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Framework Assessment for SFA 29 West Scallop Fishery

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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 sea scallop, *Placopecten magellanicus*, is a sedentary, filter feeding bivalve; as a broadcast spawner, it tends to aggregate in densely populated beds. In 2000, an exploratory survey of Scallop Fishing Area (SFA) 29 (west of 65° 30) (West) revealed the commercial potential of the area, with catch rates significantly higher than surrounding areas. The sea scallop fishery in SFA 29 West started in 2001 with a 400 t total allowable catch, fished by the Full Bay fleet. In 2002, some East of Baccaro scallop licence holders joined the fishery. Since then, the fishery has occurred every year.

For sea scallop, bottom type has been identified as a determining factor for distribution, a relationship that was demonstrated in SFA 29 West through multibeam acoustic mapping undertaken in 2002. Fisheries and Oceans Canada’s Science Branch has conducted a survey in SFA 29 West annually since 2001. Survey results were used in 2001 to subdivide the area into subareas A–E. Over time, the survey design has changed. In 2005, the results from the multibeam mapping project were used for the first time to re-stratify the survey. The survey design changed again in 2007, as a result of new information and a greater understanding of the bottom types and how those related to scallop habitat. Assessment of stock status has changed over time. Initial assessments were based on commercial catch rates, removal densities, and recruitment signals in the survey. Eventually, models were tested on the survey data. Trends in catch rate were examined using a depletion model, and exploitation estimates were derived from both survey and commercial data.

Application of a new scallop habitat suitability model demonstrated that higher fishing intensities were associated with the higher suitability areas, which in turn exhibited the higher densities based on survey estimates. A new assessment model that incorporates these habitat suitability features provided a clearer understanding of the population dynamics for scallops in this area and offers a model-based approach for assessing stock status. Harvest control rules and reference points have not been set for this fishery. Methods for determining the upper stock reference and lower reference point are proposed based on methods accepted for other inshore scallop fishing areas, but modified to take into account scallop habitat suitability in SFA 29 West.

Évaluation du cadre pour la pêche du pétoncle dans la ZPP 29 Ouest

RÉSUMÉ

Le pétoncle géant, *Placopecten magellanicus*, est un bivalve filtreur sédentaire. Comme il libère ses gamètes au hasard, il a tendance à former des gisements densément peuplés. En 2000, un relevé exploratoire de la zone de pêche du pétoncle 29 à l'ouest de la longitude 65° 30' O (ZPP 29 Ouest) a révélé le potentiel commercial de la zone qui affichait un taux de prises beaucoup plus élevé que les zones environnantes. La pêche du pétoncle dans la ZPP 29 Ouest a commencé en 2001 avec un total autorisé des captures de 400 tonnes réalisé par la flottille de la totalité de la baie. En 2002, certains titulaires de permis de pêche au pétoncle pour l'est de Baccaro ont commencé à participer à cette pêche. Depuis lors, la pêche a lieu chaque année.

Il a été établi que le type de fond est un facteur déterminant de la répartition du pétoncle géant. Ce lien a été démontré dans la ZPP 29 Ouest grâce à l'établissement de cartes au moyen de techniques de balayage acoustique multifaisceaux entrepris en 2002. La Direction des sciences de Pêches et Océans Canada effectue un relevé chaque année dans la ZPP 29 Ouest depuis 2001. Les résultats du relevé ont servi en 2001 à subdiviser la zone en sous-zones de A à E. La conception du relevé a changé au fil du temps. En 2005, les résultats du projet de cartographie multifaisceaux ont servi pour la première fois à restratifier la zone de relevé. La conception du relevé a encore été modifiée en 2007, avec l'arrivée de nouveaux renseignements et l'amélioration des connaissances sur les types de fonds et leur relation avec l'habitat des pétoncles. L'évaluation de l'état des stocks a évolué avec le temps elle aussi. Les premières évaluations se basaient sur les taux de capture commerciale, les densités de récolte et les signes de recrutement du relevé. Pour finir, les modèles ont été mis à l'essai avec les données des relevés. Les tendances en matière de taux de capture ont été examinées à l'aide d'un modèle d'appauvrissement et les estimations d'exploitation ont été obtenues à partir du relevé et des données commerciales.

L'application d'un nouveau modèle des habitats propices aux pétoncles a démontré que les zones où l'intensité de la pêche est la plus élevée correspondent aux zones de pêche les plus propices, lesquelles affichent aussi les densités les plus élevées d'après les estimations des relevés. Un nouveau modèle d'évaluation de la qualité de l'habitat qui comprend ces caractéristiques d'habitats propices a permis de mieux comprendre la dynamique des populations de pétoncles dans cette zone et offre une approche fondée sur le modèle pour évaluer l'état des stocks. Il n'y a pas de règles de contrôle des prises ni de points de référence établis pour cette pêche. Les méthodes pour déterminer le point de référence supérieur et le point de référence inférieur sont proposées en s'inspirant des méthodes acceptées pour d'autres zones de pêche du pétoncle côtière que l'on a modifiées pour tenir compte des habitats propices aux pétoncles dans la ZPP 29 Ouest.

INTRODUCTION

Scallop Fishery Area (SFA) 29 encompasses a large inshore area of Nova Scotia from Yarmouth to Cape Breton, but for the purposes of this report the area is limited to the portion west of 65° 30′ where the current fishery occurs (SFA 29 West, Figure 1). While there had been some scallop fishing in this area prior to 1986, a fleet separation agreement between the inshore and offshore fleets came into effect in 1986 restricting Bay of Fundy-based inshore vessels to areas north of 43° 40′ and offshore vessels to areas outside of the 12 mile limit. This resulted in SFA 29 West not being included in either fishing area (Smith and Lundy, 2002b). In 1995, Fisheries and Oceans Canada (DFO) proposed the northern part of SFA 29 West as a part of a larger closed area, including adjacent portions of German Bank and the southern area of Scallop Production Area (SPA) 3, as refugia for scallop brood stock in response to concerns over recruitment overfishing in the broader adjacent areas (Kenchington and Lundy, 1996). This proposal was not supported by either the inshore or offshore industry and was never implemented by DFO (Smith and Lundy, 2002b). A limited fishery was granted to the Full Bay fleet in a portion of SFA 29 West from 1996 to 1998 conditional on having fisheries observers on some of the vessels. Access was revoked in 1999 and 2000 after reports and charges involving Full Bay vessels fishing illegally in areas outside of SFA 29 West, and after an Auditor General of Canada report in 1999 criticizing the department for allowing fishing in an area recommended for broodstock protection, which was inconsistent with the department's commitment to a precautionary approach (Office of the Auditor General, 1999, Smith and Lundy, 2002b).

In early 2001, after consultations between the Full Bay Scallop and the Lobster Fishing Area (LFA) 34 Lobster Association, DFO Fisheries Management Branch recommended a limited fishery with conditions set for fishery timing, lobster bycatch monitoring by fisheries observers, satellite-based vessel monitoring systems (VMS) for each vessel and an industry funded post-fishery survey. The fishery began in June 2001 with the Full Bay fleet, and in 2002 a limited number of East of Baccaro scallop licence holders joined the fishery. Since then, the fishery has occurred every year. The most recent assessment of the stock was reported in Smith *et al*. (2014).

A three-year joint project agreement was signed in 2002 with the two fishing fleets, Natural Resources Canada, and DFO, with all parties providing funds to conduct multibeam acoustic mapping of the sea floor and other scientific work. Beginning in 2005, the annual research survey has incorporated the bottom type into its stratified design. Details on the multibeam project including preliminary geological interpretation and analyses of the data in a fisheries science context were given in DFO (2006).

Scientific advice for this fishery has been mainly based on annual survey and commercial catch trends, as well as trends in exploitation estimates based upon these same data (e.g., Smith *et al*., 2014). This approach makes it difficult to implement a structured fisheries management plan that incorporates sustainable fishing requirements such as required by DFO's precautionary approach[1] and the Marine Stewardship Council (MSC) certification[2]. Conditions from the MSC certification for SFA 29 West require the establishment of precautionary reference points by the second annual audit (July 2015). This document reviews the background information and data on the scallop fishery in SFA 29 West for the development of a new framework assessment. A new assessment model, which incorporates habitat information based on the multibeam data is

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[1] See A Fishery Decision-Making Framework Incorporating the Precautionary Approach for background documents on precautionary approach for Canadian fisheries (accessed on March 25, 2015).

[2] See MSC Sustainable Fisheries Certification: FBSA Canada Full Bay Sea Scallop Fishery (PDF accessed on March 25, 2015).

reported in (S.J. Smith, J.A. Sameoto, and C. Brown, unpublished manuscript) and will be used to develop candidate reference points for this fishery.

BIOLOGY AND ECOLOGY

Sea scallop, *Placopecten magellanicus*, are sedentary filter feeding bivalves found only in the Northwest Atlantic from Labrador to Cape Hatteras.

REPRODUCTION AND STOCK/RECRUITMENT

Unlike most scallops, sea scallops have separate sexes and can become sexually mature at age 2, but significant reproductive output may not occur before age 4 (MacDonald and Thompson, 1988). Reproduction is thought to be controlled by many factors, among them local food supply (MacDonald and Thompson, 1988), tidal cycles (Parsons *et al.,* 1992), and other environmental conditions (Langton *et al*., 1987). Scallops exhibit discrete reproductive cycles with a spawning period that is highly synchronised within the population (MacDonald and Thompson, 1988). Like many other invertebrates, individual scallops do not release all of their gametes at the same time, instead releasing them over a number of events within a spawning period (Langton *et al*., 1987, Parsons *et al*., 1992, Marshall and Bolton, 2007). In Canadian offshore scallop areas (e.g., Georges Bank), there is a possibility of both a spring and fall spawn, with the fall spawn contributing the larger portion of reproductive output (Dibacco *et al*., 1995, Jonsen *et al*., 2009). Langton *et al*. (1987) found that egg number is an exponential function of shell height for sea scallops, therefore, a high density of small individuals may have a similar production of fertilized eggs as a low density of large animals (Levitan, 1991). However, gonad weight by size can be subject to large inter-annual fluctuations (Parsons *et al*., 1992), and the number of eggs produced can also vary with depth (Barber and Blake, 2006). In other scallop species, larger males can release sperm over a longer period than smaller males, although larger males may not produce greater amounts of sperm at any one time (Styan and Butler, 2003). Interestingly, high concentrations of sperm may not be advantageous because fertilization success can decrease due to either polyspermy (more than one sperm fertilizes the egg resulting in an unviable egg) or sperm attaching to the outside of a recently fertilized egg before a permanent block is formed and therefore, unavailable to fertilize other eggs (Marshall and Bolton, 2007, Williams, 2005, Tettelbach *et al*., 2011). After spawning, external fertilization occurs and the fertilized eggs develop into a larval stage (veliger) within a few days. Larvae are weak swimmers relative to ocean currents and can be transported long distances from the spawner location during the 30–60 days spent in the water column. The next stage of development is the pediveliger stage, in which more time is spent near the bottom. The process of scallop settlement is not well-studied. It is believed that pediveliger larvae can delay metamorphosis for up to a month (Culliney, 1974) and may have some control over the substrate they settle on. Juveniles attach themselves to objects such as gravel or shells via byssus threads to anchor themselves and avoid being re-suspended into the water column.

Many forces act on the scallop from the time of fertilization to settlement to the time it is recruited into the fishery. In the case of SFA 29 West, scallops legally enter the fishery at a shell height of 100 mm. This temporal gap between spawning and recruitment four or five years later is one of the characteristics of scallop populations that make understanding the stock/recruit relationship difficult. The assumed relationships between stock and recruitment based on Ricker or Beverton-Holt models may not adequately take into account the complex progression from eggs/sperm to the year-class strength of recruited scallops. In SFA 29 West, only one large recruitment event (subarea D in 2003) has been observed since the fishery began. Data from Bay of Fundy scallop stocks suggests that recruitment levels were very low over a wide range of spawning stock sizes, with the exception of very large year-classes, which originated from very low spawning stocks. This pattern does not resemble any stock recruitment model used for finfish but is not unusual when compared to other bivalves (Hancock, 1973). In particular, the lack of productivity from the larger stock sizes is fairly typical for both inshore and offshore scallop stocks in the Maritimes Region (see also Smith and Hubley, 2012). Year-class strength is determined by the number of gametes (eggs and sperm) released, fertilization rate, and survival through the planktonic, settlement, and juvenile stages. Parsons *et al*. (1992) concluded after looking at spawning cycles over 13 years, that the main determinants of year-class strength were probably factors that affected the survival of the larvae rather than being functions of the amount of eggs or sperm produced. Slater (2005) also supposed that post-spawning survival was the main determinant of year-class strength after finding no significant relationship between gonad size and spatfall intensity for the king scallop, *Pecten maximus*.

GROWTH

Scallop growth is highly variable and dependent on local environmental conditions. Scallops can commonly reach sizes of 100–150 mm in shell height, with longevity being greater in northern populations than southern (MacDonald and Thompson, 1988). Depth is thought to influence growth (Schick *et al*., 1988), probably reflecting the fact that depth generally correlates with temperature, food availability, and oxygen. Food availability (e.g., plankton blooms), spawning, and other seasonal factors can also cause variation in growth and condition (e.g., Robert *et al*., 1990, Kenchington *et al*., 1997), but since the survey occurs at similar times each year, this variation should be minimized among assessments.

Shell growth (age) is estimated from rings on the shell that represent annual intervals. A number of studies (e.g., Stevenson and Dickie, 1954, Tan *et al*., 1988) suggest that annual rings are formed in early winter when growth ceases due to low temperatures. However, the latter study was based on relating oxygen isotope ratios in the shell to temperature trends and was only based on two shells from Browns Bank. In contrast, a more recent study using oxygen isotopes for 14 shells from Georges Bank to the southern Mid-Atlantic Bight suggested that the rings form at the temperature maximum for the year, which is coincident with spawning (August in the northern part of the range (Chute *et al*., 2012). Chute *et al*. (2012) hypothesized that shell growth ceases around the temperature maximum due to the stress of spawning and then starts up again once spawning is over. They also demonstrated that shell growth slows in the winter months for older scallops (>100 mm). Rings are also formed when scallops experience trauma, such as from storms or contact with fishing gear, and are referred to as shock rings (Black *et al*., 1993). If shock rings are not distinguished from annual rings, the age of scallops can be overestimated (MacDonald, 1984). Ages for scallop stocks in the DFO Maritimes Region are determined assuming that growth ceases in early winter. Details regarding the modelling of shell height growth using von Bertalanffy models are given in Appendix 1.

Estimates of annual biomass growth rates are based on von Bertalanffy model estimates for shell growth and meat weight/shell height relationships. The latter relationship was modelled using an isometric meat weight/shell height relationship similar to the other scallop assessments in the region (Hubley *et al.*, 2011). Shell heights were expressed in decimetres so that the coefficient in the relationship corresponds to the expected meat weight for a 100 mm shell, which is referred to as condition in this report. The meat weight/shell height model also incorporates spatial pattern when used to convert from numbers per tow in the survey to weight per tow. In the past, the expected annual growth in population biomass was estimated assuming that the meat weight/shell height relationship was constant over time. However, analysis for this stock and others in the region demonstrated that this relationship can vary annually. An alternative model is used here where the mean shell height of the commercial size animals in the current year and the expected mean shell height of these same animals one year later are converted to biomass using the associated annual estimates of condition. The ratio of the annual biomass estimates were used to calculate the growth rate. Growth rate estimates from both estimates are presented in Figure 2, demonstrating the greater annual variability captured by the latter method. Note that the growth from the latter method can be less than one indicating negative growth from one year to the next. Negative growth has been observed in subarea A in 2004, in C in 2010 and 2011, and in D in 2011.

NATURAL MORTALITY

Natural mortality of sea scallop is highest during its planktonic larval stage. During this stage environmental conditions such as low temperatures can delay larval development and settlement, thereby increasing exposure to predators (Medcof and Bourne, 1964). Once settled, scallops can be preyed upon by other invertebrates (e.g., starfish, crabs, lobsters) and fish such as cod, plaice, and wolffish (Medcof and Bourne, 1964). Juvenile and adult scallops are subject to parasites, and shell pests such as boring sponges and shell worms (Medcof and Bourne, 1964). On rare occasions, infections can spread through the population causing mass mortality. It has been postulated that a mass mortality event that occurred in 1989 in the Bay of Fundy (Smith and Lundy, 2002b) could have been caused by an invasive species of protozoan that was responsible for other scallop mortality events on the east coast of North America. This was based upon similarities in the reported physical condition of the scallops (Moyer *et al*., 1993).

In SFA 29 West, clappers (paired, empty shells) caught in the survey are recorded as a measure of non-fishery mortality (Figure 3). From the onset of the 2006 fishery, fishermen reported large numbers of clappers in subarea D. From previous survey data, it was known that this subarea contained higher numbers of clappers than the other subareas, but fishermen were reporting higher numbers than the 10–30% of the total catch observed previously and that they were more widespread. Estimates from fishers and observers ranged from 30–70% (Smith *et al*., 2007). A total of 25 tows were conducted by science staff on the Fishing Vessel (F/V) *Royal Fundy* in July 2006 with tows in locations identified by industry. Sampling and measuring protocols were conducted as per established survey protocols. The proportion of clappers in the survey catches of both live and clapper scallops ranged from 0 to 0.41 with a mean of 0.15. There were no apparent trends in the spatial distribution. Samples of live scallops were sent to University of Prince Edward Island, where they were tested for disease and overall condition. There was no evidence of infection, and all were found to be in fair to good condition.

Scallops not harvested can be subject to incidental fishing mortality, such as disturbance to the habitat caused by drags, damage while in drags (e.g., with rocks), boarding, dumping, and prolonged exposure to extreme cold or heat while on deck (Medcof and Bourne, 1964, Orensanz *et al*. 2006).

STOCK STRUCTURE

The stock structure of the scallop beds in SFA 29 West has not been studied. The long-term persistence of dense scallop beds in these areas suggests some level of self-recruitment within beds and the potential for small-scale differentiation. However, previous research using microsatellite loci found that scallops sampled from within the Bay of Fundy, its approaches, and offshore areas were not significantly different and may be components of a loosely-connected mega-population (Kenchington *et al.,* 2006). There is evidence of genetic structure and differentiation in inshore areas of the eastern Gulf of Maine, while in the Western Gulf Maine there is little genetic differentiation over a larger scale (Owen and Rawson 2013). Retention of larvae in the inshore areas is likely aided by local oceanographic processes that may isolate particular bays and inlets.

HABITAT

Sea scallops inhabit a depth range of about 10–100 m. They generally aggregate in patches and harvestable concentrations are called beds. For sea scallop, bottom type has been identified as a determining factor for distribution and the characterisation of sea bed habitat in

SFA 29 West became a priority as the fishery developed. In offshore areas, multibeam bathymetric data collected on Browns Bank in 1996 and 1997 showed that sediment distribution was more complex than previous mapping studies had shown, and that the existing sediment maps were too generalized to be useful when trying to correlate with fishery catch information (Kostylev *et al*., 2003). This same work demonstrated the strong influence of sediment type on scallop distribution, based on finding a high correlation between acoustic backscatter strength and density of adult (>100 mm) scallop. In 2002, a three-year joint project agreement was signed with the Full Bay and East of Baccaro fleets, Natural Resources Canada, and DFO, with all parties providing funds to conduct multibeam sonar acoustic mapping of SFA 29 West (DFO, 2006, Todd *et al*., 2012). In addition, benthic data were collected using photographic and video equipment for the analysis of the distribution of benthic assemblages in relation to bottom type. Bathymetry and backscatter maps were available to the agreement partners in 2003, with surficial geology maps becoming available in 2004 (Figure 4). These maps were updated in 2008 based on additional analysis of side scan and seismic data with the geophysical interpretation given in the context of the glacial history of the area (Figure 6).

Smith *et al*. (2009a) used bottom type information from the multibeam project to model the relationship between survey catch, bottom type and depth to look at changes due to the scallop fishery, and any impact of the fishery on these relationships, using VMS position data. They were able to quantify habitat suitability for scallops, with a high proportion of survey tows having non-zero catches in the glaciomarine silt, ice-contact, and post-glacial sand and gravel bottom types. In contrast, scallop catches were more variable and lower on igneous rock and metamorphic bedrock bottom types (Figure 6; Smith *et al*., 2009a). However, habitat associations that were observed in the first few years of the fishery were no longer observed in the survey five years later. Over this time there was increasing cumulative fishing activity, as seen in the VMS records. Over the course of the SFA 29 West fishery, all areas of suitable scallop habitat have been exploited. As the higher density areas were fished down, mean number per tow of scallops by bottom type became more similar over time (Smith *et al*., 2009a). However, there was a persistent relationship between fishing effort and bottom type. This analysis showed how spatial distribution of fishing effort exhibited higher concentrations of fishing on the post-glacial sand and gravel bottom type and in the shallower depths, both of which were identified as having the higher densities of scallops in the survey data. While fishing may mask the association between bottom type and abundance, the spatial patterns of fishing effort were a good indicator of the habitat association of sea scallop.

Further to the above work, Brown *et al*. (2012), showed suitable habitat for scallop in SFA 29 West concentrated in the northeastern, post-glaciated, shallower water regions of the survey area, and that subareas B, C and D had the highest proportion of suitable habitat. Comparison of the VMS data from 2002 to 2010 against scallop habitat suitability revealed an increase in fishing activity with increasing habitat suitability, with over 80% of fishing activity occurring in suitabilities ≥ 0.5 (Brown *et al*., 2012). Comparing SFA 29 West fishing activity from VMS records and habitat suitability maps corroborated that there was a strong spatial correlation between fishing effort and predicted scallop habitat suitability.

OCEANOGRAPHIC CONDITIONS

SFA 29 West lies south of Nova Scotia in the Gulf of Maine. Historically, the Gulf of Maine has supported productive fisheries, likely due to high rates of primary productivity. Productivity can vary annually and is influenced by inputs into the Gulf of Maine (Balch *et al*., 2008). North Atlantic Slope Water (NASW) or Labrador Sea Water (LSW) can enter the Gulf of Maine though the Northeast Channel. Changes in the nutrients in Gulf of Maine have been linked to the influence of warm, salty NASW or cold and less saline LSW, which in turn have been linked to North Atlantic Oscillation (NAO; Balch *et al*., 2012), with the NAO leading the LSW by about two years (Mountain, 2012). SFA 29 West, however, is more likely influenced by water entering the

Gulf of Maine from the Scotian Shelf, looping around the southern end of Nova Scotia and then moving northward into the Bay of Fundy (Balch *et al*., 2012). Scotian Shelf water is generally cooler and less saline than water in other parts of the Gulf of Maine.

The Gulf of Maine North Atlantic Time Series (GNATS) began in 1998 (Balch *et al*., 2012). It monitors a suite of environmental, chemical and physical parameters along a permanent transect from Yarmouth, NS to Portland, ME to document changes in the Gulf of Maine over time. In contrast to other areas along this transect, there has been little change in nutrients in the Scotian Shelf water. Nutrient changes observed in parts of the Gulf of Maine may have effects on the planktonic ecosystem in the offshore waters, with respect to relative abundances of diatoms and dinoflagellates, in that when there were more diatoms there were fewer dinoflagellates (Townsend *et al*., 2010).

Looking at a 115 year record of temperature in the Gulf of Maine, Balch *et al*. (2012) noted a highly significant increase in temperature in the Gulf of Maine. The SFA 29 West survey collects bottom temperature data from loggers attached to the survey gear. Data collection began in 2012 and only two years of data have been collected to date. Bottom temperature in all parts of SFA 29 West was higher in 2012 than in 2013 (Figure 7). This is in agreement with bottom temperature patterns seen in data collected on other scallop surveys. In those areas, 2012 had very high bottom temperatures, and a decrease in temperatures was seen in 2013. Average bottom temperature from the SFA 29 West survey in 2012 was 11.4°C (range: 7.7 to 13.2°C), and in 2013 the average was 8.6°C (4.3 to 10.8°C).

FISHERY

Tables 1(a,b) and 2 provide summaries of total allowable catches (TAC), seasons, and significant milestones (with associated references) for the SFA 29 West fishery, some of which are highlighted below.

In 2001, a 200 t scallop fishery was initiated on June 11 with the condition that each vessel take an observer for one trip to monitor the lobster bycatch and record scallop shell height frequencies. The 200 t was caught by late July. The lobster bycatch data was reviewed with the LFA 34 Lobster Association and the weight of bycatch was shown to be not significant relevant to the catch by the lobster fishery. An additional 200 t was allocated to the Full Bay fleet. This was caught by the end of August and the fishery closed (Smith and Lundy, 2002c). The area covered during the 2001 fishery was mostly in the southern portion of the area, which differed from the area fished in 1996–1998 (Smith and Lundy, 2002a). A total of 305 t of catch came out of a portion (82.5 nm^2), of the area that would be later called subarea C. Catch rates were high at an average of 109.6 kg/h. After a review of the 2001 survey results SFA 29 West was subdivided into five subareas (A–E, Figure 1). The high abundances found throughout the 2001 survey and consistently high catch rates in the fishery led to a TAC of 800 t for the 2002 fishery (A, B, and C only; Table 1a,b, Figure 5). Subarea D remained closed to the fishery to allow the smaller animals observed there to reach commercial size. Initially, only the Full Bay Scallop Fleet had access to the fishery in SFA 29 West but in 2002, the Minister of Fisheries granted access to the area to a limited number of the East of Baccaro scallop licence holders. A TAC sharing arrangement of 75% Full Bay and 25% East of Baccaro was used (Smith *et al*., 2003).

Subarea D remained closed in 2003. Approval for the opening of the fishery for the remaining areas was delayed by the Minister until the end of July, and the fishery in subarea B was closed August 22 due to high lobster bycatch (Smith *et al*., 2005). The rest of the area closed September 12. The western portion (west of Longitude 65°N 40°W) of D was opened for the 2004 season after it was determined from the 2003 survey that there would be enough commercial size scallops for a fishery. The eastern portion remained closed pending evaluation of the size composition from the post-fishery survey.

In 2005, DFO Fisheries Management introduced a minimum shell height restriction of 100 mm for the commercial catch. The 2005 TAC was set at less than half the TAC from the previous year based on the 2004 survey (Smith *et al*., 2006). While all of subarea D was open for the 2005 fishery, the TAC was caught quickly, and the fishery in that subarea overran the TAC by 34% and closed after 36 hours.

The 2006 TAC was set at 400 t based on the 2005 survey results and the results of fitting a state-space assessment model similar to those used in the Bay of Fundy (Smith *et al*., 2006).

The sharing arrangement between fleets was amended by the Minister of Fisheries in 2009 to be 65% and 35% for the Full Bay Fleet and East of Baccaro licence holders, respectively. For the 2010 fishery, the two fleets were combined into a single SFA 29 West licence holders group for TAC, landings, and seasons. There were no closures for lobster bycatch in 2010 and 2011 (Sameoto *et al*., 2012).

In 2012, the TAC was set lower than the advice from the stock assessment based on recommendations by the industry. This was the lowest TAC set since the start of the current fishery in 2001. Subareas B and D were closed on July 9th and 10th, respectively. On July 26th, all other areas were closed with 10 t of TAC remaining. The Minister directed the fishery to be reopened from August 30th to September 15th so that licence holders could catch up to 75% of their uncaught allocation. A total of 6.3 t were landed during this re-opening. There were no closures for lobster bycatch in 2012 (Smith *et al*., 2014).

BYCATCH

At-sea observer coverage to monitor bycatch of the inshore scallop fleet is a mandatory part of the management of SFA 29 West. Observed trips from SFA 29 West were used to evaluate the discard rates from the inshore scallop fishery in the area (Table 3). The discard rate is defined as the sum of bycatch species weight from observed trips divided by the sum of landed scallop weight from observed trips (Sameoto and Glass, 2012). Data collected from 10 trips each in 2010, 2011 and 2012 were used to update the data presented in Sameoto and Glass (2012). In 2010, there were 11 observed trips but only 10 contained useable data. At-sea observer protocols and analysis methods are consistent with data previously presented in Sameoto and Glass (2012).

At present, only the lobster bycatch data are monitored during the season for potential management actions. Other species are recorded and reported in assessments or other studies (e.g., Sameoto and Glass, 2012).

