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Scallop Fishery Assessment of the Southern Gulf of St. Lawrence in 2018: Commercial Fishery and Survey Data

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Canada

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

This document presents the commercial fishery indicators used for the sea scallop stock assessment conducted in 2018 for the southern Gulf of St. Lawrence inshore waters up to the 2016 fishing season. The document includes methodologies, commercial fishery statistics, and results from research surveys (2012-2016). We present landings, effort and catch rates at the Scallop Fishing Area (SFA) level and the bed level for the available time series (2003 to 2016). A Leslie model was used for the first time to estimate exploitable biomass and exploitation rates for the two major beds of SFA 22, Cape Tormentine, and West Point, for each year of available data (2003 to 2016). We also present estimates for certain years (2003, 2011 and 2012) of the Pictou bed in SFA 24; the model did not fit the data properly for the other years. Depletion estimates for the SFA 21A bed are presented for years in which the model was able to be fit (2003, 2005, 2006, 2013 and 2014).

INTRODUCTION

BIOLOGY

The sea scallop (*Placopecten magellanicus*) is a bivalve mollusc found in the Northwest Atlantic Ocean ranging from the north shore of the Gulf of St. Lawrence (Canada) to Cape Hatteras, North Carolina (USA) (Posgay 1957, Squires 1962). It is an epibenthic and sedentary species. Sea scallops feed by filtering phytoplankton, microzooplankton and detritus particles. Scallops are frequently found in dense aggregations commonly called beds. In the southern Gulf of St. Lawrence (sGSL), scallop beds are located at depths between 15 m and 37 m, mostly on hard bottom types such as sand-gravel or gravel-pebble substrates.

Sea scallops can grow in water temperatures ranging from 8 to 18°C while the optimal temperature for growth is between 10 to 15°C (Young-Lai and Aiken 1986, Stewart and Arnold 1994, Frenette 2004). Temperatures above 18°C can induce stress to sea scallops while temperatures above 21°C can be lethal (Dickie 1958, Stewart and Arnold 1994). Scallop mass mortality has historically been reported in portions of the southern Gulf experiencing high temperatures. In the sGSL, scallops can commonly reach a shell height (from umbo to shell margin) between 125 and 145 mm. Annual growth rings are formed on the shell in late winter and are especially pronounced in northern shallow-water populations (Naidu 1975) like in the sGSL. Oxygen isotope records in scallop shells have confirmed that growth lines are annual events (Tan et al. 1988). Scallops can be aged by counting these rings and growth rates can be determined by measuring the distance between two subsequent annular rings (Stevenson and Dickie 1954). Growth rates are highly variable, dependent on numerous factors such as the sampling location (Naidu and Robert 2006), water temperature, food availability, water depth, current velocity, standing stock biomass and fishing intensity (Harris and Stokesbury 2006).

Sea scallops are harvested mostly for their meat (i.e. adductor muscle). Generally, the weight of the meat increases exponentially with shell height. However, discrepancies are notable in same size scallops where meat weight can vary spatially and temporally (annually and seasonally) according to temperature (MacDonald and Thomson 1985), food availability (Shumway et al. 1987, MacDonald et al. 2006), current speed (Wildish and Saulnier 1993, Pilditch and Grant 1999), and their reproductive cycle (Robinson et al. 1981, Bonardelli and Himmelman 1995). In a nine year study, Sarro and Stokesbury (2009) found 29 % variability in meat weight among months and 31 % variability between different areas on Georges Bank (US) in the same month.

The sexes are separate, with males and females being easily identified by their white and orange-colored gonads, respectively (Drew 1906). Sex ratio of males to females is generally 1:1, with the occasional hermaphrodite (Worms and Davidson 1986). Sea scallops reach sexual maturity (i.e. fully emptying their follicles) at shell heights greater than 60 mm (Davidson 1998, Davidson and Worms 1989) at approximately three years old in the sGSL (Chouinard 1984). Scallops are highly fecund with a single female having the capacity to produce from 1 to 270 million eggs per annual spawning event. Egg production increases exponentially with shell height (MacDonald and Thompson 1985) and significant contributions to egg production may not occur until scallops reach 85 to 90 mm (Hart and Chute 2004). Spawning is triggered by physiological and environmental cues, mainly temperature but also the lunar cycle, current speed and food supply (Barber and Blake 2016, Parsons et al. 1992). Sudden changes in temperature from the vertical mixing of warm waters were linked to spawning in the Gulf of St. Lawrence (Bonardelli et al. 1996). Spawning involves the release of male and female gametes synchronously into the water column. Fertilization is external, hence the importance of individual scallops being in close proximity to one another on beds. In the sGSL, spawning time varies annually but typically begins between mid-August and mid-September, lasting from 2 to 4 weeks (Table 1, Davidson et al. 2019).

Following fertilization, scallop larvae are planktonic for 4 to 5 weeks before their settlement on a suitable substrate when they begin benthic life as juveniles (Culliney 1974). Suitable substrate can consist of pebbles, filamentous fauna (i.e. hydroids, bryozoans), and shell fragments as well as shells colonized with hydroids (Caddy 1972, Larsen and Lee 1978, Minchin 1992, Harvey et al. 1993, Stewart and Howarth 2016). Adult scallop shells can effectively provide substrate for byssal attachment and refuge from predation (Bourgeois et al. 2006). Juvenile scallops are vulnerable to predators and to disturbances of the sediment (habitat) caused by scallop dredging, or any other epibenthic disruption. Current scientific knowledge supports the avoidance of scallop dredging during spawning events and during spat settlement periods, between August and October. Another potential benefit of avoiding dredging during these crucial periods is the recovery of fast-growing hydroids which act as a suitable substrate for spat settlement (Bradshaw et al. 2005). Adult scallops, on the other hand, have a low natural mortality. Their main predators are sea stars (e.g. *Asterias vulgaris* and *Leptasterias polaris.*) and crustaceans (e.g. *Cancer irroratus* and *Homarus americanus*). While sea scallops are considered mostly sedentary, they can swim short distances as an escape response to predators and to unfavorable environmental conditions (Manuel and Dadswell 1993).

DESCRIPTION OF THE FISHERY

Commercial, recreational, and limited Indigenous Food, Social and Ceremonial fisheries for sea scallop occur in the southern Gulf of St. Lawrence. The fishery is important to many coastal communities often supplementing the lobster, herring, and groundfish fisheries (Lanteigne and Davidson 1991). It is a competitive fishery without quotas and managed under the jurisdiction of the Gulf Region by input controls including a limited number of licences, fishing seasons, spatial closures, gear restrictions, and meat count limits (Table 2). Catches are monitored through sales slips from registered buyers and logbooks from scallop harvesters. In the Gulf Region, the price paid to harvesters increased from \$0.57/kg (\$0.26/lb) in 1967 to \$17.64/kg (\$8/lb) in 1994 and have since been fluctuating between \$13.26 and \$28.66/kg (\$6/lb and \$13/lb) (Mallet 2010).

While price can drive fishing effort, there is no indication that this is the case in the Gulf scallop fishery. An historical review of the Gulf scallop fishery can be found in Lanteigne and Davidson 1991.

FISHING AREAS

Management of the scallop fishery in the sGSL is structured into four (21, 22, 23, and 24) Scallop Fishing Areas (SFA). Furthermore, one zone (SFA 21) is divided into three sub-zones since 1996 (21A, 21B, 21C) (Fig. 1). This sub-division facilitated the management of a scallop enhancement project conducted from 1999 to 2010 by the Maritime Fishermen’s Union (MFU) (Davidson et al. 2019). Each SFA and sub-zone has its own management measures (Table 2).

BUFFER ZONES

In the Gulf Region, buffer zones have been implemented to prevent trawling and dredging, including scallop dredging, over selected areas to primarily protect habitat of juvenile American lobster (*Homarus americanus*) (Davidson et al. 2007) (Fig. 1). Over the last twenty years, the fishing industry and the Department of Fisheries and Oceans (DFO) fishery managers collaborated to establish these buffer zones which can be revisited and redefined as needed through a formal process. As a result, buffer zone depth criteria can vary from one SFA to another and are described in Table 3.

AREA CLOSURES

In the sGSL, temporary fishery closures have been used over the years for resource management purposes (Table 3). For example, from 2005 to 2010, a 210 km^2 area west of the Confederation Bridge was closed at the request of the scallop harvesters in SFA 22. This area was closed to allow the scallop stock to rebuild. However, this area covered only 2 % (1.7 km^2) of the main Cape Tormentine bed (as defined below by kernel density analysis; the 20 trip per km^2 contour). In the Chaleur Bay, the entirety of SFA 21A has been closed twice (2010 to 2012 and 2016 to 2018) following a catch rate decision rule unique to this SFA which states that the fishery will be closed for a period of three years following a year in which the catch rate is below 0.5 kg $h^{-1}m^{-1}$ (i.e. 3 kg h^{-1}). This catch rate limit is founded on an economic threshold.

FISHING SEASONS

Scallop fishing in the sGSL is limited to the ice-free period occurring generally from mid-April to mid-December (https://www.canada.ca/en/environment-climate-change/services/ice-forecasts-observations/latest-conditions.html). Within this overall fishing period, one of the management strategies in place to control fishing effort is the implementation of fishing seasons. Each SFA has its own season which is defined from discussions and agreement by the scallop advisory committees comprised of representatives from DFO, provincial government, the fishing industry, aboriginal groups and other stakeholders. The timing of the season is often influenced by that of other commercial fisheries, particularly the lobster fishery, since most scallop licences holders have licences to fish other species. SFA 22 has a five-week spring fishery, while SFA 21 has mostly a summer fishery and SFA 23 combines both a summer and fall fishery. Since 1998, SFA 24 has been a fall-only fishery of six weeks duration. Prior to this time, it also included a spring fishery. Most SFAs restrict fishing to between 6 am and 6 pm and include weekend closures (Saturday and/or Sunday). The exception is SFA 21B where each week fishing starts Monday at 5:30 am and ends Friday at 2 pm. The fishing season dates, time open, weekend closures, and number of fishing days per season for each SFA for 2015 and 2016 are presented in Table 2.

FISHING GEAR

Commercial scallop fishing takes place with fishing vessels less than 14 m (45’). Most industry members use a Digby-type drag (Fig. 2) while some use sweep chain drags. The maximum dredge width permitted varies from one SFA to another from 4.88 m to 6 m. The total length of the drag, the ring size, type, and number washers and tow bar are described in the condition of licence for each SFA (Table 2).

Since the beginning of the fishery, many changes have occurred to industry practices, notably to the fishing gear. For example, in 2001, the minimum ring size diameter used in the buckets increased from 76 mm (3”) to 82.6 mm (3¼”) in SFA 22. This change was implemented as a conservation measure to reduce the catch of small scallops. As of 2003, this change was implemented in all SFAs.

MEAT COUNT

There are no minimum size regulations for scallops landed in the Gulf fishery. However, size is to a certain extent dictated by ring size of the dredge (82.6 mm). Otherwise, there is a meat count regulation (number of meats per 500 g) which varies between SFAs (Table 2). The regulatory meat count is highest in SFA 24 which 52 reflects the smaller meat weights relative to shell height in this area (Worms 1984). In SFA 22, the meat count decreased from 52 to 44 meats per 500 g in 2001 in line with the ring size increase at that time. All other SFAs have a maximum meat count of 39. However, the common practice of blending the catch allows for small scallops to be shucked together with larger ones while still making the meat count limit. This renders the meat count regulation rather ineffective in protecting small scallops from being harvested (Worms 1986).

LICENCES

The scallop fishery in the Gulf Region has had a limited entry since the 1970s when the number of licences was already at very high levels. There were 768 to 773 commercial scallop fishing licences issued in 2012 to 2016, including 44 communal commercial licences held by 15 Indigenous groups. Over half of the commercial licences are in SFA 24 (Table 4). For the purpose of this report, a scallop licence is said to be active if at least one landing is reported during the fishing season. Active licences, estimated from records of landings in official statistics and from logbooks, are far fewer than issued licences and ranged from 145 to 189 over the same time period. During 2011 to 2016, between 19 and 25 % of the licence holders were active. The highest percentage of active licences has been in SFA 22 (42 to 54 %) and the lowest in SFA 23 (1 to 10 %) (Table 4). The trend in number of active licences from 1986 to 2016 (Fig. 3) shows that recent participation in the fishery has been low with around 200 active licences since the early 2000s compared to over 500 active licences in the 1993 to 1998 period. Therefore there is a substantial amount of latent effort that needs to be considered in the precautionary approach for future management decisions.

LANDINGS AND LOGBOOKS

The last sea scallop assessment in the Gulf was conducted in 2011 and presented landings and logbook data up until 2010 (Davidson et al. 2012). The data was analysed at the SFA level and no empirical models were used. The 2011 assessment reported that the Gulf stock abundance was low based on historical landings information. Similarly, commercial landings in this 2018 assessment are reported in meat weights and are obtained from sale slips from registered buyers and also, since 2001, from scallop harvester logbooks. Unlike the last assessment, this current assessment does not include Supplementary B forms (Buyer code 9000) that were estimates of unreported landings by fishery officer personnel. These estimates had been included in the landings since 1982 and discontinued in 2009. However, no defined or consistent method for obtaining these estimates was followed.

Logbooks are included in the licence conditions and are mandatory. Fish harvesters must log fishing activity for each day fished. Daily information includes date fished, hours fished, landings in pounds, drag width in feet, latitude and longitude of general fishing location, as well as a comment box for observations such as meat count and anomalies. Since 2003, the number and average duration of tows in minutes were added to the logbook to improve the quality of effort data. Completed logbooks (in paper form) need to be submitted to DFO within two weeks following the end of the fishing season. Commercial data to 2016 were available and are included in this assessment.

Each logbook record is matched to its corresponding sales slip from registered buyers. Logbooks that do not have a corresponding sales slip are interpreted as local sales or personal consumption. On the other hand, sales slips without corresponding logbooks are considered as non-compliant to the licence conditions.

RECREATIONAL FISHERY

Recreational catches by scuba divers have been recorded in logbooks since 2003. There were 264 recreational licences issued in 2016. Management measures in this fishery include maximum daily limit of 50 scallops per diver, except in SFA 24 where it is 100; a season (May 1 – Oct. 31); and shell height minimum size limit (102 mm). The number of annual active licences (i.e. reporting landings in logbooks) varied between 11 and 55 over the 2003 to 2016 period (Table 5). Most of the activity occurred in SFA 21.

CATCH STATISTICS

The Science Branch of DFO uses the sales slips and logbook data to calculate landings, the amount of fishing effort and the catch rates or catch per unit effort (CPUE). Effort is expressed in hours (h). Effort can be obtained from two sources of logbook data:

1. The total number of hours from the start of the first tow to the end of the last tow of the day, and is named “hours fished” (data available since 2001).
2. The number of tows multiplied by the average duration of tows, herein called “hours towed” (data available since 2003). This is the effort metric used in this assessment because it is considered more informative.

However, effort data is typically not available for all catch records. For catches without effort data (catch $_{\text{no logs}}$), the effort (Effort $_{\text{no logs}}$) is calculated using the known catch rate (catch rate $_{\text{logs}}$) of the SFA (or bed), where the catch rate is the catch in kilograms of scallop meat divided by hours towed of fishing effort (kg h^{-1}) from logs that do have effort :

$$Effort_{\ no\ logs}(h) = \frac{\text{catch}_{\ no\ logs}(kg)}{catch\ rate_{logs}\ (kg\ h^{-1})} \quad (1)$$

When effort is expressed as hours-meter (hm), it is the effort in hours multiplied by the width of the drag in meters. It allows for the comparison of effort and catch rates when drag width is different (e.g. between DFO regions). In the previous assessment (Davidson et al. 2012), CPUE was expressed in kilograms of scallop meat per hours fished of fishing effort multiplied by drag width (i.e. kg $h^{-1}m^{-1}$) (equation 2). In this assessment, the preferred and more intuitive expression of catch rate is kilograms of scallop meat divided by hours towed of fishing effort (kg h^{-1}) (equation 3). Furthermore, catch per hours towed is a more accurate and informative index of abundance than catch per hours fished (Caddy 1989). Catch rates were similarly calculated from the at-sea sampling program from 2001 to 2005 (Davidson et al. 2012). These latter data were obtained from one day of commercial fishing per bed per year with a DFO biologist on board.

$$catch\ rate\ (kg\ h^{-1}m^{-1}) = \frac{\sum catch\ (kg)}{\sum hours\ fished\ (h) * drag\ width\ (m)} \quad (2)$$

$$catch\ rate(kg\ h^{-1}) = \frac{\sum catch\ (kg)}{\sum hours\ towed\ (h)} \quad (3)$$

SPATIAL ANALYSIS

Using the daily fishing geolocations from the logbooks from 2001 to 2016, this assessment also examines the data spatially by scallop bed. This makes sense biologically for sea scallops which are a sedentary species which commonly aggregates on beds (Caddy 1989). The focus on beds can enhance our understanding of how the fishery affects scallop populations since this is where the fishing pressure is concentrated. When fishery data are not segregated spatially, it can inadvertently mask catch rate declines while beds are sequentially being depleted and keeping average catch rates stable. In terms of the environmental impact of dragging on the sea bottom, spatial analysis can also quantify the footprint of the fishing activity over time.

Scallop beds were defined as a function of the spatial concentration of fishing effort. While direct spatial mapping of scallop density could potentially result in greater accuracy, in absence of this information the local knowledge of fish harvesters can serve as a proxy for bed location (Brown et al. 2012, Smith et al. 2015). To evaluate the density and spatial distribution of effort, daily fishing coordinates from the years 2003 to 2016 were analyzed using a kernel density estimator to produce a continuous surface of fishing activity (see Fig. 10 and Annex 11). This approach creates a smoothed map of the density of logbook records expressed as trips km-$_2$. The function used a neighborhood search radius (i.e. bandwidth) of 1000 m and produced an output raster with 250 m pixel edge length. This analysis was conducted using the Spatial Analyst extension in ArcGIS v10.5. Bed boundaries were identified through contour mapping of the kernel density output with a threshold value of 20 trips km-$_2$ over the period from 2003 to 2016.

Logbook records were assigned to scallop beds within SFAs as determined by the daily fishing location. Landings within an SFA without specific fishing locations are assigned to beds by proration based on landings data from the SFA with fishing locations. We assume that the proportion of landings per bed reported in the logbooks reflects the proportion in landings without fishing locations. These proportions vary annually and also weekly during the season. Therefore, we applied the weekly proportions to obtain the prorated landings for each bed. In the same manner, it is assumed that catch rates reported in logbooks are equal to catch rates for the landings data for which effort is unknown. The geographic data allows for effort and catch rate to be spatially examined and separated by scallop bed.

The total landings and cumulative effort for each year were plotted using the create fishnet and spatial join tools in ArcGIS v10.5. Logbook average catch rates were mapped by interpolating continuous surfaces using an inverse-distance weighted (IDW) scheme. This approach is an exact interpolator that preserves data values at sample point locations, fitting a surface based on the value and distance of neighboring points. For this application, the interpolation was based on a minimum of ten neighboring points, and weights were adjusted by the inverse distance squared. Mean values were used for coincident points. The use of IDW was intended for the purposes of exploratory data visualization, and should not be considered a statistically rigorous approach. The analysis was conducted using the Geostatistical Analyst extension in ArcGIS v10.5.

The area swept by scallop fishing, or footprint, was estimated using the total prorated effort, and, assuming that fish harvesters use a similar fishing speed, a static vessel speed of 2.5 knots (or 4.6 km h^{-1}) (Davidson et al. 2012), and the maximum regulated drag width of the SFA. This calculation does not take into account re-dredging over the same area and may lead to overestimating the actual swept area. If Vessel Monitoring Systems (VMS) become available in the future, the footprint estimates would be greatly improved.

DEPLETION MODEL

A Leslie stock assessment depletion model was applied to the logbook reported data of daily catch rates (kg h^{-1}) against cumulative landings for the most important scallop beds in the sGSL. Logbook and landings data considered for each bed were defined by the research survey strata shown in Fig. 4. In a separate analysis, the depletion model was also applied to data for each bed as defined by the kernel density 20 trips km^{-2} contour (see Annex 11). The Leslie depletion model described in Leslie and Davis (1939) has been used successfully for other scallops stocks to estimate exploitation rates (e.g. Bay of Fundy - Scallop Production Areas (SPAs) 3 and 6; SFA 29 (Smith et al. 1999, Smith et al. 2008b, Sameoto et al. 2012); Québec –SFA 16E, 16F, 19A and 20A (Trottier et al. 2017)). This model assumes that the population is closed (i.e. no recruitment, no migration, minimal growth and minimal natural mortality), which, considering the short duration of the fishing season and the sedentary and low natural mortality characteristics of the species, is a reasonable assumption. It also assumes that the commercial catch rate is proportional to the exploitable biomass and that catchability is constant within the season.

For each year, from 2003 to 2016, the Leslie method was used to estimate the fishery exploitable biomass (B_0) prior to fishing, by referring to the linear regression between daily catch rate (kg h^{-1}) and cumulative landings (t) (Fig. 5). From this analytical method, two subsequent depletion estimates can be obtained, which are the catchability (q) and the annual exploitation rate (Ê) for the bed (Ricker 1975, Ogle 2017). These estimates are for the effective area fished which is smaller than the stratum or bed area, and varies over years.

Using the Leslie method, the biomass of the population before the fishery (B_0) should decrease as a function of catches (C_i) up to time *t*, such that:

$$B_t = B_0 - \sum_{i=0}^{t-1} C_i \qquad (4)$$

Where B_t is the population biomass at time *t*. Assuming catch rate (K_i) observed at time *t* is proportional to the biomass over time, then:

$$K_t = qB_t \qquad (5)$$

Therefore, by replacing B_t by equation 1,

$$K_t = q\left(B_0 - \sum_{i=0}^{t-1} C_i\right) \qquad (6)$$

and

$$K_t = qB_0 - q\sum_{i=0}^{t-1} C_i \qquad (7)$$

Where *q* is the catchability coefficient for the fishery, or the fraction of the biomass that can be caught by one unit of effort, -*q* is the slope of the linear regression, and qB_0 is the intercept on the y-axis. Visually, as illustrated in Fig. 5, B_0 is the intercept of the regression line with the x-axis when catch rate is equal to zero. We therefore obtain B_0 by dividing the intercept by the catchability coefficient:

Exploitation rate (i.e. catch in year *t* divided by biomass in year *t*) at the end of the fishery, $\hat{E}$, is then:

$$\hat{E} = \frac{\sum_{i=0}^{t} C_i}{B_0} \qquad (8)$$

The model was run on commercial data for each year for which reliable catch rate data was available, that is, from 2003 to 2016 (see R script in Annex 12). Daily cumulative catch is the sum of the daily reported landings (per bed) up to that day. Daily commercial catch rates (kg h^{-1}) are obtained from the logbook data as in equation 3. To estimate the total daily landings for each bed for landings for which no positional information was available, we applied the weekly proportion of landings from the bed (Annex 1 and 2) to the total SFA reported landings for that day. A statistically significant model is one for which the slope of the linear relationship between daily catch rate and cumulative catch over the season is significantly different from zero ($p < 0.05$) and negative in sign, indicating a decline in biomass. The mean results from the depletion model are presented to provide a relative index of exploitable biomass and exploitation rate.

ASSESSMENT

LANDINGS

Recreational landings (i.e. by scuba diving) based on logbook reports are estimated to range between 0.02 t and 0.19 t per year over the 2003 to 2016 period summed across all SFAs in the sGSL, mostly (85 %) from SFA 21A (Table 5). In terms of landings, the recreational fishery is considered negligible in comparison to the commercial fishery and is therefore not included in this assessment.

Historical commercial landings are reported in Lanteigne and Davidson (1991) and DFO (2011). Commercial landings and the number of trips (i.e. days) fished in the sGSL scallop fishery to 2016 are presented in Tables 6 and 7, and Fig. 6. Landings have been low and relatively stable since 2002, averaging 102 t annually, following a persisting decrease in landings since 1996. Landings for 2015 and for 2016 were 71 t and 66 t, respectively, well below the long term (1968 to 2010) mean of 264 t. Scallop Fishing Areas were established around 1987 and corresponding annual landings and number of trips by SFA for the period 1987 to 2016 are shown in Fig. 7. On average, landings from SFA 22 (64 %) and SFA 24 (24 %) account for 88 % of the total annual landings from the sGSL over the 2001 to 2016 period, while SFAs 21(11 %) and 23 (1 %) account for the remainder (Fig. 8).

The spatial distribution of effort (Fig. 9), based on geographic positions reported in logbooks for each day of fishing from 2011 to 2016 corresponds fairly well with scallop beds delineated from past surveys (Worms and Chouinard 1983, 1984) and indicates that the scallop concentrations in the sGSL have persisted over time. To further refine the fishing activity footprint, we used the kernel density of aggregated number of fishing trips km^{-2} from the 2001 to 2016 logbooks (Table 8, Fig. 10). Here, one point equals one day of fishing by one vessel. This density map clearly depicts three major scallop beds, Cape Tormentine (SFA 22 south), West Point (SFA 22 north) and Pictou (SFA 24), all within the Northumberland Strait. In fact, approximately 80 % of the Gulf landings are harvested from these three beds alone, based on the 2011 to 2016 data (Table 9). In contrast, the proportion harvested from these same three beds in the earlier period (2001 to 2005) was only around 53 %. Other, smaller beds, such as the SFA 21A bed in Chaleur Bay, are found in patches throughout the sGSL. While not a major scallop bed, the SFA 21A bed was analysed similarly to the major beds because of its distinctive management rules, in place since 2009, which closed the entire SFA 21A twice for a period of three years each (2010 to 2012 and 2016 to 2018). This possibly allows for a unique understanding into how the scallop stock responds to such closures.

LOGBOOK REPORTS AND DATA QUALITY

Over the period from 2001 to 2016, compliance with the requirement to complete and return paper logbooks to DFO within two weeks of the end of the season, has been variable (Tables 10-13, Fig. 11). Compliance seemingly deteriorated for SFA 22, with compliance rates of about 70 % since 2012. This means that about 30 % of trips reported by sales slips do not have a corresponding logbook report. There is no system in place at the present time to independently monitor scallop landings reported in logbooks nor to quantify unreported landings, i.e. landings without sales slips and for which no logbooks were returned. This is especially challenging for SFA 24 where a high percentage (65 %) of the reported catch is from local sales (Fig. 12). Since 2011, the percentage of logbook reports that are usable for spatial catch rate analysis is around 45 % to 60 % (Tables 10-13), which is suboptimal.

Over 33,000 logbook records of fishing activity between the years of 2001 to 2016 were reviewed for this assessment, with a majority occurring within the three main beds (Table 9).

Inappropriate records were screened out using various categories of errors, such as: incorrect SFA, incorrect dates, lack of reported catch, missing fishing coordinates, missing effort, etc. A large amount of uncertainty is associated with inconsistency in quantification of the effort where it was reported either as “hours fished” or as the number and average duration of tows, “hours towed”. There is no clear indication whether effort in ‘’hours fished’’ included time between tows (i.e. steaming or sorting time). For each bed on a yearly basis, several records reported “hours fished” greater than the allowed 12 hours, further highlighting the latter discrepancy. A small proportion of records also had suspected data entry errors from the digitalization of logbooks data, with either very large or very small estimates of effort due to data entry or other human errors (e.g. 11.5 h misrepresented as 115 h). These were corrected when possible with corroborating evidence, or otherwise omitted.

As expected, catch rates calculated from hours towed data were greater than when calculated from hours fished. Because of the greater uncertainty with hours fished, the preferred and more reliable metric was hours towed. Hours towed were therefore used in the following effort and catch rate analyses.

Additional issues may be present due to inaccurate geolocation of fishing activity and due to reporting only a single set of coordinates for each day of fishing. Also, some scallop harvesters commonly reported the same geographic coordinates for multiple days, and it is impossible to assess if this represented repeated fishing or convenience in data reporting. Some logbooks continue to report coordinates in Loran-C even though transmission ended in 2010. Loran-C are less accurate than latitude and longitude coordinates and can lead to conversion issues resulting in the invalidation of logbook records.

Consequently, missing and inaccurate logbook data is the main driver of uncertainty of the landings and the effort data that are used in this assessment.

SFA 21A

Landings

During 2001 to 2016, annual landings from SFA 21A increased between 2001 and 2004 from 9.4 t to 16.3 t but have been declining since and reached a low of 3 t in 2014 (Fig. 13). Low landings in 2015 are not disclosed to in accordance with the *Privacy Act* (fewer than five fishing licence were active). In 2013, the buffer zone area boundary was increased from a 15 m to an 18 m water depth limit cutting the fishable area of the bed by half. This could explain some of the decrease in landings. Over this time series, landings from this sub-area accounted for between 34 % and 96 % of SFA 21 landings, except for years 2010 to 2012 and 2016 when the SFA 21A fishery was closed.

During 2001 to 2016 (excluding closure years), annual prorated landings that came from the SFA 21A bed ranged from 2 t (2009) to 10 t (2002) of scallop meat and represented 31 % to 100 % of all landings in SFA 21A (Table 14, Figs. 13 and 14).

Catch statistics

Mean catch rates varied from a low of 1.9 kg h^{-1} (2009) to a peak of 5.3 kg h^{-1} (2013) (Figs. 15 and 16). Commercial catch rates derived from at-sea sampling data (2001−2005) are within the range obtained from the logbook data and match almost perfectly when taking into account the sampling week (Annex 3). The highest catch rate in the time series was recorded in 2013 after a three year closure of the sub-zone. However, average catch rates immediately fell below this SFA’s management threshold of 3 kg h^{-1} (i.e. 0.5 kg h^{-1} m^{-1}) for the next two years. Catch rates at the start of season were around 7.4 kg h^{-1} in 2013 and 2.8 kg h^{-1} in 2014 and declined to 3.5 kg $h^{-1}$and 1.9 kg h^{-1} respectively by the end of the four week season (Fig. 17). Weekly cumulative catch shows that over 75 % of the catch is reached by the end of the third week (Fig. 18).

Spatial analysis

From the 2003 to 2014 commercial data, the area dredged each year is estimated at roughly 43 km^2 (range: 29 to 121 km^2) (Fig. 19).

Depletion model estimates

The depletion models for the SFA 21A bed in 2003, 2005, 2006, 2013, and 2014 provided usable parameter estimates for catchability (q), initial Biomass (B_0), and exploitation rate ($\hat{E}$) (Figs. 20 and 21). In the other years the fishery was closed or there was no evidence for a relationship between catch rate and commercial landings; in these years usable model parameters could not be estimated. The estimated initial exploitable biomass and exploitation rates for all years are presented in Table 15. The estimate for exploitable biomass before the fishery in 2003 and 2004 was 28.85 t and 18.59 t, respectively, but declined rapidly to 8.17 t by 2006. Following the three year fishery closure from 2010 to 2012, the estimate of exploitable biomass before the fishery in 2013 was only 7.2 t, of which 5 t were reported to have been landed. The catch rates in 2013 declined rapidly from 7.4 kg h^{-1} at the start of the season to 3.5 kg h^{-1} when the fishery ended after four weeks (Figs. 17 and 21). Estimated exploitation rates from years with statistically significant depletion models were above 30 %, and was 65 % in 2013.

SFS 22

SFA 22 landings for the logbook time series (2001 to 2016) vary annually from a maximum of 95 t (2001) to a low of 34 t (2016) following five years of declining landings, effort and catch rates (Fig. 22). According to recent logbook records from 2011 to 2016, the majority of SFA 22 landings (about 85 %) are shared between the Cape Tormentine and West Point beds (Table 14, Fig. 23). This is an increase compared to an earlier period (2001 to 2006) when these beds accounted for only 66 % of the landings. Seasonally, the partition between the two beds varies, sometimes starting with a higher proportion of landings from Cape Tormentine in the first weeks of the season and ending with a higher proportion of landings from West Point or vice versa. The weekly variations can be viewed in Annex 1.

Annual catch rates averaged 6 kg h^{-1}, fluctuating between 4.4 kg h^{-1} (2006) and 8.1 kg h^{-1} (2013) since the beginning of the time series in 2003 (Fig. 22). Results at the SFA 22 level need to be interpreted with caution in consideration of the fluctuations of catch rates over the season between the two major beds. This dynamic would tend to dampen any fluctuation, necessitating bed-level analysis to interpret trends in SFA 22.

The area swept by scallop fishing each year averages 254 km^2 in this SFA (Fig. 24). This was estimated from the prorated effort, and assuming a static towing speed of 2.5 knots and the maximum regulated drag width of 4.9 m.

WEST POINT

Landings

During 2001 to 2016, annual prorated landings from the West Point bed ranged from 3 t (2016) to 49 t (2007) of scallop meat and represented 9 % to 64 % of SFA 22 landings (Table 14, Fig. 25). Low landings in 2016 may reflect small meat weights in relation to scallop shell size as reported by fish harvesters and confirmed by samples (DFO, unpublished data). The effort was most likely displaced towards other beds in SFA 22 that year to avoid the small meats as indicated by both industry members and logbook data. This year also represented the lowest proportion of SFA 22 landings coming from West Point over the period from 2001 to 2016 at 9 % (Table 14). A boom and bust cycle is noticeable for the West Point bed by the oscillation between high and low landings in sequential years since 2001.

Catch statistics

Mean annual catch rates for the 2003 to 2016 period fluctuated between a low of 3.6 kg h^{-1} (2016) to 7.4 kg h^{-1} (2011) (Figs. 26 and 27, Annex 4). Commercial catch rates derived from at-sea sampling data (2001 to 2005) are within the range obtained from the logbook data and match almost perfectly when taking into account the sampling week (Annex 3). A breakdown of catch rates by week for the years 2011 to 2016 depicts a general decline over the fishing season, and this trend is consistent most years (Fig. 28). Overall, the mean weekly catch rates at the start of the season were at about 8 kg h^{-1} (range: 4.5 − 9.5 kg h^{-1}). The season typically ended with catch rates at around 4 kg h^{-1} (range: 3.2 to 5.5 kg h^{-1}). Exceptions are found in 2013 and 2016. In 2013, effort was directed towards the Cape Tormentine bed at the beginning of the season. In 2016, the season started with low catch rates of around 4.5 kg h^{-1} which can be explained by the small meat weights in relation to shell size observed that year. Weekly cumulative catch shows that 73 % to 94 % of the total catch is harvested by the end of the third week except in 2013 (Fig. 29). The season lasts 5 weeks.

Spatial analysis

The spatial variation of landings, effort and catch rates are illustrated in Figs. 30 to 33. For analyses focusing on the bed level, the extent of the bed itself where most of the effort is directed was defined as the kernel density contour of 20 trips per km^2. According to this calculation, the West Point bed has a spatial extent of about 137 km^2. From the 2003 to 2016 commercial data, the mean area swept by scallop drags each year is estimated at 84 km^2 (range: 14 – 130 km^2) (Fig. 34).

Depletion model estimates

The depletion model, fit to the West Point commercial landings and catch rate data for 2003 to 2016, was significant for all years ($p < 0.05$) (Table 15, Figs. 35 to 37 The exploitable biomass estimates from the depletion models varied between 7 t in the most recent analysis year (2016) and 83 t (2009), while the annual exploitation rates varied from 22 % to 65 % averaging 52 % (Fig. 38). The decrease in exploitable biomass estimates observed over the last five years may be an indication that fishing is occurring at unsustainable levels.

CAPE TORMENTINE

Landings

During 2001 and 2016, annual prorated landings from the Cape Tormentine bed fluctuated between 5 t and 36 t of scallop meat, with an exceptional peak of 68 t in 2013 (Fig. 39). This bed accounted for 12 % to 80 % of SFA 22 landings (Table 14). There was a partial closure of the western portion of the Cape Tormentine bed from 2005 to 2010. However, the western portion (west of the Confederation Bridge) accounts for only about 7 % of the bed landings, according to logbooks. A boom and bust cycle is noticeable for the Cape Tormentine bed landings since 2001.

Catch statistics

Mean annual catch rates derived from hours towed data for the 2003 to 2016 period varied from 3.4 kg h^{-1} (2005) to 9.5 kg h^{-1} (2013) (Figs. 40 and 41 and Annex 4) on the Cape Tormentine bed. Landings, effort and catch rates all peaked in 2013. It should be highlighted that this occurrence was to a certain extent masked at the SFA level (Fig. 22). Commercial catch rates derived from at-sea sampling data (2001 to 2005) are within the range obtained from the logbook data, even though it represented only one day of fishing per year, on one commercial vessel (Fig. 40 and Annex 3). A breakdown of catch rates by week depicts a general decline over the fishing season, and this trend is consistent yearly (Fig. 42). The catch rates at the start of the season are higher than those for the West Point bed (8 kg h^{-1}) at about 10 kg h^{-1} (range: 7.3 to 12.2 kg h^{-1}) and end the season at around 5 kg h^{-1} (range: 3.5 – 6.2 kg h^{-1}). Effort also tends to decline over the season, though with some variability from week to week possibly related to fish harvesters switching between different beds in SFA 22 (Fig. 42). Weekly cumulative catch shows that 76 % to 94 % of the total catch is taken by the end of the third week (Fig. 43). The season lasts 5 weeks.

Spatial analysis

The spatial plots of landings, effort and catch rates from 2011 to 2016 are presented in Figures 44 to 47. The spatial variation of landings, effort and catch rates indicate the 2013 fishing season as exceptional. The high catch rates are distributed in patches over the central part of the bed.

The extent of the bed itself where most of the effort is directed (i.e. kernel density contour of 20 trips km^{-2} over the period from 2001 to 2016) was estimated at about 92 km^2 (Table 8). Between 2003 and 2016, the average swept area by the scallop fishery on Cape Tormentine each year was estimated at 89 km^2 (range: 52 to 150 km^2) (Fig. 48).

Depletion model estimates

The depletion models for the Cape Tormentine bed in 2003 to 2016 provided usable parameter estimates for catchability (q), initial Biomass (B_o), and exploitation rate ($\hat{E}$) ($p < 0.001$; Table 15, Figs. 49 to 51). The annual exploitation rates estimated from the depletion model varied from 42 % to 62 % with a mean of 55 % (Fig 52). The exploitable biomass fluctuated from a low of 17 t (2005) to 122 t (2013) and averaged 48 t (Fig. 52). Except for 2016, biomass has been above average since 2011.

SFA 24

In contrast to other SFAs, a majority of the landings (65 %) from SFA 24 are categorized as local sales, potentially increasing uncertainty around unreported catches as local sales do not have corresponding sales slips to be used for data verification (Fig. 12). Annual landings varied from 16.7 t (2008) to 32.6 t (2013) (Fig. 53). Landings and effort decreased gradually from 2006 to 2008 and then increased with effort until 2013, without a discernable trend in catch rates. Annual catch rates over the 2003 to 2016 time series average 3.6 kg h^{-1} within a relatively narrow range between 2.6 kg h^{-1} (2005) to 4.6 kg h^{-1} (2016) (Fig. 53). This is notably lower than the average annual catch rate in SFA 22 of 6 kg h^{-1} over the same period (Fig. 22).

According to logbook data, more than 90 km^2 and as much as 180 km^2 are dredged for scallops each year in this SFA (Fig. 54).

PICTOU

Landings

A large percentage (68 % to 86 %) of the landings from SFA 24 were taken from the Pictou bed (Table 14). Weekly trends in proportion of landings attributed to the Pictou bed are found in Annex 2. The annual reported and prorated landings for the Pictou bed ranged between 12.9 t to 23.7 t of scallop meat for the 2001 to 2016 time series (Fig. 55).

