low and high abundance related to gear changes (Nordmøre grate), they opted to use the Standardised Maritimes CPUE data, which predicted yields and biomasses similar to the historical averages.

The generalized and logistic models yielded similar results with linear fits between observed and modelled CPUEs. The model outputs suggested that fishing mortality had been low and biomass had been high for the past 8 years (2000-2008). Predicted yields (yield at equilibrium and F_{msy}) for the past 5 years were similar to actual TAC/landings. Bootstrapping suggested a high degree of uncertainty in the parameter estimates, particularly for K. Projections of F and biomass suggested that catches on the order of 3000-5000 mt per year would result in F well below F_{msy} and biomass well above B_{msy} under model assumptions. Biomass at Maximum Sustainable Yield (B_{MSY}) and MSY were quite high from the model, and higher than seen in the assessment. The authors concluded that while the SPM showed that the TAC in recent years had been similar to F_{MSY}, they pointed out that there was considerable uncertainty in model outputs, and that it was problematic that it did not incorporate environmental factors or trophic linkages that are known to be very important for shrimp.

A similar exploratory analysis of contemporary data (up to 2014) was first undertaken using the Schaefer formulation of the SPM based on equations in Hilborn and Walters (1992) in R. Fitting the model to the shrimp data (each CPUE series separately, as in Koeller et al. 2009) proved to be extremely sensitive to minor adjustment in starting values for r, q, B_0, but particularly in carrying capacity, K. This approach was abandoned in favour of a Bayesian state-space modeling approach for reasons outlined below.

BAYESIAN STATE-SPACE MODEL

A simple stock assessment model in the form of a modified discrete logistic model or Biomass Dynamic Model (BDM) was used to combine the biomass indices with landings data. This modeling approach was chosen as it is one of the simplest, and most robust, families of models that can be used to explore population dynamics. Briefly, the variations in biomass in year t, B_t, are described as a function of the previous year's biomass, B_{t-1} and other population specific parameters, specifically r, the intrinsic population growth parameter and K, or the population carrying capacity.

$$B_t = B_{t-1} + rB_{t-1}\left(1 - \frac{B_{t-1}}{K}\right) - C_{t-1} \qquad \text{Eq.1}$$

In BDMs *r* is an integrative parameter accounting for population recruitment, mortality and growth. A Bayesian State-Space Modeling (BSSM) approach was used to estimate the states of B_t, *r* and *K*. This approach was proposed by Millar and Meyer (2000) because it allowed for the incorporation of random errors in both the population dynamics (process errors) and the observed data (observation errors) and because it incorporates non-linearity in the dynamics. These 'process errors' refer to the errors propagated through the transition between states B_{t-1} and B_t, whereas the 'observation errors' refer to the uncertainties associated with measurement and observation. This SSM approach is useful for fishery time series analysis because the data collected are typically indices of the true stock biomass or abundance that cannot be observed directly. Moreover, SSM has been suggested to provide more realistic parameter estimates and more credible forecasts.

The simple formulation of BDMs also provides parameter estimates that can be used to define maximum sustainable yield (MSY) reference points. Simply MSY=0.25rK, B_{MSY}=0.5K and F_{MSY}=0.5r. In a SSM framework, the estimates of process error can be incorporated to provide stochastic MSY reference points (Bousquet et al. 2008).

As per the suggestion of Millar and Meyer (2000), the B_t's and C_t's in equation 1 were rescaled by *K* as $P_t = B_t / K$ and $c_t = C_t / K$ to improve the convergence of the Gibbs sampler. The resulting model was:

$$P_t = P_{t-1} + rP_{t-1}(1 - P_{t-1}) - c_{t-1} \qquad \text{Eq. 2}$$

The biomass of shrimp, similar to most other species, was assumed to follow a lognormal distribution, and a multiplicative observation model with variance, τ^2, estimated as:

$$I_t \sim LN[\log(q^*K^*P_t), \tau^2] \qquad \text{Eq. 3}$$

where I_t was the biomass index at time *t*, *q* was the catchability or proportionality constant that scales the index to estimates of the 'true' biomass. Similarly, the process errors, were assumed to also follow a (multiplicative) lognormal distribution with variance σ^2,

$$P_t \sim LN[\log(P_{t-1} + rP_{t-1}(1 - P_{t-1}) - c_{t-1}), \sigma^2] \qquad \text{Eq. 4}$$

For this work, all three biomass indices, the Survey Catch Rate (SCR), the Gulf fleet catch rate (GCR) and the Standardised Catch Rrate (SSCR) were modelled separately. This modelling strategy was employed over the more commonly used multiple 'q' modelling approach where several biomass indices are simultaneously fitted as it does not rely on 'data-weighting' methods and yields descriptors of the full range of potential model results (Francis 2011).

Priors for Bayesian State-Space Model Parameters

The prior for *r* was assumed to follow a normal distribution centered at 0.85 with a standard deviation of 0.13, similar to other invertebrate species (Cook et al. 2014). The prior for the parameter K followed a lognormal distribution of the mean and standard deviation were estimated by setting the 90% quantile range to the maximum observed biomass from each of the biomass index and six times that index's maximum. A uniform prior on *q* was used for all survey series following the probability distribution of U[0.005,0.4]. The priors for process error were assumed to follow a uniform distribution. In winBUGS, the second moment (variance or scale) used for distributions is the inverse of many typical implementations of probability distributions (i.e. statistical software R). As such, process errors are estimated as the precision (variance^{-1}) of the lognormal distribution. Prior distributions for process precision, herein referred to as *inv.*τ^2, were U[0.02,400]. Similar to the process errors, the observation errors σ^2 followed a uniform distribution and was the inverse of variance, herein referred to as *inv.*τ^2 with prior distributions of U[0.02,400] for all biomass indices.

Model Selection

The software winBUGS (version 1.4.2; Lunn et al. 2000) was used to perform the Markov Chain Monte Carlo (MCMC) integration required to implement the Bayesian state-space filter. Three chains of length 300,000 with a burn in phase of 20,000 and thinning of 125 were determined to be sufficient to allow for adequate mixing, removal of initialization and decrease in autocorrelation, respectively. Convergence of chains was tested with a Gelman-Rubin diagnostic (Gelman and Rubin 1992).

Results and Discussion

For each BDM fitted to a survey series, the posterior distributions for estimated parameters were updated from prior distributions suggesting that there was sufficient information in the data to describe the results (Figures 40-42). There was substantial overlap between parameter estimates between the standardised and Gulf commercial catch rate based models while the survey catch rate based model yielded disparate results (Figures 43-45, Table 16). Commercial catch rate median estimates of r (0.98, 1.04) and K (19 160, 17 820) for Gulf and standardised data, respectively, were very similar, yielding *MSY* values around 4500 mt and F_{MSY} around 0.5 (Table 16, Figures 46-47). The survey data based median parameter estimates suggest that the ESS shrimp stock is even smaller (K = 10 840) than the already implausibly low median carrying capacity predicted from commercial data model fits. The survey data also predicted very high median productivity (r = 1.62) and high F_{MSY} of 0.8 as a result (Figure 48). That said, even the higher commercial data-based estimates of carrying capacity for shrimp on the Scotian Shelf appear to be low relative to current understanding, where conservative swept-area biomass estimates are on the order of 30-50,000 mt, so at least 2-3 times above the BDM estimated carrying capacity. The lower survey data-derived carrying capacity is even less plausible. The use of BDM modeling to estimate population parameters and MSY reference points relies on the assumptions that the survey index reflects the changes in population size through time and the influence of the fisheries landings are an important determinant of the transitions of biomass. Given the precautionary approach of the Scotian Shelf fishery, the relative magnitude of landings may be lower than the natural fluctuations in the population, which would result in an underestimate of 'true' population carrying capacity.

One simple way to test whether or not fishing mortality is an important determinant of biomass fluctuations is called the AIM (An Index Method) method. If fishing mortality contributes to the biomass signal, one could expect to observe a negative relationship between relative fishing mortality and relative change in biomass. For ESS shrimp, there is no such negative relationship (Figure 49), which provides evidence that the conservative exploitation levels in the ESS shrimp fishery do not appear to be important determinants of annual biomass variation.

Failures of BDMs are often derived from data failure due to poor contrast between fishing effort and stock abundance (Hilborn 1979), and the ESS shrimp stock appears to be no exception. Without contrast in spawning stock size, the stock-recruitment relationship cannot be clearly understood. In the context of parameter estimation for BDMs, this means that one must have high historical variation in stock size and fishing pressure to estimate the parameters of the model with any reliability. As a result, the BDM analytical approach is not considered to be a valid avenue to pursue for the provision of science advice for this stock.

CONCLUSTION: ADAPTIVE CO-MANGEMENT OF EASTERN SCOTIAN SHELF SHRIMP

The TLA has provided a simple, effective and comprehensive means to provide science advice for the co-managed ESS shrimp fishery for nearly a quarter century. Although the TLA is not without its limitations and caveats, it is difficult to find fault with this track record. It is important not to overlook the role that the increase in the shrimp stock to the current and sustained high productivity state has played in easing the provision of science advice over this period. Hence, by the same token, one should not overlook the lengthy track record of conservative quota increases in the face of these strong biomass trends, as well as, immediately substantial quota retractions in response to stock decreases and subsequent science advice. The exploratory analysis of deterministic (HCR model) and stock projection (BDM) models discussed herein are problematic for a number of reasons, but perhaps most importantly, their adoption risks disrupting the close cooperative relationship between science, industry and management that has proven so successful. This overall result is not novel; it confirms the conclusions of past considerations of similar approaches (e.g. Koeller 2000, Koeller at al. 2009).

The HCR model explored herein as a means to provide deterministic quota recommendations based on the results of the TLA does yield TACs that are relatively consistent with management history and the conservative exploitation of this stock, although the advice risks being substantially less conservative at high biomass. Developing a means to more clearly define management responses to science advice at low-moderate abundance levels than the current subjective approach is tempting. The impetus to develop guidance at lower stock abundance derives from the fact that the co-management system for this fishery has relatively little recent experience with this. However, as mentioned above, past and ongoing prompt and conservative responses to science advice based on the TLA suggest that appropriate management responses to a declining stock would be very likely. Such decisive responses to science advice depend on high levels of communication and trust between science and stakeholders that a deterministic interpretation may lessen. An approach that is tied so strongly to biomass trends also risks imparting more interannual variation in quotas than is advisable for economic and logistical reasons. Management regimes that “chase biomass” have often been problematic. Perhaps most significantly, though, a deterministic interpretation of the TLA cannot be achieved without weighting indicators. As discussed in detail, appropriate weights for highly correlated indicators are a moving target, particularly given the possibility of polarity reversal, and identifying a compelling means to achieve this remains a serious and probably insurmountable stumbling block to a deterministic application of the TLA to the provision of TAC advice.

The earliest work to quantitatively model ESS shrimp population dynamics concludes with what has proven to be an enduring statement. Mohn and Etter (1982) wrote: *in light of the probability that it is environment, not effort, that is the major determinant of (shrimp) stock size, it would appear that MSY from classical fisheries models must be received critically, if not cynically.*” The influence of environmental determinants of shrimp stock size has been incorporated into similar methods (e.g. Hvingel and Kingsley 2006), but for conservatively exploited shrimp stock such as the ESS, wherein historical fishing mortality appears to have little detectable influence on biomass trends, such methods are likely to remain problematic. Although the implementation of the Precautionary Approach has put pressure on assessment scientists to develop models that provide the ability to project the probability of various management actions on stock biomass, methods that depend on a detectable instantaneous response between fishing mortality and biomass are unlikely to provide robust parameter estimates for ESS shrimp, particularly given its conservative management history.

The TLA distances stock assessment from model error that arises from the use of inevitably variable, uncertain or limited monitoring data implicitly in the models to set target yields (Koeller 2000). It brings together information from a suite of stock specific quantitative and qualitative indicators in a manner that is transparent to all stakeholders, to provide political and intellectual equity in the decision making process. The result has been a long track record of the provision of science advice resulting in conservative and sustainable management of the ESS shrimp fishery. It is recommended that the ESS shrimp assessment continues with the holistic, qualitative interpretation of the TLA, and that future research efforts be focused on the refinement and further validation of the Traffic Light indicators rather than exploring quantitative alternatives to the TLA.

Research Recommendations

The ESS shrimp Framework meeting resulted in a number of research recommendations aimed at further development and improvement of Traffic Light indicators. These recommendations included:

1. Further exploration of Cod, Turbot and Snow Crab ecosystem indicators to study the degree to which abundance trends of these species are interrelated, and how they subsequently influence shrimp. It was also recommended to investigate Atlantic Halibut trends, given that abundance of this species has increased in recent years.
2. Exploration of Atlantic Zone Monitoring Program indicators as more direct ecosystem indicators to track potential ecosystem shifts that may relate to shrimp life history and abundance.
3. Due to uncertainty about the interpretation (i.e. polarity) of the population age-length evenness index, depending on the influence of particularly abundant year classes, it was recommended that alternative means of providing an index of the distribution of the stock across year classes be explored.
4. The addition of shrimp trap fishery catch rate as an additional fishery-dependent abundance index that derives from different gear and is spatially and temporally distinct from trawl fishery catch rate indices. It was also recommended to explore the suitability of shrimp abundance in the annual ecosystem and snow crab surveys as additional fishery-independent abundance indices.
5. Bycatch analyses to compare bycatch from the shrimp survey and bycatch from other fisheries on the ESS to that observed in the shrimp fishery. Currently, only bycatch from the shrimp fishery is reported.
6. It was recommended that total fishing effort be added to the analysis as a fishery-dependent exploitation index.
7. Consider reformatting the document and presentation to reflect the functional emphasis on primary and secondary indices, including but not limited to removing individual indicator bar-charts in favour of a focus on plots and trends currently presented in figures.
8. Clearly define triggers to warrant a break from interim assessments (to trigger a full assessment). These triggers might include core abundance or productivity index triggers.

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REFERENCES

Appolonio, S., D.K. Stevenson, and E.E. Dunton Jr. 1986. Effects of Temperature on the Biology of Northern Shrimp, *Pandalus borealis*, in the Gulf of Maine. NOAA Tech. Rep. NMFS 42. 22p.

Berenboim, B.I., A.V. Dolgov, V.A. Korzhev, and N.A. Yaragina. 2000. The Impact of Cod on the Dynamics of Barents Sea Shrimp (*Pandalus borealis*) as Determined by Multispecies Models. J. Northw. Atl. Fish. Sci. 27: 69−75

Bousquet, N., T. Duchesne, and L.P. Rivest. 2008. Redefining the Maximum Sustainable Yield for the Schaefer Population Model Including Multiplicative Environmental Noise. J. Theoret. Biol. 254(1): 65-75.

Boutillier, J.A., and J.A. Bond. 2000. Using a Fixed Escapement Strategy to Control Recruitment Overfishing in the Shrimp Trap Fishery in British Columbia. J. Northwest Atl. Fish. Sci. 27: 261–271.

Caddy, J.F. 1998. A Short Review of Precautionary Reference Points and Some Proposals for Their Use in Data-poor Situations. FAO Fish. Tech. Pap. No. 379.

Charnov, E., and U. Skúladóttir. 2000. Dimensionless Invariants for the Optimal Size (Age) of Sex Change. Evol. Ecol. Res. 2: 1067-1071.

Cook, A.M., B.M. Zisserson, B.J. Cameron, and J.S. Choi. 2014. Assessment of Scotian Shelf Snow Crab in 2013. DFO Can. Sci. Advis. Sec. Res. Doc. 2014/052.

DFO. 2000. Proceedings of the Maritimes Regional Advisory Process of the Eastern Scotian Shelf Shrimp. DFO. Can Sci. Advis. Sec. Proc. 2000/008.

DFO. 2013. Scotian Shelf Shrimp 2012-2013. DFO Can. Sci. Advis. Sec. Res. Doc. 2013/034.

DFO. 2014. Eastern Scotian Shelf Shrimp Stock Status Update for 2013-2014. DFO Can. Sci. Advis. Sec. Sci. Resp. 2014/012.

DFO. 2015. Assessment of Northern Shrimp on the Eastern Scotian Shelf (SFAs 13-15). DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2015/004.

Etter, M.L., and R.K. Mohn. 1989. Scotia-Fundy Shrimp Stock Status – 1988. DFO Can. Sci. Advis. Sec. Res. Doc. 1984/004.

Francis, R.I.C.C. 2011. Data Weighting in Statistical Fisheries Stock Assessment Models. Can. J. Fish. Aquat. Sci. 68(6) 1124-1138.

Frank, K.T., J. Simon, and J.E. Carscadden. 1994. Recent Excursions of Capelin (*Mallotus villosus*) to Scotian Shelf and Flemish Cap During Anomalous Hydrographic Conditions. NAFO SCR Doc. 94/68.

Gelman, A., and D. B. Rubin. 1992. Inference from Iterative Simulation Using Multiple Sequences. Stat. Sci. 7: 457–511.

Gulland, J.A. 1971. The Fish Resources of the Ocean. Fishing News Books, West By Fleet, UK.

Halliday, R.G., and P.A. Koeller. 1981. A History of Canadian Groundfish Trawling Surveys and Data Usage in ICNAF Divisions 4TVWX; pp. 27-41. In: W.G. Doubleday and D. Rivard (Editors). Bottom Trawl Surveys. Can. Spec. Publ. Fish. Aquat. Sci. 58.

Halliday, R.G., L.P. Fanning, and R.K. Mohn. 2001. Use of the Traffic Light Method in Fishery Management Planning. DFO Can. Sci. Advis. Sec. Res. Doc. 2001/108.

Hannah, R.W. 1995. Variation in Geographic Stock Area, Catchability, and Natural Mortality of Ocean Shrimp (*Pandalus jordani*): Some New Evidence for a Trophic Interaction with Pacific Hake (*Merluccius productus*). Can. J. Fish. Aquat. Sci. 52: 1018–1029.

Hardie, D., M. Covey, M. King, and B. Zisserson. 2013. Scotian Shelf Shrimp 2012-2013. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/078.

Hilborn, R. 1979. Some Failures and Successes in Applying Ssystems Analysis to Ecological Systems. J. App. Syst. Anal. 6: 25-31.

Hilborn, R. and C.J. Walters. 1992. Quantitative Fisheries Stock Assessment. Springer US. 570 p.

Hvingel, C., and M.C.S. Kinglsey. 2006. A framework to Model Shrimp (*Pandalus borealis*) Stock Dynamics and to Quantify the Risk Associated with Alternative Management Options, Using Bayesian Methods. ICES J. Mar. Sci. 63: 68-82.

Ingibjörg, G., I.G. Jónsdóttir, H. Björnsson, and U. Skúladóttir. 2012. Predation by Atlantic Cod *Gadus morhua* on Northern Shrimp *Pandalus borealis* in Inshore and Offshore Areas of Iceland. Mar. Ecol. Prog. Ser. 469: 223-232.

Koeller, P. 1996. Aspects of the Biology of Pink Shrimp *Pandalus borealis* Krøyer on the Scotian Shelf. DFO Atl. Fish. Res. Doc. 96/9.

Koeller, P. 2000. Relative Importance of Environmental and Ecological Factors to the Management of the Northern Shrimp Fishery (*Pandalus borealis*) on the Scotian Shelf. J. Northw. Atl. Fish. Sci. 27: 37-50.

Koeller, P. 2006. Inferring Shrimp (*Pandalus borealis*) Growth Characteristics from Life History Stage Structure Analysis. J. Shell. Res. 25: 595-608.

Koeller, P., M. Covey, and M. King. 1997. The Scotian Shelf Shrimp (*Pandalus borealis*) Fishery in 1997. DFO Atl. Fish. Res. Doc. 97/125.

Koeller, P., R. Mohn, and M. Etter 2000a. Density Dependant Sex Change in Pink Shrimp, *Pandalus borealis*, on the Scotian Shelf. J. Northw. Atl. Fish. Sci. 27: 107-118.

Koeller, P., M. Covey, and M. King. 2003a. An Assessment of the Eastern Scotian Shelf Shrimp Stock and Fishery for 2003. DFO Can. Sci. Advis. Sec. Res. Doc. 2003/005.

Koeller, P., L. Savard, D. Parsons, and C. Fu. 2000b. A Precautionary Approach to Assessment and Management of Shrimp Stocks in the Northwest Atlantic. J. Northw. Atl. Fish. Sci. 27: 235-247.

Koeller, P., M. Covey, and M. King. 2003b. Is Size at Transition a Measure of Growth or Abundance in Pandalid Shrimp? Fish. Res. 65: 217-230.

Koeller, P., C. Fuentes-Yaco, T. Platt, S. Sathyendranath, A. Richards, P. Ouellet, D. Orr, U. Skúladóttir, K. Wieland, L. Savard, and M. Aschan. 2009. Basin-scale coherence in phenology of shrimps and phytoplankton in the North Atlantic Ocean. Sci. 324: 791-793.

Koeller, P., C. Fuentes-Yaco, M. Covey, M. King, and B. Zisserson. 2011. The Last Traffic Light on the Scotian Shelf: Shrimp 2009-2010: An Assessment of the Eastern Scotian Shelf Shrimp Stock and Fishery in 2008 and Outlook for 2009. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/061.

Lilly, G.R., D.G. Parsons, and D.W. Kulka. 2000. Was the Increase in Shrimp Biomass on the Northeast Newfoundland Shelf a Consequences of a Release in Predation Pressure from Cod? J. Northw. Atl. Fish. Sci. 27: 45-61.

Lunn, D.J., Thomas, A., Best, N., Spiegelhalter, D. 2000. WinBUGS – A Bayesian Modelling Framework: Concepts, Structure, and Extensibility. Stat. Computing 10: 325-337.

Macdonald, P.D.M., and T.J. Pitcher. 1979. Age-groups from Size-frequency Data: A Versatile and Efficient Method of Analysing Distribution Mixtures. J. Fish. Res. Board Can. 36: 987-1001.

Millar R.B., and R. Meyer. 2000. Non-Linear state space modelling of fisheries biomass dynamics by using Metropolis-Hastings within-Gibbs Sampling. J. Royal Stat. Soc. C. 49: 327-342.

Mohn, R.J., and M.L. Etter. 1982. Review of the Scotian Shelf Shrimp Fishery. Can. Atl. Fish. Sci. Advis. Comm. Res. Doc. 82/16.

Mohn, R., J. Black, and P. Koeller. 2001. Traffic Light Indicators. BIO Review 2000. 88 p.

Ouellet, P., L. Savard, and P. Larouche. 2007. Spring Oceanographic Conditions and Northern Shrimp *Pandalus borealis* Recruitment Success in the North-western Gulf of St. Lawrence. Mar. Ecol. Prog. Ser. 339: 229-241.

R Development Core Team. 2005. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Roddick, D. 1994. Status of the Scotian Shelf Shrimp (*Pandalus borealis*) Fishery 1994. DFO Can. Atl. Fisheries Res. Doc. 95/22.

Shumway, S.E., H.C. Perkins, D.F. Schick, and A.P. Stickney. 1985. Synopsis of Biological Data on the Pink Ahrimp, *Pandalus borealis* Krøyer, 1838. NOAA Tech. Rept. NMFS 30.

Smith, S.J. 1997. Bootstrap Confidence Limits for Groundfish Trawl Survey Estimates of Mean Abundance. Can. J. Fish. Aquat. Sci. 54: 616-663.

Smith, S.J., H. Bourdages, J. Choi, E. Dawe, J.S. Dunham, L. Gendron, D. Hardie, M. Moriyasu, D. Orr, D. Roddick, D. Rutherford, B. Sainte-Marie, L. Savard, P. Shelton, D. Stansbury, M.J. Tremblay, and Z. Zhang. 2012. Technical Guidelines for the Provision of Scientific Advice on the Precautionary Approach for Canadian Fish Stocks: Section 7 – Invertebrate Species. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/117.

Worm, B., and R.A. Myers. 2003. Meta-analysis of Cod-shrimp Interactions Reveals Top-down Control in Oceanic Food Webs. Ecology 84:162−173.

TABLES

Table 1. Total allowable catches (TACs; trawls) and catches (trawls and traps) from the eastern Scotian Shelf shrimp fishery (SFAs 13-15), 1980-2014 (dashes indicate lack of data).

	TAC	TAC	Trawl Catch				Trap	Total
Year	Trawl	Trap	SFA 13	SFA 14	SFA 15	Total	Catch	Catch
1980	5021	-	491	133	360	984	-	984
1981	-	-	418	26	10	454	-	454
1982	4200	-	316	52	201	569	-	569
1983	5800	-	483	15	512	1010	-	1010
1984	5700	-	600	10	318	928	-	928
1985	5560	-	118	-	15	133	-	133
1986	3800	-	126	-	-	126	-	126
1987	2140	-	148	4	-	152	-	152
1988	2580	-	75	6	1	82	-	82
1989	2580	-	91	2	-	93	-	93
1990	2580	-	90	14	-	104	-	104
[1]1991	2580	-	81	586	140	804	-	804
1992	2580	-	63	1181	606	1850	-	1850
[2]1993	2650	-	431	1279	317	2044	-	2044
[3]1994	3100	-	8	2656	410	3074	-	3074
1995	3170	-	168	2265	715	3148	27	3175
1996	3170	-	55	2299	817	3171	187	3358
1997	3600	-	570	2422	583	3574	222	3797
1998	3800	-	562	2014	1223	3800	131	3931
1999	4800	200	717	1521	2464	4702	149	4851
2000	5300	200	473	1822	2940	5235	201	5436
2001	4700	300	692	1298	2515	4505	263	4768
2002	2700	300	261	1553	885	2699	244	2943
2003	2700	300	612	1623	373	2608	157	2765
2004	3300	200	2041	755	376	3172	96	3268
2005	4608	392	1190	1392	1054	3636	9	3645
2006	4608	392	846	1997	1111	3954	32	3986
2007	4820	200	267	2633	1678	4578	4	4582
2008	4912	100	349	2703	1265	4317	4	4321
2009	3475	25	298	2450	727	3475	2	3477
2010	4900	100	280	1846	2454	4580	1	4581
2011	4432	168	254	2340	1653	4247	111	4358
2012	3954	246	197	2296	1227	3693	199	3892
2013	3496	304	158	2514	708	3380	224	3604
2014[4]	4140	360	644	2259	996	3919	122	4041
2014[5]	4140	360	697	2444	999	4140	360	4500

Notes:

[1] Nordmøre separator grate introduced.
[2] Overall TAC not caught because TAC for SFAs 14 and 15 was exceeded.
[3] Individual SFA TACs combined.
[4] Current year to date (November 27, 2014).
[5] Current year prorated to total TAC.

Table 2. Number of active vessels and total licences (in brackets) for the ESS shrimp fishery.

	Trap	**Trawl**	
Year	**Scotia-Fundy**[1]	**Scotia-Fundy**[2]	**Gulf**[3]
1995	4	24(23)	6(23)
1996	9(17)	21(24)	6(23)
1997	10(17)	18(23)	6(23)
1998	15(26)	17(28)[4]	10(23)[5]
1999	15(22)	19(28)[4]	10(23)[5]
2000	12(21)	18(32)[6]	10(23)[5]
2001	10(28)	18(28)[4]	10(23)[5]
2002	10(14)[7]	15(23)	6(23)
2003	9(14)	14(23)	5(23)
2004	6(14)	14(23)	6(23)
2005	2(14)	20(28)[8]	7(24)[9]
2006	5(14)	18(28)	7(24)
2007	2(14)	20(28)	7(24)
2008	1(14)	18(28)	7(24)
2009	1(14)	17(28)	6(14)[10]
2010	3(14)	18(28)	7(14)
2011	7(14)	15(28)	5(14)
2012	8(14)	12(28)	5(14)
2013	11(14)	13(28)	6(14)
2014	7(14)	9(28)	5(14)

Notes:

[1] All but one active trap licences are vessels <45'. They receive about 8% of the TAC.
[2] These vessels receive about 70% of the TAC according to the management plan. Inactive NAFO 4X licences (15) not included in total.
[3] All licences 65-100' length over all (LOA). Eligibility to fish in Scotia-Fundy for about 23% of the TAC.
[4] Temporary allocation divided among 5 vessels.
[5] Temporary allocation divided among 4 vessels.
[6] Temporary allocation divided among 9 licences.
[7] Nine (9) licences were made permanent for 2002. The reduction in the total number of trap licences is due to cancellation of some non-active exploratory licences.
[8] Five (5) temporary licences made permanent.
[9] One (1) temporary licence made permanent.
[10] The previously reported number of licenses included (10) that were invalid for a number of reasons. The number of valid licenses was updated in 2009.

Table 3. Observer coverage statistics for the ESS shrimp fishery from 2004-2014. (Note: In was no observer coverage in 2007.)

Year	Trips Observed	Sets Observed	Fishing Hours Observed	Shrimp Catch (MARFIS, kg)	Shrimp Catch (Observer, kg)	SFA Covered
2004	3	40	133	47,455	45,895	13,14,15
2005	3	51	211	72,914	71,761	14,15
2006	3	35	110	71,020	68,107	14,15
2007	0	0	0	0	0	0
2008	2	36	126	101,009	103,316	14,15
2009	3	35	138	64,096	62,933	14,17
2010	7	87	311	98,201	99,275	13,14,15,17
2011	2	31	150	67,639	67,858	14,15
2012	3	55	211	101,025	108,174	14,15,17
2013	1	13	67	45,661	47,865	14
2014	2	21	83	39,013	37,981	14,17
Total	**29**	**404**	**1540**	**708,033**[1]	**713,165**[1]	

[1] The difference between the MARFIS and Observer shrimp weight could be due to the 1% “bag allowance”.

Table 4. Fish and shellfish bycatch by year recorded on all observed trips on the ESS from 2004-2014 relative to the shrimp catch, number of tows and summarized by season (all years). Dash (-) cells indicates none caught.

	TOTAL CATCH		**ANNUAL BYCATCH AND (# of tows)**										**SEASON**	
SPECIES	**Weight (kg)**	**total %**	**2004 (40)**	**2005 (51)**	**2006 (35)**	**2008 (36)**	**2009 (35)**	**2010 (87)**	**2011 (31)**	**2012 (55)**	**2013 (13)**	**2014 (21)**	**Spring (337)**	**Fall (67)**
SHRIMP	***708033***	***98.22%***	***97.95%***	***97.23%***	***98.96%***	***99.45%***	***99.04%***	***96.89%***	***97.81%***	***98.33%***	***99.29%***	***97.21%***	***98.33%***	***97.34%***
HERRING(ATLANTIC)	2947	0.41%	0.13%	0.53%	0.03%	0.01%	0.18%	0.61%	0.70%	0.25%	0.02%	2.43%	0.38%	0.62%
SILVER HAKE	2396	0.33%	0.05%	0.01%	0.48%	-	-	1.37%	0.09%	0.52%	0.07%	0.01%	0.26%	0.97%
WITCH FLOUNDER	1656	0.23%	0.39%	0.59%	0.18%	0.08%	0.21%	0.14%	0.32%	0.18%	0.26%	0.02%	0.24%	0.12%
AMERICAN PLAICE	1487	0.21%	<0.01%	0.75%	0.05%	0.09%	0.22%	0.22%	0.33%	0.16%	0.09%	0.01%	0.20%	0.22%
REDFISH UNSEPARATED	886	0.12%	0.07%	0.36%	0.04%	0.11%	0.05%	0.21%	0.16%	0.04%	0.08%	0.01%	0.11%	0.22%
TURBOT,GREENLAND HALIBUT	691	0.10%	0.87%	0.09%	0.01%	-	0.02%	0.04%	0.14%	0.03%	0.02%	0.01%	0.10%	0.08%
EELPOUTS (NS)	651	0.09%	0.04%	0.21%	0.04%	0.01%	0.05%	0.06%	0.34%	0.10%	-	0.01%	0.10%	0.05%
CAPELIN	570	0.08%	0.02%	0.07%	0.03%	0.13%	0.12%	0.21%	0.01%	0.05%	-	0.01%	0.06%	0.24%
BLENNIES (NS)	228	0.03%	-	0.01%	0.03%	0.09%	0.01%	0.03%	0.04%	-	0.10%	-	0.03%	<0.01%
SQUID (NS)	229	0.03%	0.07%	0.01%	0.01%	-	-	0.01%	<0.01%	0.16%	-	-	0.03%	0.01%
ALEWIFE	210	0.03%	<0.01%	<0.01%	<0.01%	-	0.03%	0.04%	-	0.04%	-	0.26%	0.03%	0.04%
WINTER FLOUNDER	147	0.02%	0.29%	-	-	-	-	-	0.01%	-	-	-	0.02%	-
ROCKLING (NS)	112	0.02%	-	-	<0.01%	0.01%	0.01%	0.02%	-	0.06%	0.04%	-	0.02%	0.01%
THORNY SKATE	95	0.01%	0.01%	0.03%	-	0.01%	0.01%	0.03%	-	0.02%	0.01%	<0.01%	0.01%	0.02%
ATLANTIC SEA POACHER	64	0.01%	-	0.05%	0.01%	-	0.02%	0.01%	-	<0.01%	-	-	0.01%	-
ALLIGATORFISH	43	0.01%	-	<0.01%	0.02%	0.02%	-	0.01%	-	-	-	-	0.01%	0.01%
SNOW CRAB (QUEEN)	41	0.01%	0.01%	0.01%	0.01%	-	0.01%	<0.01%	-	0.01%	<0.01%	-	0.01%	<0.01%
SKATES (NS)	40	0.01%	-	-	0.02%	-	-	0.01%	-	0.02%	-	-	0.01%	<0.01%
OCEAN POUT(COMMON)	34	<0.01%	-	<0.01%	0.05%	-	-	-	-	-	-	-	0.01%	-
SAND LANCES (NS)	32	<0.01%	<0.01%	<0.01%	-	-	0.01%	0.01%	0.02%	-	-	0.01%	<0.01%	<0.01%
DAUBED SHANNY	29	<0.01%	-	-	-	-	-	0.01%	0.02%	-	-	-	<0.01%	0.01%
AMERICAN EEL	28	<0.01%	0.05%	-	<0.01%	-	-	-	-	-	-	-	<0.01%	-
YELLOWTAIL FLOUNDER	26	<0.01%	0.01%	0.01%	<0.01%	-	<0.01%	0.01%	-	-	-	-	<0.01%	0.01%
SEA CUCUMBERS	23	<0.01%	-	-	-	-	-	-	-	0.02%	-	-	<0.01%	-
WHITE BARRACUDINA	22	<0.01%	-	<0.01%	-	-	<0.01%	0.01%	0.02%	-	-	-	<0.01%	0.01%
COD(ATLANTIC)	21	<0.01%	<0.01%	<0.01%	<0.01%	-	-	0.01%	-	<0.01%	-	-	<0.01%	0.01%
MARLIN-SPIKE	17	<0.01%	-	-	-	-	-	0.02%	-	-	-	-	<0.01%	-
SCULPINS (NS)	15	<0.01%	0.02%	<0.01%	-	-	-	<0.01%	-	<0.01%	-	-	<0.01%	<0.01%
RHODICHTHYS SPP.	14	<0.01%	-	-	-	-	0.01%	<0.01%	-	-	-	-	<0.01%	-
SQUIRREL OR RED HAKE	10	<0.01%	-	0.01%	-	-	-	<0.01%	-	<0.01%	-	-	<0.01%	-
WRYMOUTH	8	<0.01%	-	-	<0.01%	-	0.01%	<0.01%	-	-	-	-	<0.01%	<0.01%
WHITE HAKE	8	<0.01%	<0.01%	-	0.01%	-	-	<0.01%	-	-	-	-	<0.01%	-
STRIPED ATLANTIC WOLFFISH	6	<0.01%	-	<0.01%	-	-	<0.01%	<0.01%	-	-	-	-	<0.01%	<0.01%
POLLOCK	4	<0.01%	-	-	-	-	-	<0.01%	-	-	-	<0.01%	<0.01%	<0.01%
TOAD CRAB, UNIDENT.	4	<0.01%	-	-	<0.01%	-	<0.01%	<0.01%	-	-	-	-	<0.01%	-
ATLANTIC WOLFFISH	3	<0.01%	-	-	<0.01%	-	-	<0.01%	-	<0.01%	-	-	<0.01%	<0.01%
MACKEREL(ATLANTIC)	3	<0.01%	-	-	-	-	-	-	<0.01%	<0.01%	-	-	<0.01%	-
ARISTOSTOMIAS POLYDACTYLUS	2	<0.01%	-	-	-	-	-	-	-	<0.01%	-	-	<0.01%	-
SPONGES	2	<0.01%	-	-	<0.01%	-	-	-	-	-	-	-	<0.01%	-
ATLANTIC SAURY,NEEDLEFISH	2	<0.01%	<0.01%	-	-	-	-	-	-	-	-	-	<0.01%	-
HADDOCK	2	<0.01%	-	-	-	-	-	-	-	<0.01%	-	<0.01%	<0.01%	-
ASTEROIDEA S.C.	1	<0.01%	<0.01%	-	-	-	-	-	-	-	-	-	<0.01%	-
ATLANTIC HAGFISH	1	<0.01%	-	-	-	-	-	<0.01%	-	-	-	-	-	<0.01%
ATLANTIC HALIBUT	1	<0.01%	-	-	<0.01%	-	-	-	-	-	-	-	<0.01%	-

	TOTAL CATCH		ANNUAL BYCATCH AND (# of tows)										SEASON	
SPECIES	**Weight (kg)**	**total %**	**2004 (40)**	**2005 (51)**	**2006 (35)**	**2008 (36)**	**2009 (35)**	**2010 (87)**	**2011 (31)**	**2012 (55)**	**2013 (13)**	**2014 (21)**	**Spring (337)**	**Fall (67)**
FISH DOCTOR	1	<0.01%	-	<0.01%	-	-	-	-	-	-	-	-	<0.01%	-
HERMIT CRAB	1	<0.01%	-	-	-	-	-	<0.01%	-	-	-	-	-	<0.01%
MONKFISH	1	<0.01%	-	-	<0.01%	-	-	-	-	-	-	-	<0.01%	-
NORTHERN WOLFFISH	1	<0.01%	-	-	<0.01%	-	-	-	-	-	-	-	<0.01%	-
SEASNAILS	1	<0.01%	-	-	-	-	-	<0.01%	-	-	-	-	-	<0.01%
SEA SCALLOP	<1	<0.01%	<0.01%	-	-	-	-	-	-	-	-	-	<0.01%	-
CUSK	<1	<0.01%	<0.01%	-	-	-	-	-	-	-	-	-	<0.01%	-
GRAND TOTAL	***720849***	***100%***	***100%***	***100%***	***100%***	***100%***	***100%***	***100%***	***100%***	***100%***	***100%***	***100%***	***100%***	***100%***
% BYCATCH		**1.78%**	**2.05%**	**2.77%**	**1.04%**	**0.55%**	**0.96%**	**3.11%**	**2.19%**	**1.67%**	**0.71%**	**2.79%**	**1.67%**	**2.66%**

Notes:

SHRIMP (weight landed) includes *P. borealis*; *P. montagui*; Crangon.
EELPOUTS(NS) includes; Short Tailed Eelpout(vahl) and Pale Eelpout.
BLENNIES (NS) includes; Snake Blenny; *blenniidae sp.*; eel-unidentified.
SQUID (NS) includes; Short-fin; Longfin Squid; Longfin Inshore; Northern Shortfin Ssquid.
SCULPINS (NS) includes; Ribbed Sculpin; nybelini sculpin.
ROCKLINGS (NS) includes; Threebeard Rockling; Fourbeard Rockling.
SKATES (NS) includes; Smooth Skate.
Weights may be overestimated due to data collection restrictions (minimum recorded weight is 1 kg).