ANNUAL SURVEYS

SURVEY DESIGN

Table 4 provides a summary of survey designs and changes for SFA 29 West. In 2000, an exploratory survey of 47 tows was conducted by the Canadian Coast Guard Ship (CCGS) *J.L. Hart* to confirm the suspected high scallop densities in SFA 29 West. The survey gear used was the four-gang, 2.5 foot Digby gear used in the Bay of Fundy surveys at the time. Two drags were unlined and the other two were lined with 38 mm polypropylene mesh. As it was a preliminary survey, the entire area of 29 West was not surveyed. Survey catch rates were significantly higher than surrounding areas and the commercial potential was regarded as high (Smith and Lundy, 2002c).

A joint project agreement was established between Industry and DFO in 2001 to provide funding to cover science survey expenses for SFA 29 West. A catch of 2 t was allocated to cover the expenses incurred by the vessel while conducting the stock assessment survey. The F/V *Julie*

Ann Joan owned and operated by Captain Kevin Ross was used to conduct the survey after the 2001 fishery had occurred. The vessel used standard commercial gear with 9 two-foot wide miracle drags made with 75–78 mm inside diameter rings knit with rubber washers. The two end drags were sampled each tow. One end drag was lined with 38 mm polypropylene mesh with the other eight drags left unlined (Smith and Lundy, 2002a). Sampling and measuring were conducted with established scallop survey protocols (Smith and Lundy, 2002a). A total of 125 randomly located, 8 minute tows were conducted over an area of 600 km^2. This survey identified commercial size scallops in densities in the southern area not covered in the 2000 survey that were more than double what was found in the 2000 survey, as well as large concentrations of recruits (shell height 90–99 mm) and pre-recruits (shell height <90 mm; Smith and Lundy, 2002a).

The 2001 survey results were used to subdivide SFA 29 West into five subareas (A–E) of similar commercial scallop densities (Smith and Lundy, 2002a). These subdivisions were treated as sampling strata for the 2002 survey and were also assigned separate TACs for the 2002 fishery. In 2002, the survey was again conducted after the fishery by the F/V *Julie Ann Joan*. There was a slight change in gear configuration in that the rings were knit with steel washers instead of rubber washers and rubber chaffers were added to the outside of the gear. All sampling and measuring protocols remained as in previous surveys (Smith *et al*., 2003). A total of 125 random survey tows were completed in the subarea strata A, B, C, and D. Few scallops were found in subarea E in 2001 and this subarea was not included in the 2002 survey.

This design was used until 2004. The effect of the steel washers used in the 2002 survey was explored in Smith *et al*. (2003), through a selectivity analysis of the shell height frequencies from the lined and unlined drags. The lined gear should be unaffected by the washers used as the 38 mm polypropylene mesh closes in the gear more than the washers do. The unlined gear was only analysed for areas B, C and D as there was not enough data to analyse area A. Results for areas B and D indicated that the unlined gear was catching on average 18–20% more scallops with the steel washer configuration than with the rubber washer configuration, but the variability was quite high and the differences between the gears were not significant. In area C, the results showed little difference between the two gear configurations. Thirty-seven exploratory tows were conducted to compliment and groundtruth the multibeam acoustic mapping that was being conducted at the time (DFO, 2006).

The survey in 2004 was conducted by the F/V *Branntelle*. Unfortunately, there was no opportunity to conduct comparative study between the *Branntelle* and *Julie Ann Joan*. Protocols and survey fishing gear used were the same as in the 2001-2003 surveys of the area (Smith *et al*., 2005). In addition to the 125 stratified random survey tows, 26 exploratory tows were conducted in the area north of subareas C and D.

In 2005, the survey work was split between two vessels, one from the Full Bay and the other from the East of Baccaro fleet. The F/V *Julie Ann Joan* (side dragger) conducted stations in subareas A–D, while the F/V *Overton Bay* (stern dragger) conducted tows in areas C and D. A total of ten comparative tows were made between these two vessels, as well as an additional vessel, F/V *Faith Alone* from the East of Baccaro Fleet. In an attempt to make the unlined gear comparable, the rubber washers in the F/V *Overton Bay's* end drag were replaced with steel washers. Only three of the ten tows had tracks close enough to be considered comparative tows. The results from these three tows were highly variable and there were not enough data to be able to determine if there were differences between the catches from the three vessels (Smith *et al*., 2006, 2007).

The first results from the surficial sediment interpretation of the data from the multibeam acoustic mapping project were used to re-stratify the survey area in 2005 (Figure 4). The original stratification extended over the subarea boundaries because there was discussion about eliminating these boundaries and setting one TAC for the whole area. However, Fisheries

Management retained the five subarea system due to a lack of agreement between the two fleets on changing the boundaries. Domain estimates were used to express abundance and biomass estimates from the survey based on the surficial sediment strata in terms of subarea (See Appendix 2). Both of the survey vessels found similar densities of scallops on bedrock and glacial till in areas C and D. Commercial size scallop densities were higher for thin sand and glacial till bottom types. The implementation of the new stratification scheme did not change the overall trend of biomass for commercial scallops (Smith *et al*., 2006).

The 2006 survey was conducted by the F/V *Julie Ann Joan* and the F/V *Faith Alone*. Ten comparative tows were conducted between the two vessels on thin sand bottom in subarea D (Smith *et al*., 2007). While these tows were successful with respect to the tow tracks being much closer together than the comparative tows in 2005, the shell height frequencies from the two vessels did not match very well on a tow-by-tow basis reflecting either small scale patchiness, differences in how the measuring boards were used by the fisheries observer on the *Faith Alone*, or both. However, the aggregate indices for recruit size and commercial size scallops from the two vessels survey stations were in close agreement.

The survey in 2006 was designed as a stratified random survey using surficial sediment strata within each of the subareas and standard stratified survey estimates were used (Appendix 2). The complete survey estimate time series was recalculated using the surficial sediment strata with the estimates for 2001–2004 derived using post-stratification estimates (Appendix 2). The impact of these changes for 2001 to 2004 was minimal for subareas A and B. The trend remains the same for the two sets of estimates from subarea C, although those based on bottom type for 2001-2004 were lower overall. The major change that occurred for the estimates in D was the decrease in the 2003 estimate to account for non-proportional sampling between the bedrock and the thin sand bottom. The decline from 2003 to 2004 based on the subarea strata was noted as being higher than expected given the size of the fishery that year. Smith *et al*. (2007) noted that even with the change to surficial strata, cohorts were difficult to follow in the shell height frequencies for each of the subareas. In particular, changes in abundance between 2003 and 2006 in subarea D appeared to be too abrupt to be explained by population dynamics or fishery impacts.

The joint program agreement that funded this survey starting in 2001 was terminated in late 2006 due to the LaRocque court decision and interim funding was provided by the department to fund the survey. The arrangement of one vessel from the Full Bay fleet conducting 90 survey tows in subareas A–D and 30 survey tows by a vessel from the East of Baccaro fleet in subarea C and D continued in 2007. The 2007 survey design was the same as in 2006 with surficial strata within subareas. A strong pulse of 1 and 2 year old pre-recruits was observed during the 2007 survey. Abundance estimates of scallops this size found in the survey are only qualitative measurements due to the selectivity of the gear. The stock assessment noted the continuing difficulty in following cohorts and considered this issue as a possible consequence of patchy distribution and low sampling intensity relative to the other surveys for inshore scallop stocks (Smith *et al*., 2008).

In 2008, the surficial bottom type maps were revised now that an analysis had been completed of the sidescan sonar and seismic data collected during the multibeam project. In addition, geophysical categorization of bottom type was used which incorporated the glacial history of the area (Figure 6). The new categories were defined as (Smith *et al*., 2009a),

1. Pg: Post-glacial sand and gravel: well-sorted sand, grading to rounded, and subrounded gravels;
2. Gm: Glaciomarine silt: acoustically stratified, poorly sorted clayey and sandy silt with some gravel; sometimes embedded with underlying ice-contact sediment;
3. Ic1: Ice-contact sediment (till): unconsolidated drift probably consisting of heterogeneous mixture of clay, sand, gravel, and boulders varying in size and shape;

4. Dg: igneous bedrock mantled with discontinuous sediments;
5. Є-Oᴍ: metamorphic bedrock granite mantled with discontinuous sediments.

The 2008 survey was designed using these new geophysical strata within subareas (Todd *et al*., 2009). The time series estimates were recalculated using the new strata using the post-stratification estimates for 2001–2004, domain estimates for 2005–2007 and stratified random estimates for 2008. Estimates calculated for the different stratification schemes used to date were compared in Smith *et al*. (2009b; see Figure 8). Smith *et al*. (2009a) evaluated the three different survey designs used here with respect to the precision of the associated estimates of mean number per tow for commercial size scallops from the 2001 to 2007 surveys. Overall, the geophysical based design resulted in more precise estimates (lower variance) of the mean when compared to a simple random sample design. The design efficiency for 2008 of 16.17% was similar to that estimated for the 2007 survey using the geophysical design. This study also concluded that while there was strong evidence for an association between bottom type and scallop abundance at the beginning of the time series, fishing had reduced the densities to be similar throughout the area resulting in the survey design based on bottom type becoming less efficient over time.

With the established new stratification scheme for the area, surveys for 2009–2013 were designed and conducted with the same methodology used in 2008. The survey mean number per tow estimates for the complete times series up to 2012 for commercial size and recruit size scallops based on the geophysical strata are presented in Figure 9. The numbers of clappers (empty paired shells) are also collected during the survey (Figure 3). Clappers are assumed to be an indicator for changes in natural mortality (see Smith and Lundy, 2002b)

Departmental funding in response to the LaRocque decision supported the survey from 2007 to 2011, and the F/V *Julie Ann Joan* and *Faith Alone* continued to do the surveys. In 2012, the survey was conducted by one vessel, F/V *Hit 'N Miss*, due to changes in contracting and departmental funding arrangements. The same gear and sampling protocols were used and based on the results of comparative work completed in the Bay of Fundy (Smith *et al*., 2012), a similar experiment was not considered to be needed in SFA 29 West. Subarea E was allotted five exploratory tows due to increased fishing activity in this area during the 2012 fishery. The interim funding due to the LaRocque decision was discontinued in 2012 and with modifications to the *Fisheries Act* passed by Parliament in 2012, a funding arrangement based on the sale of a portion of the quota to support science activities was established to support the survey in 2013.

LOBSTER CATCHES

Information on lobster caught in the SFA 29 West survey has been recorded since 2001. The mean number of lobster per tow in the survey has increased in all subareas over recent years (Figure 10). The increased presence in the scallop survey is likely due to increases in the lobster population. As noted in Smith *et al*. (2014), lobster landings in LFAs corresponding to SFA 29 West and surrounding areas have been increasing over the past few years, and were at record highs in 2011/2012 (in LFA 34).

ASSESSMENT METHODS

PREVIOUS METHODS

Initially science advice for this area was mainly concerned with its value as a broodstock area that would influence recruitment in existing fisheries on German Bank, SPA 3 and the Bay of Fundy. However, once the current fishery began in 2001, advice was focussed on setting TACs that would not negatively impact the long-term productivity of the stock and were in line with sustainable fishing practices in place in other SFAs. The first attempts at setting TACs were based on catch rates and how the TAC related to the density of removals. In 2001, catch rates were quite high and the removal density (t/nm^2) was comparable to SPA 4 (Smith and Lundy, 2002a). Once there was a second year of survey data, scallop densities were compared between surveys to determine if removals from the fishery were compensated for by incoming recruitment (Smith *et al*., 2003, 2005). In subareas where this did not occur, the differences between surveys were used to adjust the TAC accordingly (Smith *et al*., 2003, 2005).

In 2005, the first attempt was made to fit the assessment model used in the Bay of Fundy assessment to the SFA 29 West time series, despite the time series being only five years long at the time (Smith *et al*. 2006). The results were used to inform catch advice but they were also highly variable, and there was a high degree of uncertainty about whether a given TAC would result in a decline in biomass or not. In 2006, there was an attempt to augment this approach by also considering catch rate information from the fishery but these data did not correlate very well with the survey data at the time (Smith *et al*., 2007). It was also at this time that the differences between low density and high density scallop beds were considered in how the data was interpreted. It was hypothesized that the spatial distribution of effort may be proportional to abundance indicating that fisherman are able to concentrate their effort in the best fishing areas until catch rates become more similar between high and low density areas (Smith *et al*., 2007). This seemed to explain somewhat the observations of extremely high catch rates at the beginning of the fishery but fell short of providing an alternative index as the effects of density and fishing behaviour were confounded. Growth information was also used around this time to set exploitation rates that were in the range of the expected growth in biomass and which would result in small or negligible declines in population biomass assuming that recruitment just balanced off losses due to natural mortality (Smith *et al*., 2008).

The trends and patterns of the catch rate data were examined more closely once daily information became available (Smith *et al*., 2008). The daily catch rates exhibited declines over the short season making them amenable to analysis using depletion type models to quantify the impact of the fishery on the population (Leslie and Davis, 1939). Assuming a closed population, that is, no recruitment, natural mortality and minimal growth during the period of the fishery, then the population biomass at the beginning of the fishery (B_0) should decrease simply as a function of the catches (C_i) up to time t. That is,

$$B_t = B_0 - \sum_{i=0}^{t-1} C_i \tag{1}$$

where $C_0 = 0$. Assuming that commercial catch rate K_t was observed at time t and that the catch rate was proportional to the biomass over time then,

$$\begin{aligned} K_t &= qB_t \\ &= q(B_0 - \sum_{i=0}^{t-1} C_i) \\ &= qB_0 - q\sum_{i=0}^{t-1} C_i \end{aligned} \tag{2}$$

There are three main quantities that can be obtained from the model in equation 2. The slope is the catchability coefficient for the fishery, while dividing the intercept by the slope gives the population biomass B_0 at the beginning of the fishery. The exploitation rate of the fishery on the population at the end of the fishery (time I) can be estimated as,

$$\hat{E} = \frac{\sum_{i=1}^{\mathrm{l}} C_i}{B_0} \tag{3}$$

In Smith *et al*. (2008), the depletion model was cast as a Bayesian model with the likelihood for K_t in equation 2 set to be for a normal distribution with mean at time *t* equal to $B_0' - q\sum_{i=0}^{t-1} C_i$ and variance σ^2. A normal non-informative prior was assigned to B_0' (mean=0, variance=10^6) while a positive half normal distribution was used as the prior on q. A uniform (0,100) distribution was used as the prior on σ.

Catch rates within each of subareas A to D were calculated as the ratio of catch to effort by fleet and by day. Only commercial log data where catch, effort, date and location were provided were used here. The number of records available by day and fleet were highly variable in addition to there being differing levels of variability of catch and effort for any one day and fleet. This variability was incorporated into the analysis by weighting the variance σ^2 in the model by the standard error associated with each daily catch rate estimate. That is, the variance associated with the model in equation 2 was expressed as $V\sigma^2$, where V is a diagonal matrix with element v_{ii} equal to the standard error for the catch rate for day *i*. The standard error was estimated using the jackknife estimate recommended by Smith (1980) for catch rate estimates.

Monte-Carlo Markov Chain simulations using the Gibbs sampler in WinBugs (Lunn *et al*., 2013) were used to find the estimates for this model. Two chains with separate starting values were used for each run with the first 10,000 replicates discarded as a burn-in and the second 10,000 replicates per chain kept to describe the posterior distributions of the parameters. The degree of convergence to the posterior distribution was evaluated using the Brooks-Gelman-Rubin method (Brooks and Gelman, 1998).

In 2010, a second attempt was made to fit a simplified version of the state-space assessment model to the survey data. This model was set up in such a way that fishery information was not included and exploitation was estimated from changes in the survey biomass (Smith *et al*. 2010). The most basic version of this model can be written as,

$$B_t = g_{t-1}\,(B_{t-1} + R_{t-1}) \tag{4}$$

where B_t is the biomass of the commercial size animals in the current year, and B_{t-1} and R_{t-1} are the commercial and recruitment biomass from the previous year, respectively. The term g_{t-1} is simply the proportional change from one year to the next and is a function of natural mortality (M_{t-1}), fishing mortality (F_{t-1}) and growth (G_{t-1}). The commercial biomass and recruitment biomass are related to their survey estimates, I_t and r_t, of the same as follows,

$$I_t = q_I B_t \tag{5}$$

$$r_t = q_R R_t \tag{6}$$

where q_I and q_R are catchability coefficients.

An alternative approach examined by Trenkel (2008) and Mesnil *et al*. (2009) (see also Hoenig and Gedamke, 2007) simply models the dynamics of the survey data and focuses on estimates of g_{t-1} to determine stock status — increasing, decreasing or stable. In this approach, $q_I = q_R = 1$ and the resulting estimates of B_t and R_t provide a smoothing estimate for the survey trend over time. Here, this model is cast into Bayesian framework as follows.

$$\log(I_t) \sim \mathrm{Normal}(\log(B_t), \sigma_I^2) \tag{7}$$

$$\log(r_t) \sim \mathrm{Normal}(\log(R_t), \sigma_r^2) \tag{8}$$

Further, recruitment is assumed to follow a lognormal relationship without any stock-recruitment relationship,

$$\log(R_t) \sim \mathrm{Normal}(\mu_R, \sigma_R^2) \tag{9}$$

Finally, g_t are constrained from varying wildly by applying a random walk process on the log scale (Trenkel, 2008).

$$\log(g_t) = \log(g_{t-1}) + \epsilon_t \tag{10}$$

where the error term, ϵ_t is distributed as a normal random variate with mean $-0.5\sigma^2_g$ and variance σ^2_g.

Noninformative priors (uniform(0,100)) were used for σ_I, σ_r, σ_R and σ_g. The prior for the recruitment process was set to Normal $(0,10^6)$. The posterior distribution was simulated using WinBugs (Lunn *et al*., 2013) with two chains of 100,000 iterations each and a burn-in of 50,000 iterations. Every tenth iteration was kept after burn-in. Convergence to the posterior was checked using the Brooks-Gelman-Rubin method (Brooks and Gelman, 1998).

The advantage of this approach was to have two exploitation estimates to compare that were derived from independent data sources, fishery data (depletion estimates) and survey data (assessment model).The results were fairly consistent in subareas C and D where the depletion estimates worked well and less so in subarea B where the depletion method had difficulty due to fishing behaviour patterns. This approach was also compared to fishing effort in the 2012 and 2013 assessments, because exploitation and effort are highly correlated in the fisheries in the Bay of Fundy (Figure 11; Smith *et al*., 2014).

HABITAT-BASED ASSESSMENT

As discussed above there appears to be a strong relationship between the spatial distribution of fishing effort and bottom type that may be reflective of the spatial distribution of scallop productivity (Smith *et al*., 2007, 2009a). Spatial patterns for growth, density and settlement are major common features for most scallop species (Brand, 2006). Such patterns have been extensively documented for sea scallop (*Placopecten magellanicus*) and are associated at the local scale with depth and substrate type (Thouzeau *et al*., 1991, Smith *et al*., 2001, Brand, 2006). Productive grounds for sea scallop have been associated with gravel and gravel lag deposits which can be readily identified from multibeam backscatter data (Kostylev *et al*., 2003). However, sediment type by itself may not be the driver for scallop distribution but instead be a proxy for the currents in the area (pages 132–133, Roff and Zacharias, 2011).

Previous analyses of the spatial distribution of scallops in SFA 29 West have been based on a geophysical interpretation of the multibeam and associated groundtruth data, and scallop densities from the annual surveys (e.g., Smith *et al.* 2009a, 2009b). Brown *et al.* (2012) took a different approach by modelling the association between scallop presence only data from underwater image surveys and multibeam data including bathymetry, the first three principle components from a QTC[3] analysis of the backscatter data (Q1, Q2, Q3), Benthic Position Index (BPI, at three different resolutions: 1×5 pixels, 5×10 pixels and 10×50 pixels; pixels were 50 m in dimension), slope, curvature, backscatter intensity and aspect. The use of presence only data avoided issues of the trend to similar densities throughout the area due to fishing and the direct inclusion of multibeam based data allowed for more flexibility in the interpretation of these data than provided by the single geophysical interpretation. The results of the model were expressed in terms of the probability of encountering a scallop as a function of the above covariates with this probability interpreted in terms of habitat suitability (increasing from 0 to 1; Figure 12). Comparison of the habitat suitability map with a preliminary analysis of fishing effort based on the VMS data from SFA 29 West indicated that the higher concentrations of fishing intensity were associated with the areas of higher habitat suitability (Figure 7d in Brown *et al.* 2012).

Stock assessment models used for the other scallop fisheries in the region (e.g., Smith and Lundy, 2002b) were applied to survey biomass estimates and commercial catch for the stock areas as a whole to capture the population dynamics. The basis for these and other standard fisheries models are that both the fishery and the species being fished are uniformly distributed in space so that all animals being harvested share the same vital rates and are at equal risk of being caught (Beverton and Holt, 1957). The basic relationships developed between fishing effort, probability of capture and fishing mortality by Beverton and Holt (1957) were based on this assumption and required that fish were able to re-mix after the disturbance of each fishing event. As noted previously, fishing effort is not distributed uniformly in space and instead indicates that fishing is more concentrated in areas where densities of scallops are higher. Many authors have noted that ignoring spatial pattern in stock assessment models can result in misleading interpretations of abundance indices and the impacts of fishing on productivity (e.g., Caddy 1975, Booth 2000, Pelletier and Mahevas 2005).

Vessel monitoring system data

(S.J. Smith, J.A. Sameoto, and C. Brown, unpublished manuscript) have developed a spatial habitat-based version of the assessment model currently used for the other scallop fisheries in the DFO Maritimes Region that partitions the commercial effort data, and survey data using the habitat suitability definitions given in Brown *et al.* (2012). The commercial effort data is derived from the VMS data that has been collected for this fishery.

Monitoring fishing activity using VMS has been a mandatory requirement for the inshore scallop fishery in SFA 29 West since the fishery began in 2001; however, the data has only been recorded by the department since 2002. VMS data consists of a vessel name, vessel registration number (VRN), date-time stamp, and position in decimal degrees (World Geodetic System 1984). Vessels are not required to transmit their speed. The VMS polling interval for SFA 29 West was 60-min from 2001–2009 and since 2010 has been at 15-min. To be consistent throughout the time period, data since 2010 were resampled to 60-min.

VMS data do not indicate if a vessel is fishing, therefore, speed criteria are often used to differentiate between activity states (e.g., fishing, steaming). Since instantaneous speeds are not available for this fishery, derived speeds must be calculated from the positions and time

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[3] Image-based classification software QTCMultiview (Quester Tangent Corporation; accessed on March 25, 2015).

differences between successive VMS records. The following approach was taken to analyze the VMS from SFA 29 West for the framework. Vessel tracks were constructed via straight-line interpolation although this may not necessarily reflect the true fishing patterns of the vessels (Deng *et al*. 2005, Eastwood *et al*. 2007). This consequently results in an underestimation of a vessel's true distance travelled and derived speeds that underestimate transmitted instantaneous speeds (Gerritsen and Lordan 2011, Skaar *et al*. 2011). Speed criteria used to differentiate fishing activities are often assessed from the shape of a speed histogram, where the mode(s) are used to identify the speed break points (Mills *et al*. 2007, Lee *et al*. 2010). However, if vessels exhibits frequent turning manoeuvers at a temporal scale that is significantly finer than the VMS polling frequency, derived speeds will highly underestimate instantaneous speeds, and there will be no discernible mode in the speed histogram from which to derive the speed criteria. This can be clearly seen in SFA 29 West where the average tow time is approximately 15-min and a vessel will often tow repeatedly over a small area of only a few kilometers (Figure 13).

To account for derived speeds that highly underestimate instantaneous speeds, a speed criterion range criterion of [0.191, 1.175 knots] was defined to identify fishing. This range gave the best fit in terms of VMS effort to observed daily logbook effort. VMS records in SFA 29 West were identified as fishing where the associated derived speed of a VMS record was within the bounds of the speed criteria. The location of the VMS records were matched with the habitat suitability measures binned into ten intervals of width 0.1 probability. The VMS effort hours were totaled by bin and then standardized by the associated area of the bin since bin areas differed (i.e., effort (or fishing intensity) was measured as hours/km^2). Fishing effort per area or fishing intensity was consistently higher in the higher suitability areas for all of the subareas except 29A (Figures 14–17). This continued to be the case even as catches declined over time.

Survey data

The number of survey tows in any one year was not enough to cover all of the ten VMS bins. The habitat suitability bins were further grouped into [0,0.3][4] (Low), [0.3,0.6] (Medium) and [0.6,1.0] (High) categories to re-stratify the survey data from 2001 to 2012 (Figure 18). The area associated with each of these categories in each subarea are presented in Table 5. The mean number per tow for commercial and recruit size scallops was calculated for each of the above suitability categories within subareas using post-stratified estimates for 2001 to 2004 data and domain estimates for the remaining years (See Appendix 2). Over the whole time series there was only one tow in the High category in 29A and, therefore, survey indices could not be calculated for this category in this area.

The annual trend for the mean numbers per tow of commercial size scallops shows that the means were highest in the High suitability category followed by the Medium and Low categories at the beginning of the time series. Over time, the means for Medium and High categories declined and became similar with each other and approached the mean for the Low category (Figure 19). This pattern of declining and more similar catch rates over the subareas was also identified in Smith *et al*. (2009b) as the reason behind the declining efficiency with time of the geophysical-based survey design. The same pattern is evident for the recruit size scallops with the higher mean numbers per tow occurring in the High habitat suitability areas (Figure 20).

Separating the survey estimates by habitat suitability appears to provide clearer patterns to the population dynamics than the survey estimates by subarea alone. The zig-zag pattern in subarea 29A appears to be more a reflection of the mean per tow for the Low habitat areas than the Medium areas (Figure 19). This pattern was probably due to which habitat suitability area had more survey tows in it in any one year. Note that the survey only sampled the High

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[4] The notation [0,0.3] denotes an interval starting at 0 and ending up to but not including 3.0.

suitability area in 2004, a reflection of the fact that probabilities of 0.6 and above from the species distribution model were only found in less than 1% of the area in 29A (Table 5). In 29D, the single peak in 2005 after two good years of high recruitment followed by an overall decline in 2006 despite high recruitment in 2005 has always seemed puzzling (Figure 19). However, the trend is clearer for the habitat suitability based indices where the higher densities of recruits led to higher densities of commercial size from 2002 to 2006 in the High suitability areas, while the single peak in commercial size occurred in the Medium suitability area. The High suitability grounds covered 15.6% of the area while the Medium area comprised 43.6% and the trend for the latter dominated the subarea trend (Table 5). The Medium habitat area trend also dominated the subarea trend in 29B and 29C mainly as a function of the larger area associated with this habitat suitability type (44.8 and 41.4%, respectively) relative to the High area (less than10% for both areas).

Assessment model

The process portion of the stock assessment model is indexed for each habitat suitability category within each subarea (Smith and Lundy, 2002b, Smith and Hubley, 2014),

$$B_{h,t+1} = (exp(-m_{ht})(g_{ht}B_{ht} + \bar{w}_{kt}R_{ht}) - C_{ht})\ \tau_h$$

where B_{ht}, C_{ht}, and R_{ht} are the population biomass of commercial size animals, commercial catch, and recruit numbers, respectively for each habitat suitability class h (Low, Medium and High) in year t. Annual rates of natural mortality by habitat suitability class are denoted as m_{ht} and were modelled from trends in the clapper index (hinged empty shells) using the “popcorn” model described in Smith and Lundy (2002b). The annual growth rate for biomass, g_{ht}, was estimated by the method in Nasmith *et al*. (2013) due to annual variability in the relationship between meat weight and shell height (Figure 2). The term $\bar{w}_{kt}$ is the average weight of the recruit size scallops when they recruit to the fishery in year t. The expected value of B_{h1} is assumed to be equal to the dynamic carrying capacity K_h for each habitat suitability area. The process error term τ_h was assumed to be log normal with variance $\sigma^2_{\tau h}$. Further details about the model are given in (S.J. Smith, J.A. Sameoto, and C. Brown, unpublished manuscript).

While population biomass estimates (Figure 21) indicate that the higher biomasses tended to be in the Medium suitability class, biomass density was much higher in the High suitability class at the beginning of the fishery before being reduced to be more similar to the densities in the Medium for 29B to 29D (Figure 22). The larger changes in the density in the High suitability areas were a direct reflection of the higher fishing intensities in these areas as measured by the VMS data. With the exception of 29A, recruitment densities tended to be higher in the High suitability areas (Figure 23).