Catch statistics

During 2003 to 2016, catch rates fluctuated between 2.7 kg h^{-1} (2005) to 4.4 kg h^{-1} (2016) with a mean of 3.4 kg h^{-1} and were generally higher post-2009 (Figs. 56 and 57, Annex 4). The catch rates on the Pictou bed were lower than for the two major beds in SFA 22 in all years except for 2016 where West Point was lower, corresponding to the small meat weight issue discussed above where fishing effort was redirected to the Cape Tormentine bed. Commercial catch rate derived from the single at-sea sampling trip in 2004 was within the range obtained from the logbook data and matches almost perfectly when taking into account the sampling week (Annex 3). In contrast to the seasonal pattern of catch rates from scallop beds in SFA 22, catch rates from the Pictou bed remain stable at a relatively low level of about 4.5 kg h^{-1} (range of mean: 2.7 to 4.8 kg h^{-1}) over the six or seven week season (Fig. 58). More than 75 % of the landings are caught by the end of week five (Fig. 59).

Spatial analysis

The spatial variation of landings, effort and catch rates for the Pictou bed are illustrated in Figs. 60 to 63 for each year from 2011 to 2016.

The Pictou bed has a spatial extent of about 78 km^2 as estimated from kernel density analysis (Table 8). From the 2003 to 2016 commercial data, the area swept by scallop fishing each year was estimated at 108 km^2 (range: 73 – 140 km^2) (Fig. 64).

Depletion model estimate

The depletion model relating catch rates and cumulative landings from the Pictou bed of SFA 24 was significant for 2003, 2011 and 2012 (Table 15). The catch rates are very low for this area relative to other areas analyzed for this assessment and there are little to no declines in catch rates over the season (Figs. 65 to 67). The model estimate for exploitable biomass before the fishery in 2011 was 82 t for a corresponding exploitation rate of 28 %. The fact that catch rates are very low suggests that the population is at low abundance level, and this area may not be suitable for the application of Leslie depletion methods.

RESEARCH SURVEYS 2012−2016

Between 1986 and 2011, only one research survey was conducted in the Gulf Region, occurring in 1997 and covering only SFA 22 (Hanson 1998). Fifteen years later, in 2012, an annual, rotational, multispecies research survey program for scallop in the sGSL was initiated to gain fishery-independent indices of abundance, biomass, and biological characteristics (i.e. shell height, meat weight, age). One section of a SFA or the SFA in its entirety was surveyed per year with the exception of SFA 23 which was excluded because of the low scallop fishing effort reported from this area in recent years (Table 4, Fig. 7). Survey areas, dates, stratum descriptions, and number of sampling tows are found in Table 16. The surveys conducted in SFA 21A and SFA 24 occurred before the fishery began in the corresponding years whereas the surveys in SFA 22, SFA 21B and 21C occurred after the annual fishery had finished. A stratified random design was applied to each survey (Smith and Gavaris 1993). The survey area excluded water depth less than 5.5 m which corresponds to the navigational limit of the research vessel. Each survey area was partitioned into non-overlapping subareas called strata which related to the sea scallop commercial fishing effort distributional pattern (Fig. 68). Buffer strata signify areas where scallop dragging is prohibited with the purpose of protecting juvenile lobsters and their habitat. The number of survey tows was allocated proportionally to the size of the stratum and subsequently weighted by fishing effort to assign more stations where fishing effort was highest. Tow locations were randomly generated using the create random points tool in ArcGIS v10.1.

The 2012 survey was conducted aboard the Canadian Coast Guard Ship (CCGS) Opilio while subsequent surveys (2013 to 2016) were aboard the CCGS MPerley. An eight-gang toothed Digby scallop drag was used as the survey gear (Fig. 69). All buckets were lined with a Vexar® liner (mesh size of 14 mm) to retain small scallops and small benthic species. In 2014, the drag was replaced with a similar drag except that it was equipped with runners (32.6 cm X 30.5 cm) and a shorter tow bar (3.4 m vs 4.6 m) to better fit the sorting table (Annex 5). At each sampling station, a 2 minute tow at a speed of 2.5 knots was conducted. The catch of each tow was sorted, counted and weighed by species. Scallops were measured for shell height to the nearest 0.01 mm increment (i.e. maximum distance from umbo to the outer shell margin). Clappers were counted and measured. Clappers are dead scallops with the two shells still attached at the hinge that are used as an index of natural mortality. The index is based on the dissolution of the resilium, the attachment between the two shells, and can be affected by many factors, such as the physical interactions with fishing gear. Therefore, caution should be exercised in the interpretation of this metric particularly when data are collected after the annual fishery ends as was the case for SFAs 21B and 21C as well as 22.

Biological sampling of scallops was performed in the laboratory post-survey to obtain live weights and meat weights using a digital balance with an accuracy of 0.1 g. Sex and age were also recorded. Shell height frequency distributions were determined from the scallop sampling data. The shell height-meat weight relationships were obtained by performing a linear regression between the logarithmic transformation of meat weight and that of the shell height. A detailed analysis of the shell height to meat weight relationship was conducted using the DFO Maritimes Region model and results were compared to those from the Maritimes Region scallop beds (see Annex 6).

An index of natural mortality of scallops was estimated using the ratio of live scallops to clappers in the following equation from Merrill and Posgay (1964):

$$\text{Clapper Ratio} = (C/L)\,(52/t) \quad (9)$$

Where;

C= number clappers in sample

L= number of live scallops in sample

t= time in weeks that clappers remain attached [33 weeks based on Merrill and Posgay (1964)]

The catch data were standardized to a tow distance of 153.7 m (target tow duration of 2 minutes at 2.5 knots), and to a tow area of 437.3 m^2 (0.0004 km^2) based on the inside width of the survey gear of 2.8 m. The mean abundance (i.e. number of individuals) and round weight (kg) of scallops per standard tow was calculated for each survey stratum. Based on commercial fishery at-sea sampling data (2001-2005, Davidson et al. 2012) and on a commercial ring size of 82.6 mm, we estimated a minimum shell height of 80 mm entering the commercial fishing gear (commercial size). The meat weight (kg) per standard tow of commercial size (i.e. ≥ 80 mm shell height) scallops was then calculated for each bed (stratum corresponding to high fishing effort) to obtain estimates of exploitable biomass and exploitation rate. Similarly as with the commercial fishery catch rates, spatial analysis using an inverse-distance weighted (IDW) scheme was applied to the research survey catch rate (kg h^{-1} m^{-1}) data from the relevant years for the Cape Tormentine, West Point, and Pictou beds.

Included in the current analysis are the fishery-dependent size distributions of scallop in the commercial fishery catch as described from the at-sea sampling programs conducted from 2001 to 2005 with DFO personnel onboard (Davidson et al. 2012). Data were re-analysed at the bed level as opposed to the SFA level as was the case in the last assessment.

SURVEY RESULTS

Between 2012 and 2016 five surveys were conducted, each targeting a different SFA or section of the Gulf Region (Table 16). Overall, 481 survey tows were sampled of which 177 had sea scallops in the catch. This signifies that 63 % of survey tows contained zero scallops. In fact, no scallops were caught in seven strata that together represent an area greater than 12,000 km^2 (54 % of total survey area). For these reasons, scallop density will only be presented by stratum in order to reduce any dilution effects on abundance estimates, with particular attention to the analysis of high effort strata coincident with major scallop beds (West Point, Cape Tormentine and Pictou).

With the exception of SFA 24, the spatial distribution of scallops from the survey (Figs. 70 and 71) is in agreement with the commercial fishery data from logbooks (Fig. 9). For SFA 24, the large size of the high fishing effort stratum and the random allocation of stations was not optimal and failed to characterize the Pictou bed as defined by commercial fishing effort (Figs. 10 and 68), which is the main fishing bed of this SFA. In general, the distribution of small scallops (< 80 mm) and commercial-sized scallops (≥ 80 mm) overlapped. In SFA 22, scallops were absent in the buffer zones (Annex 7). In contrast, high densities were found in the buffer zones of SFA 21A and SFA 24. In the case of SFA 21A, this can partially be explained by recent changes in buffer limits from 15 to 18.6 m of water depth, now encompassing a portion of the moderate effort area (bed).

Biological characteristics of scallops sampled during the research survey are summarized in Table 17. A total of 2,797 scallops were measured over the five year survey period. The shell height of scallops ranged from 13 to 146 mm (Table 17). The shell height size frequency distributions from the survey catches are shown in Fig. 72. Scallop recruitment to the fishery was evident in all sampled areas. In SFA 21A, pre-recruits sizes (< 80 mm) were abundant, while fewer scallops fell in the size range between 80 and 110 mm. There were very few scallops with shell height greater than 110 mm in SFA 22 south (Cape Tormentine bed), and the maximum shell height recorded at this site was 125 mm. There were relatively fewer small scallops in SFA 24, where 50 % of all scallops were greater than 86 mm in height. The shell heights of scallops sampled from the major scallop beds (i.e. high effort strata) during the surveys are described in Table 18 and Figs. 73 to 76 and are compared to the commercial fishery shell height distributions from the at-sea sampling program (Davidson et al. 2012). Of particular interest is the Cape Tormentine bed where there were few scallops larger than 120 mm. On the other hand, two healthy pulses of recruitment in the 35 to 40 mm and the 75 to 80 mm size ranges were observed, possibly explaining higher landings reported the following year in 2013, when 76 % of SFA 22 landings were from this bed.

The size distribution of scallops retained in the commercial gear (minimum ring diameter of 82.6 mm), in contrast to the survey gear (14 mm mesh), was strongly peaked in the vicinity of 90 mm, and declined rapidly on either side of this mode (Figs. 73 to 76). The truncated distribution above 90 mm reflects the relative lower abundance of these large animals in the Cape Tormentine and Pictou beds. This pattern is consistent among years and reflects the size selectivity of the commercial drag for the larger sizes.

The shell height to meat weight relationships of scallops from the Gulf Region were compared to those of the Maritimes Region (i.e. Bay of Fundy and Georges Bank ‘a’) and are documented in Annex 6. Predicted meat weight of a scallop with 100 mm shell height (also called condition) was lowest in SFA 24 and highest in SFA 22 north. The smaller meats observed in SFA 24 were in accord with Worms (1984) and Davidson et al. (2012). The results suggest that the average meat weight of a 100 mm scallop from the Gulf Region is around 15 g and is within the ranges observed on relatively productive area of Georges Bank 'a' (i.e. 16 g) and generally greater than those observed for Scallop Production Area (SPA) 4 (i.e. 11 g) in the Bay of Fundy. However, this comparison does not consider inter-annual variations of the Gulf data, which may be relevant since each survey area was sampled in a different year.

The age of the scallops retained by the survey drag ranged from 2 to 16 years old (Table 17). The maximum age observed in SFA 22 and SFA 21B and C was 13 years old. An index of natural mortality, based on the ratio of clappers to live scallop with shell heights ≥ 80 mm, ranged from around 0.09 in SFA 21B and C to 0.25 in SFA 22 south, similar to rates reported in Lanteigne et al. (1987).

Over 100 other species were retained by the survey drag (Annex 9 and 10). The most abundant species were the Echinoderms (e.g. sand dollars, sea stars, and brittle stars). Crustaceans such as rock crab, lady crab, snow crab and lobster were also frequently captured by the drag. The most abundant commercially exploited species harvested with the drag was rock crab followed closely by the target species, sea scallops.

SURVEY ESTIMATES

Estimates of exploitable biomass (≥ 80 mm shell height) derived from the research surveys for the major scallop fishing beds (SFA 21A, West Point, Cape Tormentine and Pictou) are presented in Table 19. Landings from each bed corresponding to the year of the survey are from the commercial logbook data and are used to estimate exploitation rates. Note exploitation from survey estimates are unadjusted for gear efficiency.

SFA 21A

SFA 21A in Chaleur Bay was surveyed June 28 to July 5, 2013, before the fishing season. The mean density of commercial sized scallops (≥ 80 mm shell height) in the scallop bed was 0.033 g m^{-2} (i.e. 0.14 kg per standard tow). The exploitable biomass, in meat weight, before the fishery, was estimated to be 8 t (for the high fishing effort stratum). With commercial landings of 5 t in 2013 for this area, the exploitation rate based on the index of exploitable biomass would be 59 %.

SFA 22 north - West Point

SFA 22 West Point bed was surveyed between May 31 and June 11, 2014, after the fishing season. The estimated exploitable biomass, in meat weight, was equivalent to 68 t. The pre-fishery commercial-sized biomass index, considering the landings that had occurred prior to the survey, was estimated at 100 t resulting in an estimated exploitation rate of 32 %.

SFA 22 south - Cape Tormentine

SFA 22 Cape Tormentine bed was surveyed between June 27 and July 5, 2012, after the fishing season. The estimated exploitable biomass, in meat weight, from the survey was equivalent to 127 t. The pre-fishery commercial size biomass index was then estimated to be 158 t by adding the landings that occurred prior to the survey, resulting in an estimated exploitation rate of 20 %.

SFA 24 Pictou

SFA 24 Pictou bed was surveyed between August 14 and 29, 2015, before the fishing season. The estimated exploitable biomass, in meat weight, from the survey is equivalent to 91 t. The estimated exploitation rate for a harvest of 14 t is 15 %.

SURVEY VERSUS DEPLETION MODEL ESTIMATES

Average catch rates are spatially represented for both the survey data and the commercial fishery logbook data for the three major scallop beds, West Point, Cape Tormentine and Pictou (Figs. 77 to 79). Due to differences in the areas covered between the survey estimates (strata) and the depletion model (fished area), as well as differences between the gear types used on the survey and in the fishery, these estimates are not directly comparable. Estimated exploitable biomass indices from the depletion models are generally lower than the survey commercial size (≥ 80 mm shell height) biomass indices for the corresponding years where both are available. In part, this could be explained by differences in the components of the scallop population which are included in the biomass estimates. The survey fishing gear had a liner and the size distribution of the scallop in the catch indicated a higher retention rate (i.e. higher relative selectivity) for scallops between 80 and 90 mm shell height than is indicated for the commercial gear (e.g. see Figs. 73- to 76 for examples). In addition, the depletion model estimates of biomass are driven by the catch rates and depletion on the bed area of high abundance which is smaller in extent than the survey stratum used to define the survey commercial biomass indices. This difference in biomass estimates results in higher exploitation rates inferred from the depletion model than from the survey estimates. However, although not directly comparable, exploitation estimates from the fishery data depletion analysis and the survey exploitation analysis indicate that exploitation levels are relatively high on the sGSL stocks.

DISCUSSION

The sea scallop fishery in the Southern Gulf of St. Lawrence is managed by the Gulf Region through input controls including seasons, area closures, limited entry of licences, gear restrictions and meat counts limitation. Both landings and number of active licences are low since 2002 relative to previous years (DFO 2011). Only 19 % of the 768 licences have participated in the scallop fishery in 2015 and 2016, suggesting a large amount of latent effort. This suggests that there could be reactivation of latent licences at the first signs of recovery of the scallop stock and this warrants consideration in future management strategies. Since 2002, Gulf-wide landings fluctuated between 55 t and 160 t per year. On average, SFA 22 (63 %) and SFA 24 (25 %) together account for 88% of the Gulf landings. Using spatial analysis, we found that fishing effort occurs primarily on three beds: West Point (SFA 22 north), Cape Tormentine (SFA 22 south) and Pictou (SFA 24), all located within the Northumberland Strait. Approximately 80 % of the Gulf landings were harvested from these three beds alone. Smaller beds, in terms of effort and landings such as in Chaleur Bay (SFA 21A), were found in patches throughout the sGSL.

While there has been no change to the Gulf fishery management measures since the last assessment (DFO 2011), certain notable changes have occurred in the last 20 years. First, an increase in ring size from 76 mm to 82.6 mm was established in the early 2000s with the objective of reducing the number of small scallops being caught by the drag as a conservation measure. At around the same time, a decrease in the meat count limit was adopted in SFA 22 from 52 to 44 per 500 g with the objective of shifting fishing pressure to larger scallops. Second, fishing effort has been reduced recently (2016) with shorter days in SFA 22. Third, since 2009, SFA 21A has adopted a catch rate decision rule, closing the fishery when catch rate is low (< 3 kg h^{-1}), and since 2013, has expanded its closed area (i.e. buffer zone).

Mean catch rates based on information which more accurately reflects actual fishing effort (i.e. ''hours towed'' vs. ''hours fished'') are only available since 2003, corresponding to a time period when the resource was already considered to be at low abundance in the sGSL (DFO 2011). Catch rates from the sGSL fishery were generally lower than 10 kg h^{-1} even at the start of the fishing season and decrease rapidly over a period of a few weeks. Catch rates from the commercial logbook data are well within the range of those obtained from the at-sea sampling program from 2001 to 2005. This strengthens our confidence in the accuracy of commercial catch rates derived from logbooks, especially when considering within-season and between-vessel variations and that each at-sea sampling was conducted on a single fishing day, from a single vessel. In the 2003 to 2016 time series covered by this assessment, catch rates have mostly been highest in SFA 22, with a mean value of 6.0 kg h^{-1} varying from 4.4 to 8.1 kg h^{-1}, while they generally remained below 3.5 kg h^{-1} in SFAs 21A and 24. Overall, annual catch rates are relatively low in the Gulf in comparison to those reported in other Atlantic Canadian scallop fisheries in areas such as the Bay of Fundy (10 to 25 kg h^{-1}) (DFO 2006, Sameoto et al. 2012, Nasmith et al. 2016). Reference points based on catch rates have been established for SPA 6 in the Bay of Fundy using a Lower Reference Point (LRP) of 6.2 kg h^{-1} and an Upper Stock Reference (USR) of 9.1 kg h^{-1} (Nasmith et al. 2016). These higher catch rates cannot simply be explained by small differences in drag width; the Bay of Fundy fishery has a total drag width limit of 5.5 m while SFAs 22 and 24 have one of 4.9 m and 5 m, respectively. Conversely, SFA 22 catch rates are within the range of those observed in the Magdalen Islands scallop fishery (i.e., SFA 20, Quebec Region), also in the sGSL. In SFA 20, where 7.32 m drags are used, the catch rates have stabilized in the upper range (1.46 to 1.86 kg h^{-1} m^{-1}; based on the average drag width in the sGSL this corresponds to 7.3 to 9.3 kg h^{-1}) since the implementation of certain management measures such as days-at-sea limits (see DFO 2013 and Trottier et al. 2017).

For the first time, we fit a stock assessment depletion model to the logbook-reported data representing landings and catch rates for the most important scallop beds in the sGSL. This allows a new understanding of the impact of the fishery on the scallop population. Estimates of exploitable biomass and exploitation rates were derived from statistically significant models for each year analyzed (i.e. 2003 to 2016) for the Cape Tormentine and West Point beds in SFA 22. For the Pictou bed in SFA 24, the model was only significant for the 2011 data, possibly indicating that the amount of scallops removed during the fishing season was insufficient to detect a decline in abundance. Further, abundances in this area are relatively low. In general, the levels of exploitation from the model are high. They averaged 53 % (range: 22 %–65 %) for the two major scallop beds in SFA 22 over the period from 2003 to 2016. Despite the uncertainty surrounding fishery-dependent data, these estimates are at levels well above what could be considered sustainable fishing. As far back as 1984, Worms reported exploitation rates averaging 50 % and expressed concern for the sustainability of the Gulf scallop resource at that level of fishing intensity. In contrast, sea scallop fisheries considered sustainable (i.e. that remain in the healthy stock status zone of the Precautionary Approach and MSC-certified) and are found on some of the most productive beds for this species, target exploitation rates are set at 15 % and 25 % for the inshore Bay of Fundy and the offshore Georges Bank fisheries, respectively (Smith et al. 2012a, Smith and Hubley 2012). For the Bay of Fundy scallop population, exploitation rates at 20 % and higher have always led to declines in biomass (Smith and Hubley 2012), and 15 % has been adopted as the removal reference point (i.e. the maximum exploitation rate) for this area in relation to the Precautionary Approach (DFO 2015).

The most important source of uncertainty in the depletion model exploitable biomass estimates stems from the uncertainty in the commercial data. Improving commercial logbook reporting would greatly increase the accuracy of these estimates, allowing for greater confidence in stock assessment and improved sustainable management of the resource. The percentage of logbook reports that are usable for spatial catch rate analysis varies annually from 45 % to 60 %. Certainly, an independent verification system to corroborate the quality and accuracy of logbooks would improve confidence in the data. Many systems are readily available such as electronic logbooks, vessel monitoring systems (VMS), dockside monitoring, harvester pre-departure and pre-arrival notifications (i.e. hail-in and hail out) and data entry verification systems, among others. In the Maritimes Region, efforts to improve logbook data quality in SFA 29 West led to a complete review and verification of logbooks, with the resulting rate of high-quality logbook records available for analysis approaching 99 % (Sameoto et al. 2012).

In 2003, new data requirements were introduced to the logbooks used in the sGSL fishery to include the number and average duration of tows in order to improve fishing effort data. Effort measured in hours towed (as opposed to total hours fished as previously recorded) gives a more realistic catch rate than with hours fished (hours from start of first tow to end of last tow of the day) while showing similar trends. However, a space for hours fished was kept in the logbook document alongside the new metric. Following this change, some fishers used one or both of the metrics inconsistently. To reduce any confusion, moving forward the field for hours fished should simply be removed from the logbook, and clear instructions should be provided for accurately completing critical components representing fishing effort in particular. In addition, the directions for entering spatial coordinates should be improved to ensure that coordinates are entered consistently in a single format, reducing the burden of data entry and quality control while improving the data available for spatial analysis. The importance of accurate and high-quality logbook data for the production of scientific advice towards appropriate and effective management of the scallop fishery needs to be emphasized now. Better (complete and accurate) fishery data leads to better understanding of the stock status and better (appropriate and effective) management measures and ultimately improves both the ecological and economical sustainability of the scallop fishery. Conversely, incomplete or unreturned logbooks and misreporting impact on the confidence in the fishery data and in the advice given to fishery managers.

This assessment represents a first step towards spatial analysis of sGSL scallop fishery data. Further refinements of spatial analyses will improve our understanding of how the scallop stock responds to the fishery and its management measures in the Gulf Region. We have analysed the fishery and survey data at different spatial scales (scallop bed area as defined by survey strata corresponding to high fishing effort and, in Annex 11, scallop bed area as defined by effort kernel density) and all have pointed to the same outcomes of high exploitation rates, higher than the removal rate rule in the Bay of Fundy fishery (DFO 2015). Spatial scale is critical in managing scallops as described by Caddy (1989) and demonstrated by Smith et al. (2015, 2017) who found that the highest catches occurred in the areas of highest habitat suitability, highest densities and catch rates. Moving towards greater understanding of the spatial dynamics of the fishery should be a focus of future efforts, leading to improved sustainable management of the fishery as demonstrated in Maritimes Region (Smith et al. 2008a).

The three year closure from 2010 to 2012 in SFA 21A gives some insight of the impact of the fishery on the scallop population. In 2013, when the fishery reopened, catch rates hit their peak values for the time series (2003 to 2015), and quickly fell below the threshold the following year, pointing to the short term benefit of the closure. The strong decline in catch rates over the 2013 season indicates heavy exploitation. In fact, depletion models estimated an exploitation rate of 65 % giving a reasonable explanation for the low catch rates at the start of the 2014 season.

Clearly, any potential increase of fishable biomass resulting from the three year closure was quickly removed upon resumption of the fishery in 2013. Experiences elsewhere suggest longer closure periods of six years for sea scallops could optimize the benefits for future closures (Hart 2003), though it is unclear if these dynamics would hold true for depleted beds such as those that occur in the sGSL.

The research surveys completed between 2012 and 2016 provided a snapshot of biological information but covered a different area each year, so that each area was surveyed only once. For the survey years, condition (i.e. predicted meat weight of a 100 mm scallop) was comparable to some of the most productive areas for sea scallop in the Maritimes Regions (Annex 6). Signs of recruitment (i.e. the abundance of scallops < 80 mm shell height) were evident from shell height distributions in each area surveyed. However, the usefulness of these single ''snapshot'' surveys to provide estimates of abundance is questionable in view of the limited temporal and spatial coverage. In particular, the coverage of the main beds was too sparse, particularly in SFA 24, while the coverage of large areas of non scallop habitat weakened any signal from the beds.

Because of the uncertainties surrounding the scallop fishery-dependent data noted earlier (i.e. commercial logbooks), it is paramount to build fishery-independent stock monitoring data and indices. The purpose of this would be to build a time series of empirical data to complement and inform the depletion model estimates derived from fishery-dependent data. Consideration could be given to undertaking periodic, preferably annual, surveys of those scallop beds which contribute to the majority of the fisheries effort and landings. Efficiency in survey design could be achieved by focusing the monitoring efforts on these scallop beds thus potentially providing an opportunity to monitor the main beds in a single season. Data from these surveys could be used to monitor the productive state of the resource, including the condition, indices of recruitment, indices of natural mortality, and indices of exploitable biomass to estimate relative exploitation rates by the fishery. Improving confidence around data from both fishery-dependent and fishery-independent sources will enable a better understanding of how scallop stocks respond to the fishery and provide the best scientific advice possible to fishery managers and decision makers, in line with the sustainable fisheries framework (DFO 2006).

For future surveys to be more informative, there should be increased consideration as to the spatial scale and sampling intensity in its design. The results from the spatial analysis of the commercial fishery data and the survey data should be helpful in defining and informing future survey design to target the major scallop beds where the fishery is concentrated and impacting the population. Also, the timing of any future surveys will be important to monitor annual trends in condition (i.e. predicted meat weight of a 100 mm scallop). Condition can vary spatially and temporally, related to factors such as environmental conditions to which the scallop are exposed. Annual variations in condition may mask, or otherwise falsely contribute, to perceptions in variations of numerical abundance, and violate the important assumption in assessments that catch rates are proportional to abundance. The absence of standardized and systematic monitoring of condition (i.e. meat weights) therefore adds uncertainty regarding the use of catch rates, even those derived from fishery-independent data, as indices of stock status.

The assumption that the clapper ratio can be an index of natural mortality may be inappropriate in cases when the clapper ratio data are collected after the fishery. Clapper integrity, beyond natural deterioration of the hinge membrane, can be compromised by interactions with the fishing gear and by stated fishing practices associated with breaking the clappers when retrieved before discarding to reduce handling and sorting effort of the catches (Caddy 1989). Information of greater relevance would be obtained if these data were collected prior to the fishery, particularly if the period from the end of the fishery to the survey exceeds the expected duration of clappers, 33 weeks for the sGSL. Clapper ratios should also be presented by size group as the resilience of the membrane may differ according to scallop shell size (MacDonald and Thompson 1986). Natural mortality could be underestimated using clapper index in cases where predation does not result in clapper formation (i.e. lobster). These issues would need to be addressed and resolved before integrating the clapper ratio as an index of natural mortality into the scallop stock assessment.

There are concerns regarding the effects of climate change, especially increases in sea temperatures, on scallop growth, reproduction, and survival in the sGSL. The major scallop beds in the sGSL are located within the Northumberland Strait, a shallow and well mixed area where near-bottom water temperatures can exceed optimal temperatures (10-15°C) and even exceed temperatures (>18°C) (Chassé et al. 2014) that are physiologically stressful for sea scallop (Dickie 1958). Bearing in mind that temperatures above 21°C can be lethal to sea scallops, some of the warmest mean daily bottom temperatures have been observed in September (i.e. mean daily 18.9°C in 2017) on the Cape Tormentine bed at 19 m depth (Ouellet et al. 2019). The consequences of increasing water temperatures and climate change in general on the Gulf scallop stock (i.e. productivity), independent of fishery effects on the population, are unknown but likely detrimental, and should be considered in the next assessment (Rheuban et al. 2018).

PRECAUTIONARY APPROACH

The Precautionary Approach definition is to use caution in future management processes when scientific information is uncertain, unreliable or inadequate (DFO 2006). The lack of scientific information should not be used to postpone or fail to take measures intended to prevent serious harm to the resource (FAO 1995).

The Precautionary Approach involves developing a harvest strategy that identifies three stock status zones: 1) healthy, 2) cautious where fishing should be reduced and 3) critical, where serious harm is occurring. The strategy sets the removal rate at which fish may be harvested within each stock status zone.

The Department of Fisheries and Oceans has set guidelines and definitions for harvest strategies to be compliant with the Precautionary Approach. They include a Removal Reference for three stock status zones delineated by a Limit Reference Point and an Upper Stock Reference (DFO 2006).

Definitions (from DFO 2006):

The Upper Stock Reference (USR) point is the stock level threshold below which the removal rate is reduced. The zone above the USR is called the Healthy zone.

The Limit Reference Point (LRP) is the stock level below which productivity is sufficiently impaired to cause serious harm but above the level where the risk of extinction becomes a concern. The stock status zone above the LRP but below the USR is called the Cautious zone. The zone below the LRP is called the Critical zone.

The Removal reference is the maximum acceptable removal rate. It must be less than or equal to the removal rate associated with maximum sustainable yield.

The framework recommends using B_{MSY} (or proxy) which is the biomass that results in the maximum sustainable yield. The reference points should then be set at 80 % and 40 % levels of the B_{MSY} (or proxy) for the USR and LRP, respectively. In the absence of a modeled B_{MSY}, potential candidates for a proxy of B_{MSY} could include catch rates, 50 % of maximum historical biomass or average biomass over a productive period (Smith et al. 2012b). Examples of using catch rates for determining reference points can be found in other sea scallop fisheries

(Magdalen Islands in the Quebec Region, DFO 2010; and Area 6 in the Maritimes Region, Nasmith et al. 2016). Generally, LPR is set at the lowest catch rates recorded and USR is set the average catch rate over what is considered a productive period.

Reference points that conform to the Precautionary Approach could not be defined at this time. There are no long term indicators of abundance, productivity, or sustainable exploitation with which to define appropriate reference points. Catch rates based on the relatively short time series from fishery logbooks are inherently very uncertain, particularly in terms of being proportional to abundance. In any case, the catch rate data available are from the recent decade and represent a time period for which the resource is already considered to be at low abundance.

Nonetheless, this document presents the best currently available data for this stock to start discussions with fisheries management and the fishing industry on developing potential reference points that are in line with the precautionary principle. Quality issues with both fishery-dependent and fishery-independent data have been highlighted above and key improvements proposed. Substantial improvements in these complementary sources of data are needed in order to provide a more thorough evaluation of stock status in the future.

REFERENCES CITED

Barber, B.J. and Blake, N.J. 2016. Reproductive Physiology. Pp 253-299. {In}: S. Shumway and G.J. Parsons (eds). Scallops: Biology Ecology and Aquaculture (3rd edition) Elsevier, Amsterdam, Netherlands. 1196 p.

Bonardelli J.C. and Himmelman, J.H. 1995. Examination of assumptions critical to body component indices: application to the giant scallop *Placopecten magellanicus*. Can. J. Fish. Aquat. Sci. 52: 2457-2469.

Bonardelli, J.C., Himmelman, J. H. and Drinkwater, K. 1996. Relation of spawning of the giant scallop, *Placopecten magellanicus* to temperature fluctuations during downwelling events. Mar. Biol. 124:637-649.

Bourgeois M., Brêthes, J.-C. and Nadeau, M. 2006. Substrate effects on survival, growth and dispersal of juvenile sea scallop, *Placopecten magellanicus* (Gmelin 1791). J. Shellfish Res. 25:43-49.

Bradshaw, C., Collins, P. and Brand, A. R. 2005. To what extent does upright sessile epifauna affect benthic biodiversity and community composition? Mar. Biol. 143: 783–791.

Brown, C.J., Sameoto, J.A., and Smith, S.J. 2012. Multiple methods, maps, and management applications: Purpose made seafloor maps in support of ocean management. J. Sea Res. 72:1-13.

Caddy, J.F. 1972. Progressive loss of byssal attachment with size in the sea scallop (*Placopecten magellanicus*)(Gmelin). J. Exp. Mar. Biol. Ecol. 9:179-190.

Caddy, J.F. 1989 A perspective on the population dynamics and assessment of scallop fisheries, with special reference to sea scallop, *Placopecten magellanicus* (Gmelin). {In}: Caddy JF (ed.) Marine invertebrate fisheries: their assessment and management. John Wiley & Sons, New York, NY, p 559–589

Chassé, J., Lambert, N., Comeau, M., Galbraith, P.S., Larouche, P. and Pettipas, R.G. 2014. Environmental conditions in the southern Gulf of St. Lawrence relevant to lobster. DFO Can. Sci. Advis. Sec. Res. Doc. 2014/031. v + 25 p.

Chouinard, G.A.1984. Growth of the sea scallop (*Placopecten magellanicus*) on the Tormentine bed, Northumberland Strait, Canada. ICES. C.M. 1984/K:42.

Culliney, J.L. 1974. Larval development of the giant scallop *Placopecten magellanicus* (Gmelin) Biol. Bull. 147: 321:332.

Cyr, C. 2006. Amélioration de la qualité de la collecte du pétoncle géant, *Placopecten magellanicus* (Gmelin 1791) par un meilleur contrôle de la période d'immersion des collecteurs aux Îles-de-la-Madeleine, Québec. Thèse du grade de maîtrise en océanographie. Rimouski : Université du Québec à Rimouski. xxii + 152 p.

Cyr, C. 2010. Suivi et monitoring associés à l'élevage du pétoncle géant pour l'année 2009. SODIM. Merinov, Centre des Iles-de-la-Madeleine. Dossier n°710.196. 20 p.

Davidson, L.-A. 1998. Maturation gonadique du Pétoncle Géant *Placopecten magellanicus*, (Gmelin) du stade juvénile au stade adulte. Thèse, MSc., Université de Moncton, 112 p.

Davidson, L.-A ., Niles, M. and Légère, L. 2007. Proceedings of the Southern Gulf Scallop Fishery Workshop: Moncton, New Brunswick, March 30-31, 2006. Can. Tech. Rep. Fish. Aquat. Sci. 2785: vii +87 p.

Davidson, L.-A., Biron, M. and Niles, M. 2012. Scallop Fishery Assessment of the Southern Gulf of St. Lawrence in 2010: Commercial Fishery Data. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/007. ii + xx p.

Davidson, L.-A., Niles, M., Nowlan, R. et Frenette, B. 2019. Ensemencement du pétoncle géant (*Placopecten magellanicus*) au large du Nouveau-Brunswick, Canada. Rapp. tech. can. sci. halieut. aquat. 3294: ix + 46 p.

Davidson, L.-A. and Worms, J. 1989. Stages of gonad development in the sea scallop *Placopecten magellanicus* (Gmelin) based on both macroscopic and microscopic observation of the gametogenic cycle. Tech. Rep. Fish. Aquat. Sci. 1686: 20p.

DFO. 2006. A Harvest Strategy Compliant with the Precautionary Approach. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2006/023.

DFO. 2010. Stock assessment on scallop of the inshore waters of Quebec in 2009. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2010/044.

DFO. 2011. Assessment of the scallop fishery (*Placopecten magellanicus*) of the southern gulf of St. Lawrence. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2011/039.

DFO. 2013. Stock assessment on scallop of the inshore waters of Quebec in 2012. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2013/027.

DFO. 2015. Integrated Fisheries Management Plan – Inshore Scallop – Maritimes Region.

Dickie, L.M. 1958. Effects of high temperature on survival of the giant scallop. J. Fish. Res. Bd. Canada. 15(6): 1189-1211.

Dickie, L.M. and MacInnes, C.D. 1958. Gulf of St. Lawrence Scallop Explorations - 1957. Fish. Res. Bd. Canada. MS. Rept. Ser. (Biol.) No. 650. 62 p.

Drew, G.A. 1906. The habits, anatomy and embryology of giant scallop (*Pecten tenuicostatus*, Mighels). Univ. Maine Stud. 6. 71 p.

Food and Agriculture Organization (FAO). 1995. Code of conduct for responsible fisheries. FAO, Rome, Italy, 41 p.

Frenette, B. 2004. Environmental factors influencing the growth and survival of juvenile sea scallops, *Placopecten magellanicus* (Gmelin, 1791). M.Sc. Thesis, Memorial University of Newfoundland, St. John's, NL, Canada. 142 p.

Giguère, M., Brulotte, S. et Goudreau, P. 2000. État des stocks de pétoncles des eaux côtières du Québec. CSAS. Res. Doc. 2000/086. 46 p.

Hanson, J.M. 1998. Survey of sea scallop abundance and distribution in western Northumberland Strait (SFA 22), June 1997. DFO Atl. Fish. Res. Doc. 98/71. 17 p.

Harris, B.P. and Stokesbury, K.D.E. 2006. Shell growth of sea scallops (*Placopecten magellanicus*) in the southern and northern Great South Channel, USA. ICES Journal of Marine Science, 63: 811-821.

Hart, D.R. 2003. Yield- and biomass-per-recruit analysis of rotational fisheries, with an application to the sea scallop *Placopecten magellanicus*. Fish Bull. 101: 44-57.

Hart, D.R. and Chute, E.S. 2004. Essential Fish Habitat Source Document: Sea Scallop, *Placopecten magellanicus*, Life History and Habitat Characteristics. NMFS-NE-189. 21 p.

Harvey, M., Bourget, E. and Miron, G. 1993. Settlement of Iceland scallop *Chlamys islandica* spat in response to hydroids and filamentous red algae: field observations and laboratory experiments. Mar. Ecol. Prog. Ser.99: 283-292.

Lanteigne, M., Davidson, L.-A. and Worms, J. 1987. Status of the southern Gulf of St. Lawrence scallop stocks – 1986. CAFSAC Res. Doc. 87/84. 40 p.

Lanteigne, M. and Davidson, L.-A. 1991. Catch and effort statistics for the giant scallop (*Placopecten magellanicus*) fishery in the southern Gulf of St. Lawrence – historical review from 1923 to 1989. Can. Tech. Rep. Fish. Aquat. Sci. 1804. 59 p.

Larsen, P. F. and Lee, R. M. 1978. Observations on the abundance, distribution and growth of post-larval sea scallops, *Placopecten magellanicus*, on Georges Bank. Nautilus 92(3): 112-116.

Leslie, P. and Davis, D. 1939. An attempt to determine the absolute number of rats on a given area. J. Animal. Ecol. 8: 94-113.

MacDonald, B.A., Bricelj, M. and Shumway, S.E. 2006. Physiology: Energy acquisition and utilization. {In}: S. Shumway and G.J. Parsons (eds). Scallops: Biology Ecology and Aquaculture. Elsevier, Amsterdam, The Netherlands: 417-492.

MacDonald, B.A., and Thompson, R.J. 1985. Influence of temperature and food availability on the ecological energetics of the giant scallop *Placopecten magellanicus* (Gmelin). I. Growth rates of shell and somatic tissue. Mar. Ecol. Prog. Ser. 25: 279-294.

MacDonald, B.A. and Thompson, R.J. 1986. Production, dynamics and energy partitioning in two populations of the giant scallop *Placopecten magellanicus* (Gmelin). J. Exp. Mar. Biol. Ecol. 101:285-299.

MacLean, L.A. and Gillis, D.J. Collection and early growth of sea scallop (*Placopecten magellanicus*) spat around Prince Edward Island, 1996. PEI Department of Fisheries and Environment. Technical Report #217. 22 p.

Mallet, M. 2010. Commercial Scallop (*Placopecten magellanicus*) Fishery Profile in the Gulf Region. Statistical and Economic Analysis Series. No. 1-5: v + 25 p.

Manuel, J.L. and Dadswell, M.J. 1993. Swimming of juvenile sea scallops, *Placopecten magellanicus* (Gmelin): a minimum size for effective swimming? J. Exp. Mar. Biol. Ecol. 174: 137-175.

Merrill, A.S. and Posgay, J.A. 1964. Estimating the natural mortality rate of sea scallop (*Placopecten magellanicus*). ICNAF Res Bull 1:88–106.

Minchin, D. 1992. Biological observations on young scallops, *Pecten maximus*. J. Mar. Biol. Assoc. U.K. .72:807-819.

Naidu, K.S. 1975. Growth and population structure of a northern shallow-water population of giant scallop, *Placopecten magellanicus* (Gmelin). ICES C.M. 1975/K:37. 17 p.

Naidu K.S. and Robert, G. 2006. Fisheries Sea Scallop, *Placopecten magellanicus.* {In}: S. Shumway and G.J. Parsons (eds). Scallops: Biology Ecology and Aquaculture (2nd edition) Elsevier, Amsterdam, The Netherlands. 1460 p.