Table 5. The history of survey vessels, survey trawls/modifications and comparative fishing of the ESS shrimp survey.

Year	**Vessel**	**Trawl**	**Trawl Performance/comparative Fishing Notes or References**
1982-88	*FRV EE Prince*	Yankee 36	None
1993	*W.A. Moore* *April & Colette*	Commercial	None
1995	*Cody & Kathryn*	Commercial	None
1996	*Lady Megan II*	Commercial	Comparative fishing with *Cody& Kathyrn*/commercial net (Koeller et al. 1997)
1997	*Miss Marie*	Survey trawl A (Nordsea)	Comparative fishing with *Cody& Kathyrn*/commercial net (Koeller et al. 1997)
1998	*Cody & Kathryn*	Survey trawl A	None
1999-01	*Carmel VI* (named *Amelie Zoe* in 1999)	Survey trawl A	None
2002-03	*All Seven*	Survey Trawl B (Pescatrawl)	None
2004-08	*All Seven*	Survey Trawl C (new in 2004)	Declining grate angle over time detected in 2008 as resulting in low catches (see Koeller et al. 2011)
2009	*Cody & Kathryn*	Survey trawl C	Capt. Shrader brought grate angle back to specifications. Protocol added to have trawl inspected annually (Koeller et al. 2011)
2010	*Cody & Kathryn*	Survey trawl C	Pre-survey inspection by Capt. Shrader, DFO and IMP
2011	*Cody & Kathryn*	Survey trawl D	Pre-survey inspection by Capt. Shrader and IMP. Chafer length adjustment to new trawl during survey (to match trawl C). Stations from first trip repeated.
2012	*Cody & Kathryn*	Survey trawl D	Pre-survey inspection by Capt. Shrader and IMP. Capt. Shrader observed that net not taking bottom well in deep water when the tide was strong. Weight addition suggested (discussed herein)
2013	*Cody & Kathryn*	Survey trawl D	Pre-survey inspection by Capt. Shrader and IMP. Survey completed with weight added to doors and footgear. 16 stations repeated without additional weight (discussed herein)
2014	*Cody & Kathryn*	Survey trawl D	Pre-survey inspection by Capt. Shrader and IMP. Survey completed with heavier trawl.

Table 6. Comparative fishing results of weighted and unweighted trawl configurations during the 2013 ESS shrimp survey.

Station	Stratum	Warp (Fathoms.)	Avg. Depth (Fathoms)	Standardised Heavy Trawl Catch (kg)	Standardised Light Trawl Catch (kg)	Heavy/Light Trawl Catch Ratio	Heavy Trawl Juvenile Catch (#s)	Light Trawl Juvenile Catch (#s)
4	15	350	116	112.00	241.52	46%	2	1
5	15	325	107	76.09	76.74	99%	6	0
9	15	375	127	83.41	87.29	96%	40	77
11	15	375	133	263.02	192.27	137%	9	14
24	14	375	123	837.49	757.66	111%	0	0
26	14	450	145	293.95	456.17	64%	0	0
14	17	375	120	206.13	177.66	116%	11	8
54	17	325	105	237.62	185.74	128%	0	1
42	13	450	147	267.71	218.24	123%	0	1
43	13	400	132	167.57	185.10	91%	0	0
36	13	500	162	249.34	128.22	194%	0	0
35	13	500	207	36.65	58.21	63%	0	0
28	14	425	136	535.81	534.35	100%	0	2
27	14	425	139	24.70	20.48	121%	0	0
47	17	350	127	555.24	450.06	123%	33	13
48	17	275	088	401.68	290.93	138%	31	19
Average				**271.78**	**253.79**	**109%**	**8.3**	**8.5**

Table 7. Set statistics from DFO-industry survey CK1401 conducted by motor vessel (MV) Cody & Kathryn from 1-12 June 2014.

SET	SFA	DATE	LAT.	LONG.	SPEED (kts)	DIST. (n.m.)	DUR. (min)	WING. (m)	DEPTH (fth)	TEMP (°C)	RAW CATCH (kg)	STAND. CATCH (kg)	DENSITY (gm/m2 or m.t./km2)
1	15	01-Jun-14	445940	605870	2.67	1.22	30	17.17	104.57	2.37	22.68	23.53	0.58
2	15	01-Jun-14	445652	610178	2.72	1.31	30	16.72	105.57	2.25	48.99	48.78	1.21
3	15	01-Jun-14	445417	610375	2.67	1.31	30	16.99	110.29	2.28	82.55	80.59	2.00
4	15	01-Jun-14	445340	605812	2.62	1.19	30	17.92	134.29	2.26	175.45	179.55	4.46
5	15	02-Jun-14	444817	605615	2.53	1.06	30	16.36	136.14	2.33	53.52	66.90	1.66
6	15	02-Jun-14	445603	604637	2.50	1.18	30	17.51	120.57	2.62	151.05	158.82	3.94
7	15	02-Jun-14	445035	604076	2.25	1.16	30	17.37	156.14	3.23	112.72	121.28	3.01
8	15	02-Jun-14	444683	603692	2.44	1.18	30	17.67	127.00	3.30	37.56	39.10	0.97
9	15	02-Jun-14	445676	602762	2.67	1.31	30	17.67	133.43	3.76	80.74	75.95	1.89
10	15	02-Jun-14	445478	602344	2.56	1.16	30	17.51	129.43	3.87	231.70	247.86	6.15
11	15	02-Jun-14	445009	602189	2.55	1.18	30	17.58	164.43	3.98	69.85	73.12	1.82
12	15	02-Jun-14	444928	601633	2.41	1.21	30	17.09	163.43	3.88	35.38	37.17	0.92
13	15	03-Jun-14	445518	601166	2.37	1.18	30	17.59	142.86	3.81	281.23	294.46	7.31
14	15	03-Jun-14	445786	600828	2.40	1.22	30	17.08	118.43	3.64	220.45	229.62	5.70
15	15	03-Jun-14	445470	595846	2.48	1.19	30	16.86	105.71	4.02	230.43	249.12	6.18
16	14	03-Jun-14	444831	595825	2.57	1.20	30	16.59	133.00	4.23	91.99	100.48	2.49
17	14	03-Jun-14	444062	600737	2.38	1.16	30	16.54	103.00	4.43	60.78	68.84	1.71
18	14	03-Jun-14	444154	600079	2.24	1.09	30	16.98	116.43	4.70	93.89	109.96	2.73
19	14	03-Jun-14	444320	594712	2.62	1.28	30	18.27	139.29	4.47	256.74	238.91	5.93
20	14	03-Jun-14	444153	593595	2.29	1.14	30	17.11	115.57	4.17	184.39	205.63	5.10
21	14	04-Jun-14	445610	581975	2.48	1.16	30	17.35	139.00	3.76	464.48	502.89	12.48
22	14	04-Jun-14	445055	583181	2.54	1.23	30	17.47	138.17	3.47	258.82	263.05	6.53
23	14	04-Jun-14	444768	583798	2.60	1.26	30	17.40	139.43	3.57	223.17	221.73	5.50
24	14	04-Jun-14	445608	584304	2.52	1.20	30	17.69	142.29	3.17	541.50	556.64	13.82
25	14	04-Jun-14	444768	585328	2.50	1.20	30	17.57	144.86	3.30	396.90	409.01	10.15
26	14	04-Jun-14	445145	590318	2.43	1.17	30	17.29	128.57	3.06	415.04	445.70	11.06
27	14	04-Jun-14	444755	591130	2.43	1.21	30	17.08	124.71	3.07	279.42	293.31	7.28
28	14	05-Jun-14	443858	590260	2.51	1.25	30	17.31	117.29	2.96	279.51	281.56	6.99
29	14	05-Jun-14	445107	592792	2.54	1.19	30	17.57	141.71	3.72	381.02	395.01	9.81
30	14	05-Jun-14	445120	594204	2.39	1.18	30	17.24	122.71	4.11	571.17	608.51	15.11
31	17	09-Jun-14	451530	595534	2.51	1.18	30	17.03	105.86	2.95	917.54	996.54	24.74
32	17	09-Jun-14	451827	594767	2.46	1.24	30	16.55	74.14	2.44	3.63	3.85	0.10
33	17	09-Jun-14	452126	595370	2.41	1.22	30	16.55	82.00	2.69	166.20	179.48	4.46
34	17	09-Jun-14	452743	594376	2.61	1.19	30	16.55	71.57	2.48	0.00	0.00	0.00
35	17	09-Jun-14	452465	595780	2.34	1.15	30	16.33	91.43	3.18	119.21	137.74	3.42
36	17	09-Jun-14	452831	600317	2.31	1.35	30	16.92	97.29	3.12	95.26	90.53	2.25
37	17	09-Jun-14	453417	600517	2.37	1.25	30	17.28	97.57	2.75	1242.86	1247.02	30.96
38	17	09-Jun-14	453683	595958	2.40	1.21	30	17.65	94.29	2.76	542.32	552.88	13.73
39	13	10-Jun-14	453651	584011	2.36	1.20	30	17.99	161.14	4.33	103.42	104.23	2.59
40	13	10-Jun-14	453507	583505	2.43	1.19	30	17.47	138.14	4.11	163.02	169.84	4.22
41	13	10-Jun-14	453233	582894	2.20	1.06	30	17.21	139.00	4.26	251.66	299.21	7.43
42	13	10-Jun-14	453397	582090	2.30	1.16	30	15.83	203.14	4.60	82.10	96.85	2.40
43	13	10-Jun-14	454047	581950	2.21	1.14	30	16.49	201.50	4.48	53.52	62.16	1.54
44	13	10-Jun-14	454079	582818	2.51	1.23	30	16.30	205.57	4.70	65.32	71.09	1.76
45	13	10-Jun-14	454778	583130	2.30	1.21	30	17.49	163.00	4.98	403.25	416.00	10.33
46	13	10-Jun-14	454705	583537	2.32	1.17	30	17.94	163.57	5.01	241.31	250.79	6.23
47	13	11-Jun-14	454645	583988	2.29	1.15	30	17.44	154.71	4.99	122.47	132.37	3.29
48	13	11-Jun-14	455074	584991	2.37	1.21	30	17.37	134.29	4.83	270.34	279.15	6.93
49	13	11-Jun-14	454771	585745	2.45	1.20	30	17.35	129.29	4.78	305.00	318.10	7.90
50	13	11-Jun-14	454440	590030	2.57	1.26	30	17.45	138.71	4.75	414.86	411.36	10.21
51	13	11-Jun-14	454298	585611	2.37	1.13	30	17.48	138.71	4.79	160.57	176.12	4.37
52	13	11-Jun-14	454213	585126	2.78	1.23	30	17.55	132.43	4.76	143.79	145.17	3.60
53	13	11-Jun-14	453709	590463	2.67	1.16	30	17.67	142.14	4.68	120.66	128.04	3.18
54	17	12-Jun-14	452878	602425	2.13	1.15	30	16.71	118.57	2.87	271.34	308.25	7.65
55	17	12-Jun-14	453321	602851	2.31	1.33	30	16.43	84.86	2.62	616.26	613.13	15.22
56	17	12-Jun-14	452977	603177	2.58	1.20	30	17.24	95.86	2.86	922.07	971.05	24.11
57	17	12-Jun-14	452925	603731	2.59	1.26	30	15.93	81.00	2.50	384.56	416.34	10.34
58	17	12-Jun-14	452634	603460	2.50	1.27	30	15.81	88.57	2.72	500.41	540.39	13.42
59	17	12-Jun-14	452552	604165	2.46	1.24	30	15.56	76.29	2.36	458.50	517.32	12.84
60	17	12-Jun-14	452259	605979	2.42	1.26	30	16.73	58.71	0.92	151.54	156.82	3.89

Table 8. Input data for Traffic Light Analysis.

Year	RV_CPUE	G_CPUE	St_CPUE	RV_CV	Comm_area	RVSSB	BB_1	RV_2	RV_4	sex_mm	max_mm	pred	count	Exp_tot	Exp_fem	fem_prop	fem_size	pop_even	Rvtemp	Spring SST	Capelin	Cod_R	G_halibut	snow_c
1982	34.50	128.00	NAN	89.06	NAN	5040.65	NAN	NAN	NAN	21.46	28.24	179.29	NAN	NAN	NAN	NAN	NAN	0.81	NAN	NAN	NAN	2.38	0.00	NAN
1983	71.50	127.70	NAN	78.52	NAN	7323.05	NAN	NAN	NAN	21.80	28.03	164.05	NAN	NAN	NAN	NAN	NAN	0.77	NAN	2.78	NAN	2.42	0.00	NAN
1984	39.00	109.50	NAN	75.84	NAN	4460.96	NAN	NAN	NAN	22.17	27.69	353.25	NAN	NAN	NAN	NAN	NAN	0.73	NAN	0.48	NAN	5.57	0.06	NAN
1985	17.00	75.40	NAN	83.09	NAN	2417.71	NAN	NAN	NAN	21.77	27.87	236.37	NAN	NAN	NAN	NAN	NAN	0.75	NAN	-0.07	1.55	1.71	0.05	NAN
1986	23.00	87.30	NAN	106.13	NAN	3187.87	NAN	NAN	NAN	23.63	27.94	144.33	NAN	NAN	NAN	NAN	NAN	0.74	NAN	-0.77	0.13	0.37	0.09	NAN
1987	25.50	90.70	NAN	67.53	NAN	3424.46	NAN	NAN	NAN	23.16	27.94	187.04	NAN	NAN	NAN	NAN	NAN	0.79	NAN	-1.32	0.77	0.87	0.16	NAN
1988	31.50	85.10	NAN	60.14	NAN	4047.02	NAN	NAN	NAN	23.84	28.12	142.81	NAN	NAN	NAN	NAN	NAN	0.76	NAN	-0.92	0.17	1.19	0.06	NAN
1989	NAN	133.40	NAN	NAN	NAN	NAN	NAN	NAN	NAN	NAN	NAN	66.58	NAN	NAN	NAN	NAN	NAN	NAN	NAN	-1.07	18.38	1.75	0.00	NAN
1990	NAN	134.50	NAN	NAN	NAN	NAN	NAN	NAN	NAN	NAN	NAN	67.33	NAN	NAN	NAN	NAN	NAN	NAN	NAN	-1.02	9.23	1.16	0.00	NAN
1991	NAN	197.90	NAN	NAN	NAN	NAN	NAN	NAN	NAN	NAN	NAN	46.91	NAN	NAN	NAN	NAN	NAN	NAN	NAN	-0.77	5.07	0.17	0.46	NAN
1992	NAN	176.30	NAN	NAN	NAN	NAN	NAN	NAN	NAN	NAN	NAN	32.10	NAN	NAN	NAN	NAN	NAN	NAN	NAN	-1.72	34.88	0.17	0.08	NAN
1993	75.00	187.89	142.20	80.33	31.00	NAN	NAN	NAN	NAN	23.78	30.45	68.53	NAN	NAN	NAN	NAN	NAN	NAN	NAN	-2.07	193.36	0.29	1.86	NAN
1994	NAN	213.52	188.40	NAN	48.00	NAN	NAN	NAN	NAN	NAN	NAN	66.17	NAN	NAN	NAN	0.89	26.05	NAN	NAN	-1.52	1563.89	0.30	1.98	NAN
1995	173.02	187.02	181.17	82.84	71.00	10912.15	NAN	358.50	875.92	24.05	29.27	66.52	55.92	13.44	21.04	0.72	26.03	0.83	1.59	-1.17	138.62	0.54	1.74	NAN
1996	213.92	244.58	224.35	64.88	99.00	13368.38	NAN	307.34	1247.63	24.73	29.99	32.56	54.47	11.50	16.11	0.68	26.01	0.83	1.72	-0.92	87.53	0.16	4.78	NAN
1997	193.00	236.26	218.89	53.46	146.00	12100.80	NAN	128.85	1257.47	24.94	29.78	35.85	56.35	14.41	19.08	0.64	26.44	0.80	2.74	-0.47	146.64	0.40	2.91	6588.78
1998	238.38	343.73	298.94	74.42	209.00	15707.48	NAN	39.89	1883.71	24.33	29.51	59.87	53.22	12.08	14.73	0.60	25.68	0.78	1.97	-0.06	284.31	0.31	0.41	8446.24
1999	268.40	395.70	325.53	72.20	258.00	17607.48	NAN	165.63	3010.18	24.08	29.31	64.13	55.30	13.24	16.90	0.63	25.46	0.75	3.24	-0.50	159.96	1.39	1.67	10482.22
2000	233.36	383.66	365.48	72.00	242.00	15893.36	NAN	280.34	0.00	24.74	29.74	76.29	55.19	17.06	19.79	0.58	25.57	0.78	3.60	0.07	32.38	0.79	11.44	5128.69
2001	183.32	428.24	443.46	126.03	221.00	14475.58	NAN	174.90	1184.11	24.29	29.19	73.28	54.70	19.05	19.56	0.63	25.15	0.79	2.36	-0.55	15.99	1.58	3.66	4664.29
2002	161.40	572.36	523.48	111.15	192.00	14133.20	980.00	134.00	399.17	24.45	29.02	57.30	52.53	14.17	13.43	0.70	25.61	0.78	2.77	-0.09	49.85	0.32	3.88	2212.31
2003	204.42	675.41	520.72	104.48	265.00	16916.16	196.00	576.74	1411.07	24.31	29.05	100.65	53.48	9.83	10.91	0.73	25.68	0.84	2.69	-1.30	2.70	1.03	6.69	1656.46
2004	353.70	793.14	549.32	78.00	263.00	26856.47	316.00	354.09	839.46	24.13	29.44	57.46	54.96	6.75	9.48	0.80	25.41	0.80	1.99	-0.43	5.93	0.64	3.44	1248.30
2005	312.90	683.25	496.53	83.01	364.00	18587.50	198.00	187.02	4502.48	23.63	29.46	99.05	58.93	8.20	13.05	0.66	25.72	0.73	2.41	0.47	99.41	0.25	14.00	1500.56
2006	275.20	716.40	614.86	75.86	296.00	16288.53	61.00	121.30	0.00	23.39	29.35	77.47	63.23	10.55	13.57	0.55	25.96	0.75	3.62	1.03	5.78	0.80	18.92	3012.34
2007	281.20	696.62	507.79	66.34	389.00	18345.54	194.00	39.00	0.00	23.67	29.07	51.64	65.30	11.92	12.28	0.45	25.70	0.73	2.30	-0.73	8.45	0.29	7.77	5482.42
2008	226.10	664.07	520.17	72.25	423.00	12119.42	484.11	134.72	1046.18	23.84	28.57	92.82	61.52	13.98	20.50	0.52	24.98	0.73	1.96	0.03	1.36	1.24	6.51	6145.07
2009	333.10	648.76	628.16	91.70	324.00	24853.59	566.52	304.05	463.00	24.21	28.74	55.35	57.56	7.65	9.37	0.72	25.06	0.77	2.59	-0.61	0.21	0.57	5.42	4424.86
2010	273.00	536.23	465.57	105.47	350.00	21706.69	205.08	188.00	1036.00	24.53	28.87	70.88	57.77	12.31	15.45	0.74	25.20	0.80	2.35	1.54	11.06	0.16	2.55	6264.81
2011	223.60	671.18	456.36	78.89	320.00	16823.67	97.34	85.22	1044.08	24.27	28.51	149.12	61.34	14.28	18.61	0.71	25.19	0.77	2.99	0.72	0.57	0.93	1.96	4912.83
2012	205.30	552.28	496.05	66.78	294.00	14762.95	124.76	273.22	1022.00	23.88	29.01	31.80	59.61	15.01	18.93	0.72	25.22	0.79	4.20	0.43	1.25	0.65	1.37	4436.99
2013	287.60	626.68	672.22	91.88	337.00	20679.51	24.92	302.00	1693.00	23.79	29.11	101.00	59.30	9.64	13.27	0.74	25.56	0.76	3.04	0.40	0.17	1.94	1.17	3363.25
2014	**284.30**	**417.43**	**478.84**	**91.86**	**342.00**	**20358.62**	**789.32**	**125.00**	**0.00**	**24.29**	**28.97**	**115.00**	**55.54**	**9.80**	**14.56**	**0.70**	**25.72**	**0.77**	**3.64**	**-0.35**	**0.10**	**0.04**	**3.27**	**3214.33**

Note: NAN = not a number.

Table 9. Correlation matrix of Traffic Light Indicators (1982-2014 data) used in the ESS shrimp stock assessment.

indicator	**nrm_cpue**	survey	gfcpue	stcpue	rvcv	area	ssb	bb	rv2	rv4	sexmm	maxmm	pred	count	exp	femexp	femprop	femsize	popeven	botemp	surtemp	Capelin	Cod	turbot	Crab
nrm_cpue	**1**	0.54	0.67	0.56	-0.23	0.00	0.33	-0.10	0.13	0.17	-0.46	0.38	-0.13	0.13	-0.56	-0.44	0.08	0.04	-0.15	-0.33	-0.05	0.13	0.18	0.33	-0.23
survey	***0.54***	**1**	0.21	0.21	-0.13	0.21	0.59	0.00	0.13	-0.01	-0.31	0.33	-0.03	0.03	-0.77	-0.44	0.16	0.04	-0.21	-0.18	-0.05	-0.08	-0.13	0.08	-0.13
gfcpue	***0.67***	0.21	**1**	0.38	-0.31	-0.08	0.10	-0.23	-0.05	0.09	-0.38	0.36	-0.05	0.21	-0.28	-0.36	-0.11	0.17	-0.21	-0.36	-0.08	0.36	0.15	0.51	-0.26
stcpue	***0.56***	0.21	0.38	**1**	-0.05	-0.13	0.10	-0.03	0.26	-0.01	-0.23	0.26	-0.15	0.00	-0.38	-0.41	0.11	-0.04	0.01	-0.15	-0.23	0.00	0.36	0.21	-0.21
rvcv	***-0.23***	-0.13	-0.31	-0.05	**1**	-0.15	0.23	0.26	0.18	0.12	0.56	0.03	0.18	-0.59	-0.05	-0.13	0.45	0.01	0.43	0.08	0.00	0.03	-0.13	-0.18	-0.18
area	***0.00***	0.21	-0.08	-0.13	-0.15	**1**	0.00	-0.08	-0.36	0.14	-0.23	-0.10	0.10	0.41	0.03	0.15	-0.32	-0.09	-0.54	-0.31	0.08	-0.15	-0.05	0.10	0.41
ssb	***0.33***	0.59	0.10	0.10	0.23	0.00	**1**	0.15	0.23	-0.01	0.10	0.23	0.03	-0.28	-0.62	-0.44	0.53	0.01	0.21	-0.23	-0.10	-0.03	-0.23	-0.08	-0.13
bb	***-0.10***	0.00	-0.23	-0.03	0.26	-0.08	0.15	**1**	0.00	-0.25	0.38	-0.10	-0.15	-0.46	-0.08	-0.10	0.00	-0.12	0.10	-0.26	-0.23	0.10	-0.41	0.05	-0.10
rv2	***0.13***	0.13	-0.05	0.26	0.18	-0.36	0.23	0.00	**1**	0.33	0.21	0.08	-0.13	-0.44	-0.31	-0.23	0.47	-0.17	0.54	-0.03	-0.15	-0.03	0.18	-0.13	-0.23
rv4	***0.17***	-0.01	0.09	-0.01	0.12	0.14	-0.01	-0.25	0.33	**1**	-0.09	0.01	0.33	-0.01	-0.09	0.07	0.26	-0.26	0.08	-0.14	0.17	0.04	0.43	-0.14	-0.04
sexmm	***-0.46***	-0.31	-0.38	-0.23	0.56	-0.23	0.10	0.38	0.21	-0.09	**1**	-0.31	0.05	-0.51	0.18	0.00	0.37	-0.27	0.57	0.00	-0.13	-0.05	-0.21	-0.31	0.05
maxmm	***0.38***	0.33	0.36	0.26	0.03	-0.10	0.23	-0.10	0.08	0.01	-0.31	**1**	-0.03	-0.13	-0.46	-0.44	0.05	0.55	-0.01	-0.08	-0.05	0.33	-0.13	0.33	-0.54
pred	***-0.13***	-0.03	-0.05	-0.15	0.18	0.10	0.03	-0.15	-0.13	0.33	0.05	-0.03	**1**	-0.03	-0.10	0.18	0.13	0.06	-0.01	0.18	0.15	-0.28	0.18	-0.13	-0.08
count	***0.13***	0.03	0.21	0.00	-0.59	0.41	-0.28	-0.46	-0.44	-0.01	-0.51	-0.13	-0.03	**1**	0.21	0.28	-0.45	-0.06	-0.57	-0.03	0.26	0.03	0.18	0.08	0.44
exp	***-0.56***	-0.77	-0.28	-0.38	-0.05	0.03	-0.62	-0.08	-0.31	-0.09	0.18	-0.46	-0.10	0.21	**1**	0.62	-0.26	-0.17	-0.01	0.21	0.23	0.05	0.05	-0.21	0.36
femexp	***-0.44***	-0.44	-0.36	-0.41	-0.13	0.15	-0.44	-0.10	-0.23	0.07	0.00	-0.44	0.18	0.28	0.62	**1**	-0.21	-0.14	-0.07	0.28	0.41	-0.08	0.08	-0.23	0.44
femprop	***0.08***	0.16	-0.11	0.11	0.45	-0.32	0.53	0.00	0.47	0.26	0.37	0.05	0.13	-0.45	-0.26	-0.21	**1**	-0.25	0.62	-0.03	-0.05	-0.16	0.11	-0.39	-0.16
femsize	***0.04***	0.04	0.17	-0.04	0.01	-0.09	0.01	-0.12	-0.17	-0.26	-0.27	0.55	0.06	-0.06	-0.17	-0.14	-0.25	**1**	-0.08	0.22	-0.04	0.19	-0.27	0.35	-0.40
popeven	***-0.15***	-0.21	-0.21	0.01	0.43	-0.54	0.21	0.10	0.54	0.08	0.57	-0.01	-0.01	-0.57	-0.01	-0.07	0.62	-0.08	**1**	0.10	-0.10	-0.01	0.01	-0.29	-0.18
botemp	***-0.33***	-0.18	-0.36	-0.15	0.08	-0.31	-0.23	-0.26	-0.03	-0.14	0.00	-0.08	0.18	-0.03	0.21	0.28	-0.03	0.22	0.10	**1**	0.15	-0.28	0.03	-0.28	-0.03
surtemp	***-0.05***	-0.05	-0.08	-0.23	0.00	0.08	-0.10	-0.23	-0.15	0.17	-0.13	-0.05	0.15	0.26	0.23	0.41	-0.05	-0.04	-0.10	0.15	**1**	0.10	0.00	-0.15	0.21
Capelin	***0.13***	-0.08	0.36	0.00	0.03	-0.15	-0.03	0.10	-0.03	0.04	-0.05	0.33	-0.28	0.03	0.05	-0.08	-0.16	0.19	-0.01	-0.28	0.10	**1**	-0.33	0.38	-0.08
Cod	***0.18***	-0.13	0.15	0.36	-0.13	-0.05	-0.23	-0.41	0.18	0.43	-0.21	-0.13	0.18	0.18	0.05	0.08	0.11	-0.27	0.01	0.03	0.00	-0.33	**1**	-0.13	0.03
turbot	***0.33***	0.08	0.51	0.21	-0.18	0.10	-0.08	0.05	-0.13	-0.14	-0.31	0.33	-0.13	0.08	-0.21	-0.23	-0.39	0.35	-0.29	-0.28	-0.15	0.38	-0.13	**1**	-0.18
crab	***-0.23***	-0.13	-0.26	-0.21	-0.18	0.41	-0.13	-0.10	-0.23	-0.04	0.05	-0.54	-0.08	0.44	0.36	0.44	-0.16	-0.40	-0.18	-0.03	0.21	-0.08	0.03	-0.18	**1**

Table 10. Survey biomasses, commercial shrimp catches, and exploitation rates (catch/biomass) by survey strata (13-15, offshore part), and the inshore area (17), 1998-2014.

Survey Metric	SFA	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Mean
Biomass (mt)	**13**	7188	9517	5866	4089	3114	7047	12184	9687	6129	7507	4144	6208	2688	4537	6011	7970	8204	6324
	14	11279	11040	9364	12325	12020	12035	20228	20035	18929	15957	12710	20544	16009	14614	10941	17682	11801	13984
	15	4549	7807	7268	2073	2766	3751	4399	4378	5130	5345	4227	7235	4784	4223	4232	2594	3022	4975
	17	9530	8262	9365	6541	2872	5296	11627	10333	7581	9622	9823	11438	13731	7136	6793	11136	15765	8086
	Total	**32546**	**36626**	**31863**	**25028**	**20773**	**28130**	**48438**	**44433**	**37769**	**38431**	**30904**	**45424**	**37212**	**30510**	**27978**	**39381**	**38791**	**33401**
Catch (mt)	**13**	517	616	233	432	270	585	2011	1145	630	85	212	11	125	4	0	0	438	445
	14	2029	1516	1750	1206	1552	1621	752	1372	1998	2640	2696	2026	1844	2309	2126	2509	2283	1897
	15	486	442	915	965	247	226	338	613	444	612	534	540	1123	982	694	407	192	631
	17	899	2276	2538	2165	874	333	168	515	915	1245	879	900	1490	1062	827	688	1002	983
	Total	**3931**	**4851**	**5436**	**4768**	**2943**	**2765**	**3268**	**3645**	**3986**	**4582**	**4321**	**3477**	**4581**	**4358**	**3647**	**3604**	**3916**	**3955**
Exploitation (%)	**13**	7.2	6.5	4.0	10.6	8.7	8.3	16.5	11.8	10.3	1.1	5.1	0.2	4.6	0.1	0.0	0.0	5.3	6.8
	14	18.0	13.7	18.7	9.8	12.9	13.5	3.7	6.8	10.6	16.5	21.2	9.9	11.5	15.8	19.4	14.2	19.3	15.0
	15	10.7	5.7	12.6	46.6	8.9	6.0	7.7	14.0	8.6	11.5	12.6	7.5	23.5	23.3	16.4	15.7	6.4	12.9
	17	9.4	27.5	27.1	33.1	30.4	6.3	1.4	5.0	12.1	12.9	8.9	7.9	10.9	14.9	12.2	6.2	6.4	12.8
	Total	**12.1**	**13.2**	**17.1**	**19.1**	**14.2**	**9.8**	**6.7**	**8.2**	**10.6**	**11.9**	**14.0**	**7.7**	**12.3**	**14.3**	**13.0**	**9.2**	**10.1**	**12.4**

Table 11. Minimum survey population numbers at age from modal analysis. Numbers x 10^6.

Age	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Avg.
1[1]	-	-	-	-	980	196	316	198	61	194	484	567	263	97	113	25	790	316
2	40	166	280	175	134	616	354	187	121	39	114	304	188	85	348	302	125	215
3	785	27	757	362	383	312	3118	652	880	506	396	267	1020	752	1018	1157	628	754
4	1884	3010	0[4]	1184	399	1506	839	4502	0[4]	0[4]	1190	463	1036	1044	1022	1693	0[4]	1428
5+	2047	1952	3374	2110	1847	1727	3324	2224	5106	5506	3017	6020	4109	2488	1666	2398	4980	2891
TOTAL	4755	5155	4412	3831	2763	4161	7636	7763	6169	6244	5201	7622	6616	4467	4167	5574	6523	5161
Age 4+ males[2]	2243	3235	1784	1771	938	1526	1549	4956	3916	2804	3317	4263	3454	1755	1211	1032	3276	2424
Primiparous[3]	889	736	728	817	678	551	870	786	771	1739	892	1492	1324	930	281	860	659	868
Multiparous	647	991	863	706	630	1188	1698	1183	480	1157	482	1295	630	945	1309	2224	1835	885
Total females	1535	1727	1591	1523	1308	1739	2568	1969	1251	2896	1374	2787	1954	1875	1590	3084	2494	1753

Notes:

[1] Belly-bag.
[2] Total population less ages 2, 3 males, transitionals and females, i.e. males that will potentially change to females the following year.
[3] Includes transitionals.
[4] Four year olds of the 1996 and 2002, 2003 year classes were not distinguishable in the MIX analysis. These year classes appear to be small and are contained in the ages 3 or 5+ categories.

Table 12. Shrimp predators on the ESS with stomach contents data from 2000-2010 summer ecosystem surveys. Fish species found to have shrimp in their stomach more than 5% of the time that they are examined are in bold.

Ecosystem survey species Code<1000	Number Sampled (With Prey)	Shrimp Percent Weight in Diet	Shrimp Frequency in Diet
TomCod, Atlantic[1]	**3**	**44.0%**	**0.333**
Halibut, Greenland	**830**	**13.0%**	**0.152**
Hake, White	**1462**	**4.2%**	**0.120**
Eelpout, Newfoundland	**27**	**16.4%**	**0.111**
Halibut, Atlantic	**369**	**1.1%**	**0.103**
Atlantic Cod	**4180**	**3.9%**	**0.100**
Cusk	**21**	**2.2%**	**0.095**
Skate, Smooth	**311**	**10.6%**	**0.090**
Hake, Longfin	**105**	**21.1%**	**0.067**
Hake, Squirrel/Red	**370**	**5.7%**	**0.059**
Plaice, American	**1868**	**10.7%**	**0.049**
Sculpin, Longhorn	1310	1.5%	0.040
Redfish[2]	873	6.2%	0.034
Pollock	744	1.5%	0.031
Sea raven	470	0.1%	0.028
Skate, Thorny[2]	1213	3.2%	0.028
Hake, Silver	1754	2.2%	0.027
Skate, Winter[2]	183	5.2%	0.027
Skate, Little	39	3.1%	0.026
Spiny Dogfish	525	0.2%	0.023
Monkfish	272	0.3%	0.022
Haddock	3388	0.8%	0.017
Wolffish, Atlantic	198	0.1%	0.015
Eelpout, Vahl's[2]	169	3.4%	0.006
Herring, Atlantic	1132	0.4%	0.002
Flounder, Witch	1059	0.3%	0.001
Flounder, Yellowtail	1006	0.0%	0.001
Alligatorfish	0	n/a.	n/a.
American Shad	0	n/a.	n/a.
Butterfish	0	n/a.	n/a.
Capelin	0	n/a.	n/a.
Dragonfish, Boa	0	n/a.	n/a.
Eelpout, Laval's	0	n/a.	n/a.
Hagfish, Northern	0	n/a.	n/a.
Lanternfish, Horned	0	n/a.	n/a.
Lumpsucker, Atlantic Spiny	0	n/a.	n/a.
Mackerel, Atlantic	0	n/a.	n/a.
Northern Sand Lance	0	n/a.	n/a.
Rockling, Fourbeard	0	n/a.	n/a.
Sculpin, Hookear	0	n/a.	n/a.
Sculpin, Mailed	0	n/a.	n/a.
Sculpin, Twohorn	0	n/a.	n/a.
Shanny, Daubed	0	n/a.	n/a.
Snakeblenny	0	n/a.	n/a.
Wrymouth	0	n/a.	n/a.

Note:

[1] Atlantic tomCod are excluded from all analysis due to low sample size (N=3).

[2] Several other species stomach contents contain a relatively high proportion of shrimp by weight, despite being infrequently (<5%) found to have any shrimp in their stomachs.

Table 13. Base Total Allowable Catch (baseTAC) used for the HCR model for each 10% increment (of average 2000-2010 SSB) above the lower reference point. The Critical Zone (column 2) is shown in red, the Cautious Zone (column 3-7) is shown in yellow and the Healthy Zone (column 8-10) is shown in green.

SSB_t (% of 2000-2010)	<30%	30-40%	40-50%	50-60%	60-70%	70-80%	80-90%	90-100%	>100%
$baseTAC_t$ (% of $Biomass_{t-1}$)	0%	0%	0.75%	2.5%	6%	9%	10%	10%	10%

Table 14. Hypothetical relative weights applied to Traffic Light indicators and characteristic in the HCR model. Rows corresponding to Abundance and Fishing Effects indicators are shaded grey, while rows corresponding to Productivity and Ecosystem indicators are unshaded.

Traffic Light Indicator (Characteristic)	**Indicator Weight**	**Characteristic Weight**	**Maximum Possible (%)**
survey (abund)	0.33	4	1.33%
gfcpue (abund)	0.22	4	0.89%
stcpue (abund)	0.22	4	0.89%
rvcv (abund)	0.11	4	0.44%
area (abund)	0.11	4	0.44%
ssb (prod)	baseTAC	baseTAC	0-10%
bb (prod)	0.20	2	0.40%
rv2 (prod)	0.20	2	0.40%
rv4 (prod)	0.20	2	0.40%
sexmm (prod)	0.10	2	0.20%
maxmm (prod)	0.10	2	0.20%
pred (prod)	0.20	2	0.40%
count (fish)	0.14	1	0.14%
exp (fish)	0.29	1	0.29%
femexp (fish)	0.29	1	0.29%
femprop (fish)	0.14	1	0.14%
femsize (fish)	0.14	1	0.14%
popeven (eco)	0.13	1	0.13%
Botemp (eco)	0.27	1	0.27%
surtemp (eco)	0.27	1	0.27%
Capelin (eco)	0.07	1	0.07%
Cod (eco)	0.13	1	0.13%
turbot (eco)	0.07	1	0.07%
crab (eco)	0.07	1	0.07%
TOTAL			18%

Table 15. Extrapolated survey biomass (B_S) corresponding to the SSB in 10% increments of the PA SSB index and corresponding minimum and maximum hypothetical total allowable catch using the HCR model. n/a indicates not applicable. The Critical Zone (row 2) is shown in red, the Cautious Zone (row 2-6) is shown in yellow and the Healthy Zone (row 8-10) is shown in green.

% PA SSB	SSB	Extrapolated B_s	baseTAC (mt)	maxTAC (mt)
<30%	n/a	n/a	0	0
30%	5459	15550	0	1244
40%	7279	18385	138	1609
50%	9099	21220	531	2228
60%	10919	24055	1443	3368
70%	12738	26890	2420	4571
80%	14558	29725	2972	5350
90%	16378	32559	3256	5861
100%	18198	35394	3539	6371

Table 16. Bayesian Surplus Production model parameters.