The estimates of natural mortality for the commercial size scallops indicated higher rates in the earlier years of the fishery (Figure 24). In fact there seems to be very strong evidence for density-dependent survival especially for the Medium and High suitability areas (Figure 25). In 2006, scallop fishermen reported unusually large numbers of clappers in subarea 29D which was also picked up in the survey after the fishery that year as being in the Medium suitability area (Figure 24). No evidence of disease was found from scallops sampled during the fishery but the clappers may have been generated earlier in the year as a consequence of the high densities due to the large recruiting year-class and winter food limitations (Johnson *et al*., 2012).

Estimates of catch by habitat suitability show the importance of the High suitability areas as a source of catch in the earlier part of the time series when densities were high (Figure 26). As the fishery developed, more of the catch came from the Medium suitability areas. Commercial catch rates estimated from the model exhibit a similar trend to the survey series with the High suitability areas having higher catch rates in the first few years and then decreasing to be similar to the levels in the Medium suitability areas (Figure 27). The catch rates from the subareas as a whole more closely resemble those in the Medium suitability areas.

Exploitation trends by habitat suitability reflect the fishing intensity trends from the VMS data with the higher exploitation rates in the High suitability areas for 29B to 29D and in the Medium suitability areas for 29A (Figures 28, 29). The subarea exploitation rate trend was closest in agreement to the effort trend used in previous assessments as an indicator for exploitation (Figure 30).

STOCK STATUS

STOCK PRODUCTIVITY: REFERENCE POINTS

The Canadian system for applying the precautionary approach to fisheries decision-making defines three stock status zones according to two biomass-based stock reference points defined as the lower reference point (LRP) and the upper stock reference (USR) point, as well as a removal reference (RR) point (Figure 31). When the commercial size biomass is above the USR level, the stock is designated as healthy, while commercial size biomass between the LRP and USR levels is considered to be in the cautious zone resulting in management action being taken to increase the biomass over a designated time frame. Commercial size biomass below the LRP level will be denoted as being in the critical zone and fishery removals are to be reduced to their lowest levels to promote rapid stock biomass recovery to the healthy zone. The removal reference point is defined as the maximum acceptable removal rate for the population and is usually assumed to be less than or equal to the removal rate associated with maximum sustainable yield.

For those areas in the Bay of Fundy where an assessment model has been used, the fishing industry has agreed with setting the LRPs to the lowest biomass in the time series from which a sustained recovery occurred (Smith and Hubley, 2012). The USR was based on the equilibrium biomass and exploitation rate associated with maximum catch. These were obtained by projecting the assessment model forward by 50 years from the current year for a range of constant exploitation rates (Nasmith *et al*., 2014). These projections represent a very conservative view of stock productivity as recruitment was set to the median observed level even though all scallop areas have experienced large recruitment events in the past. An exploitation level of 0.15 has been used as a removal reference point for the Bay of Fundy scallop fisheries for a number of years now and was based on comparing exploitation rates and resulting biomass (either model-based or survey estimated) changes for the historical data. Biomass levels tended to increase after a fishery where the exploitation was 0.15 or less, while these levels decreased at higher exploitation rates, excluding high recruitment years (Smith and Hubley, 2012). As an independent check, the results from the equilibrium simulations for determining the USR suggested that the equilibrium exploitation rates would be in the range of 0.14 to 0.16 (Nasmith *et al*., 2014).

In the above approach, population biomass was assumed to be a proxy for the productive capacity of the whole population. However, the results of the habitat-based assessment model show that the more productive grounds are defined in terms of density of scallops and do not always have the highest biomass associated with them. This makes sense in terms of commercial catch rate, which is a fishery measure of productivity. The major impact of the SFA 29 West fishery in terms of changes in survey indices and consequent changes in model estimates of population density occur in the High suitability areas in subareas B–D. In the case of subareas B and D, the highest catches (second highest for C) in their time series came from the High suitability areas where the highest densities and catch rates occurred. Therefore, any attempts to manage the fishery in ways to improve the productivity will need to focus their efforts on the High suitability areas. While the spatial distribution of the different habitat suitability areas makes it impossible to manage these areas separately, the proportional distribution of effort by habitat suitability areas appears to be quite stable at least for the last four or five years (Figure 32). Assuming that this relationship between the effort levels from the different habitat suitability areas continues into the future, it may be possible to design fishing strategies around setting target exploitation rates for the High suitability area only. The assessment model included the standard catch-effort equation resulting in linear relationships between exploitation and effort (Figure 33). Setting a target exploitation rate for the High suitability areas corresponds to a specific level of effort, which in turn based on Figure 32 can estimate the effort levels and exploitation rates for the Medium and Low areas.

Equilibrium biomass and exploitation rate associated with maximum catch for a range of constant exploitation rates in the High suitability area were estimated for each subarea. Methods similar to those used in Nasmith *et al*. (2014) were used to project the habitat-based model forward with natural mortality estimated from the relationships between survival and density given in (S.J. Smith, J.A. Sameoto, and C. Brown, unpublished manuscript). The growth factors were more affected by variation in the condition factor than in the mean shell height of the commercial size scallops and were modelled here simply as a normal random variate with mean and standard deviation estimated from the existing time series (Figure 23). Median recruitment was assumed due to the lack of evidence for stock/recruitment relationships.

While a target rate was used for the High suitability areas in 29B–29D, only the Medium and Low areas were available for 29A and the Medium area was used to set the target rate. The equilibrium biomass for no fishing indicates a maximum biomass of 200 t for 29A (Figure 34, upper panel), which is lower than the maximum estimated for the time series of 444 t (see Figure 21). This underestimate was mainly a function of the median recruitment assumption. However, the calculations here are intended to compare the biomass estimates across a range of exploitation levels and not to estimate the biomass for any one level. Increasing exploitation levels will reduce the biomass in the Medium areas more quickly than in the Low areas as expected given the differences in relative exploitation rates. The maximum catch occurs at an exploitation rate of 0.1 for the Medium areas, which corresponds to 0.019 for total area (Figure 34, lower panel). Higher levels of exploitation would result the maximum total area catch of 3 t but biomass in the Medium areas would eventually be eliminated, and all of the catch would come from the Low areas at very low catch rates.

Increasing exploitation reduced the biomass in the High areas of 29B until it reached the level where the biomass mainly reflected the annual median recruitment (Figure 35, upper panel). Fishing the whole area at an exploitation rate of 0.16 resulted in the maximum catch of 82 t. Exploitation rates around 0.15 have been used in the Bay of Fundy to manage fisheries, but here it is seen that this would be at the expense of the High area biomass and commercial catch rate (Figure 15, lower panel). Based on the maximum catch for the High area, a maximum catch of 57 t would result in a more sustainable exploitation rate of 0.175 for the High area. The situations are similar for 29C and 29D where, as expected, increasing exploitation rates have a greater impact on biomass in the High areas (Figures 36–37, upper panel). Again, maximum catch for the High areas occurred at lower exploitation rate overall than the maximum catch for whole area. In these areas, the exploitation rates for maximum catch in the High areas were also close to 0.2 (Figures 36–37, lower panel). The corresponding overall exploitation rate for 29C and 29D of 0.11 and 0.14, respectively, were also closer to rates used to manage other inshore scallop fisheries.

The patterns of decreasing biomass in the High areas and more catch coming from the Medium areas with increasing exploitation were very similar for subareas 29B–29D. In the case of 29A, the trend was for decreasing biomass in the Medium areas while increasing amounts of catch came from the Low areas. The declining catch rates with increasing exploitation reflected the larger portion of the catches coming from the lower density areas. Given that the time series for

SFA 29 West are shorter than for the other inshore fisheries, it is unlikely that the lowest biomass observed would necessarily fit the definition of the LRP used elsewhere. Pending further research on stock/recruitment dynamics for scallop populations, tentative LRPs could be set as proportions of their respective USRs in the range calculated from the Bay of Fundy (0.48 to 0.71).

HARVEST CONTROL RULES

Currently, harvest control rules are being developed for the Bay of Fundy scallop fishery. A candidate set of rules was presented in Nasmith *et al*. (2014) to evaluate potential benefits for managing a fishery in this manner. Further discussions will be held with Fisheries Management and the industry to develop these rules before they are fully implemented. Given that the assessment methods and definitions of reference points for the Bay of Fundy and SFA 29 West are similar, a similar set of rules should apply.

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TABLES

Table 1a. Scallop commercial fishery landings, total allowable catch (TAC), and landings for food, social and ceremonial purposes (FSC) by First Nations (meats, t) for Scallop Fishing Area (SFA) 29 West from 2001 to 2012. TAC for subareas A and E are combined. Landings by fleets were combined in 2010, 2011 and 2012. n/a indicates no TAC or landings for that fleet/subarea/year.

Year	Subarea	Full Bay		East of Baccaro		First Nation	Total	
		TAC (t)	Landings (t)	TAC (t)	Landings (t)	FSC Landings (t)	TAC (t)	Landings (t)
2001	A	n/a	2	n/a	n/a	n/a	n/a	2
	E	n/a	n/a	n/a	n/a	n/a	n/a	0
	B	n/a	71	n/a	n/a	n/a	n/a	71
	C	n/a	309	n/a	n/a	n/a	n/a	309
	D	n/a	18	n/a	n/a	n/a	n/a	18
	Total	400	400	0	0	n/a	400	400
2002	A	75	0.74	25	3.603	n/a	100	4.343
	E	n/a	n/a	n/a	n/a	n/a	0	0
	B	150	193.417	50	74.974	n/a	200	268.391
	C	375	331.703	125	105.676	n/a	500	437.379
	D	n/a	n/a	n/a	n/a	n/a	0	0
	Total	600	525.86	200	184.253	n/a	800	710.113
2003	A	n/a	n/a	n/a	n/a	n/a	0	0
	E	n/a	n/a	n/a	n/a	n/a	0	0
	B	150	115.513	51	40.457	n/a	201	155.97
	C	188	33.456	63	39.873	n/a	251	73.329
	D	n/a	n/a	n/a	n/a	n/a	0	0
	Total	338	148.969	114	80.33	n/a	452	229.299
2004	A	150	70.794	50	9.943	n/a	200	80.737
	E	n/a	0.154	n/a	2.438	n/a	0	2.592
	B	n/a	34.426	n/a	47.093	n/a	0	81.519
	C	187.5	122.844	62.5	34.726	n/a	250	157.57
	D	112.5	149.978	37.5	40.168	n/a	150	190.146
	Total	450	378.196	150	134.368	n/a	600	512.564
2005	A	45	2.5	15	0.9	n/a	60	3.4
	E	n/a	8.8	n/a	1.7	n/a	n/a	10.5
	B	30	22.7	10	26.3	n/a	40	49
	C	75	91.9	25	23.4	n/a	100	115.3
	D	41.25	63.5	13.75	10.7	1.1	55	75.3
	Total	191.25	189.4	63.1	62.9	1.1	255	253.4
2006	A	18.75	20.4	6.25	1.1	n/a	25	21.5
	E	n/a	0.8	n/a	1	n/a	n/a	1.8
	B	93.75	87.9	31.25	27.8	n/a	125	115.7
	C	75	85.7	25	25.6	n/a	100	111.3
	D	112.5	113	37.5	42.9	6.0	150	161.9
	Total	300	307.7	100	98.4	6.0	400	412.1
2007	A	18.75	10.49	6.25	0.1	n/a	25	10.59
	E	n/a	0.2	n/a	n/a	n/a	n/a	0.2
	B	75	56.2	25	24.32	n/a	100	80.52
	C	37.5	48.5	12.5	10.9	n/a	50	59.4
	D	56.25	68	18.75	26.35	5.4	75	99.75
	Total	187.5	183.4	62.5	61.7	5.4	250	250.5
2008	A	7.5	3.05	2.5	n/a	n/a	10	3.05
	E	n/a	0.65	n/a	0.44	n/a	n/a	1.09
	B	82.5	44.65	27.5	20.5	n/a	110	65.15
	C	33.75	42	11.25	12.3	0.2	45	54.5
	D	63.75	99.9	21.25	26.1	5.6	85	131.6
	Total	187.5	190.3	62.5	59.3	5.8	250	255.4
2009	A	9.75	4.47	5.25	0.05	n/a	15	4.514
	E	n/a	0.01	n/a	1.96	n/a	n/a	1.965
	B	48.75	36.46	26.25	23.43	n/a	75	59.884
	C	48.75	50.19	26.25	27.35	0.7	75	78.238
	D	55.25	67.20	29.75	31.46	5.4	85	104.056
	Total	162.5	158.38	87.5	84.23	6.1	250	248.71

Table 1b. Scallop commercial fishery landings, total allowable catch (TAC), and landings for food, social and ceremonial purposes (FSC) by First Nations (meats, t) for Scallop Fishing Area (SFA) 29 West. n/a indicates no TAC or landings for that fleet/subarea/year.

Year	Subarea	TAC (t)	Landings (t)	FSC Landings	Total
2010	A	25.0	9.4	0.0	9.4
	E	n/a	5.4	n/a	5.4
	B	65.0	50.7	1.4	52.1
	C	45.0	60.6	n/a	60.6
	D	65.0	72.1	4.5	76.6
	Total	200.0	198.2	5.9	204.0
2011	A	25.0	18.1	n/a	18.1
	E	n/a	5.6	n/a	5.6
	B	65.0	59.3	n/a	59.3
	C	45.0	45.5	n/a	45.5
	D	65.0	65.7	5.4	71.1
	Total	200.0	194.1	5.4	199.5
2012	A	25.0	1.02	n/a	1.02
	E	n/a	17.9	n/a	17.9
	B	60.0	76.81	4.2	81.01
	C	45.0	39.8	0.03	39.83
	D	30.0	31.72	0.4	32.15
	Total	160.0	167.2	4.7	171.86
2013	A	35.0	1.3	n/a	1.3
	E	n/a	13.5	n/a	13.5
	B	75.0	82.6	4.9	87.5
	C	25.0	18.3	n/a	18.3
	D	35.0	38.8	n/a	38.8
	Total	170.0	154.4	4.9	159.3

Table 2. Summary of fishery in Scallop Fishing Area 29 West. n/a indicates no TAC or information for that season/year.

Year	TAC	Season	Comments	Reference
1996-1998	Total 3 year-227 mt	n/a	Limited fishery for FB fleet; full observer coverage	Smith and Lundy (2002c)
1999-2000	n/a	n/a	Fishery closed; first exploratory DFO survey in 2000	Smith and Lundy (2002c)
2001	Total- 400 mt	late July (200 mt) to Aug 31st (2nd 200 mt)	DFO exploratory survey - commercially viable fishery; Consultation with lobster industry - recommended conditions - timing (summer), bycatch monitoring, VMS, industry funded post fishery survey; SFA29W subdivided into 5 subareas	Smith and Lundy (2002c
2002	Total- 800 mt A-100 mt B-200 mt C-500 mt D - 0 mt	June 1st to Aug. 31st	Minister of Fisheries granted access to SFA29W to EoB with sharing arrangement - 75%/25% for FB and EoB; JPA - Industry, NR Can and DFO -multibeam acoustic mapping of the area	Smith *et al*. (2003)
2003	Total - 452 mt A-201 mt B-251 mt	End of July to Sept 12th, except Area B closed Aug 22nd (lobster bycatch)	No comments	Smith *et al*. (2005)
2004	Total-600 mt A-200 mt C-250 mt C-150 mt	June 14th to July 27th	Western portion of Area D opened after the 2003 survey indicated biomass at commercial size	Smith *et al*. (2005)
2005	Total-255 mt A/E-60 mt B-40 mt C-100 mt D-55 mt	June 20th to July 27th	100mm minimum shell height restriction implemented (previously 76 mm); multibeam acoustic maps available to the fishermen. All of Area D is open.	Smith *et al*. (2006)
2006	Total-400 mt A/E-25 mt B-125 mt C-100 mt D-150 mt	A, E and B -June 19th to Aug 2nd; C - Jun 26th to Aug 2nd; D - July 4th to July 7th and July 17th (12 hrs)	Reports from fishermen of large numbers of clappers in Area D	Smith *et al*. (2007)
2007	Total-255 mt A/E-25 mt B-100 mt C-45 mt D-85 mt	A-E and B - June 11th to July 21st; C - June 11th to July 10th; D - June 13th to 22nd	No comments	Smith *et al*. (2008)
2008	Total- 250 mt A/E-10 mt B-110 mt C-45 mt D-85 mt	All opened June 23rd; B - closed Aug 9th; A and E - closed Aug 21st for FB and Sept 16th for EoB; C - closed July 21st for FB and July 23rd for EoB; D - closed July 8th for FB and July 11th for EoB	Two closure areas (July 26th and Aug 2nd) in Area B due to high lobster bycatch	Smith *et al*. (2009b)
2009	Total-250 mt A/E-15 mt B-75 mt C-75 mt D-85 mt	A, E and C - June 22nd to Aug 31st; B - closed Aug 1st; D - closed July 4th for FB and July 14th for EoB	Sharing arrangement between FB and EoB amended to 65%/35%, respectively. Two closure areas (July 16th and Aug 20th) in Area B due to high lobster bycatch	Smith *et al*. (2010)
2010	Total-200 mt A/E-25 mt B-65 mt C-45 mt D-65 mt	n/a	Fleets combined into SFA29West licence holders, TAC, landings, and seasons combined; Sharing arrangement no longer in place; No closures for lobster bycatch	Sameoto *et al*. (2012)
2011	Total- 200 mt A/E-25 mt B-65 mt C-45 mt D-65 mt	All - opened June 20th, A, E, and B - closed Aug 31st; C - closed July 25th; D - closed July 4th	No comments	Sameoto *et al*. (2012)
2012	Total- 165 mt A/E-25 mt B-60 mt C-45 mt D-30 mt	All- opened June 25th; A, E, and C - closed July 26th B - closed July 9th; D - closed July 10th; All - reopened Aug 30th to Sept 15th	On July 26th all areas were closed with 10 t of TAC remaining. The Minister of Fisheries directed the fishery be reopened from Aug 30 to Sept 15 for the remaining TAC to be caught	Smith *et al*. (2014)

Table 3. Discard rates for bycatch species in SFA 29 West by year. Discard rates are the amount of discards observed for the amount of scallops landed during the observed trips.

Species	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
ALLIGATORFISH	0	0	0	<0.001	0	0	0	0.001	0	0	0	0
AMERICAN EEL	0	0	0	0	0	0	0.001	0	0	0	0	0
AMERICAN LOBSTER	0.013	0.038	0.015	0.021	0.066	0.034	0.041	0.052	0.060	0.270	0.039	0.127
AMERICAN PLAICE	<0.001	<0.001	<0.001	0	<0.001	0.001	0.005	0.106		0.002	<0.001	0
ATLANTIC ROCK CRAB	0.057	0.065	0.039	0.028	0.170	0.014	0.192	0.229	0.211	0.444	0.023	0.080
BARNACLES	0	0	0	0	0.002	0	0	0	0	0	0.000	0
BARNDOOR SKATE	<0.001	0	0	0	0	0	0.007	0	0.009	0	0	0.001
BASKET STARS	0.002	0.052	0.048	0	0.001	0	0	0.108	0.002	0.042	0	0
BRITTLE STAR	0.001	0.014	0.691	0	<0.001	0	0.011	0	0	0	0.016	0
CANCER CRAB	0	0	0.001	0	0	0.065	0.061	0	0	0	0	0
CEPHALOPODA C.	0	0	<0.001	0	0	0	0	0.016	0	0	0	0
CLAMS	<0.001	0.023	0.249	0.124	0.007	0	0.008	0	0.000	0.429	0	0.095
COD (ATLANTIC)	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	0.001	0.001	<0.001	0.002	0	0.001
COMMON MUSSELS	0.034	0.073	0.112	0.173	0.263	0.017	0.242	0.148	0.001	0.689	1.459	0.094
CORALS	0	0	0	0	0.001	0	0	0	0	0	0	0
CUSK	0	<0.001	0	0	0	0	0	0	0	0	0	0
HADDOCK	<0.001	0	0	0	<0.001	0	0	0	<0.001	0	0	0
HALIBUT (ATLANTIC)	0	<0.001	<0.001	0	0	0	0.004	0	0	0	0	<0.000
HERMIT CRABS	0.018	0.015	0.019	0.014	0.019	0.131	0.052	0.091	0.030	0.109	0.012	0.034
HYDROZOA C.	<0.001	0	0	0	0	0	0	0	0	0	0	0
ICELAND SCALLOP	<0.001	<0.001	<0.001	0	0.002	0	0	0	0.001	0	0	0
JELLYFISHES	<0.001	<0.001	0	0	0	0	0	0	0	0	0	<0.000
JONAH CRAB	0.031	0.215	0.069	0.070	0.124	0.246	0.151	0.188	0.012	0.829	0.148	0.119
LEMONWEED	<0.001	0.010	0	<0.001	0.002	0	0	0	0.001	0	0	0
LITTLE,WINTER SKATE	0.006	0.007	0	0.018	0.015	0.001	0.074	0.071	0.047	0.140	0.025	0.057
LONGHORN SCULPIN	0.016	0.022	0.020	0.027	0.023	0.024	0.168	0.071	0.072	0.116	0.019	0.001
LUMPFISH	0	0	0	<0.001	<0.001	0	0.003	0.016	0	0	0	0
MONKFISH	0.025	0.010	0.009	0.008	0.006	0.003	0.019	0.036	0.004	0.019	0.003	0.003
MULLET FISH	0.001	0	0	0	0	0	0	0	0	0	0	0
NORTHERN STONE CRAB	0	0	0	0	0	0.020	0.013	0	0	0	0	0
OCEAN POUT	<0.001	<0.001	<0.001	0	<0.001	0	0	0.001	0	0.001	0	0
OCEAN QUAHAUG	0	0	0	<0.001	0	0	0	0	0	0	0	0
OCTOPUS	0	0	0	0	0	0	0	0.001	0	0	0	0
POLLOCK	<0.001	0	0	0	0	0	0	0	0	0	0	0
PRICKLEBACKS	0	0	0	0	<0.001	0	0	0	0	0	0	0
REDFISH UNSEPARATED	0	0	<0.001	0	<0.001	0	0	0	<0.001	0	0	0
ROUND SKATE	0	0.001	0	<0.001	0.004	0	0	0	0.001	0	0	0
SAND DOLLARS, SEA URCHINS	0.033	0.017	0.018	0.043	0.058	0.108	0.045	0.119	0.058	<0.001	0.001	0.018
SAND LANCES	0	<0.001	0	0	0	0	0	0	0	0	0	0
SEA ANEMONE	<0.001	0	0	0	<0.001	0	0	0	<0.001	0	0	0
SEA CUCUMBERS	0.035	0.005	0.030	0.455	0.434	0.097	0.614	0.271	0.054	0.025	0.055	0.011
SEA LAMPREY	0	0	<0.001	0	0	0	0	0	0	0	0	0
SEA PEACH	0	0	0	0	0.001	0	0	0	0	0	0	0
SEA POTATO	0	0	0	0	<0.001	0	0	0	0	0	0	0
SEA RAVEN	0.019	0.025	0.025	0.024	0.062	0.017	0.053	0.058	0.064	0.221	0.029	0.063
SEA SCALLOP	0.273	0.675	0.876	1.140	0.550	0.589	0.527	0.923	1.131	2.998	0.394	1.045
SEAROBINS	<0.001	0	0	0	0	0	0	0	0	0	0	0
SHORTHORN SCULPIN	0	0	0	0	<0.001	0	0.002	0	0	0.001	0	0
SHRIMP	0	0.001	0	<0.001	<0.001	0	0	0	0	0	<0.001	0
SILVER HAKE	0	0	0	0	0	0	0.001	0	0	0	<0.001	0
SMOOTH SKATE	0.006	<0.001	0.002	0.003	<0.001	0	0.024	0.063	0	0	<0.001	0
SNAILS AND SLUGS	<0.001	0	0.001	0.005	0.002	0	0	0.040	0.006	0	<0.001	0
SPONGES	0.089	0.047	0.739	0.126	0.019	0	0.212	0.266	0.058	0.052	0.009	0.005
STARFISH	0.180	0.091	0.129	0.285	0.353	0.279	0.823	0.575	0.092	0.486	0.010	0.044
STRIPED ATLANTIC WOLFFISH	0	0	0.001	<0.001	<0.001	0	0.001	0	0.005	0	0.001	0
THORNY SKATE	0.001	0.012	0.011	0.003	0.013	0.036	0.069	0.055	0.017	0.013	0.004	0
TOAD CRAB	0.022	0	<0.001	0	0.001	0	0.012	0	0	0.001	0	<0.000
TUNICATE	0	0	0	0	<0.001	0	0.002	0	<0.001	0	0	0
UNIDENT BIVALVES	<0.001	0.004	0	0	0	0	0	0	0	0	0	0
UNIDENT FLOUNDER	0	0	<0.001	0	0	0	0	0	0	0	0	0
UNIDENT SCULPINS	0.001	0.003	0.006	0.006	0.001	0.011	0	0	0	0.003	<0.001	0.033
UNIDENT SKATES	0.006	0.010	0.009	0.004	<0.001	0	0.087	0.058	0	0	0	0
WHELKS	0	0	0.001	0	0.002	0	0	0.022	<0.001	0	0	0.002
WHITE HAKE	<0.001	0	0	0	0	0	0	0.004	0	0	<0.001	0
WINTER FLOUNDER	0.002	0.002	0.004	0.003	0.003	0.003	0.017	0.015	0.040	0.063	0	0.064
WITCH FLOUNDER	<0.001	<0.001	0.001	<0.001	<0.001	<0.001	0.001	0.004	0.002	0.007	0.009	0
YELLOWTAIL FLOUNDER	0.001	<0.001	0.001	<0.001	0.001	0.001	0.009	0.006	0.002	0	<0.001	<0.000

Table 4. Summary of changes to annual surveys in Scallop Fishing Area 29 West.

Year	Survey Design	Vessel	Comments	Reference
2000	47 exploratory survey tows	CCGV J.L. Hart	4 gang, 2.5 foot Digby gear, 2 drags lined with 38 mm polypropylene mesh.	Smith and Lundy (2002c)
2001	120 random tows 5 exploratory tows	FV Julie Ann Joan	Joint project agreement. 9-gang miracle drags made with 75–78 mm inside diameter rings knit with rubber washers. The two end drags were sampled each tow. One end lined with 38 mm polypropylene mesh, the other unlined. SFA29 was subdivided into 5 areas of similar commercial scallop densities.	Smith and Lundy (2002a)
2002	125 random tows stratified by subareas A, B, C, D 29 tows for NR Can 8 exploratory tows	FV Julie Ann Joan	9 gang miracle gear with 75–78 mm inside diameter rings knit with steel washers and rubber chafers.	Smith *et al*. (2003)
2003	93 stratified random tows 18 adaptive tows 35 exploratory tows	FV Julie Ann Joan	No comments	No references
2004	110 stratified random tows 40 exploratory tows	FV Branntelle	No comparative tows.	Smith *et al*. (2005)
2005	127 random tows stratified by surficial sediment 31 adaptive tows, 11 exploratory tows	FV Julie Ann Joan: Subarea A–D FV Overton Bay: Subarea C–D	Multibeam results used for strata. 10 comparative tows were conducted between the vessels.	Smith *et al*. (2006)
2006,2007	120 stratified random tows	FV Julie Ann Joan: Subarea A–D FV Faith Alone: Subarea C-D	10 comparative tows were conducted between the vessels in 2006. Change in funding in 2007 after LaRocque decision.	Smith *et al*. (2007), Smith *et al*. (2008),
2008–2011	120 stratified random tows stratified by geophysical bottom type by subarea	FV Julie Ann Joan: Subarea A–D FV Faith Alone: Subarea C–D	New maps from multibeam project.	Todd *et al*. (2009) Smith *et al*.(2009a, 2009b) Sameoto *et al*. (2012)
2012	120 stratified random tows	FV Hit ‘n Miss: Subarea A–D	New contracting rules only use one vessel. 5 exploratory tows in subarea E.	Smith *et al*. (2013)

Table 5. Area for each of the habitat suitability categories used in this assessment for the scallop fishery in SFA 29 West. Note that the High category for SFA 29A was comprised of suitability bins 0.6 and 0.7 as there were no suitability bins ≥0.8 in this subarea.