Nasmith, L., Sameoto, J. and Glass, A. 2016. Scallop Production Areas in the Bay of Fundy: Stock Status for 2015 and Forecast for 2016. DFO Can. Sci. Advis. Sec. Res. Doc. 2016/021. vi + 140 p.

Ogle, D.H. 2017. FSA: Fisheries Stock Analysis. R package version 0.8.17.

Ogle, D.H. 2016. Introductory Fisheries Analyses with R. Chapman & Hall/CRC, Boca Raton, FL. Ricker, W.E. 1975. Computation and interpretation of biological statistics of fish populations. Technical Report Bulletin, Bull. Fish. Res. Board Can. 191 p.

Ouellet, M., Giard, D., Gagnon, D. and Comeau, M. 2019. Coastal temperature monitoring program from 2016 to 2017: southern Gulf of St. Lawrence. Can. Data Rep. Fish. Aquat. Sci. 1296: vii + 510 p.

Parsons, G.J., Robinson, S.M.C., Chandler, R.A., Davidson, L.-A., Lanteigne, M. and Dadswell, M.J. 1992. Intra-annual and long-term patterns in the reproductive cycle of giant scallops *Placopecten magellanicus* (Bivalvia: Pectinidae) from Passamaquoddy Bay, New Brunswick, Canada. Mar. Ecol. Prog. Ser. 80: 203-2014.

Pilditch, C.A. and Grant, J. 1999. Effect of variations in flow velocity and phytoplankton concentration on sea scallop (*Placopecten magellanicus*) grazing rates. J. Exp. Mar. Biol., *240*, 111-136.

Posgay, J.A. 1957. The range of the sea scallop. The Nautilus 71(2): 55-57.

Rheuban, J.E., Doney, S.C., Cooley, S.R., Hart, D.R. 2018. Projected impacts of future climate change, ocean acidification, and management on the US Atlantic sea scallop (*Placopecten magellanicus*) fishery. PLoS ONE 13(9): e0203536.

Ricker, W.E. 1975. Computation and interpretation of biological statistics of fish populations. Bull. Fish. Res. Board Can.191. Ottawa.

Robinson, W.E., Wehling, W.E., Morse, M.P. and McLeod, G.C. 1981. Seasonal changes in soft-body component indices and energy reserves in the Atlantic deep-sea scallop, *Placopecten magellanicus.* Fish. Bull. 79:449-458.

Sameoto, J.A., Smith, S.J., Hubley, B., Pezzack, D., Denton, C., Nasmith, L. and Glass, A. 2012. Scallop Fishing Area 29: Stock status and update for 2012. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/042. iv + 63 p.

Sarro, C.L. and K.E. Stokesbury. 2009. Spatial and temporal variability in the shell height/meat weight relationship of sea scallop *Placopecten magellanicus* in the Georges Bank Fishery. J. Shellfish Res. 28: 497-503.

Shumway, S. E., Selvin, R. and Schick, D.F. 1987. Food Resources Related to Habitat in the Scallop, Placopecten magellanicus, (Gmelin, 1791): A Qualitative Study. J. of Shell. Res. 6: 89-95.

Squires, H.J. 1962. Giant scallops in Newfoundland coastal waters. Bull. Fish. Res. Bd. Canada No. 135. 29 p.

Smith, S.J., Bourdages, H., Choi, J., Dawe, E., Dunham, J.S., Gendron, L., Hardie, D., Moriyasu, M., Orr, D., Roddick, D., Rutherford, D., Sainte-Marie, B., Savard, L., Shelton, P., Stansbury, D., Tremblay, M.J. and Zhang, Z. 2012b. Technical Guidelines for the Provision of Scientific Advice on the Precautionary Approach for Canadian Fish Stocks: Section 7 – Invertebrate Species. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/117. iv + 30 p.

Smith, S.J. and Gavaris, S. 1993. Improving the Precision of Abundance Estimates of Eastern Scotian Shelf Atlantic Cod from Bottom Trawl Surveys, North. American Journal of Fisheries Management, 13:1, 35-47.

Smith, S.J. and Hubley, P.B. 2012. Reference points for scallop fisheries in the Maritimes Region. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/018. ii + 16 p. (Erratum: August 2012).

Smith, S.J., Hubley, B., Nasmith, L., Sameoto, J., Bourdages, H. and Glass, A. 2012a. Scallop Production Areas in the Bay of Fundy: Stock Status for 2011 and Forecast for 2012. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/009: vii + 123 p.

Smith, S.J., Lundy, M.J. and Claytor, R. 1999. Scallop Production Areas 4 and 5 in the Bay of Fundy: Stock Status update for 1999. Can. Sci. Adv. Sec. Res. Doc. 99/170: 51 p.

Smith, S.J., Lundy, M.J., Tremblay, J., Frail, C. and Rowe, S. 2008a. Scallop Fishing Area 29: Stock Status and update for 2008. Can. Sci. Adv. Sec. Res. Doc. 2008/033: 49 p.

Smith, S.J., Nasmith, L., Glass, A., Hubley, B. and Sameoto, J.A. 2015. Framework assessment for SFA 29 West scallop fishery. DFO Can. Sci. Advis. Sec. Res. Doc. 2014/110. v + 69 p.

Smith, S.J., Rowe, S. and Lundy, M. 2008b. Scallop Production Areas in the Bay of Fundy: Stock Status for 2007 and Forecast for 2008. DFO Can. Sci. Advis. Sec. Res. Doc. 2008/002. vi + 116 p.

Smith, S.J., Sameoto, J.A. and Brown, C.J. 2017. Setting biological reference points for sea scallops (*Placopecten magellanicus*) allowing for the spatial distribution of productivity and fishing effort. Can. J. Fish. Aquat. Sci. 74:650-667.

Stevenson, J.A. and Dickie, L.M. 1954. Annual rings and rate of growth of the giant scallop, *Placopecten magellanicus* (Gmelin) in the Digby area of the Bay of Fundy. J. Fish Res. Bd. Canada 11(5): 660-671.

Stewart, P.L. and Arnold, S.H. 1994. Environmental requirements of the sea scallop (*Placopecten magellanicus*) in eastern Canada and its response to human impacts. Can. Tech. Rep. Fish. Aquat. Sci. 2005. ix + 36 p.

Stewart, B.D. and Howarth, L.M. 2016. Quantifying and managing the ecosystem effects of scallop dredge fisheries. {In}: S. Shumway and G.J. Parsons (eds). Scallops: Biology Ecology and Aquaculture (2nd edition) Elsevier, Amsterdam, The Netherlands. 1460 p.

Tan F.C., Cai, D. and Roddick, D.L. 1988. Oxygen isotope studies on sea scallops, *Placopecten magellanicus,* from Browns Bank, Nova Scotia. Can. J. Fish. Aquat. Sci. 45(8): 1378-1386.

Trottier, S., Bourdages, H., Goudreau, P. et Brulotte, S. 2017. Évaluation des stocks de pétoncle des eaux côtières du Québec en 2015 : données de la pêche commerciale, des relevés de recherche et des pêches exploratoires. Secr. can. de consult. sci. du MPO. Doc. de rech. 2017/037. xvi + 175 p.

Wildish, D.J. and Saulnier, A.M., 1993. Hydrodynamic control of filtration in Placopecten magellanicus. J. Exp. Mar. Biol. Ecol. 174, 65–82.

Worms, J. 1984. Scallop biomass and density estimates in the southern Gulf of St Lawrence. CAFSAC Res Doc 84/90.

Worms, J. 1986. Meat count analysis for sea scallop stocks in the southern Gulf of St. Lawrence. CAFSAC 86/15.

Worms, J. and Chouinard, G.A. 1983. Status of southern Gulf of St. Lawrence scallop stocks – 1982. CAFSAC Res. Doc. 83/68.

Worms, J. and Chouinard, G.A. 1984. Status of southern Gulf of St. Lawrence scallop stocks – 1983. CAFSAC Res. Doc. 84/57.

Worms, J.M. and Davidson, L.-A. 1986. Some cases of hermaphroditism in the sea scallop *Placopecten magellanicus* (Gmelin) from the southern Gulf of St. Lawrence, Canada. Venus (Jap. Jour. Malac.) 45(2): 116-126.

Young-Lai, W.W. and Aiken, D.E. 1986. Biology and culture of the giant scallop, *Placopecten magellanicus*: a review. Can. Tech. Rep. Fish. Aquat. Sci., 1478: iv + 21 p.

TABLES

Table 1. Spawning onset dates in various Scallop Fishing Areas (SFAs) of the southern Gulf of St. Lawrence based on the Gonodo-Somatic Index (GSI), with years of study and comments of partial spawning and corresponding references.

SFA	Area	Onset of spawning	Years of study	Comments	References
SFA 21A	Chaleur Bay (NB)	Aug. 28 – Sep. 11	2001-2005	Partial spawning Jul. 27 2001 Aug. 10 2004	Davidson et al. (2019)
SFA 19	Chaleur Bay (QC)	Aug. –mid-Sep.	1984-1994	Partial spawning Jul. 1986, 1988, 1989	Bonardelli et al. (1996) Giguère et al. (2000)
SFA 22	Northumberland Strait (Richibouctou -West Point)	Aug. 12-Sep. 1	1997-2001	-	Davidson et al. (2019)
SFA 24	Northumberland Strait (Pictou)	Aug. 16	1999	-	DFO (Unpublished data)
SFA 23	Hardy's Channel	Sep. 7	1996	-	MacLean and Gillis (1996)
SFA 20	Magdalen Islands (QC)	Aug. 17 – Sep. 8	1990-1999 2003-2004 2007-2010	Partial spawning Aug. 10 2009	Cyr (2006, 2010) Giguère et al. (2000)

Table 2. Summary of management measures for the scallop fishery in the southern Gulf of St. Lawrence.

Management measure	**Scallop Fishing Area (SFA)**					
	21A	**21B**	**21C**	**22**	**23**	**24**
Season in 2015	July 14 to Aug 8	May 10 to Aug. 8	June 22 to July 24	May 11 to June 15	July 6 to Aug. 29; Nov. 5 to Dec 1	Oct 26. to Nov. 28
Season in 2016	Closed	May 10 to Aug. 8[a]	July 4 to July 30	May 2 to June 4	July 4 to Aug.27; Oct.24 to Nov. 26	Nov. 1 to Dec. 15
Number of fishing days in season	24	42	24	30	72[b]	39
Time open	6:00 to 18:00	5:30 Monday to 14:00 Friday	5:00 to 18:00	6:00 to 17:00[c]	6:00 to 18:00	6:00 to 18:00
Days closed	Saturday & Sunday	Saturday & Sunday	Sunday	Sunday	Sunday	Sunday
Meat count (number per 500 g)	35	39	39	44	33	52
Ring size (mm)	82.6	82.6	82.6	82.6	82.6	82.6
Width of dredge (m)	6	6	6	4.88	6	5
Tow bar specifications [d]	ns	ns	ns	with 50.8 mm runners	ns	ns
Washers	Steel (8 max) & Chaffing gear or 2 rubbers on the vertical					

[a] maximum of 42 consecutive days within this season
[b] reduced to 50 in 2017
[c] 6:00 to 18:00 in 2015
[d] not specified

Table 3. Description of scallop buffer zones and temporary closures with depth limits and year of implementation for each Scallop Fishing Area (SFA).

SFA	Depth limit	Buffer Year	Closures	Description
21A	<15 <18.6 m <18.6 m mod.	1999 2013 2015	-	-
21B	<18.6 m	1999	-	Eastern half Gentlemen agreement
21C	<18.6 m	-	-	Gentlemen agreement
22	<11 m	2005	-	-
23	<27.4 west < 36 m east	-	-	Gentlemen agreement
24	<1 nm from NS shore PEI shore and < 27.4 m area <27 m W Cape Breton	1996 1999 2006	-	-
21A	No depth limit No depth limit	-	2010-2012 2016-2018	catch rate decision rule of 3 kg h^{-1}
21B	No depth limit	-	2008	Western half of SFA
22	No depth limit	-	2005-2010	West of Confederation Bridge

Table 4. Distribution of commercial scallop fishing licences and estimates of active fishing licences and total fishing licences (in parentheses) by SFA in 2011 to 2016.

SFA	Status	2011	2012	2013	2014	2015	2016	Active in 2016
21	Active (total)	6 (103)	3 (103)	11 (103)	12 (101)	5 (101)	6 (101)	6%
21A	Active (total)	0 (28)	0 (28)	9 (28)	10 (29)	3 (29)	0 (29)	0%
21B	Active (total)	3 (27)	1 (27)	0 (27)	1 (24)	1 (24)	4 (24)	17%
21C	Active (total)	3 (48)	2 (48)	2 (48)	1 (48)	1 (48)	2 (48)	4%
22	Active (total)	97 (202)	109 (201)	101 (200)	92 (200)	84 (200)	83 (200)	42%
23	Active (total)	2 (78)	2 (78)	2 (78)	8 (78)	6 (78)	5 (78)	6%
24	Active (total)	77 (390)	75 (390)	68 (390)	63 (390)	52 (389)	51 (389)	13%
sGSL	Active (total)	181 (773)	189 (772)	182 (772)	175 (769)	147 (768)	145 (768)	19%

Table 5. Number of licences, logbook returns, landings (in number of scallops) and estimate of meat weight of sea scallops in the recreational fishery of the southern Gulf of St Lawrence from 2003 to 2016.

Year	Number of Scallop recreational licences	Number of recreational logbooks returned	Number of ACTIVE recreational logbooks returned	Number of days fished	Landings Number of scallops	Estimate of meat weight (kg)*
2003	-	16	11	55	1538	26
2004	-	41	41	177	5025	83
2005	-	61	37	169	5835	97
2006	-	69	51	241	9023	150
2007	-	73	37	176	6886	114
2008	-	77	50	197	7590	126
2009	-	71	42	194	7258	120
2010	-	67	49	204	7521	125
2011	267	92	55	331	11620	193
2012	336	77	53	208	9239	153
2013	243	59	46	165	7490	124
2014	227	70	52	149	7530	125
2015	212	61	52	163	6305	105
2016	259	30	19	76	2720	45

* based on 16.6 g per 100 mm scallop

Table 6. Scallop landings (meats, t) for each Scallop Fishing Area (SFA) in the Gulf Region, from 1968 to 2016.

Year	SFA 21	SFA 22	SFA 23	SFA 24	Total (Gulf)
1968	3	619	5	274	901
1969	5	232	0	408	645
1970	55	313	1	329	697
1971	49	276	0	266	591
1972	55	178	0	276	509
1973	34	124	0	147	305
1974	37	46	0	119	202
1975	31	60	0	186	278
1976	26	218	1	120	365
1977	13	118	0	63	194
1978	13	174	1	80	268
1979	14	129	0	95	239
1980	19	100	0	90	209
1981	33	158	4	174	368
1982	20	98	1	108	227
1983	30	133	1	144	308
1984	40	132	3	60	234
1985	39	129	5	41	213
1986	26	77	2	91	196
1987	22	83	0	59	164
1988	23	96	0	42	161
1989	59	118	0	38	215
1990	70	82	0	56	208
1991	43	35	0	73	152
1992	43	44	0	76	163

Year	SFA 21	SFA 22	SFA 23	SFA 24	Total (Gulf)
1993	53	66	0	132	251
1994	81	86	1	141	308
1995	61	105	1	145	313
1996	76	87	3	162	328
1997	87	111	8	105	310
1998	97	121	8	64	291
1999	62	64	2	82	210
2000	48	98	3	87	235
2001	34	95	1	32	162
2002	23	43	0	29	95
2003	26	55	0	26	108
2004	27	67	0	27	121
2005	22	50	1	25	97
2006	8	49	0	28	86
2007	15	80	0	22	118
2008	15	77	1	17	110
2009	13	81	3	21	117
2010	5	55	1	28	88
2011	1	88	1	31	120
2012	1	85	1	30	116
2013	5	89	3	26	124
2014	3	70	7	19	99
2015	NA	50	3	17	71
2016	7	34	2	24	66

NA = not available.

Table 7. Scallop trips fished (days) for each Scallop Fishing Area (SFA) in the Gulf Region, from 1968 to 2016.

Year	SFA 21	SFA 22	SFA 23	SFA 24	Total (Gulf)
1968	NA	NA	NA	NA	NA
1969	NA	NA	NA	NA	NA
1970	NA	NA	NA	NA	NA
1971	NA	NA	NA	NA	NA
1972	NA	NA	NA	NA	NA
1973	NA	NA	NA	NA	NA
1974	NA	NA	NA	NA	NA
1975	NA	NA	NA	NA	NA
1976	NA	NA	NA	NA	NA
1977	153	424	0	450	1027
1978	441	2755	1	1820	5017
1979	448	3321	2	2407	6178
1980	735	2262	0	2089	5086
1981	1206	3910	88	3790	8994
1982	885	2379	47	2783	6094
1983	666	2867	41	4440	8014
1984	942	3261	86	1112	5401
1985	1123	2957	95	1003	5178
1986	807	2014	73	1931	4825
1987	538	2216	12	939	3705
1988	299	2049	0	763	3111
1989	1174	2115	0	710	3999
1990	1495	1496	16	1101	4108
1991	1057	812	17	1275	3161
1992	1104	1057	2	1472	3635

Year	SFA 21	SFA 22	SFA 23	SFA 24	Total (Gulf)
1993	1293	1605	6	3252	6156
1994	1925	2073	28	3719	7745
1995	1631	2574	41	3291	7537
1996	2389	2531	122	3881	8923
1997	2410	2793	293	3164	8660
1998	2446	3644	316	2378	8784
1999	1739	2047	101	2070	5957
2000	1406	2120	86	2514	6126
2001	802	2387	45	1138	4372
2002	849	1246	18	973	3086
2003	718	1496	0	1084	3298
2004	745	1442	10	823	3020
2005	695	1319	4	981	2995
2006	328	1416	0	1040	2784
2007	393	1685	5	741	2824
2008	295	1531	14	715	2555
2009	280	1972	20	724	2996
2010	22	958	32	854	1866
2011	19	1629	17	1136	2801
2012	15	1767	25	1106	2913
2013	148	1523	69	980	2720
2014	156	1534	60	843	2593
2015	NA	1198	25	641	1885
2016	58	1203	41	703	1739

NA = not available.

Table 8. Approximate spatial extent (km^2) of fishing activities used for research surveys and scallop beds of the Gulf Region according to fishing positions from 2001 to 2016 logbooks (beds are defined using the kernel density contour of 20 trips km^{-2}).

SFA	Bed	Survey strata area (km^2)	Approximate spatial extent of scallop beds (km^2)
21A	Chaleur Bay	231	22
22	West Point	557	137
22	Cape Tormentine	248	92
24	Pictou	1500	78

Table 9. Proportion of Gulf landings attributed to each major scallop bed and proportion of three beds combined reported in commercial logbook from 2001 to 2016.

SFA	22		24	Gulf
Year	Cape Tormentine	West Point	Pictou	Total
2001	0.16	0.18	0.16	0.50
2002	0.05	0.28	0.23	0.57
2003	0.12	0.25	0.16	0.53
2004	0.27	0.12	0.15	0.53
2005	0.07	0.26	0.19	0.53
2006	0.14	0.29	0.26	0.69
2007	0.15	0.42	0.15	0.71
2008	0.30	0.25	0.11	0.67
2009	0.24	0.31	0.14	0.69
2010	0.14	0.38	0.20	0.72
2011	0.22	0.34	0.19	0.76
2012	0.26	0.35	0.20	0.81
2013	0.52	0.11	0.22	0.85
2014	0.28	0.32	0.19	0.79
2015	0.40	0.24	0.25	0.89
2016	0.39	0.04	0.35	0.78

Table 10. Commercial scallop logbook reporting in relation to sales slip reporting for Scallop Fishing Area 21, from 2011 to 2016.

Year	Sales slips	Logbook records					
	Total number of days reported	Total	Percent reporting (%)	Usable for location	Useable for Effort (hours fished)	Useable for Effort (hours towed)	Percent usable logs (%)
2011	28	28	100	18	18	16	57
2012	15	15	100	7	7	7	47
2013	148	141	95	116	114	97	66
2014	156	127	81	107	96	90	58
2015	24	24	100	20	20	12	50
2016	58	58	100	36	28	26	45

Table 11. Commercial scallop logbook reporting in relation to sales slip reporting for Scallop Fishing Area 22, from 2011 to 2016.

Year	Sales slips	Logbook records					
	Total number of days reported	Total	Percent reporting (%)	Usable for location	Useable for Effort (hours fished)	Useable for Effort (hours towed)	Percent usable logs (%)
2011	1629	1446	89	1323	1287	949	58
2012	1767	1278	72	1160	1142	922	52
2013	1523	1107	73	1029	940	868	57
2014	1534	1066	69	959	848	722	47
2015	1198	934	78	814	786	565	47
2016	1203	878	73	646	583	492	41

Table 12. Commercial scallop logbook reporting in relation to sales slip reporting for Scallop Fishing Area 23, from 2011 to 2016.

Year	Sales slips	Logbook records					
	Total number of days reported	Total	Percent reporting (%)	Usable for location	Useable for Effort (hours fished)	Useable for Effort (hours towed)	Percent usable logs (%)
2011	17	17	100	10	9	10	59
2012	25	25	100	0	0	0	0
2013	69	35	51	21	21	21	30
2014	60	59	98	59	58	51	85
2015	25	25	100	25	25	14	56
2016	41	37	90	32	24	29	71

Table 13. Commercial scallop logbook reporting in relation to sales slip reporting for Scallop Fishing Area 24, from 2011 to 2016.

Year	Sales slips	Logbook records					
	Total number of days reported	Total	Percent reporting (%)	Usable for location	Useable for Effort (hours fished)	Useable for Effort (hours towed)	Percent usable logs (%)
2011	1136	1126	99	926	912	626	55
2012	1106	1083	98	913	911	593	54
2013	980	882	90	691	686	463	47
2014	843	763	91	676	659	477	57
2015	679	679	100	601	597	393	58
2016	703	703	100	561	553	376	53

Table 14. Proportion of SFA landings attributed to each major scallop bed according to logbook reports from 2001 to 2016.

SFA	21A	22		24
Year	21A bed	Cape Tormentine	West Point	Pictou
2001	0.74	0.26	0.28	0.70
2002	0.70	0.12	0.64	0.76
2003	0.67	0.23	0.50	0.70
2004	0.58	0.46	0.21	0.72
2005	0.69	0.14	0.50	0.77
2006	0.65	0.24	0.50	0.84
2007	0.42	0.21	0.60	0.80
2008	0.31	0.42	0.36	0.75
2009	0.82	0.35	0.45	0.71
2010	NA	0.21	0.60	0.66
2011	NA	0.30	0.47	0.75
2012	NA	0.36	0.48	0.75
2013	0.91	0.76	0.17	0.83
2014	0.71	0.38	0.43	0.85
2015	1.00	0.57	0.34	0.85
2016	NA	0.80	0.09	0.86

NA: not available.

Table 15. Depletion model results for each major scallop bed corresponding to the high effort strata from 2003 to 2016 showing number of logbook records (n), catchability coefficient (q), cumulative catch in tons of meat (C), estimated Biomass before the fishery (B_0 (t)) and estimated exploitation rate ($\hat{E}$). Shaded cells with italic text means non-significant model ($P > 0.05$).

Year	Area	n (logs)	q	C (t)	B_0 (t)	$\hat{E}$
2003	SFA 21A (stratum 2)	160	0.157	9	28.85	0.30
2004	*SFA 21A (stratum 2)*	*154*	*0.031*	*9*	*124.48*	*0.08*
2005	SFA 21A (stratum 2)	130	0.339	9	18.59	0.48
2006	SFA 21A (stratum 2)	39	0.431	4	8.17	0.52
2007	*SFA 21A (stratum 2)*	*42*	*0.273*	*4*	*-9.77*	*-0.39*
2008	*SFA 21A (stratum 2)*	*42*	*0.485*	*1*	*6.69*	*0.15*
2009	*SFA 21A (stratum 2)*	*34*	*0.163*	*1*	*12.23*	*0.12*
2010	SFA 21A (stratum 2)	Fishery Closed				
2011	SFA 21A (stratum 2)					
2012	SFA 21A (stratum 2)					
2013	SFA 21A (stratum 2)	86	1.130	5	7.20	0.65
2014	SFA 21A (stratum 2)	61	0.565	2	5.28	0.39
2015	*SFA 21A (stratum 2)*	-	-	-	-	-
2016	SFA 21A (stratum 2)	Fishery Closed				
2003	Cape Tormentine (Stratum 3)	232	0.264	13	24.53	0.54

Year	Area	n (logs)	q	C (t)	B_0 (t)	Ê
2004	Cape Tormentine (Stratum 3)	315	0.163	36	58.63	0.62
2005	Cape Tormentine (Stratum 3)	91	0.261	8	16.60	0.49
2006	Cape Tormentine (Stratum 3)	152	0.267	13	22.23	0.59
2007	Cape Tormentine (Stratum 3)	177	0.182	17	37.06	0.47
2008	Cape Tormentine (Stratum 3)	195	0.172	33	58.80	0.56
2009	Cape Tormentine (Stratum 3)	225	0.192	29	48.99	0.59
2010	Cape Tormentine (Stratum 3)	141	0.305	12	23.44	0.50
2011	Cape Tormentine (Stratum 3)	280	0.165	27	62.57	0.42
2012	Cape Tormentine (Stratum 3)	303	0.223	31	50.92	0.61
2013	Cape Tormentine (Stratum 3)	560	0.115	68	122.07	0.56
2014	Cape Tormentine (Stratum 3)	248	0.191	27	52.73	0.51
2015	Cape Tormentine (Stratum 3)	285	0.201	29	51.14	0.56
2016	Cape Tormentine (Stratum 3)	355	0.189	27	44.45	0.61
2003	West Point (Stratum 3)	411	0.161	28	46.31	0.60
2004	West Point (Stratum 3)	94	0.170	16	45.39	0.35
2005	West Point (Stratum 3)	383	0.101	29	64.54	0.44
2006	West Point (Stratum 3)	433	0.140	27	48.90	0.55

Year	Area	n (logs)	q	C (t)	B_0 (t)	Ê
2007	West Point (Stratum 3)	435	0.141	50	76.82	0.65
2008	West Point (Stratum 3)	273	0.218	28	45.74	0.61
2009	West Point (Stratum 3)	356	0.103	37	82.59	0.45
2010	West Point (Stratum 3)	367	0.174	33	51.45	0.64
2011	West Point (Stratum 3)	455	0.134	41	78.15	0.53
2012	West Point (Stratum 3)	452	0.123	41	76.07	0.55
2013	West Point (Stratum 3)	213	0.093	15	70.19	0.22
2014	West Point (Stratum 3)	368	0.193	32	51.94	0.61
2015	West Point (Stratum 3)	215	0.275	17	30.75	0.55
2016	West Point (Stratum 3)	71	0.742	3	6.58	0.47
2003	Pictou (Stratum 1)	230	0.030	18	96.32	0.19
2004	*Pictou (Stratum 1)*	*242*	*-0.035*	*19*	*-96.93*	*-0.20*
2005	*Pictou (Stratum 1)*	*344*	*-0.005*	*19*	*-529.51*	*-0.04*
2006	*Pictou (Stratum 1)*	*418*	*0.003*	*23*	*1115.68*	*0.02*
2007	*Pictou (Stratum 1)*	*226*	*0.012*	*17*	*251.48*	*0.07*
2008	*Pictou (Stratum 1)*	*201*	*0.000*	*12*	*-38332.11*	*0.00*
2009	*Pictou (Stratum 1)*	*209*	*0.053*	*14*	*71.61*	*0.20*

Year	Area	n (logs)	q	C (t)	B_0 (t)	Ê
2010	*Pictou (Stratum 1)*	*315*	*0.049*	*18*	*-69.94*	*-0.26*
2011	Pictou (Stratum 1)	451	0.052	23	82.50	0.28
2012	Pictou (Stratum 1)	439	0.033	22	117.58	0.19
2013	*Pictou (Stratum 1)*	*369*	*0.001*	*20*	*2855.98*	*0.01*
2014	*Pictou (Stratum 1)*	*403*	*0.015*	*15*	*216.65*	*0.07*
2015	*Pictou (Stratum 1)*	*327*	*0.033*	*14*	*-92.85*	*-0.16*
2016	*Pictou (Stratum 1)*	*299*	*0.022*	*20*	*223.87*	*0.09*

Table 16. Description of research vessel scallop survey area, dates, stratum (and depth where applicable), area, proportion of area in stratum and number of randomly selected tows for each survey year.

SFA	Dates	Year	Stratum	Description of Stratum	Area (km^2)	Proportional area in stratum	Number of Tows
21A	28 June – 5 July	2013	1	Buffer (5-18 m)	194	0.146	16
			2	Moderate effort	231	0.174	39
			3	Low effort	494	0.372	18
			4	No effort (>36.5 m)	408	0.308	14
			Total		**1327**	1.000	**87**
21BC	11 Aug-25 Aug	2016	1	Moderate effort (18-36 m)	422	0.059	23
			2	Low effort (18-36 m)	2308	0.324	52
			3	No effort (>36 m)	2659	0.373	18
			4	Buffer (5-18m and western half)	1736	0.244	24
			Total		**7125**	1.000	**117**
22 north	31 May – 11 June	2014	1	Low effort – Cap St Louis Bed	781	0.253	14
			2	Moderate effort – Miminegash Bed	825	0.268	26
			3	High effort - West Point Bed	557	0.181	37
			4	Buffer (5-11 m)	919	0.298	12
			Total		**3082**	1.000	**89**

SFA	Dates	Year	Stratum	Description of Stratum	Area (km^2)	Proportional area in stratum	Number of Tows
22 south	27 June-5 July	2012	1	Very low or no effort	410	0.234	11
			2	Low effort – West Cape Tormentine Bed	139	0.079	13
			3	High effort – Cape Tormentine Bed	248	0.142	20
			4	Buffer – NB side (5-11 m)	736	0.421	18
			5	Buffer – PEI side (5-11 m)	217	0.124	6
			Total		**1750**	1.000	**68**
24	14 Aug-29 Aug	2015	1	High effort – Pictou Bed	1500	0.147	48
			2	Moderate effort	763	0.075	22
			3	Low effort	668	0.065	18
			4	No effort	6199	0.606	12
			5	Buffer	1106	0.108	20
			Total		**10236**	1.000	**120**
Gulf			***Total***		***23520***	**-**	***481***

Table 17. Number of scallops (n), mean and standard deviation of shell height, size range, maximum meat weight, mean, maximum age of commercial scallops (≥ 80 mm) and clapper ratio (Merrill and Posgay 1964) of sea scallop for each survey (2012-2016).

			Shell Height (mm)					Mean		
SFA	Year	n	Mean	SD	Min	Max	Max Meat Weight (g)	Age ≥ 80 mm	Max Age	Clapper ratio
21A	2013	255	67.6	22.01	17	147	54	8.8	15	0.148
21BC*	2016	499	82.3	34.91	18	143	51	8.5	13	0.085
22 north*	2014	395	75.9	26.59	20	146	60	6.9	13	0.112
22 south*	2012	1112	72.1	29.35	15	125	32	7.3	13	0.245
24	2015	536	84.2	27.31	13	137	38	8.6	16	0.203

*survey conducted after fishery

Table 18. Number of scallops measured (n), mean and standard deviation of shell height, size range of sea scallops for each major scallop bed (high effort stratum) from research surveys (2012-2016).

					Shell Height (mm)			Shell Height (mm) ≥ 80 mm		
SFA	Bed	Year	N	Mean	SD	Min	Max	n	Mean ± SD	
21A	21A bed	2013	75	68.4	34.26	17	140	23	114.3	± 13.55
22	West Point	2014	339	71.0	23.67	20	132	126	103.3	± 13.89
22	Cape Tormentine	2012	917	71.0	21.66	15	125	376	91.2	± 8.24
24	Pictou	2015	153	79.1	32.35	13	134	86	95.2	± 11.31

Table 19. SFA specific research vessel scallop survey commercial size (≥ 80 mm shell height) biomass indices (not corrected for drag efficiency) of scallop as meat weight (kg per standard tow of 437.27 m^2; mean, standard error (SE)), density (g m^{-2}), corresponding area for the high effort stratum (km^2), estimated biomass (meat weight, t), total landings to the stratum, and exploitation rate.

Characteristic	**SFA 21A**	**SFA 22 north**	**SFA 22 south**	**SFA 24**
Bed	21A	West Point	Cape Tormentine	Pictou
Year	2013	2014	2012	2015
Abundance (kg per standard tow)	-	-	-	-
Mean	0.014	0.053	0.223	0.027
Standard error	0.006	0.018	0.057	0.008
Density (g per m^2)	0.033	0.12	0.51	0.06
Surface area of the stratum (km^2)	231	557	248	1,500
Biomass (t) before the fishery	8	100	158	91
Landings (t)	5	32	31	14
Exploitation rate	59%	32%	20%	15%

FIGURES

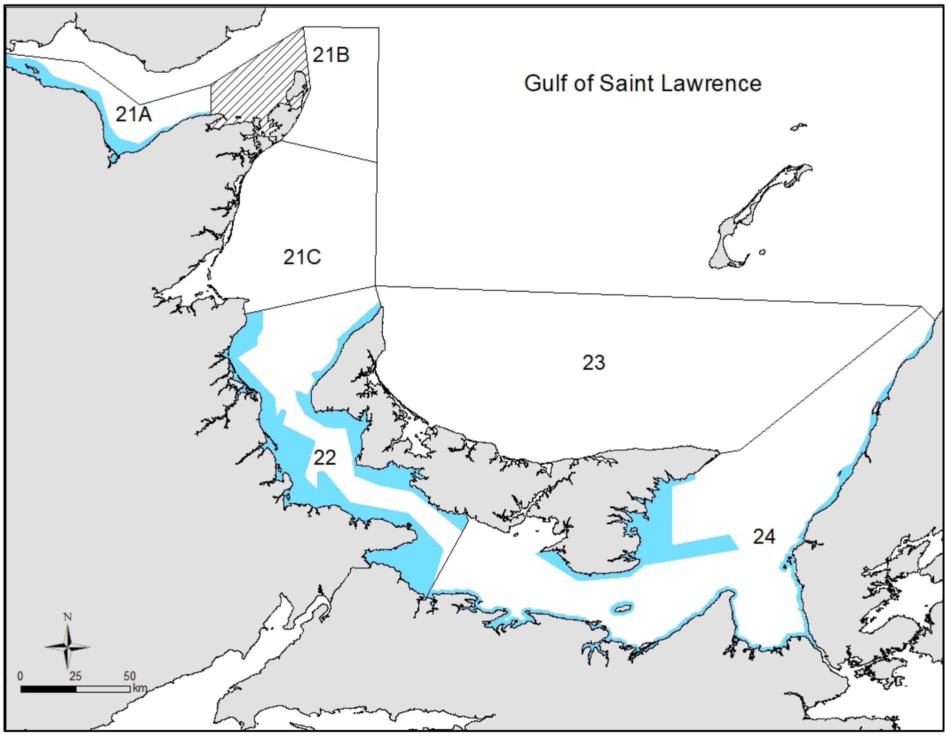

Figure 1. The Scallop Fishing Areas (SFA) in the Gulf Region showing buffer zones (shaded in blue) and closed zones (shaded in hash), Gulf of St. Lawrence.

Figure 2. Nine bucket Digby-type dredge commonly used to fish sea scallops in the Gulf Region.

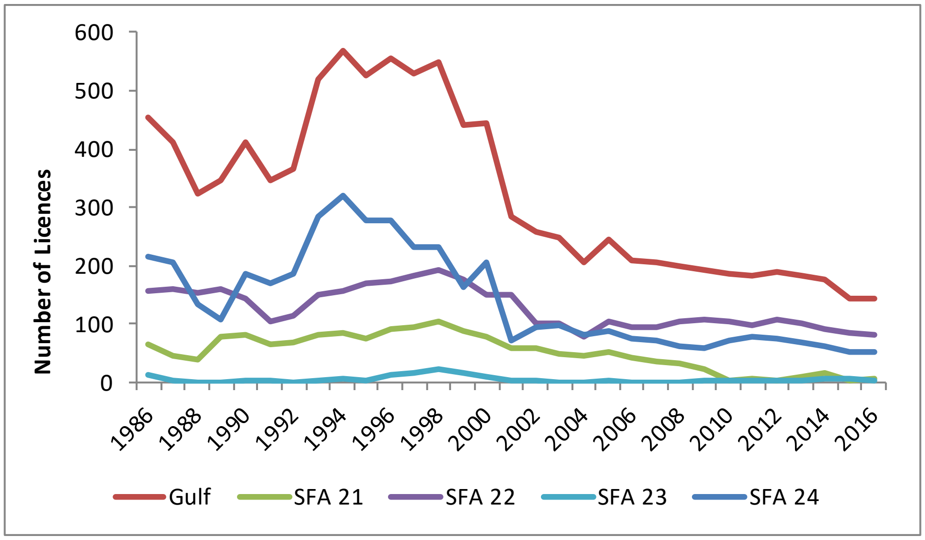

Figure 3. Number of active commercial scallop licences from 1986 to 2016 in the Gulf Region and in each Scallop Fisheries Area (SFA).

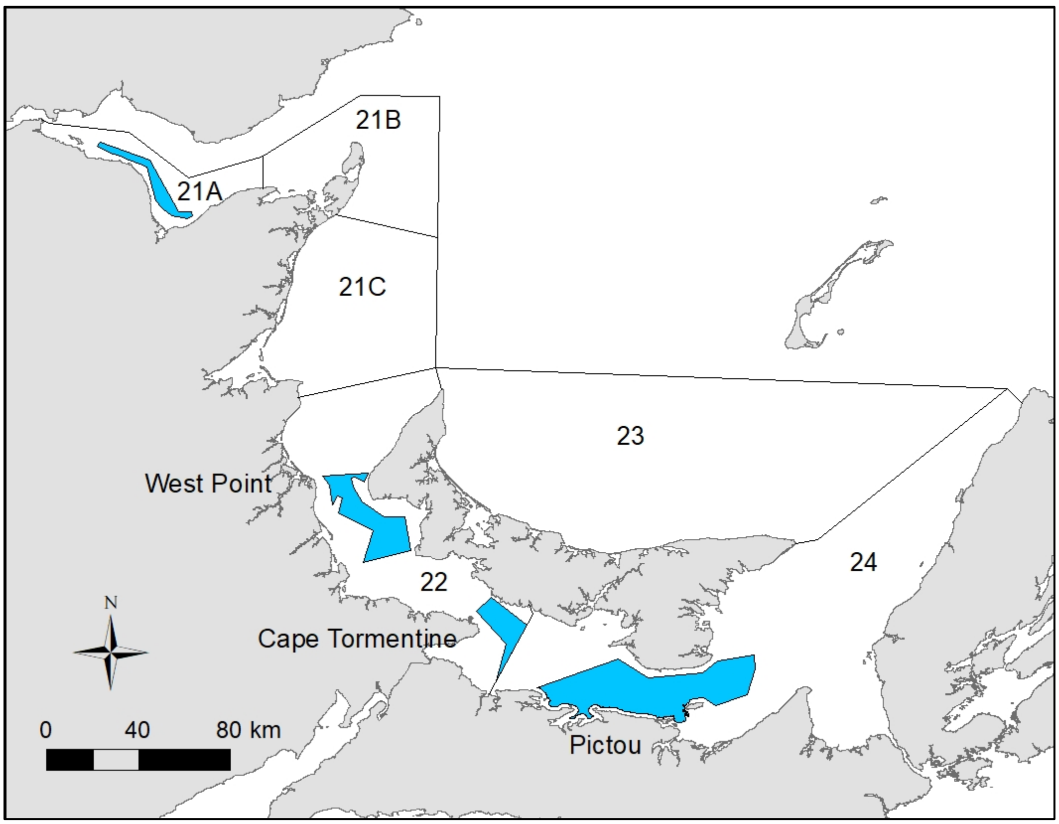

Figure 4. Survey sampling strata (blue area) used during the scallop research surveys (2012 to 2016) which define the scallop bed for catch rate and depletion model estimates.