Catch Series	r	K	B_{MSY}	MSY	F^{MSY}
Gulf	0.98	19160	9580	4470	0.49
Standardised	1.04	17820	8910	4510	0.52
Survey	1.62	10840	5420	4390	0.81

FIGURES

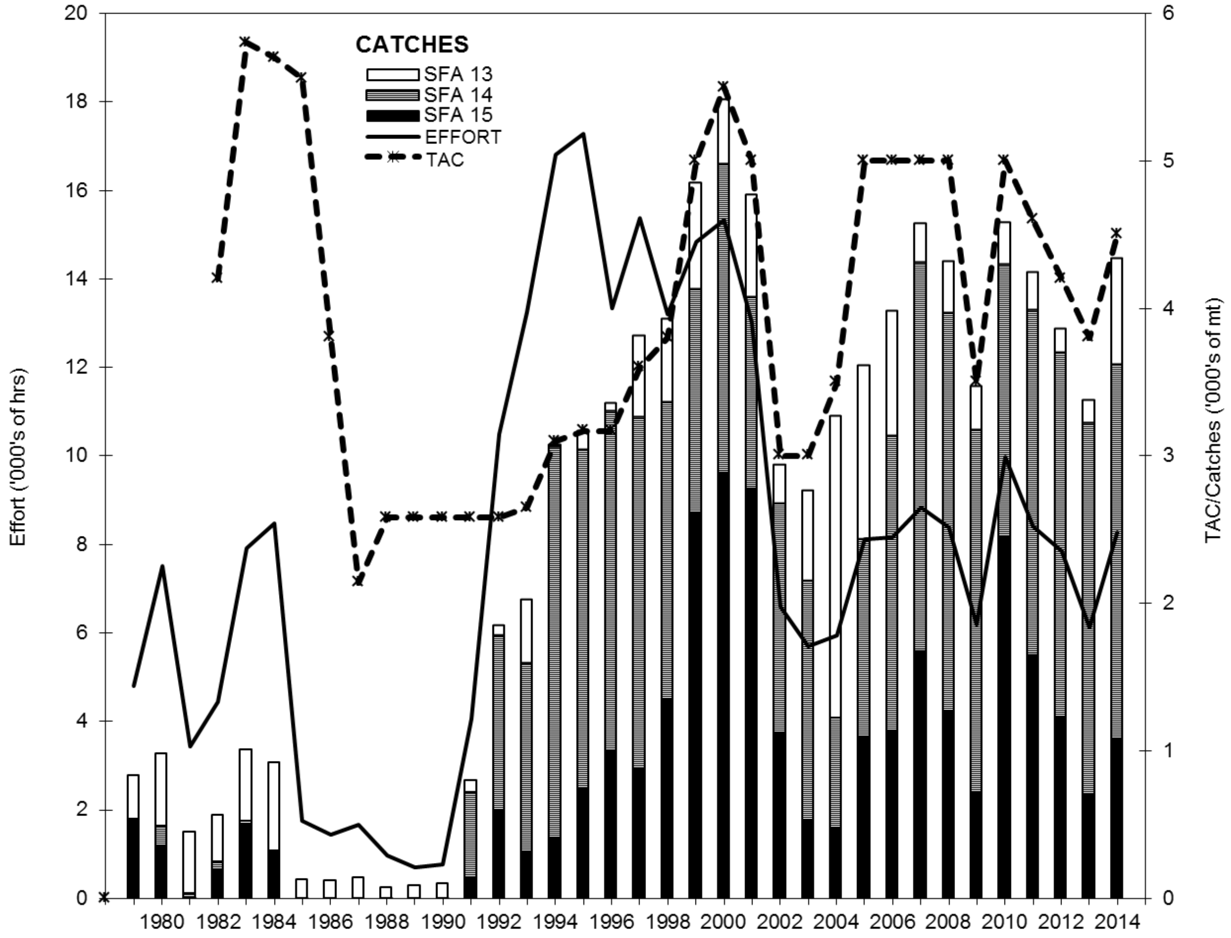

Figure 1. History of ESS shrimp fishery catches per SFA (13, 14 and 15), TAC (thousands of mt) and effort (thousands of hours), from 1980-2014.

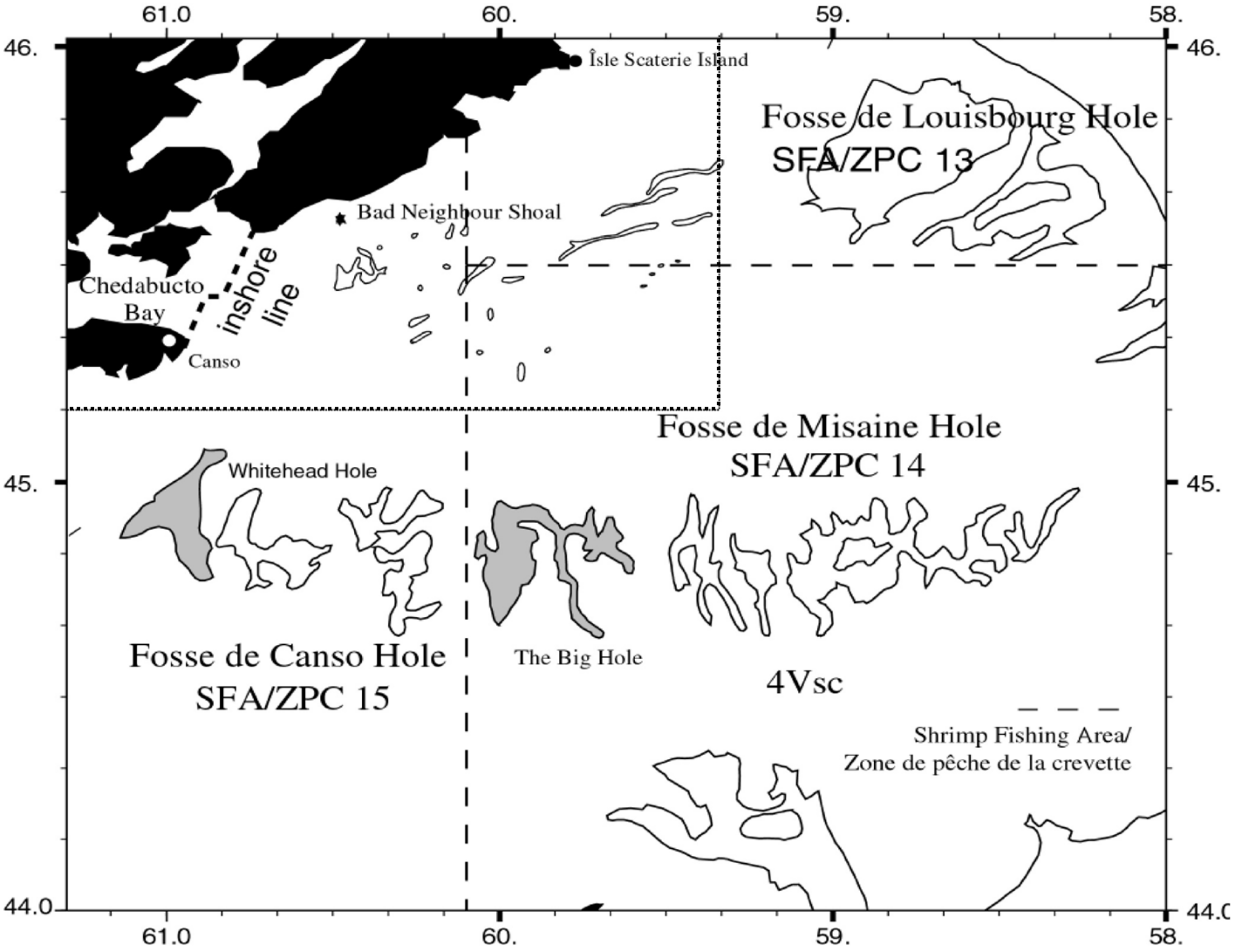

Figure 2. Shrimp Fishing Areas (SFAs) on the ESS. The heavy-dashed "inshore line" prohibits trawlers from fishing inside Chedabucto Bay during the trapping season (fall to spring). Note the distinction between SFAs used to report catches survey strata defined offshore (strata 13, 14, 15) by the 100 fathom contour (solid lines) and inshore (stratum 17) by the extent of LaHave clay north of 45°10' and west of 59°20' on surficial geology maps). Stratum 17 is defined by the stippled line, and includes portions of SFAs 14, 15 and 15. Strata 13-15 are those parts of the corresponding SFAs that are not included in stratum 17.

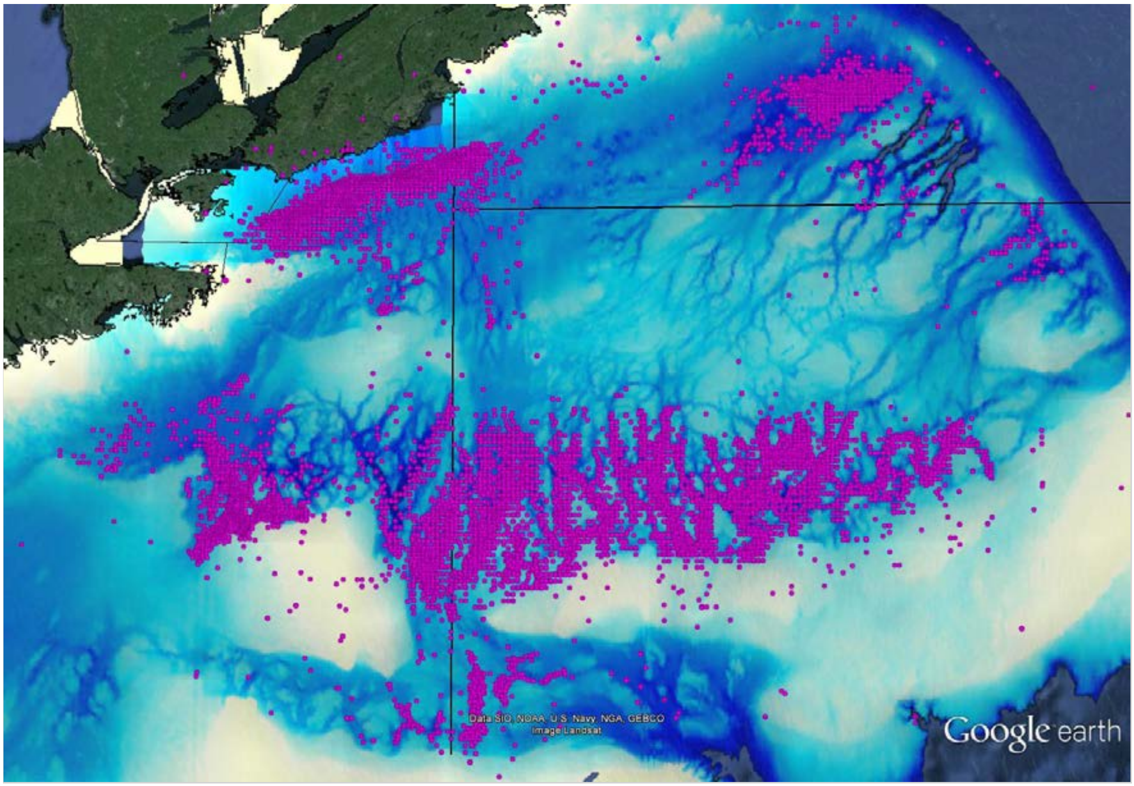

Figure 3. All shrimp fishing trawler effort (commercial fishing sets/tows) from 1993-2014.

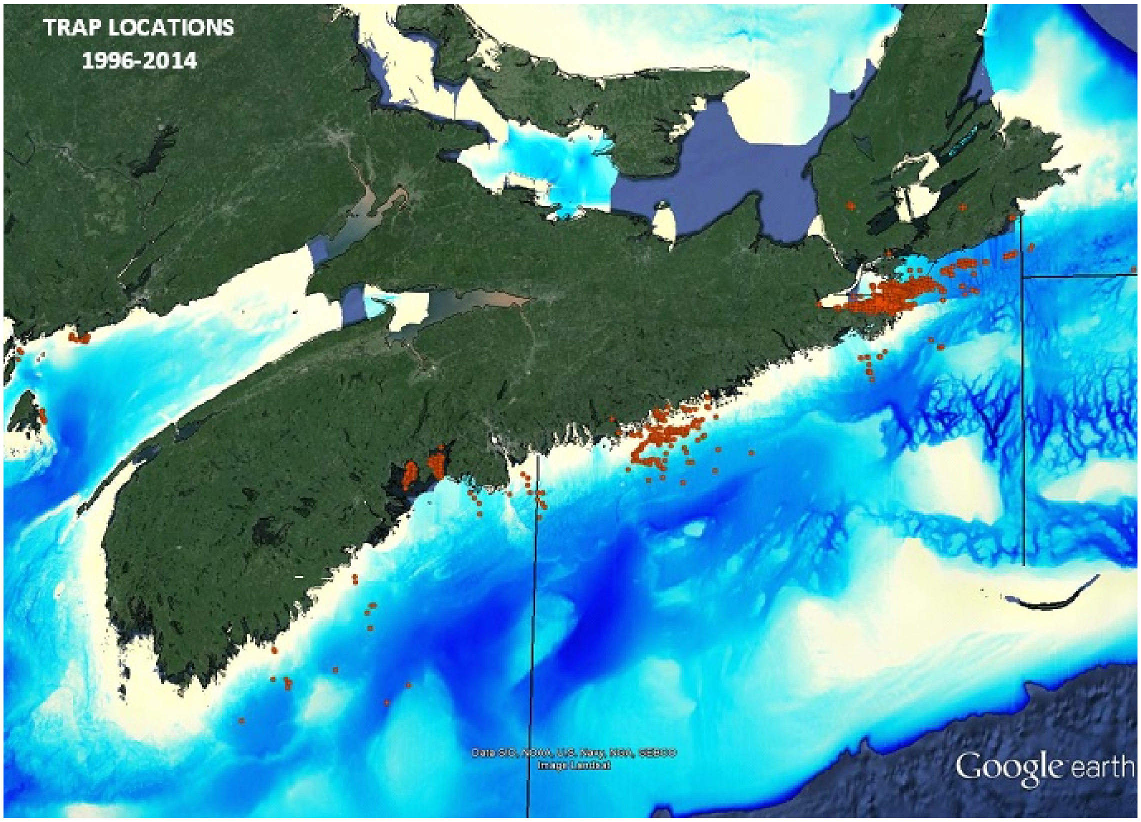

Figure 4. All shrimp fishing trapping effort (commercial fishing sets/tows) from 1996-2014.

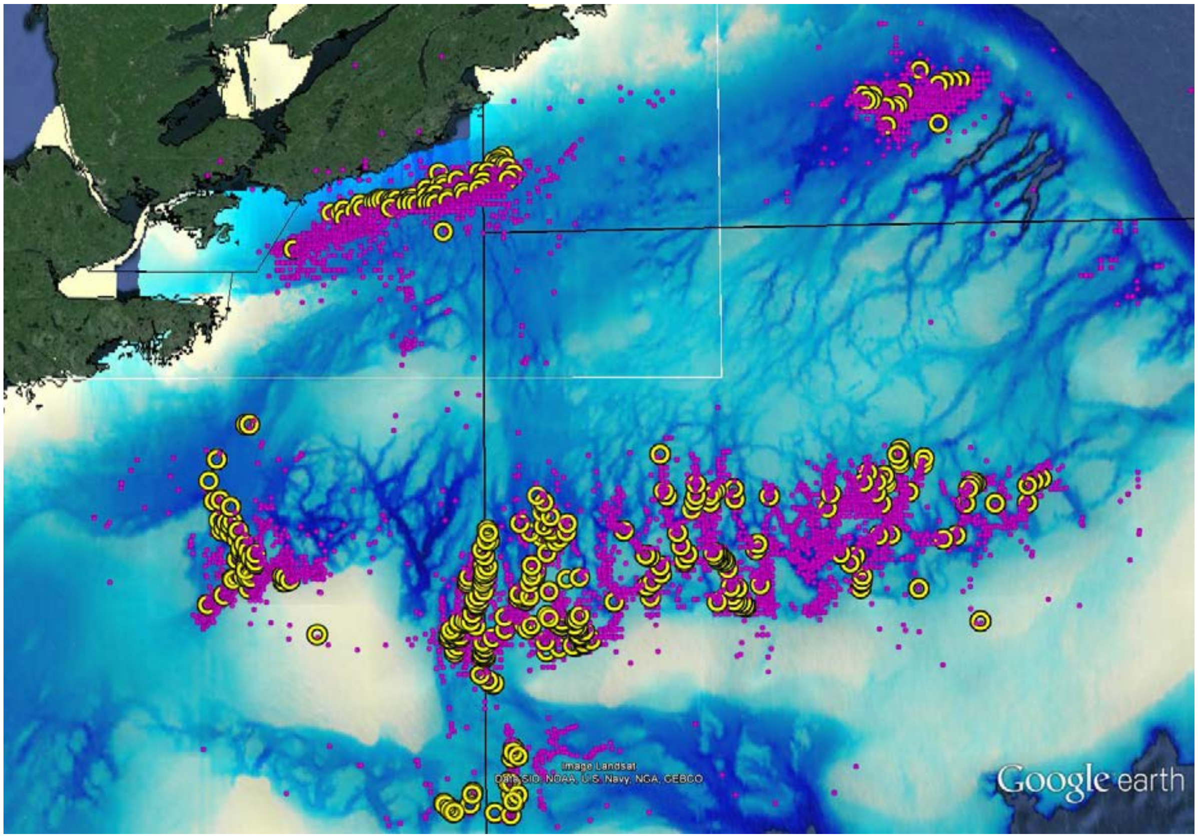

Figure 5. Observer coverage of the ESS shrimp fishery (yellow rings) compared to the distribution of effort (pink dots) from 2004-2014.

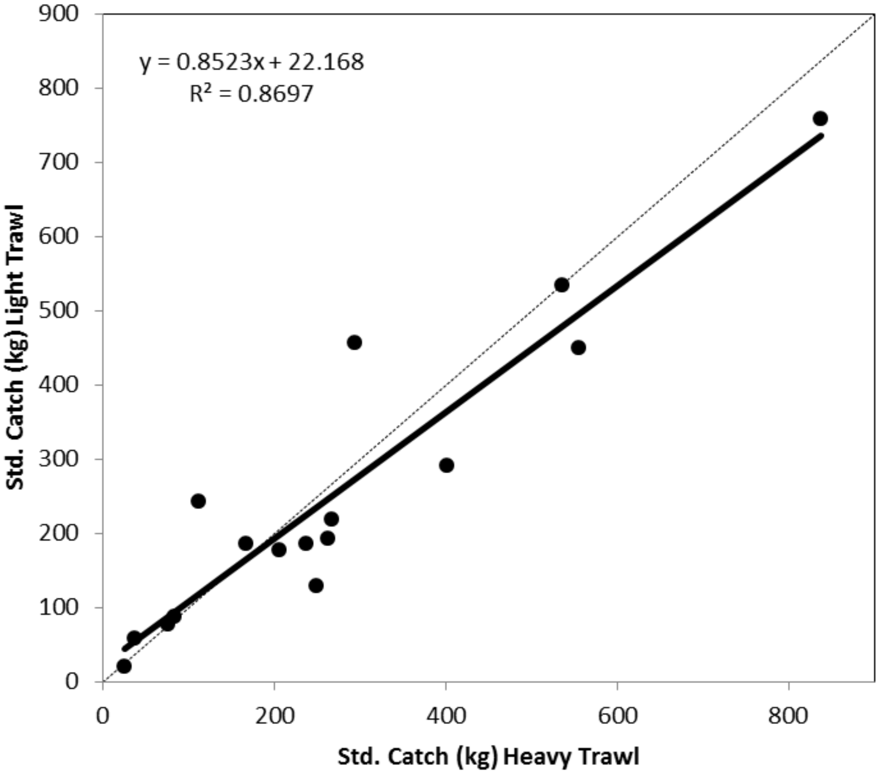

Figure 6. Comparative standardised shrimp catches from 16 repeated survey stations using unweighted (light) versus weighted (heavy) trawl configurations, relative to a 1:1 relationship (dotted line).

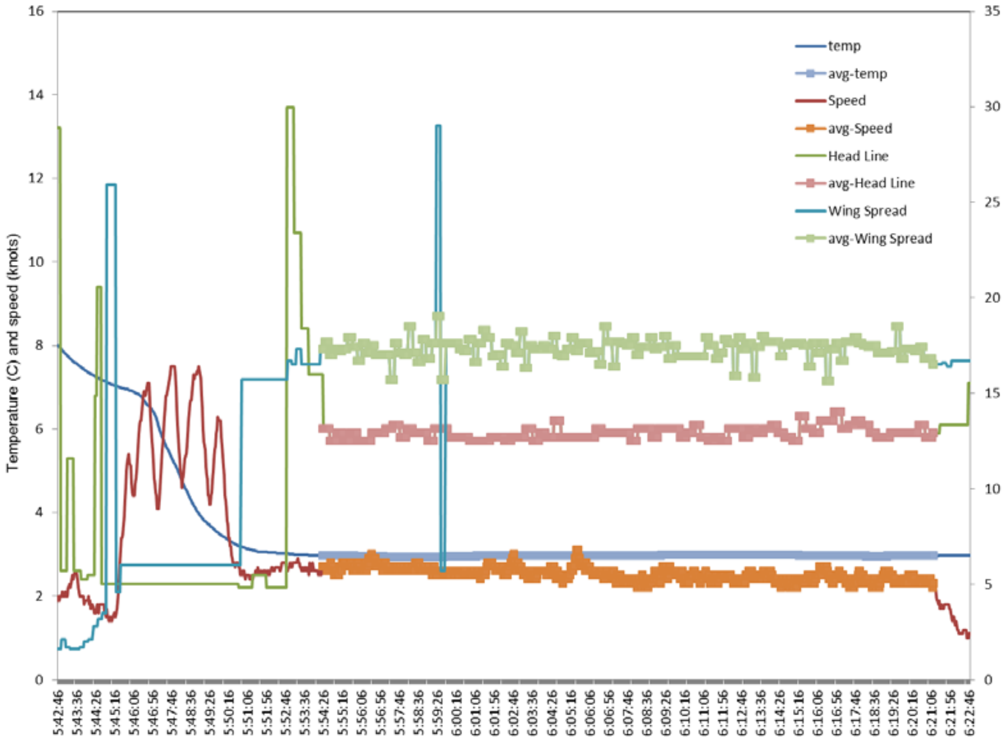

Figure 7. An example of the data plot used to establish start and end times for shrimp survey trawl mensuration.

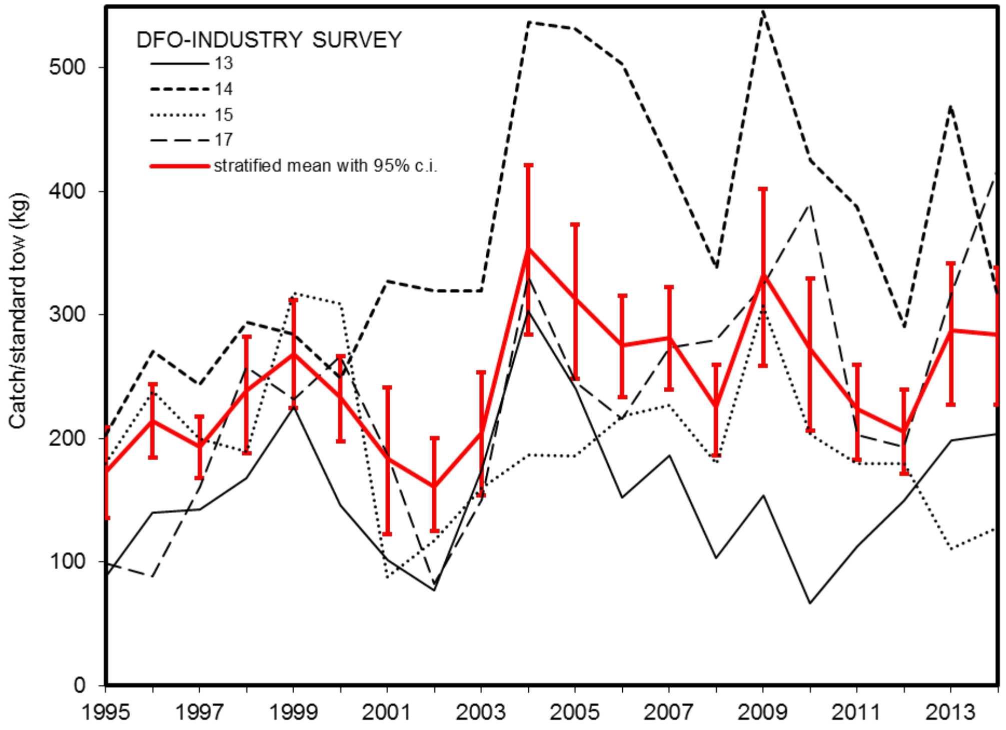

Figure 8. Stratified catch/standard tow for DFO-industry co-operative surveys from 1995-2014, and estimates for the individual strata, which approximately correspond to the main shrimp holes and SFAs. Stratum 13 - Louisbourg Hole and SFA 13; Stratum 14 - Misaine Holes and SFA 14; Stratum 15 - Canso Holes and the offshore part of SFA 15. The 'Inshore', or Stratum 17, is comprised of inshore parts of SFA 13-15.

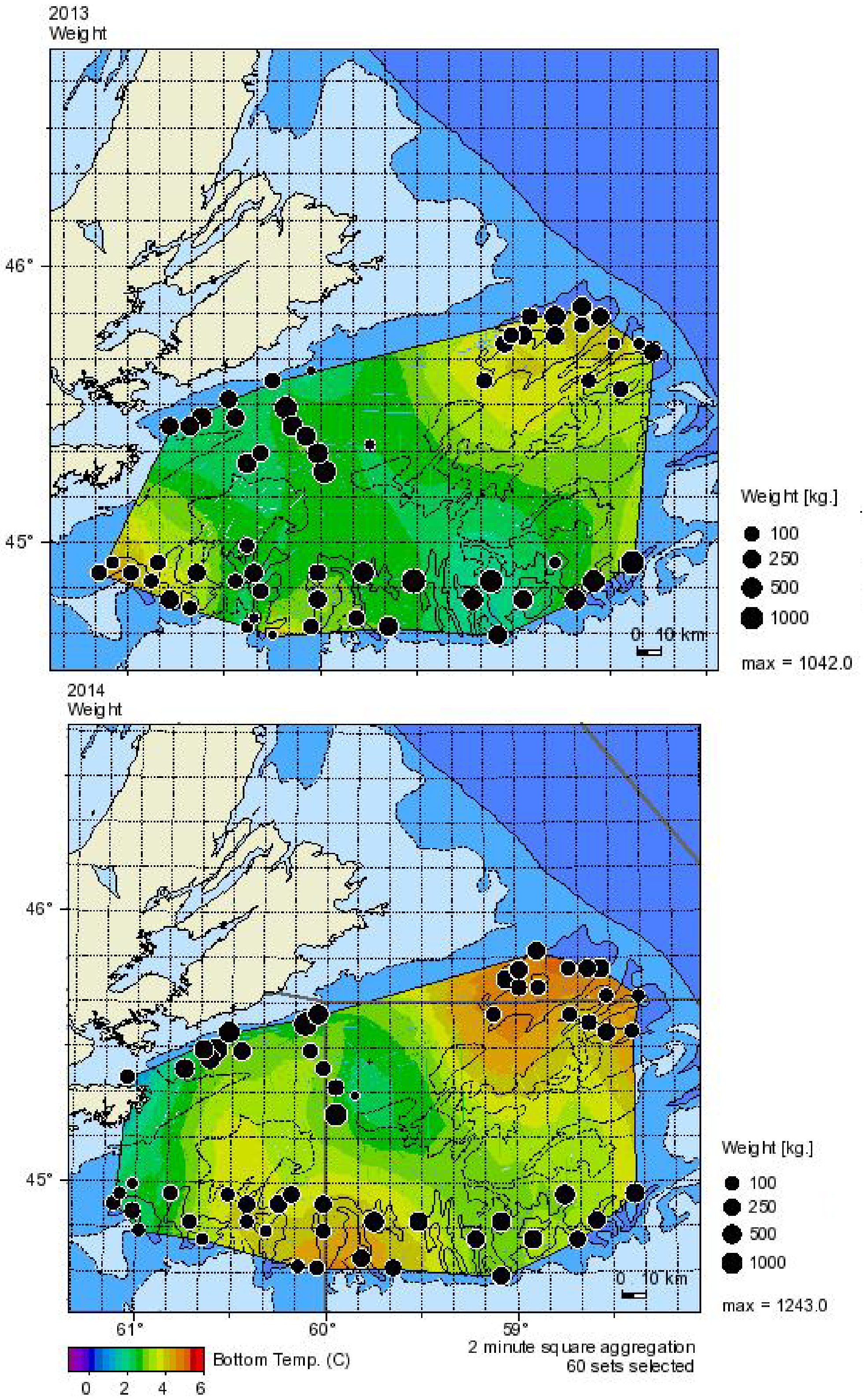

Figure 9. Distribution of catches (kg/standard 30 minute tow) and bottom temperatures from DFO-industry surveys in 2013 and 2014. See previous research documents for distributions prior to 2013.

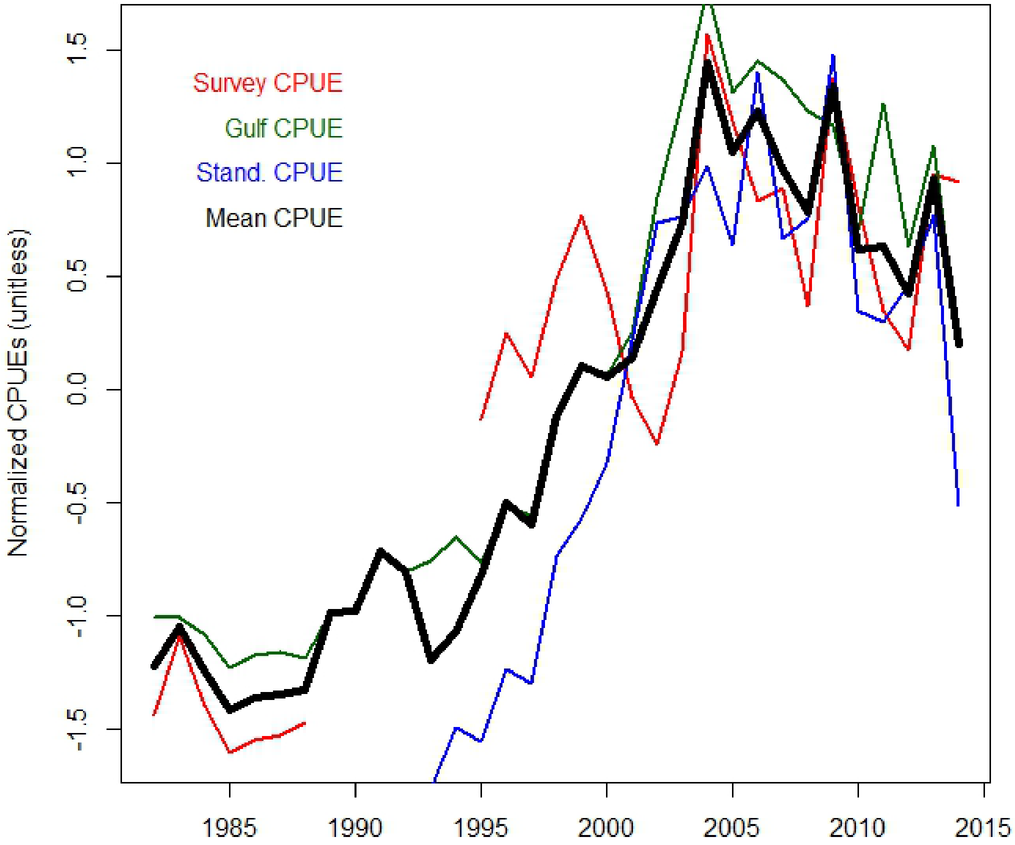

Figure 10. Research survey, unstandardised Gulf vessel and standardised Maritimes vessel CPUE normalized to the mean of each data series (coloured lines) and the overall mean normalized CPUE series (heavy black line) from 1982-2015.

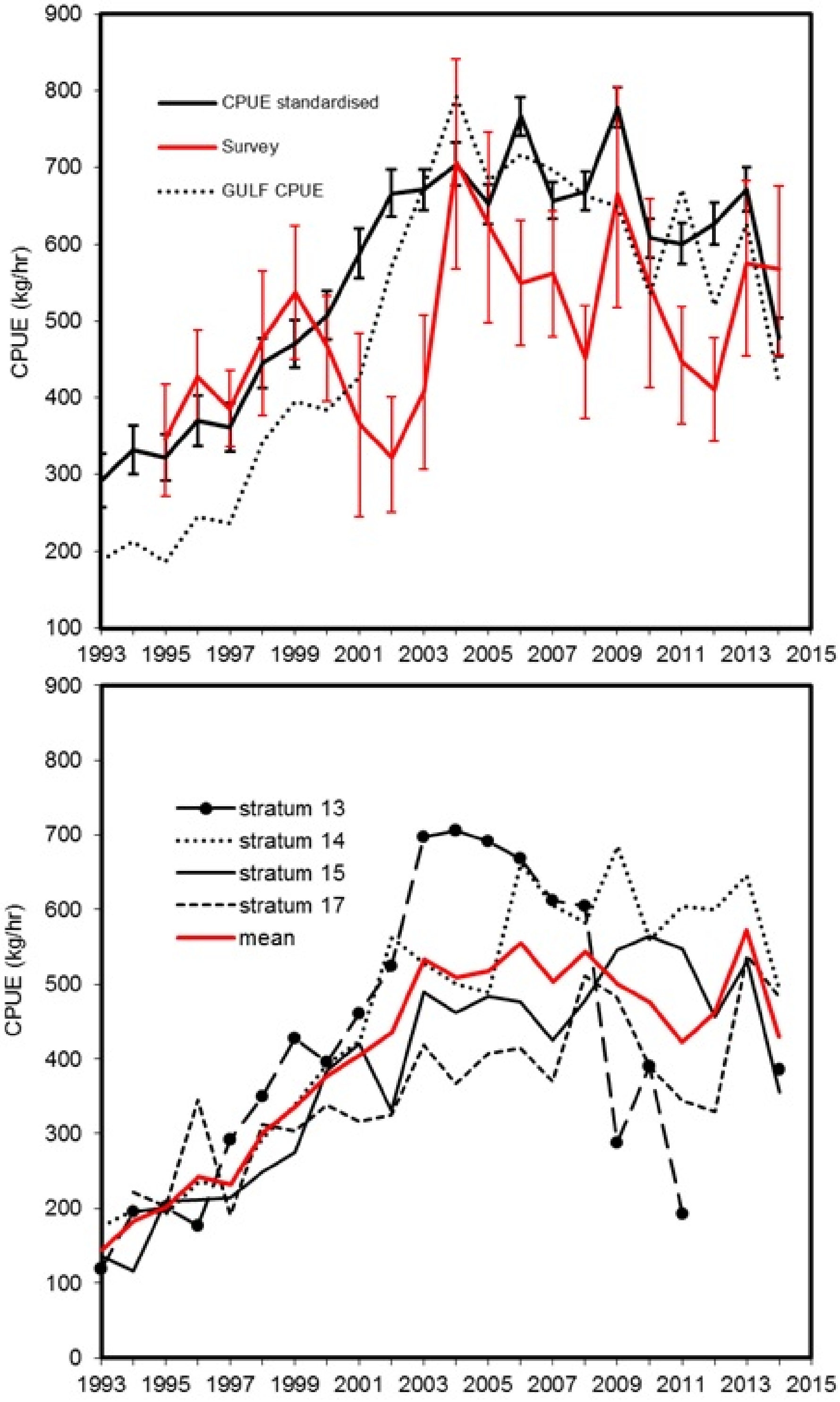

Figure 11. Survey stratified CPUE and standardised commercial CPUE with 95% confidence intervals, and unstandardised Gulf vessel CPUE (top panel); unstandardised commercial CPUE for each fishing area, from 1993-2014 (bottom penal). Note that SFA 15 includes the inshore, but the latter is also shown separately since fishing began there in 1998.

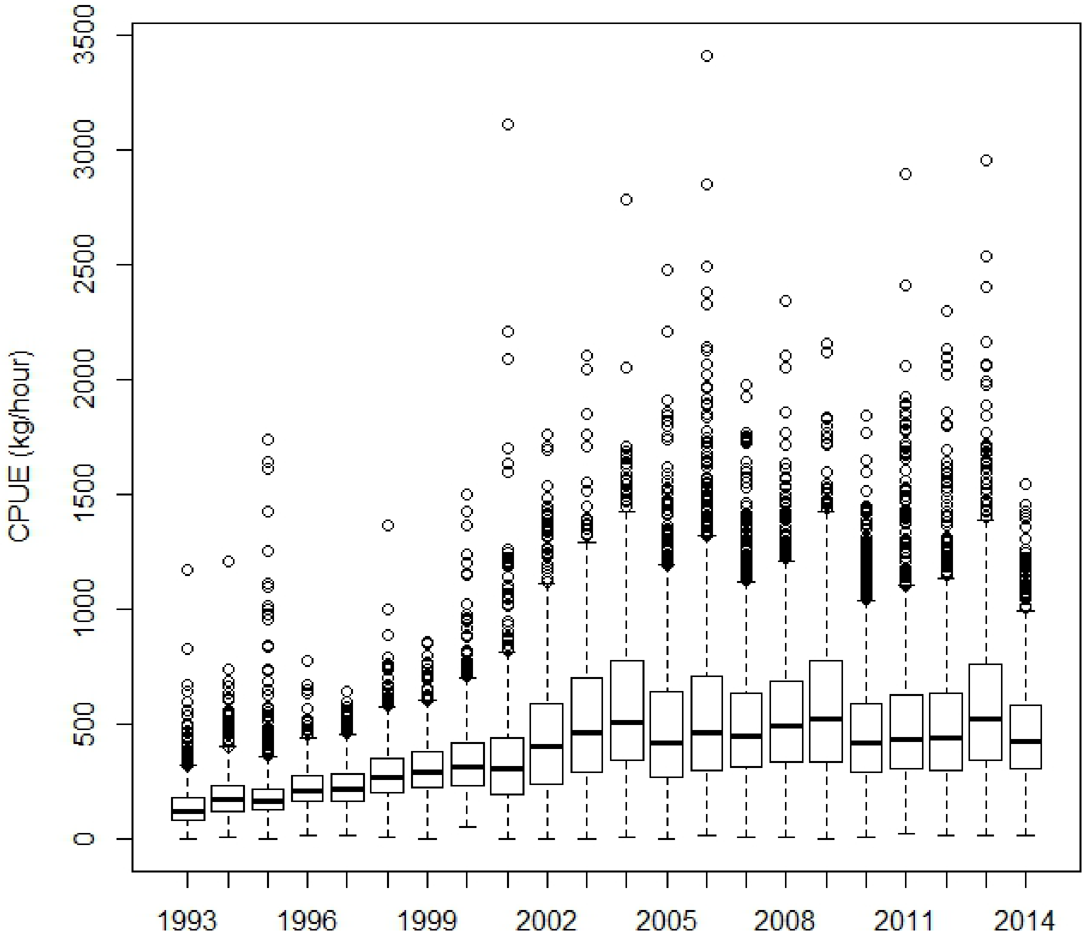

Figure 12. Boxplots of unstandardised CPUE of all (Gulf and Maritimes region) shrimp trawlers on the ESS from 1993-2014.