Habitat Suitability	A		B		C		D	
	Area km^2	Percent	Area km^2	Percent	Area km^2	Percent	Area km^2	Percent
Low	137.6	53.8	248.8	45.6	144.9	48.4	133.6	40.8
Medium	116.0	45.4	244.3	44.8	125.2	41.4	142.9	43.6
High	2.1	0.8	52.4	9.6	29.2	9.8	51.1	15.6

FIGURES

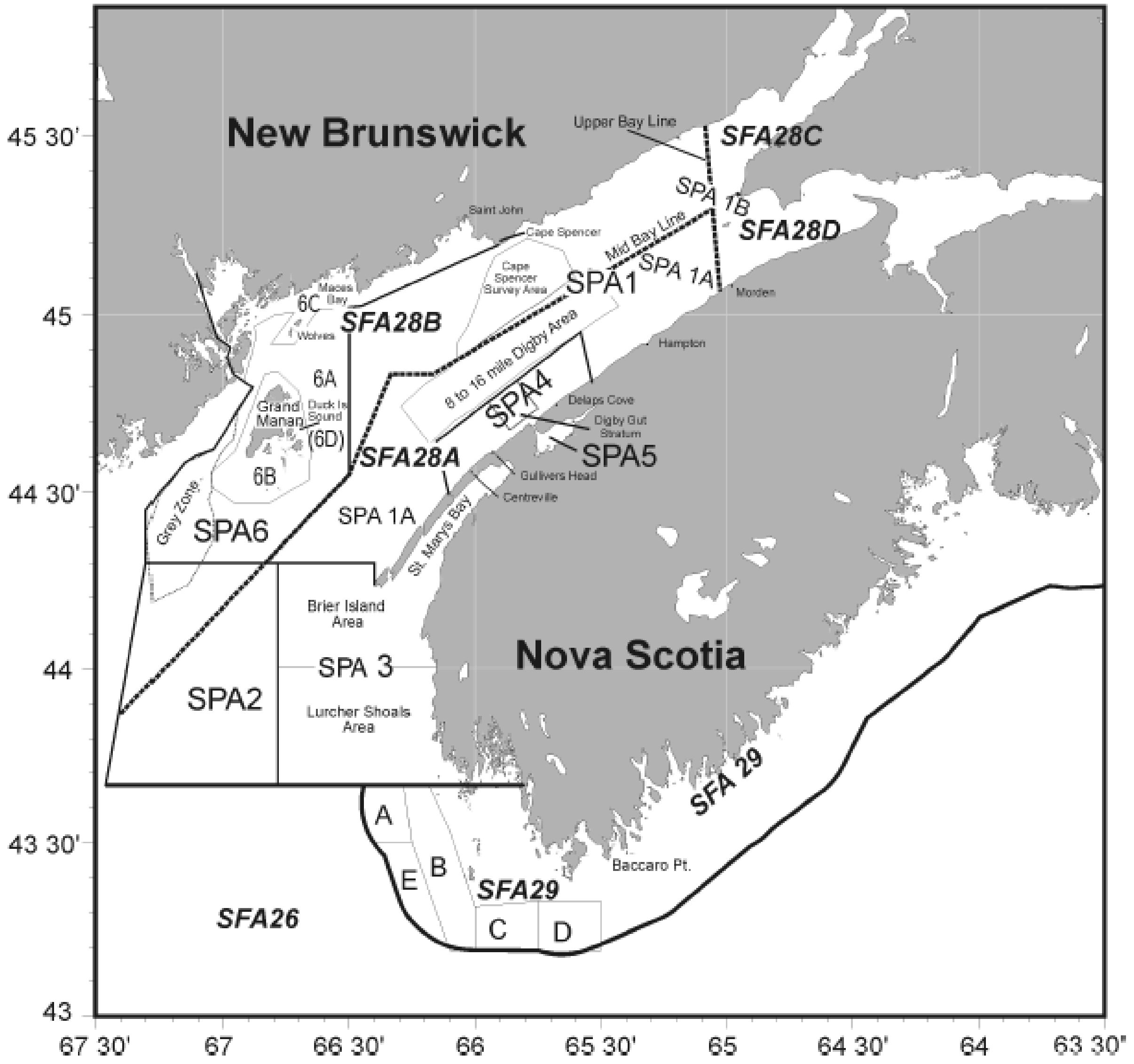

Figure 1. Map of Scallop Fishing Areas (SFAs) and Scallop Production Areas (SPAs).

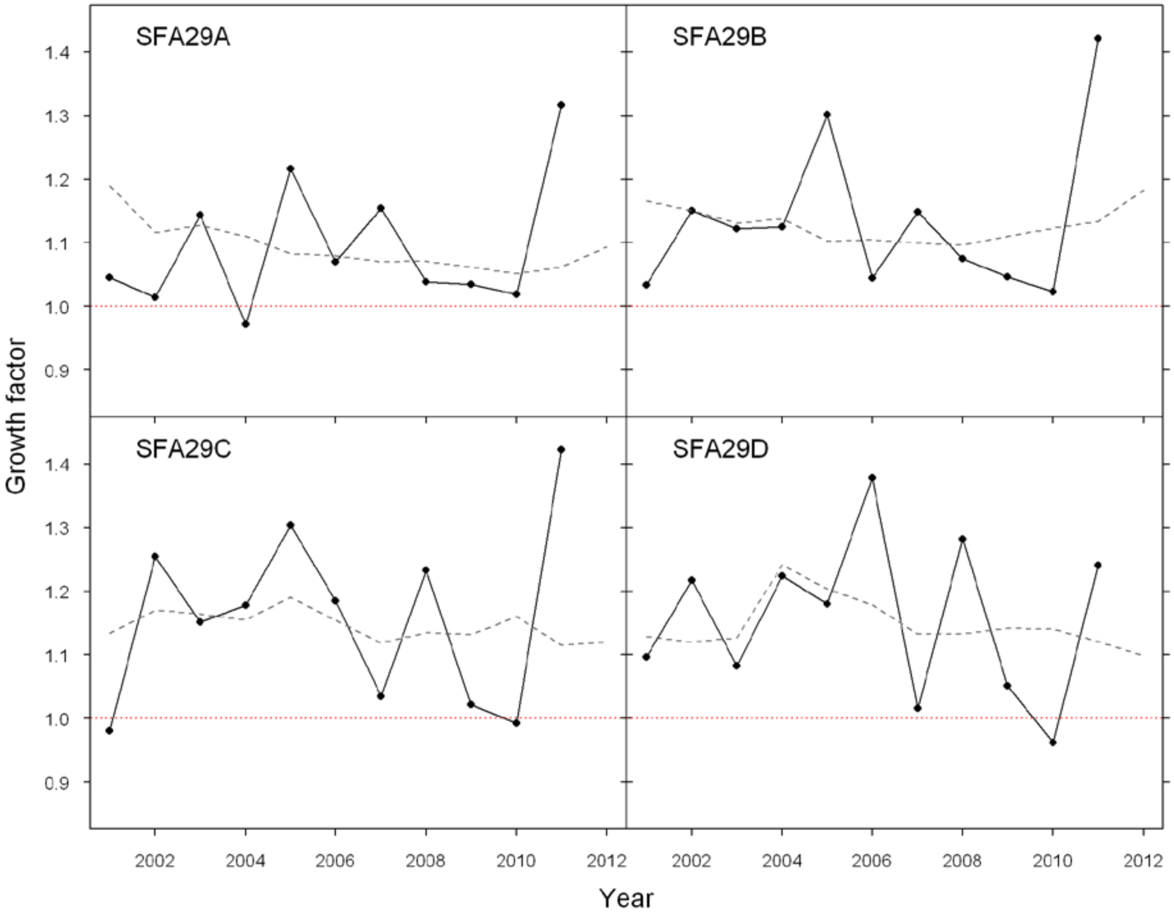

Figure 2. Annual observed growth factor for SFA 29 West by subarea A to D (2001–2012). Grey dashed line is the theoretical expected growth factor based on mean meat weight and the red dotted line indicates a growth factor of one or no growth. Growth rates are lined up beginning of year's growth rate from one year's survey to the next. For example, the 2001 point refers to growth from 2001 to 2002.

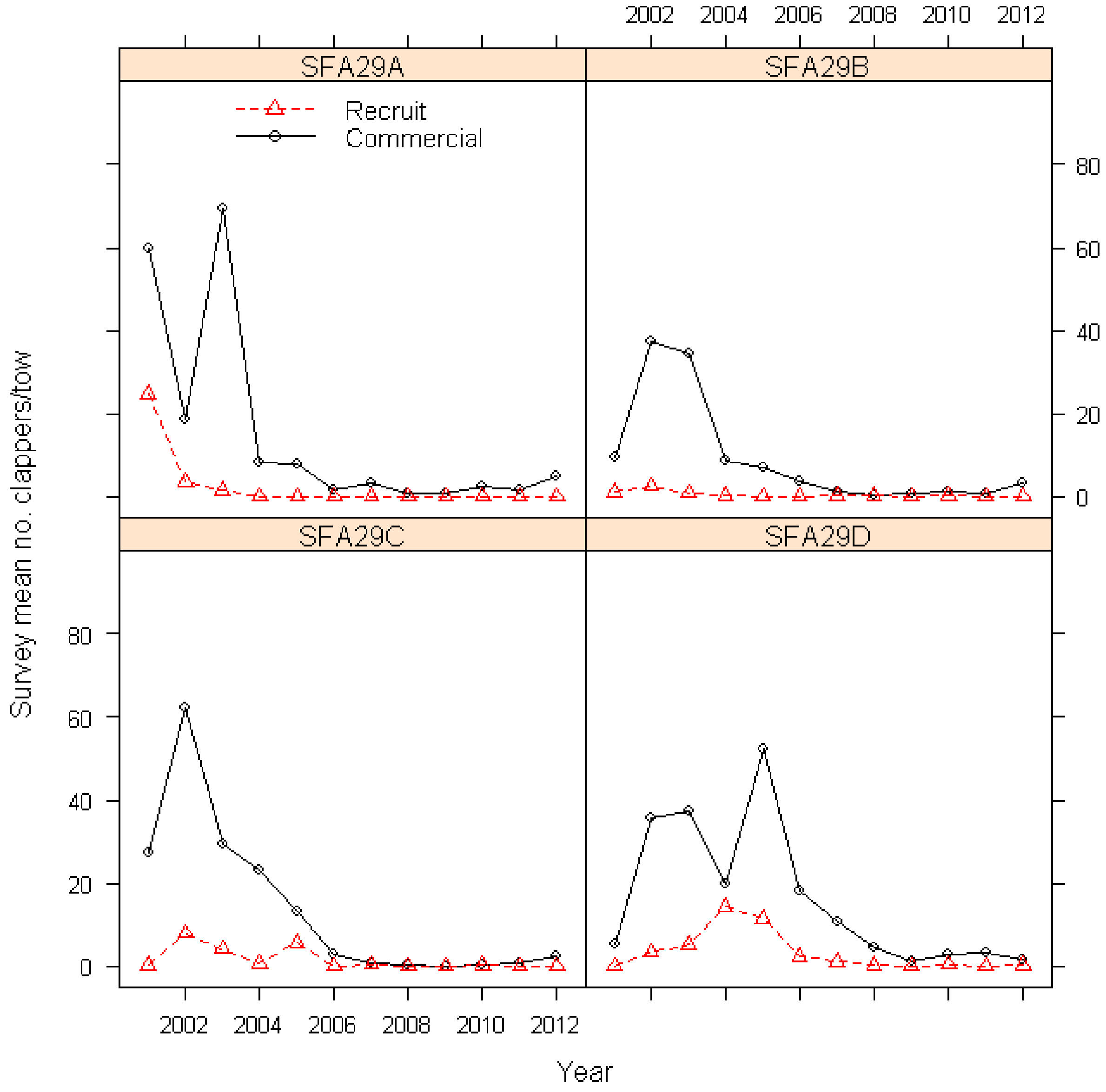

Figure 3. Annual trends in estimated mean number per tow of commercial (≥100 mm shell height) and recruit (90–99 mm shell height) size classes of clappers from research surveys by subarea in SFA 29 West commercial and recruit series estimated from F/V Julie Ann Joan (2001–2003, 2005–2011), F/V Branntelle (2004), F/V Overton Bay (2005), F/V Faith Alone (2006–2011) and F/V Hit 'N Miss (2012). Geophysical strata was used for survey design.

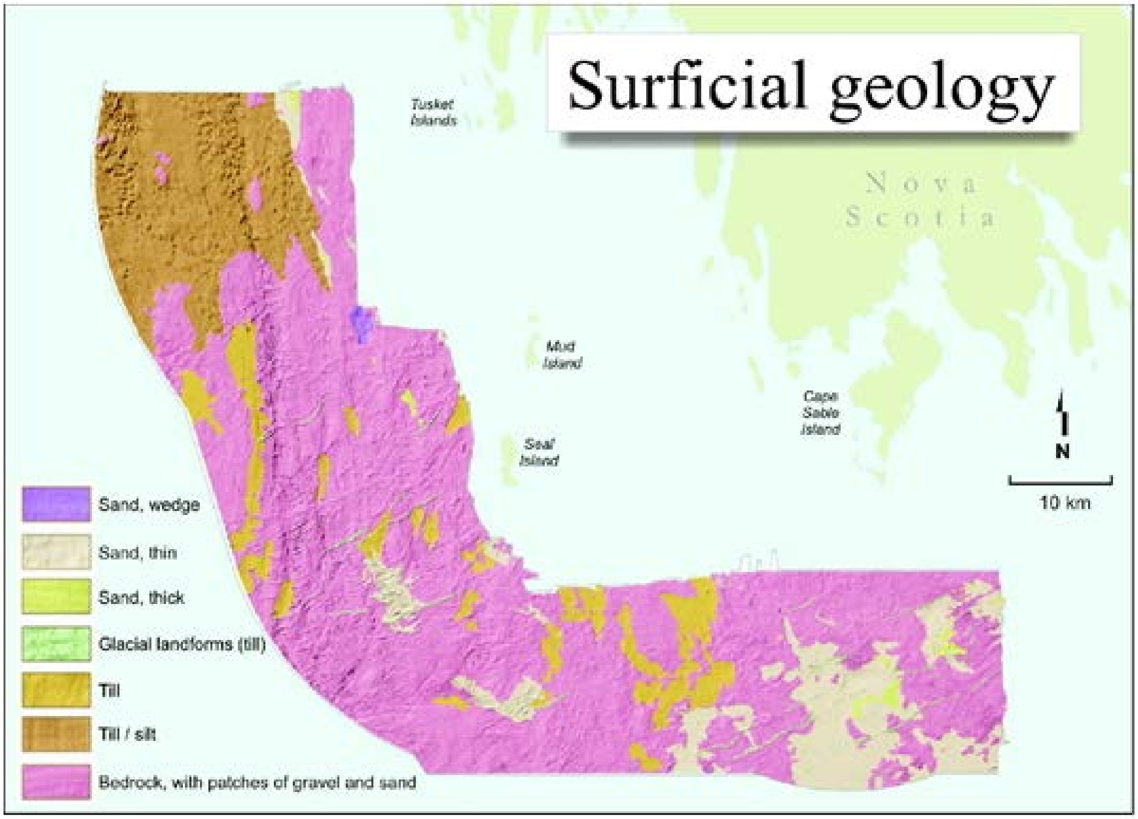

Figure 4. Map of surficial geology of Scallop Fishing Area 29 West.

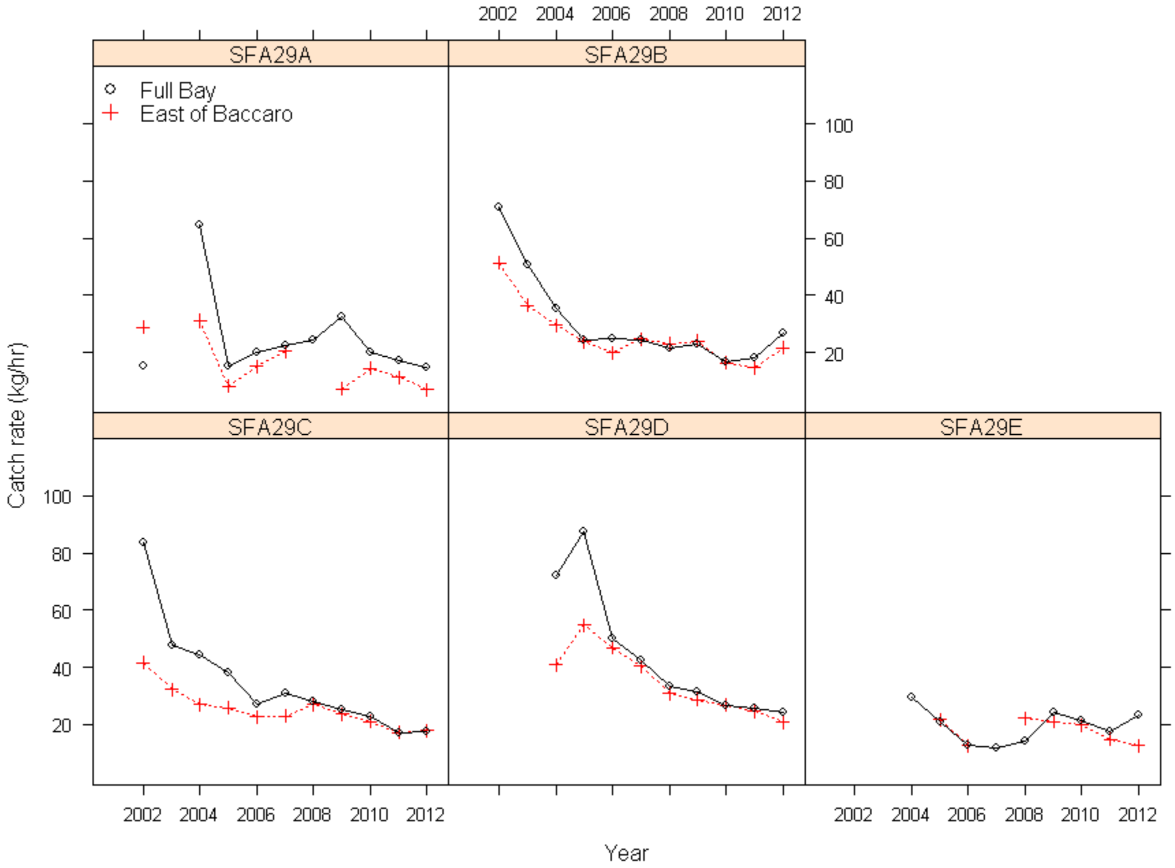

Figure 5. Annual trends for average commercial catch rate (kg/h) for SFA 29 West scallop fishery for each subarea by fleet, from 2001–2012.

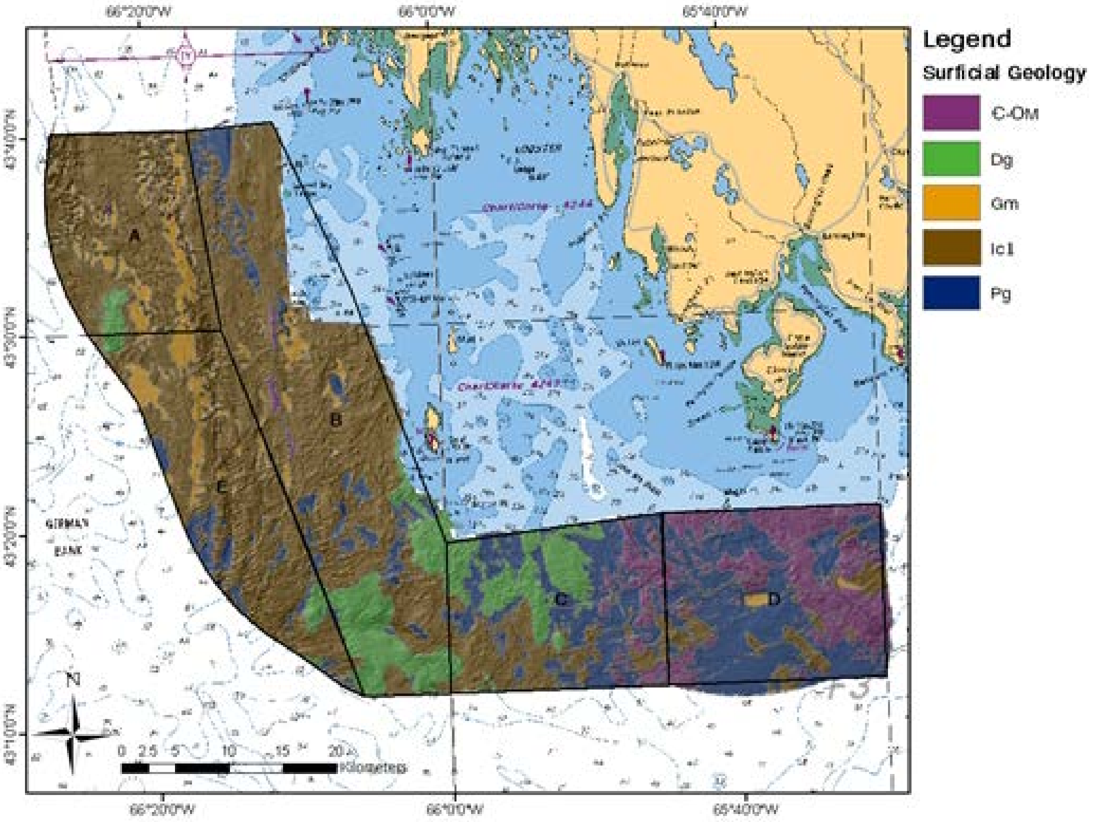

Figure 6. Scallop Fishing Area 29 West study area with geophysical bottom types defined as follows. Є-OM = Metamorphic bedrock, Dg = Igneous bedrock, Gm = Glaciomarine silt, Ic1 = Ice-contact sediment (till), Pg = Postglacial sand and gravel.

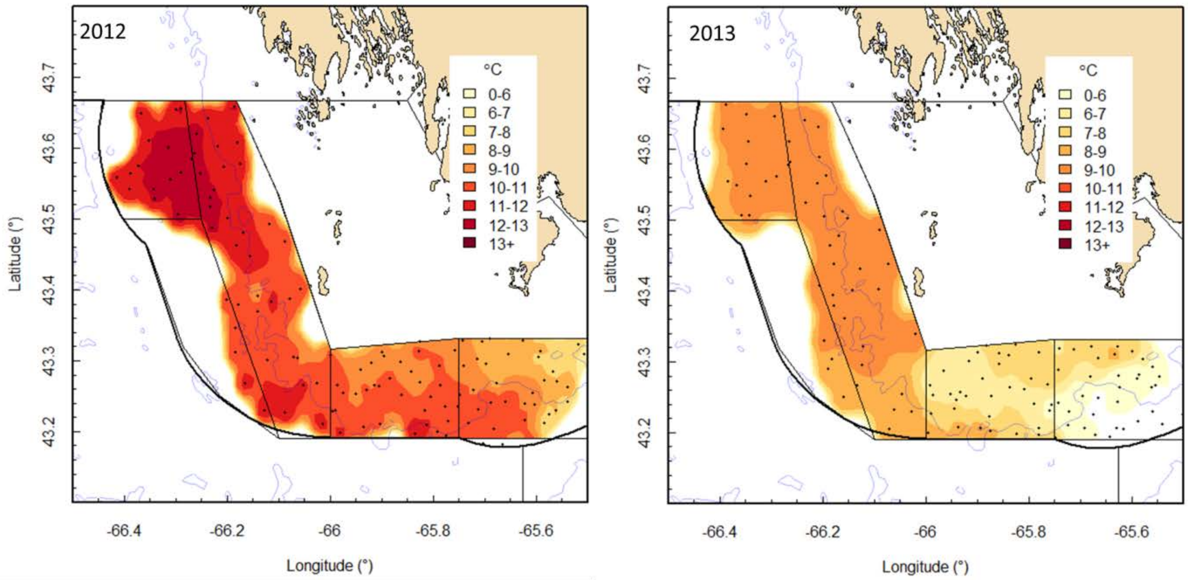

Figure 7. Bottom temperatures based on readings from data loggers on survey drag gear for SFA 29 West.

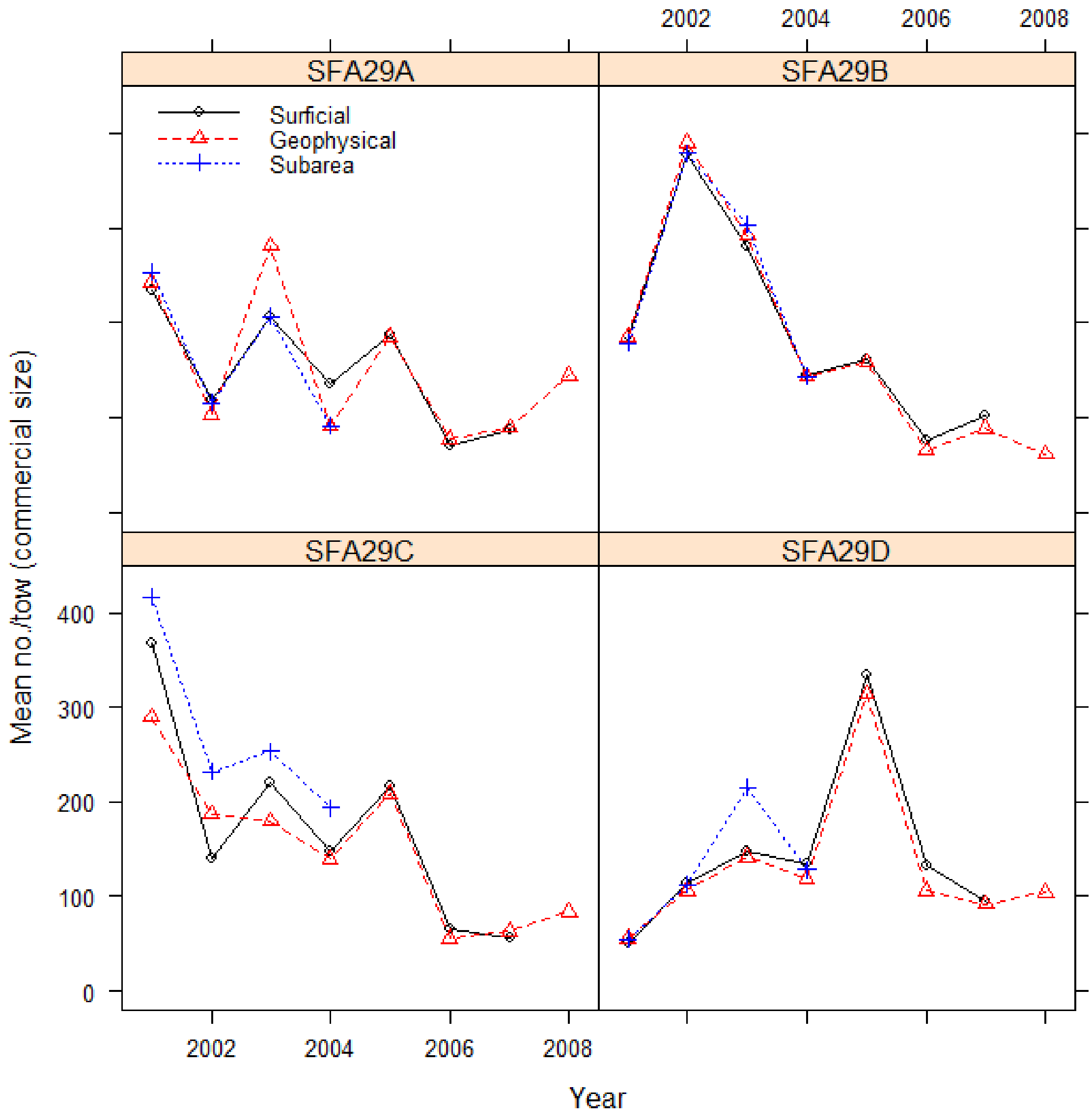

Figure 8. Comparison of estimates of mean number per tow for the three survey designs used in Scallop Fishing Area 29 West with the Full Bay Vessels. (update of Figure 17, Smith et al., 2009b)

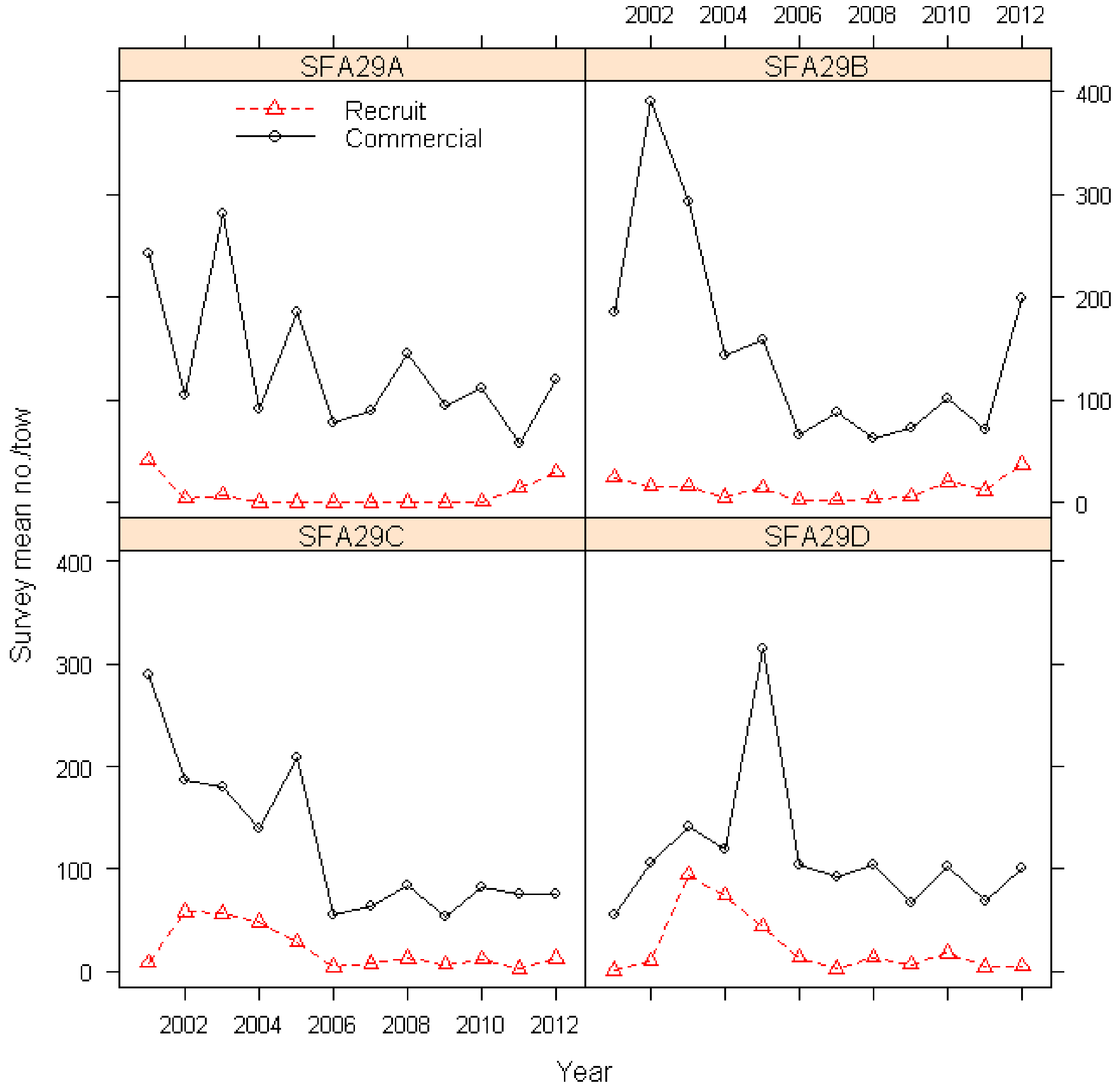

Figure 9. Annual trends in estimated mean number per tow of commercial (≥100 mm shell height) and recruit (90–99 mm shell height) size classes from research surveys by subarea in SFA 29 West. Commercial and recruit series estimated from fishing vessel (F/V) Julie Ann Joan (2001–2003, 2005–2011),F/V Branntelle (2004), F/V Overton Bay (2005), F/V Faith Alone (2006–2011) and F/V Hit 'N Miss (2012). Geophysical strata was used for survey design.