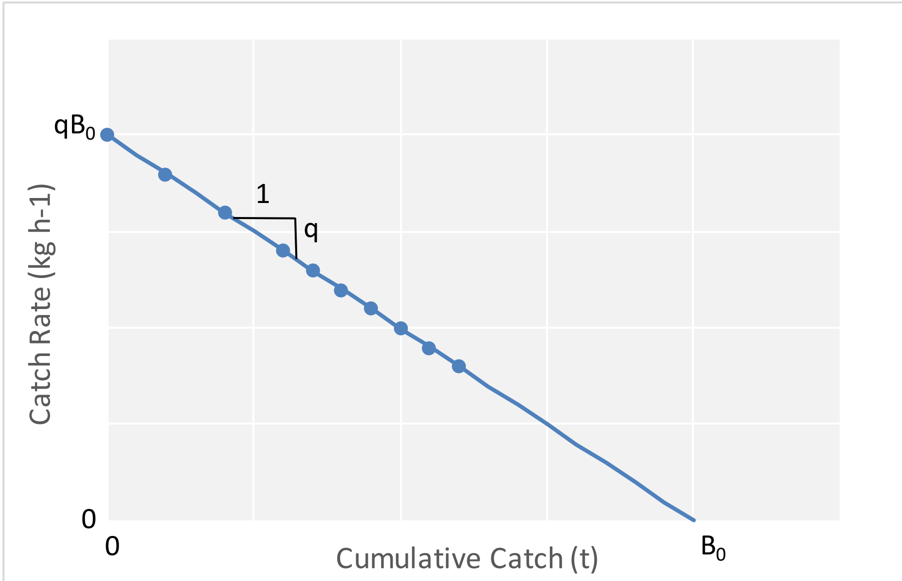

Figure 5. Plot of theoretical linear regression model of the decline in the index of abundance with increasing cumulative catch used to estimate fishable biomass before the fishery (B0), slope (q) and intercept (qB0). Modified from Ogle 2016.

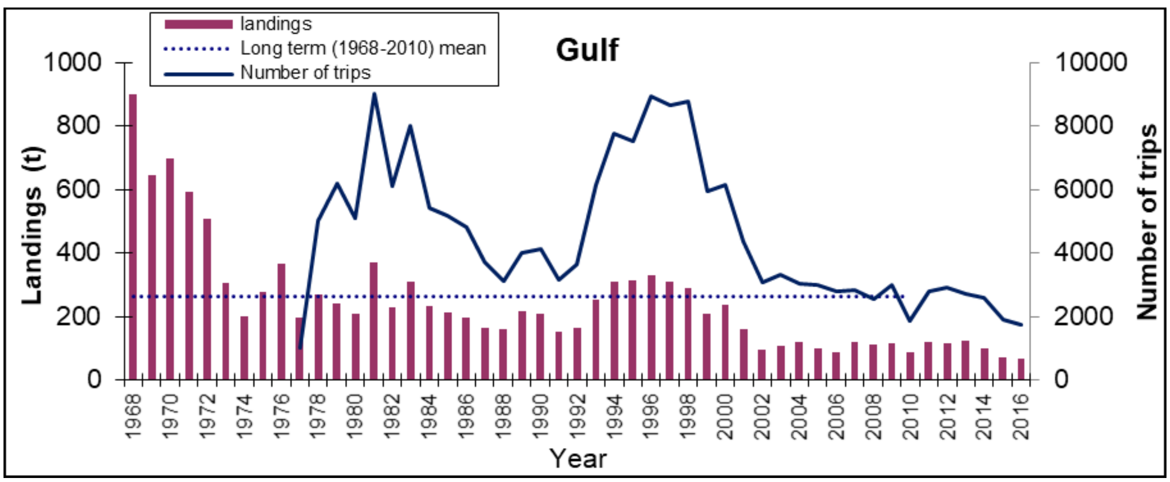

Figure 6. Recorded sea scallop landings (tons of meat weight), long term mean (dotted line) and the number of trips (days fished) in the southern Gulf of St. Lawrence, 1968 to 2016.

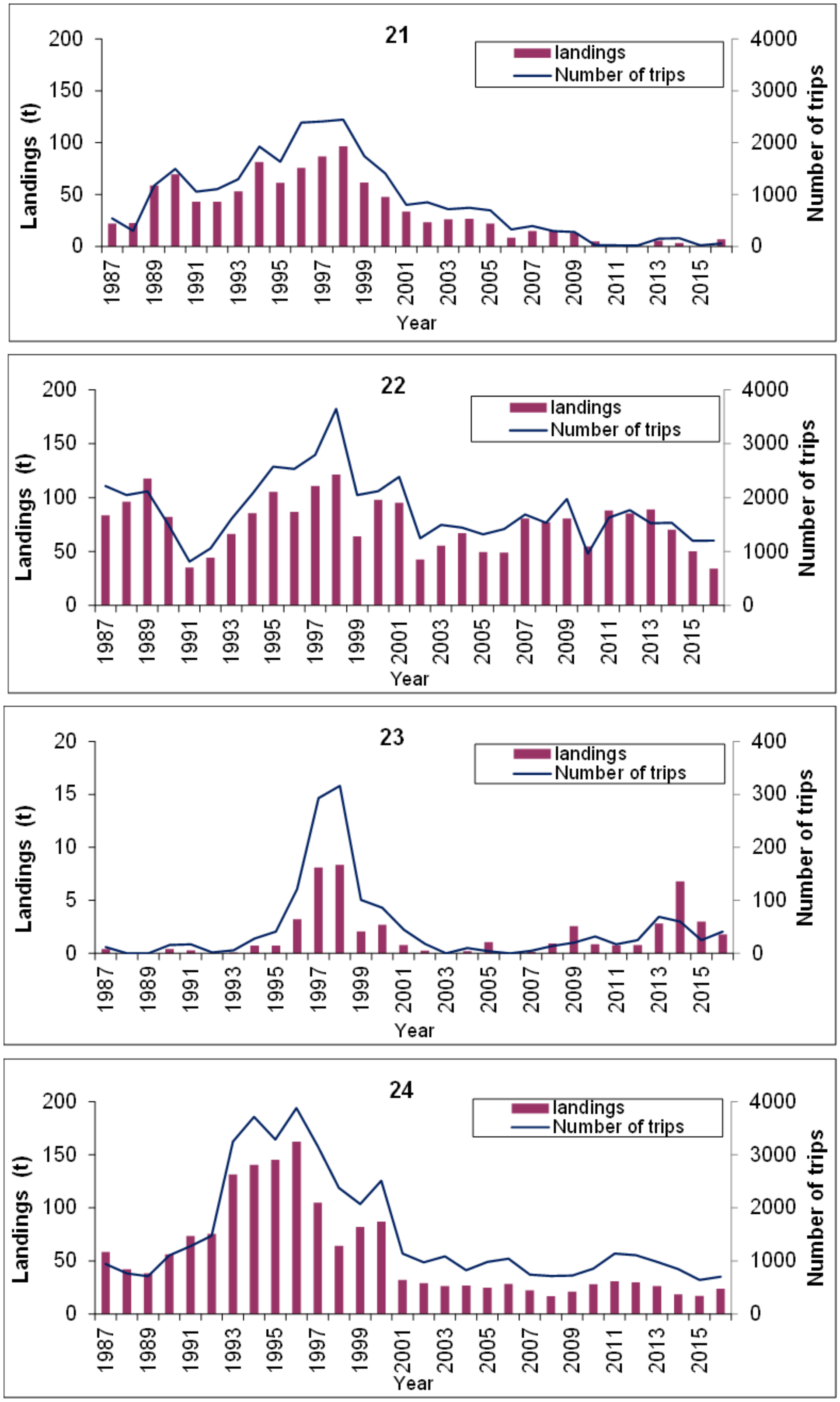

Figure 7. Commercial sea scallop landings (tons of meat weight) and the number of trips (sum of days with individual reported landings) in Scallop Fishing Areas (SFA) 21, 22, 23 and 24 in the southern Gulf of St. Lawrence fishery, 1987 to 2016. Note different y axis scale for SFA 23.

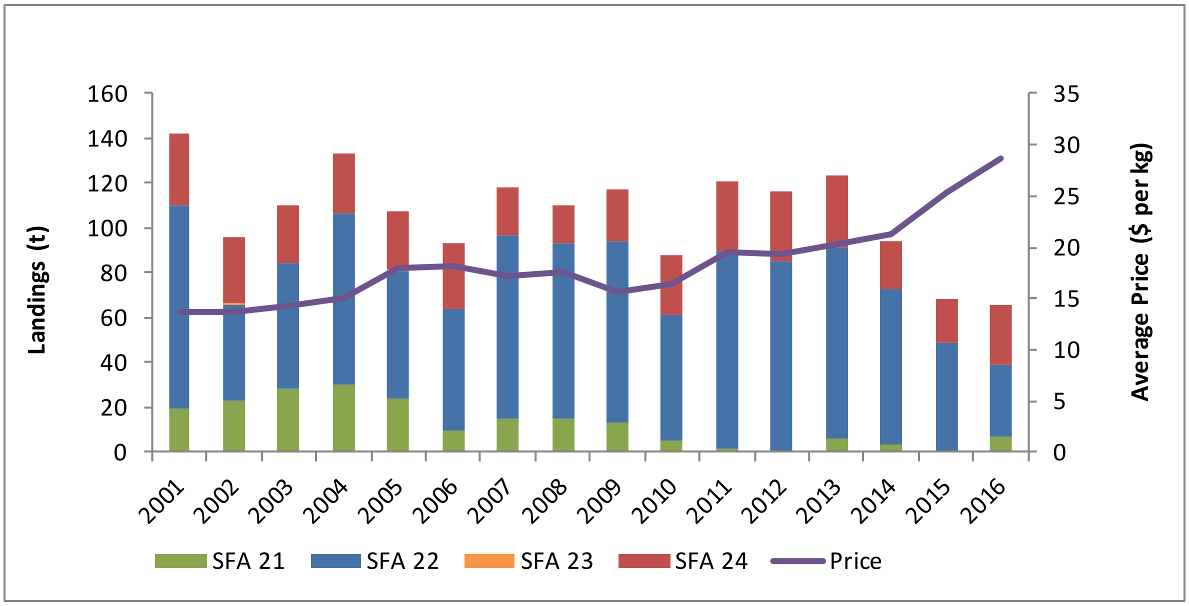

Figure 8. Annual scallop landings for the Gulf Region by Scallop Fishing Area (SFA) and average price per kg of meat.

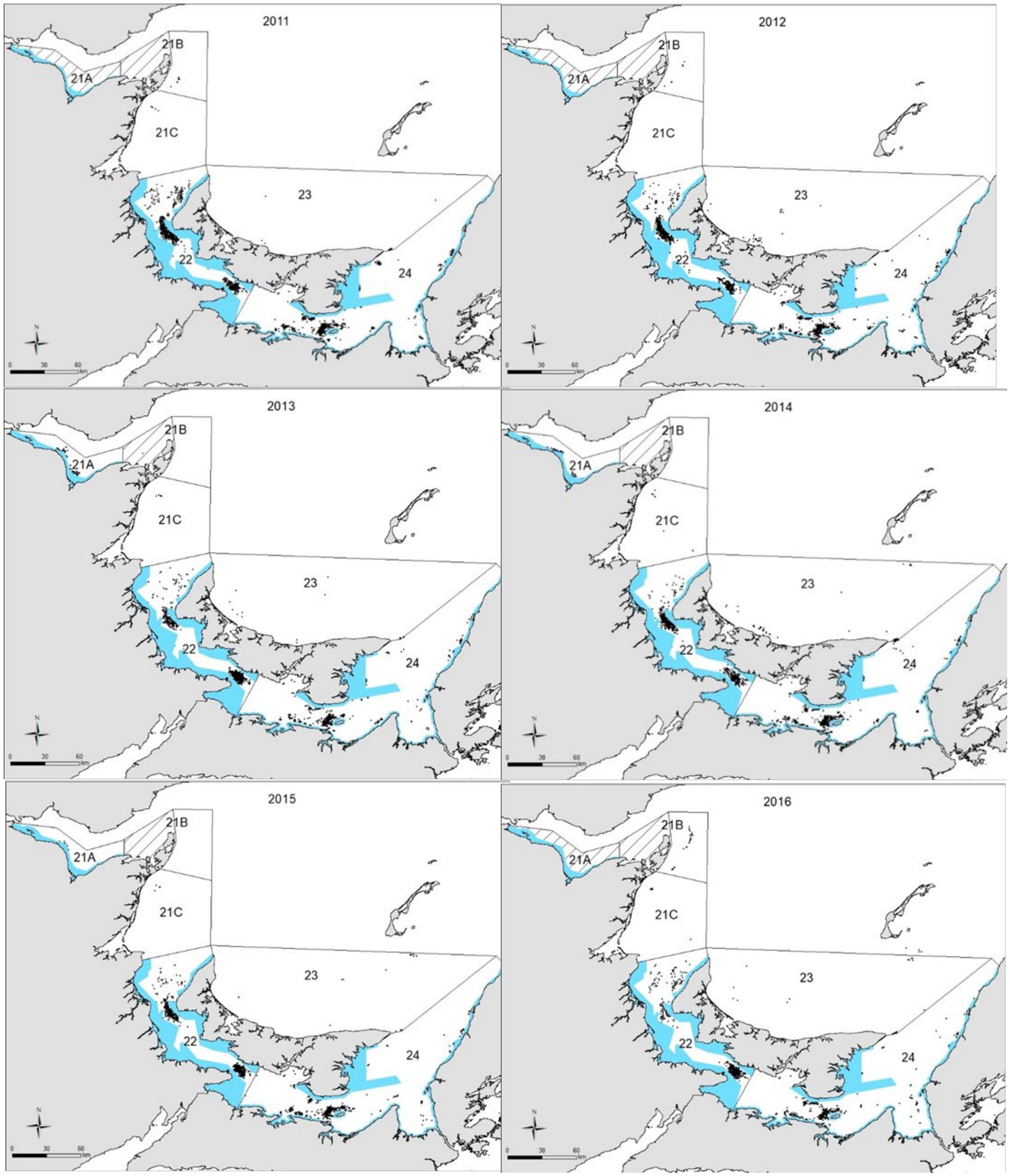

Figure 9. Spatial distribution of effort (black dots) based on the 2011 to 2016 commercial scallop logbooks and showing buffer zones (shaded blue) and temporary closures (hash).

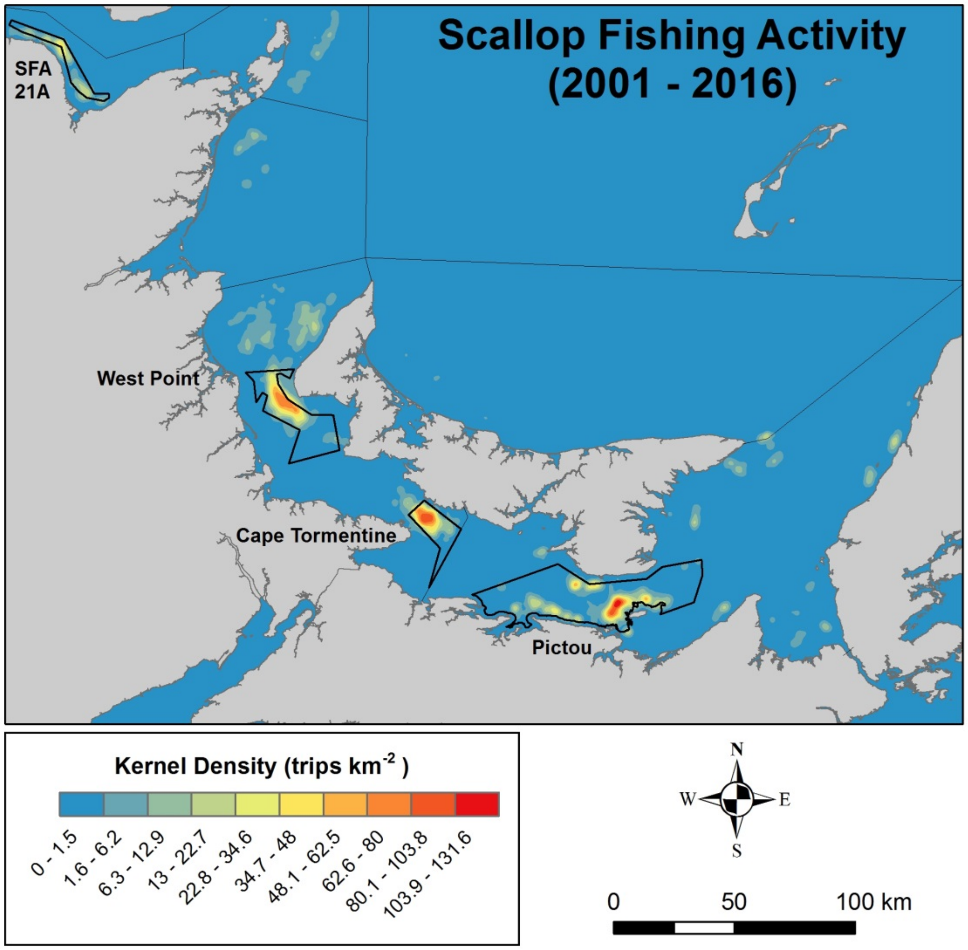

Figure 10. Kernel density plot of scallop fishing trips, expressed as number of trips with positional data from logbooks per km², for the southern Gulf of St. Lawrence commercial scallop fishery, summed over years 2001 to 2016. Fishing effort occurs primarily in three main scallop beds; from north to south, West Point and Cape Tormentine in SFA 22 and Pictou in SFA 24. Also shown are the respective survey sampling strata (black line) used during the scallop research surveys (2012 to 2016), which are used to define the scallop bed for catch rate and other estimates of abundance.

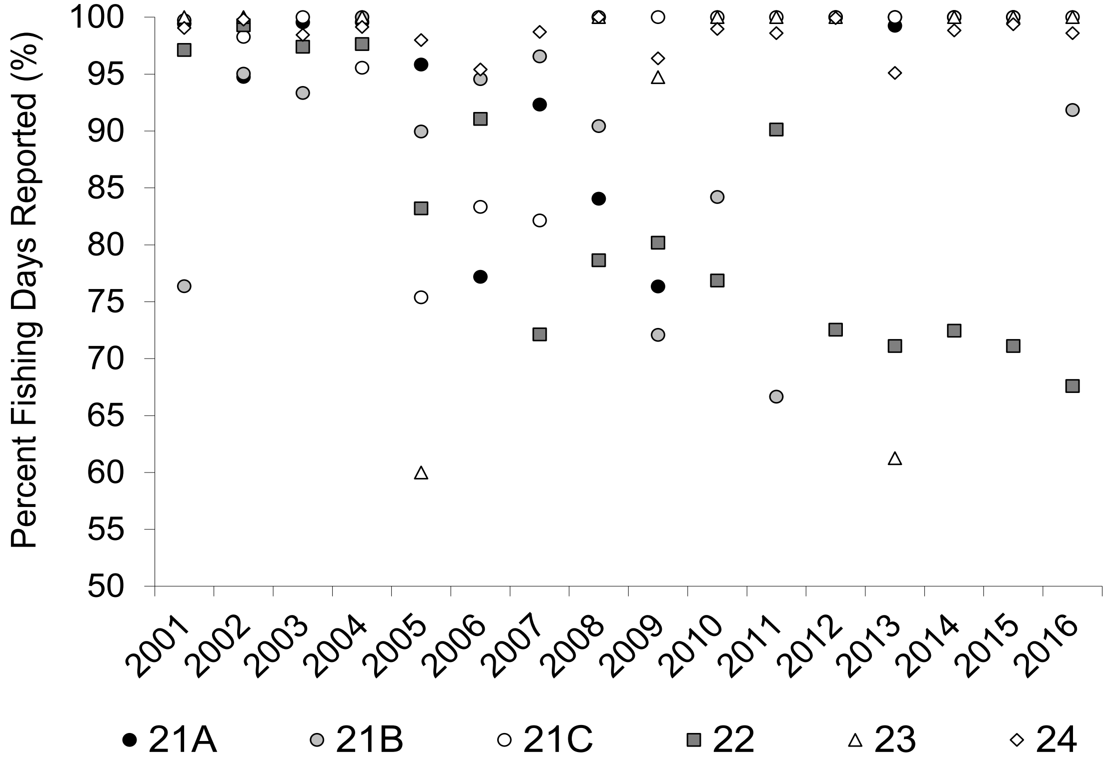

Figure 11. The percentage of the fishing days (trips) recorded in logbooks versus the fishing days estimated from purchase slips by SFA for 2001 to 2016. Note that SFA 23 2007 0 % reporting is not included in graph.

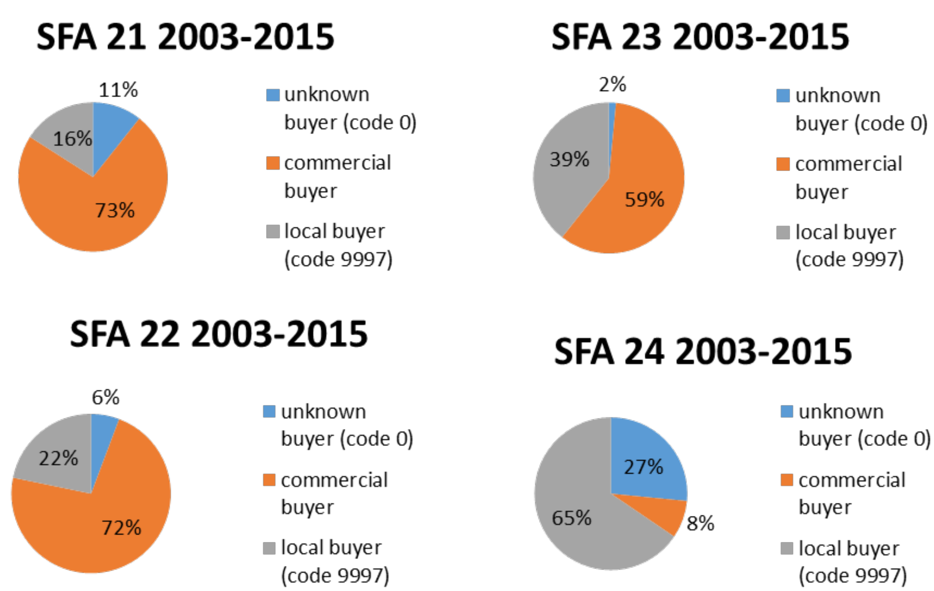

Figure 12. Percent of reported landings by types of buyer: unknown buyer, commercial buyer and local buyer for each Scallop Fishing Area (SFA) from the 2003 to 2015 logbook and sales slip records from the commercial scallop fishery.

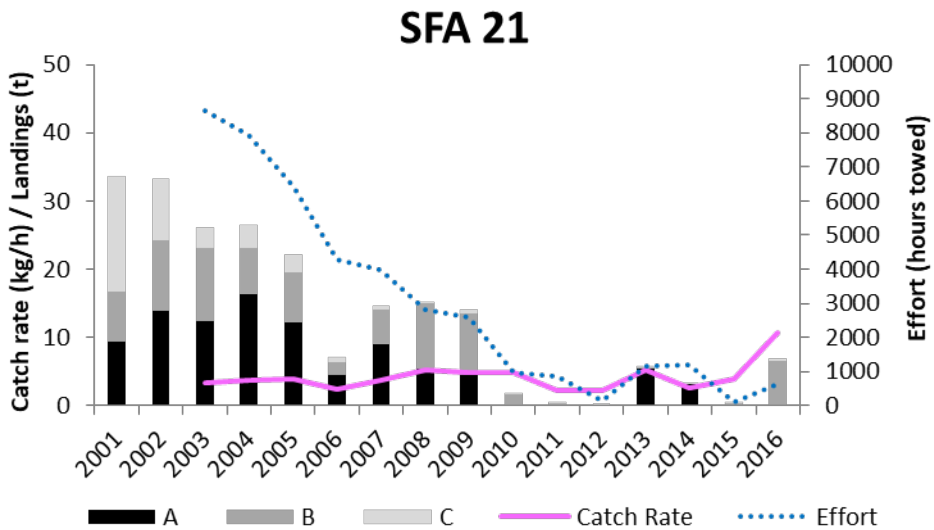

Figure 13. Annual landings (tons of meat) and corresponding catch rates (kg h^{-1}) and total fishery effort (hours towed) for Scallop Fishing Area (SFA) 21 subareas A, B and C in relation to SFA 21 as a whole, from 2001 to 2016. Note that the fishery was closed in SFA 21A from 2010 to 2012 and in 2016. Effort data is not available in 2001 and 2002.

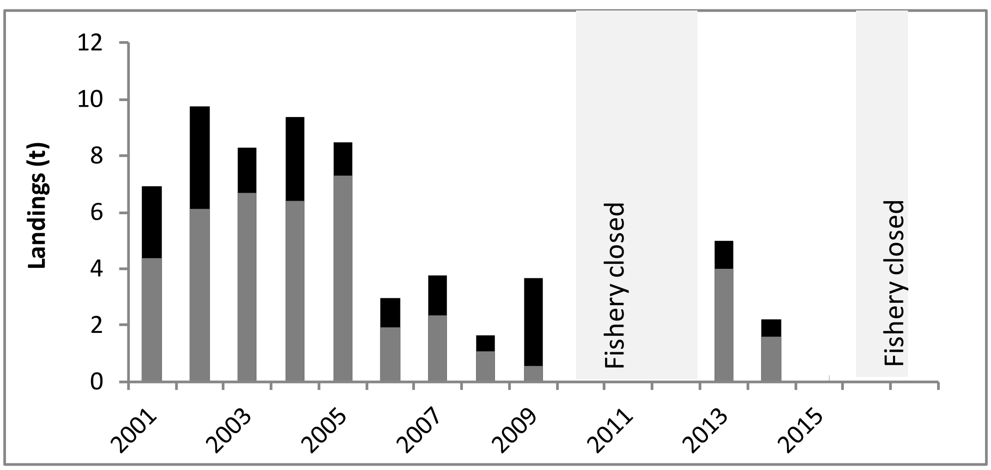

Figure 14. Annual landings (tons of meat) (gray) from 2001 to 2016 according to useable scallop logbooks for the SFA 21A bed and total (including prorated landings) annual landings (black). Note that SFA 21A fishery was closed in 2010-2012 and in 2016.

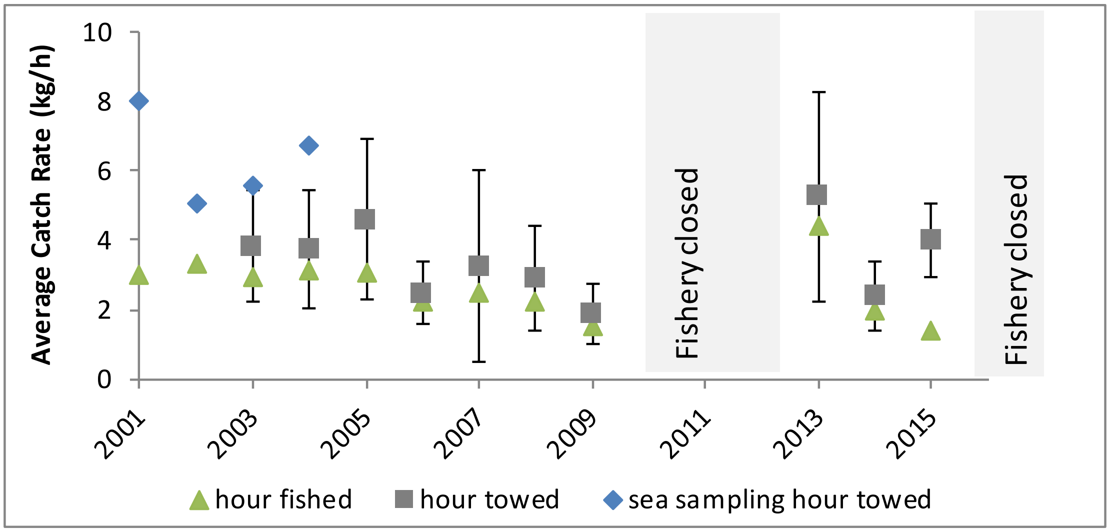

Figure 15. Annual catch rates (kg/hour towed, kg/hour fished) and references to at-sea sampling catch rates (hour towed) from 2001 to 2016 scallop logbooks for the SFA 21A bed. Note that SFA 21A fishery was closed in 2010-2012 and in 2016 according to the 3 kg/h management catch rate threshold.

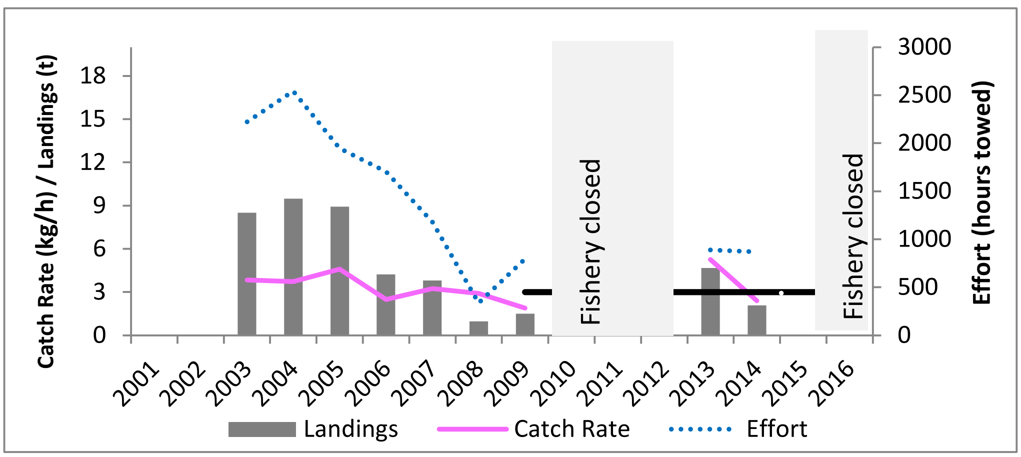

Figure 16. Annual catch rates (kg/hour towed), total fishery effort (hours towed) and landings (tons of meat) from 2003 to 2016 scallop logbooks for the SFA 21A bed. Note that SFA 21A fishery was closed in 2010-2012 and in 2016 according to the 3 kg/h management catch rate threshold (horizontal black line). Data not available for 2001 and 2002.

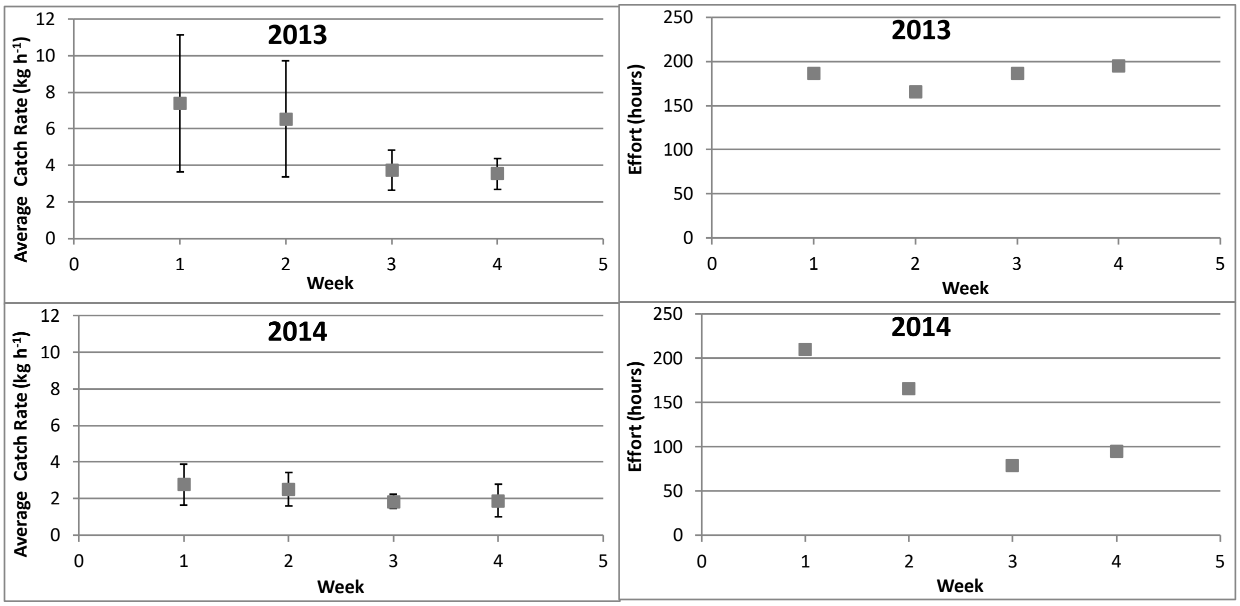

Figure 17. Weekly catch rate (kg h^{-1}) and effort (towed hours) over the four week scallop fishing season for 2013 to 2014 for the Scallop Fishing Area (SFA) 21A bed derived from logbook records.

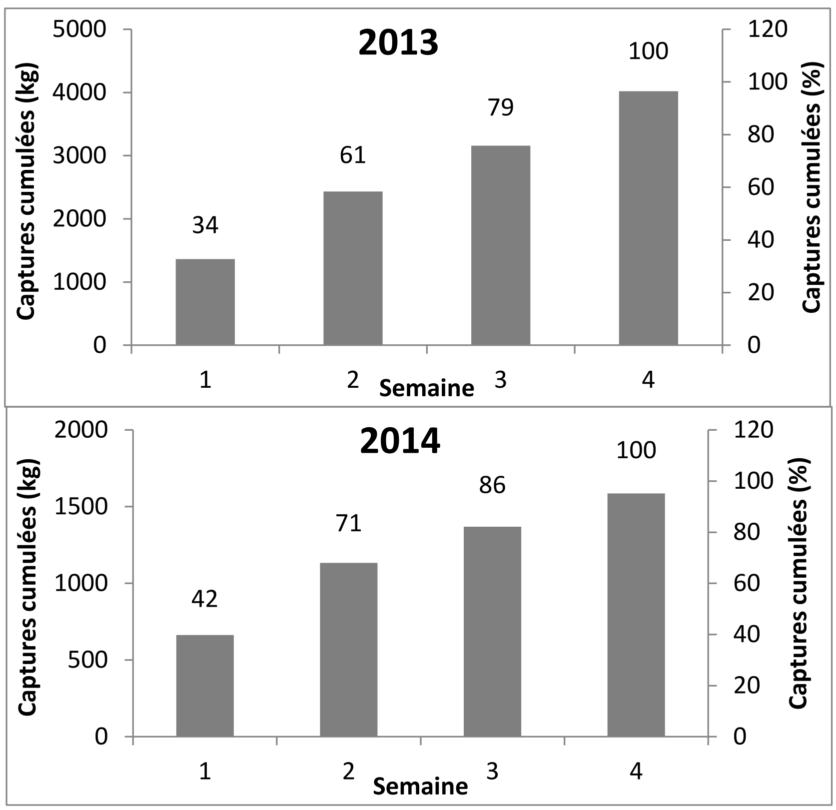

Figure 18. Weekly cumulative catch (kg) over the four week scallop fishing season for 2013 and 2014 for the Scallop Fishing Area (SFA) 21A bed derived from logbook records.

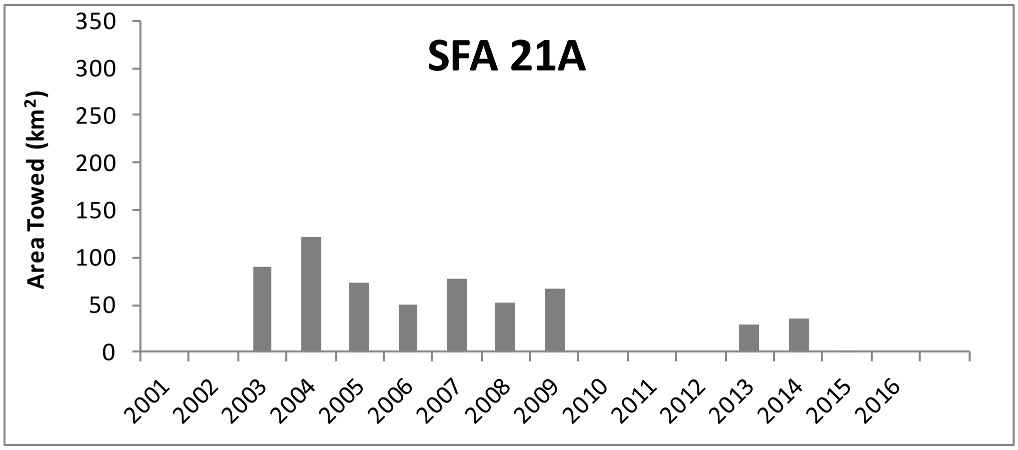

Figure 19. Estimated area towed from 2003 to 2016 according to useable scallop logbooks for the Scallop Fishing Area (SFA) 21A bed (used the mean tow speed of 2.5 knots and drag width of 6 m). Note that the fishery was closed from 2010 to 2012 and in 2016 and the amount of fishing was too low in 2015 to register. Data not available for 2001 and 2002.

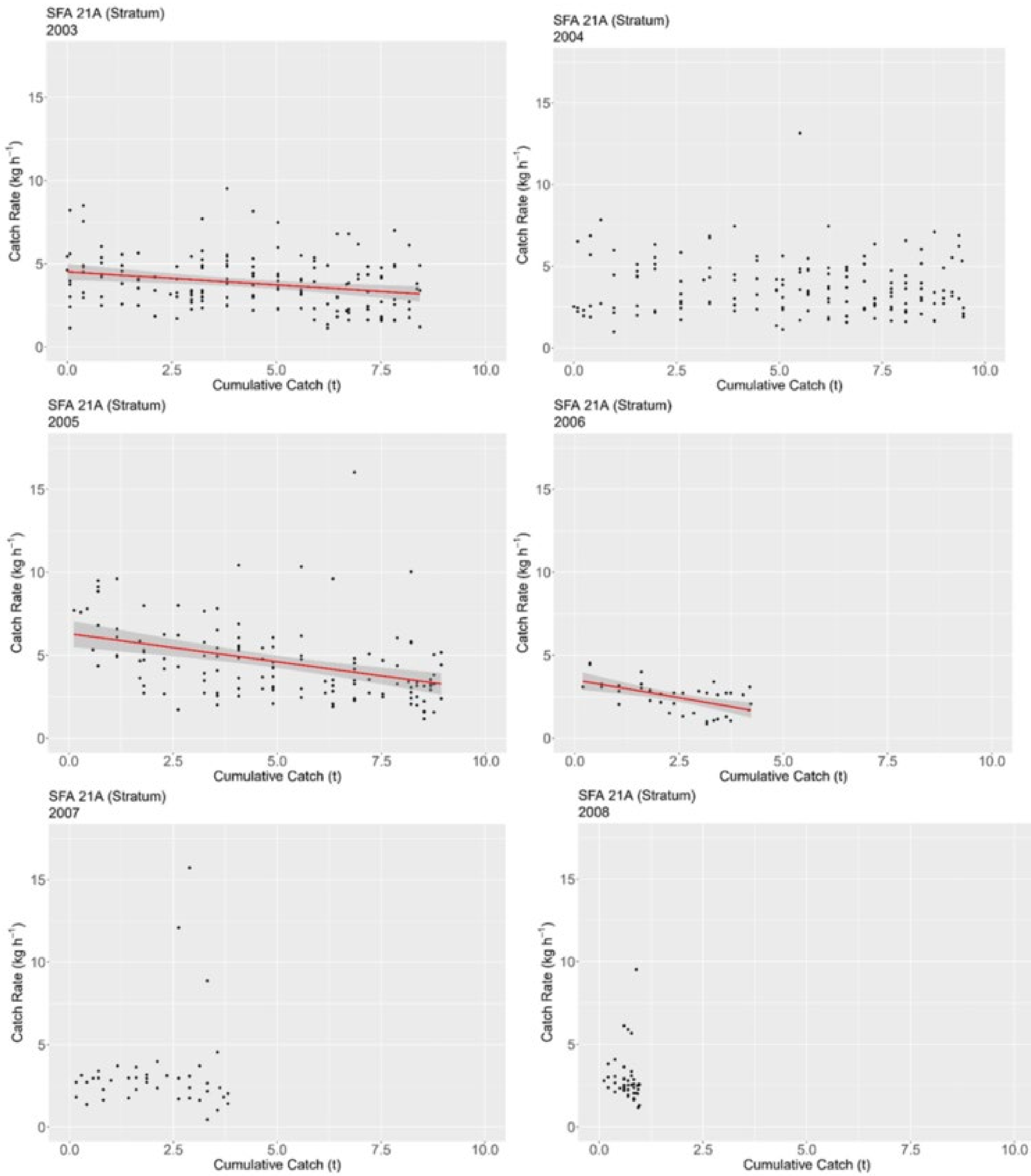

Figure 20. Plot of daily catch rates against the cumulative catch of scallops and the best-fit line (for years in which the model was statistically significant) of the Leslie depletion model for the Scallop Fishing Area (SFA) 21A bed in the Chaleur Bay for each year from 2003 to 2008.