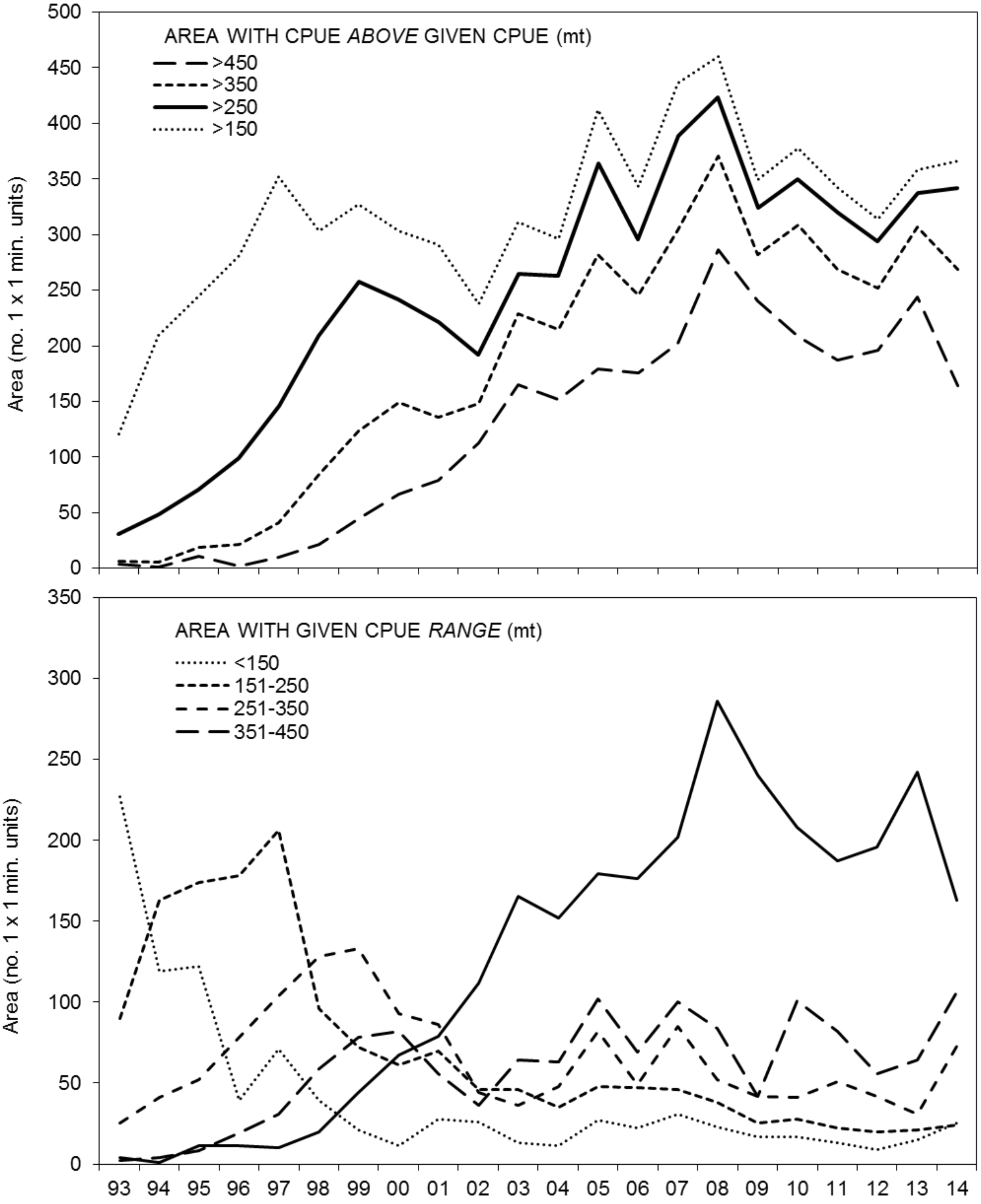

Figure 13. Number of 1 minute square unit areas fished by the shrimp fleet with mean catch rates above (top) and within (bottom) the values or ranges specified in the legend, from 1993-2014.

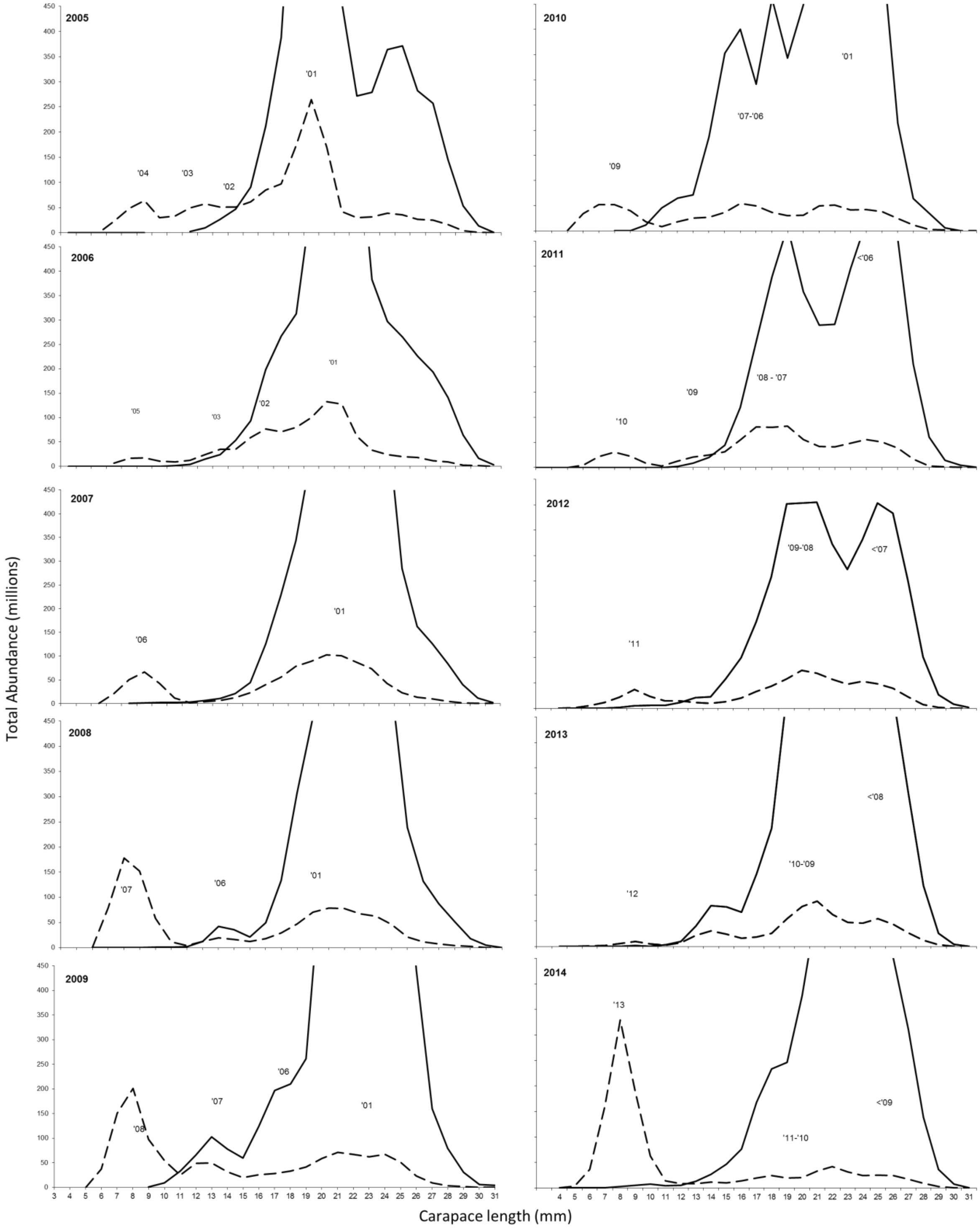

Figure 14. Population estimates from belly-bag (dashed line) and main trawl (solid line) catches for the 2005-2014 surveys.

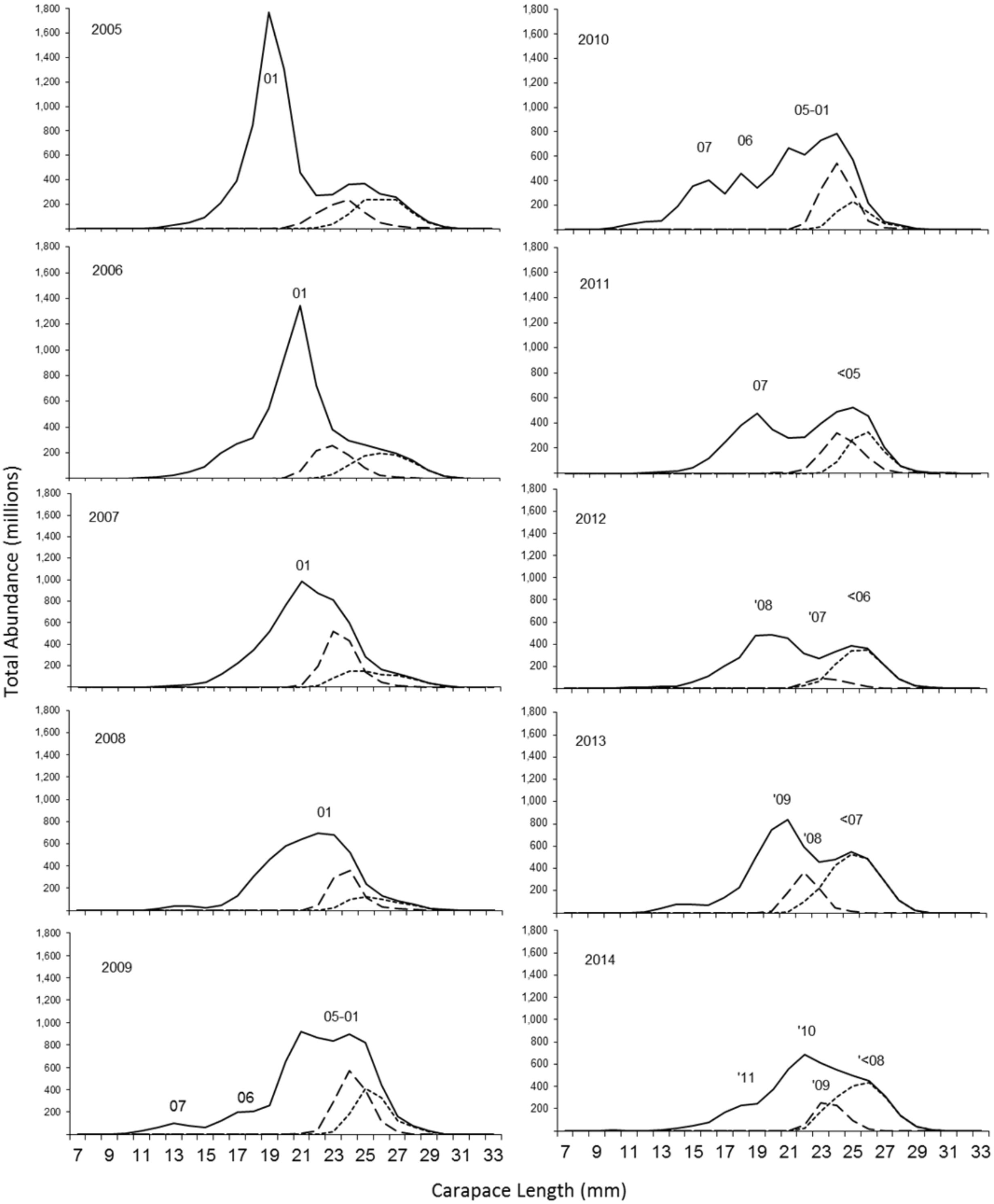

Figure 15. Population estimates at length from DFO-industry surveys, 2005-2014 (solid line). The heavy dotted line in each figure represents transitional and primiparous shrimp, and the stippled line represents multiparous shrimp.

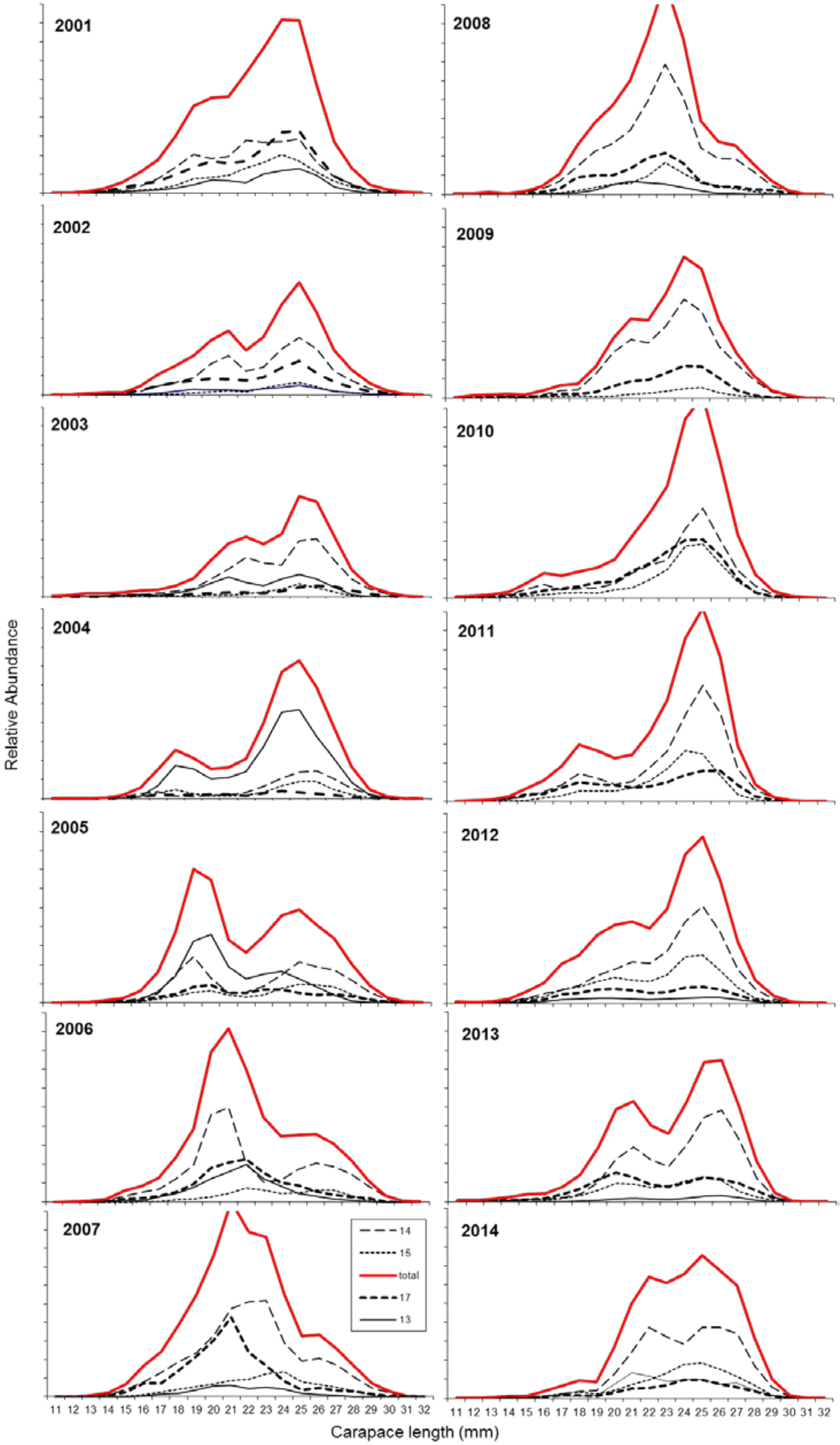

Figure 16. Catch at length from commercial sampling, 2001-2014.

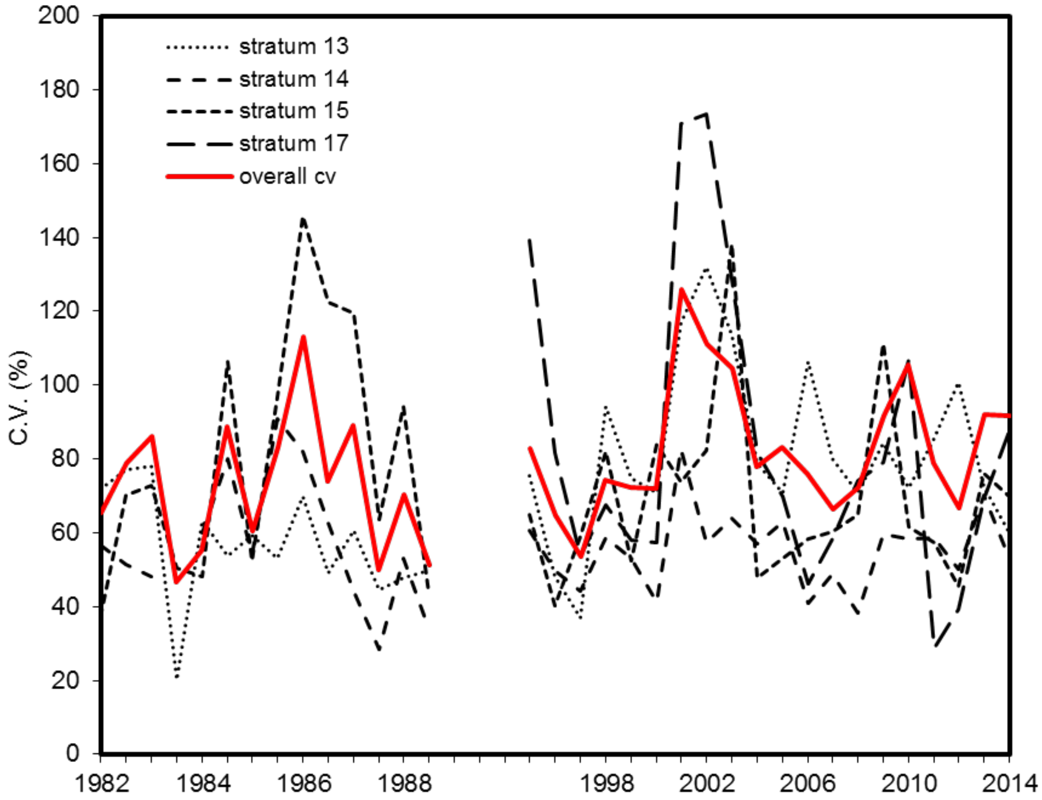

Figure 17. Coefficients of variation (CV) for shrimp survey strata 13, 14, 15, and 17, from 1992-2014. Note that the earlier survey series has two values per year, one for the spring and one for the fall survey. The use of fixed stations in 14 likely acts to constrain interannual changes in CV relative to other areas with random stations.

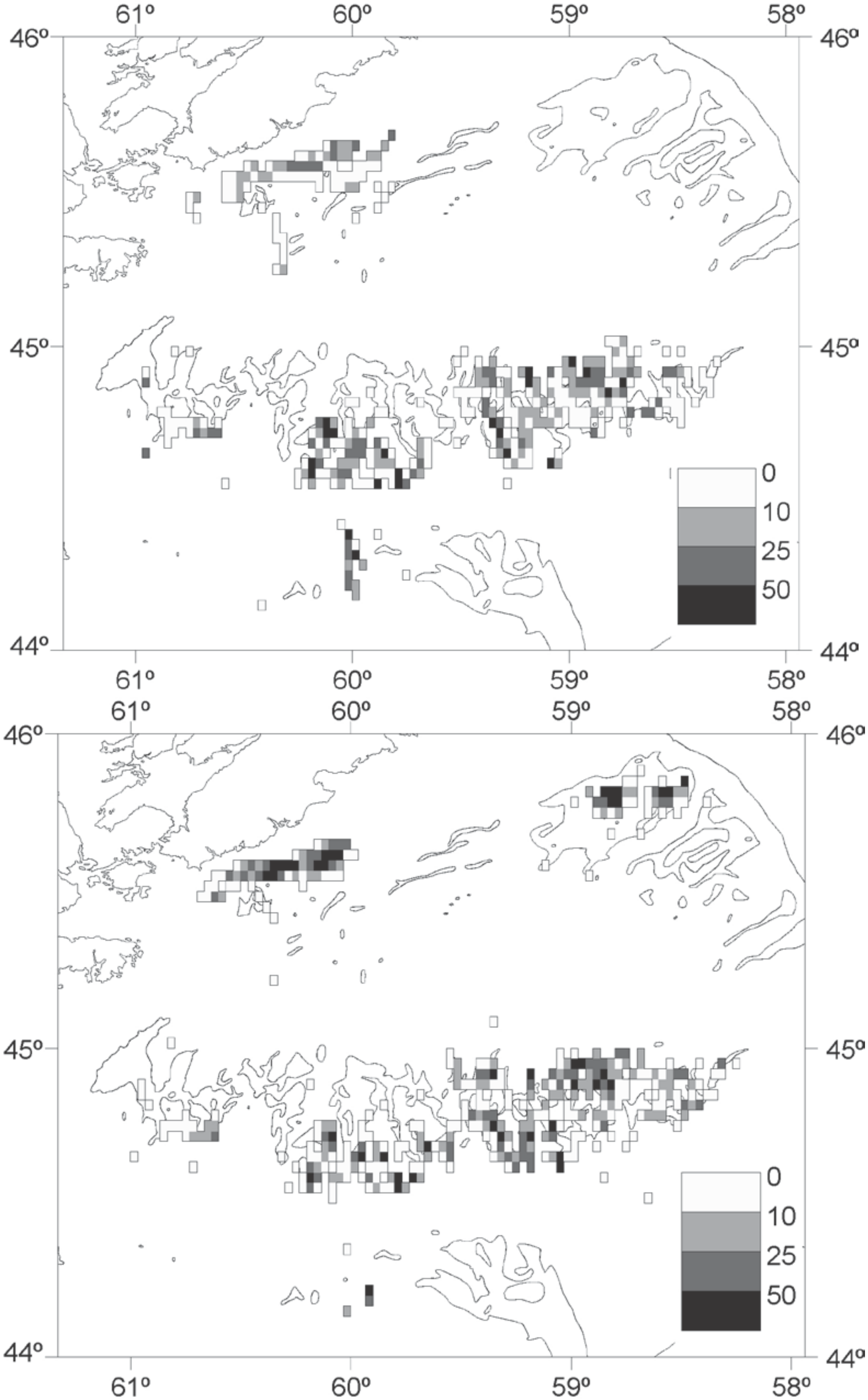

Figure 18. Annual effort by trawlers 2013 (top) and 2014 (bottom), cumulative by 1 minute squares.

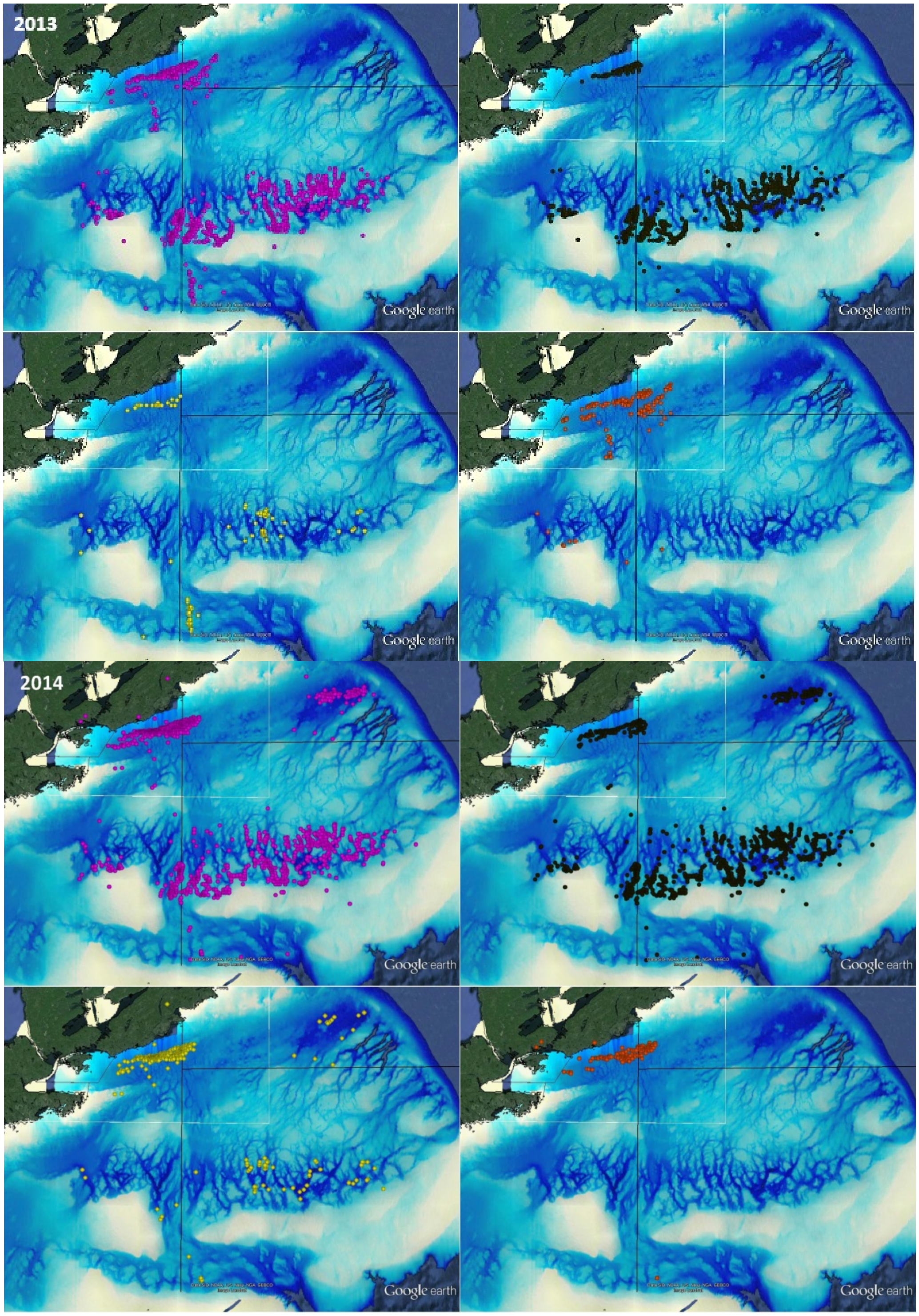

Figure 19. Shrimp fishing effort (sets) for the ESS shrimp fishery in 2013 (top) and 2014 (bottom) showing total annual (pink), spring (black), summer (yellow) and fall (orange) effort distribution.

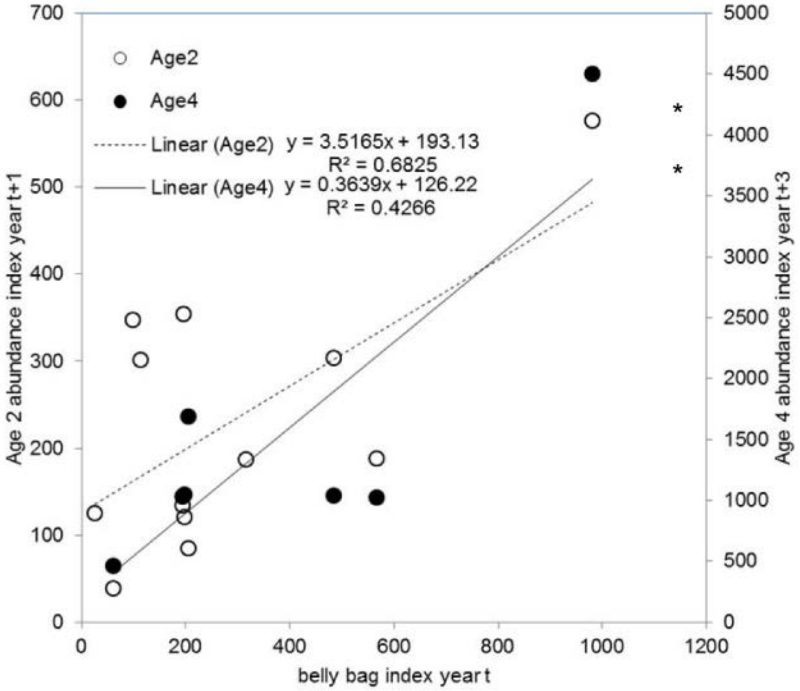

Figure 20. Regressions of the Age 2 and Age 4 abundance indices at 1 and 3 year time-lags, respectively, relative to the belly-bag index from the ESS shrimp research survey. The positive relationships for both regressions collapses to approximately flat if the datapoints associated with the large 2001 year class (*) are removed.

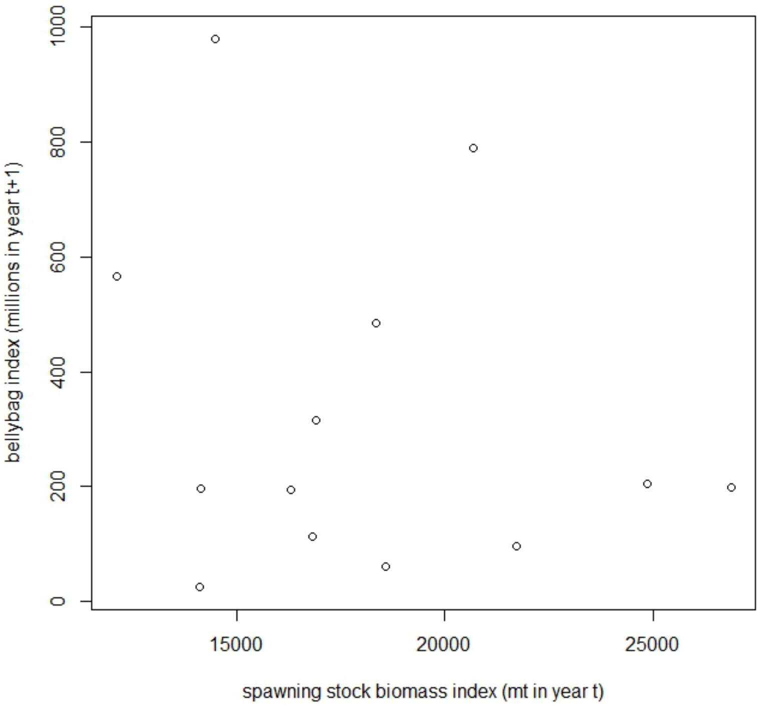

Figure 21. Shrimp juvenile recruitment index (belly-bag index) versus the preceding year's spawning stock biomass index.

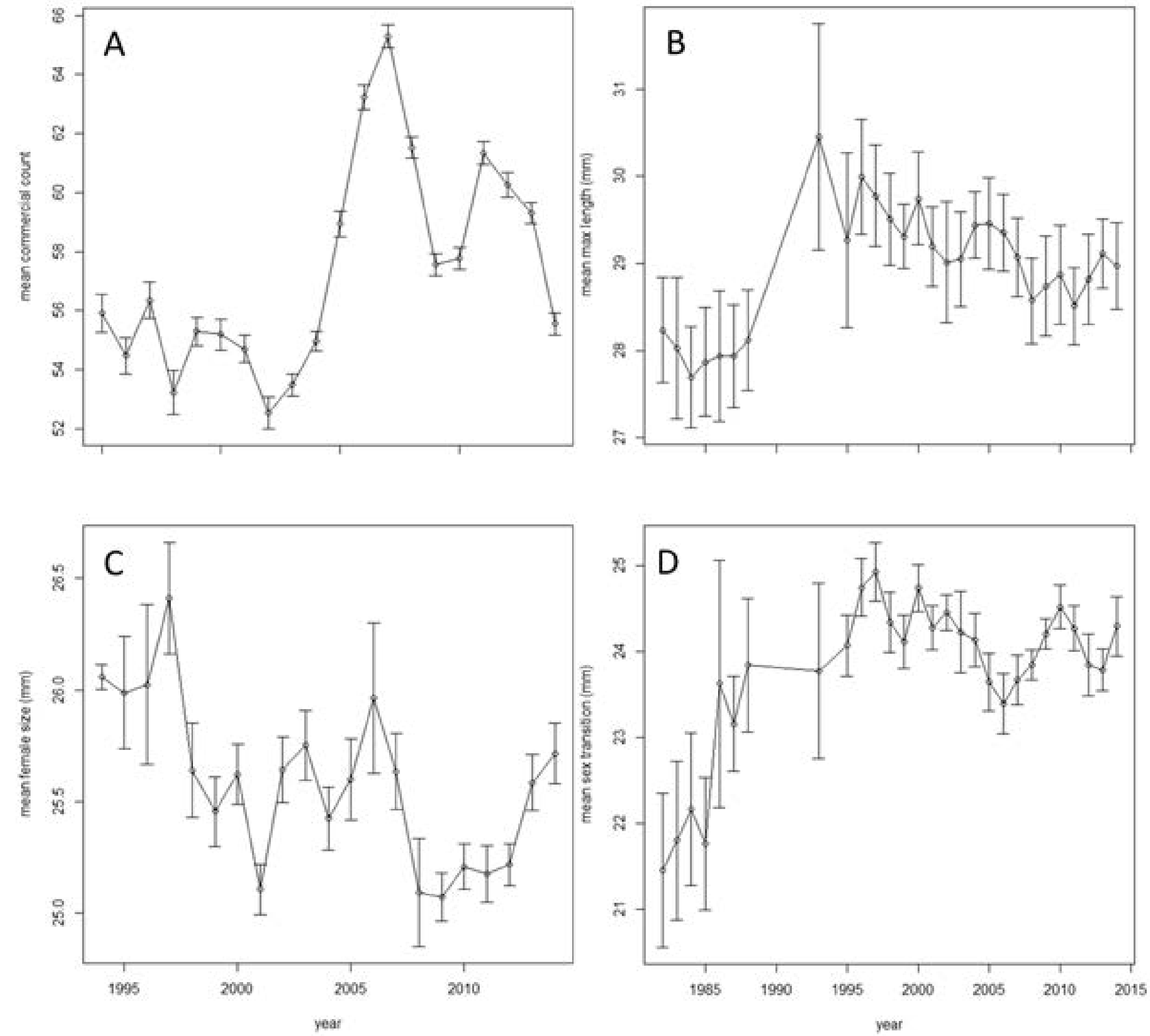

Figure 22. Averages for commercial count (A: top left), maximum length (B: top right), female size (C: bottom left), and size at sex transition (D: bottom right) for all SFAs combined for 1995-2014 with 95% confidence intervals.

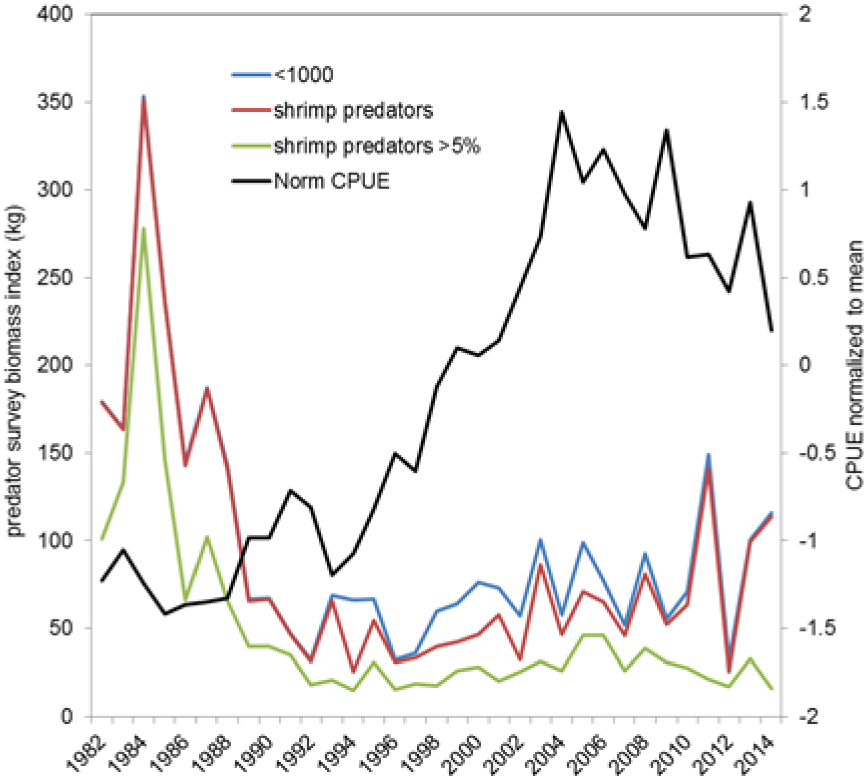

Figure 23. Annual time series of the mean normalized shrimp abundance index (black) relative to the mean annual abundance index of the three proposed predator species groupings (coloured).

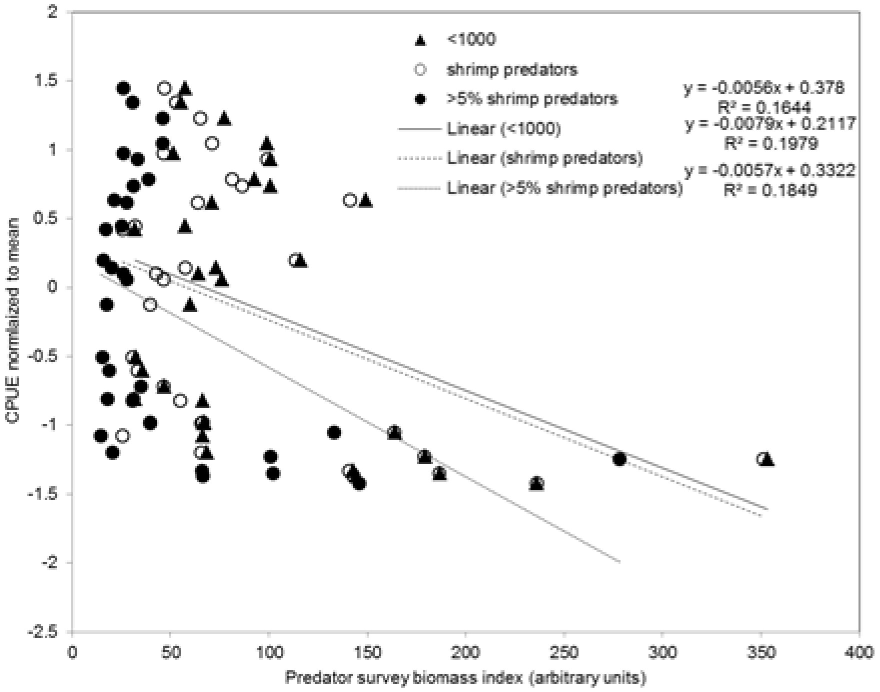

Figure 24. Regressions of annual time series of the mean normalized shrimp abundance index relative to the mean annual abundance index of the three proposed predator species groupings.