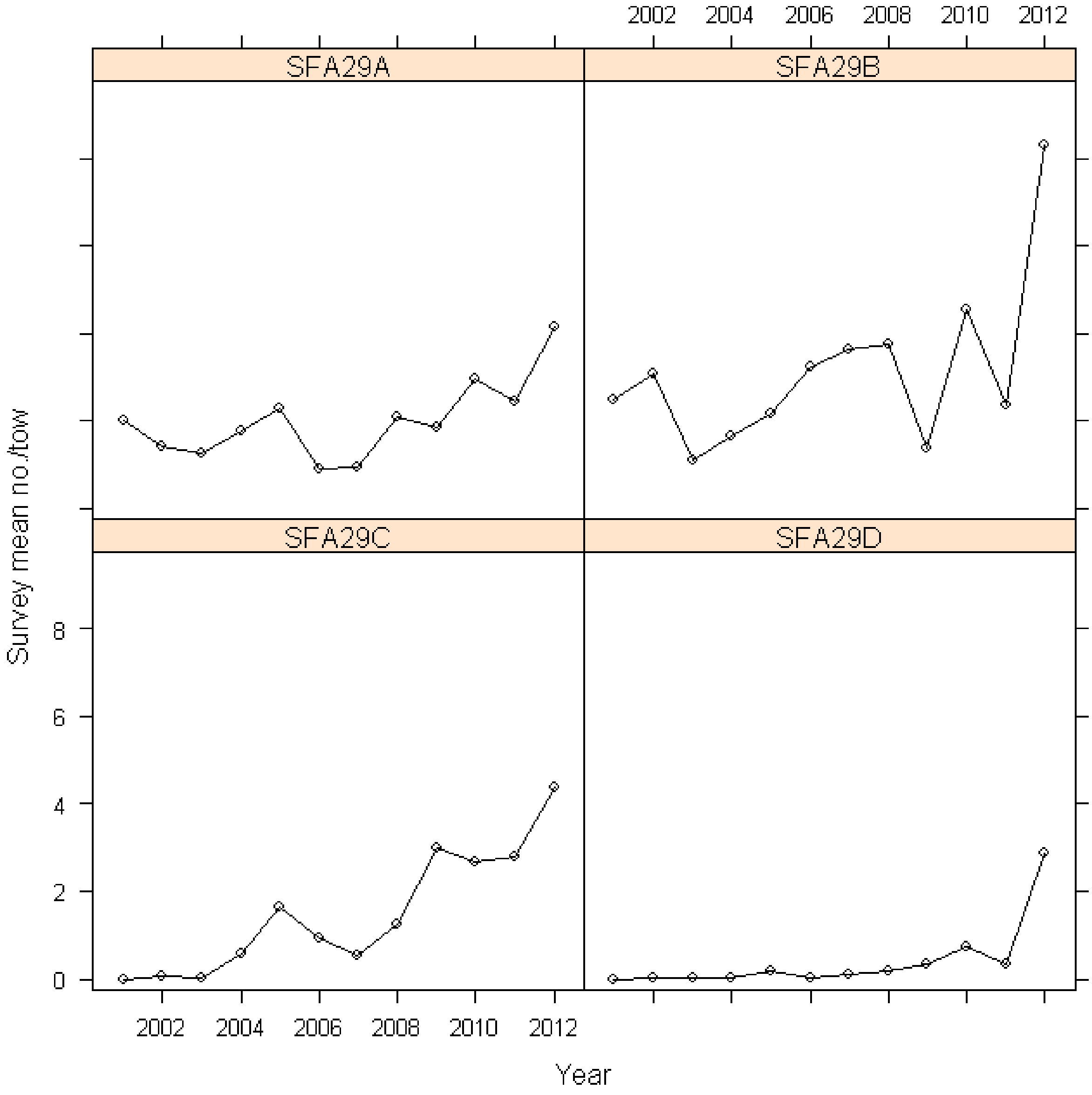

Figure 10. Lobster number per tow from scallop surveys in SFA 29 West (2001–2012). Subarea E is not routinely included in the survey. Geophysical strata used for design. Geophysical strata were used for survey design.

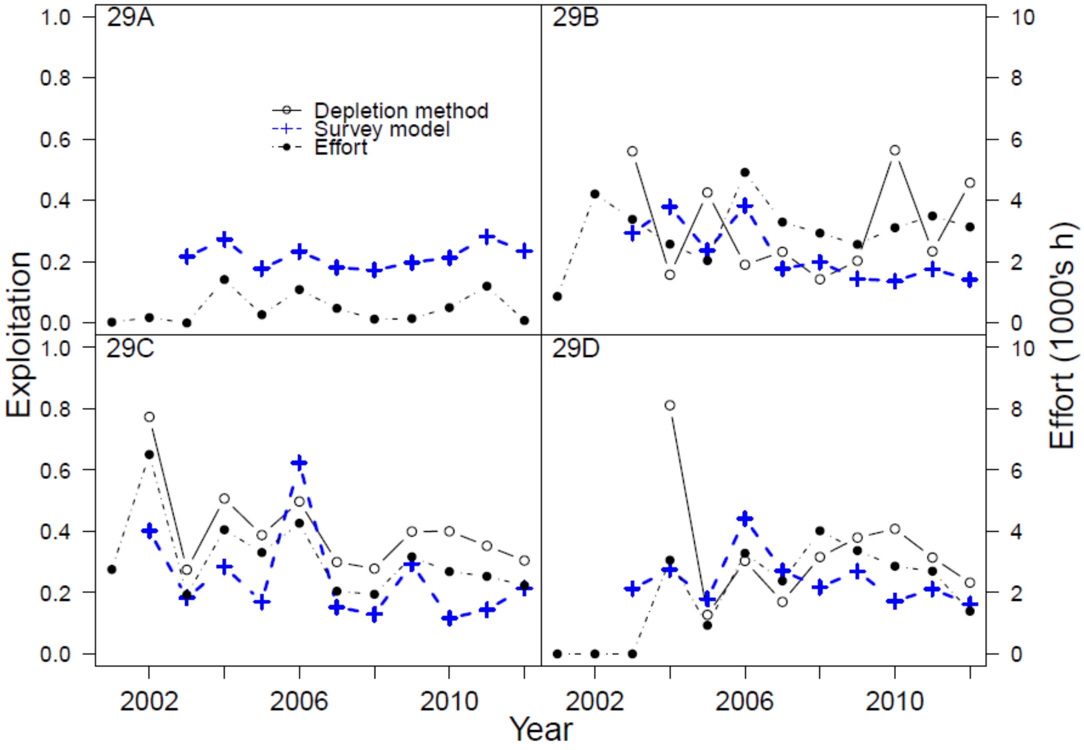

Figure 11. Comparison of exploitation estimates from the depletion method, survey biomass model and the total annual fishing effort for commercial size scallops in SFA 29 West, subareas A to D (2001–2012). Note that reliable estimates of exploitation for subarea A were not obtained from the depletion method.

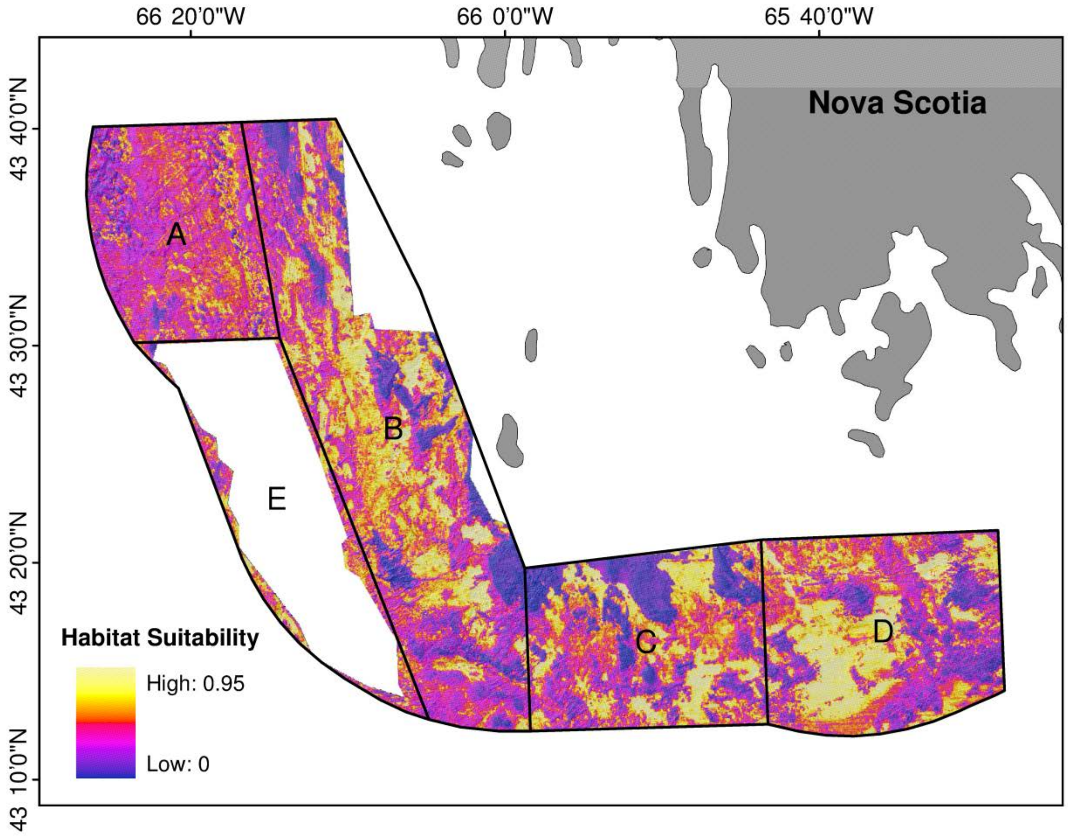

Figure 12. Scallop habitat suitability map from the Maxent Species Distribution Model from Brown et al. (2012). Habitat suitability was not available for subarea E because a different multibeam sonar had been used in this area.

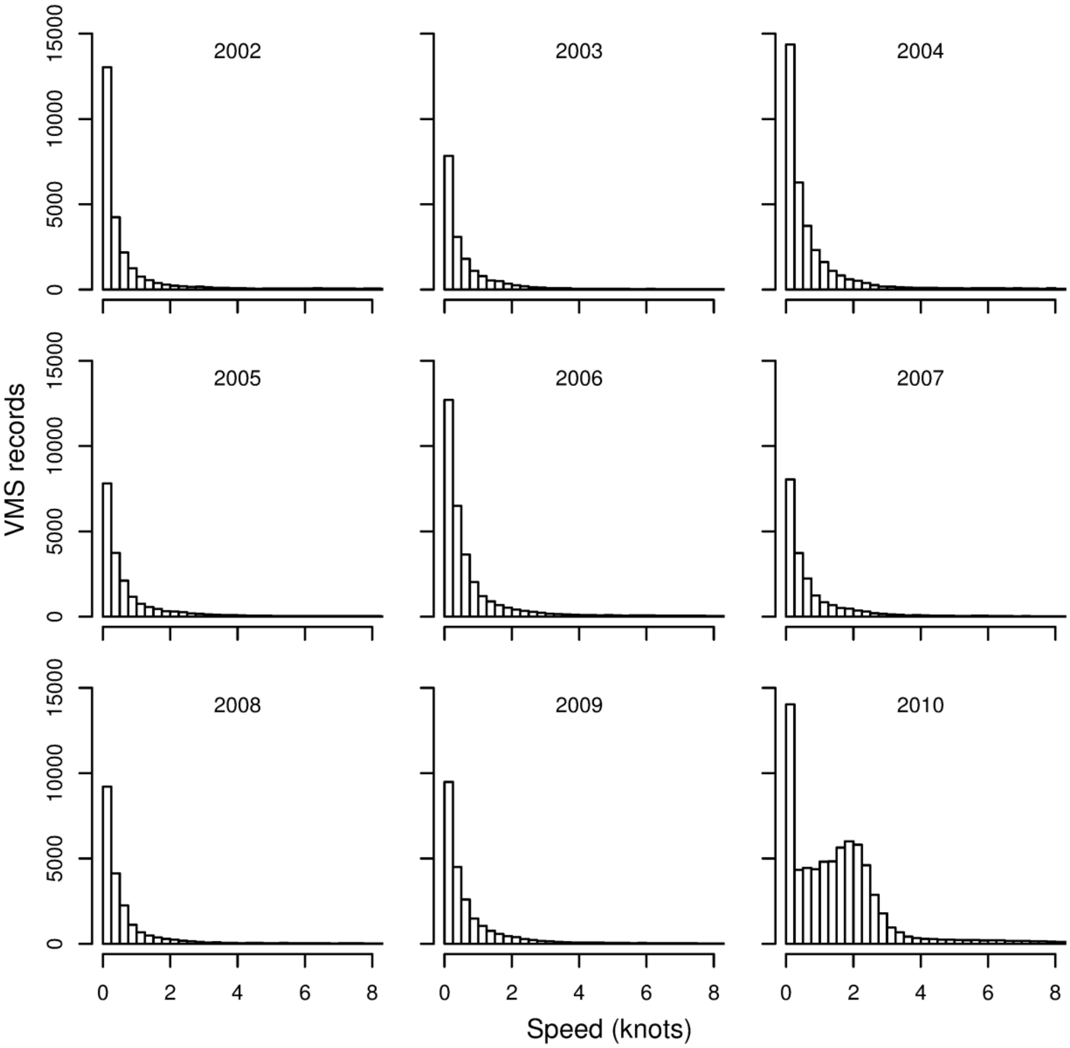

Figure 13. Derived VMS speeds of scallop fishing vessels in SFA 29 West by year. VMS was collected at a reporting interval of 60-min from 2002 to 2009, and at 15-min for 2010.

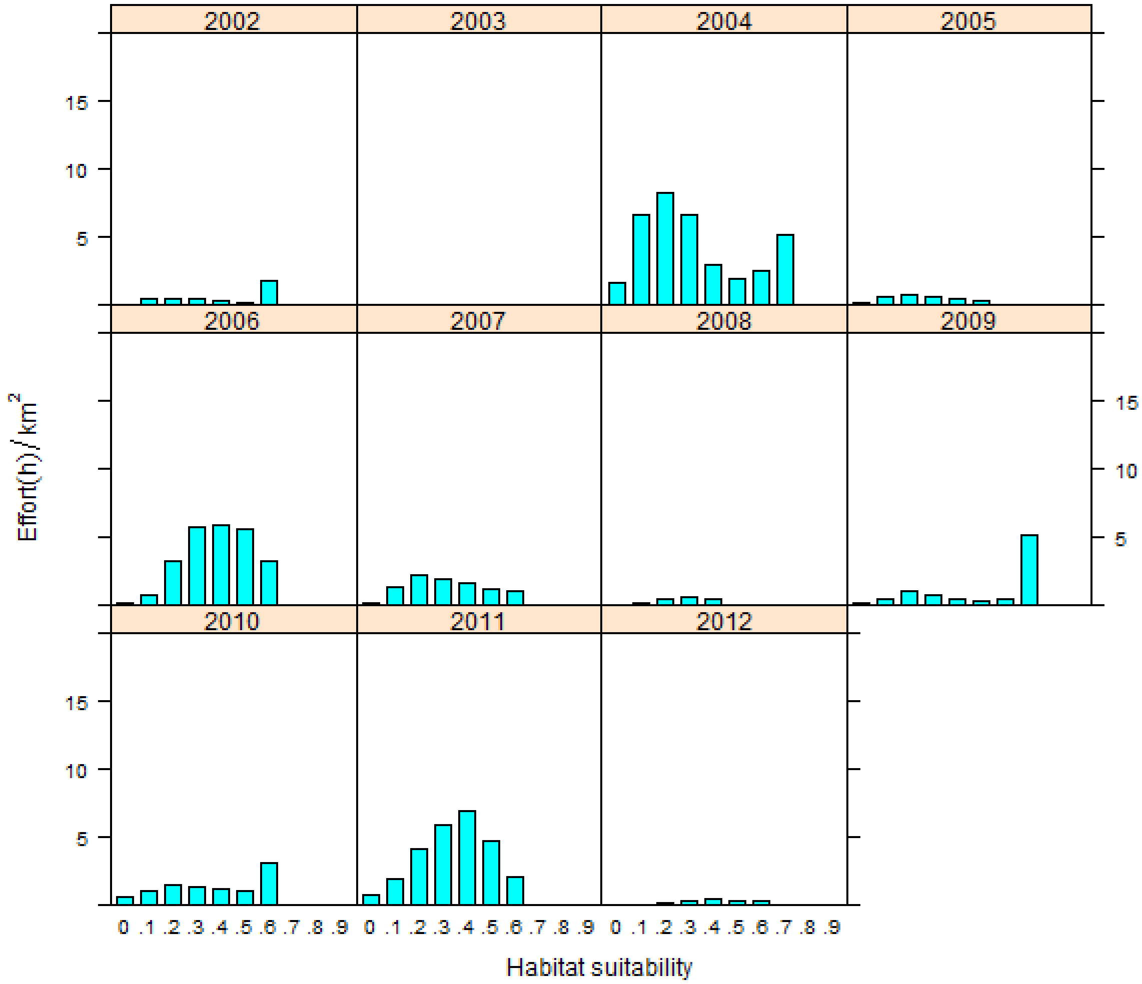

Figure 14. Fishing effort/km^2 derived from VMS data binned by 10 intervals of width 0.1 categories of habitat suitability probabilities for SFA 29A. There were no suitability bins ≥0.8 in this subarea.

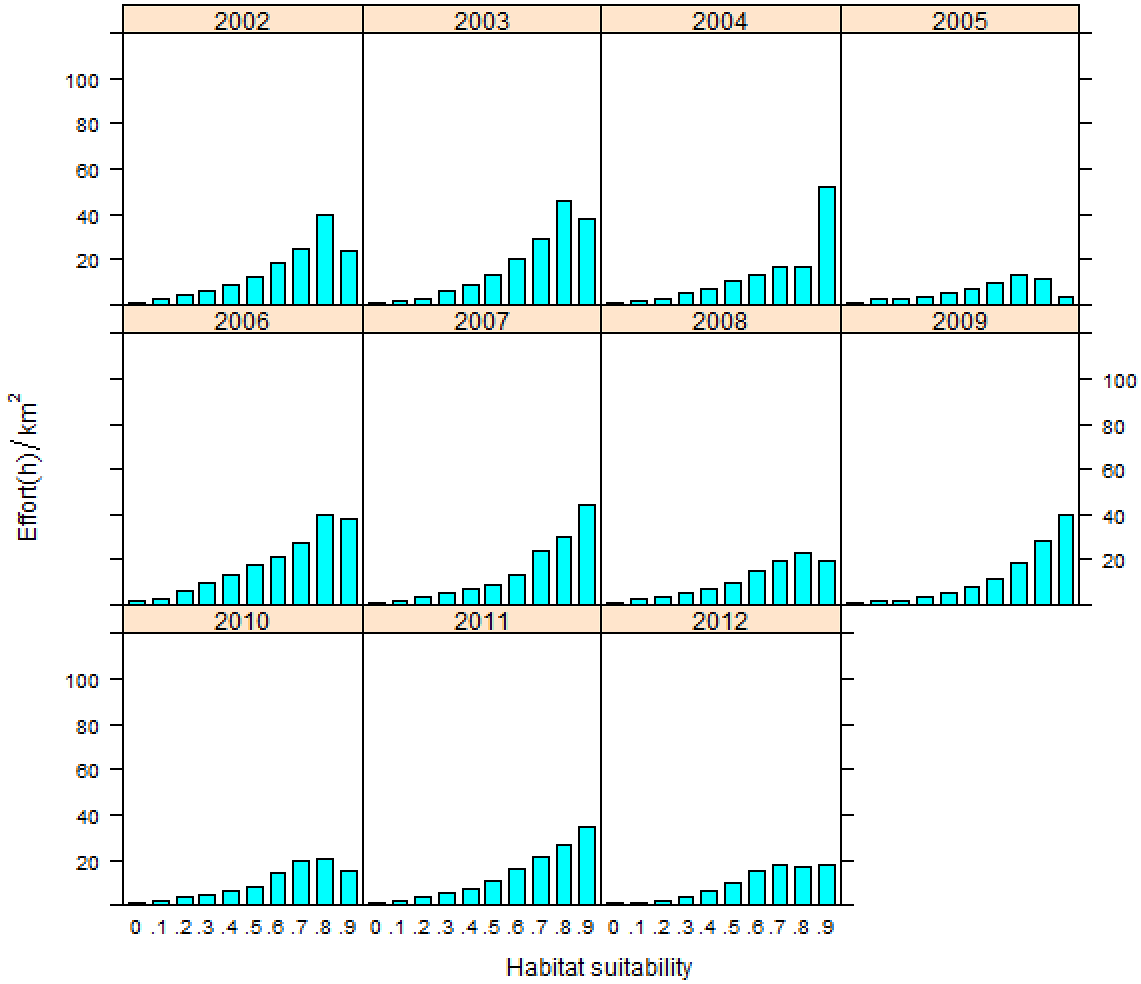

Figure 15. Fishing effort/km^2 derived from VMS data binned by 10 intervals of width 0.1 categories of habitat suitability probabilities for SFA 29B.

Figure 16. Fishing effort/km^2 derived from VMS data binned by 10 intervals of width 0.1 categories of habitat suitability probabilities for SFA 29C.

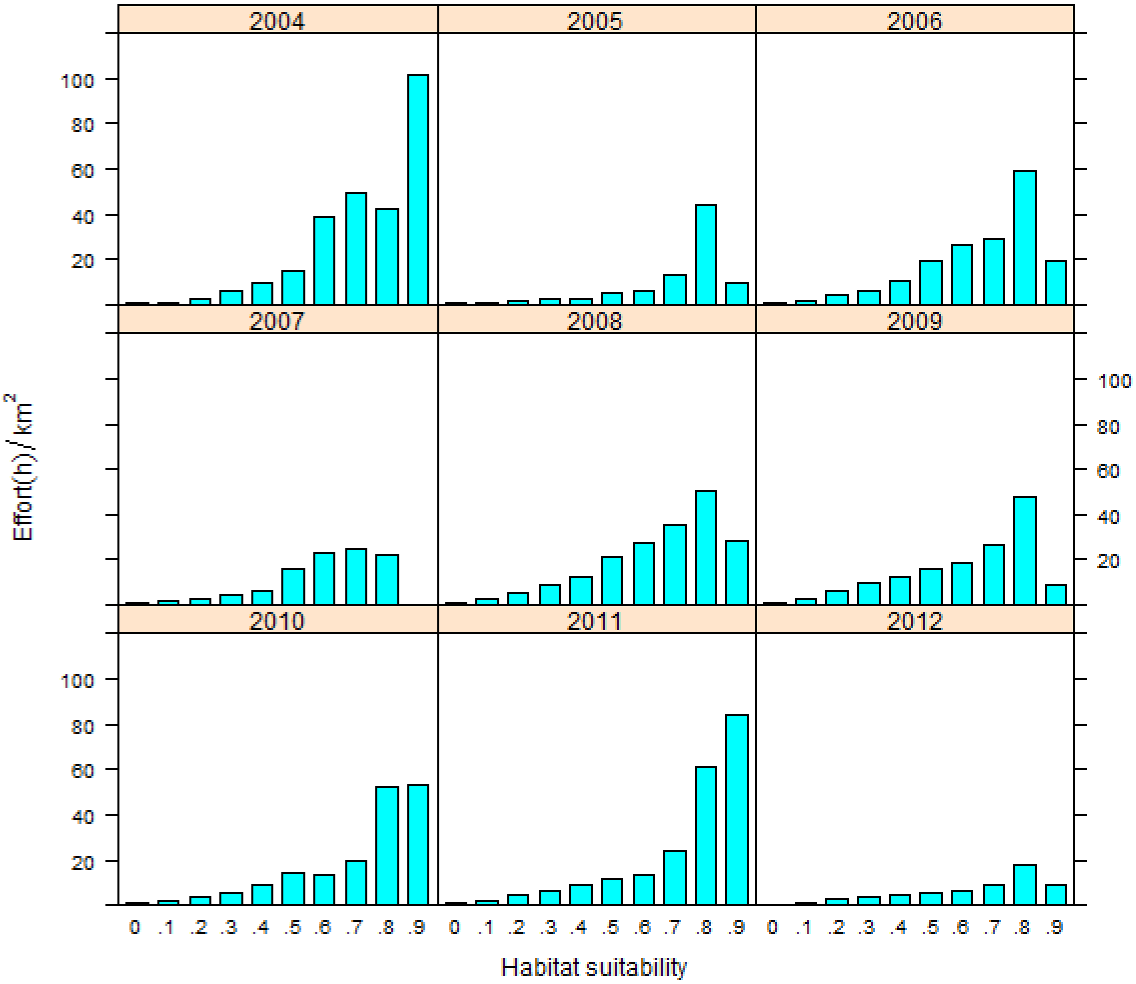

Figure 17. Fishing effort/km² derived from VMS data binned by 10 intervals of width 0.1 categories of habitat suitability probabilities for SFA 29D.