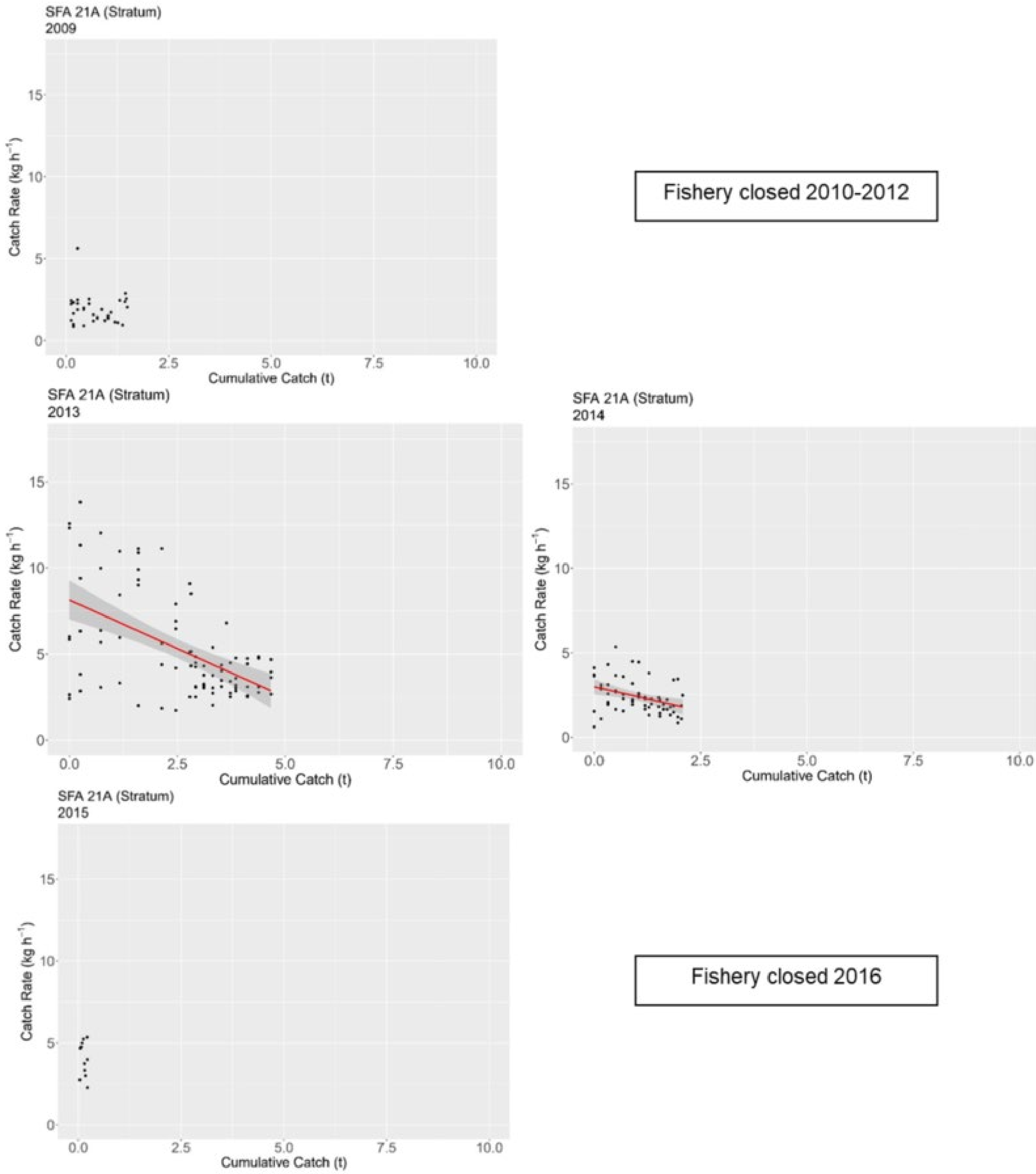

Figure 21. Plot of daily catch rates against the cumulative catch of scallops and the best-fit line (for years in which the model was statistically significant) of the Leslie depletion model for the Scallop Fishing Area (SFA) 21A bed in the Chaleur Bay for each year from 2009 to 2016.

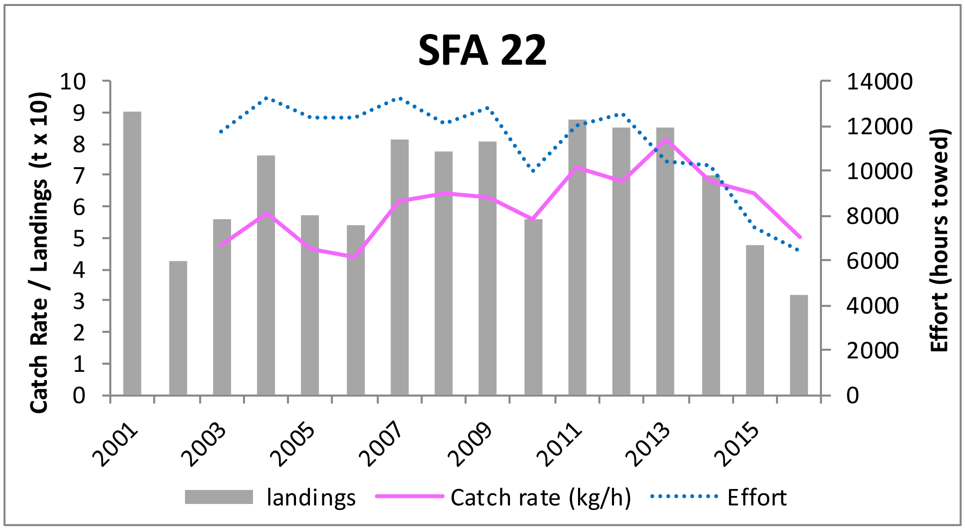

Figure 22. Annual landings and corresponding catch rates (kg h-1) and total fishery effort (hours towed) for Scallop Fishing Area (SFA) 22 in the southern Gulf of St. Lawrence based on logbook data from 2001 to 2016. Effort not recorded in logbooks is estimated from the catch rate values corrected for the total landings. Effort data not available for 2001 and 2002.

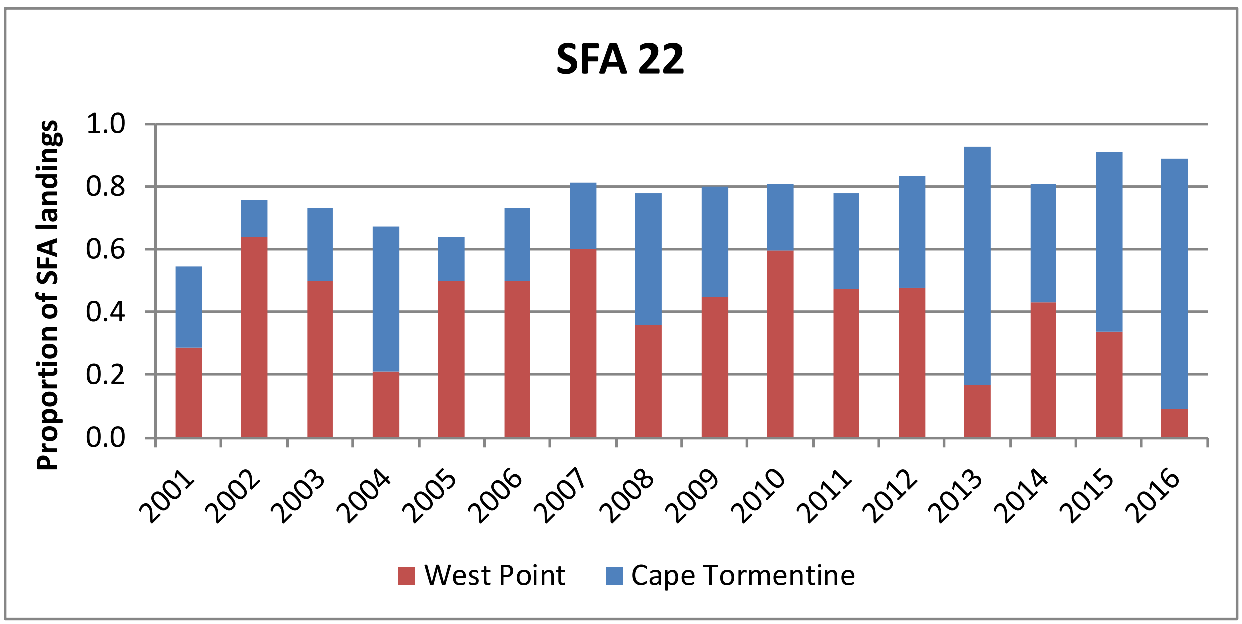

Figure 23. Proportion of Scallop Fishing Area (SFA) 22 landings from the West Point and Cape Tormentine beds between 2001 and 2016 according to fishing positions reported in logbooks.

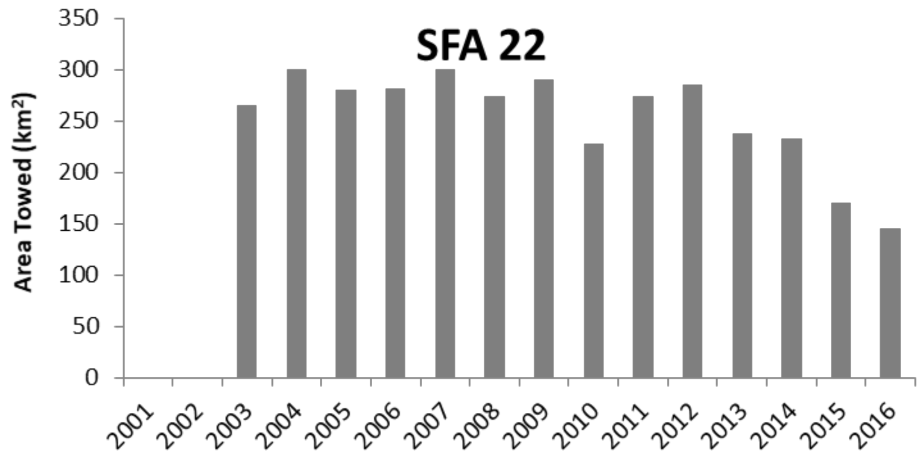

Figure 24. Estimated swept area from 2003 to 2016 according to useable scallop logbooks for Scallop Fishing Area (SFA) 22 (estimated from prorated effort and the mean tow speed of 2.5 knots and drag width of 4.9 m).

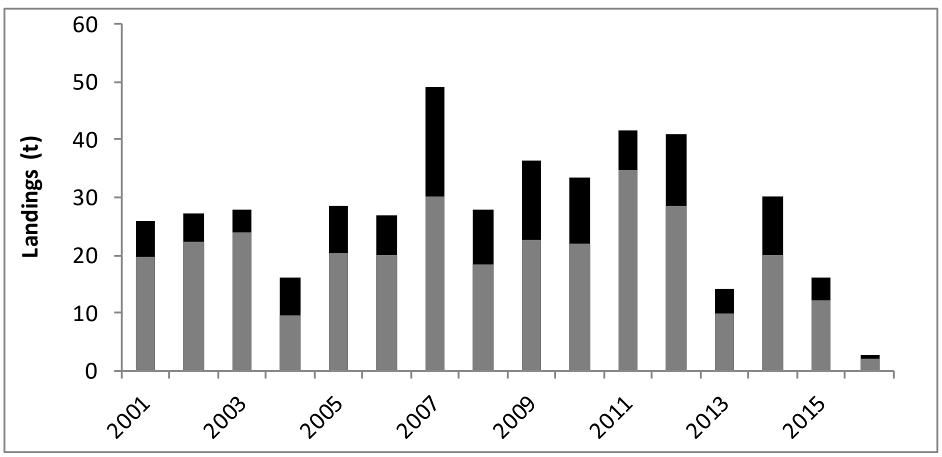

Figure 25. Annual landings (tons of meat) (gray) from 2001 to 2016 according to useable scallop logbooks for the West Point bed and total (including prorated landings) annual landings (black).

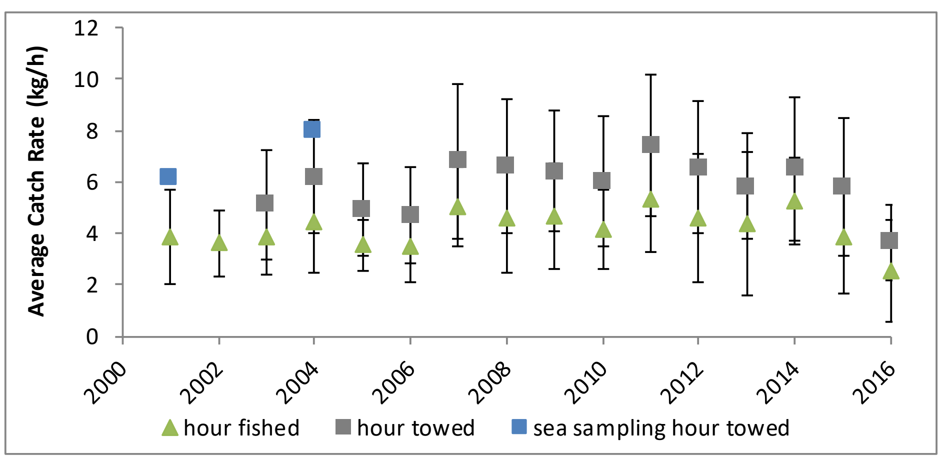

Figure 26. Annual catch rates (kg/hour towed, kg/hour fished from 2001 to 2016 scallop logbooks and references to at-sea sampling data (hour towed) for the West Point bed.

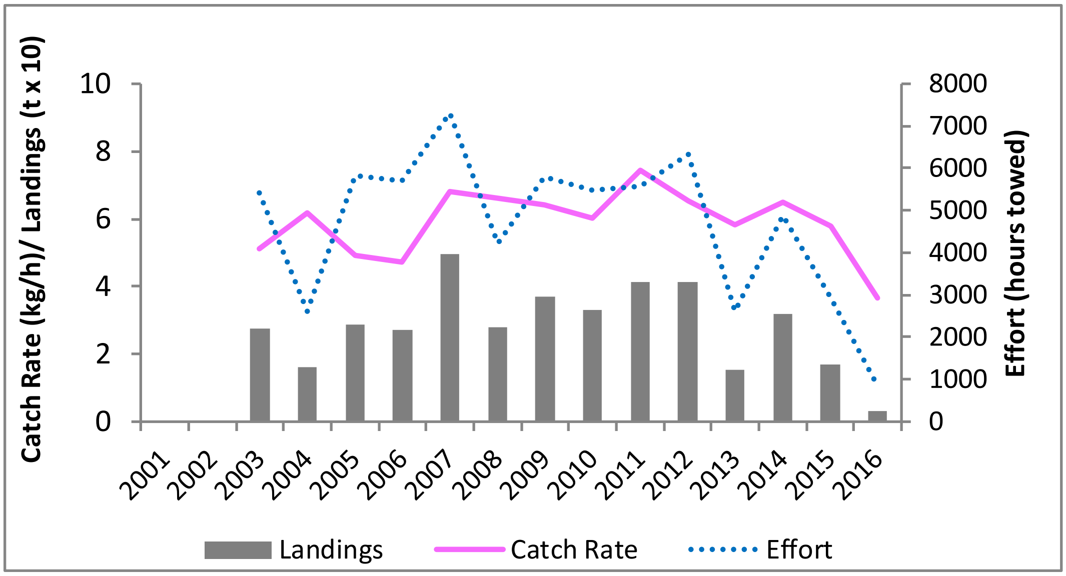

Figure 27. Annual catch rates (kg/hour towed,), landings (tons of meat x 10) and total fishery effort (hours towed) from 2003 to 2016 scallop logbooks for the West Point bed. Data not available for 2001 and 2002.

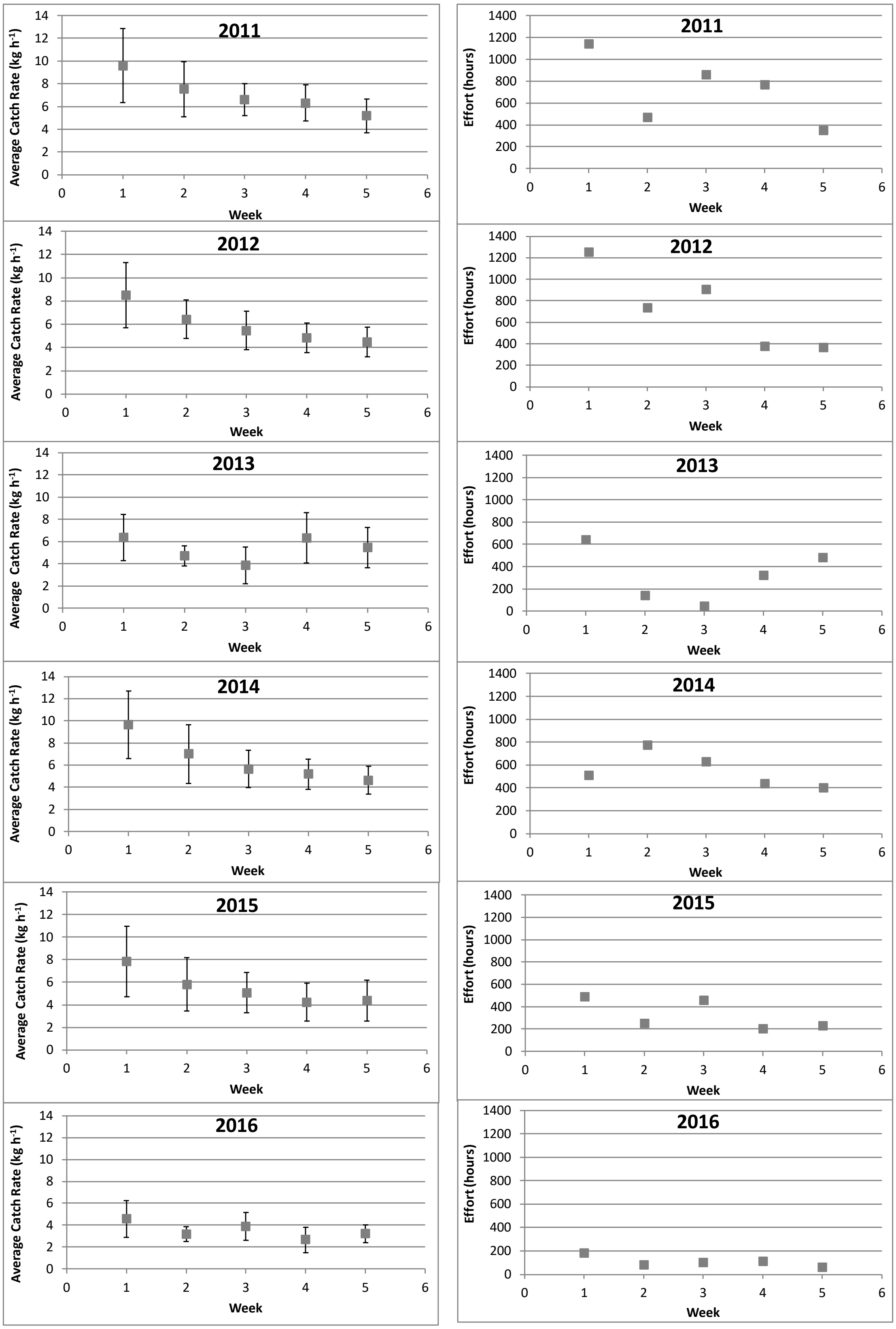

Figure 28. Weekly catch rate (kg h^{-1}) and effort (towed hours) over the five week scallop fishing season for 2011 to 2016 for the West Point bed derived from logbook records.

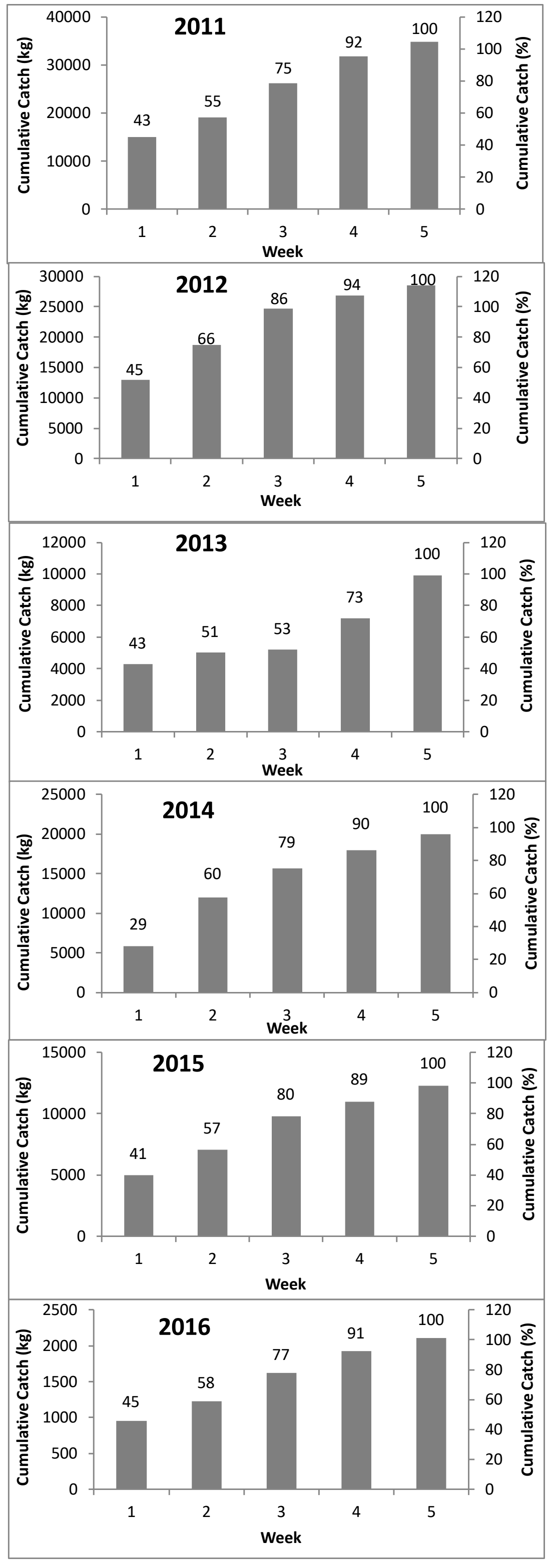

Figure 29. Weekly cumulative catch (kg) over the five week scallop fishing season for 2011 to 2016 for the West Point bed derived from logbook records.

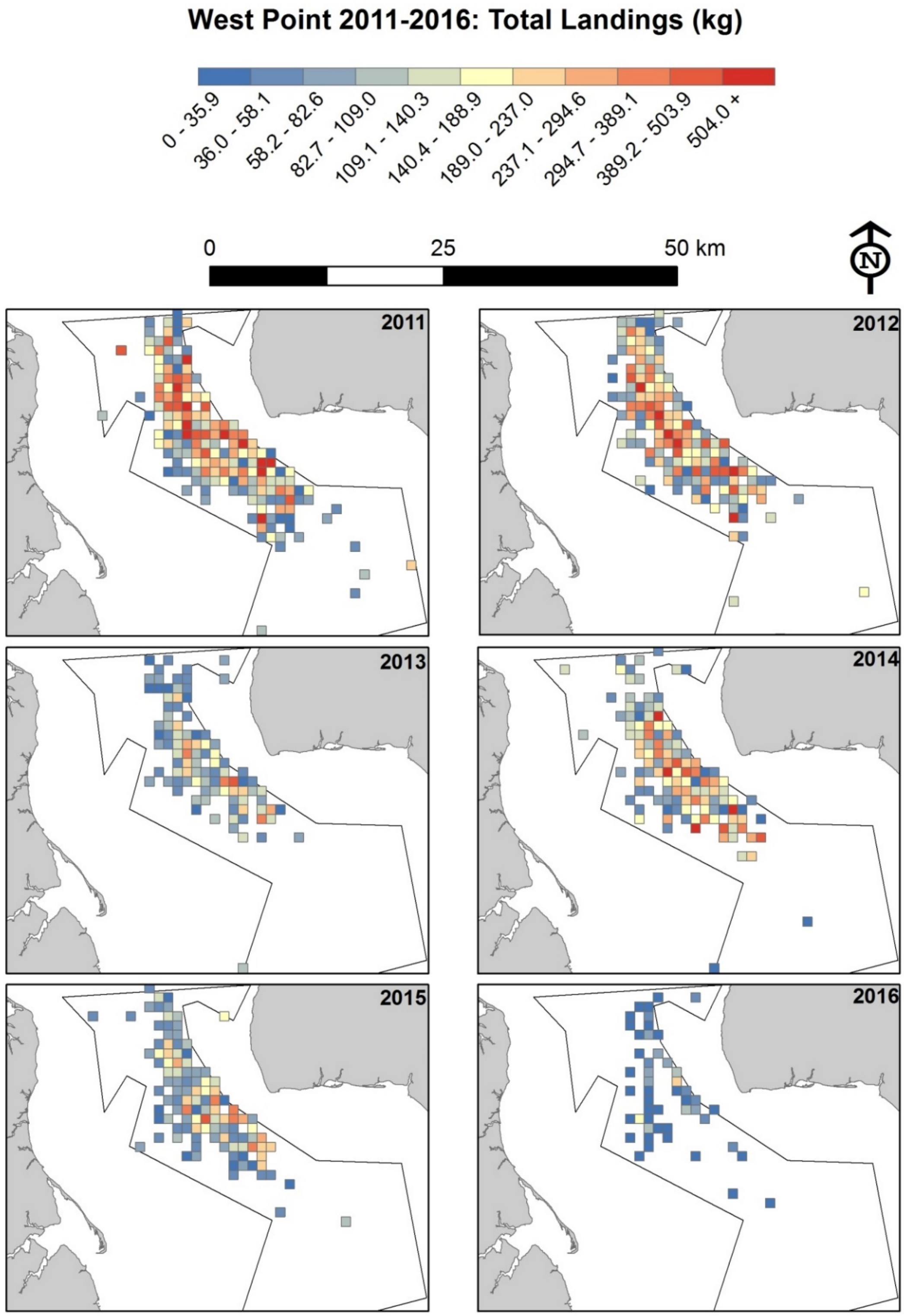

Figure 30. Spatial plot of total landings (kg) per km² of the West Point bed for each year from 2011 to 2016 from commercial logbook data.

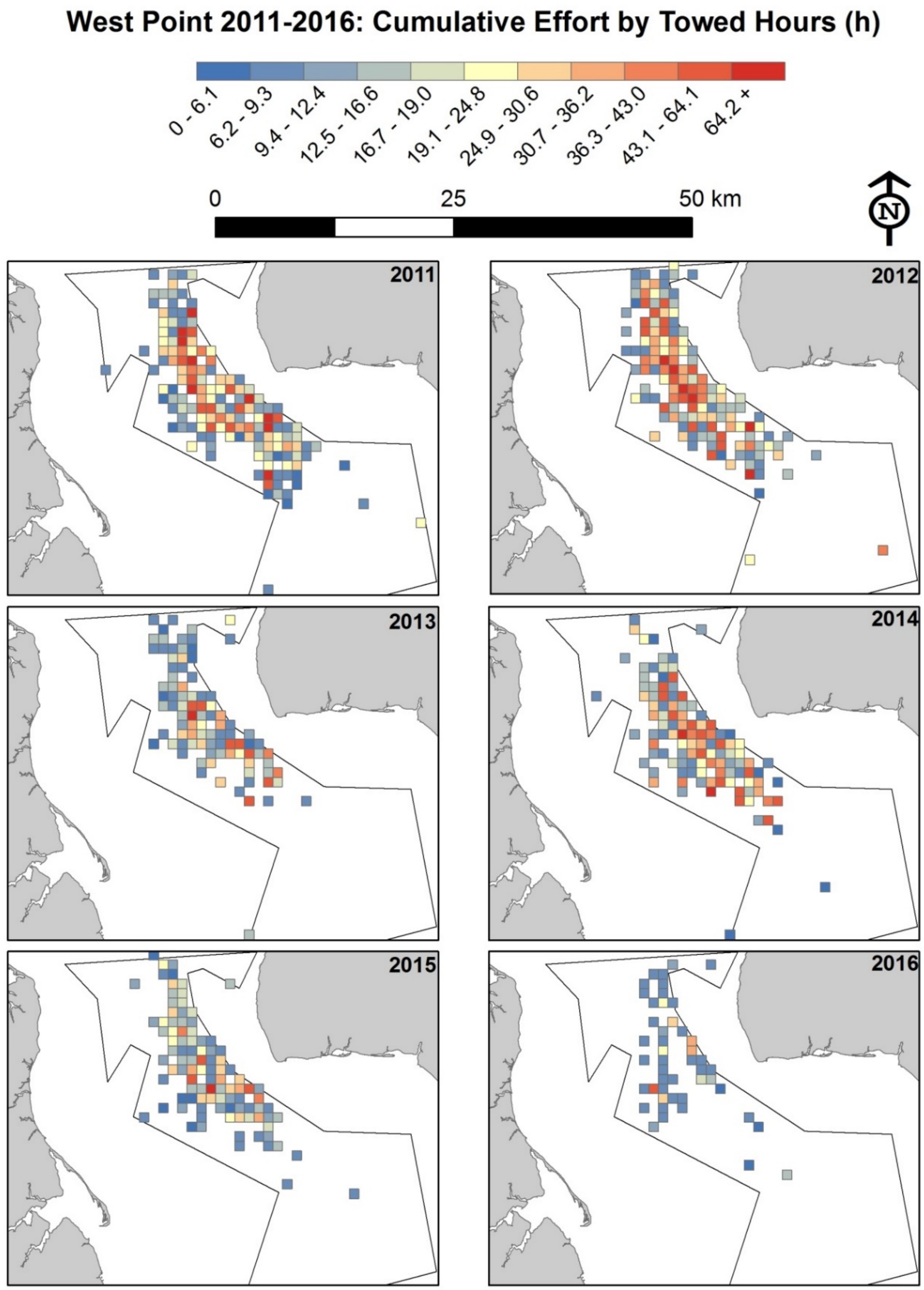

Figure 31. Spatial plot of cumulative effort (hours towed) per km² of the West Point bed for each year from 2011 to 2016 from commercial logbook data.

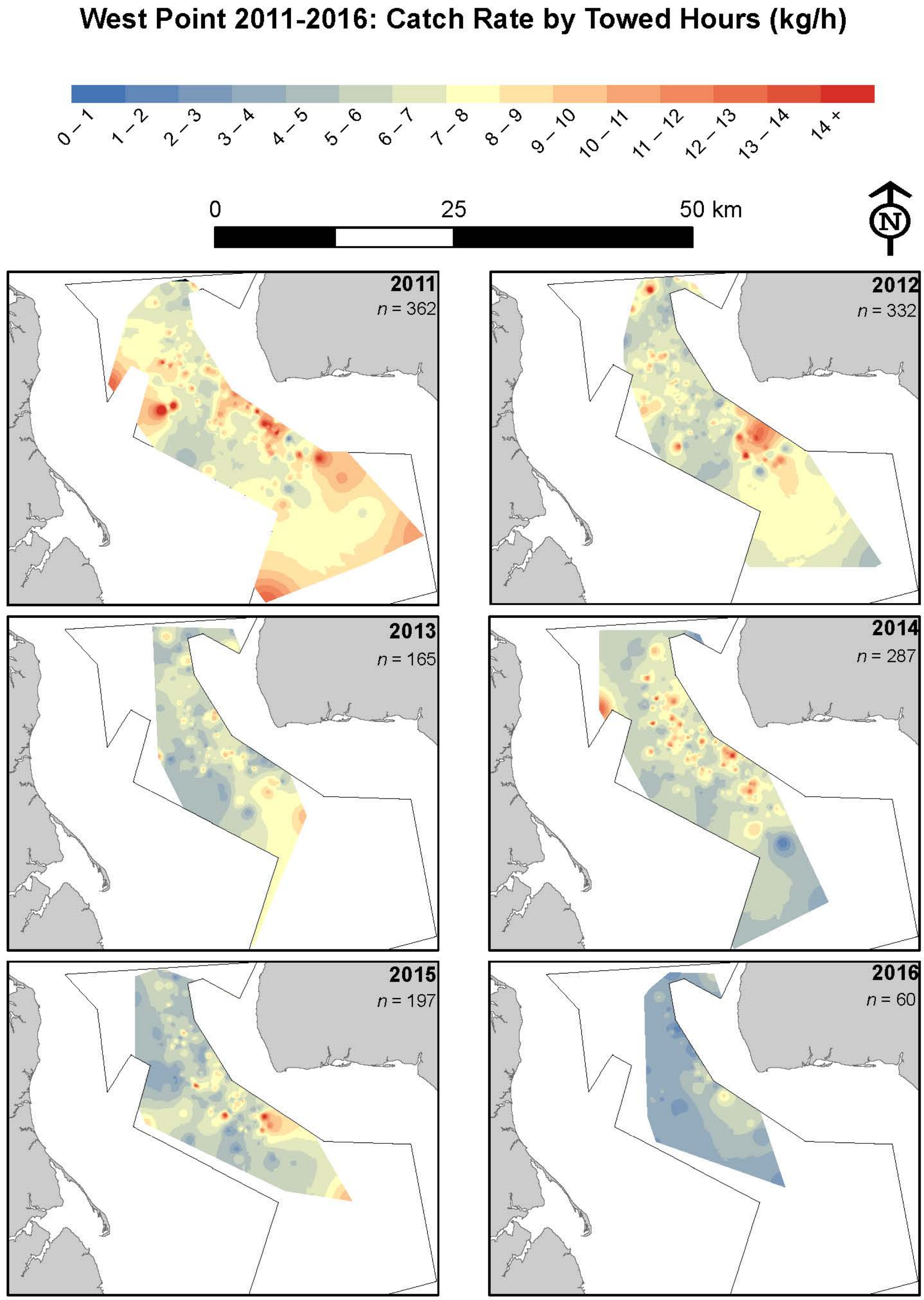

Figure 32. Spatial plot of catch rate (kg h^{-1}) of the West Point bed for each year from 2001 to 2016 from commercial logbook data.

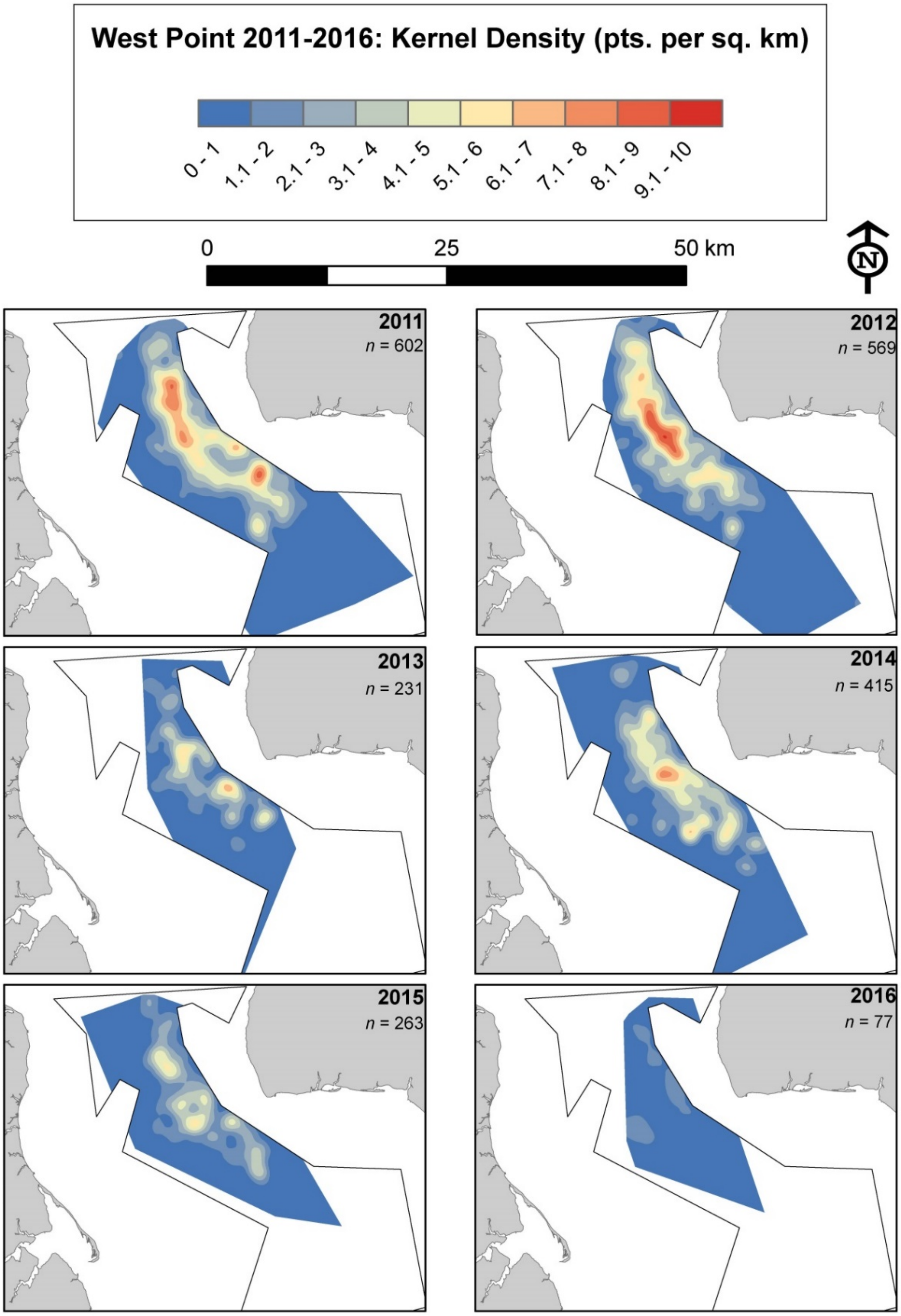

Figure 33. Spatial plot of number of trips (days) per km² of the West Point bed for each year from 2011 to 2016 from commercial logbook data.