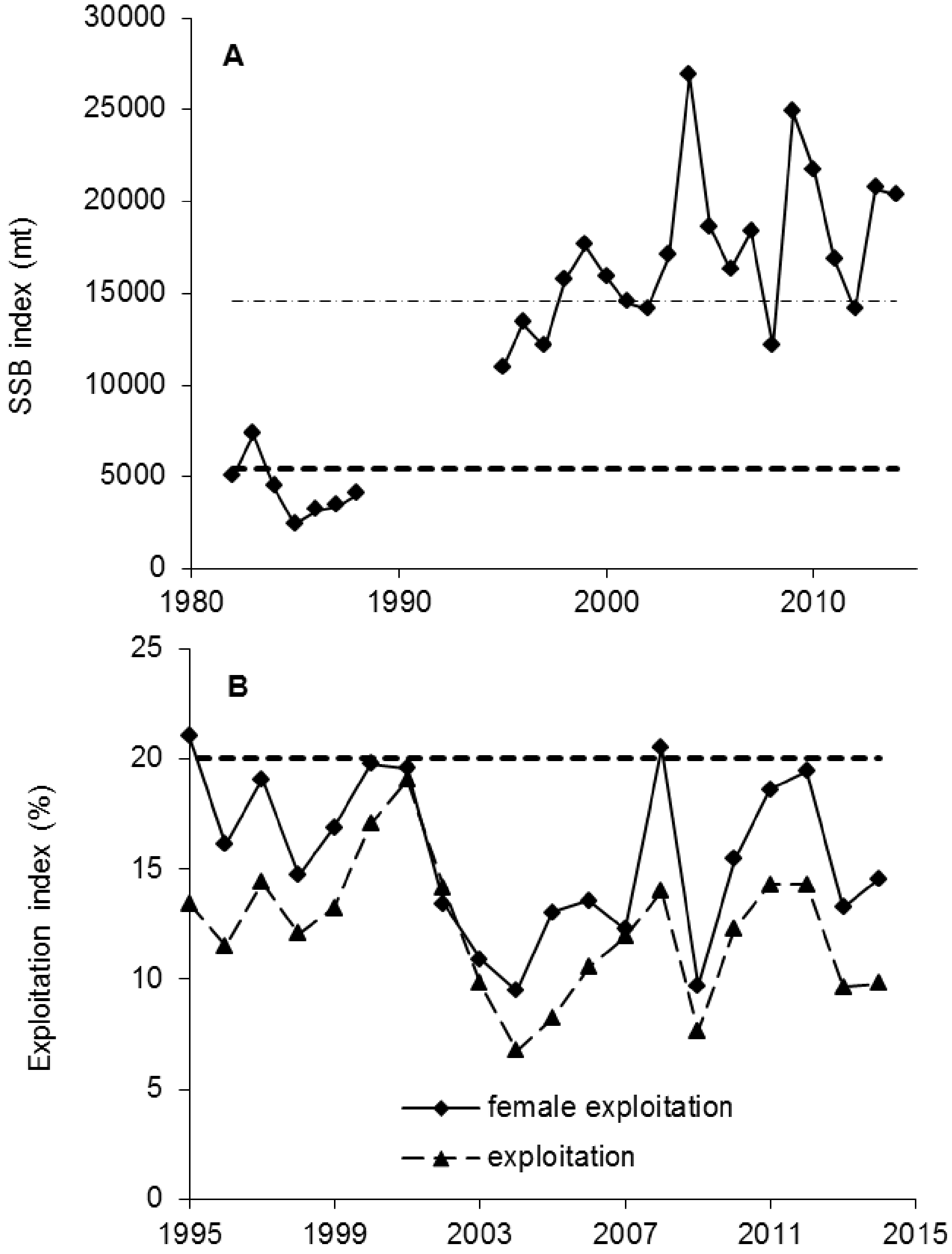

Figure 25. Changes in the SSB index (A: top) and the total and female exploitation indices (B: bottom) for the ESS shrimp population. The dashed lines shows the LRP at 30% and USR at 80% of the mean SSB value during the 2000-2010 high-productivity period (A) and the removal reference of 20% for the exploitation index (B).

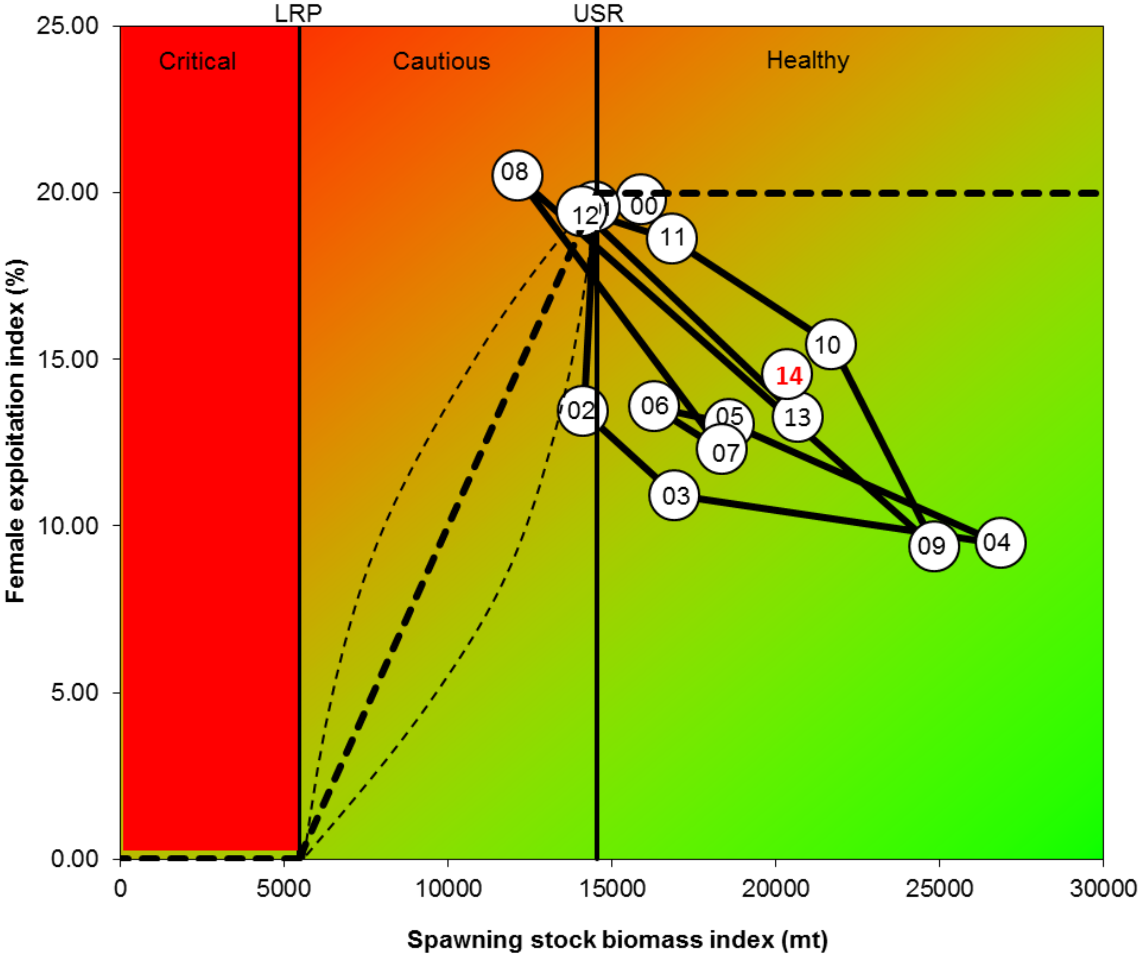

Figure 26. Graphical representation of the precautionary approach for Scotian Shelf shrimp. The dotted lines in the Cautious Zone represent a range of management actions possible, depending on whether the stock is stable, increasing or decreasing, or on trends in other indicators of stock or ecosystem health.

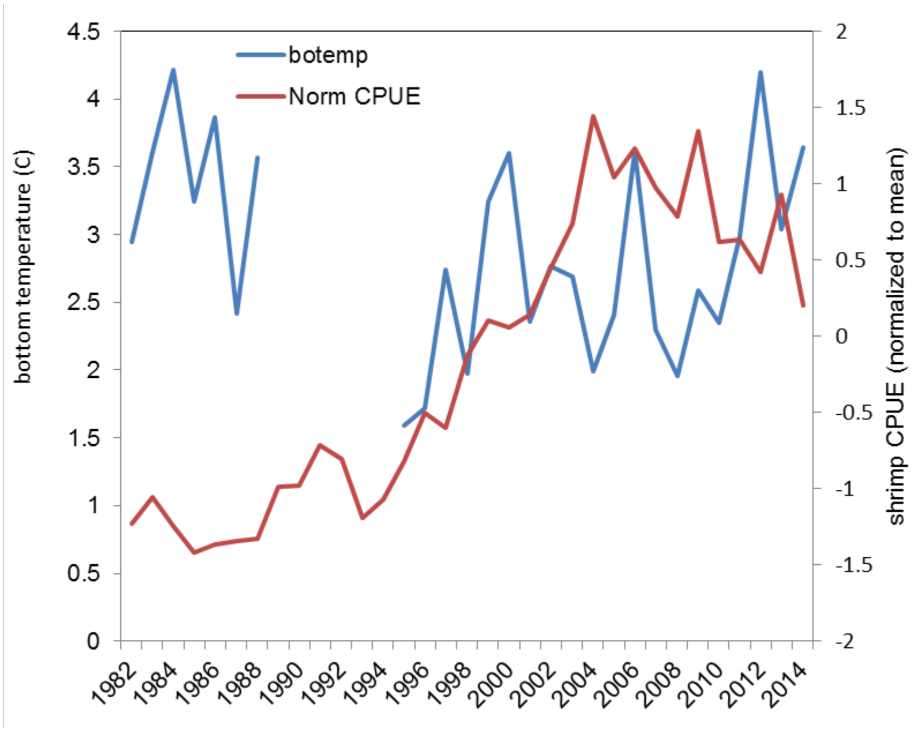

Figure 27. Annual time series of the mean normalized shrimp abundance index relative to the mean annual abundance index of the shrimp survey bottom temperature index.

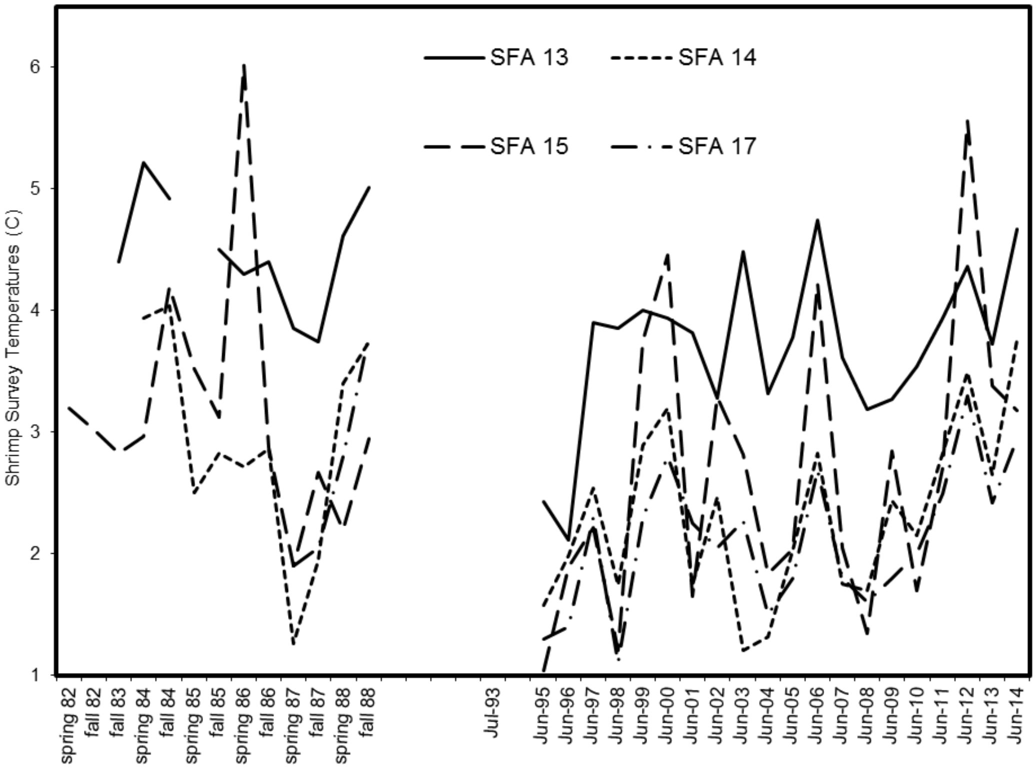

Figure 28. Mean bottom temperatures (°C) from shrimp surveys by SFA (13, 14, 15 and 17). Note that both spring and fall values were available from the earlier series (1982-1988), but only one survey (June) was conducted annually in the recent series.

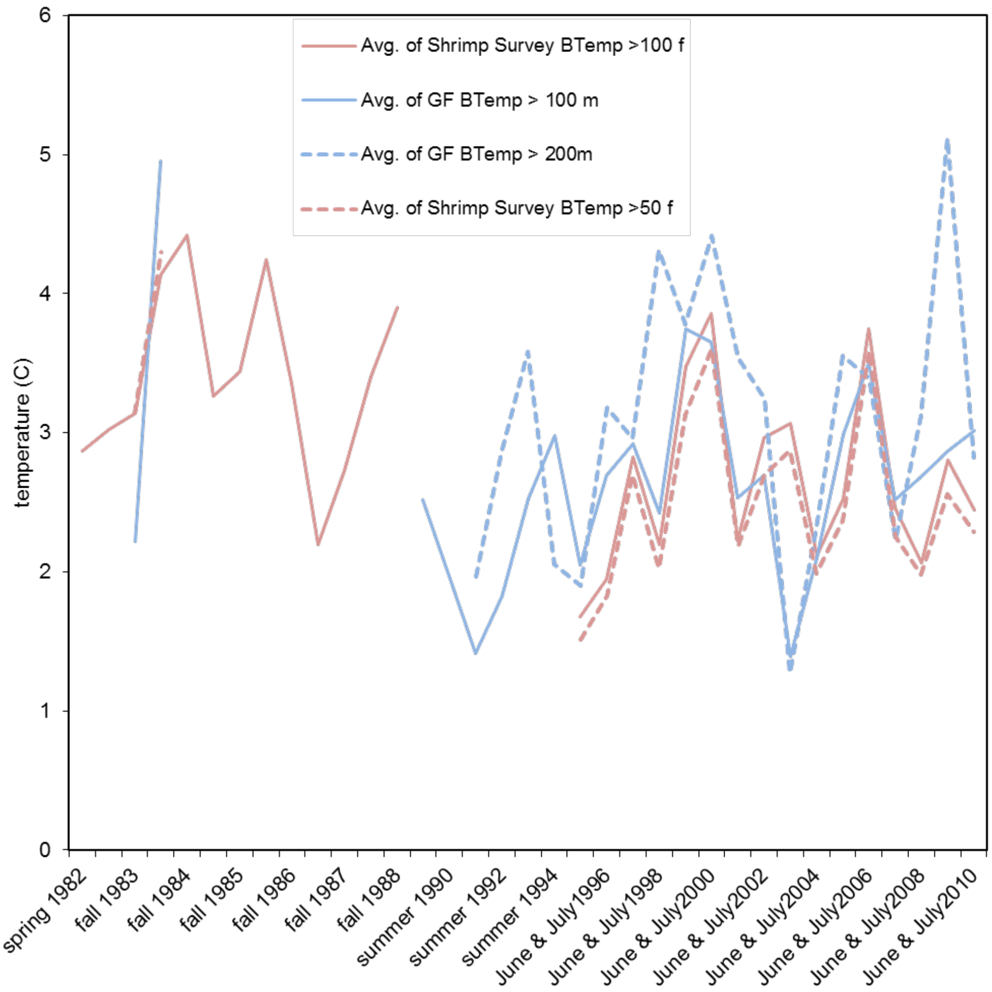

Figure 29. Comparison of average bottom temperatures among shrimp and groundfish surveys at various depths.

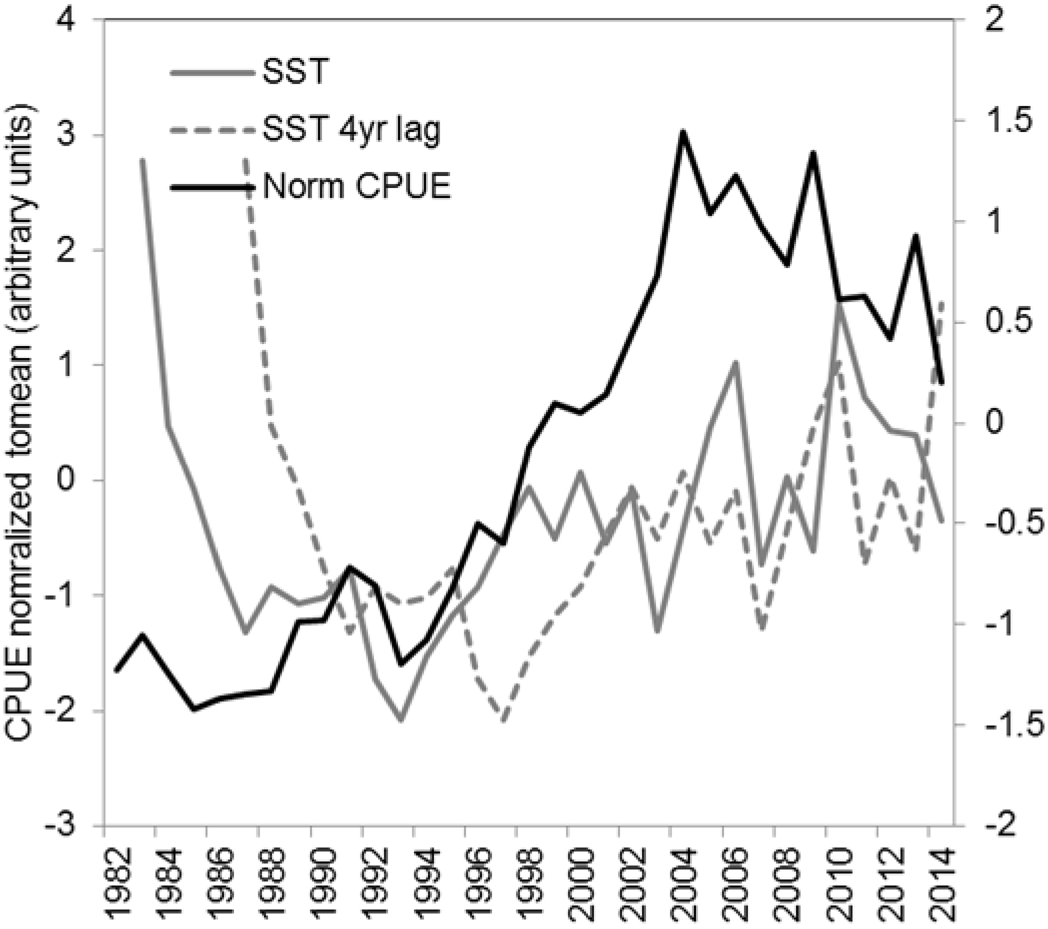

Figure 30. Annual time series of the mean normalized shrimp abundance index (black) relative to the lagged (4 years) and mean spring SST index series, unlagged and 4-year lagged.

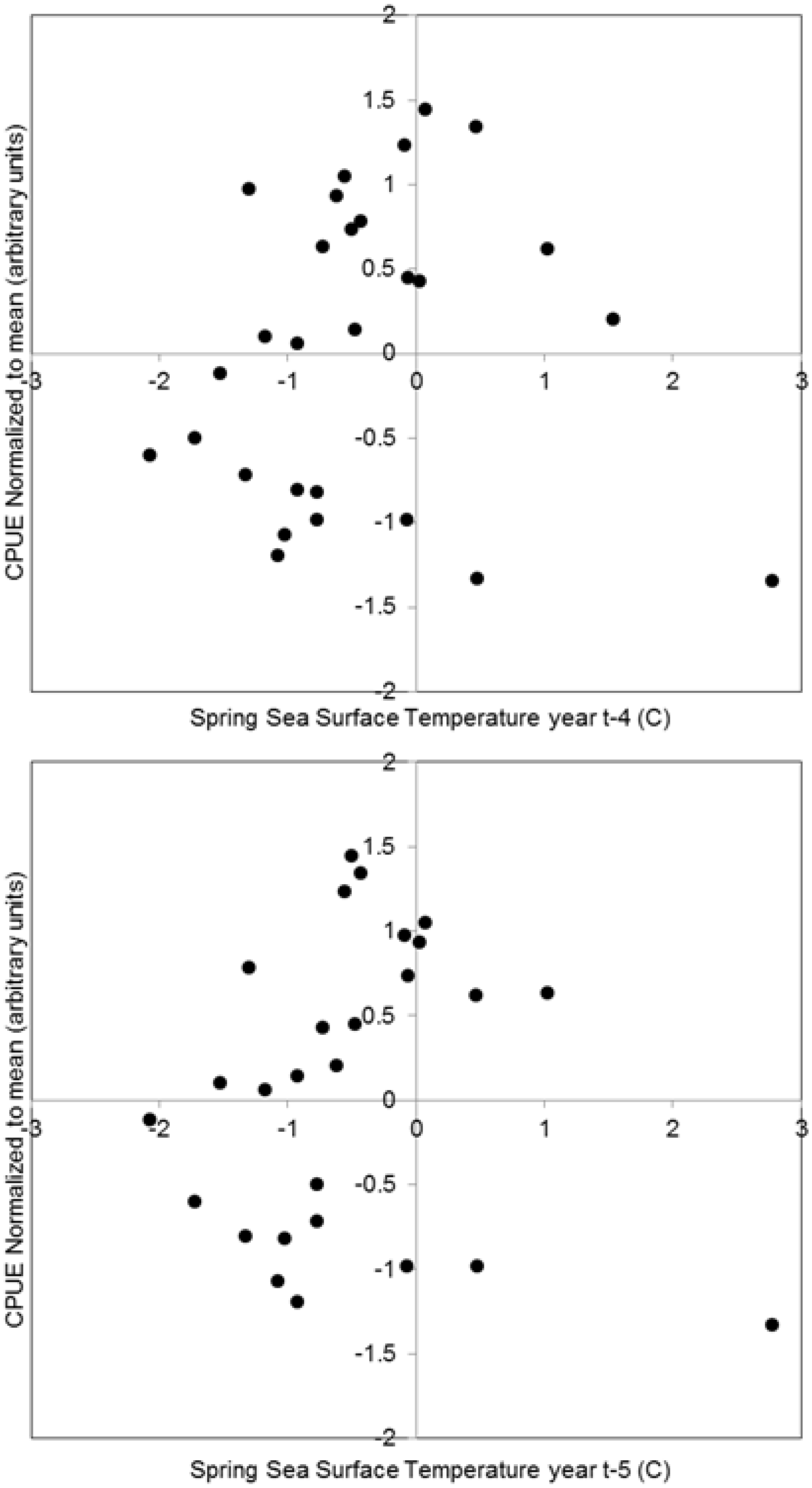

Figure 31. Correlations of the annual time series of the mean normalized shrimp abundance index relative to spring SST lagged by 4 (top panel) or 5 (bottom panel) years.

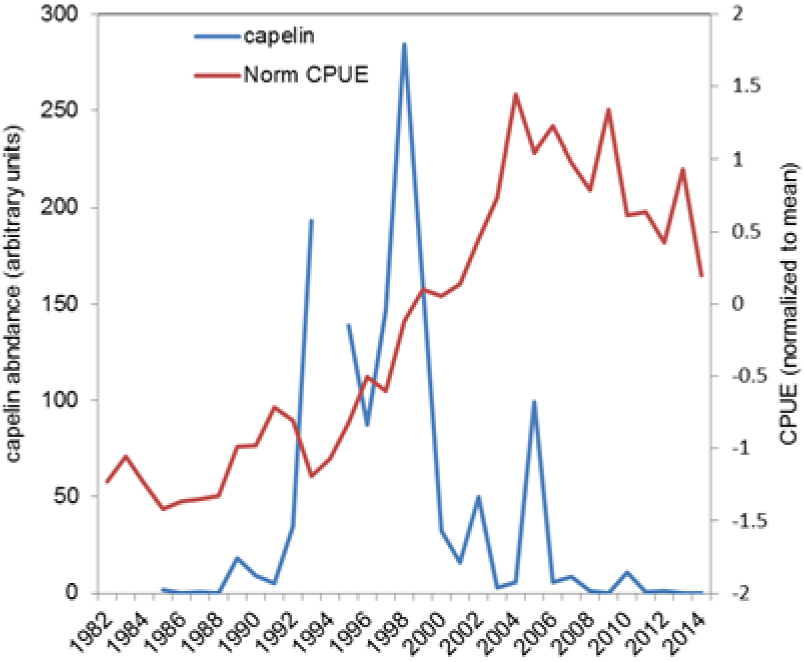

Figure 32. Annual time series of the mean normalized shrimp abundance index (red) relative to the mean Capelin annual abundance index from 1982-2014.

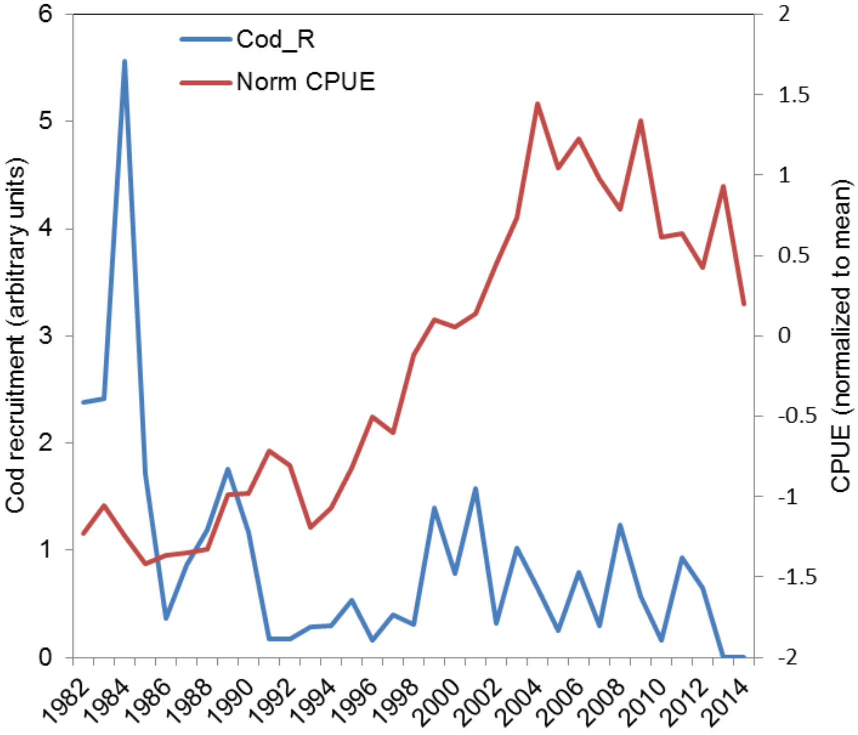

Figure 33. Annual time series of the mean normalized shrimp abundance index relative to the mean annual Cod recruitment index from 1982-2014.

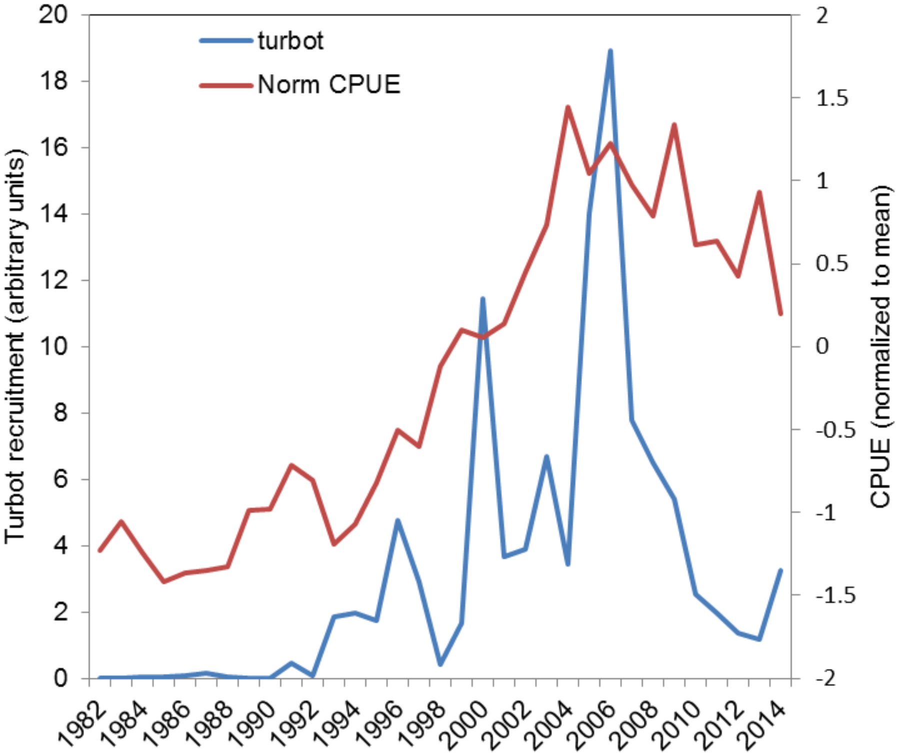

Figure 34. Annual time series of the mean normalized shrimp abundance index relative to the Turbot recruitment (<30 cm) index from 1982-2014.

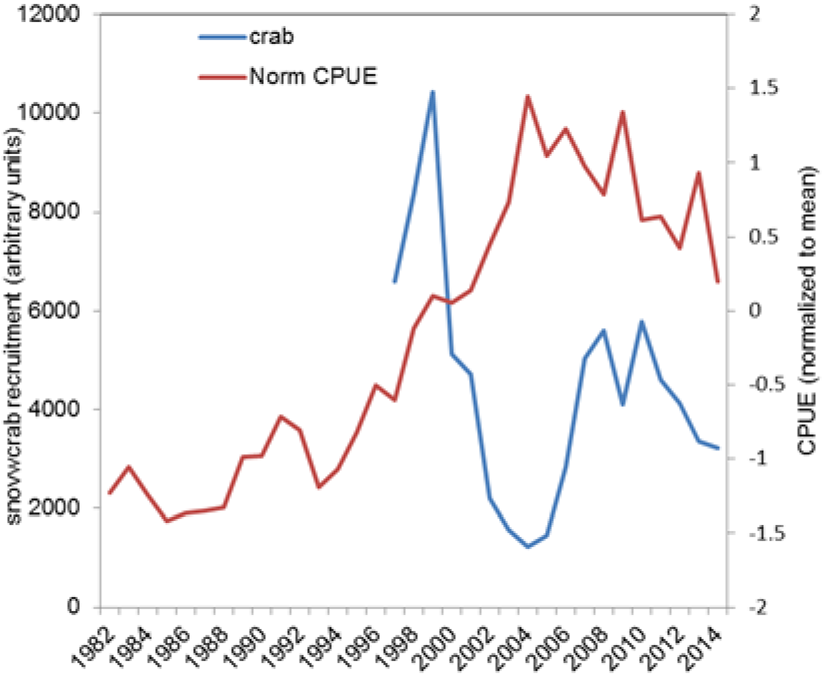

Figure 35. Annual time series of the mean normalized shrimp abundance index relative to the Snow Crab pre-recruit index from 1982-2014.

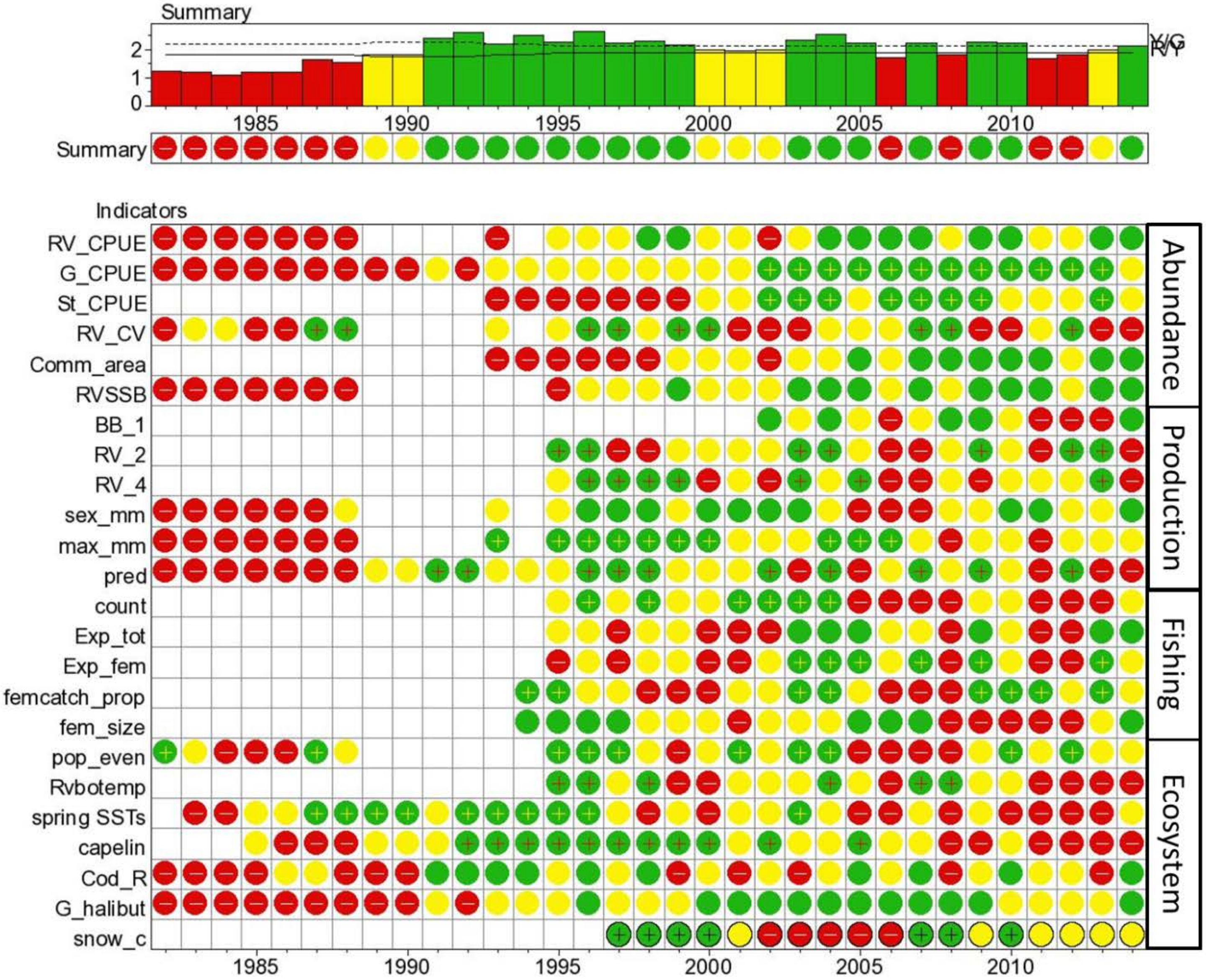

Figure 36. The Traffic Light Analysis summary from 1982-2014.

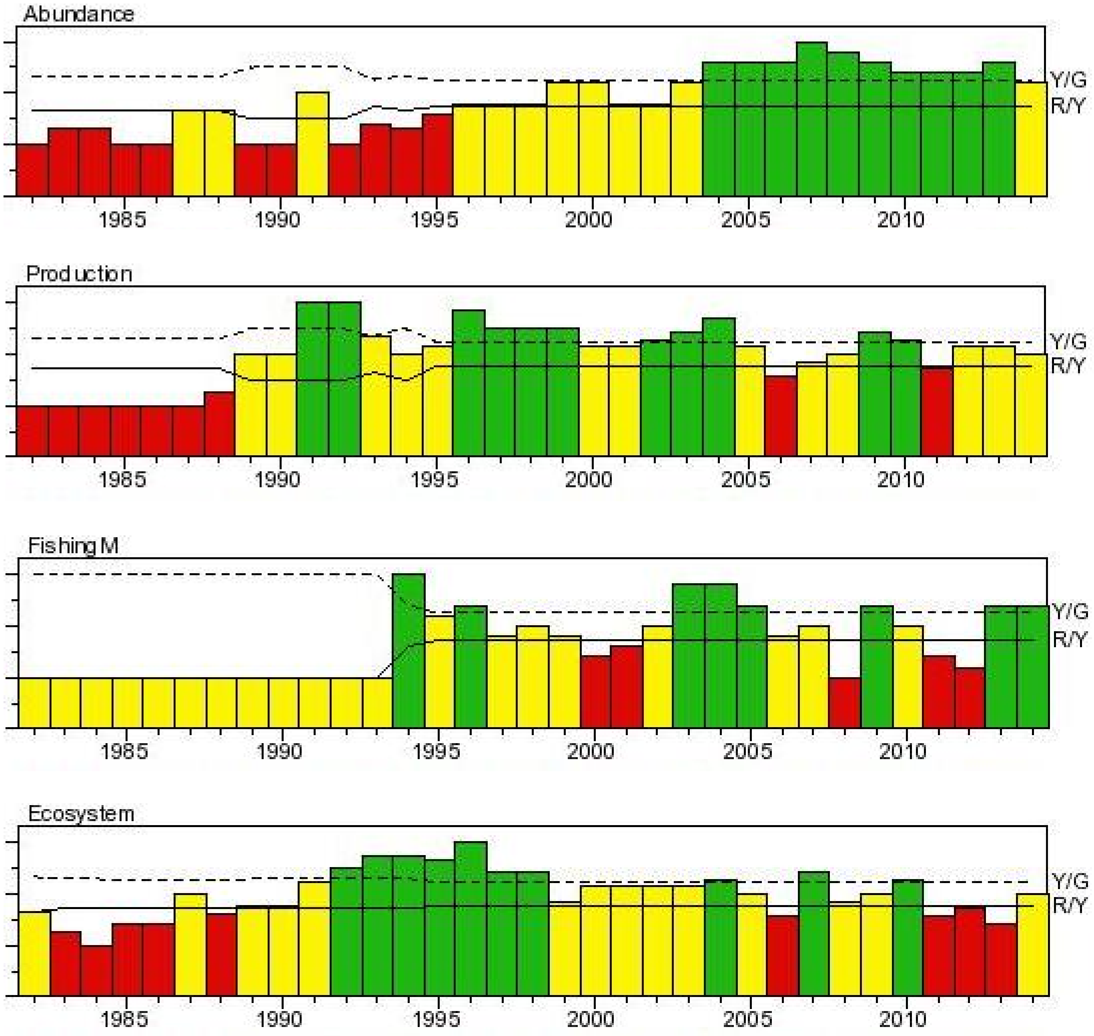

Figure 37. The Traffic Light Analysis characteristic for Abundance, Production, Fishing Mortality and Ecosystem summaries from 1982-2014.