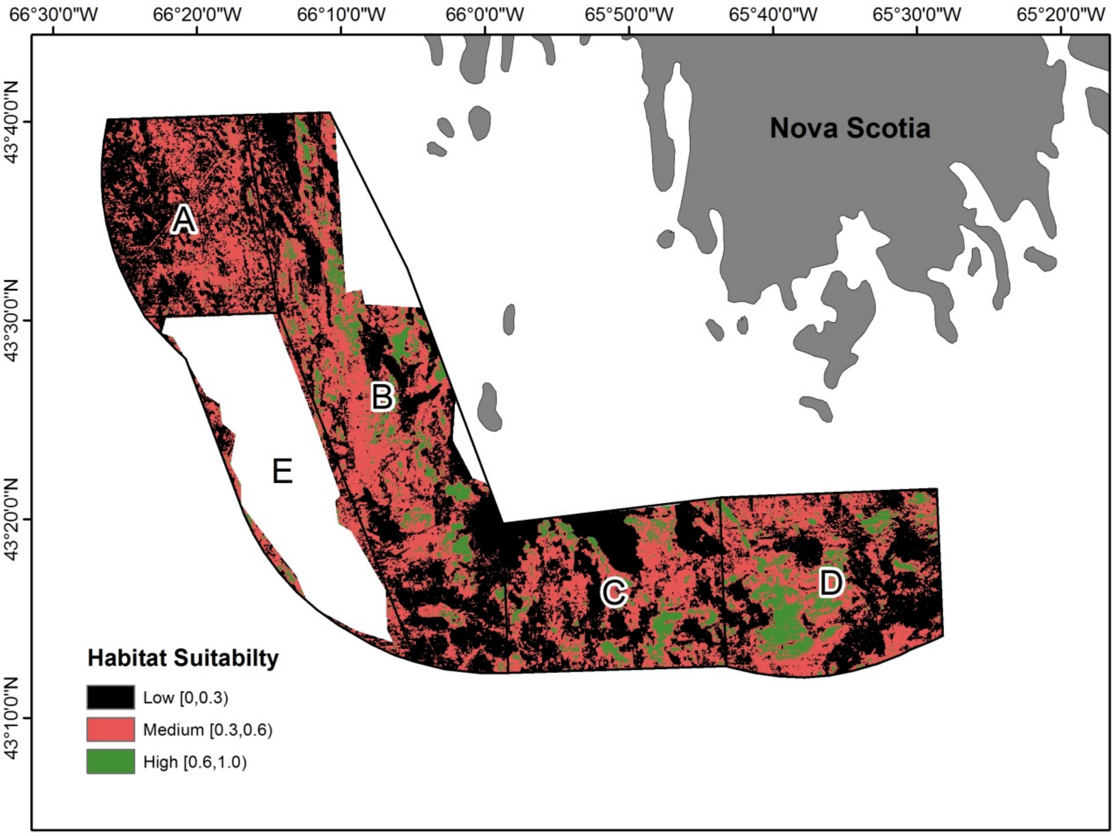

Figure 18. Scallop habitat suitability map from the Maxent Species Distribution Model binned by Low [0, 0.3), Medium [0.3, 0.6] and High [0.6, 1.0] categories of habitat suitability probabilities for SFA 29 West.

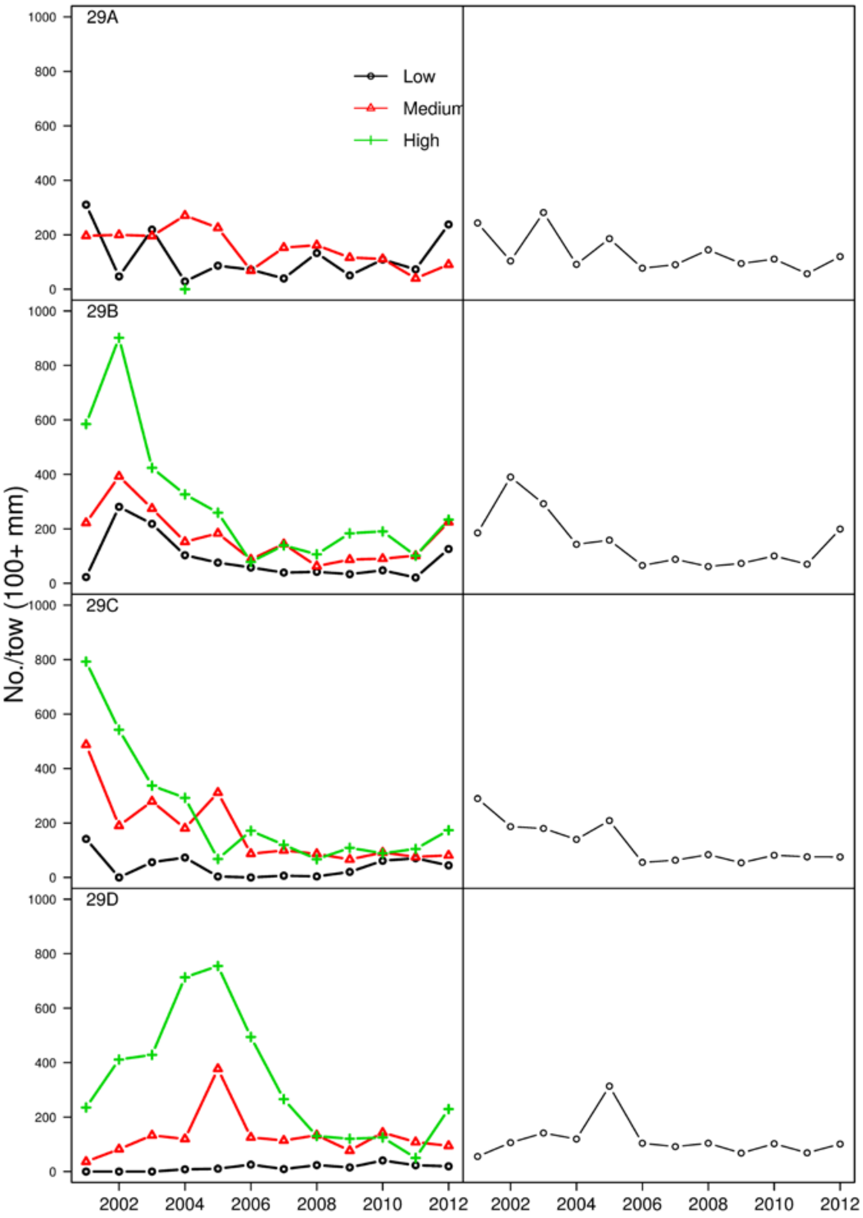

Figure 19. Survey mean number per tow for commercial size scallops (≥100 mm) by subarea for SFA 29 West. Left: Survey mean for Low [0, 0.3], Medium [0.3, 0.6] and High [0.6, 1.0] categories of habitat suitability probabilities. Right: Survey mean for whole survey area using the geophysical strata.

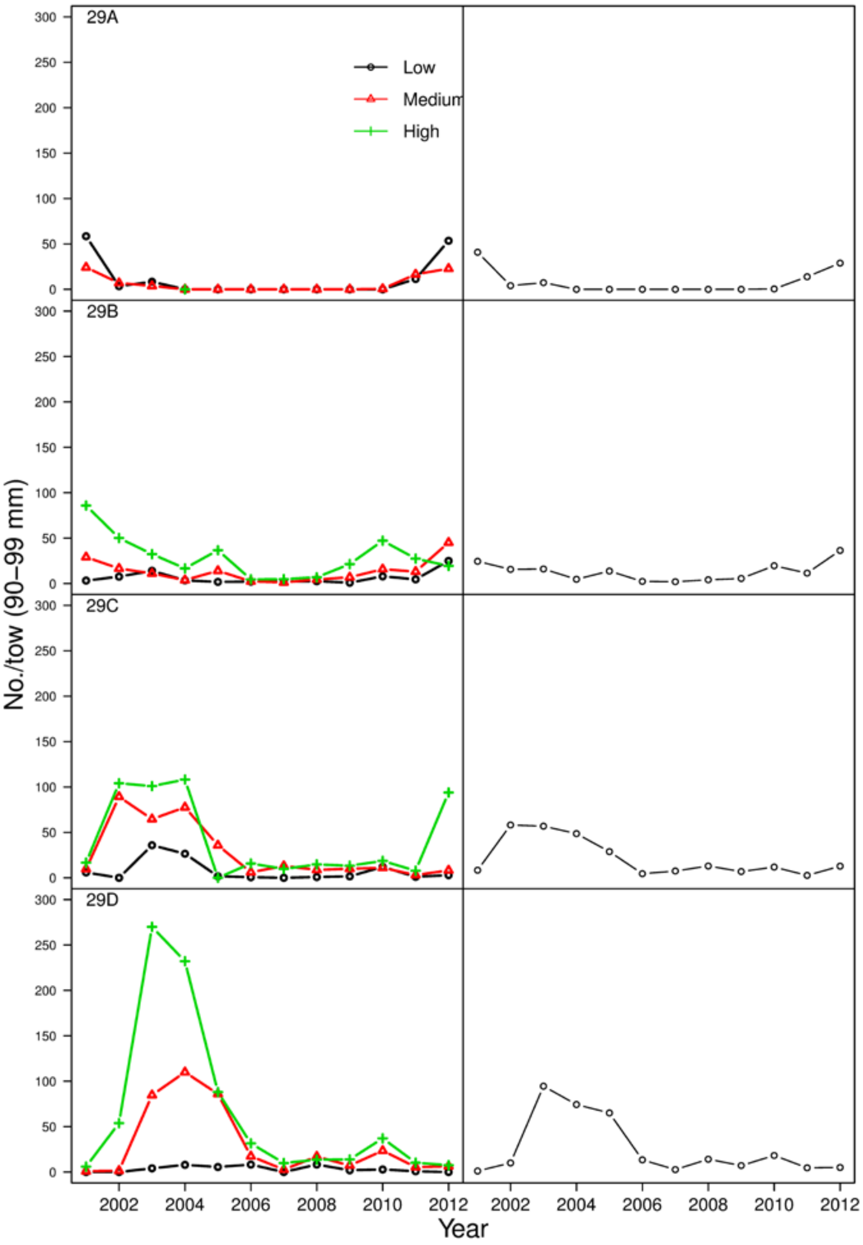

Figure 20. Survey mean number per tow for recruit size scallops (90–99 mm) by subarea for SFA 29 West. Left: Survey mean for Low [0, 0.3], Medium [0.3, 0.6] and High [0.6, 1.0] categories of habitat suitability probabilities. Right: Survey mean for whole survey area using the geophysical strata.

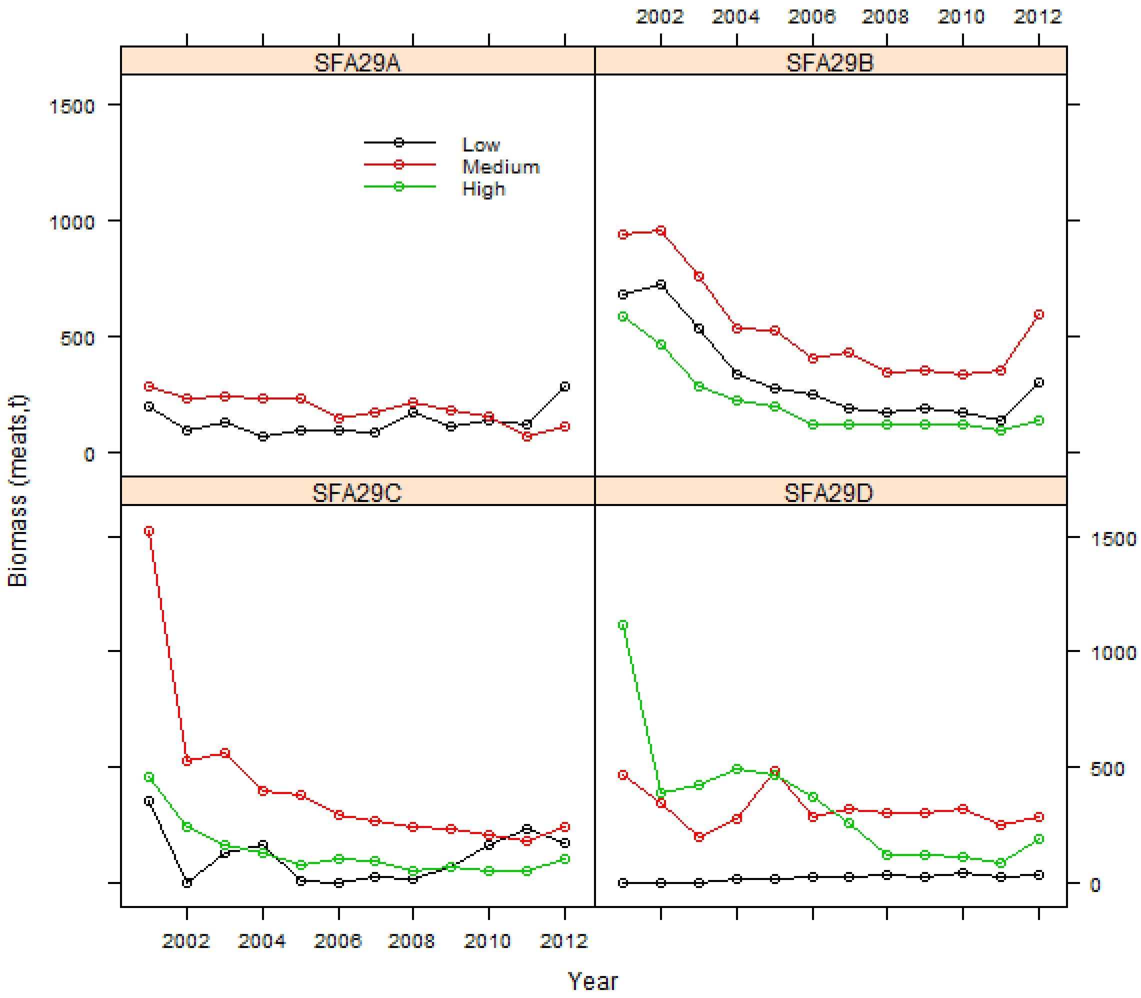

Figure 21. State-space model estimate of population biomass for commercial size scallops by Low [0, 0.3], Medium [0.3, 0.6] and High [0.6, 1.0] categories of habitat suitability probabilities in SFA 29 West.

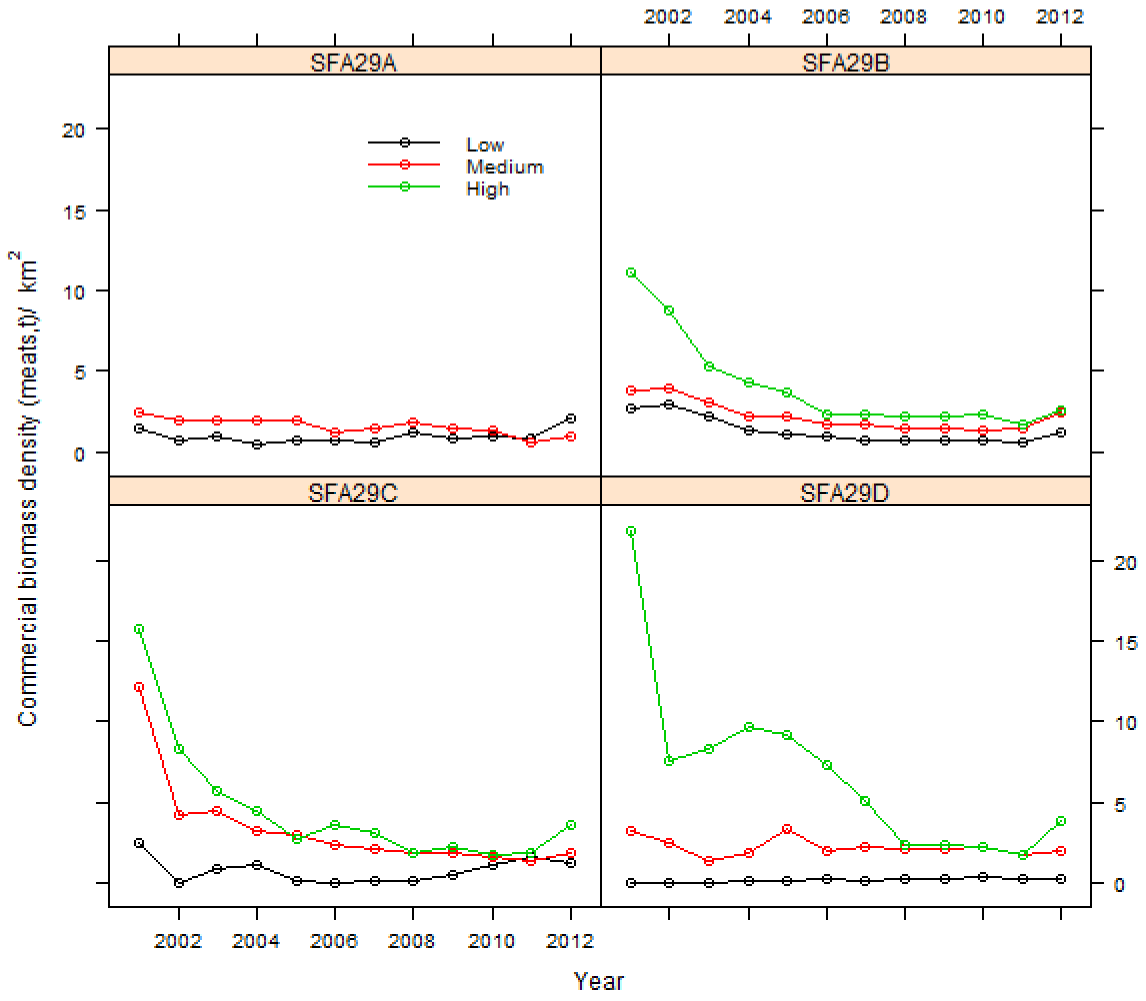

Figure 22. State-space model estimate of population biomass density for commercial size scallops by Low [0, 0.3], Medium [0.3, 0.6] and High [0.6, 1.0] categories of habitat suitability probabilities in SFA 29 West.

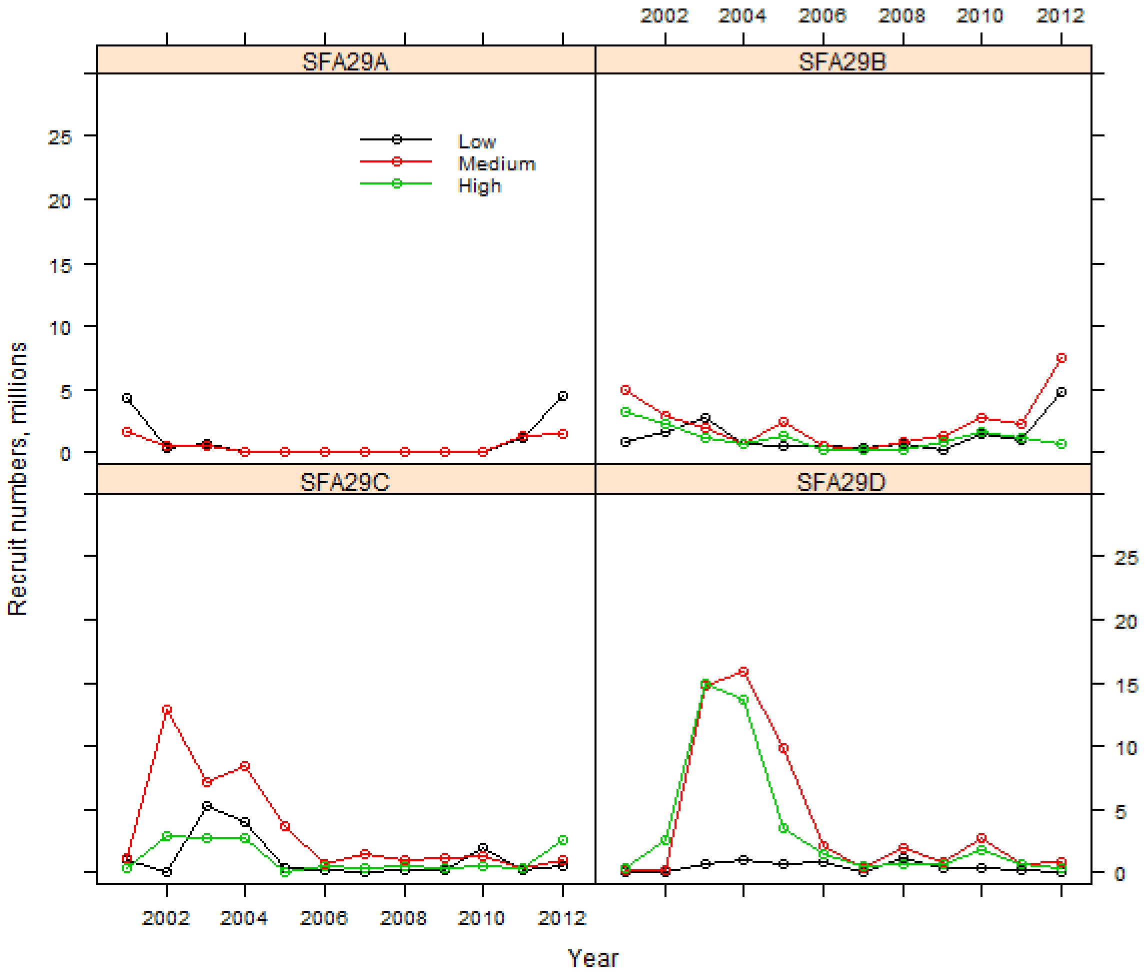

Figure 23. State-space model estimate of population density for numbers of recruit size scallops by Low [0, 0.3], Medium [0.3, 0.6] and High [0.6, 1.0] categories of habitat suitability probabilities in SFA 29 West.

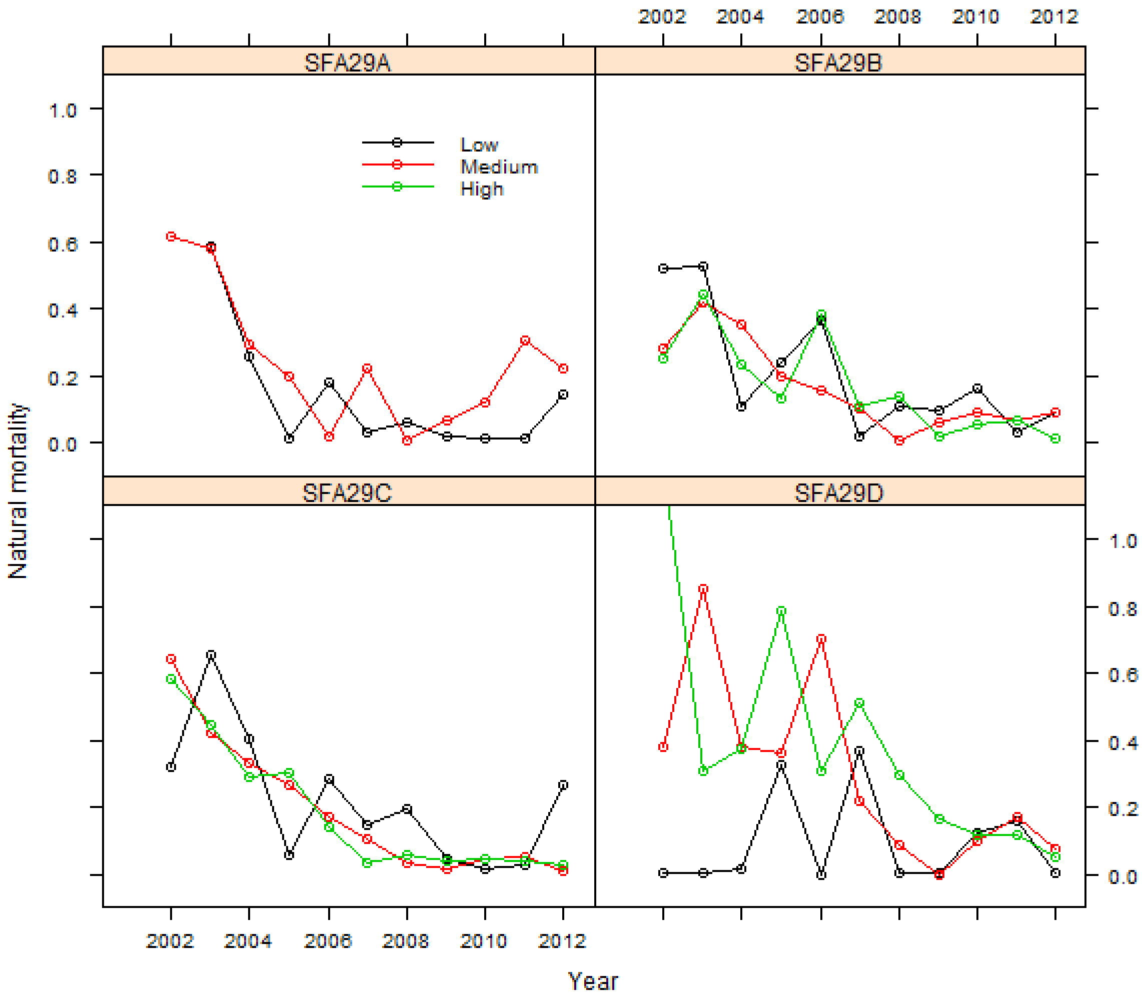

Figure 24. State-space model estimate of natural mortality for commercial size scallops by Low [0, 0.3], Medium [0.3, 0.6] and High [0.6, 1.0] categories of habitat suitability probabilities in SFA 29 West.

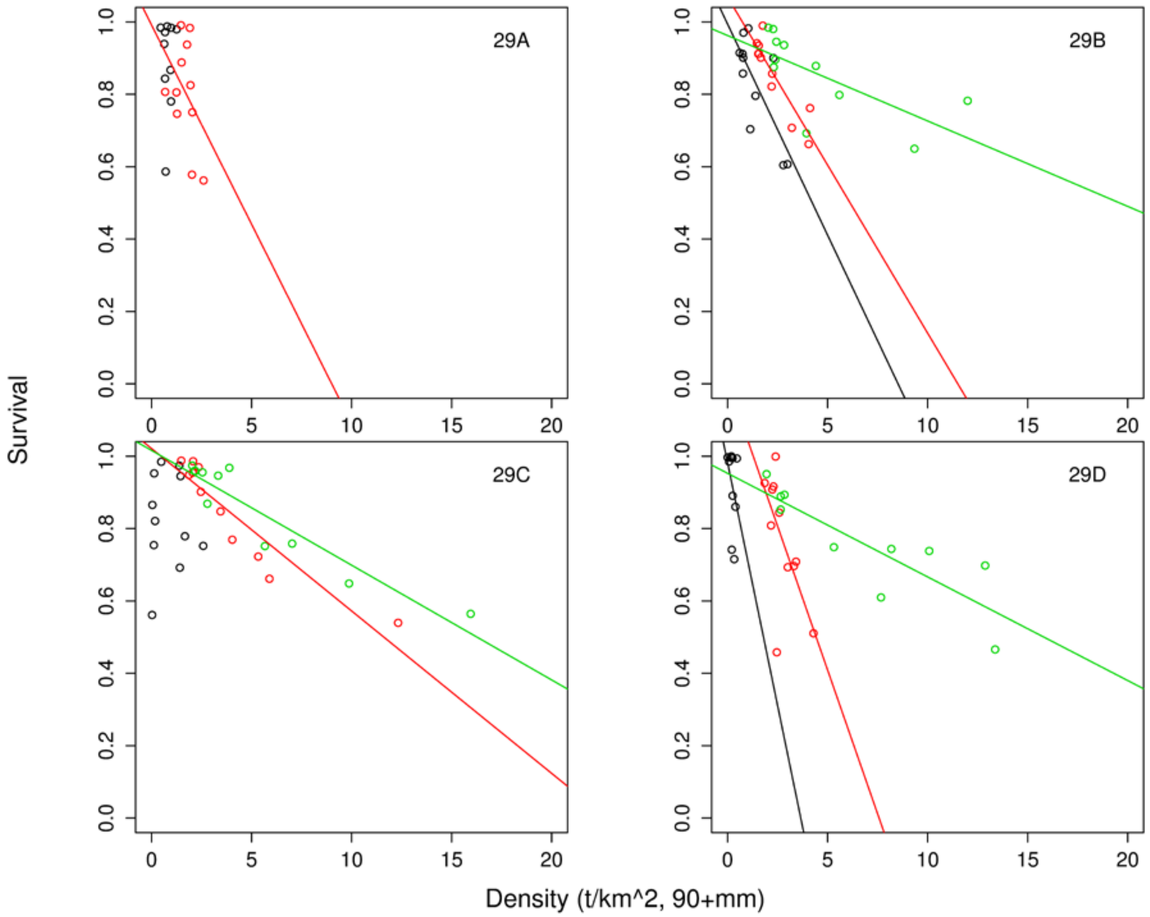

Figure 25. Comparison of survival estimates (exp(-natural mortality) and biomass density (t/km^2) for scallops with shell heights >90 mm by Low [0, 0.3] (black), Medium [0.3, 0.6] (red) and High [0.6, 1.0] (green) categories of habitat suitability probabilities in SFA 29 West.