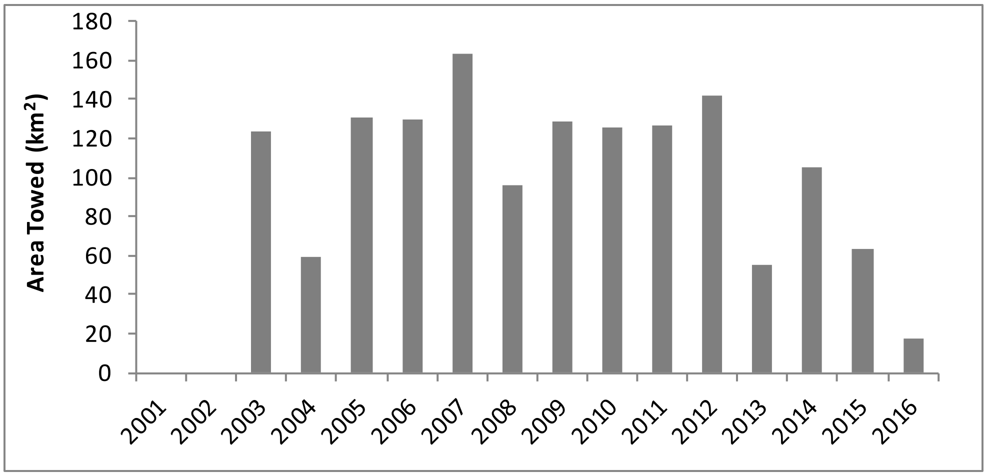

Figure 34. Estimated swept area from scallop fishing on the West Point bed from 2003 to 2016 (estimated from prorated effort, mean vessel speed of 2.5 knots and drag width of 4.9 m). Data not available for 2001 and 2002.

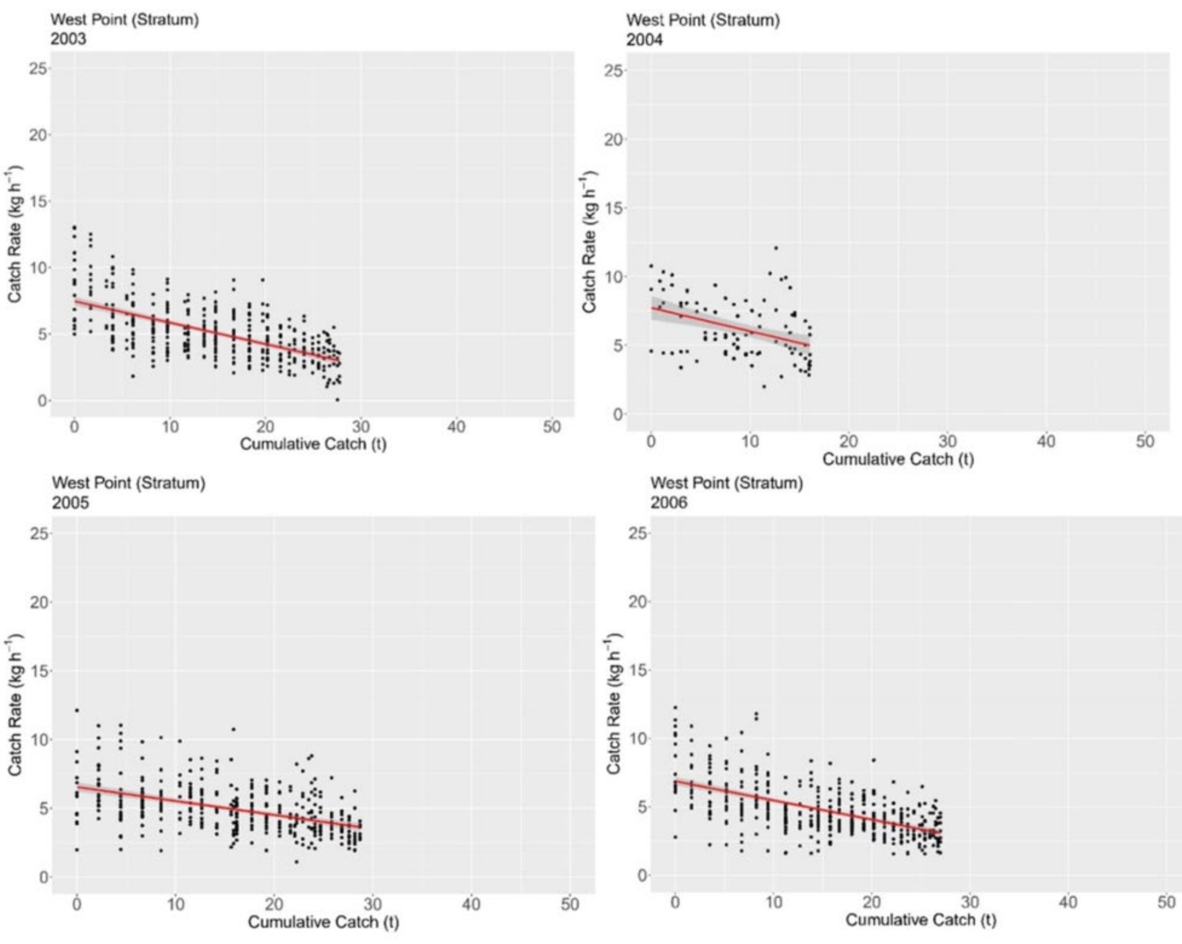

Figure 35. Plot of daily catch rates against the cumulative catch of scallops and the best-fit line (for years in which the model was statistically significant) of the Leslie depletion model for the West Point bed data as defined by the survey stratum for each year from 2003 to 2006.

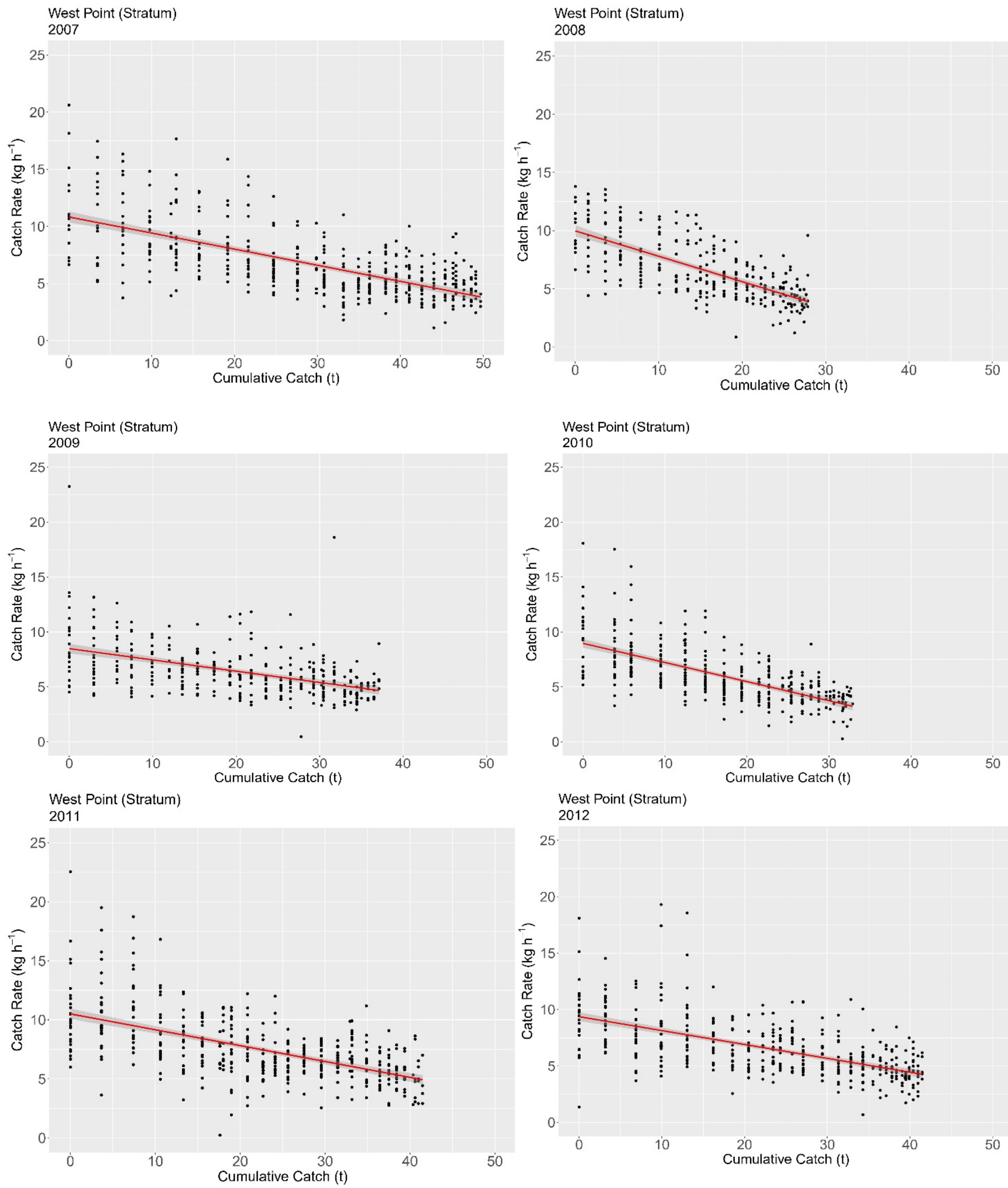

Figure 36. Plot of daily catch rates against the cumulative catch of scallops and the best-fit line (for years in which the model was statistically significant) of the Leslie depletion model for the West Point bed data as defined by the survey stratum for each year from 2007 to 2012.

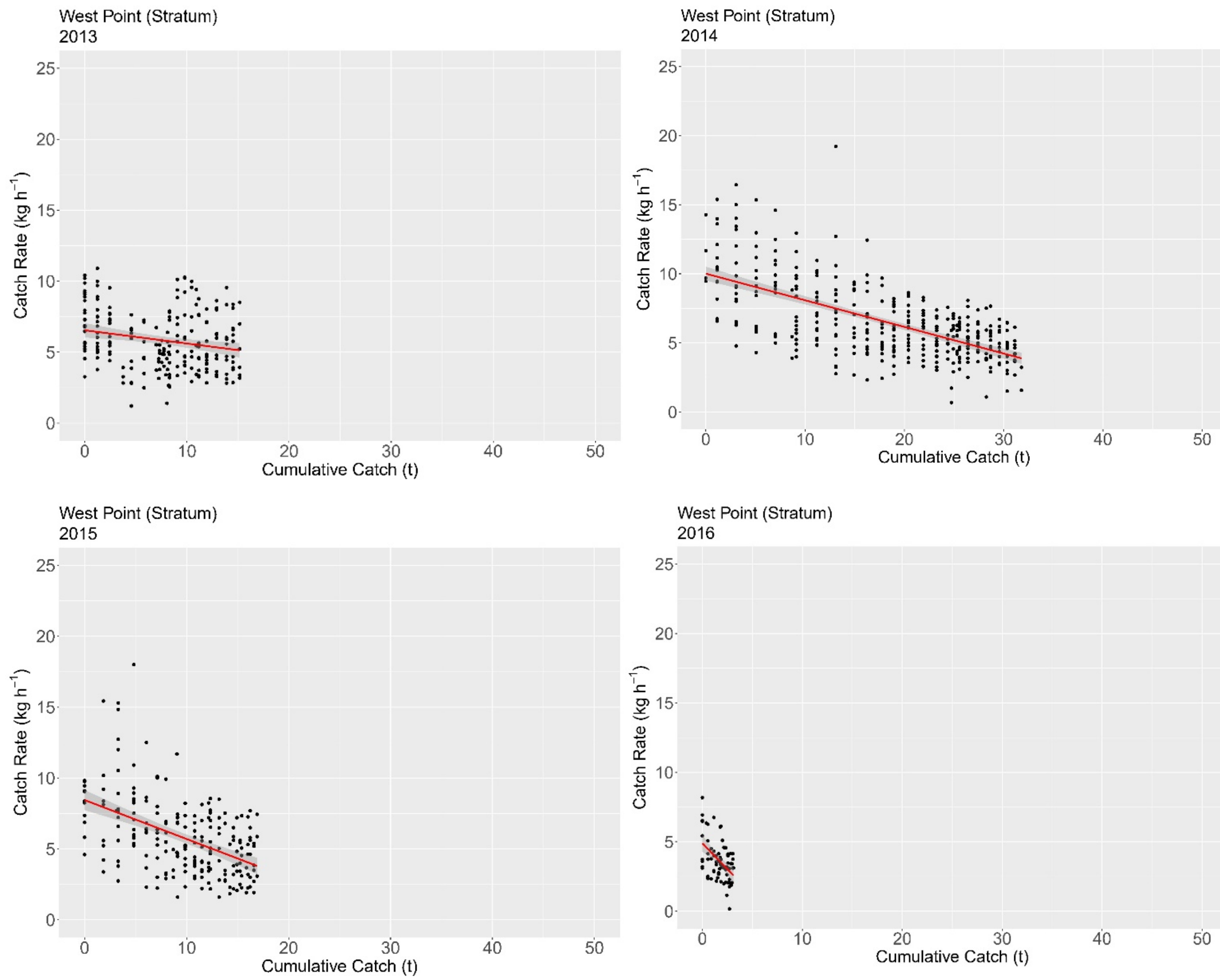

Figure 37. Plot of daily catch rates against the cumulative catch of scallops and the best-fit line (for years in which the model was statistically significant) of the Leslie depletion model for the West Point bed data as defined by the survey stratum for each year from 2013 to 2016.

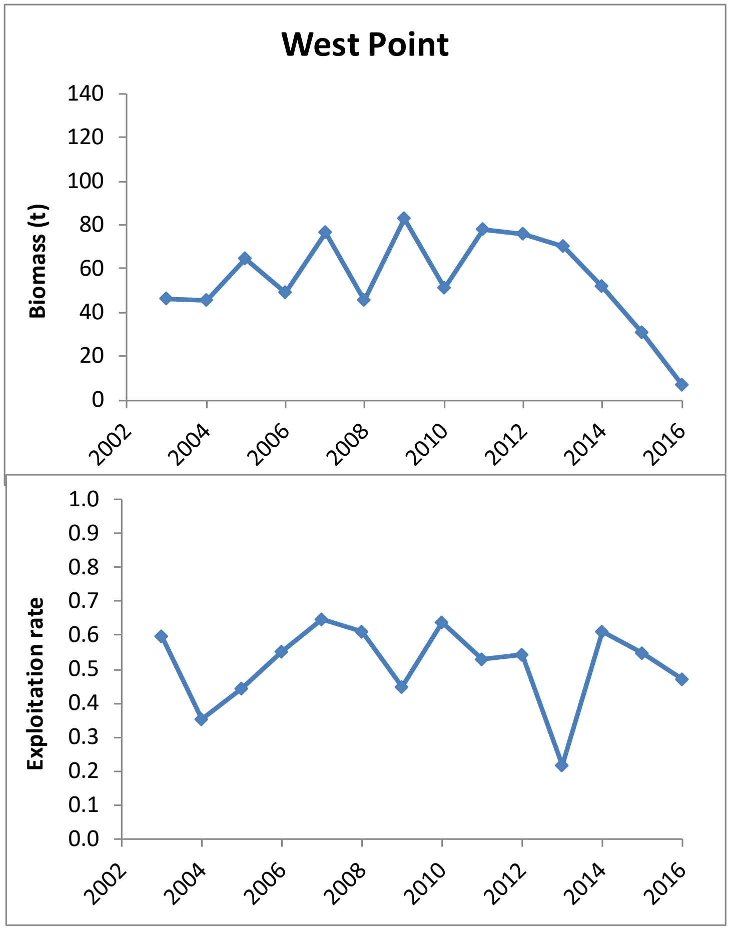

Figure 38. Depletion model estimates of exploitable biomass (B_0) at the start of the fishery and exploitation ($\hat{E}$) rate from 2003 to 2016 for the West Point bed, in Scallop Fishing Area (SFA) 22.

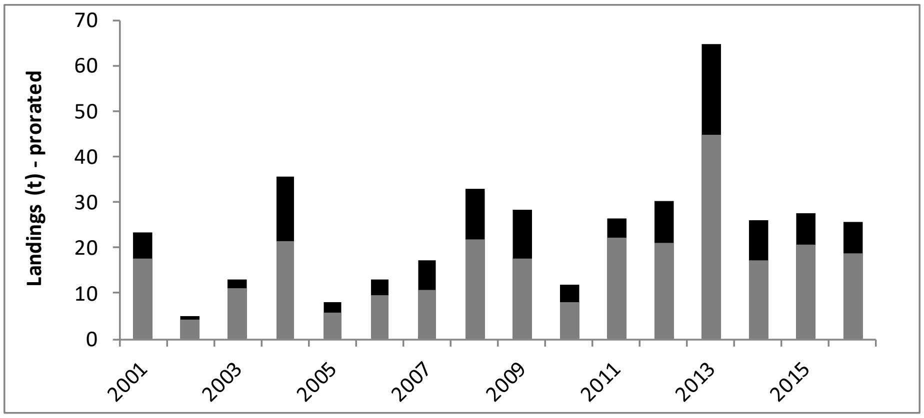

Figure 39. Annual landings (tons of meat) (gray) from 2001 to 2016 according to useable scallop logbooks for the Cape Tormentine bed and total (including prorated landings) annual landings (black).

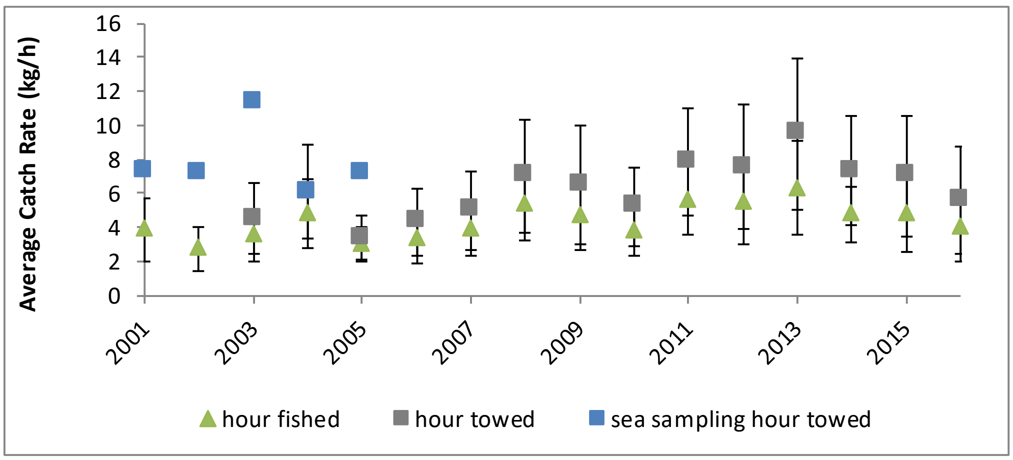

Figure 40. Annual catch rates (kg/ hours towed, kg/hours fished) from 2001 to 2016 scallop logbooks and references to at-sea sampling data for the Cape Tormentine bed.

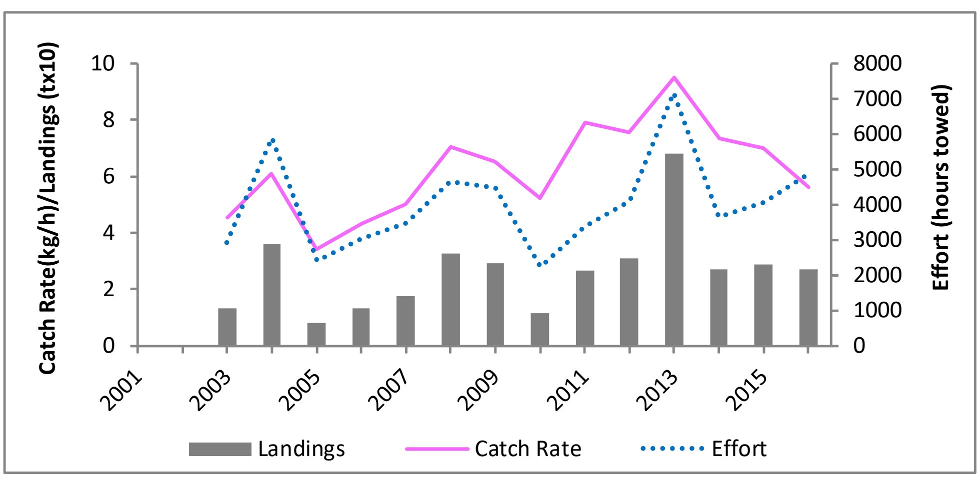

Figure 41. Annual catch rates (kg/ hours towed), landings (tons of meat x10) and total fishery effort (hours towed) from 2003 to 2016 scallop logbooks for the Cape Tormentine bed. Data not available for 2001 and 2002.

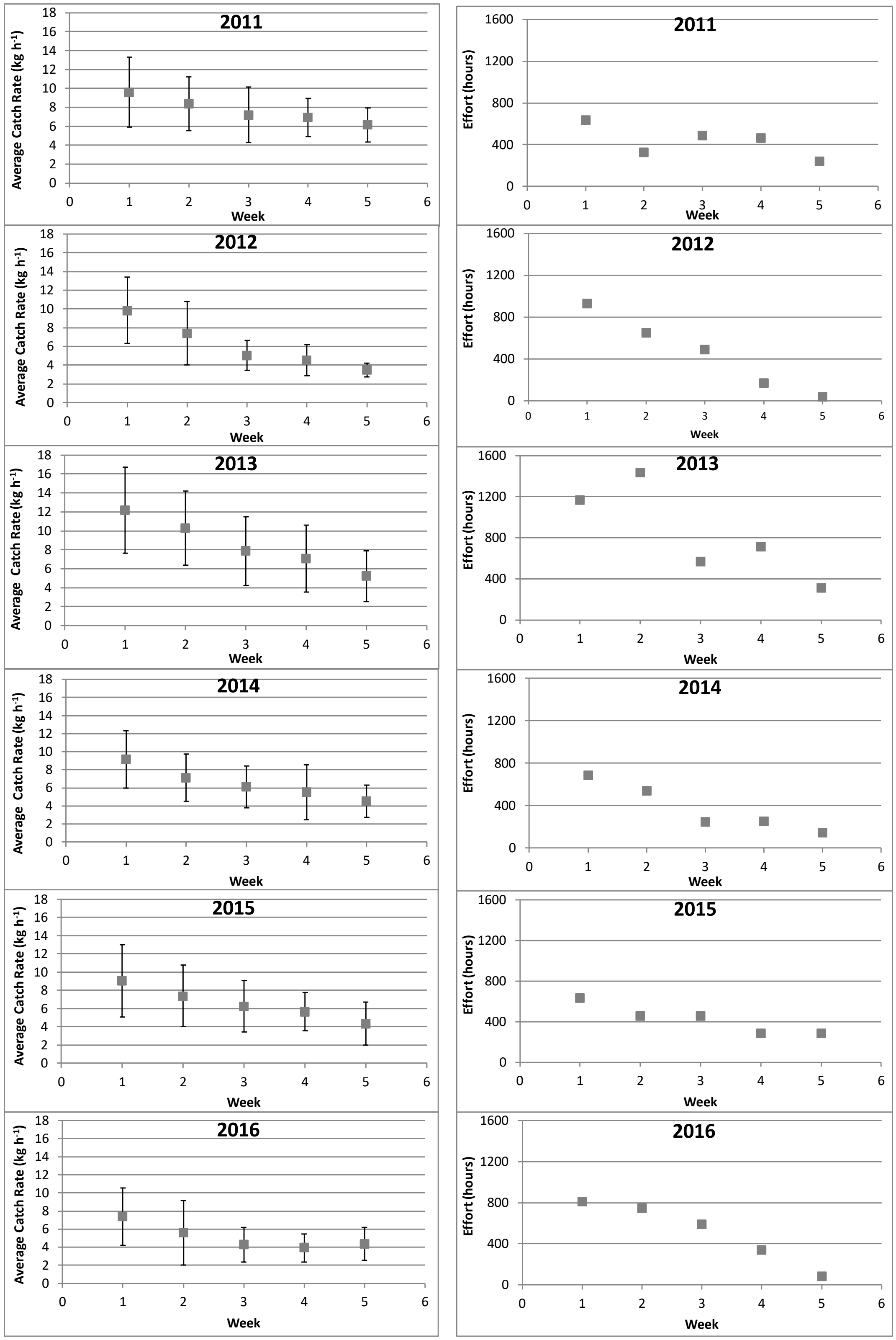

Figure 42. Weekly catch rate (kg/hour towed) and effort (towed hours) over the five week scallop fishing season for 2011 to 2016 for the Cape Tormentine bed derived from logbook records.

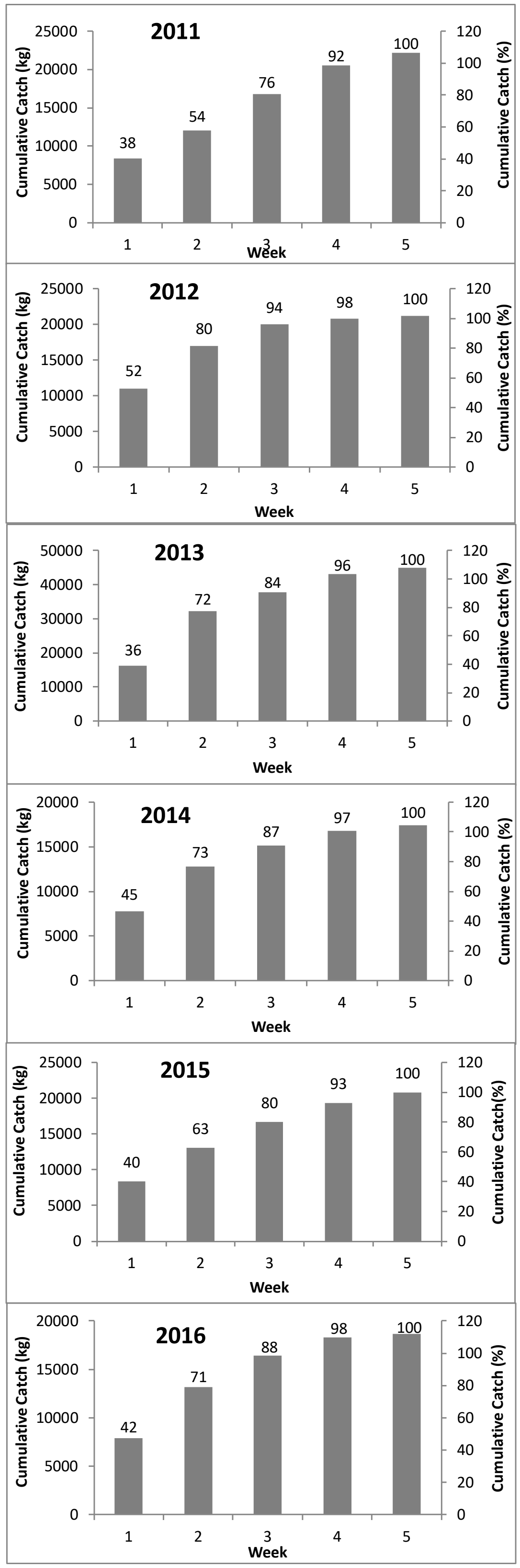

Figure 43. Weekly cumulative catch (kg) over the five week scallop fishing season for 2011 to 2016 for the Cape Tormentine bed derived from logbook records.

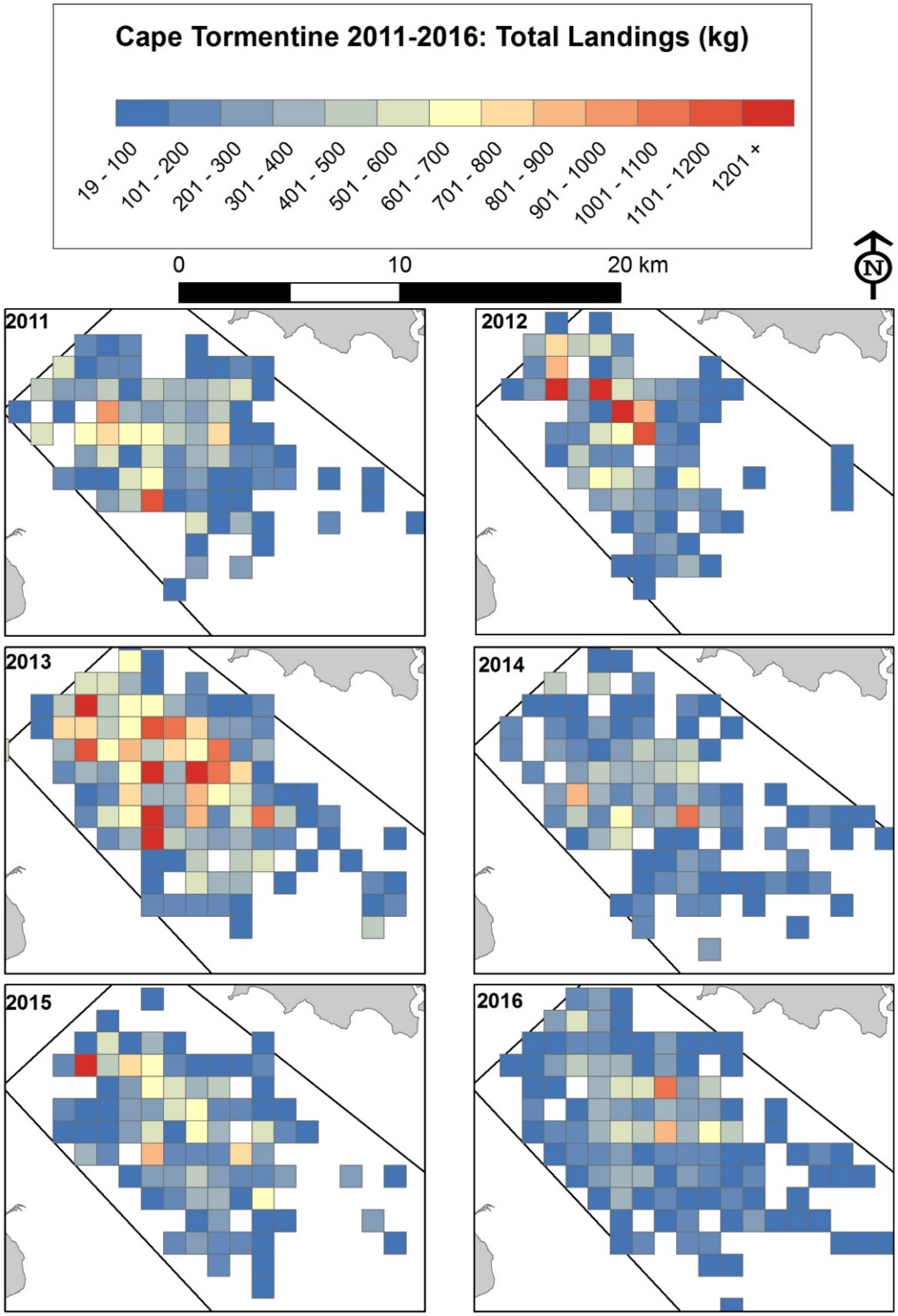

Figure 44. Spatial plot of total landings (kg) per km² of the Cape Tormentine bed for each year from 2011 to 2016 from commercial logbook data.

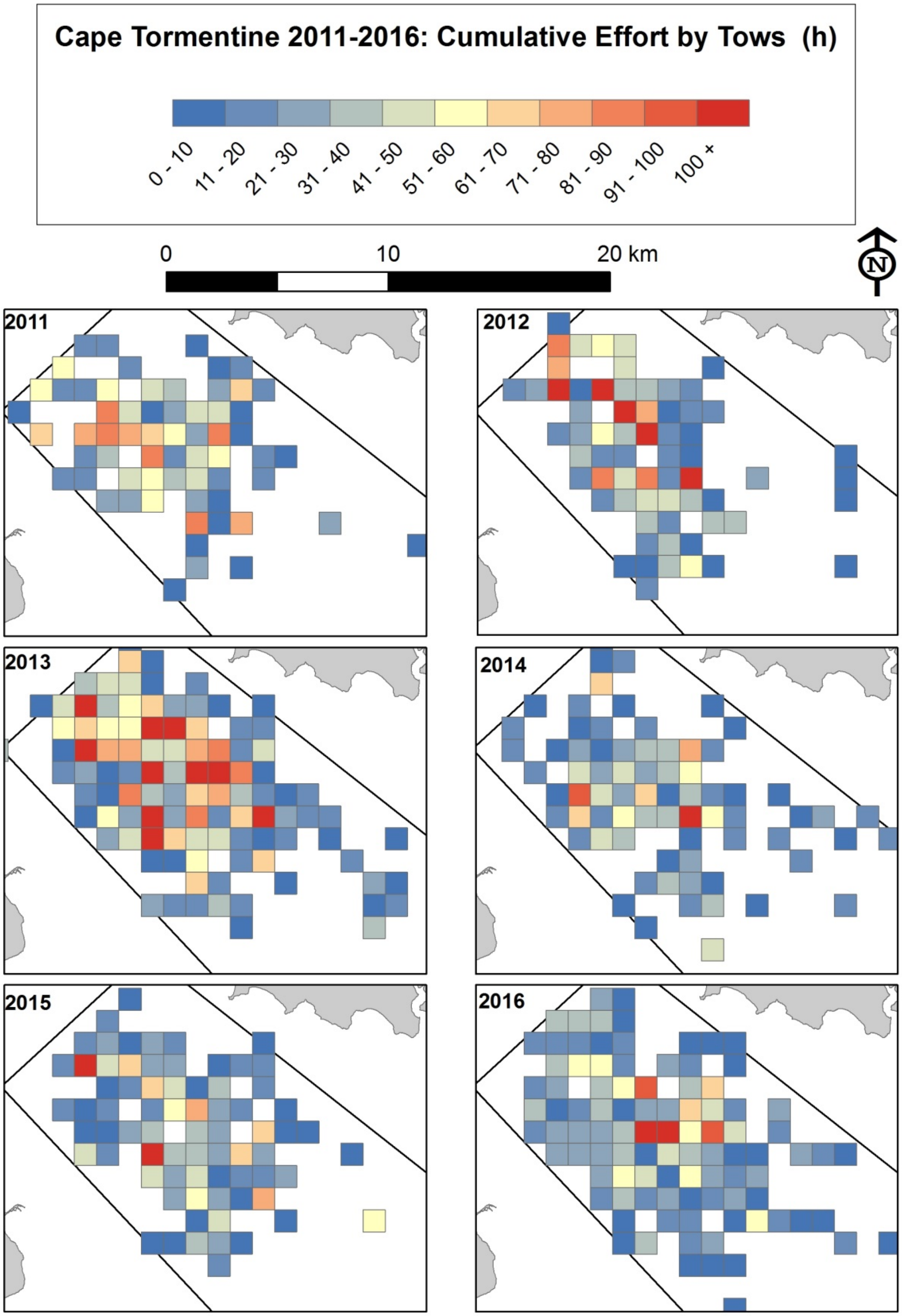

Figure 45. Spatial plot of cumulative effort (hours towed) per km² of the Cape Tormentine bed for each year from 2011 to 2016 from commercial logbook data.

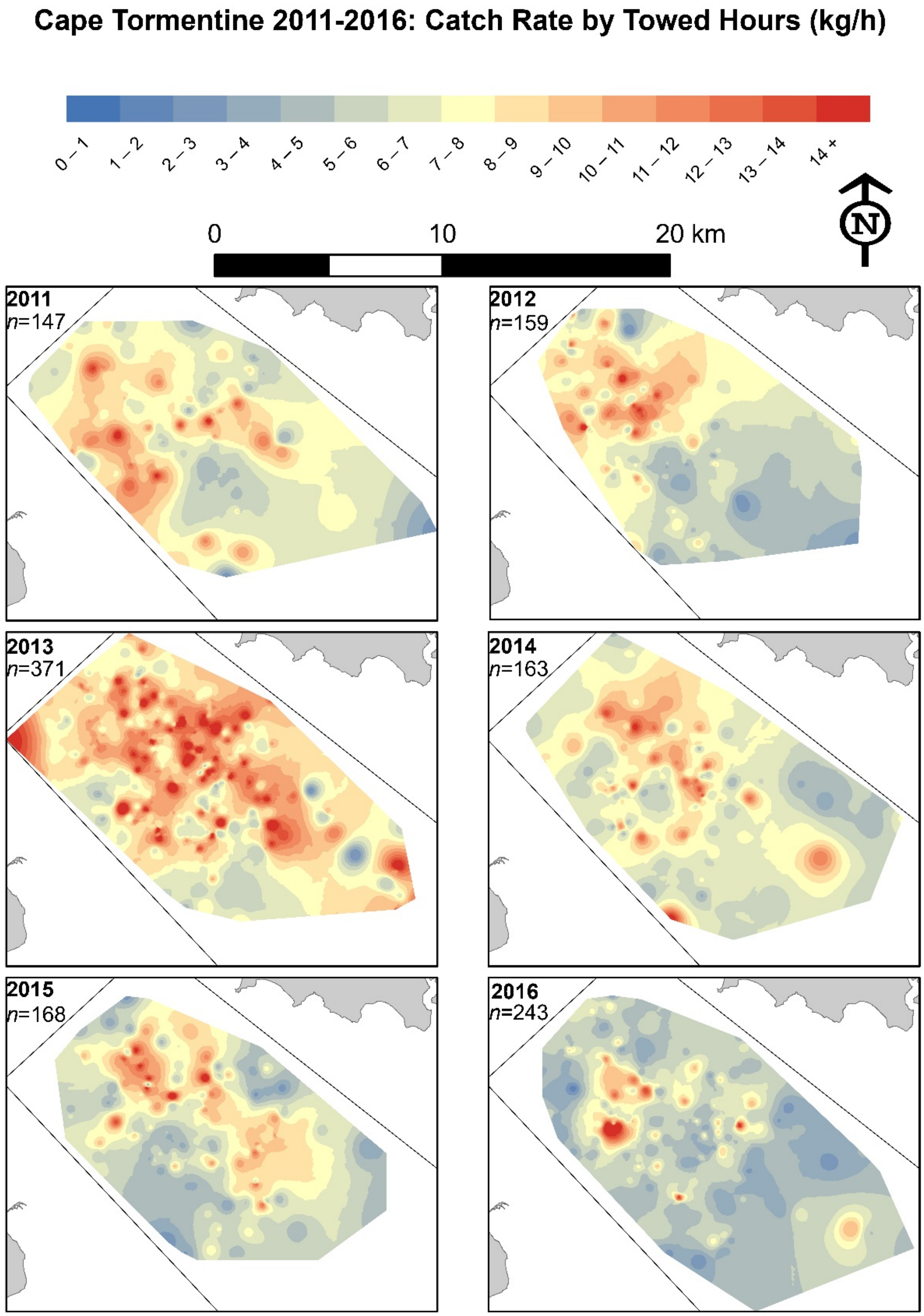

Figure 46. Spatial plot of average catch rate (kg h^{-1}) of the Cape Tormentine bed for each year from 2011 to 2016 from commercial logbook data.