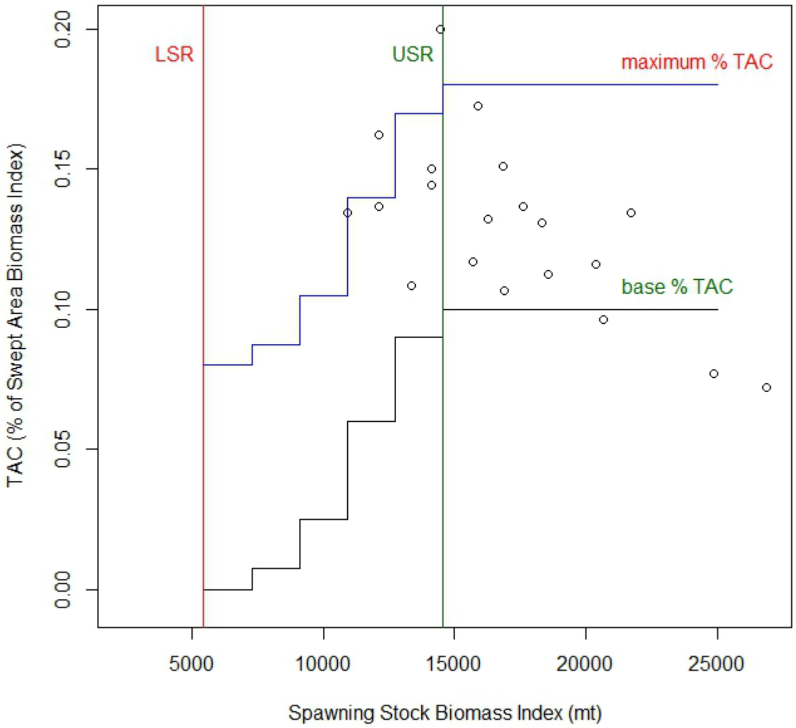

Figure 38. The minimum (baseTAC) and maximum (baseTAC plus maximum of tlaTAC) total allowable catches possible using the HCR model, relative to 10% intervals of the mean 2000-2010 SSB. Open circles are historical TACs as proportions of the preceding year's swept area biomass.

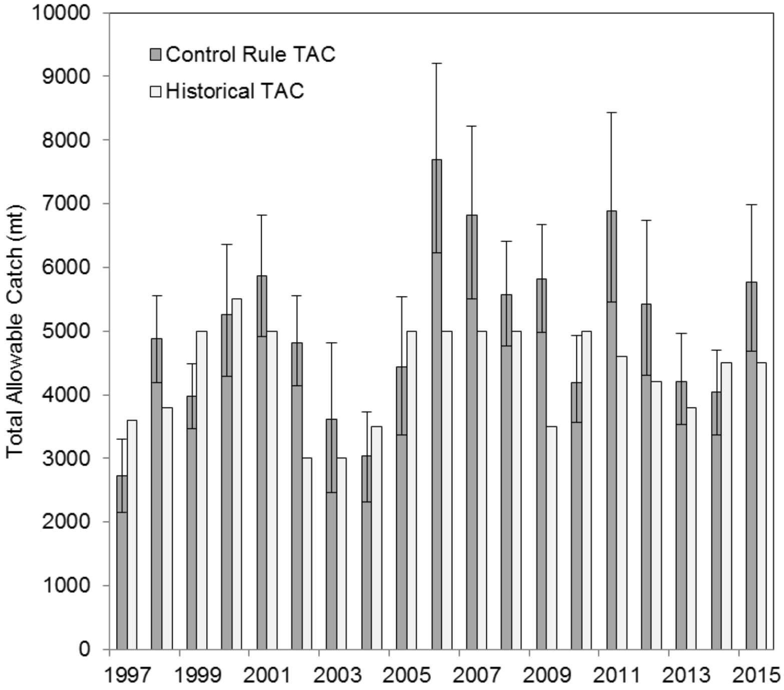

Figure 39. Retrospective analysis of historical TACs versus HCR TACs from the deterministic interpretation of the traffic light results using the HCR model from 1997-2015.

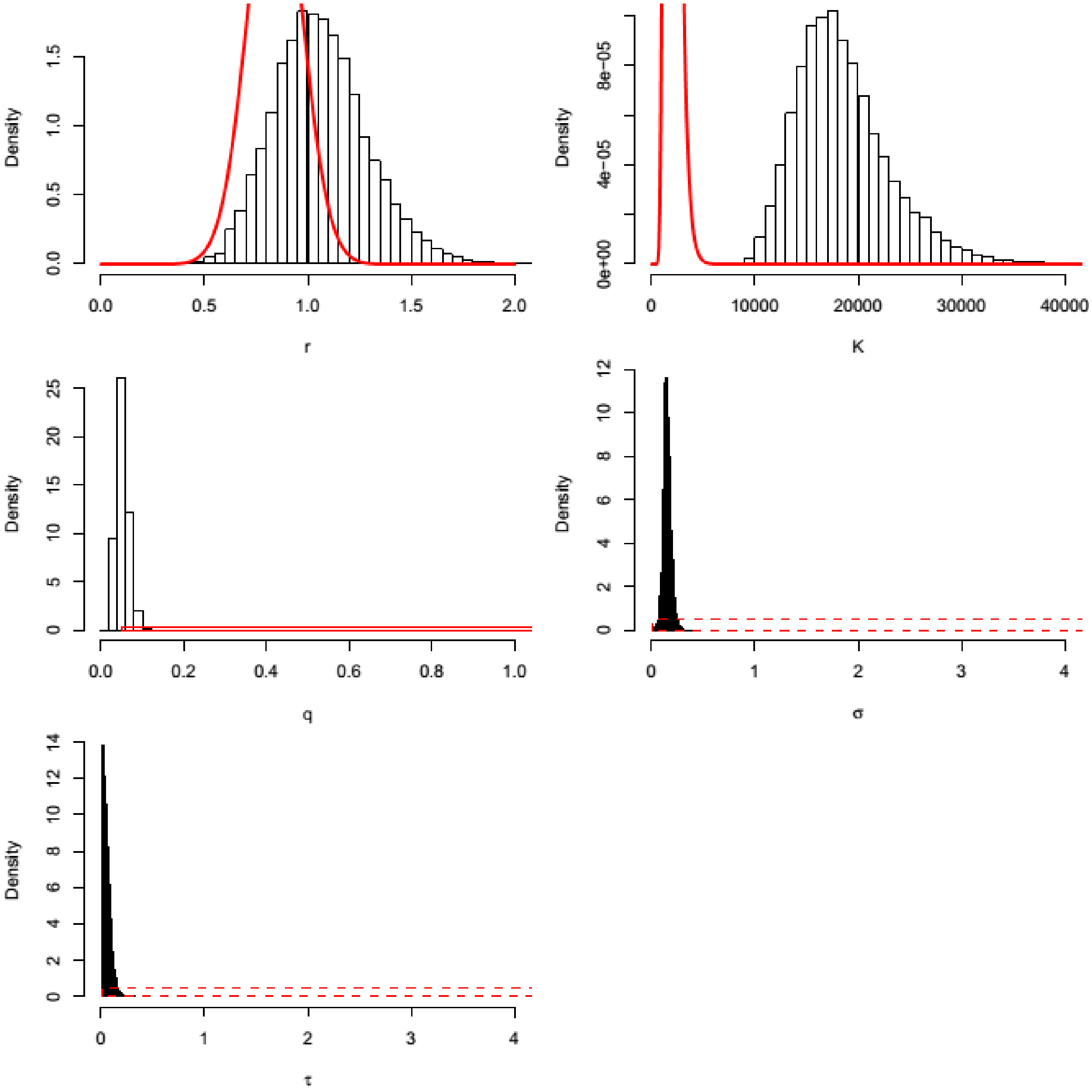

Figure 40. Prior (red dashed line) and posterior distributions (bars) of BDM parameters using the standardised fishery catch rate series as the biomass index.

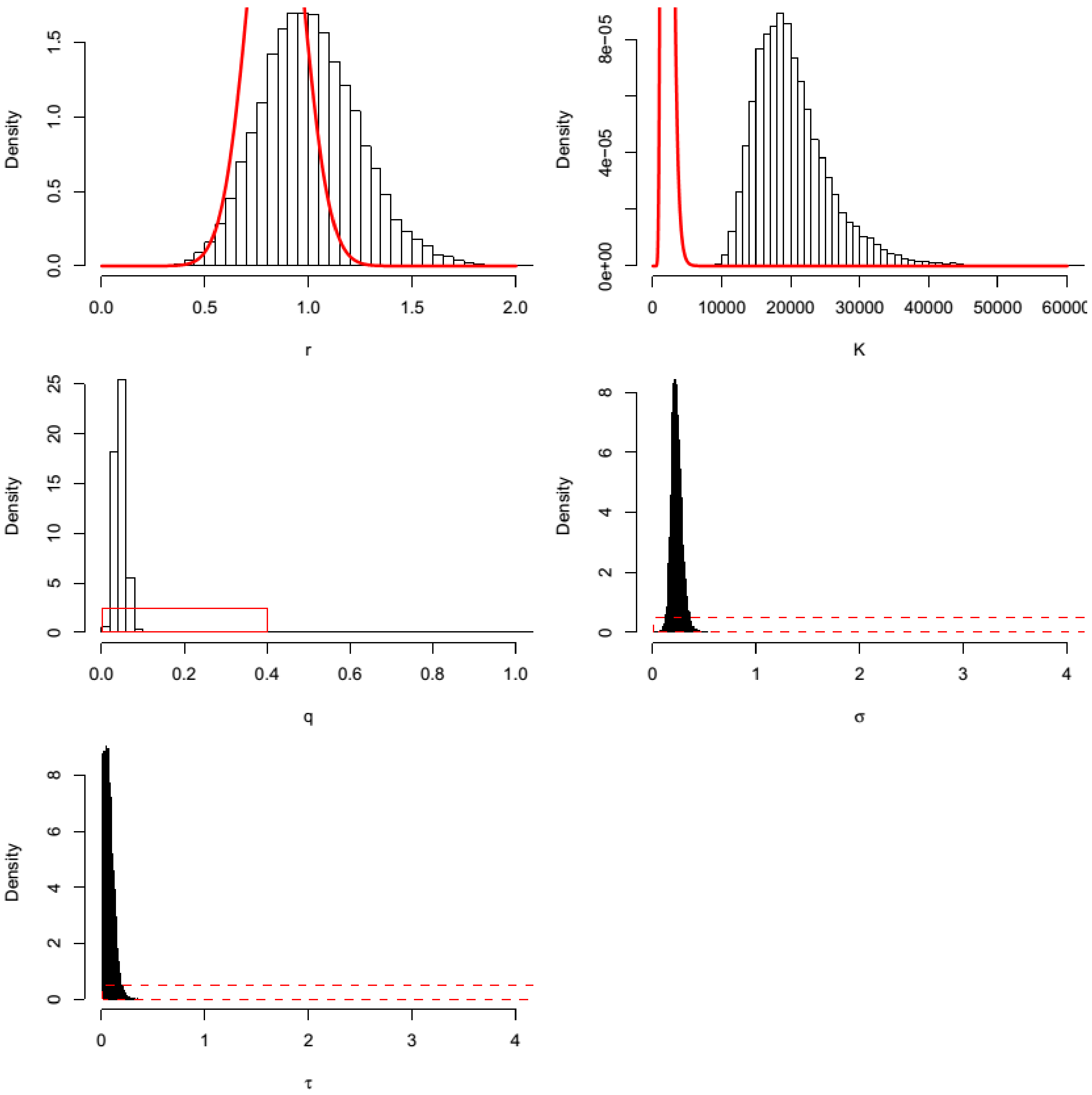

Figure 41. Prior (red dashed line) and posterior distributions (bars) of BDM parameters using the Gulf fishery catch rate series as the biomass index.

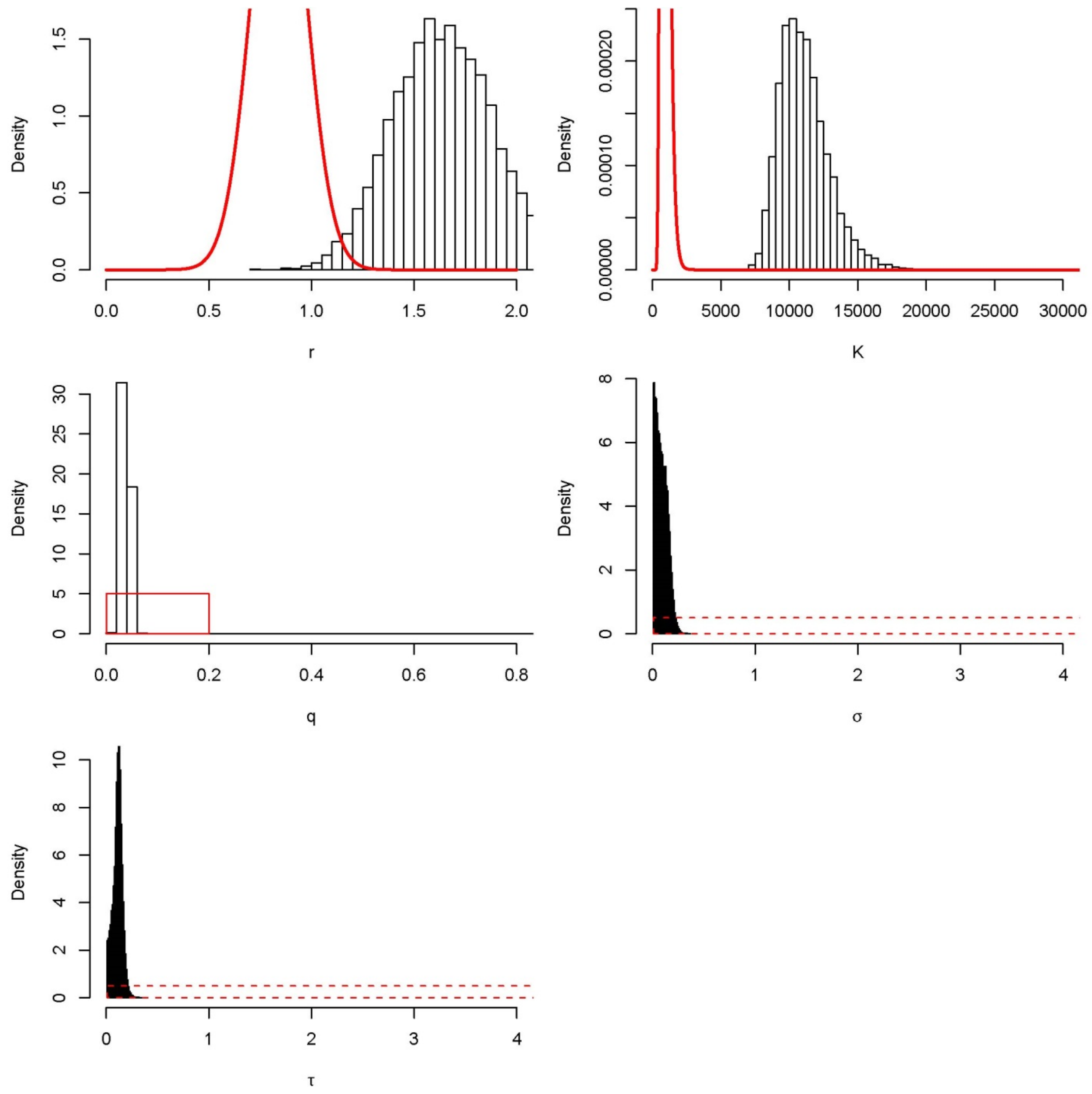

Figure 42. Prior (red dashed line) and posterior distributions (bars) of BDM parameters using the survey catch rate series as the biomass index.

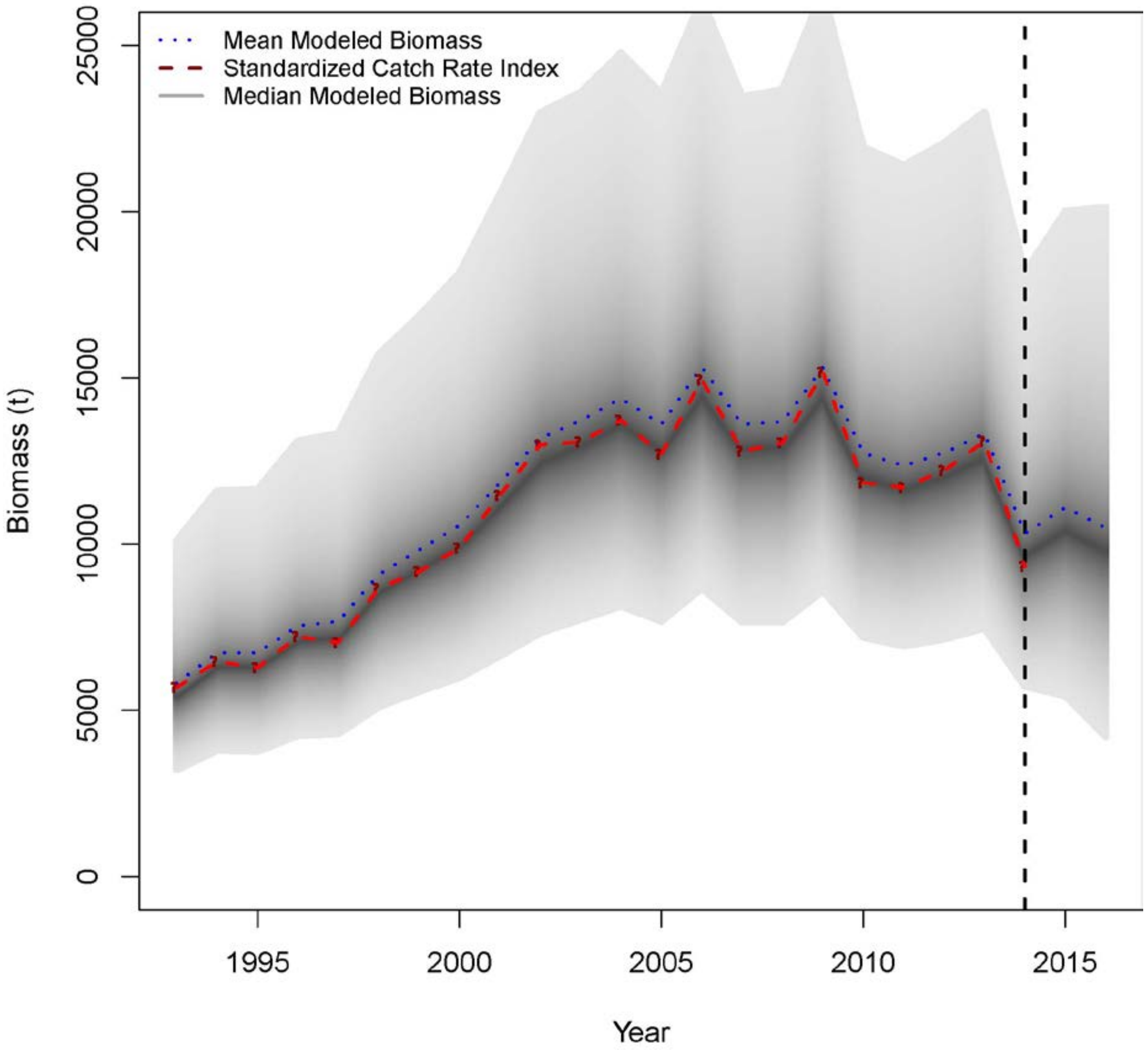

Figure 43. Modelled biomass estimate (grey polygon 95% limits) using the standardised fishery catch rates as the biomass index from 1992-2014 and projected to 2016. Dark grey line represents the median estimated biomass, blue stippled line represents the mean modelled biomass and the red line represents the survey biomass corrected by the median estimate of q. The vertical dashed line represents the end of the time series of the index and the following two years represent model projections given fixed landings of 5000 t.

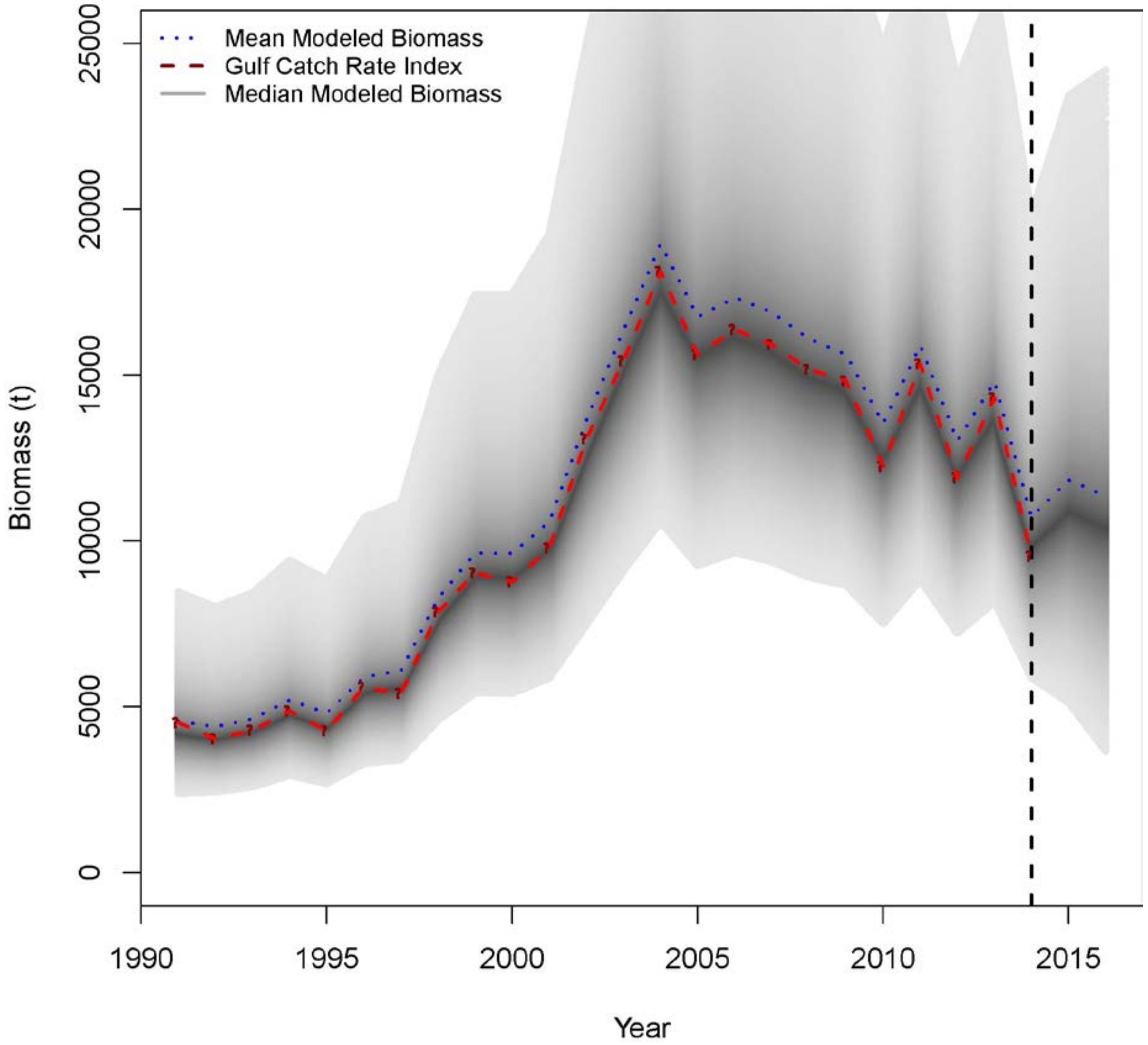

Figure 44. Modelled biomass estimate (grey polygon 95% limits) using the Gulf fishery catch rates as the biomass index from 1992-2014 and projected to 2016. Dark grey line represents the median estimated biomass, blue stippled line represents the mean modelled biomass and the red line represents the survey biomass corrected by the median estimate of q. The vertical dashed line represents the end of the time series of the index and the following two years represent model projections given fixed landings of 5000 t.

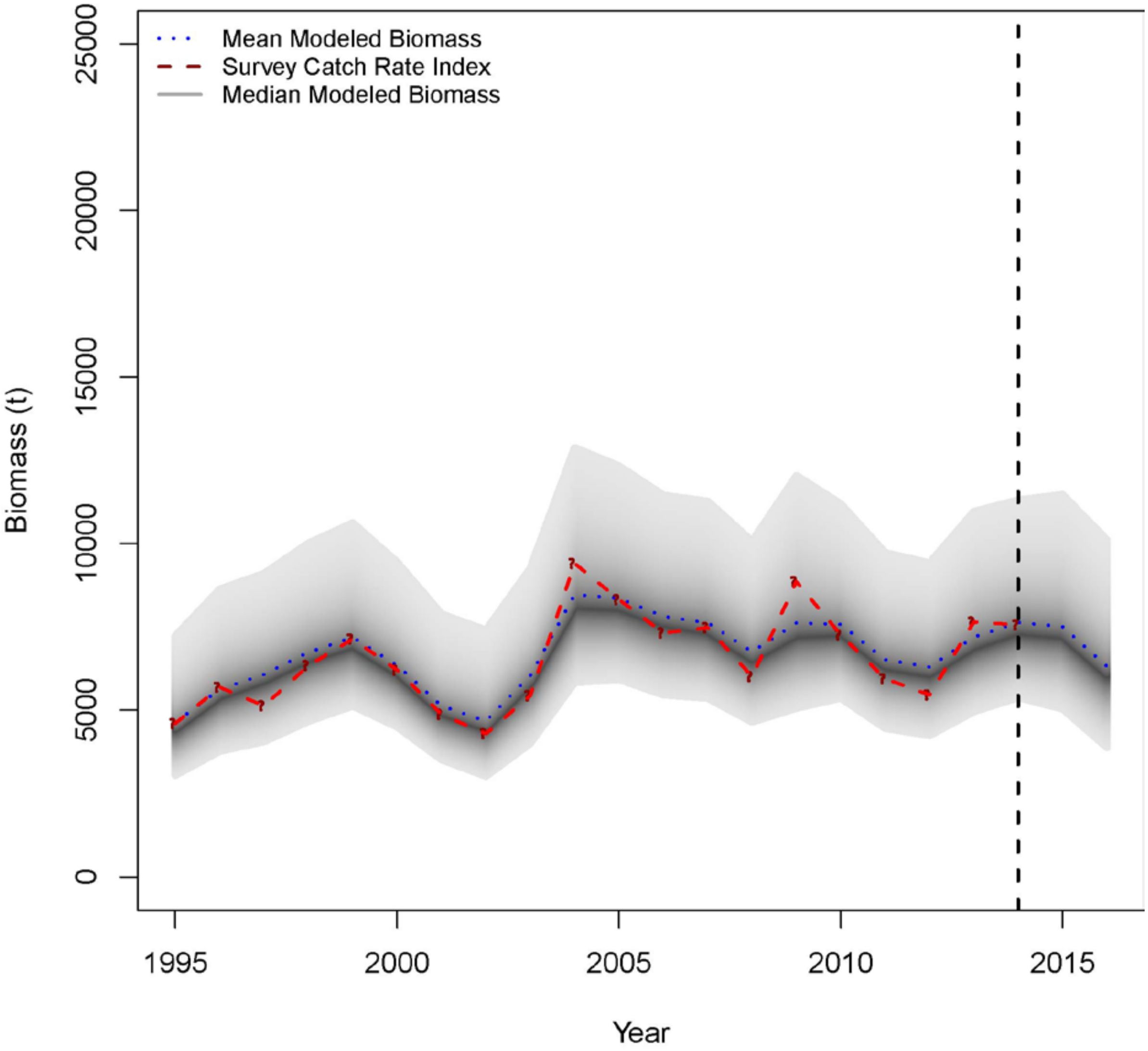

Figure 45. Modelled biomass estimate (grey polygon 95% limits) using the survey catch rates as the biomass index from 1992-2014 and projected to 2016. Dark grey line represents the median estimated biomass, blue stippled line represents the mean modelled biomass and the red line represents the survey biomass corrected by the median estimate of q. The vertical dashed line represents the end of the time series of the index and the following two years represent model projections given fixed landings of 5000 t.

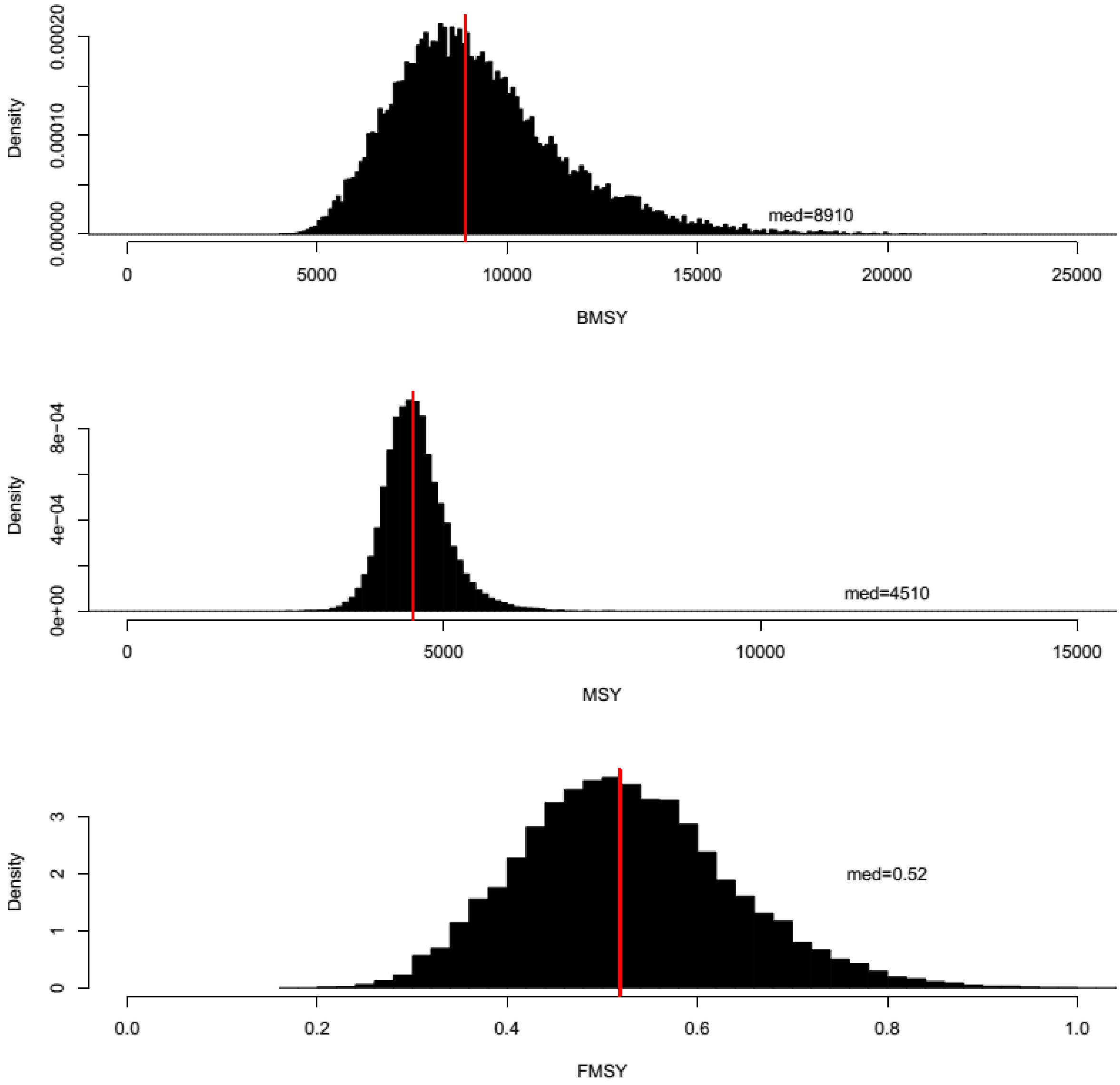

Figure 46. Stochastic MSY reference points estimated from the BDM model using the standardised fishery catch rates as the biomass index.

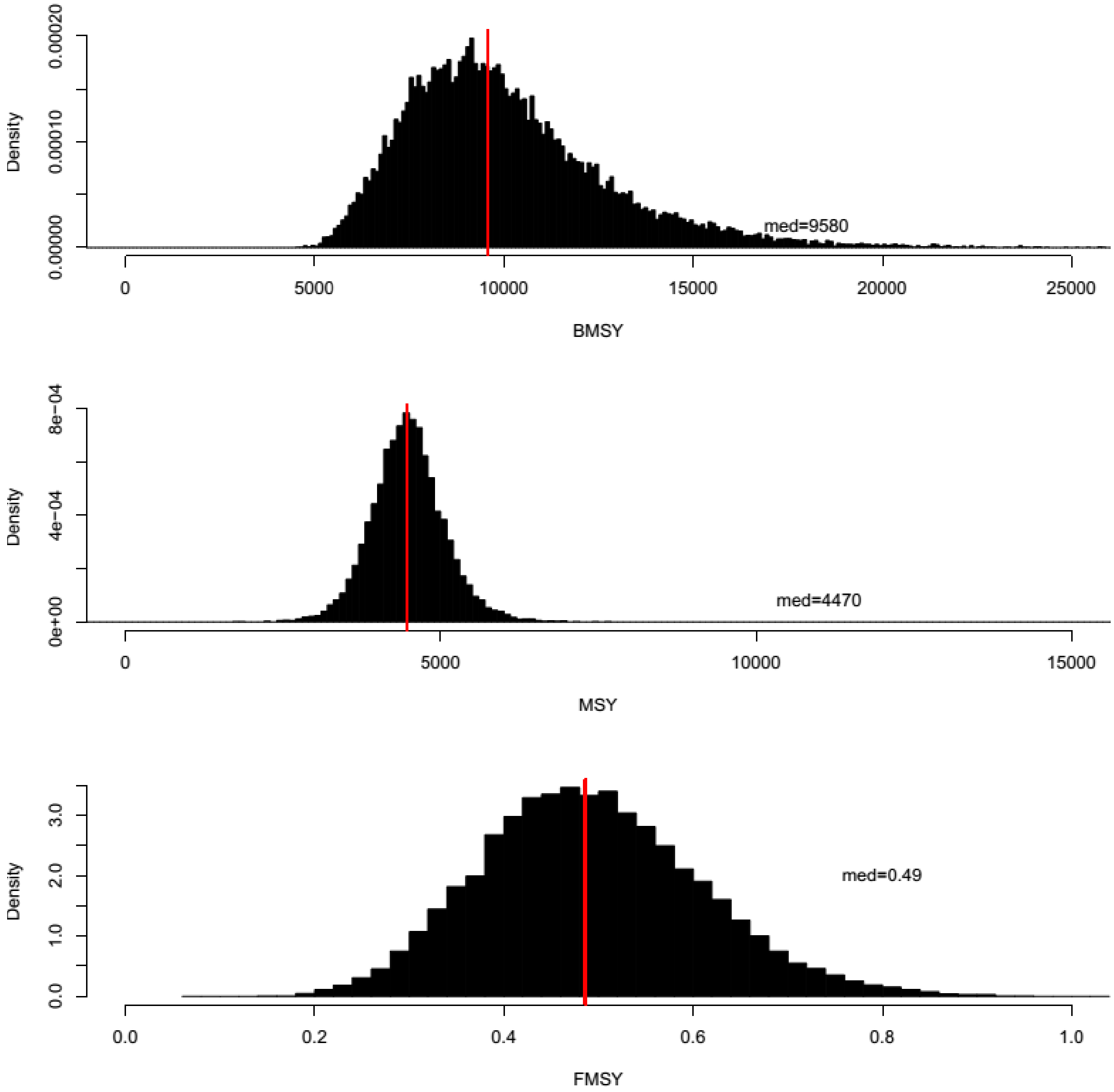

Figure 47. Stochastic MSY reference points estimated from the BDM model using the Gulf fishery catch rates as the biomass index.

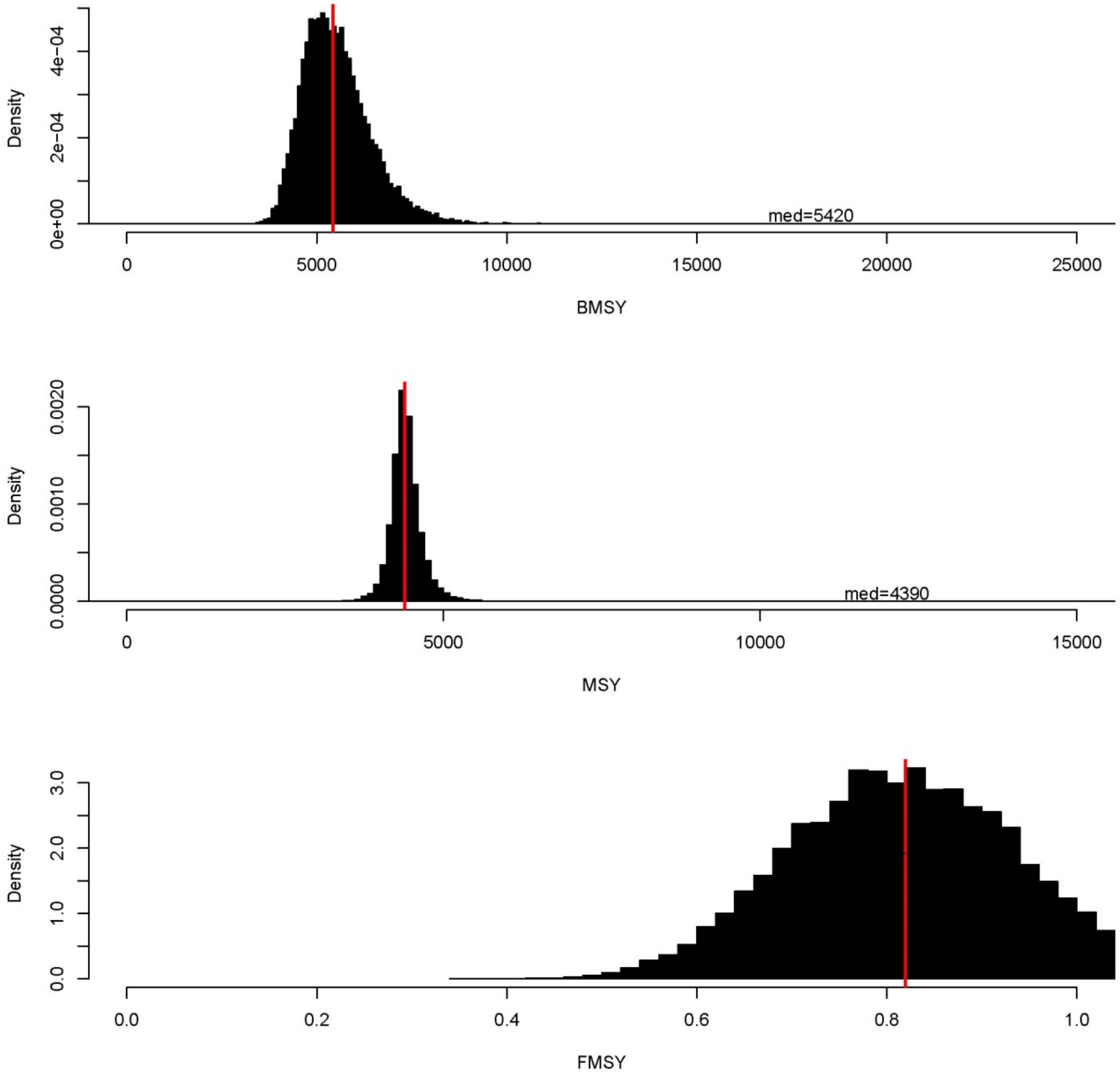

Figure 48. Stochastic MSY reference points estimated from the BDM model using the survey catch rates as the biomass index.