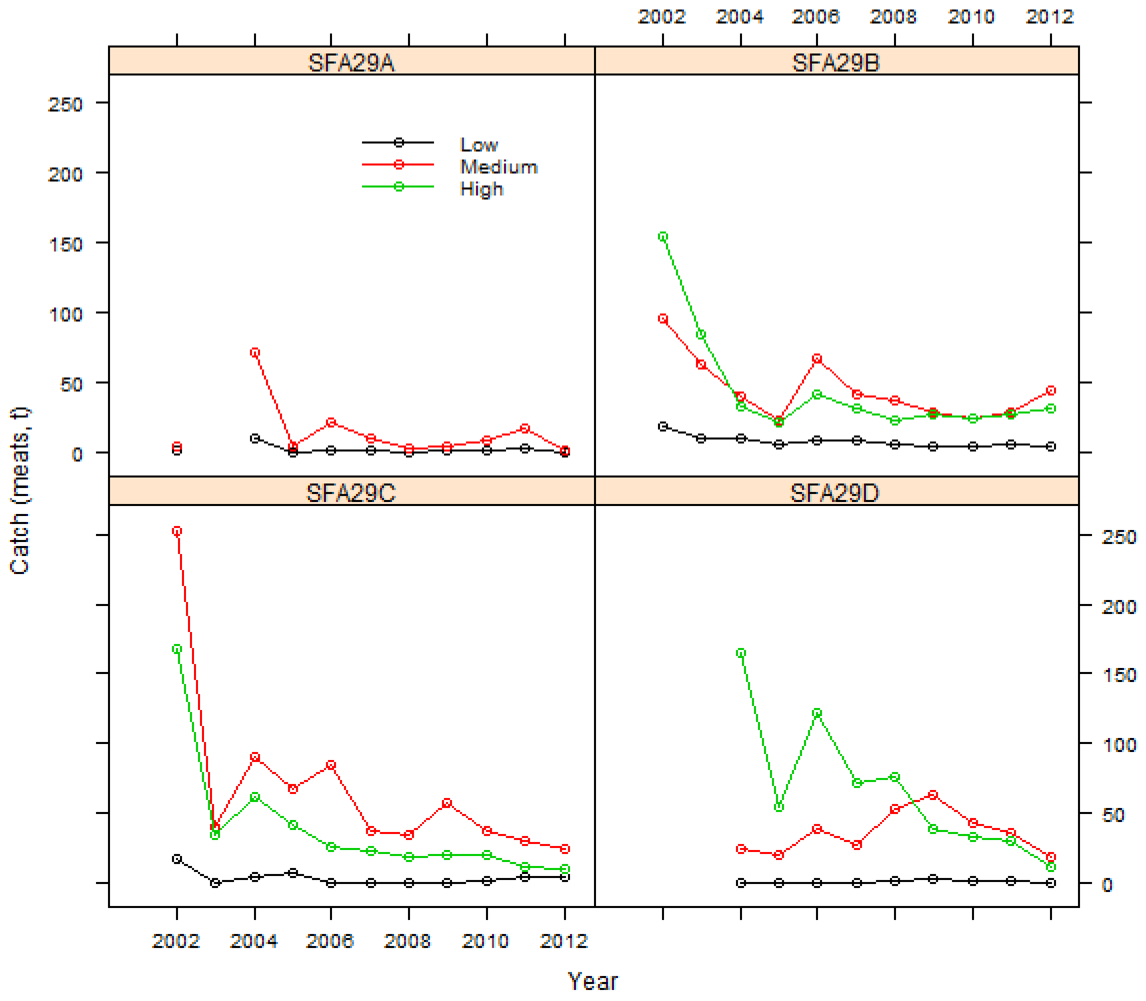

Figure 26. State-space model estimate of commercial catch by Low [0, 0.3], Medium [0.3, 0.6] and High [0.6, 1.0] categories of habitat suitability probabilities in SFA 29 West.

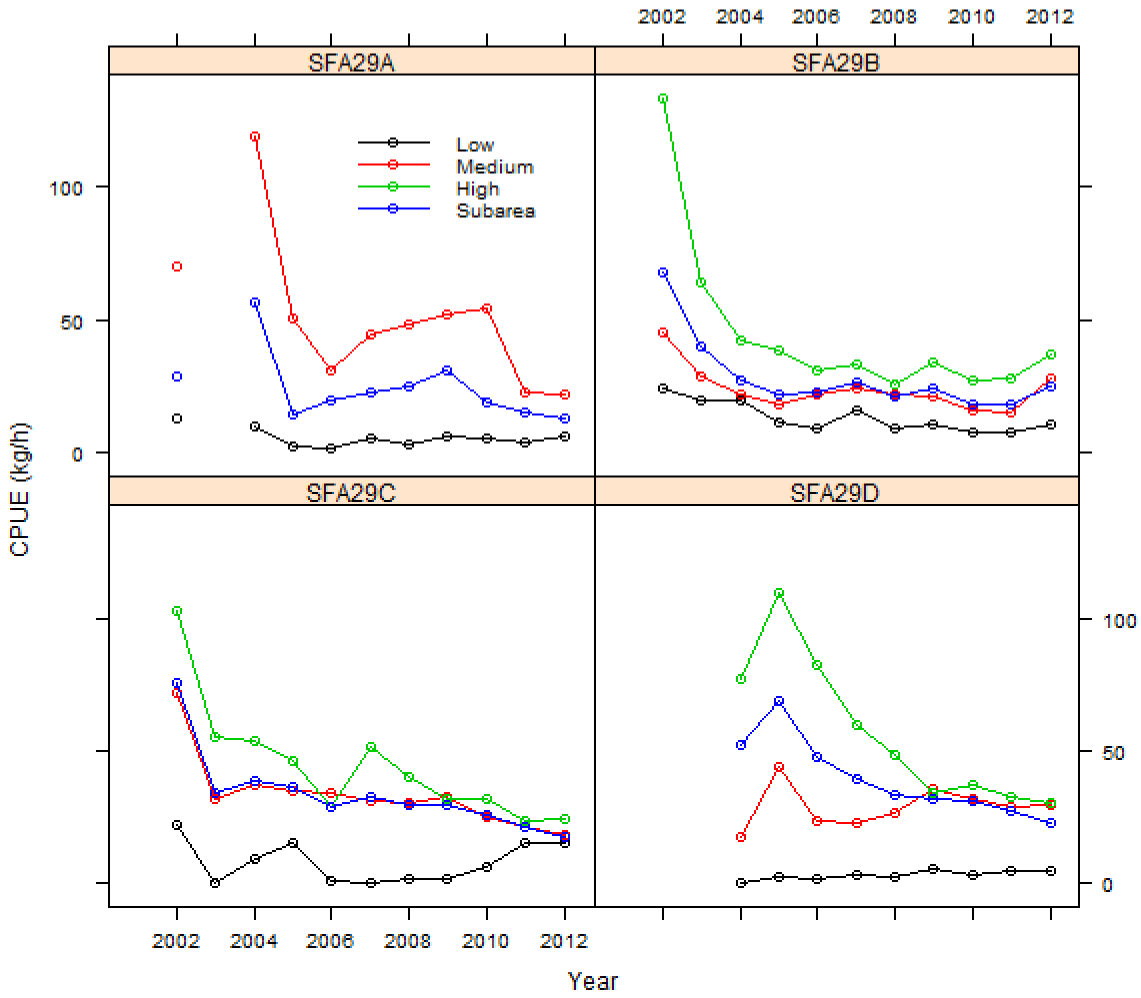

Figure 27. State-space model estimate of commercial catch rate by Low [0, 0.3], Medium [0.3, 0.6] and High [0.6, 1.0] categories of habitat suitability probabilities in SFA 29 West. The blue line labelled as subarea refers to the catch rate for the subarea as a whole.

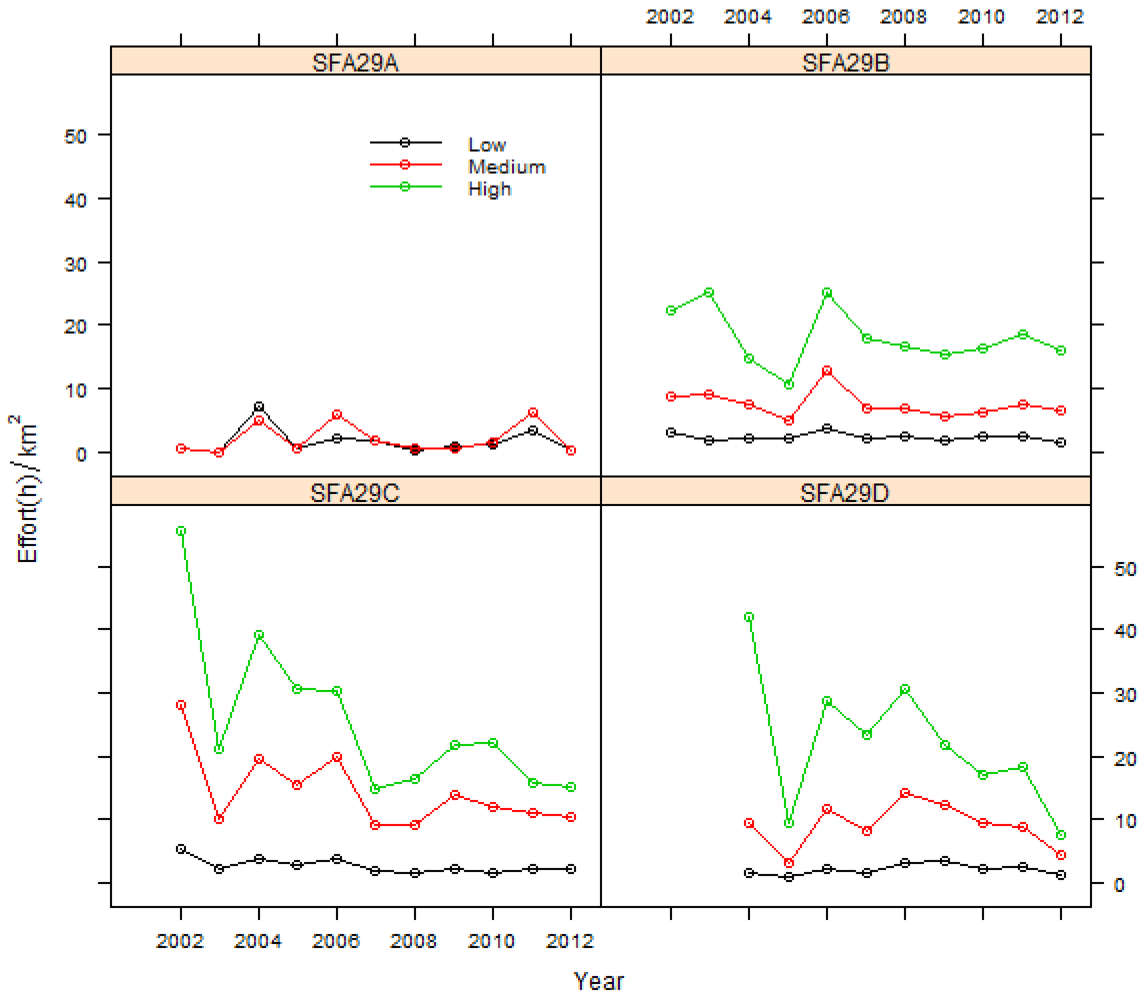

Figure 28. Fishing effort/km2 derived from VMS data binned by Low [0, 0.3], Medium [0.3, 0.6] and High [0.6, 1.0] categories of habitat suitability probabilities for SFA 29 West.

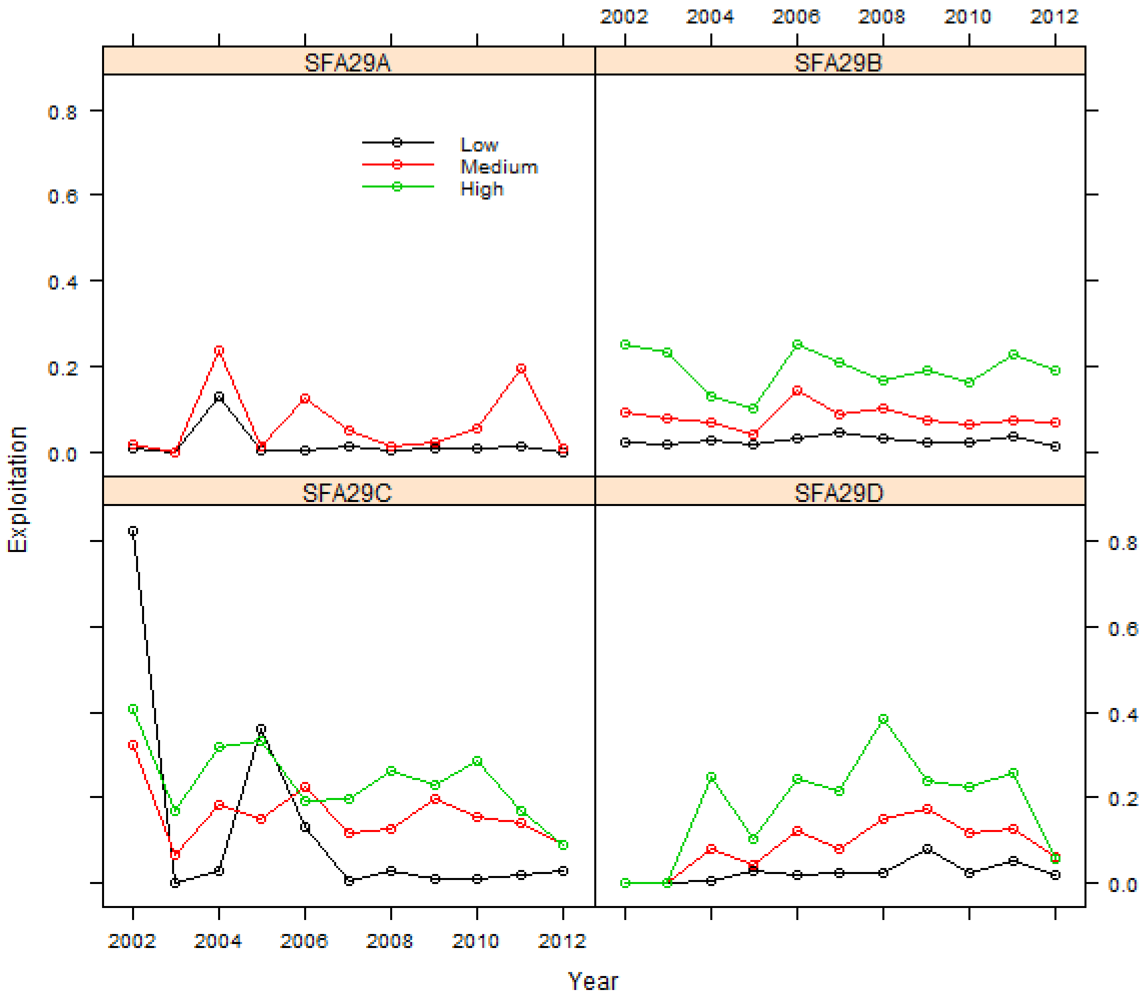

Figure 29. State-space model estimate of exploitation by Low [0, 0.3], Medium [0.3, 0.6] and High [0.6, 1.0] categories of habitat suitability probabilities in SFA 29 West.

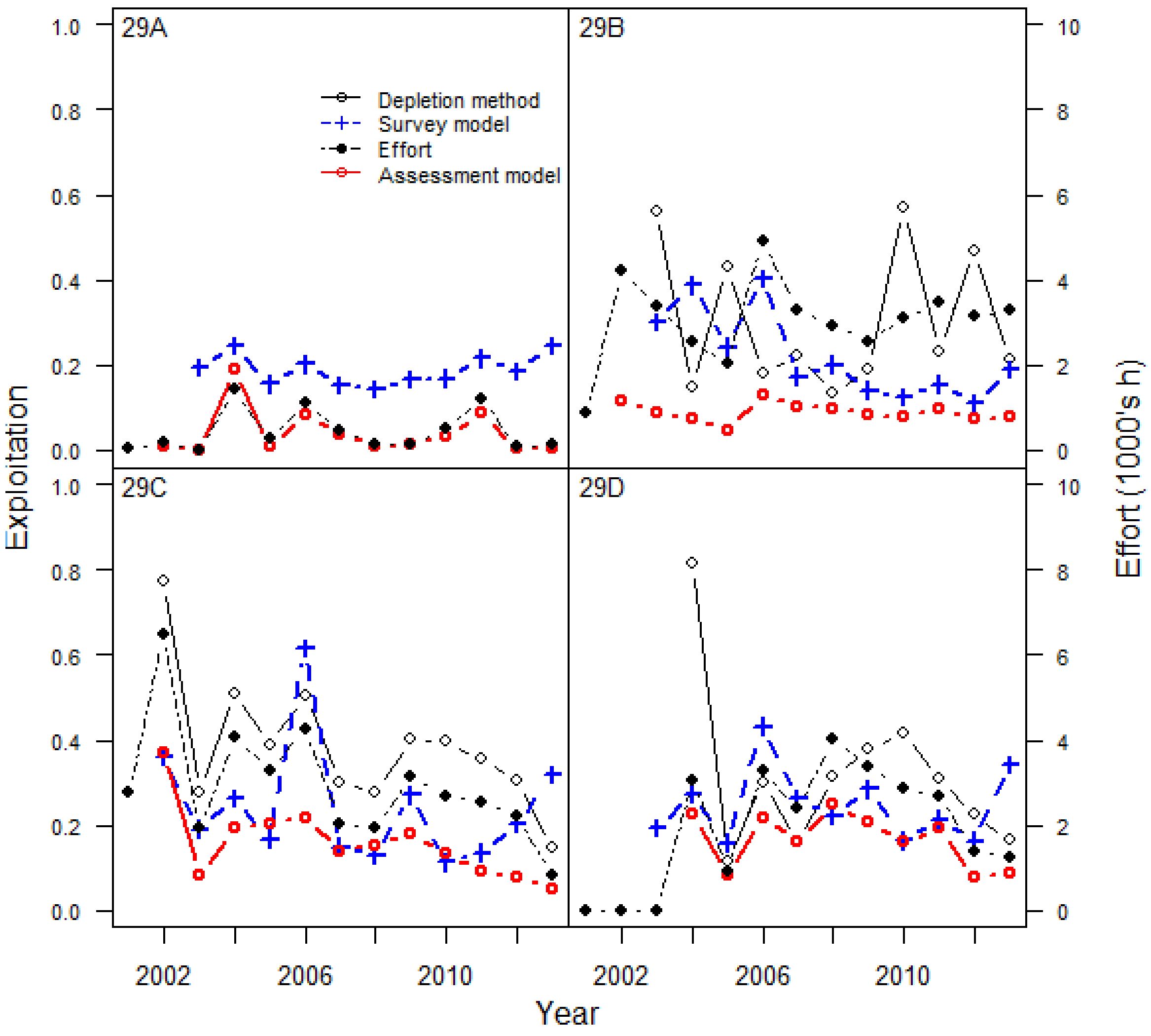

Figure 30. Comparison of exploitation estimators used in previous assessments in SFA 29 West and estimates from the state-space assessment model incorporating habitat suitability.

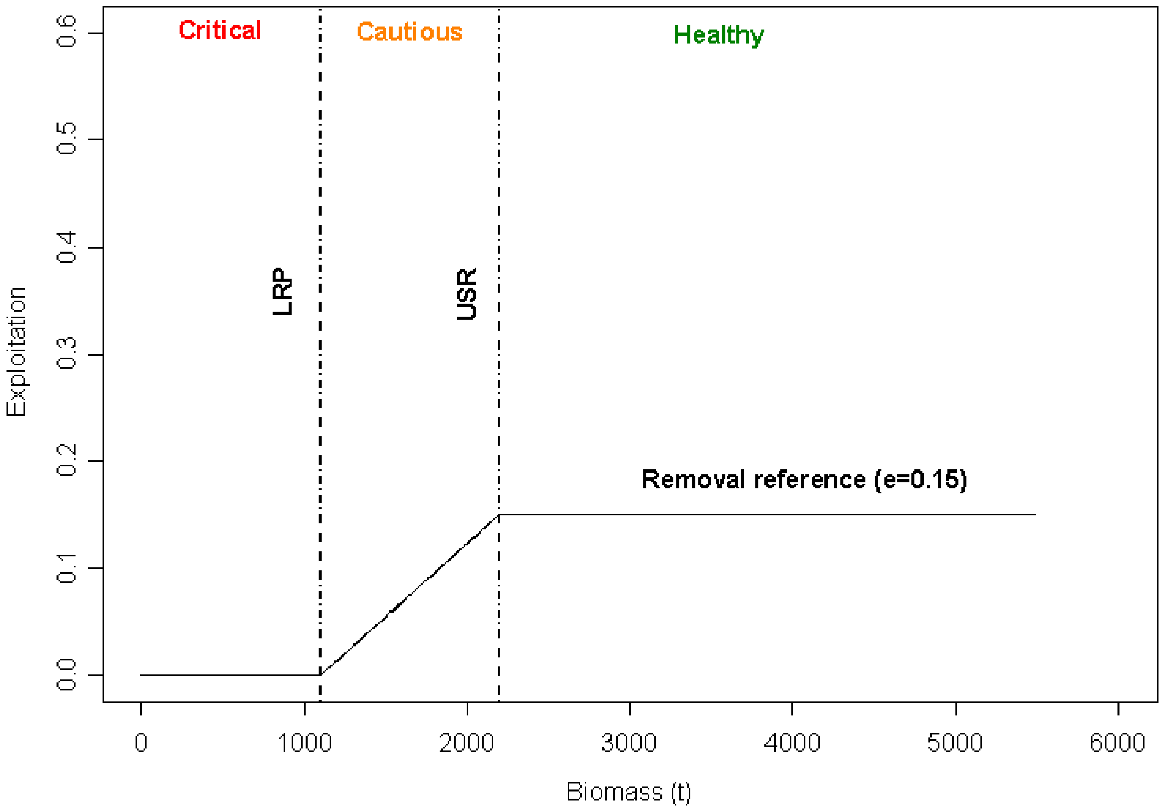

Figure 31. Idealized harvest control rule corresponding to the DFO precautionary approach to reference points. A fishery is in the Critical zone when biomass is below the Lower Reference Point (LRP), is in the Cautious zone when biomass is above the LRP and below the Upper Stock Reference (USR), and in the Healthy zone when biomass is above the USR.

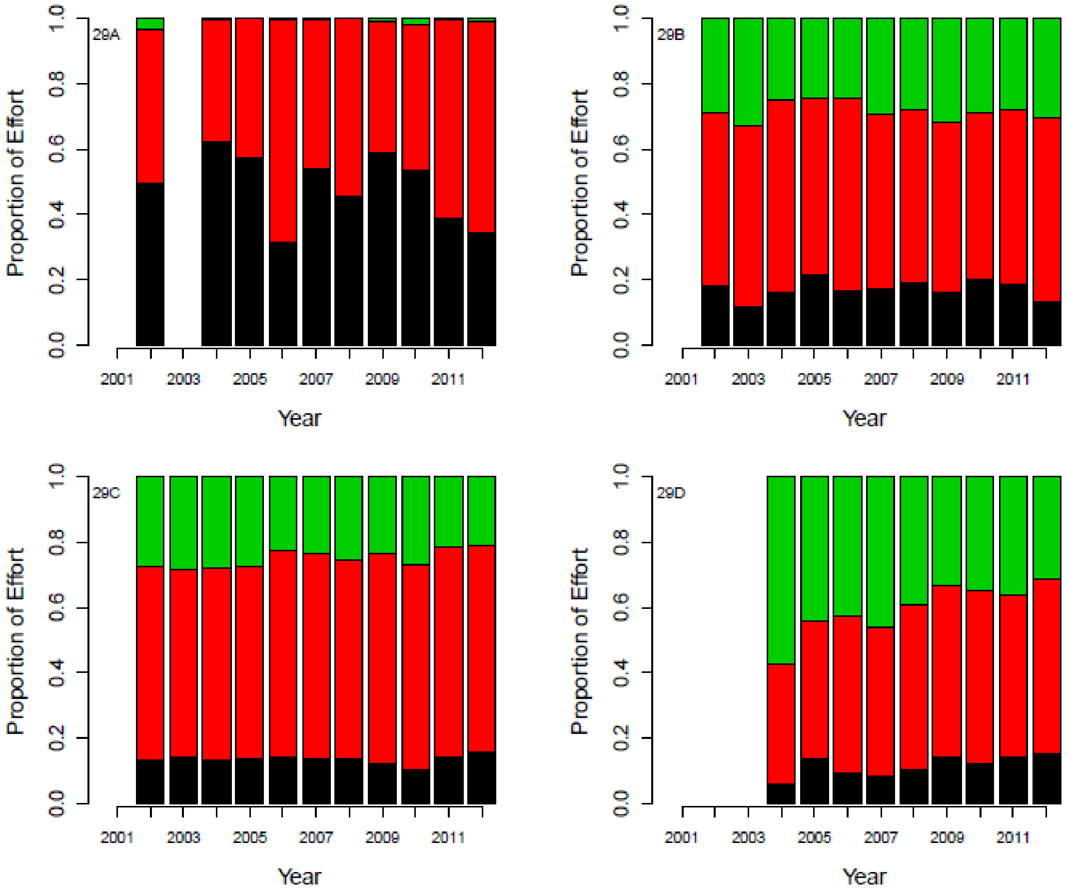

Figure 32. Proportion of effort by year based on VMS data by Low ([0,0.3], black), Medium ([0.3,0.6], red) and High ([0.6,1.0], green) categories of habitat suitability probabilities in SFA 29 West.

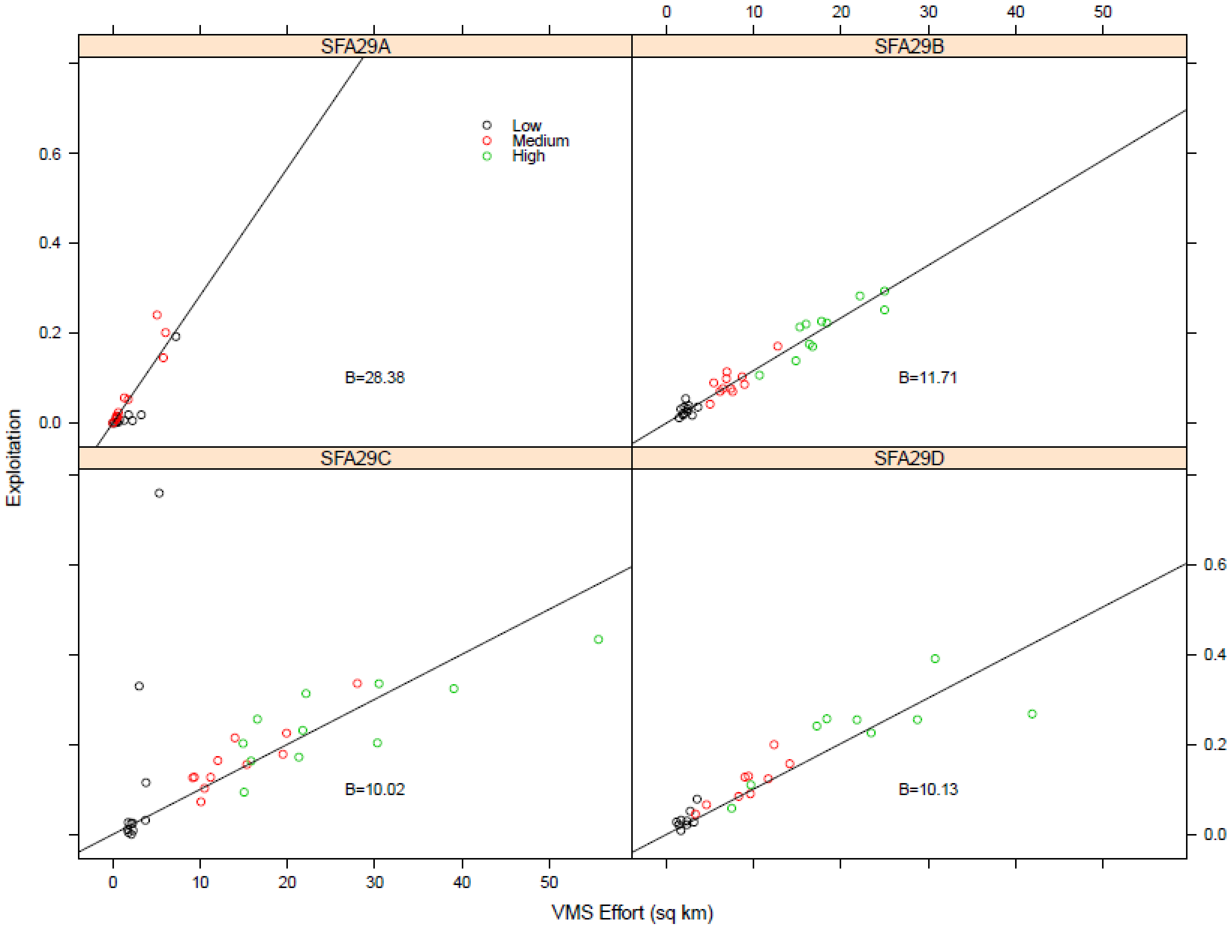

Figure 33. Comparison of exploitation with VMS effort (h/km^2) by low ([0,0.3], black), Medium ([0.3,0.6], red) and High ([0.6,1.0], green) categories of habitat suitability probabilities in SFA 29 West. The slope estimate (B) for the regression lines are given in each panel.