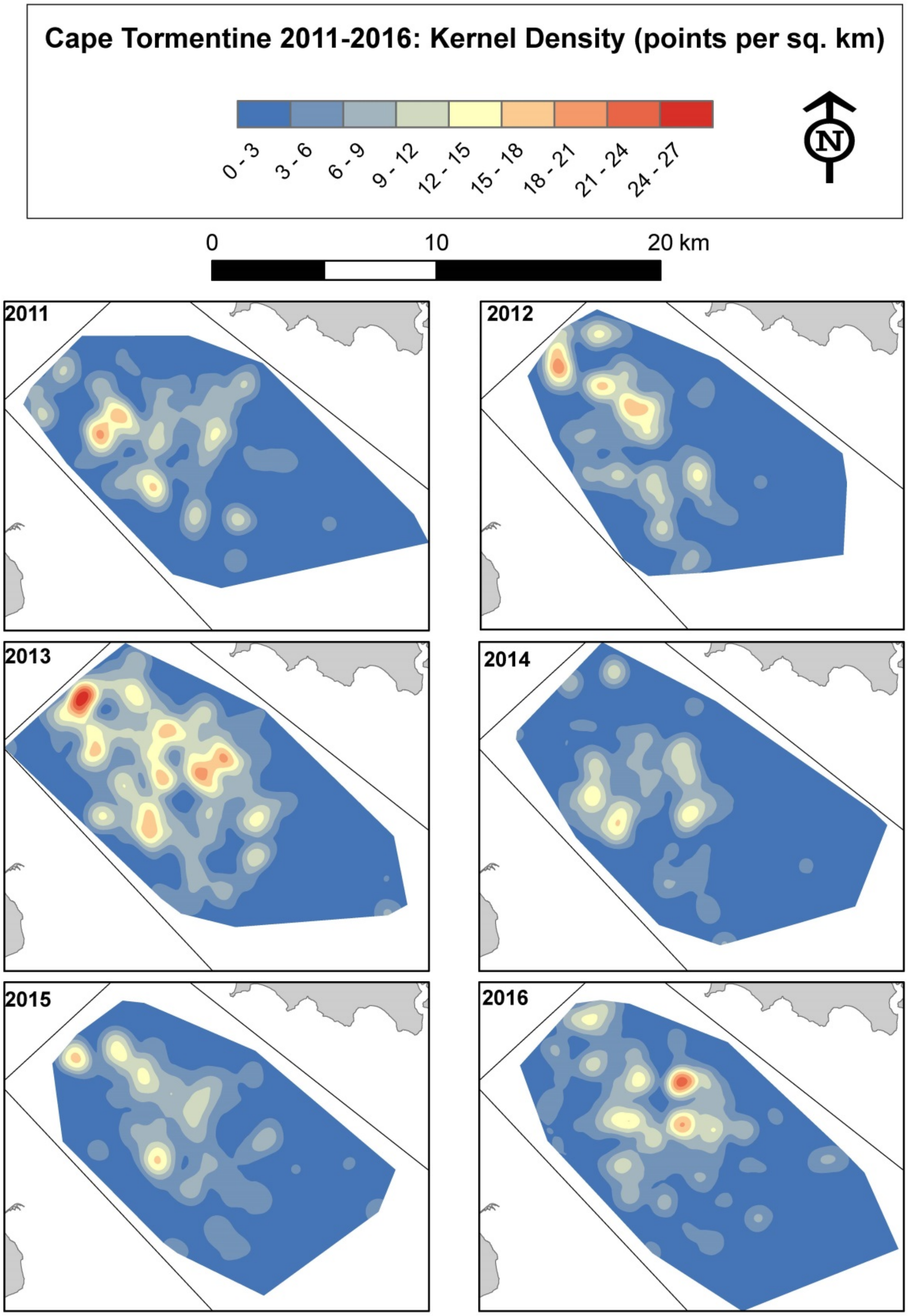

Figure 47. Spatial plot of number of trips (days) per km² of the Cape Tormentine bed for each year from 2011 to 2016 from commercial logbook data.

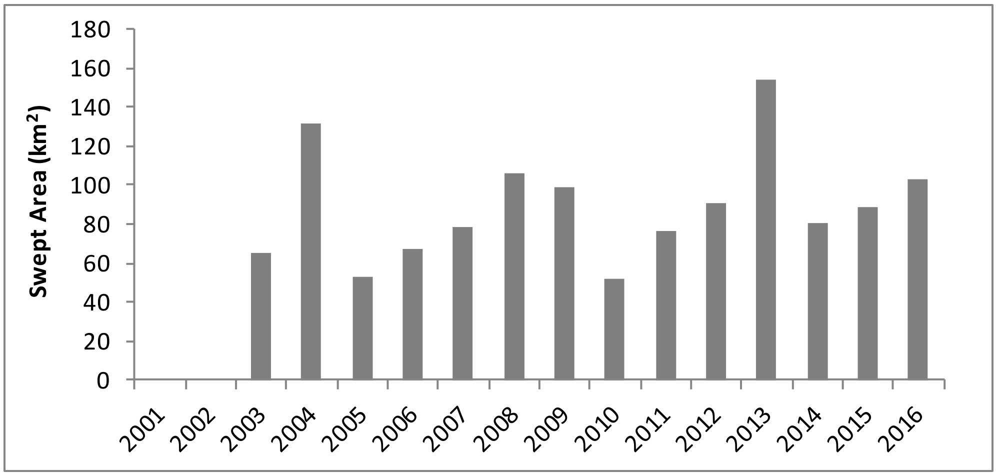

Figure 48. Estimated swept area from scallop fishing on the Cape Tormentine bed from 2003 to 2016 (estimated from total fishery effort, mean vessel speed of 2.5 knots and drag width of 4.9 m). Data not available for 2001 and 2002.

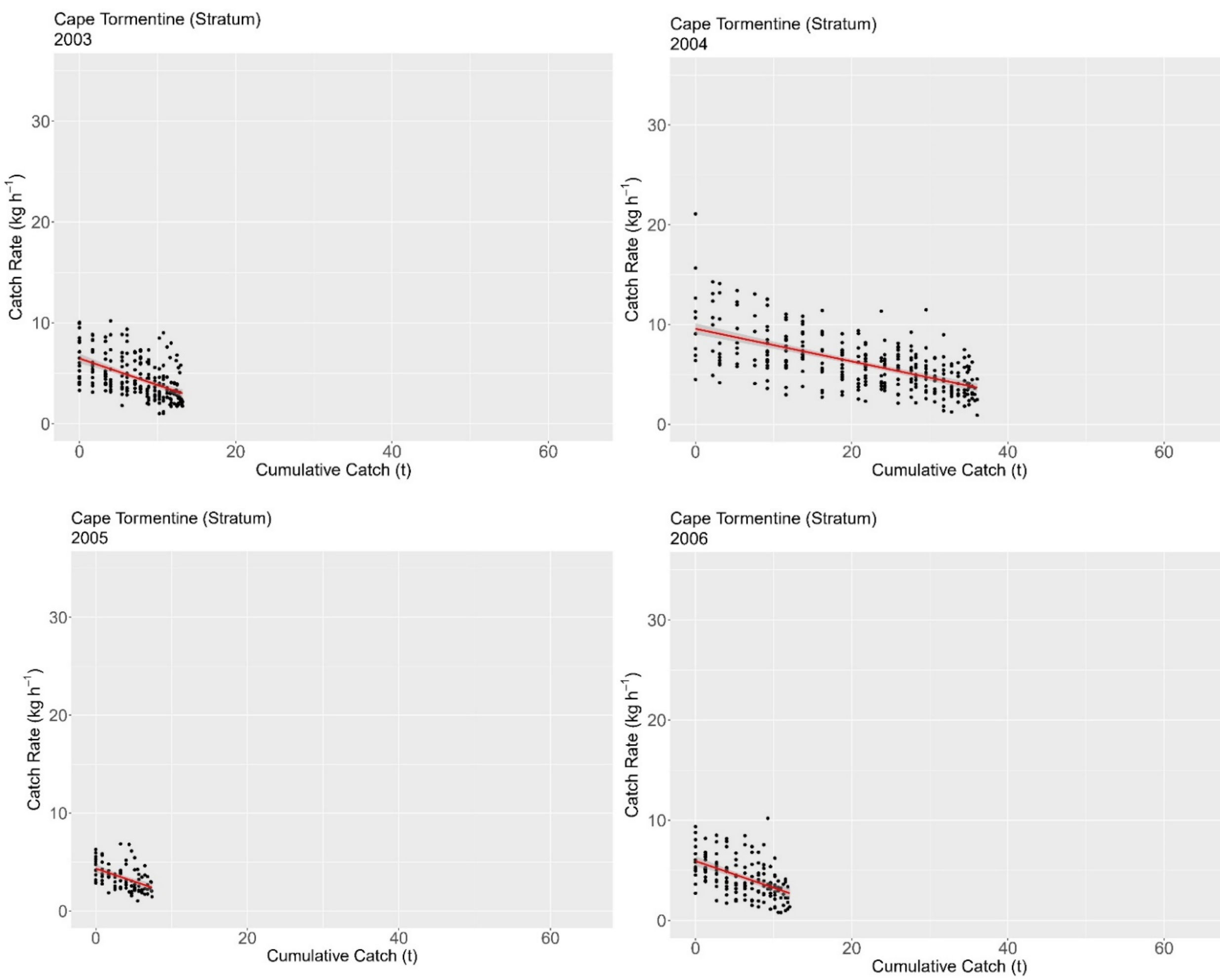

Figure 49. Plot of daily catch rates against the cumulative catch of scallops and the best-fit line (for years in which the model was statistically significant) of the Leslie depletion model for the Cape Tormentine bed data as defined by the survey stratum for each year from 2003 to 2006.

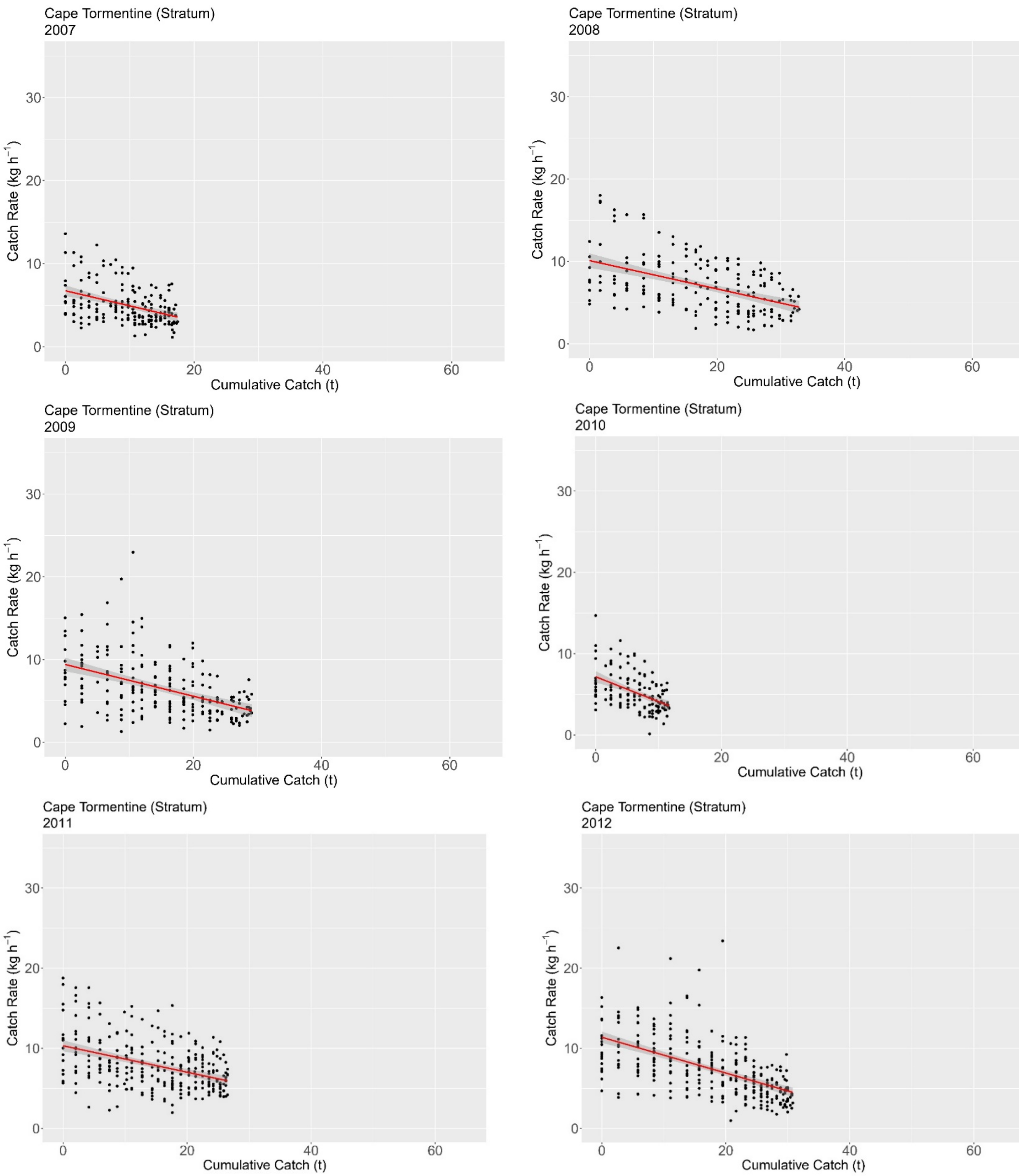

Figure 50. Plot of daily catch rates against the cumulative catch of scallops and the best-fit line (for years in which the model was statistically significant) of the Leslie depletion model for the Cape Tormentine bed data as defined by the survey stratum for each year from 2007 to 2012.

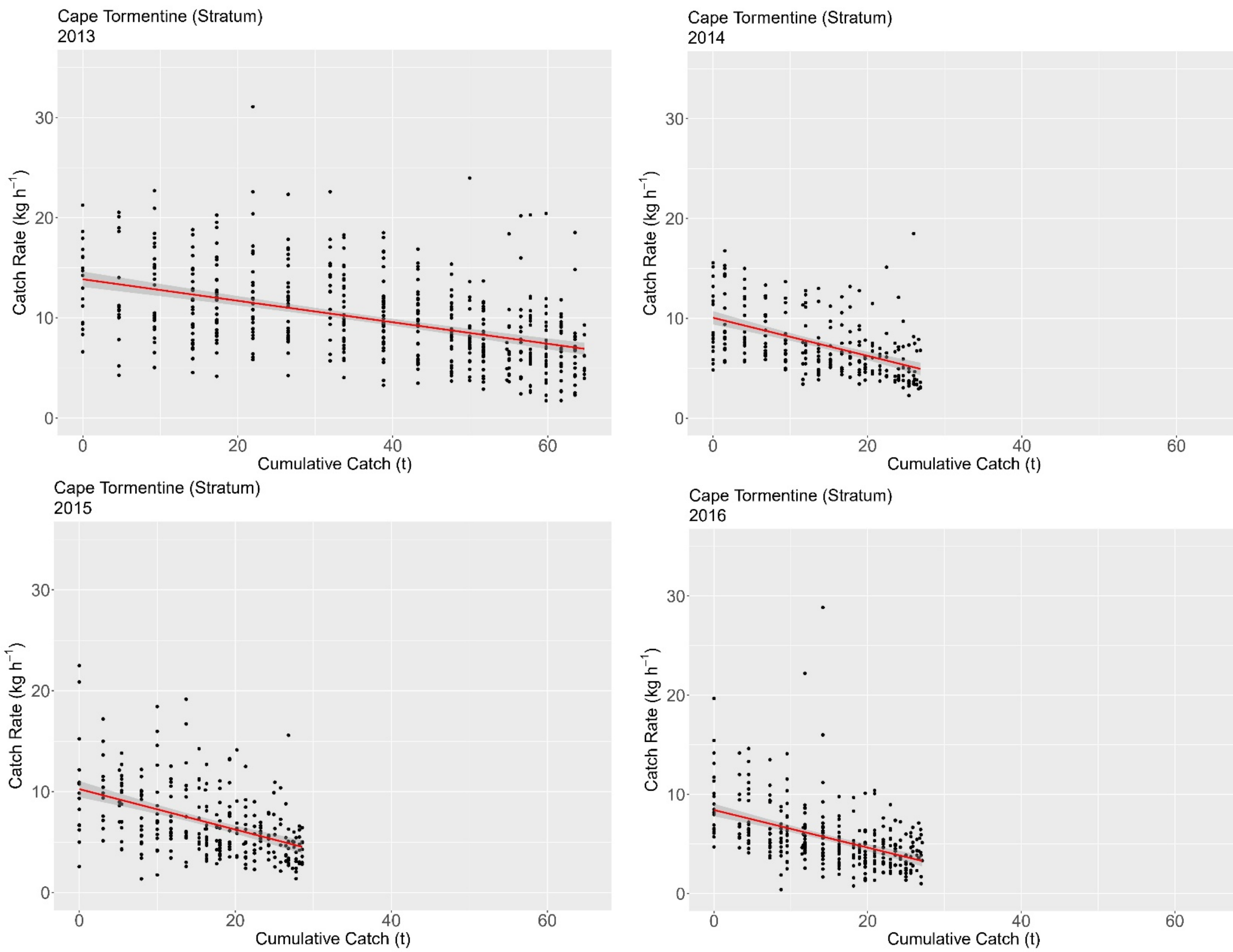

Figure 51. Plot of daily catch rates against the cumulative catch of scallops and the best-fit line (for years in which the model was statistically significant) of the Leslie depletion model for the Cape Tormentine bed data as defined by the survey stratum for each year from 2013 to 2016.

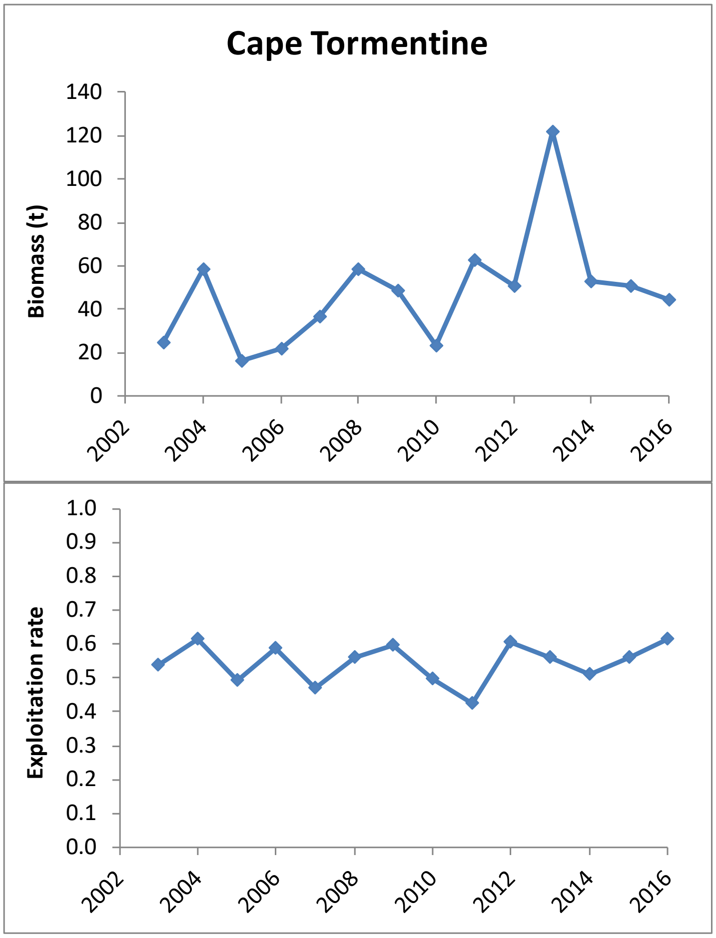

Figure 52. Depletion model estimates of exploitable biomass (B_0; t) at the start of the fishery and exploitation ($\hat{E}$) rate from 2003 to 2016 for the Cape Tormentine bed in SFA 22.

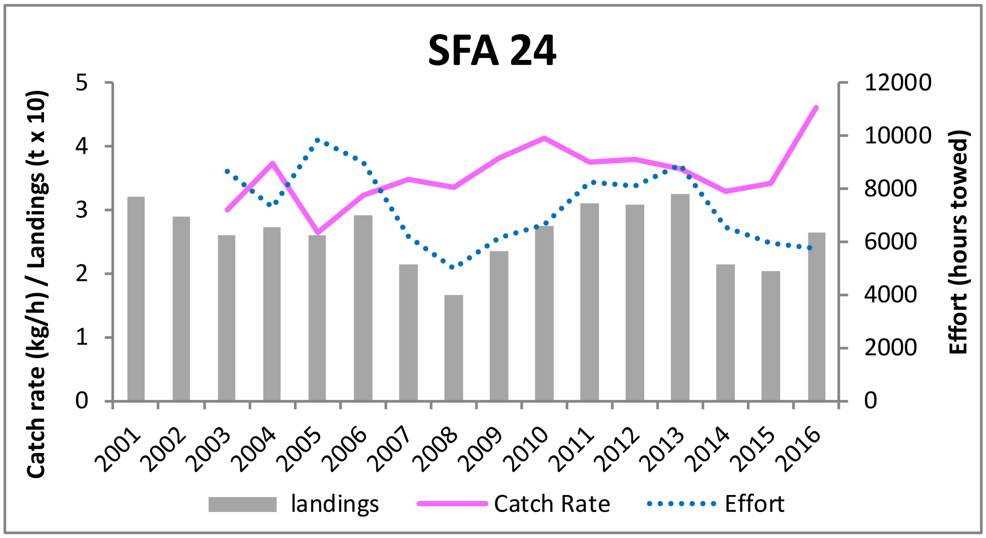

Figure 53. Annual landings (tons of meat x10) and corresponding catch rate (kg h^{-1}) and total fishery effort (hours towed) for SFA 24 in the southern Gulf of St. Lawrence based on logbook data from 2003 to 2016. Effort not recorded in logbooks is estimated from the catch rate values corrected for the total landings. Effort data not available for 2001 and 2002.

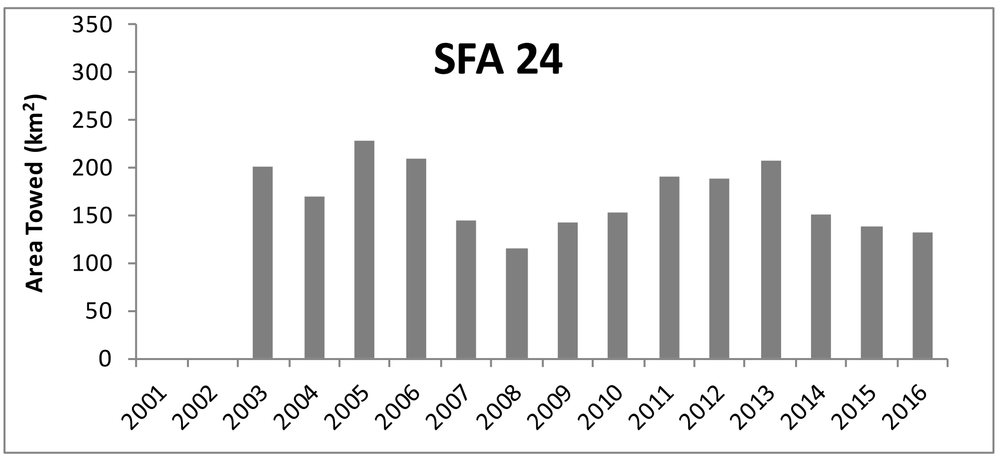

Figure 54. Estimated area towed from 2003 to 2016 according to useable scallop logbooks for Scallop Fishing Area (SFA) 24 (used total fishery effort and the mean tow speed of 2.5 knots and drag width of 5 m). Data not available for 2001 and 2002.

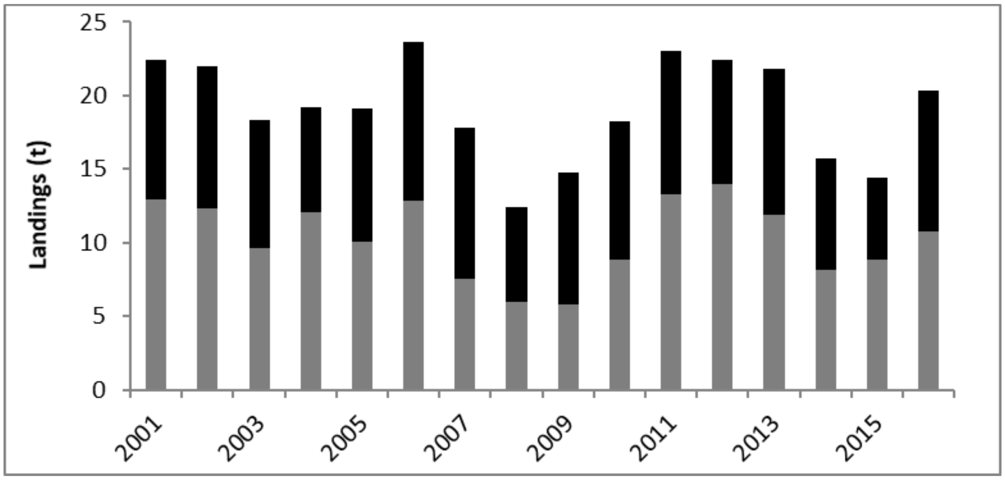

Figure 55. Annual landings (tons of meat) (gray) from 2001 to 2016 according to useable scallop logbooks for the Pictou bed and total (including prorated landings) annual landings (black).

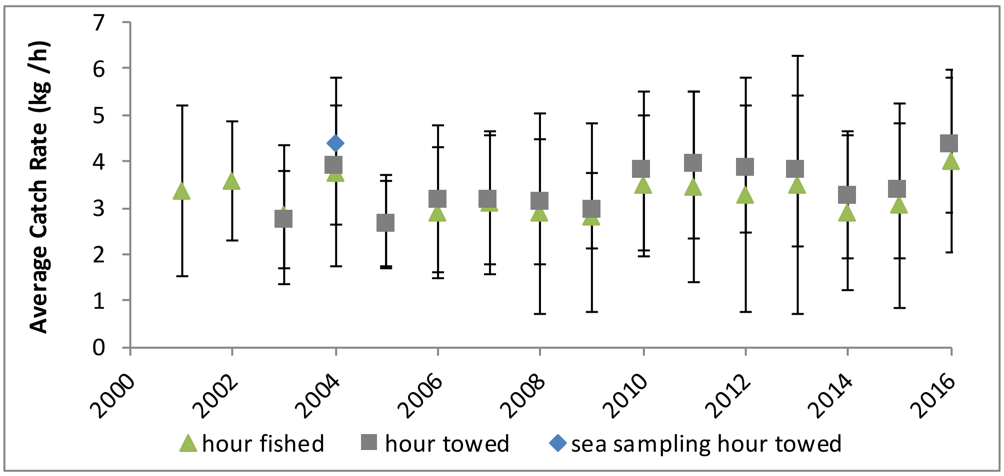

Figure 56. Annual catch rates (kg/towed hour, kg/hours fished) from 2001 to 2016 scallop logbooks and reference to at-sea sampling data for the Pictou bed.

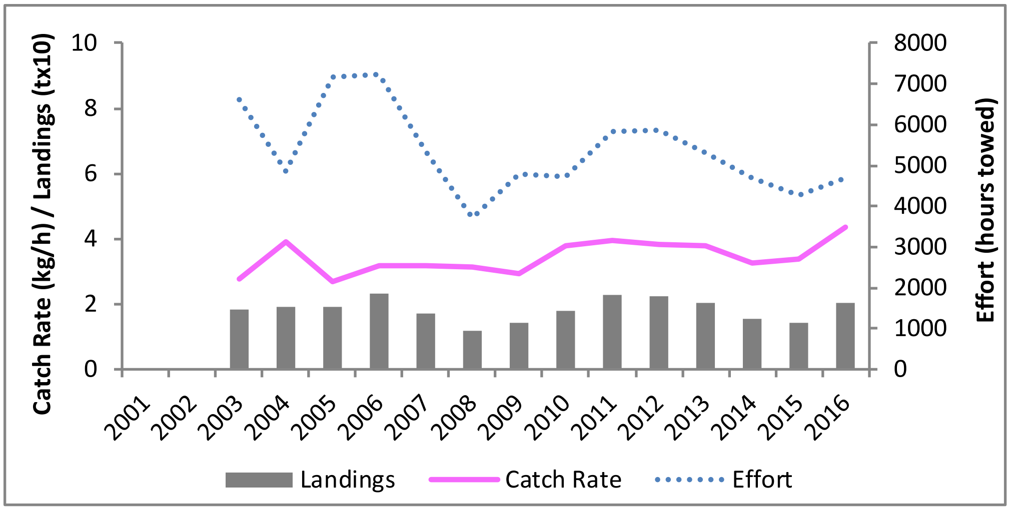

Figure 57. Annual catch rates (kg/towed hour), landings (tons of meat x 10) and total fishery effort (hours towed) from 2003 to 2016 scallop logbooks for the Pictou bed. Data not available for 2001 and 2002.

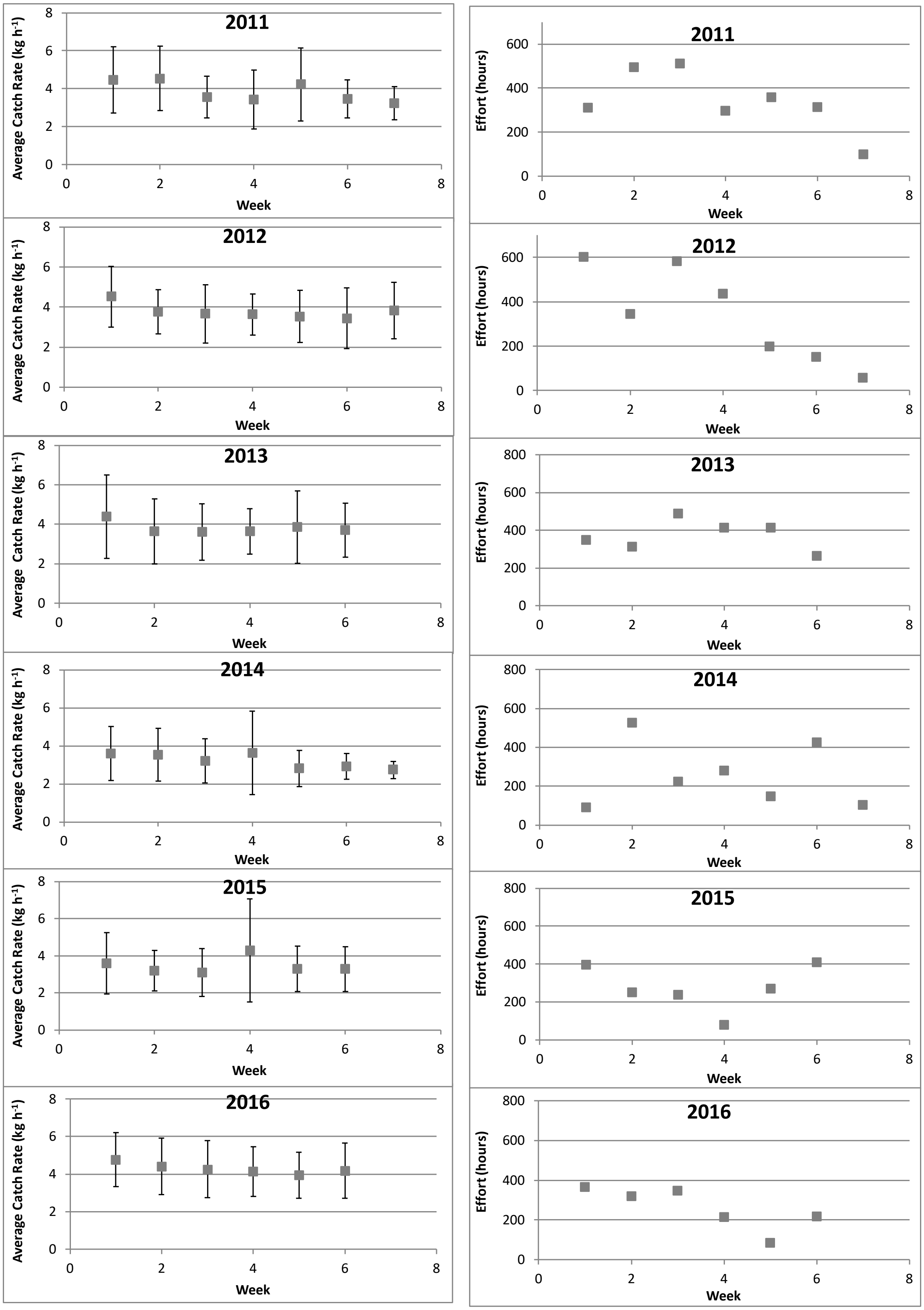

Figure 58. Weekly catch rate (kg h^{-1}) and effort (hours towed) over the six to seven week scallop fishing season for 2011 to 2016 for the Pictou bed derived from logbook records.

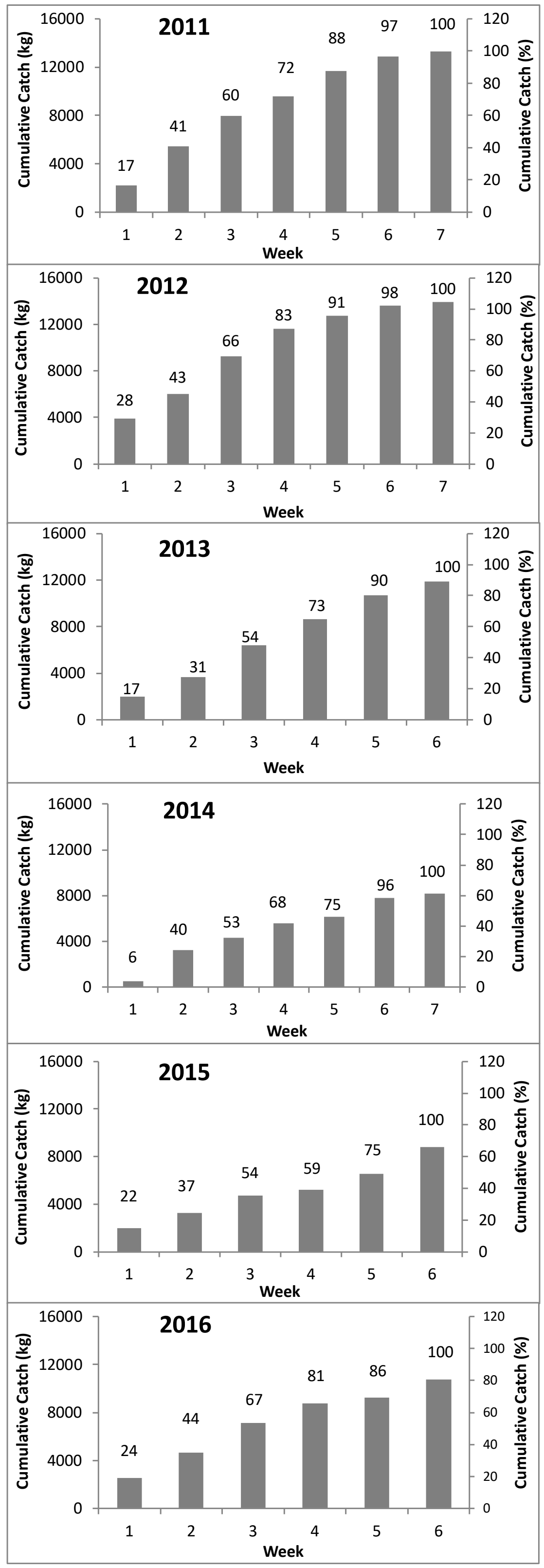

Figure 59. Weekly cumulative catch (kg) over the five week scallop fishing season for 2011 to 2016 for the Pictou bed. Over 75 % of the catch is taken by the end of week five derived from logbook records.

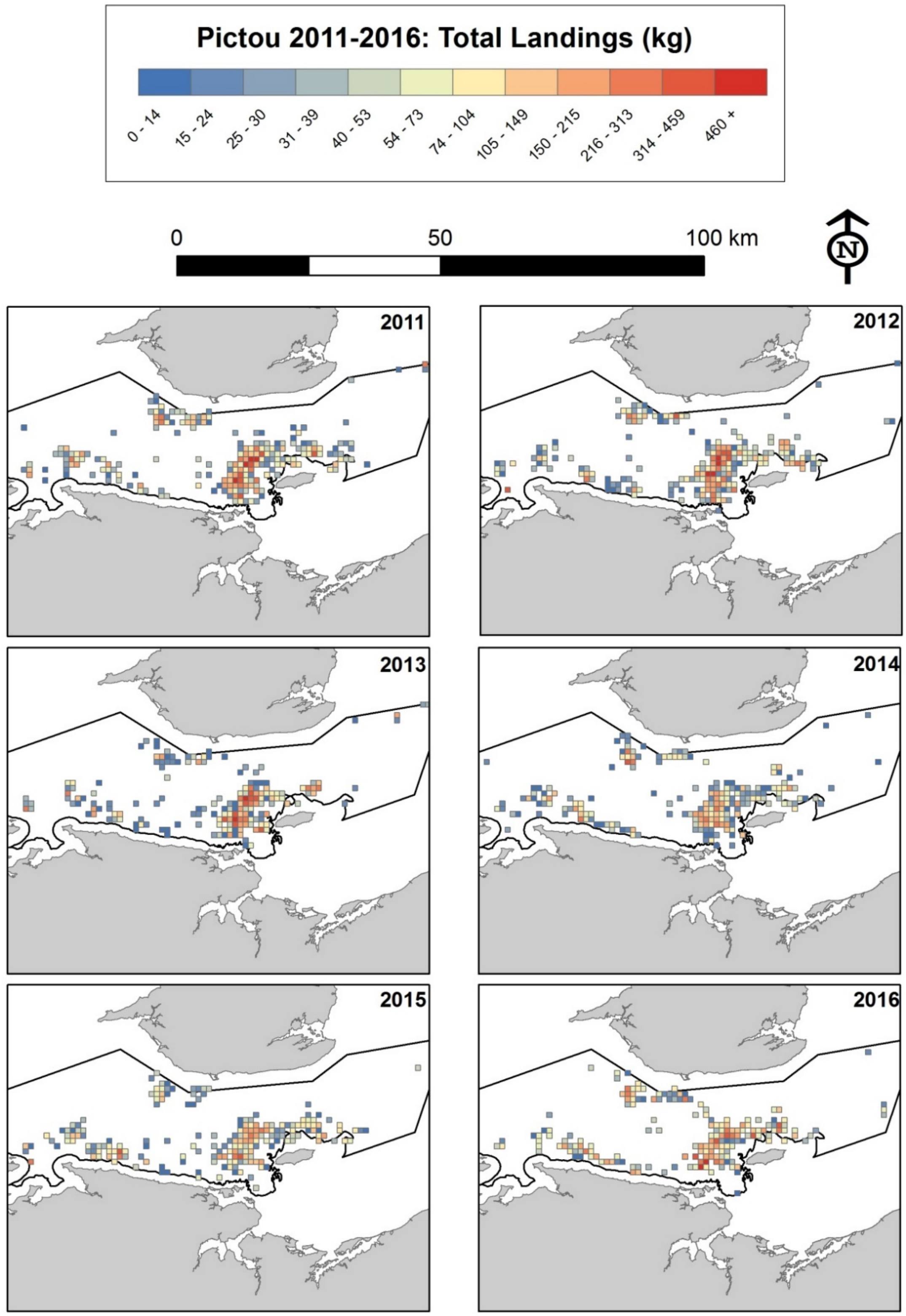

Figure 60. Spatial plot of total landings (kg) per km² of the Pictou bed for each year from 2011 to 2016 from commercial logbook data.