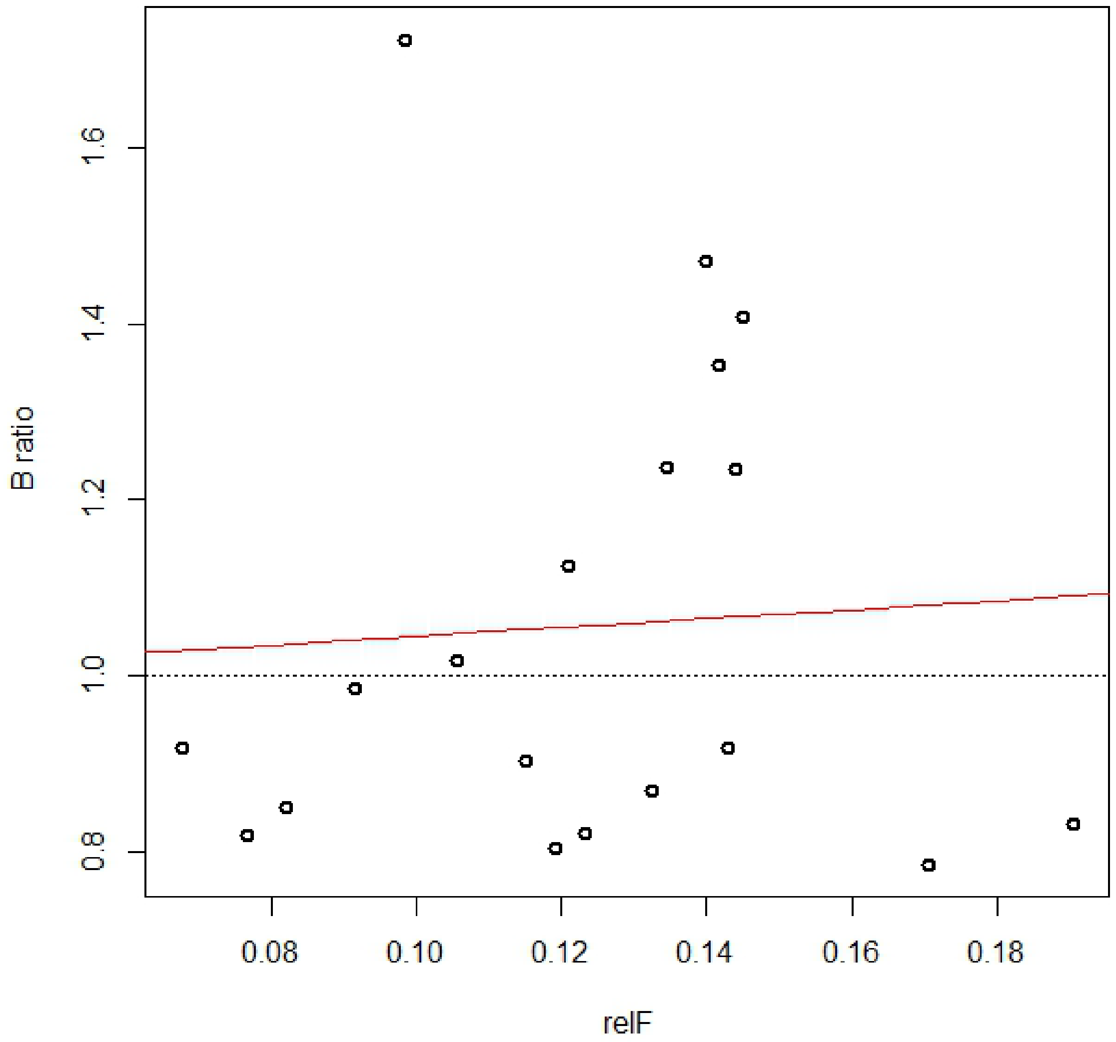

Figure 49. Biomass ratio in year t (B_t/B_{t-1}) versal relative fishing mortality in year t-1 (catch/B)$_{t-1}$

APPENDICES

APPENDIX 1: HIGH PRODUCTIVITY INDICATOR THRESHOLDS

It was suggested that consideration should be given to basing the indicator thresholds that define the boundaries of red/yellow/green indicators (33rd and 66th percentiles, respectively, or reversed for negative polarity indicators) on the current high productivity period for this stock as opposed to the entire data series. The panels below show the indicator threshold values at the 33rd and 66th percentiles based on the entire series of data available (left panel) as has been done throughout the history of the shrimp assessment using the Traffic Light Analysis, and the same 33rd and 66th percentile thresholds based only on data from 2000-2010 (the same fixed time period adopted to estimate biological reference points for this stock in the Precautionary Approach (PA)). Reversed polarities are reflected in the figures as described in the Framework and previous stock assessment documents. The 2000-2010 period was selected for this discussion because it is the same period that has been adopted for the PA, although other options exist.

Reviewers also suggested that biological thresholds (rather than the arbitrary percentiles) should be explored where possible (e.g. the preferred temperature range for shrimp is relatively well understood). Such biologically based thresholds are the subject of future work and are not explored here.

The Traffic Light indicator histograms that have been presented in shrimp stock assessment documents for several decades are produced through scripts in the Virtual Data Centre (VDC). Certain modifications (e.g. indicator polarity, threshold percentiles) can easily be made with the program in the VDC, but there is no straightforward way to change the range of data/years upon which the thresholds are based. As a result, and because the VDC is now nearly obsolete, the figures are instead generated using code independent of the VDC and presented as a more conventional time series rather than the Traffic Light histograms.

The suitability/relevance of the 2000s-truncated thresholds (i.e. 33rd and 66th percentiles of the 2000-2010 data) are discussed above each comparative figure. The Abundance, Production, Fishing Effects and Ecosystem Characteristics are also presented as calculated from annual percentile ranks based on all data (the historical Traffic Light method) compared to percentile ranks relative to 2000-2010 data only.

Survey Catch Per Unit Effort

The 2000s-truncated data series excludes the early period of very low survey catch rates before the collapse of the groundfish stocks. As a result, the 2000s-truncated thresholds are higher (more conservative) and are probably more relevant to the goals of this fishery to retain contemporary (high) survey catch rates/biomass (Figure A1).

Gulf Catch Per Unit Effort

The exclusion of nearly all of the period of very low catch rates during the early expansion of the shrimp stock and the development of the fishery results in much more conservative thresholds based on the 2000s-truncated data series. The result is that only the years of the absolute highest Gulf vessel catch rates are green values, and recent values are either yellow or red. Given that Gulf catch per unit efforts (CPUEs) have been on a declining trend for over a decade, and some recent values have been quite low, this modification (although quite extreme) may better reflect this index of abundance relative to the goals of the fishery to retain contemporary high catch rates (Figure A2).

Standardised Maritimes Vessels CPUE

The 2000s-truncated thresholds capture only the period of highest abundance for this index, and exclude the historical lows and recent moderately low values of the Standardised Maritimes vessel CPUE index. As a result, both thresholds are more conservative (Figure A3). Although this conservative interpretation of the data using the 2000s-truncated thresholds is consistent with the management and conservation of the contemporary stock, the increase in the RY threshold narrows the yellow range to such a degree that changes between green and red indicator values are prone to occur even when the data series has not changed in any biologically significant way.

Survey Coefficient of Variation

The 2000s-truncated data series excludes some of the least variable survey years and includes the highest. The result is that the yellow-red (YR) threshold is quite a bit higher (Figure A4). The yellow-green (YG) threshold is also slightly higher, but not very changed. Overall, the truncated thresholds probably better reflect what might be more meaningful signals in this fishery independent index of dispersion by virtue of a broader yellow zone, although they are less conservative then those based on the entire survey data series.

Commercial Fishing Area

The thresholds based on the 2000s-truncated data include much of the period of highest catch rates, and exclude most of the very low catch rate areas earlier in the data series. As a result, both index thresholds occur at higher levels that are more conservative and relevant to the contemporary management and conservation of this stock (Figure A5).

Spawning Stock Biomass (SSB)

The 2000s truncated data series excludes the period of low SSB early in the data series. As a result, both thresholds are raised, particularly the YR, making the truncated data indicators more conservative (Figure A6). However, the relatively larger increase in the RY than the YG threshold results in a narrowing of the yellow zone that is likely to result in inter-annual changes in indicator colour that may not be biologically relevant given the noisiness of the SSB index which derives from a fairly small survey. Given that 30% and 80% of the mean of the SSB index from 2000-2010 are currently accepted as the lower and upper stock reference points, respectively, it would be more appropriate and consistent to use these same thresholds to define indicator thresholds in the index.

Belly-bag Index

The belly-bag index series is relatively short (only beginning in 2002), so the 2000s-truncated series excludes three very poor and one very good recruitment year (2011-13 and 2014, respectively). The truncated data series raises YG threshold, while the RY threshold remains relatively unchanged compared to thresholds based on the full data series (Figure A7). The 2000s-truncated YG threshold may be more appropriate than the entire data series because it only assigns green lights to the four belly-bag years that have been considered (and generally proven) to be “strong year classes”.

Age 2 Abundance Index

The 2000s-truncated data series excludes both high and low Age 2 index values, but includes the very high Age 2 index value, which has a relatively greater influence on thresholds based on the truncated time series than on the full data series. As a result, the YG threshold is lower and the RY threshold is slightly higher using the 2000s-truncated data series, which is slightly less conservative than thresholds based on the entire data series (Figure A8).

Age 4 Abundance Index

Similarly to the Age 2 index, the 2000s-trunctaed Age 4 abundance index data also includes the very high value associated with the passage of the 2001 year class. However, because some of the high Age 4 index values from the late 1990s are excluded, the 2000s-truncated thresholds are slightly lower (less conservative) than the entire dataset (Figure A9).

Mean Size at Sex Transition

The 2000s-truncated thresholds exclude the smallest sizes at sex transition from the 1980s-1990s. As a result, the RY threshold is raised (more conservative) while the YG threshold remains similar to the threshold from the entire data series (Figure A10). The 2000s-truncated data series provides thresholds that are more consistent with the contemporary goals of the fishery.

Mean Maximum Size

The 2000s-truncated data series excludes some years of very small mean maximum sizes early in the data series, as well as some of the largest sizes from the late 1990s and some recent low values since 2010. While the YG threshold is similar to the thresholds based on all data, the 2000s-truncated RY threshold is quite a bit higher (Figure A11). The 2000s-truncated data provides thresholds that are more consistent with a conservative approach to the assessment of this stock, and would more appropriately capture the steady decline in mean maximum size in the past 20 years.

Predator Abundance

The 2000s-truncated data excludes the pre-1990 period of high predator abundance and results in a more conservative (lower) YR threshold (Figure A12). The result is that red values are nearly twice as frequent in the past 15 years based on 2000s-truncated thresholds. Similarly to the Cod recruitment index, the narrow gap between the GY and YR 2000s-truncated thresholds may result in frequent red index values due to noise in the data series.

Commercial Count

The 2000s-truncated data excludes comparable high and low average commercial count index values from before and after 2000 and 2010, respectively. As a result, the 2000s-truncated data does not change the thresholds significantly relative to the thresholds based on the entire data series (Figure A13).

Total Exploitation Index

The 2000s-truncated data series excludes several years of the highest exploitation rates in the data series (which are still low, relative to most fisheries). The result is that both the RY and the YG thresholds are slightly more conservative (lower) than those using the entire data series (Figure A14), but the influence on annual indicator colours in the data series is minimal, relative to the use of the entire data series.

Female Exploitation Index

The 2000s-truncated data series excludes high female exploitation rates in the late 1990s and the thresholds are more strongly influenced by the low female exploitation rates in the mid-2000s, resulting in more conservative threshold (particularly the YR threshold, Figure A15). Red indicator values will be triggered at quite modest female exploitation rates (approximately 15%), given that the removal reference for the PA for this stock is 20%.

Proportion of Females in the Catch

The 2000s-truncated thresholds exclude the highest proportion of females on record and include the lowest. The result is that the RY threshold is lowered, making the index slightly less conservative using the truncated data series (Figure A16).

Female Size

The 2000s-truncated data series excludes the largest average female sizes on record and includes the lowest. As a result, both thresholds are less conservative, but particularly the RY threshold (Figure A17).

Population Evenness

This suitability of this index is being reconsidered at present. However, the 2000s-truncated data series captures the highest and lowest indicator values on record, spreading the thresholds (broadening the yellow zone, Figure A18).

Bottom Temperature

The 2000s-truncated data series excludes some very low temperatures in the late 1990s and some very high post-2010 temperatures. The result is that the YR threshold is lower (more conservative) while the YG threshold is nearly identical to the thresholds from the full data series (Figure A19). As discussed in the framework meeting, biologically based thresholds should be possible here based on what is known of shrimp temperature preferences/tolerances.

Biologically-based temperature thresholds will likely have five zones. A central green zone near the optimum flanked by a yellow and then red zone towards unfavourably cold and warm temperatures. More research (literature review) is required to defend appropriate thresholds and to consider appropriate/relevant temperature data sources, so it is not presented here.

Sea Surface Temperature

The 2000s-truncated data series excludes historical and recent warmer temperatures, resulting in slightly closer and higher thresholds (slightly less conservative; Figure A20). Given what is known about the temperature regime experienced by ESS shrimp relative to the species temperature tolerances, the truncated data series is likely more appropriate. Regardless, biologically based thresholds are being developed for this index.

Cod Recruitment Index

The thresholds based on the 2000s-truncated data series are much closer together, mostly due to a decrease in the YR threshold triggering a red index value (Figure A21). This change reflects the exclusion of the early parts of the data series when Cod were abundant and shrimp were not. The triggering of red values based on frequent fluctuations in the (noisy) Cod recruitment index in the past two decades are probably not meaningful, compared to the less frequent red index values using the entire data series (which may themselves not be very meaningful in most years, relative to the red values preceding 1990).

In this case, the 2000s truncated data series is likely to result in more changes in index colours, especially triggering red lights, due to noise in the data series that may not be particularly indicative of increased Cod predation on shrimp than using the entire data series, which captures the pre-1990 period of high Cod abundance when Cod predation was very likely a factor in low shrimp abundance. The truncated data index is, however, more conservative and is consistent with the management and conservation practices for this shrimp stock.

Turbot Abundance Index

The 2000s-truncated data series excludes the early period of very low turbot abundance at the same time that the shrimp stock was low, and includes all of the highest turbot abundance data.

As a result, both thresholds are much higher (more conservative, Figure A21). The thresholds based on the entire data series probably more realistically capture the period of highest turbot abundance as green years, although only a near complete crash in turbot abundance would trigger a red year based on all years.

Snow Crab Recruitment Index

The 2000s-truncated data series excludes the very high values from the late 1990s, resulting in a lowered RY threshold that is more conservative than the RY threshold derived from the entire data series (Figure A22)

Characteristics

The Abundance, Productivity, Fishing Effects and Ecosystem characteristics are calculated as the means of the percentiles (accounting for reversed polarity as needed) for annual indicator values relative to the entire available data range (“all data”, top panel) or relative to the 2000s-truncated data (“2000-2010”, bottom panel).

The 2000s-truncated thresholds result in a slightly more conservative Abundance characteristic because both the RY and the YG thresholds are slightly higher (Figure A23). Similarly, the Production Characteristic thresholds are slightly more conservative based on the 2000s-truncated data, particularly by raising the RY threshold (Figure A24). The Fishing Effects characteristic is very similar whether the thresholds are based on the 2000s-truncated data or the entire data series (Figure A25). The Ecosystem Characteristic is slightly more conservative based on the 2000s-truncated data because both the RY and the YG thresholds are slightly increased (Figure A26).

Discussion

The indicator colour thresholds based on 33rd and 66th percentiles of 2000s-truncated data provide improved or at least equally suitable values for the survey CPUE, survey CV, commercial fishing area, belly-bag, Age 2 index, Age 4 index, size at sex transition, maximum size, count, total exploitation, population evenness and the snow crab recruitment index. The only immediately apparently problematic or unsuitable indicators using the thresholds from the 2000s-truncated data are the standardised Maritimes vessels CPUE index (too little variability in 2000s-truncated data such that thresholds are very close together such that colours will vary based on non-significant data noise). The same is true of the Cod recruitment index. For the remaining indicators it is perhaps less clear cut. The Gulf CPUE is probably over-conservative using the 2000s-truncated data. The SSB, predator abundance, female exploitation, bottom temperature, spring sea surface temperature (SST) indices using the 2000s-truncated data thresholds may also result in colour changes that are mostly due to biologically insignificant noise in the data, or at least are more prone to do so than using the entire data series. The turbot index is probably too conservative using 2000s-truncated data – too quickly triggering red indicator values.

Overall, when taken as mean percentiles in the calculation of the Characteristics summarising Abundance, Production, Fishing Effects and Ecosystem, the adoption of the 2000s-truncated thresholds appears feasible and probably more accurately reflects changes in indicators relative to a higher-abundance period. Some of the equivocal indicators discussed above, and perhaps some of the indicator colour changes triggered by data noise, are dampened by taking the mean in the summary characteristics. The mean percentile ranks based for abundance indicators against the 2000-2010 data show a more conservative summary that better reflects the gradual stock decline over the past decade that was evident in the normalized CPUE indicator series from the framework (mean of survey, gulf, standardised CPUEs each normalized to its own mean, see Figure 10). The mean percentile ranks for Production indicators against the 2000-2010 data also show a more conservative summary that may be more sensitive to periods of poor recruitment and the population declines that follow if there is poor recruitment for a number of consecutive years. Neither the Fishing Effects nor the Ecosystem summary characteristics are substantially changed by the adoption of 2000s-truncated percentiles, although both are slightly more conservative, which is likely appropriate given the apparently sustained period of high productivity of this stock and the industry goals to maintain their conservative fishing strategy to avoid stock declines due to fishing mortality. Overall, it has been agreed to proceed with indices and characteristics based on the 2000s-truncated data while working to develop biologically-based thresholds where possible (e.g. bottom temperature and spring SST).

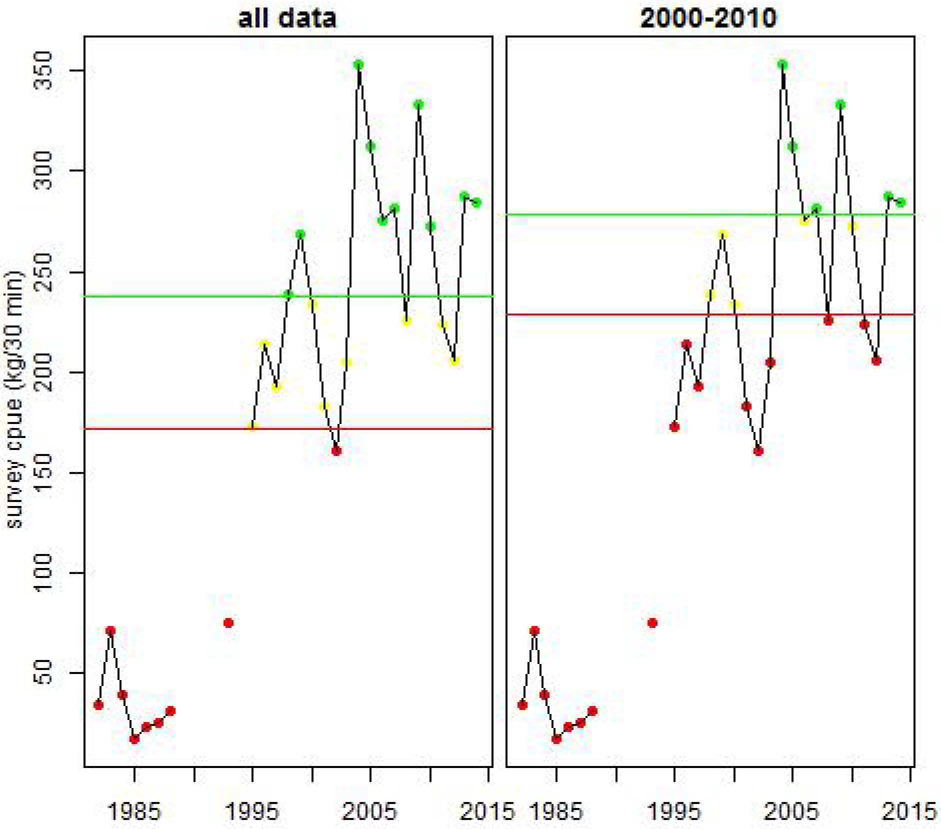

Figure A1. The survey CPUE index time series showing thresholds based on the 33rd and 66th percentiles of the entire data series (left) and only data from 2000-2010 (right).

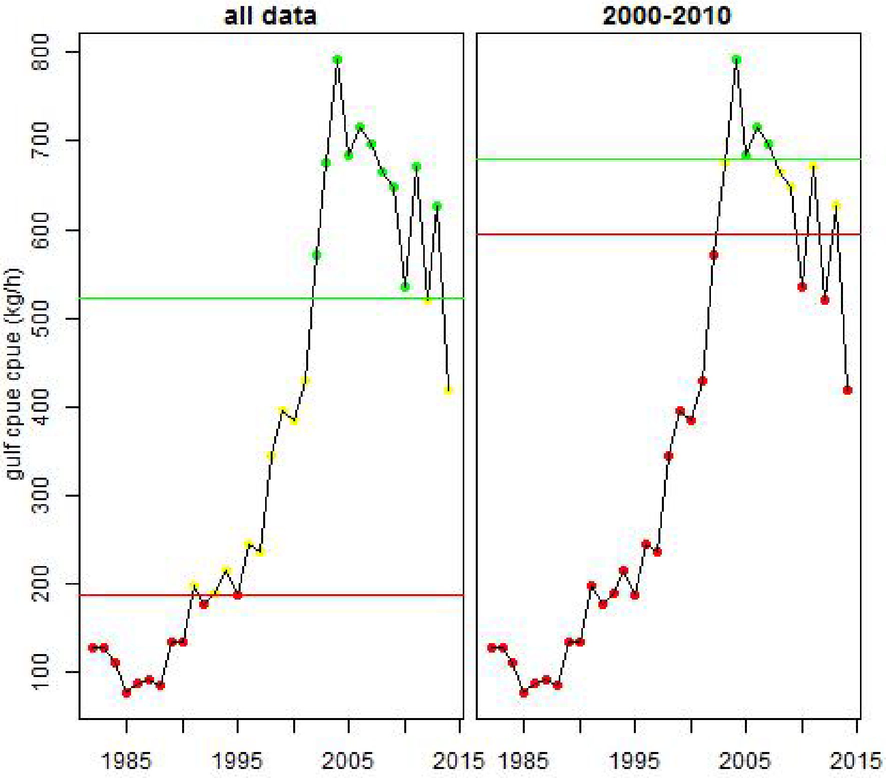

Figure A2. The Gulf vessel CPUE index time series showing thresholds based on the 33rd and 66th percentiles of the entire data series (left) and only data from 2000-2010 (right).

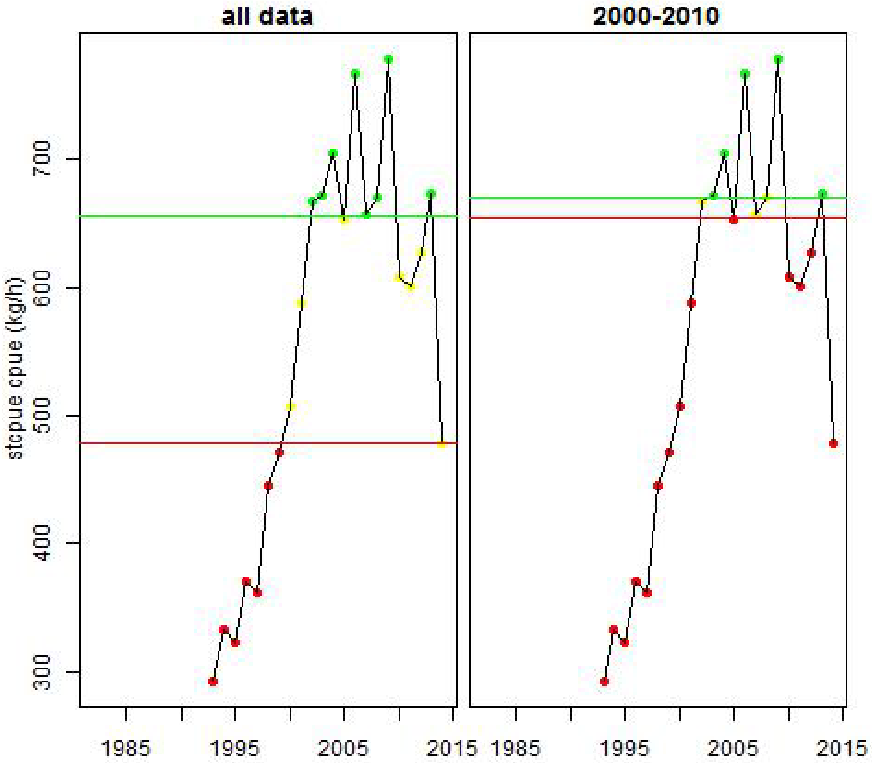

Figure A3. The Standardised Maritimes vessel CPUE index time series showing thresholds based on the 33rd and 66th percentiles of the entire data series (left) and only data from 2000-2010 (right).

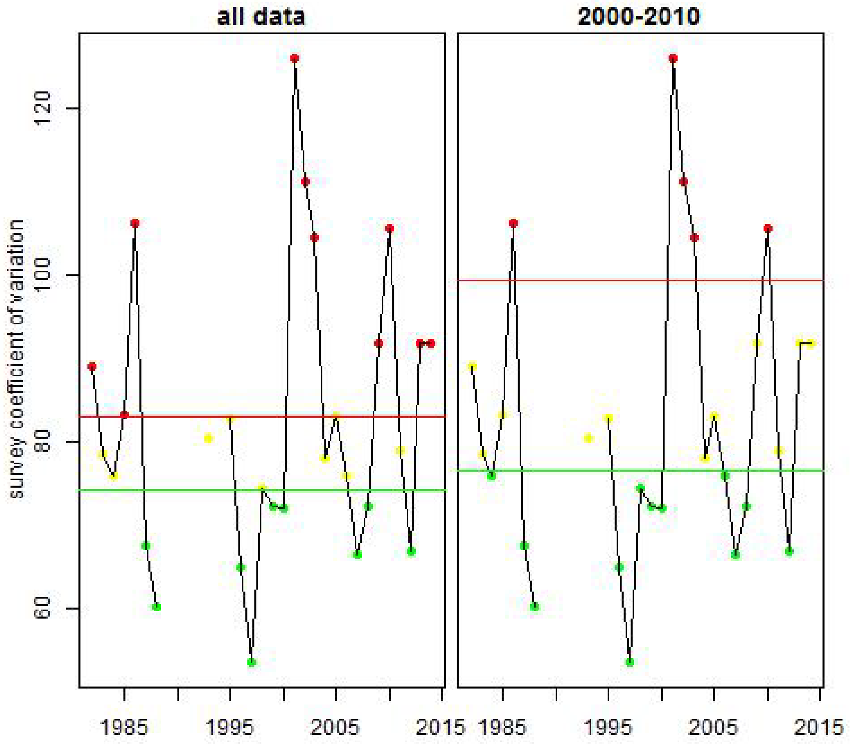

Figure A4. The Survey coefficient of variation index time series showing thresholds based on the 33rd and 66th percentiles of the entire data series (left) and only data from 2000-2010 (right).

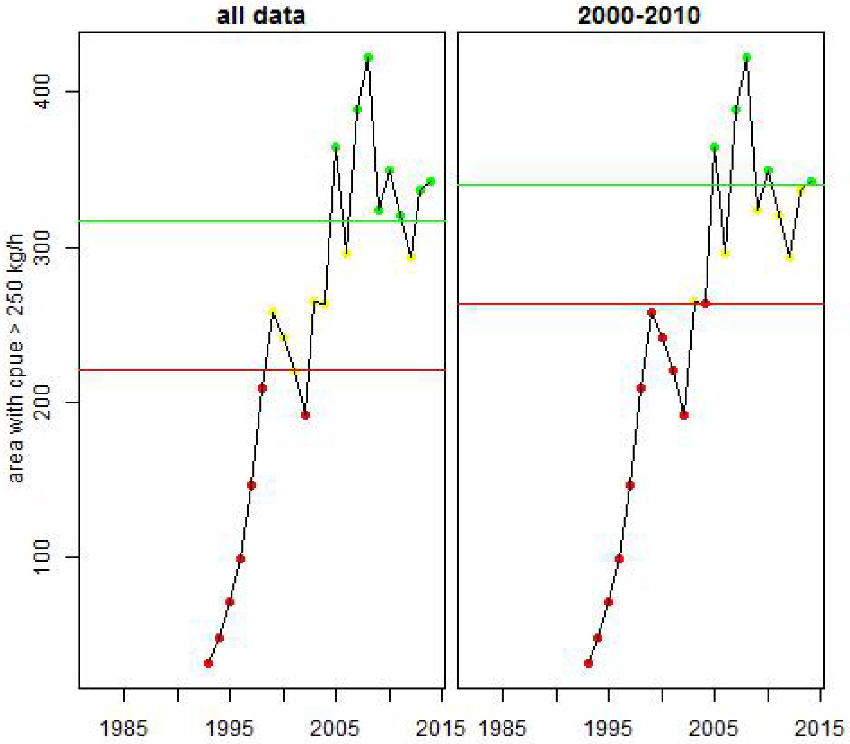

Figure A5. The Commercial Fishing Area index time series showing thresholds based on the 33rd and 66th percentiles of the entire data series (left) and only data from 2000-2010 (right).

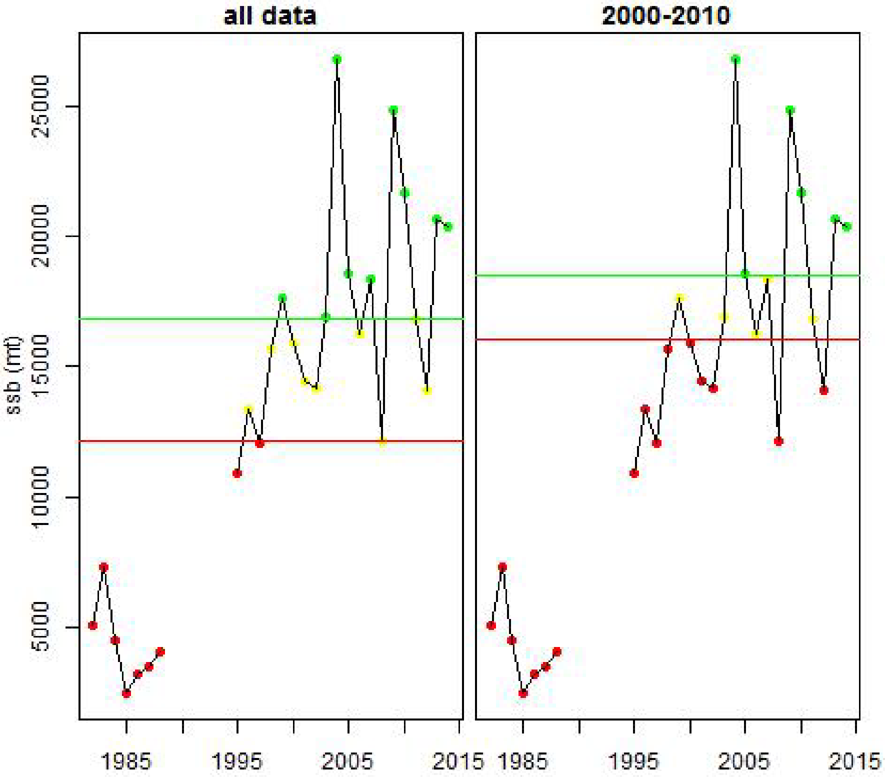

Figure A6. The SSB index time series showing thresholds based on the 33rd and 66th percentiles of the entire data series (left) and only data from 2000-2010 (right).

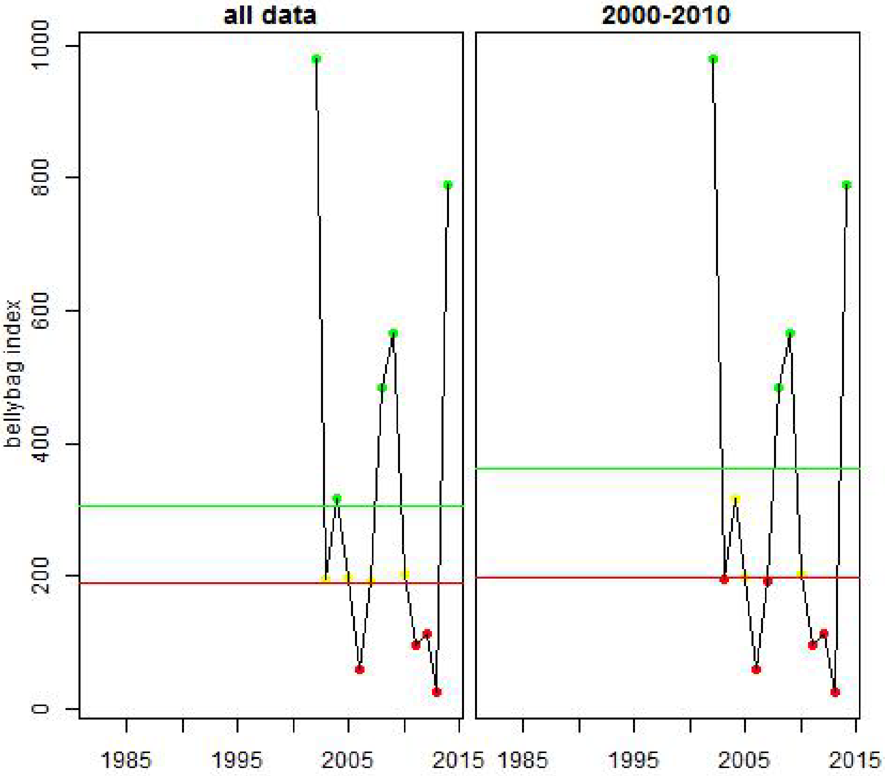

Figure A7. The belly-bag index time series showing thresholds based on the 33rd and 66th percentiles of the entire data series (left) and only data from 2000-2010 (right).

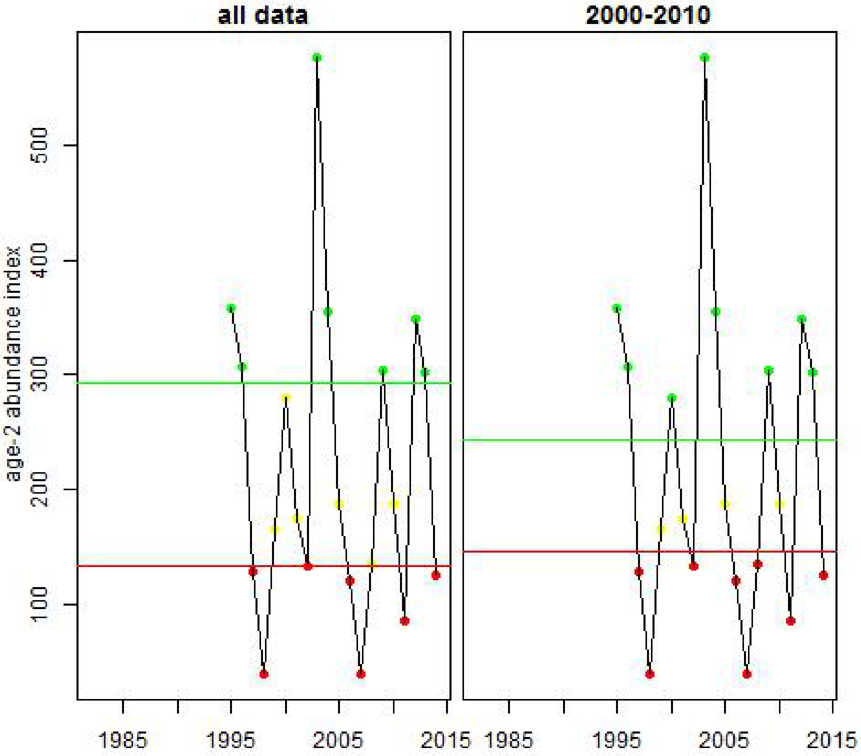

Figure A8. The Age 2 abundance index time series showing thresholds based on the 33rd and 66th percentiles of the entire data series (left) and only data from 2000-2010 (right).

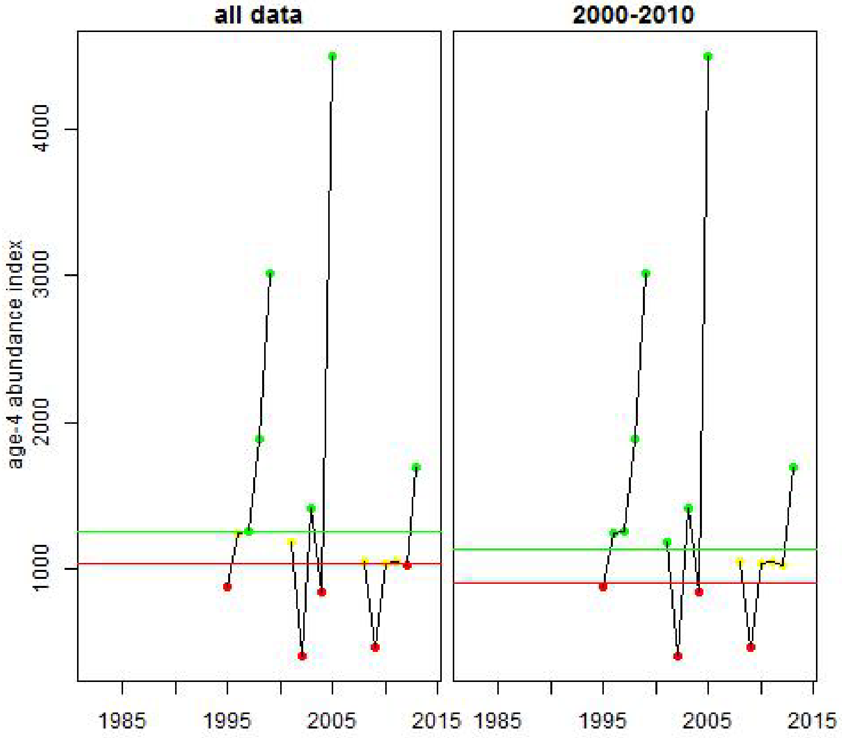

Figure A9. The Age 4 abundance index time series showing thresholds based on the 33rd and 66th percentiles of the entire data series (left) and only data from 2000-2010 (right).