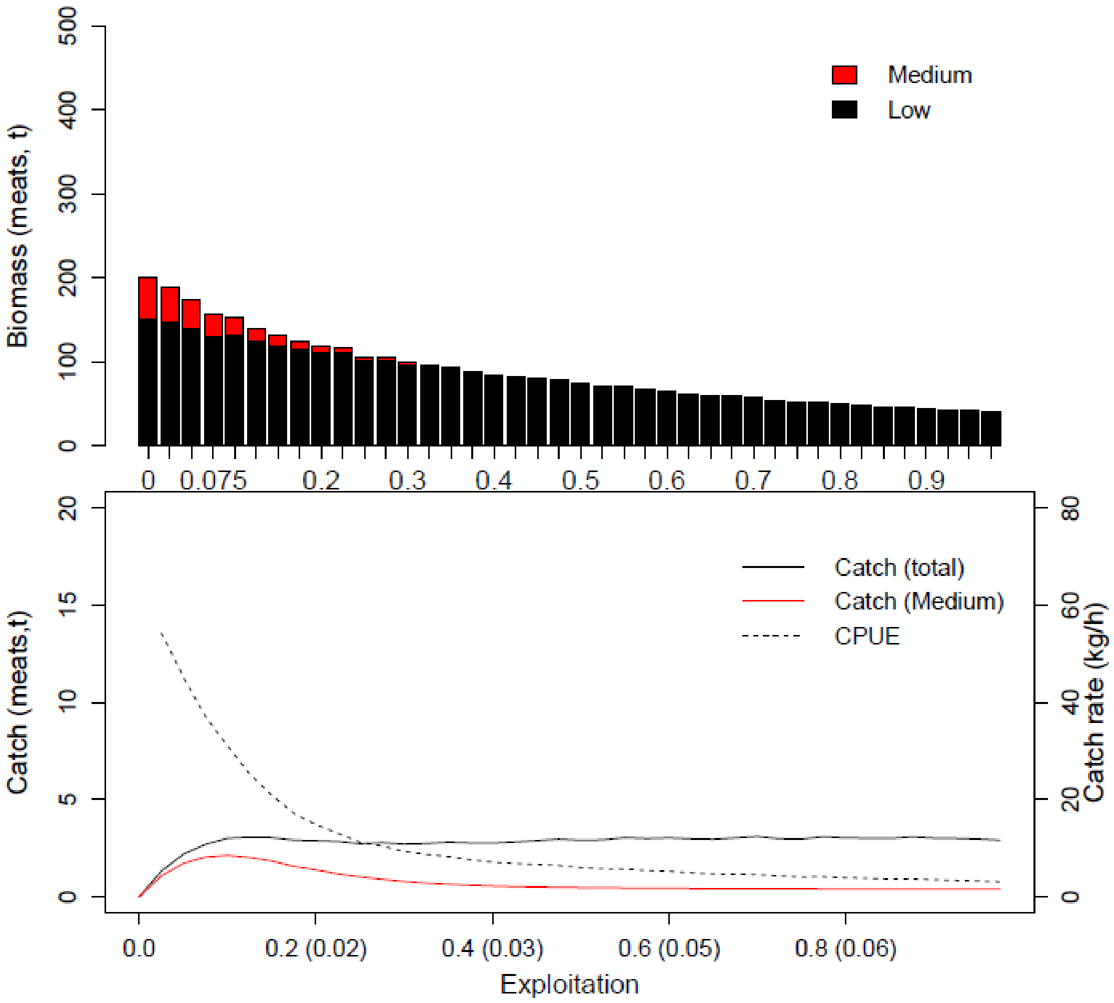

Figure 34. Equilibrium biomass (t; upper panel) used in determining the exploitation rate for maximum catch by Low ([0,0.3], black) and Medium ([0.3,0.6], red) categories of habitat suitability probabilities in SFA 29A. Exploitation rates in upper panel refer to the Medium category only. Equilibrium catch (t; lower panel) shown for total catch and Medium category only. These were obtained by projecting the model forward by 50 years from the current year for a range of constant exploitation rates. Catch rate was calculated for total catch. Exploitation rates in lower panel are for the Medium category areas followed by the corresponding rate for the total catch in brackets.

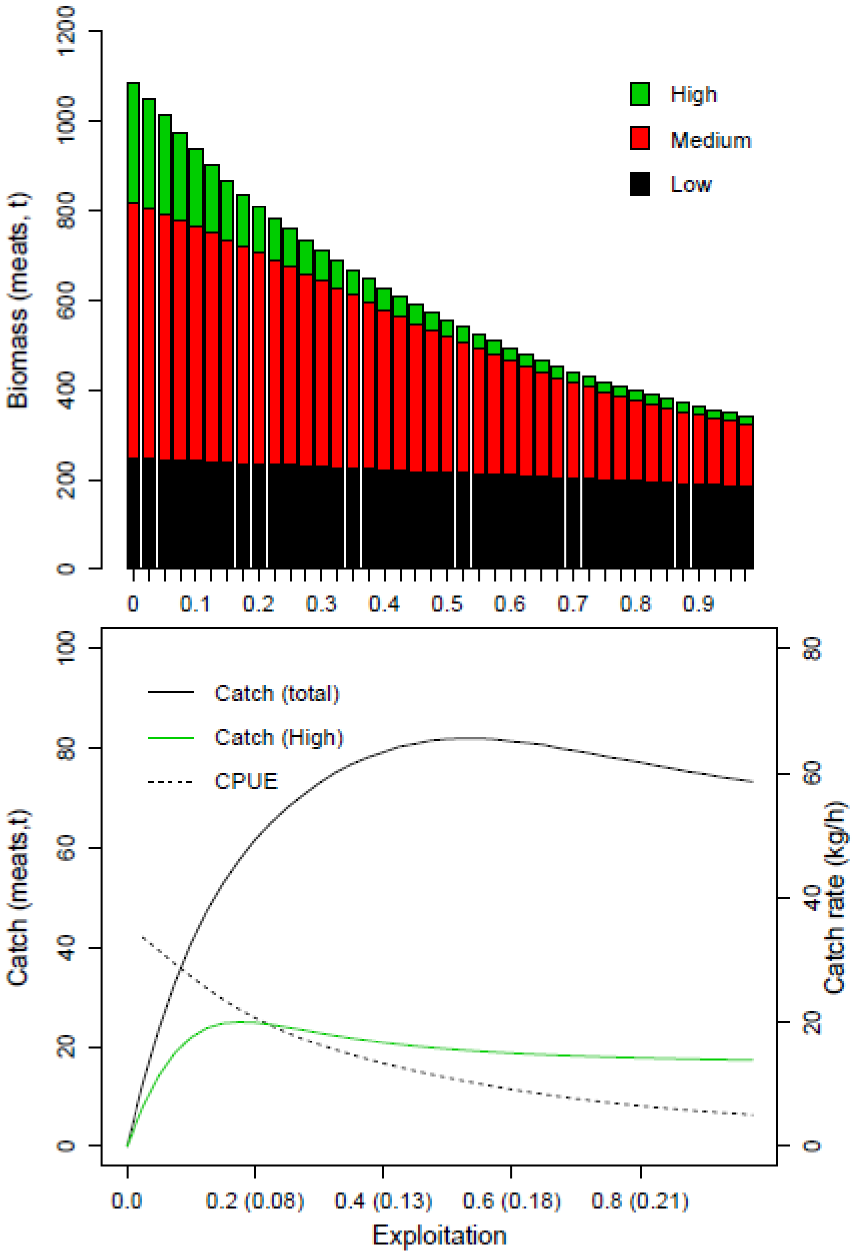

Figure 35. Equilibrium biomass (t; upper panel) used in determining the exploitation rate for maximum catch by Low ([0,0.3], black), Medium ([0.3,0.6], red) and High ([0.6,1.0], green) categories of habitat suitability probabilities in SFA 29B. Exploitation rates in upper panel refer to the High category only. Equilibrium catch (t; lower panel) shown for total catch and High category only. These were obtained by projecting the model forward by 50 years from the current year for a range of constant exploitation rates. Catch rate was calculated for total catch. Exploitation rates in lower panel are for the High category areas followed by the corresponding rate for the total catch in brackets.

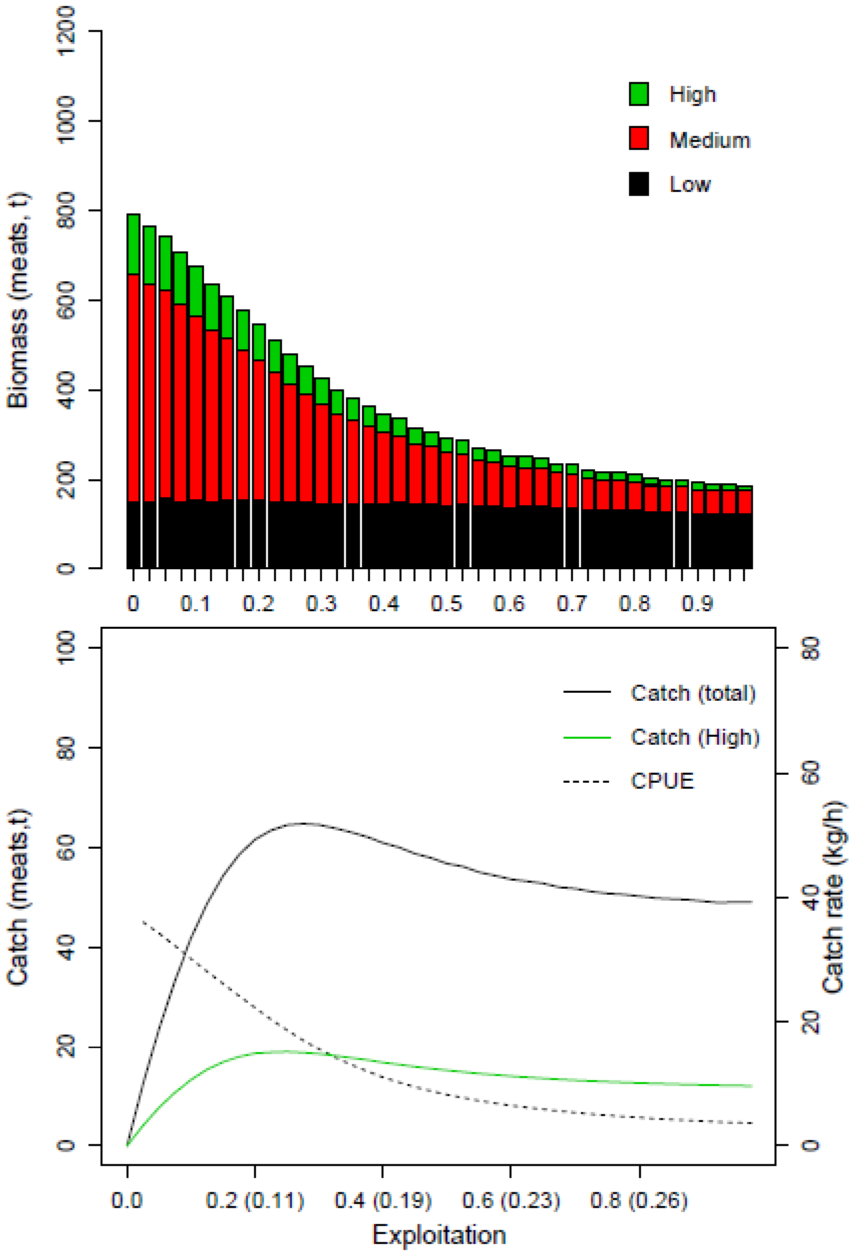

Figure 36. Equilibrium biomass (t; upper panel) used in determining the exploitation rate for maximum catch by Low ([0,0.3], black), Medium ([0.3,0.6], red) and High ([0.6,1.0], green) categories of habitat suitability probabilities in SFA 29C. Exploitation rates in upper panel refer to the High category only. Equilibrium catch (t; lower panel) shown for total catch and High category only. These were obtained by projecting the model forward by 50 years from the current year for a range of constant exploitation rates. Catch rate was calculated for total catch. Exploitation rates in lower panel are for the High category areas followed by the corresponding rate for the total catch in brackets.

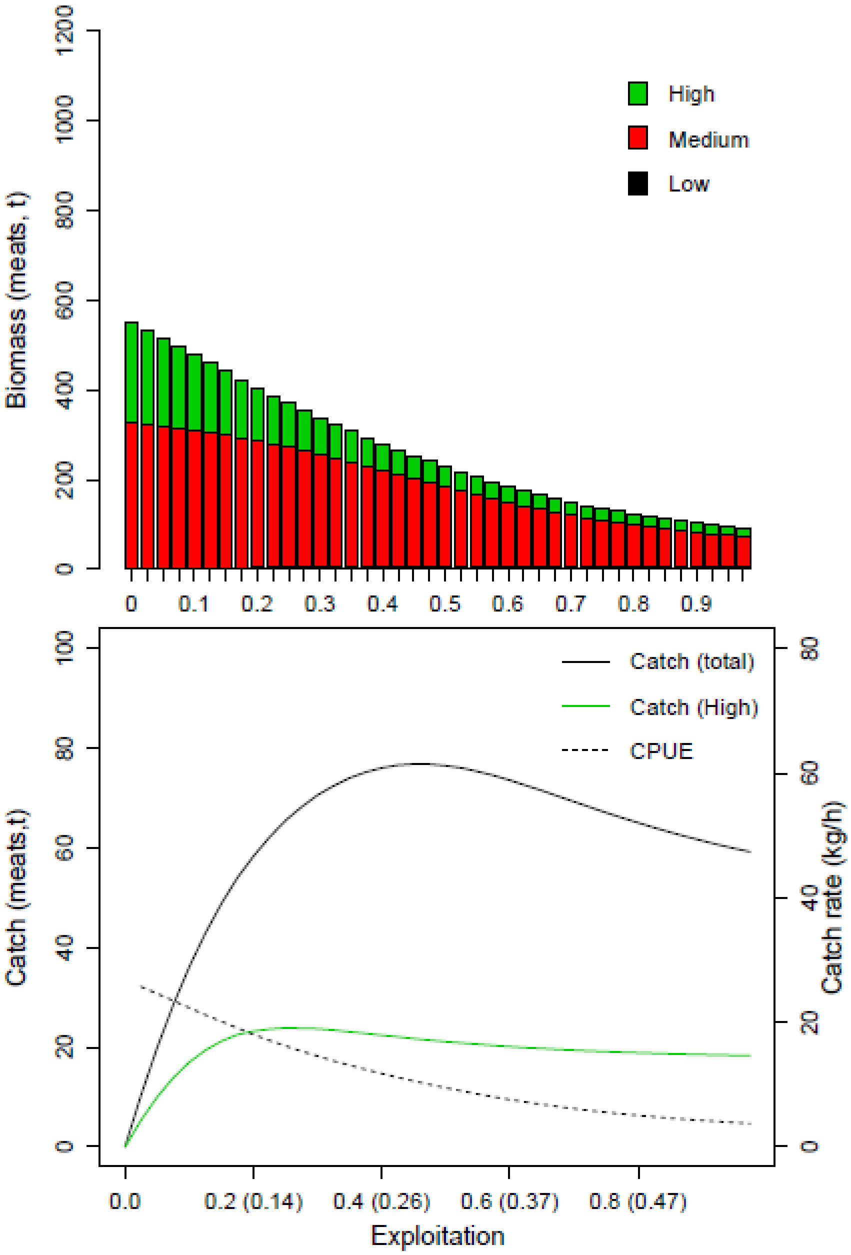

Figure 37. Equilibrium biomass (t; upper panel) used in determining the exploitation rate for maximum catch by Low ([0,0.3], black), Medium ([0.3,0.6], red) and High ([0.6,1.0], green) categories of habitat suitability probabilities in SFA 29D. Exploitation rates in upper panel refer to the High category only. Equilibrium catch (t; lower panel) shown for total catch and High category only. These were obtained by projecting the model forward by 50 years from the current year for a range of constant exploitation rates. Catch rate was calculated for total catch. Exploitation rates in lower panel are for the High category areas followed by the corresponding rate for the total catch in brackets.

APPENDICES

APPENDIX 1: COMPARISON OF GROWTH ESTIMATES

The only validation of scallop ages obtained from counting annual rings from the shells in SFA 29 West has been to compare growth parameters from obtained from fitting a standard or mixed-effects version of the von Bertalanffy growth model to scallop ages with those from a model developed by Hart and Chute (2009) for shell heights measured to each ring. The age of the ring does not have to be known, only the widths of the shell between the rings are required. This methods starts with the standard von Bertalanffy equation to model the growth of shell height (H_i) with age (A_i) for scallops.

$$H_i = H_\infty \left(1 - \exp\left(-K \times (A_i - T_0)\right)\right)$$

where ∞ is the asymptotic (or maximum) shell height, K is the growth rate (often called the Brody coefficient) and t_0 is an offset to adjust for the size at age 0. The parameter estimates are usually obtained using non-linear least-squares.

Before non-linear least squares were readily available, estimation of parameters were based upon the following relationship of shell height at some time *t* and *t +1* where t usually represented annual time steps.

$$\begin{aligned} H_{i,t+1} &= H_{i,t} + \left(H_\infty - H_{i,t}\right)\left(1 - \exp(-K)\right) \\ &= exp(-K)H_{i,t} + H_{i,t} + H_\infty\left(1 - \exp(-K)\right) \end{aligned}$$

The right-hand side suggests a linear regression of the form

$$H_{i,t+1} = H_\infty\left(1 - \exp(-K)\right) + \exp(-K)H_{i,t}$$

$$= B_0 + B_1 H_{i,t}$$

where the intercept B_0 is equal to $H_\infty\left(1 - \exp(-K)\right)$ and the slope B_1 is $\exp(-K)$.

Estimation proceeds by first fitting a regression to $H_{i,t}$ and $H_{i,t+1}$ for each scallop shell and then the von Bertalanffy parameters are obtained using the above relationships (see Figure 38). While this method will be biased when applied to the population as a whole if there is variability of the growth parameters among individuals, it can be used to model growth of individual animals. Hart and Chute (2009) include individual variability by casting the regression as a linear mixed effects model

$$H_{i,t+1} = \left(B_0 - b_{i,o}\right) + \left(B_1 - b_{i,1}\right)H_{i,t}$$

Estimation is more complicated for this kind of model requiring calculation of both fixed (population) and random effects.

Currently, a mixed-effects model with survey tows as the grouping variable is used to model growth using shell heights and ages obtained from the annual scallop surveys in SFA 29 West. Parameter estimates from this model and the shell increment model described above were quite similar (Table A1) with the mixed-effects model estimating somewhat smaller shell heights-at-age until around age 7 after which the shell heights were very close for both models (Figure A1). Although a statistical comparison of the parameters from the two models has not been done, it is unlikely that the parameters would be found to be significantly different.

Table A1. Parameter estimates from the different growth models based on standard non-linear least-squares, a mixed-effects version (with tow location as the grouping variable) and a linear mixed-effects shell-height increment version (with individual shells as grouping variable, Hart and Chute 2009) of the von Bertalanffy growth model. Shell height and age data obtained from scallop surveys in SFA 29 West. n/a indicates that parameter not applicable.

Model	H_∞	K	T_0
Non-linear least squares	141.73	0.339	0.032
Mixed effects	152.61	0.239	0.312
Shell-height increment model	149.00	0.259	n/a

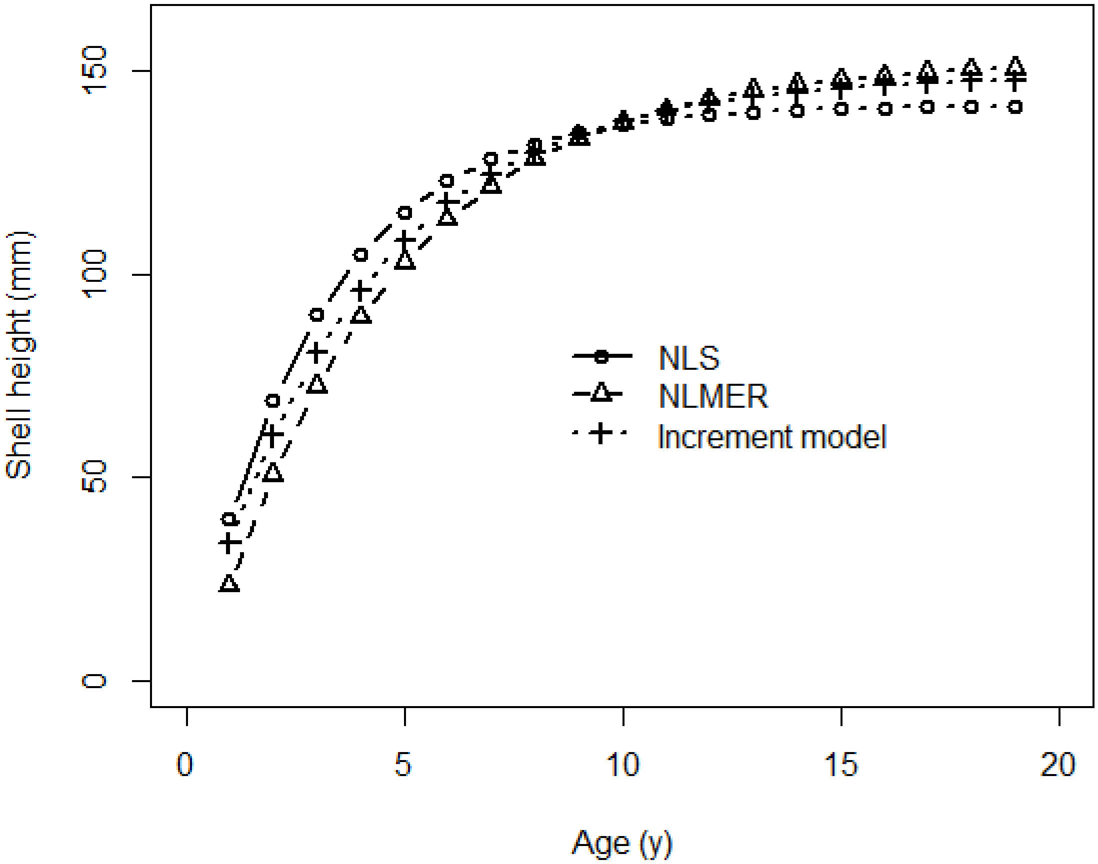

Figure A1. Predicted shell heights from the different growth models based on standard non-linear least squares (NLS), a mixed-effects version (with tow location as the grouping variable, NLMER) and a mixed effects shell height increment version (with shell has the grouping variable,Increment model) of the von Bertalanffy growth model. Shell height and age data obtained from scallop surveys in SFA 29 West.

APPENDIX 2: SURVEY ESTIMATES

A number of different kinds of sample survey estimates have been used for the scallop surveys in SFA 29 West. Starting in 2002, the surveys have been designed to be stratified random surveys, although the stratification variables have changed over time. In the case of using the stratification variable that was used to design the survey, the stratified mean in each subarea was calculated by taking the weighted mean over all strata (Thompson, 2002).

$$\bar{y}_{str} = \sum_{h}^{L} \frac{N_h}{N} \sum_{i=1}^{n_h} \frac{y_{hi}}{n_h} \tag{11}$$

where,

n_h = the number of tows sampled in stratum h (h = 1,...,L),
$n = \sum_h^L n_h$, the total number of tows sampled,
N_h = the total number of possible tows in stratum h,
$N = \sum_h^L N_h$, the total number of possible tows in the survey area, and
y_{hi} = the number of scallops in tow i of stratum h.

The variance of the stratified mean is also weighted by strata size

$$\widehat{VAR}(\bar{y}_{str}) = \sum_{h}^{L} \left(\frac{N_h}{N}\right)^2 \frac{(N_h - n_h)}{N_h} \frac{s_h^2}{n_h} \tag{12}$$

where $s_h^2 = \sum_{h=1}^{L} (y_{hi} - \bar{y}_h)^2/(n_h - 1)$ is the estimated sample variance and $\bar{y}_h$ is the sample mean in stratum *h*.

The estimates from existing surveys were adjusted in one of two ways when the stratification variables changed. For the surveys conducted in 2001 to 2004, the original designs were simple random for the first year and stratified random based on subarea boundaries for the remaining years. Re-stratification based on the surficial sediment boundaries was designed to be within the subarea boundaries allowing for a standard post-stratification estimate to be used. Within each subarea the mean was estimated as,

$$\hat{y}_{h,pos} = \frac{1}{N_h} \sum_{g=1}^{G} N_{hg} \bar{y}_{hg} \tag{13}$$

where y_{hg} is the sample mean within the new strata *g* in the old stratum *h*. Define $W_{hg} = N_{hg}/N_h$, an approximation to the variance of $\hat{y}_{h,pos}$ is given by

$$Var(\hat{y}_{h,pos}) \doteq N_h^2 \,\frac{1-f}{n_h} \sum_{g=1}^{G} W_{hg} s_{hg}^2 + N_h^2 \,\frac{1-f}{n^2} \sum_{g=1}^{G} (1 - W_{hg}) s_g^2 \tag{14}$$

where s^2_{hg} is the variance for the new strata,

$$s_{hg}^2 = \frac{1}{n_{hg}-1}\sum_{k=1}^{n_{hg}}\left(y_{hgk}-\bar{y}_{hg}\right)^2$$

The new geophysical strata overlapped with the previously defined surficial strata and therefore, a domain stratified estimate was required (Särndal *et al*., 1992). In this case the new strata are indexed with *d* and the old strata with *h* and those samples from the old strata that are in strata *d* are indexed as s_{dh}. The mean for the new strata was calculated as,

$$\bar{y}_{s_d} = \sum_{h=1}^{H}\frac{N_h}{n_h}\sum_{k}^{s_{dh}} y_k \bigg/ \sum_{h=1}^{H}\frac{N_h}{n_h}\, n_{s_{dh}} \tag{15}$$

with variance,

$$Var\left(\bar{y}_{s_d}\right) = \frac{1}{\hat{N}_d^2}\sum_{h=1}^{H} N_h^2\,\frac{1-f_h}{n_h}\,\frac{\sum_{s_{dh}}\left(y_k-\bar{y}_{s_{dh}}\right)^2 + n_{s_{dh}}(1-p_{dh})\left(\bar{y}_{s_{dh}}-\bar{y}_{s_d}\right)^2}{n_h-1} \tag{16}$$

where,

$$p_{dh} = n_{s_{dh}}/n_h$$

$$\bar{y}_{s_{dh}} = \sum_{s_{dh}}\frac{y_k}{n_{s_{dh}}}$$

and,

$$\hat{N}_d = \sum_{h=1}^{H} N_h\left(n_{s_{dh}}/n_h\right)$$