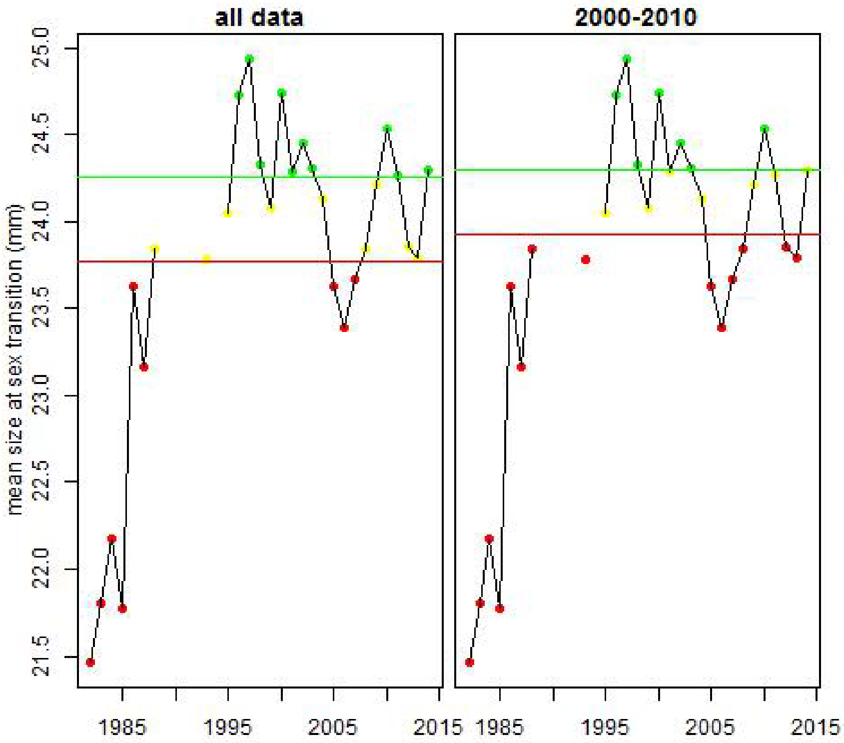

Figure A10. The mean size at sex transition index time series showing thresholds based on the 33rd and 66th percentiles of the entire data series (left) and only data from 2000-2010 (right).

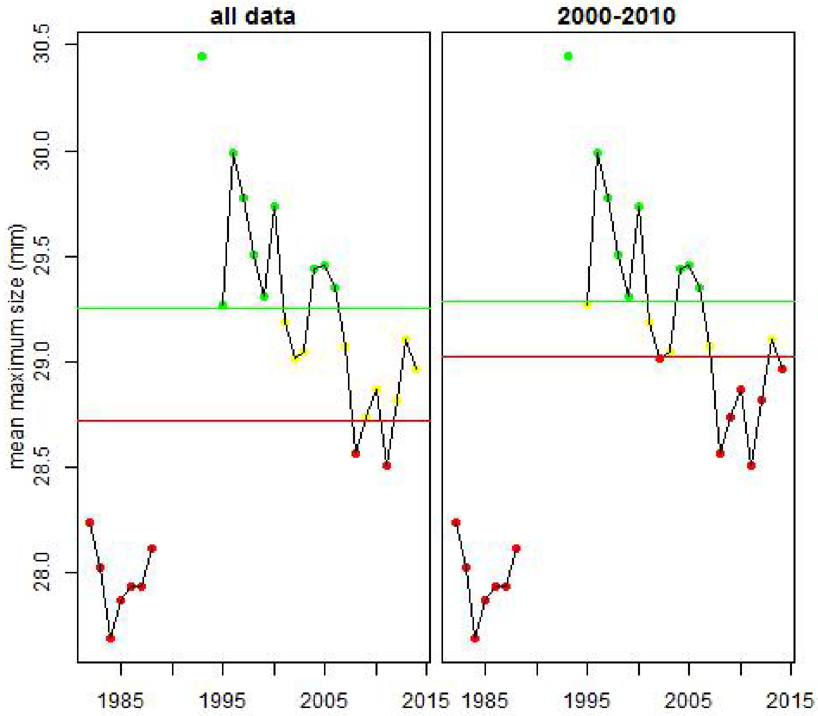

Figure A11. The mean maximum size index time series showing thresholds based on the 33rd and 66th percentiles of the entire data series (left) and only data from 2000-2010 (right).

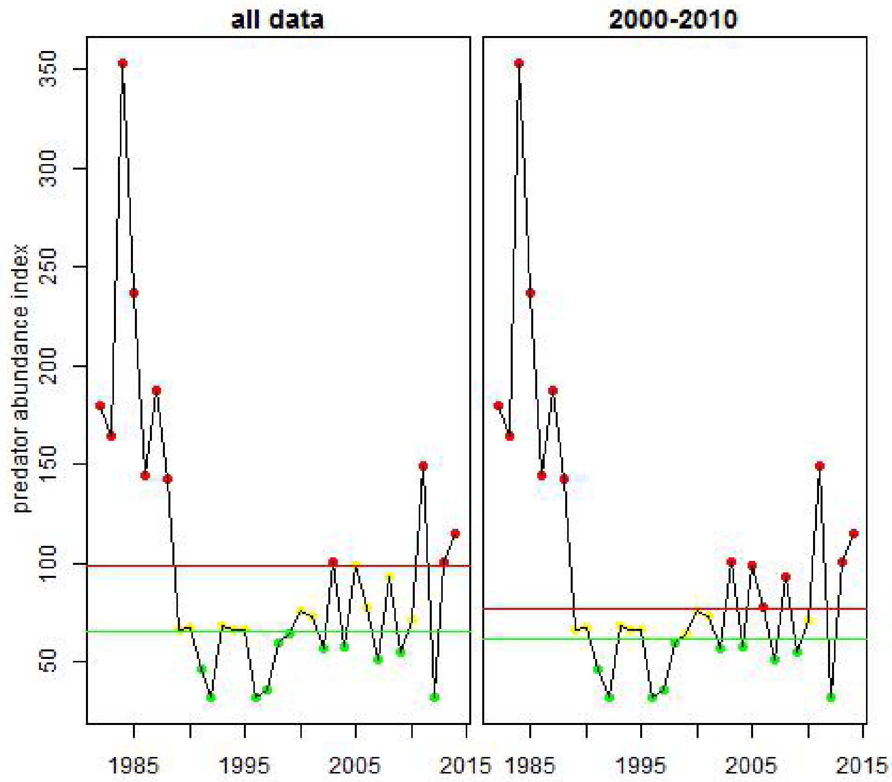

Figure A12. The predator abundance index time series showing thresholds based on the 33rd and 66th percentiles of the entire data series (left) and only data from 2000-2010 (right).

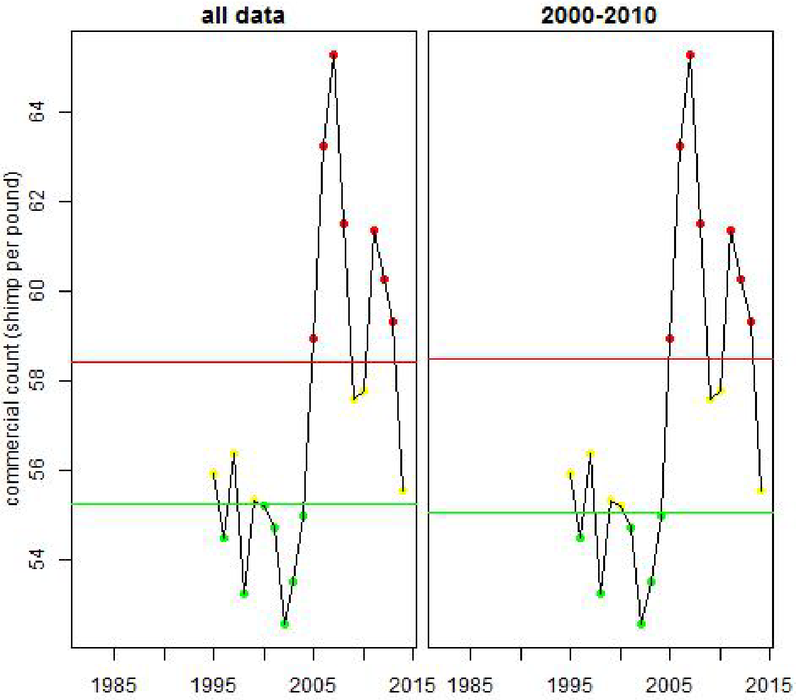

Figure A13. The commercial count index time series showing thresholds based on the 33rd and 66th percentiles of the entire data series (left) and only data from 2000-2010 (right).

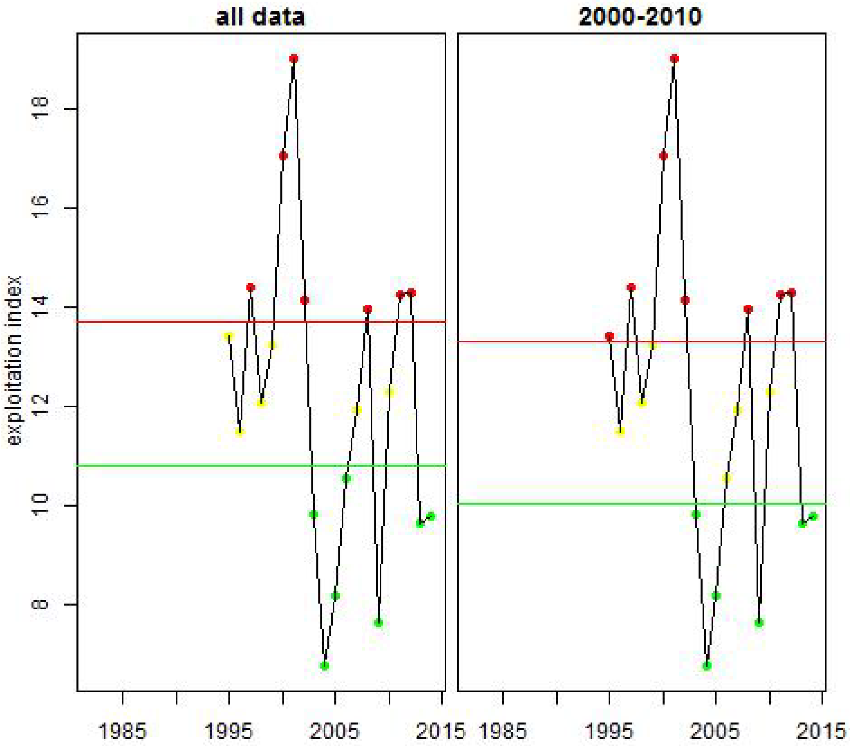

Figure A14. The total exploitation index time series showing thresholds based on the 33rd and 66th percentiles of the entire data series (left) and only data from 2000-2010 (right).

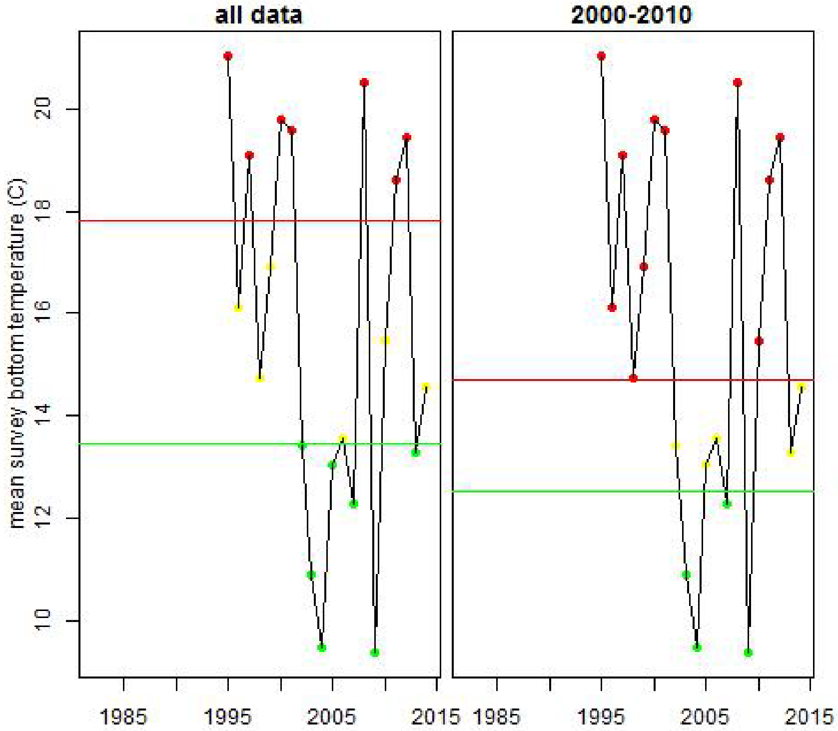

Figure A15. The female exploitation index time series showing thresholds based on the 33rd and 66th percentiles of the entire data series (left) and only data from 2000-2010 (right).

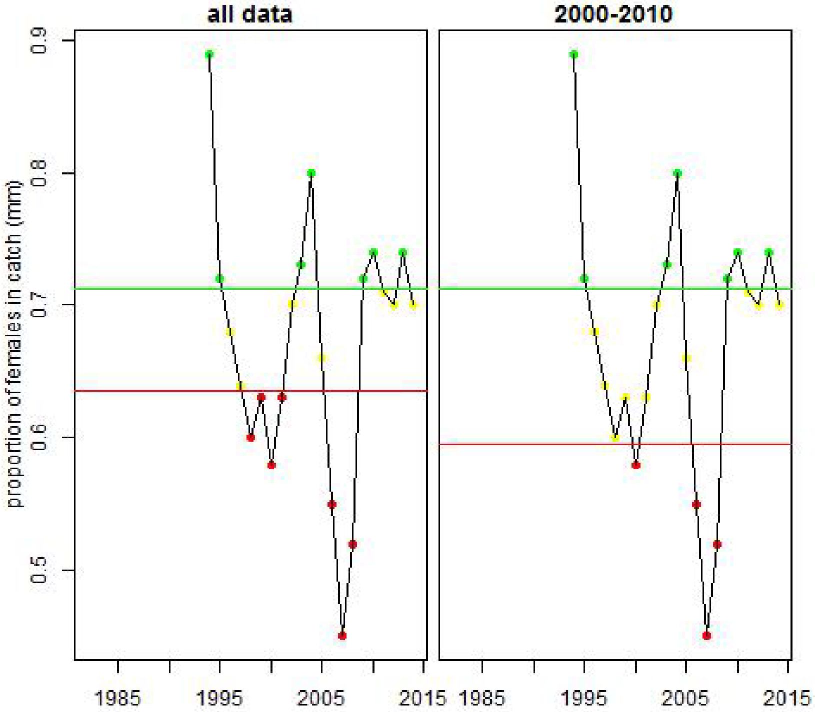

Figure A16. The proportion of females in the catch index time series showing thresholds based on the 33rd and 66th percentiles of the entire data series (left) and only data from 2000-2010 (right).

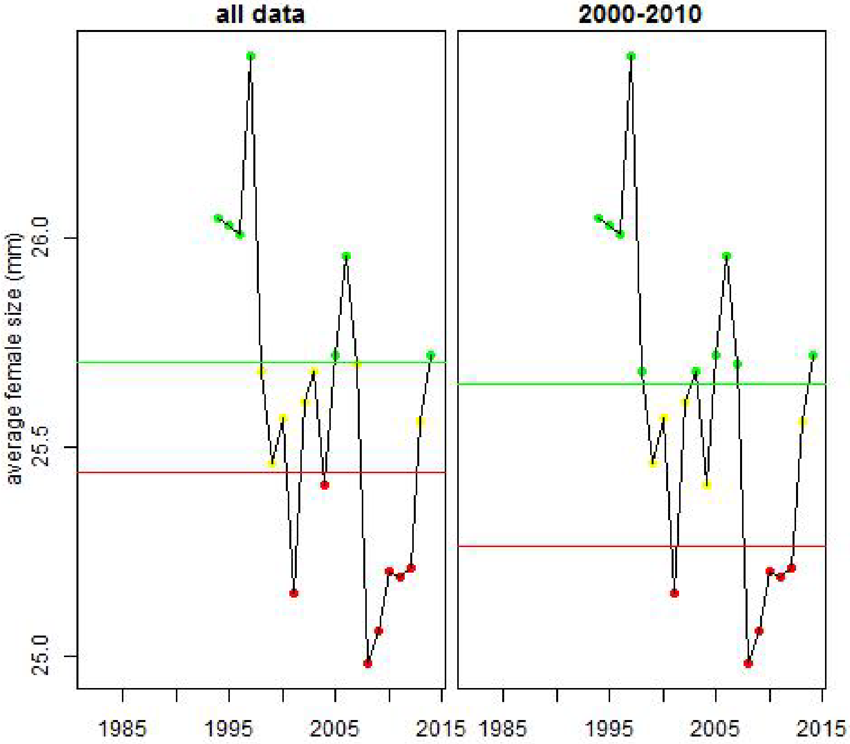

Figure A17. The female size index time series showing thresholds based on the 33rd and 66th percentiles of the entire data series (left) and only data from 2000-2010 (right).

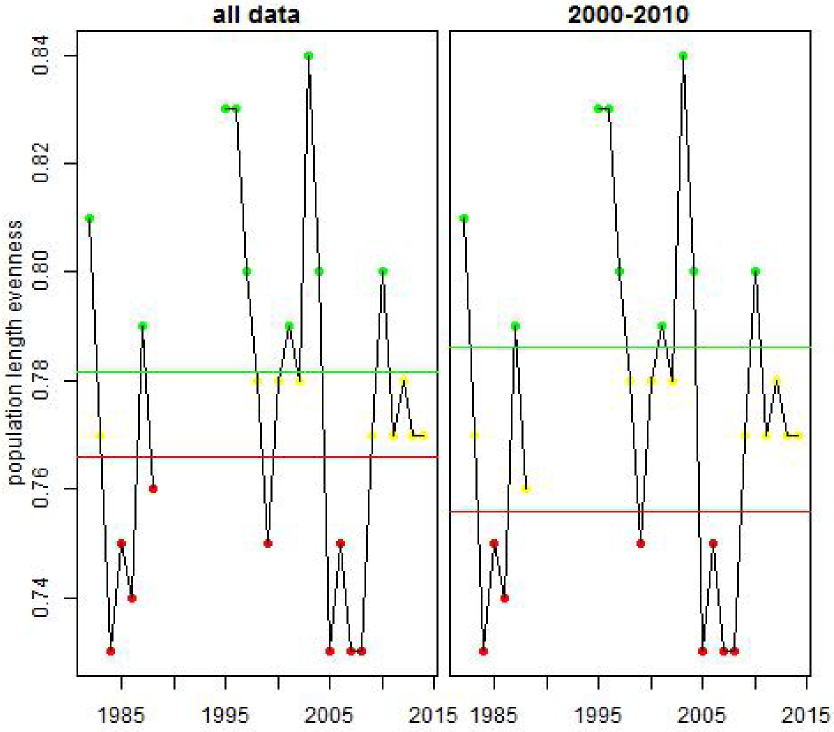

Figure A18. The population evenness index time series showing thresholds based on the 33rd and 66th percentiles of the entire data series (left) and only data from 2000-2010 (right).

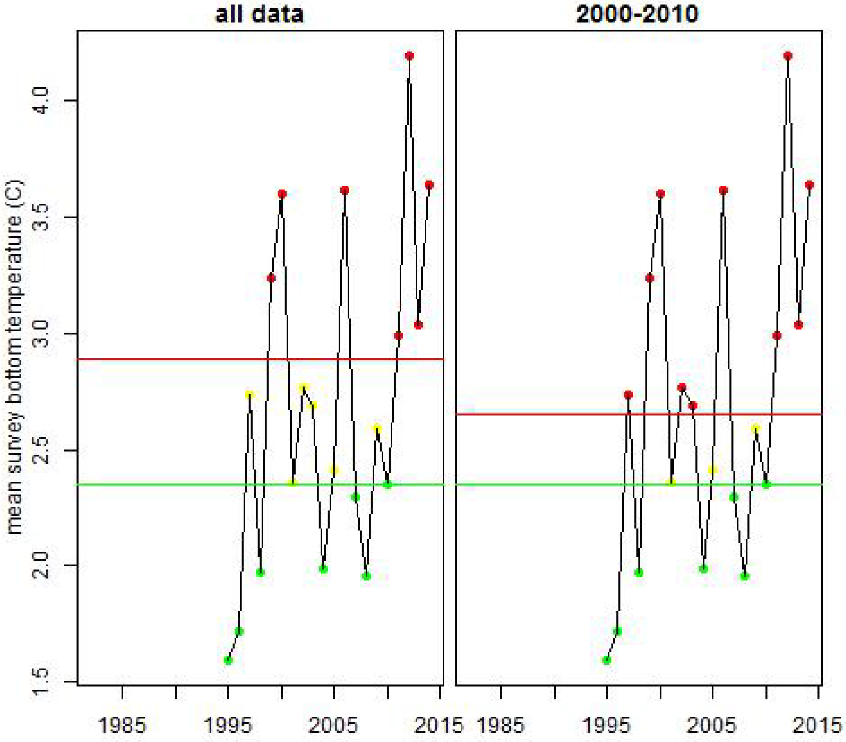

Figure A19. The survey bottom temperature time series showing thresholds based on the 33rd and 66th percentiles of the entire data series (left) and only data from 2000-2010 (right).

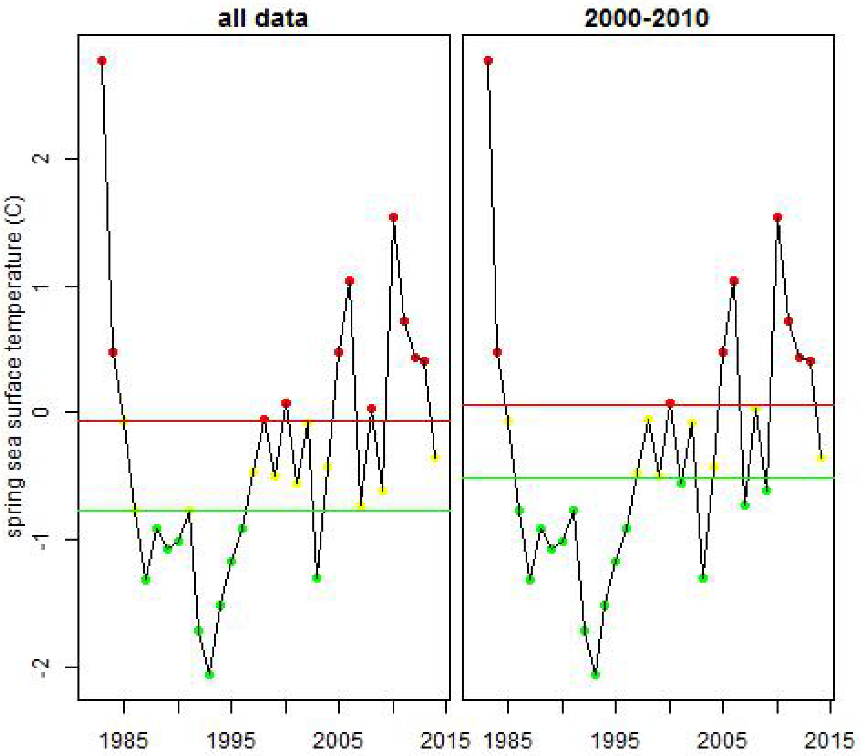

Figure A20. The spring SST index time series showing thresholds based on the 33rd and 66th percentiles of the entire data series (left) and only data from 2000-2010 (right).

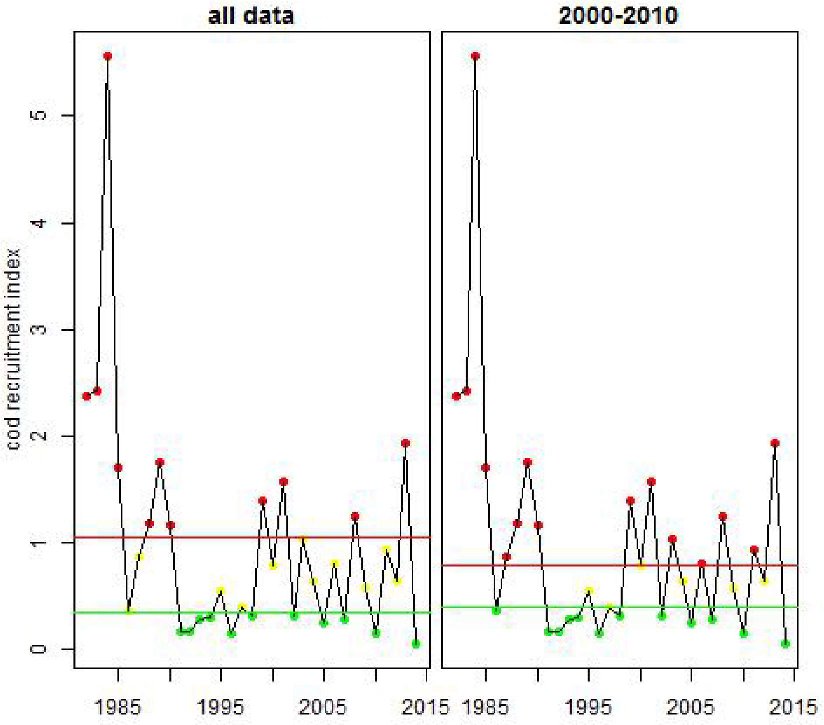

Figure A21. The Cod recruitment index time series showing thresholds based on the 33rd and 66th percentiles of the entire data series (left) and only data from 2000-2010 (right).

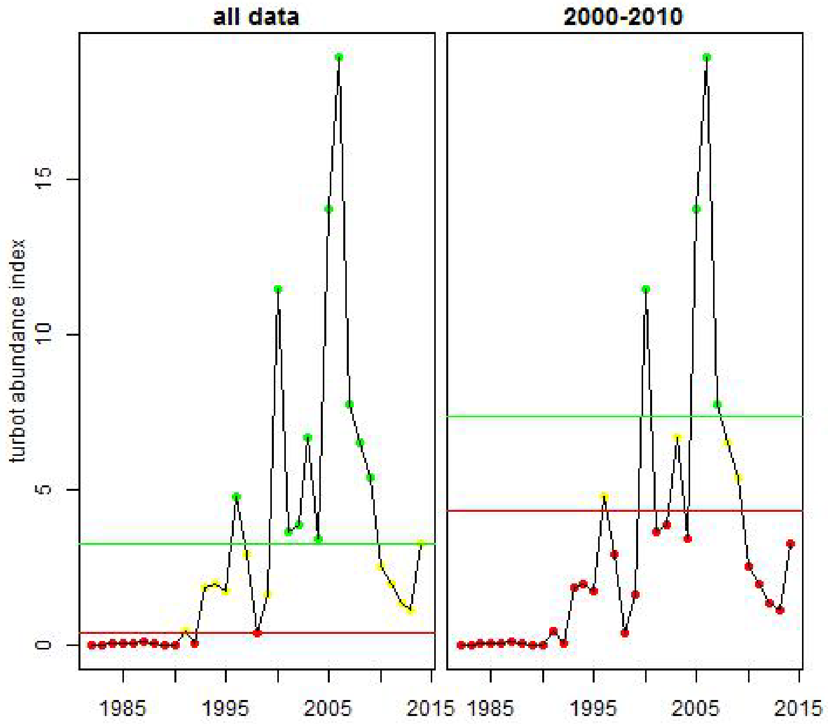

Figure A22. The Turbot abundance index time series showing thresholds based on the 33rd and 66th percentiles of the entire data series (left) and only data from 2000-2010 (right).

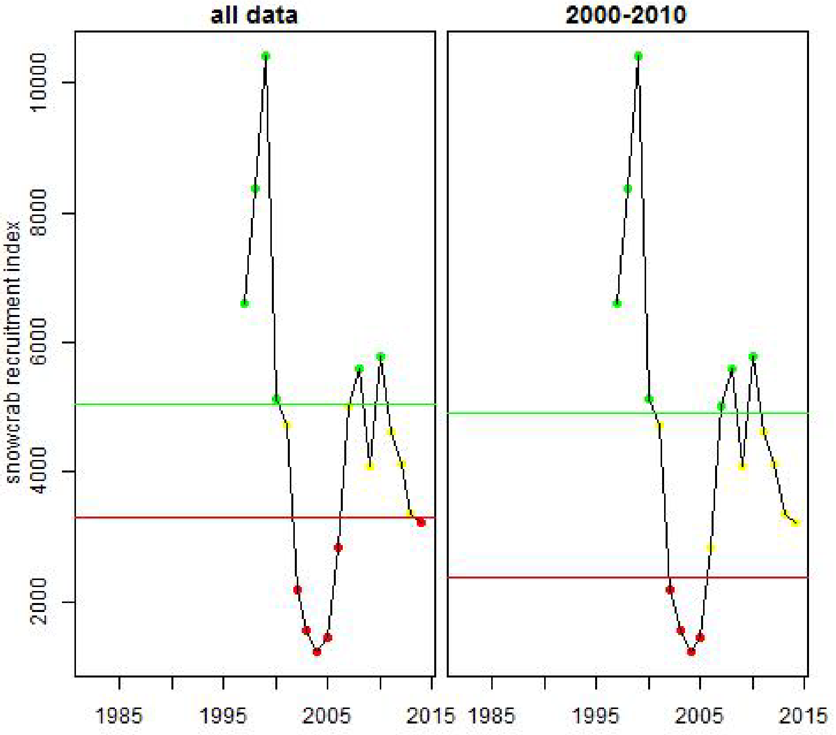

Figure A23. The Snow Crab recruitment index time series showing thresholds based on the 33rd and 66th percentiles of the entire data series (left) and only data from 2000-2010 (right).

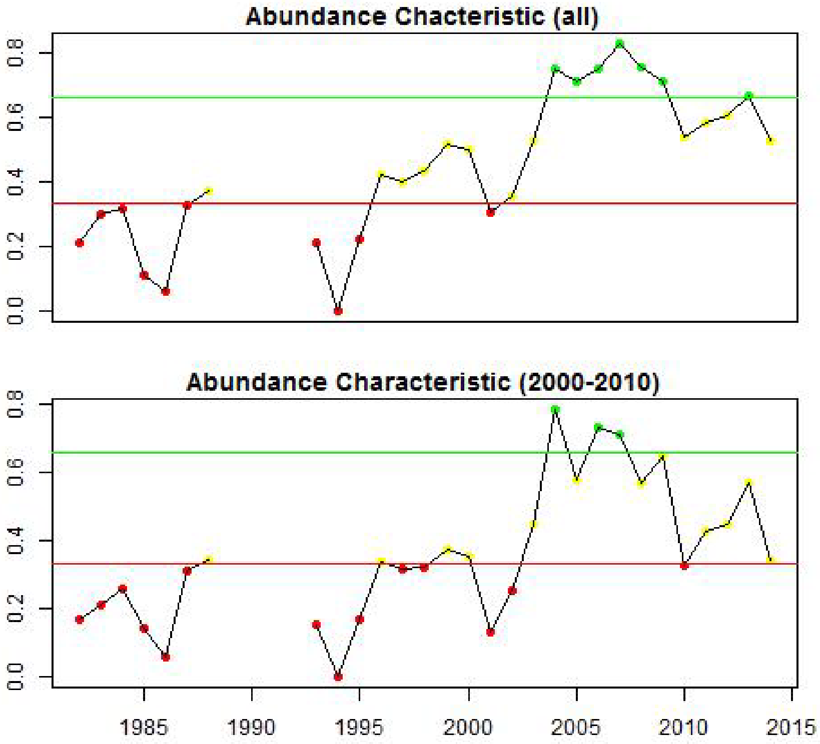

Figure A24. The Abundance Characteristic time series showing thresholds based on the 33rd and 66th percentiles of the entire data series (top) and only data from 2000-2010 (bottom).

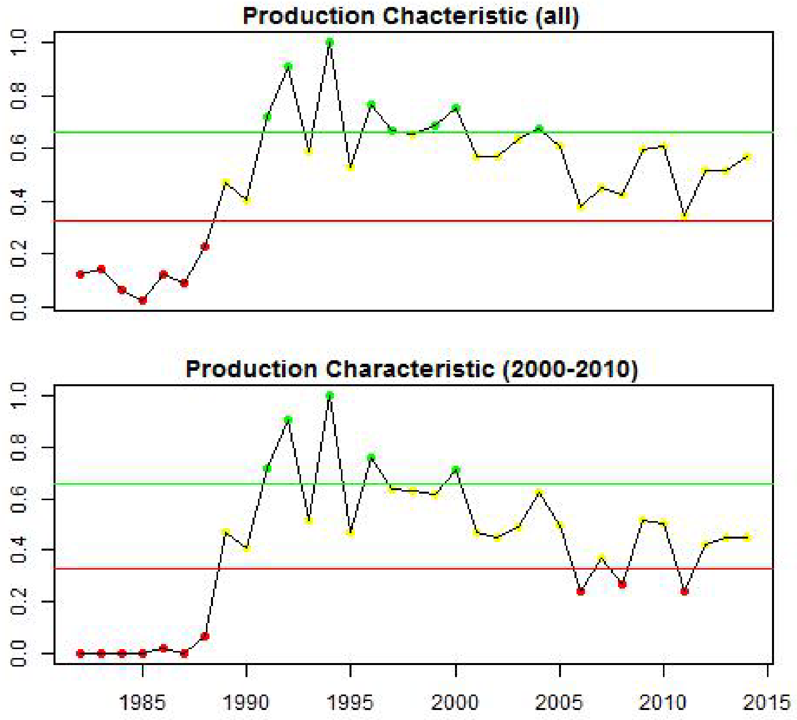

Figure A25. The Production Characteristic time series showing thresholds based on the 33rd and 66th percentiles of the entire data series (top) and only data from 2000-2010 (bottom).

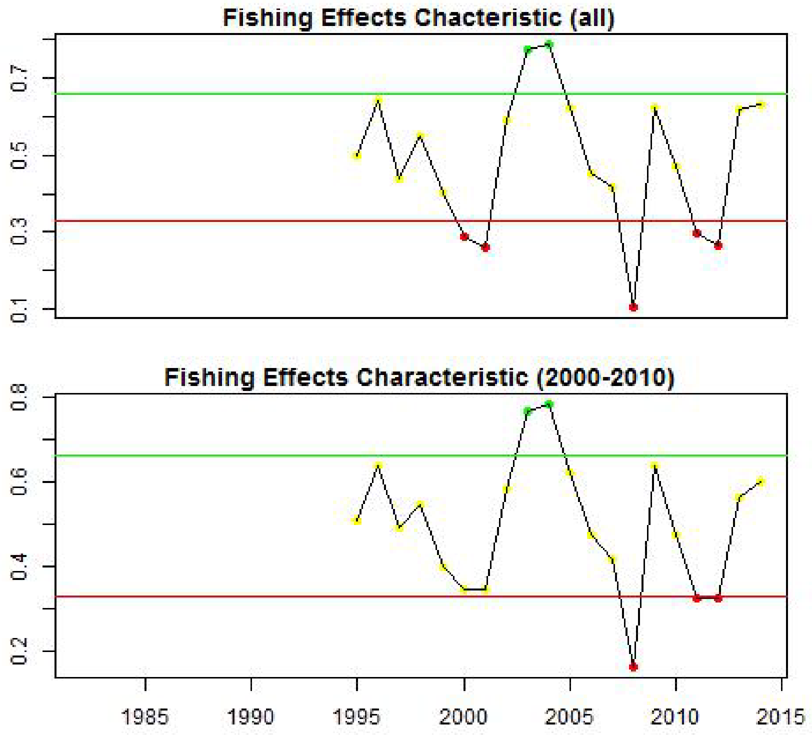

Figure A26. The Fishing Effects Characteristic time series showing thresholds based on the 33rd and 66th percentiles of the entire data series (top) and only data from 2000-2010 (bottom).

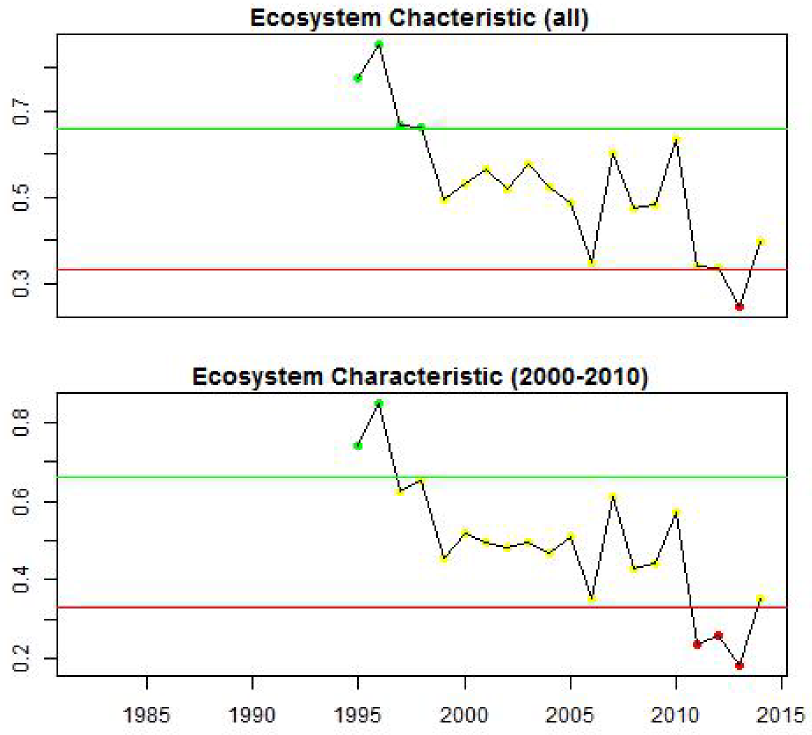

Figure A27. The Ecosystem Characteristic time series showing thresholds based on the 33rd and 66th percentiles of the entire data series (top) and only data from 2000-2010 (bottom).