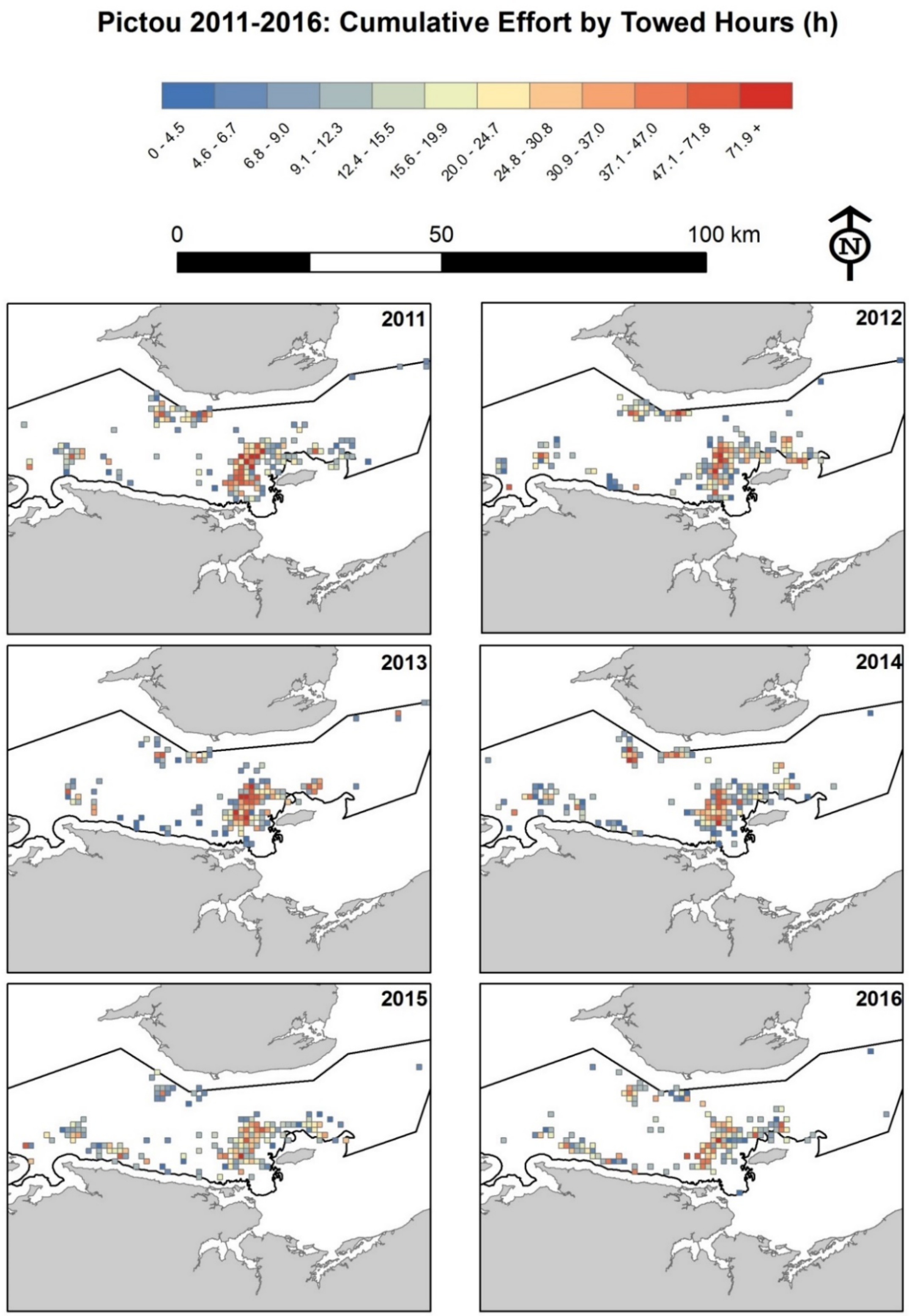

Figure 61. Spatial plot of cumulative effort (hours towed) per km² of the Pictou bed for each year from 2011 to 2016 from commercial logbook data.

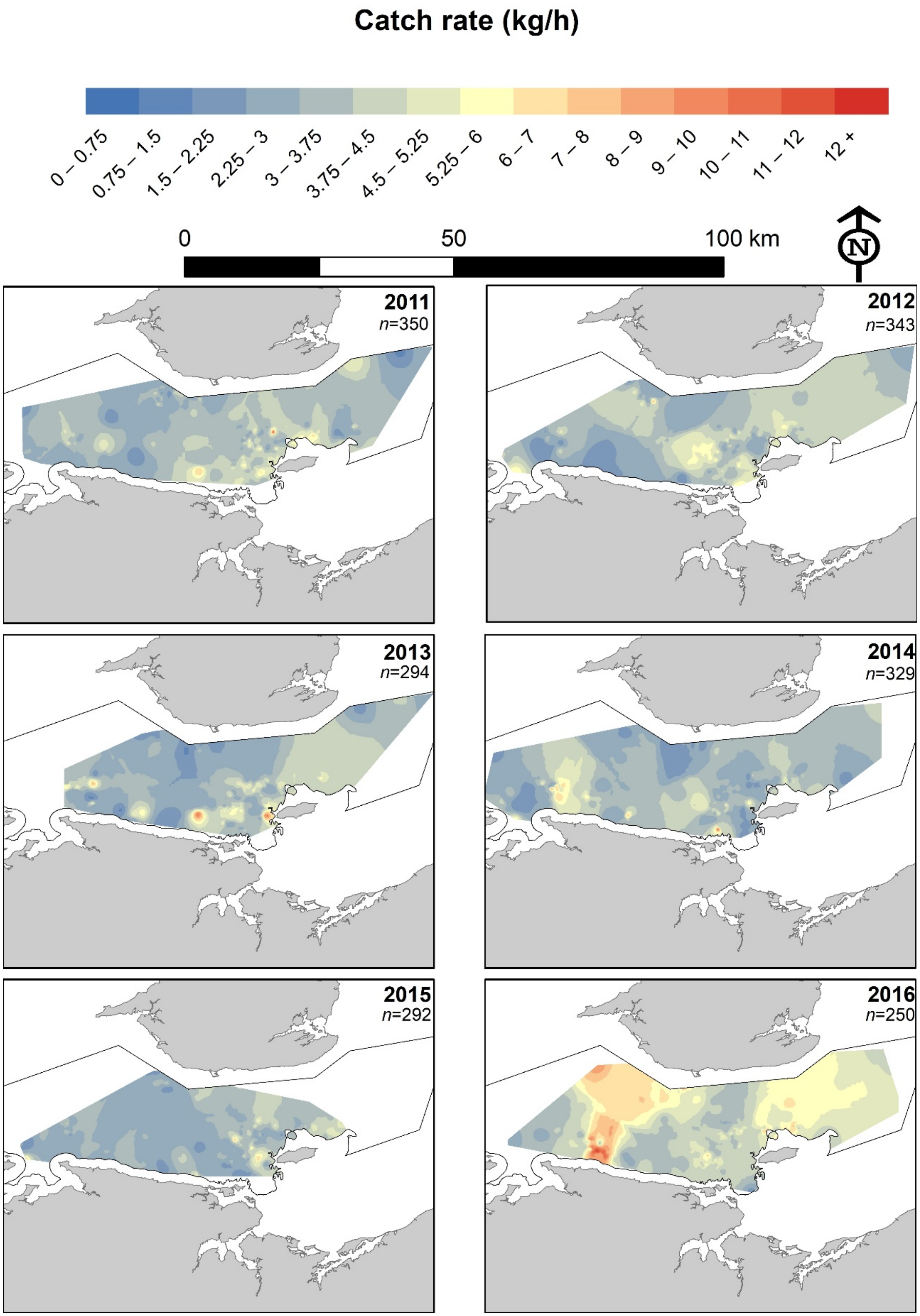

Figure 62. Spatial plot of catch rate (kg h^{-1}) of the Pictou bed for each year from 2011 to 2016 from commercial logbook data.

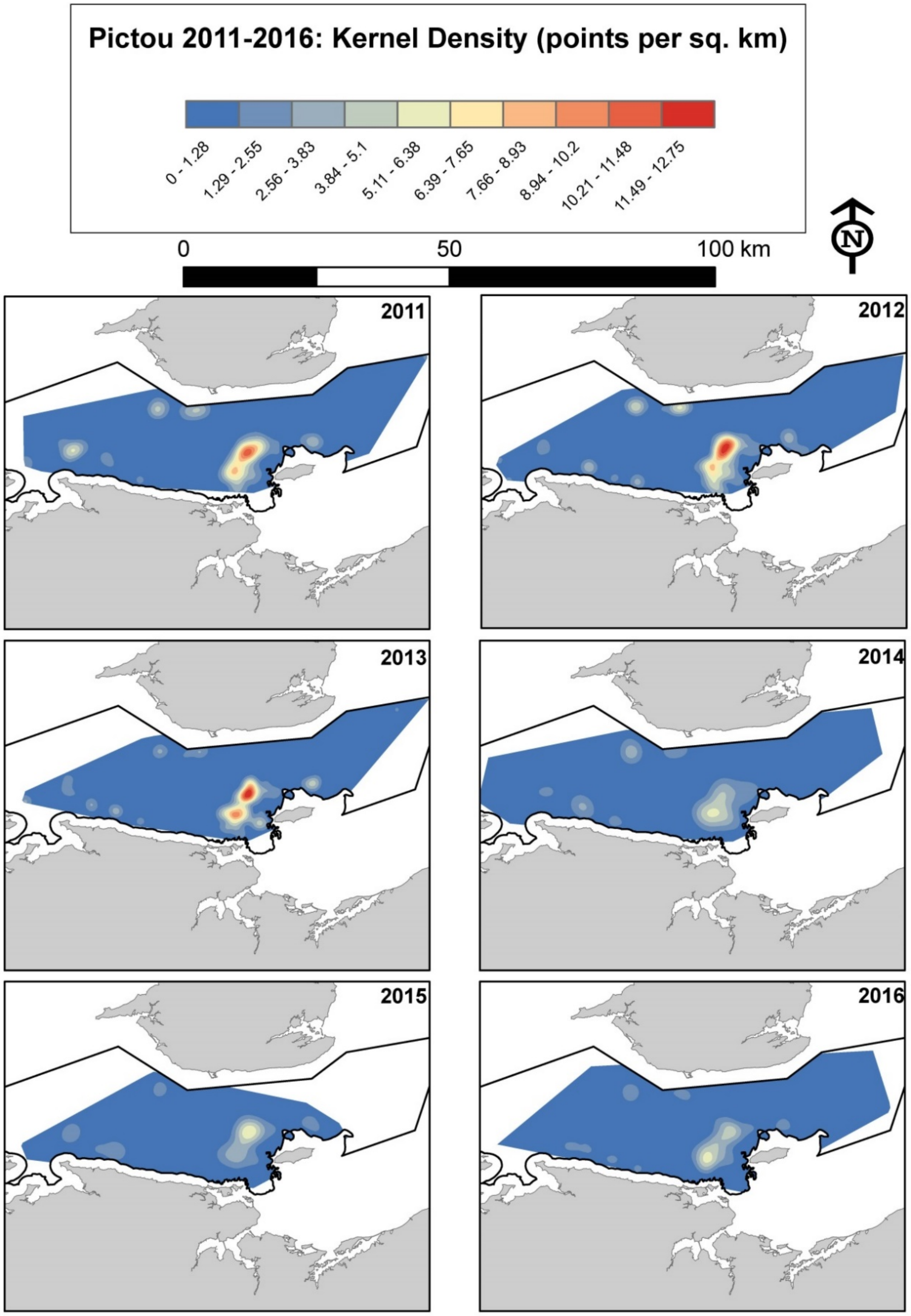

Figure 63. Spatial plot of number of trips (days) per km² of the Pictou bed for each year 2011–2016 from commercial logbook data.

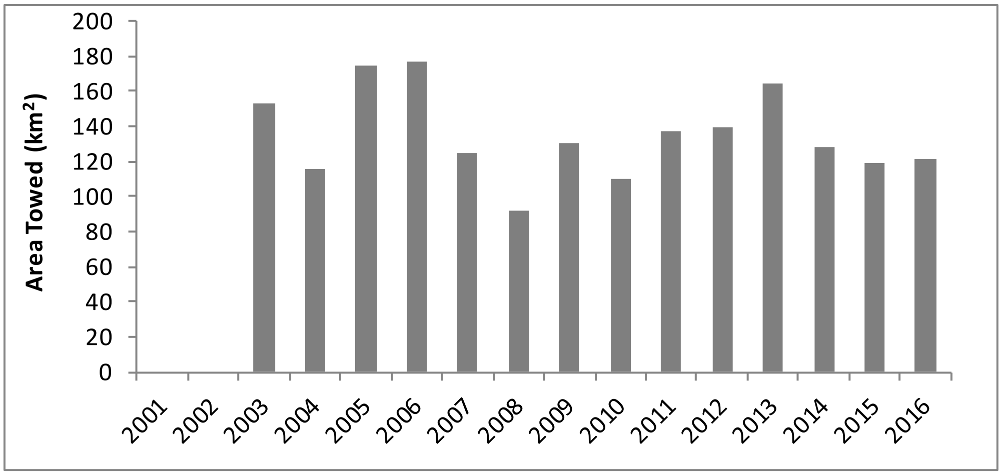

Figure 64. Estimated swept area from scallop fishing on the Pictou bed from 2003 to 2016 (estimated from prorated effort, mean vessel speed of 2.5 knots and drag width of 5 m). Data not available for 2001 and 2002.

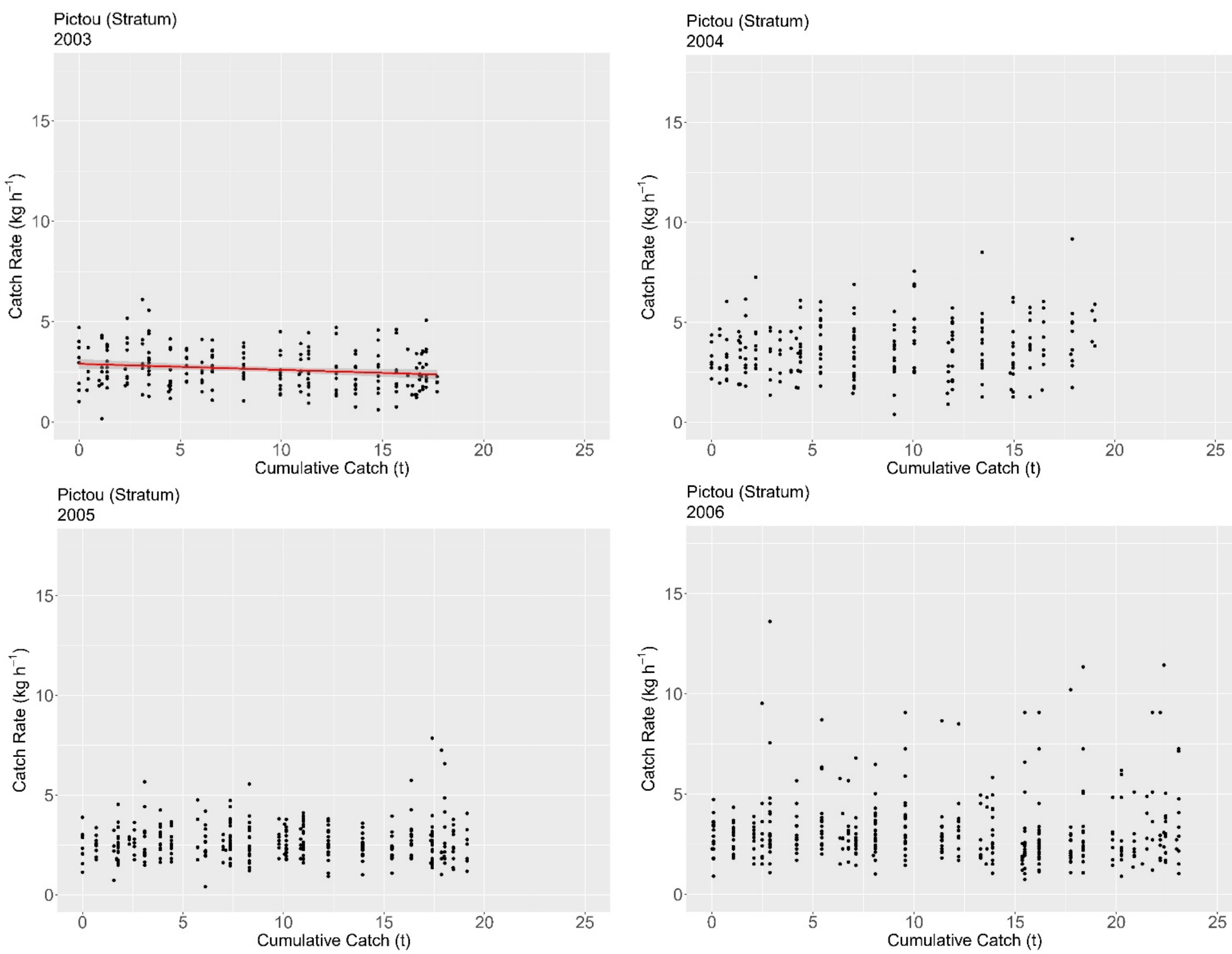

Figure 65. Plot of daily catch rates against the cumulative catch of scallops and the best-fit line (for years in which the model was statistically significant) of the Leslie depletion model for Pictou bed data as defined by the survey stratum for each year from 2003 to 2006.

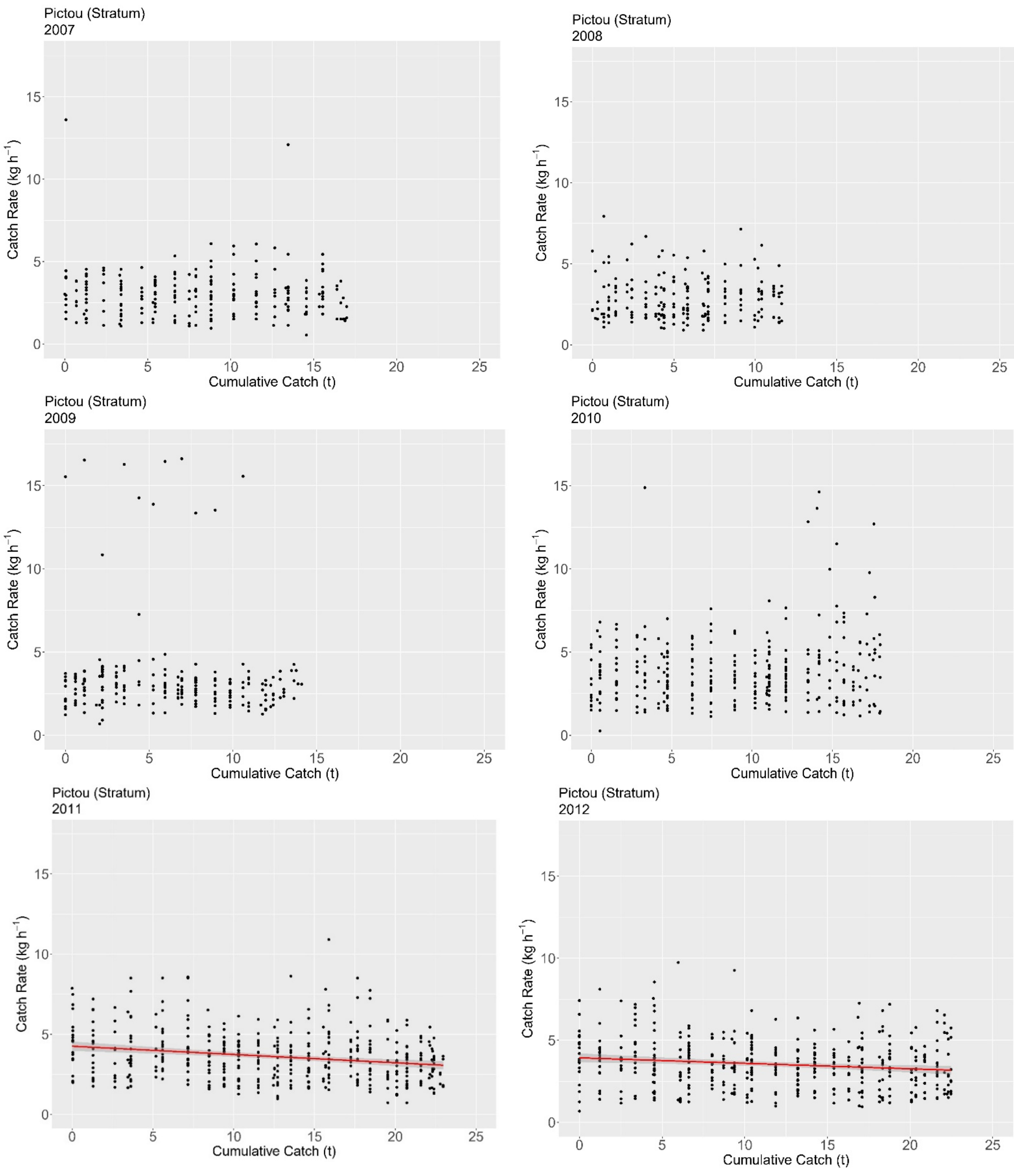

Figure 66. Plot of daily catch rates against the cumulative catch of scallops and the best-fit line (for years in which the model was statistically significant) of the Leslie depletion model for Pictou bed data as defined by the survey stratum for each year from 2007 to 2012.

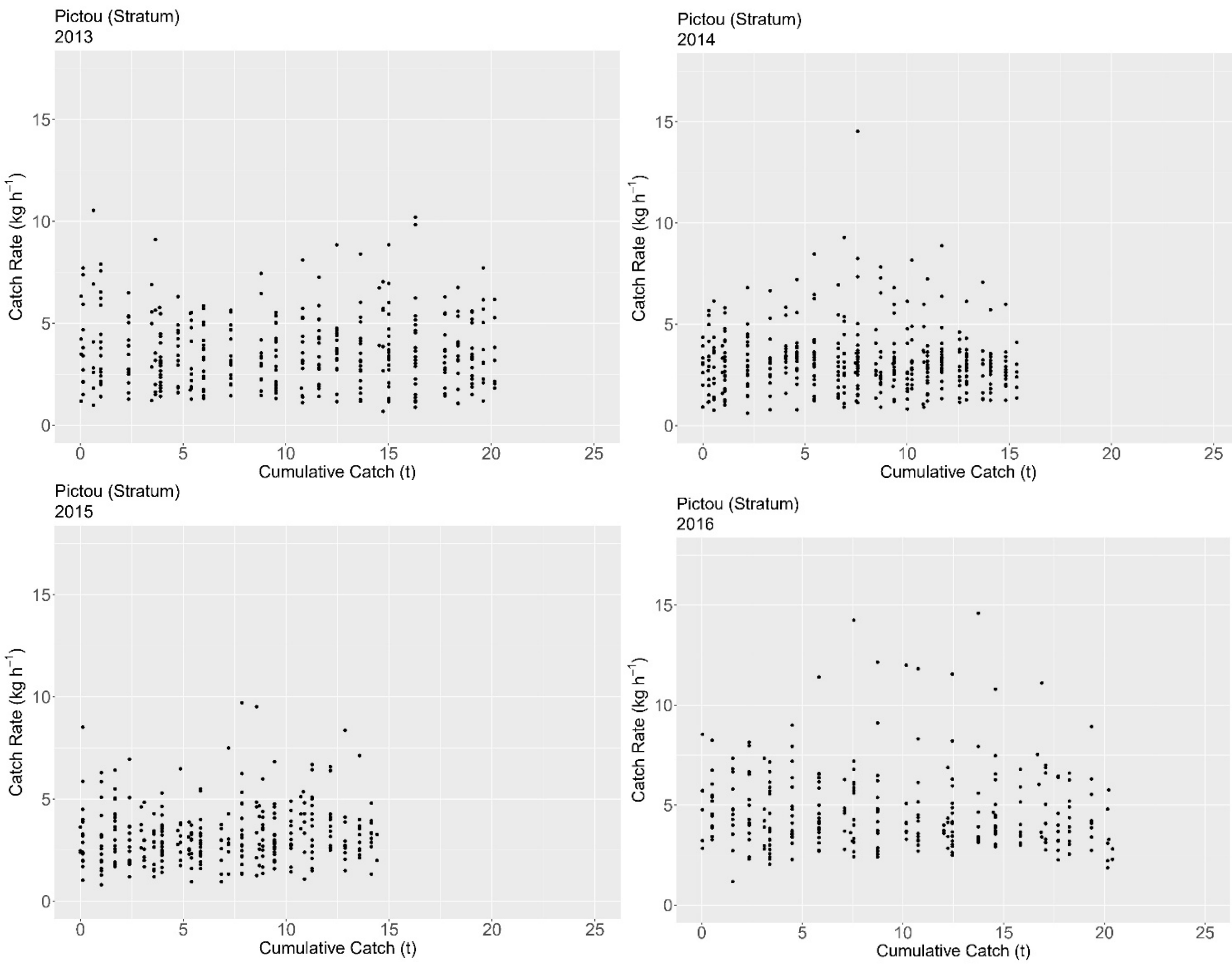

Figure 67. Plot of daily catch rates against the cumulative catch of scallops of the Leslie depletion model for Pictou bed data as defined by the survey stratum for each year from 2013 to 2016.

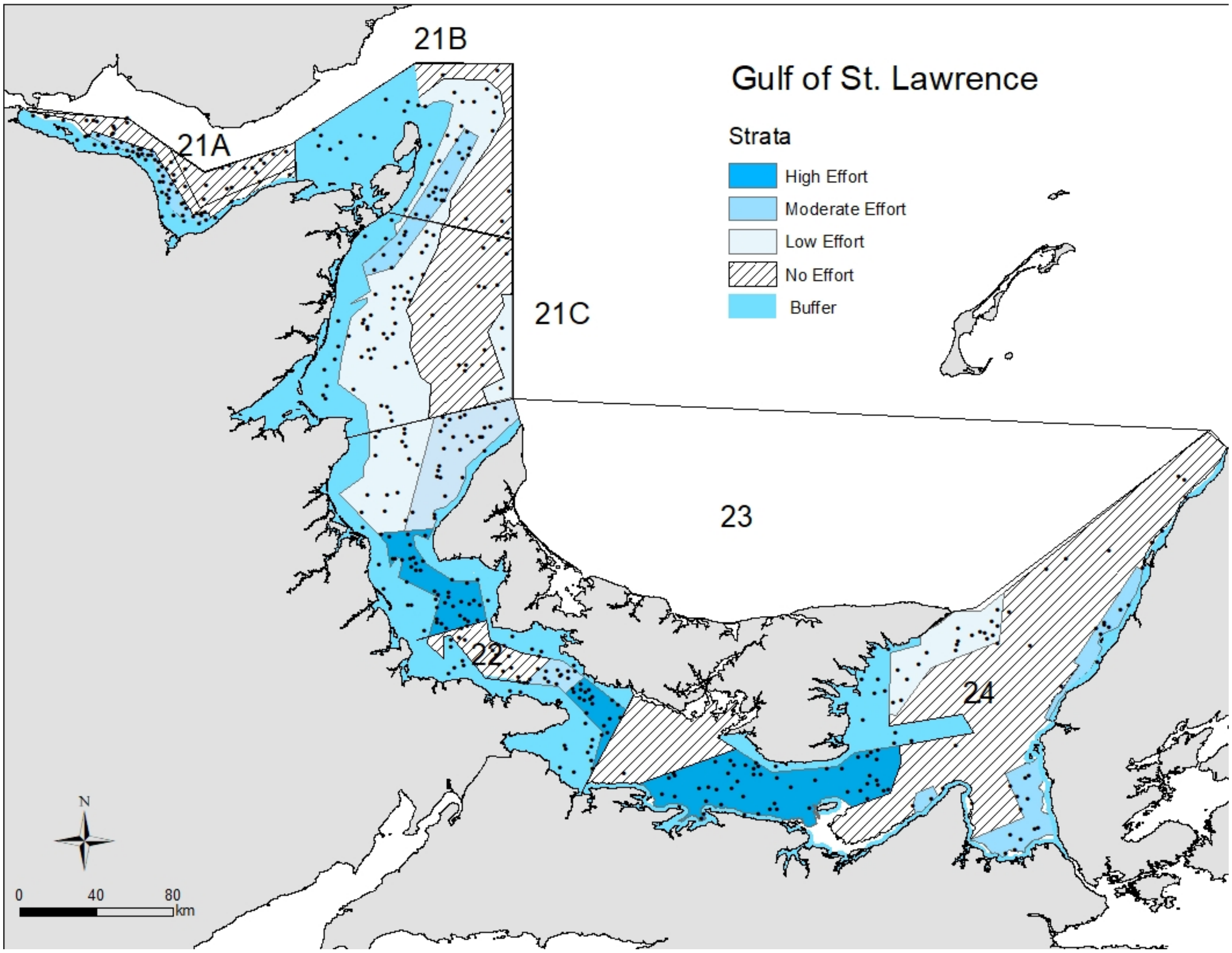

Figure 68. Survey strata and positions of randomly assigned (by stratum) sampling tows (black dots) for the scallop surveys in the southern Gulf of St. Lawrence during 2012 to 2016. Note that SFA 22 is divided into SFA 22 north and SFA 22 south and strata were assigned to each. Similarly for SFA 21A, SFA 24, and for the combined 21B and 21C.

a) b)

Figure 69. Research survey gear composed of a toothed 8-gang scallop drag used in the 2012 and 2013 scallop surveys (a) and in the 2014 to 2016 surveys (b) in the southern Gulf of St. Lawrence.

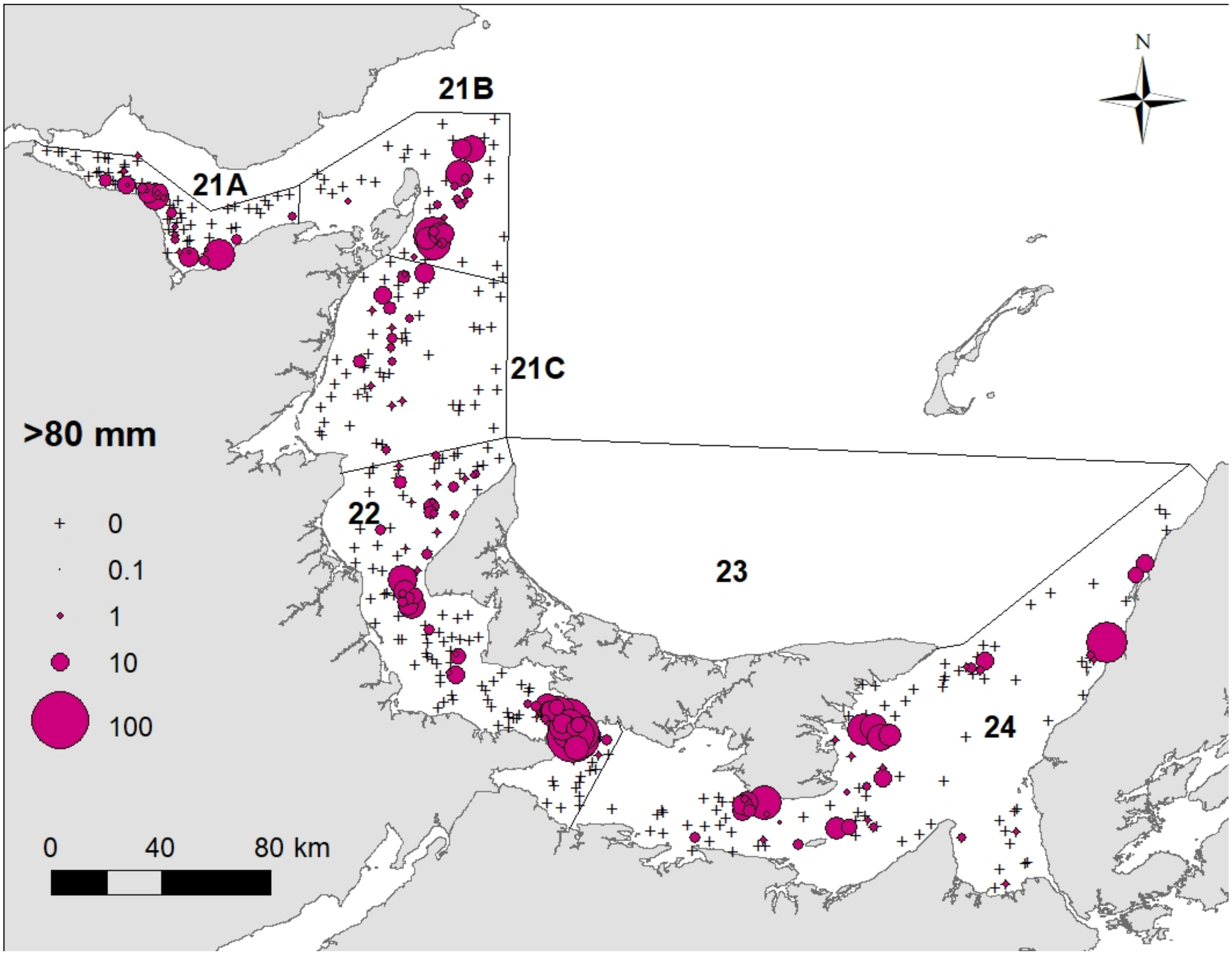

Figure 70. Spatial distribution of sea scallop density (total number per standard tow) in the Gulf region from surveys in 2012 to 2016. Circle area is proportional to scallop density. Red circles represent commercial size (≥ 80 mm) scallops.

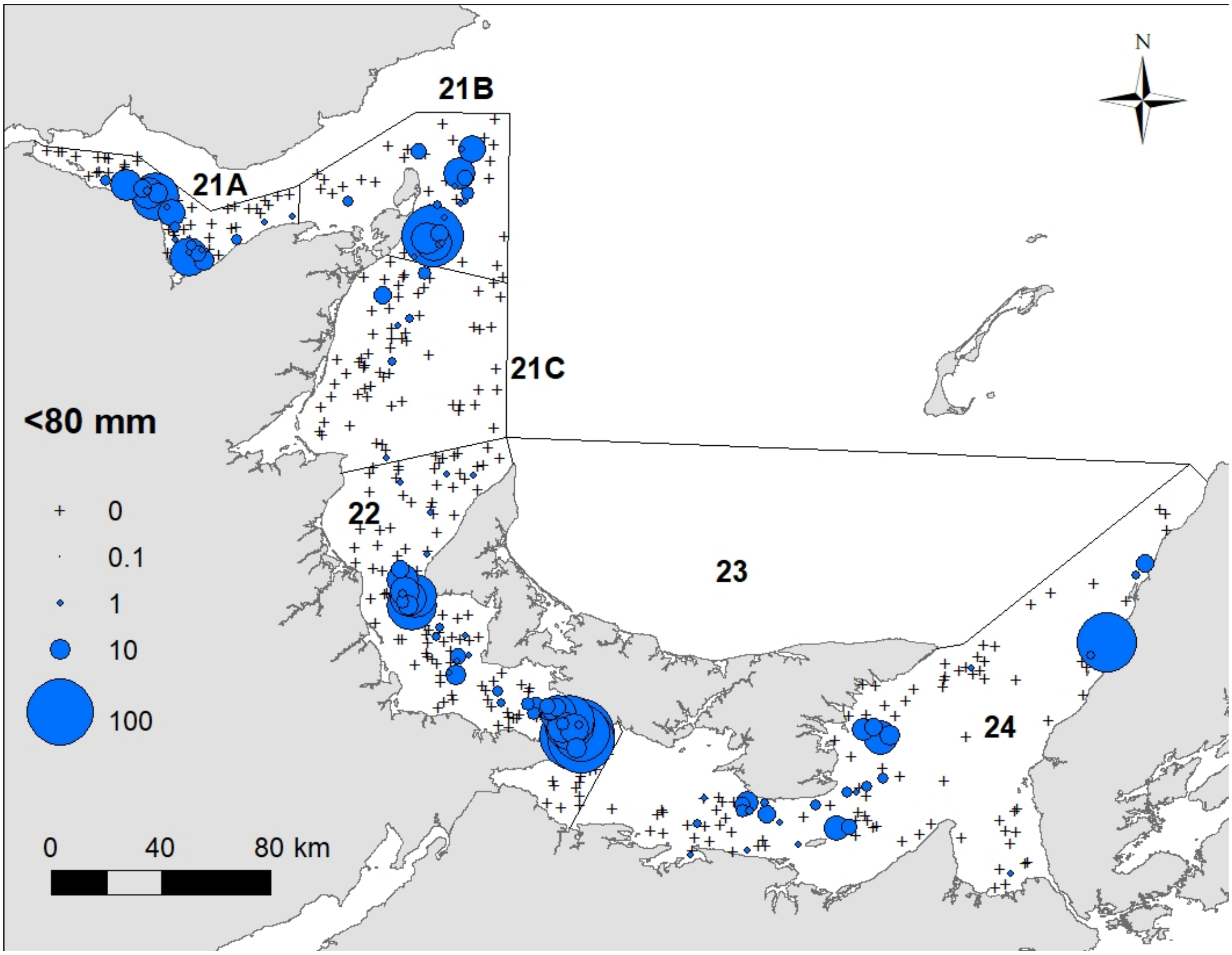

Figure 71. Spatial distribution of sea scallop density (total number per standard tow) in the Gulf region from surveys in 2012 to 2016. Circle area is proportional to scallop density. Blue circles represent small size (< 80 mm) scallops.

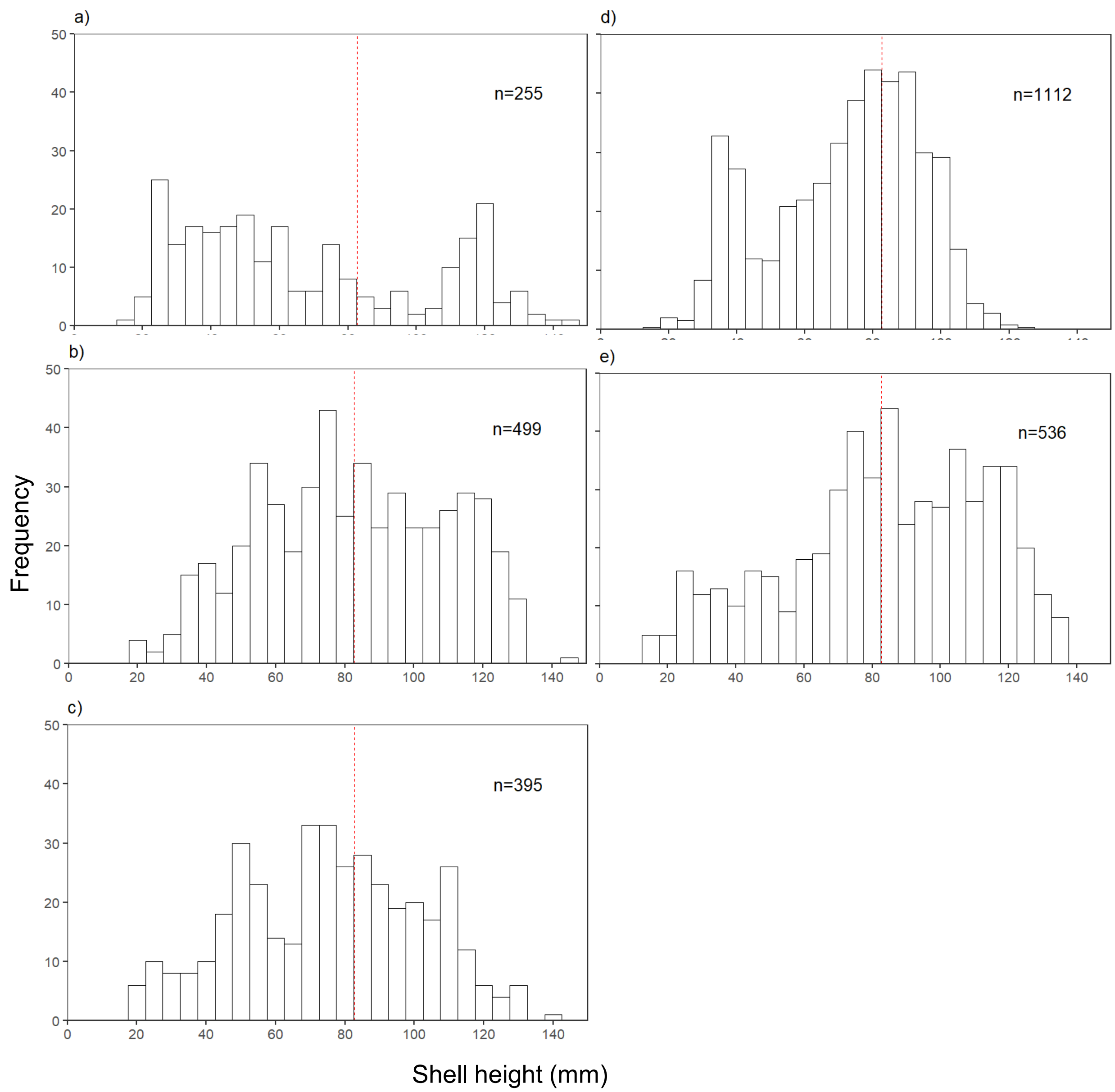

Figure 72. Shell height distribution of scallops by survey area based on research surveys conducted between 2012 and 2016. a) SFA21A in 2013, b) SFA 21 B and C in 2016, c) SFA 22 north in 2014, d) SFA 22 south in 2012, and e) SFA 24 in 2015. The red vertical dashed line in each panel shows the 82.6 mm mark corresponding to regulatory ring size.

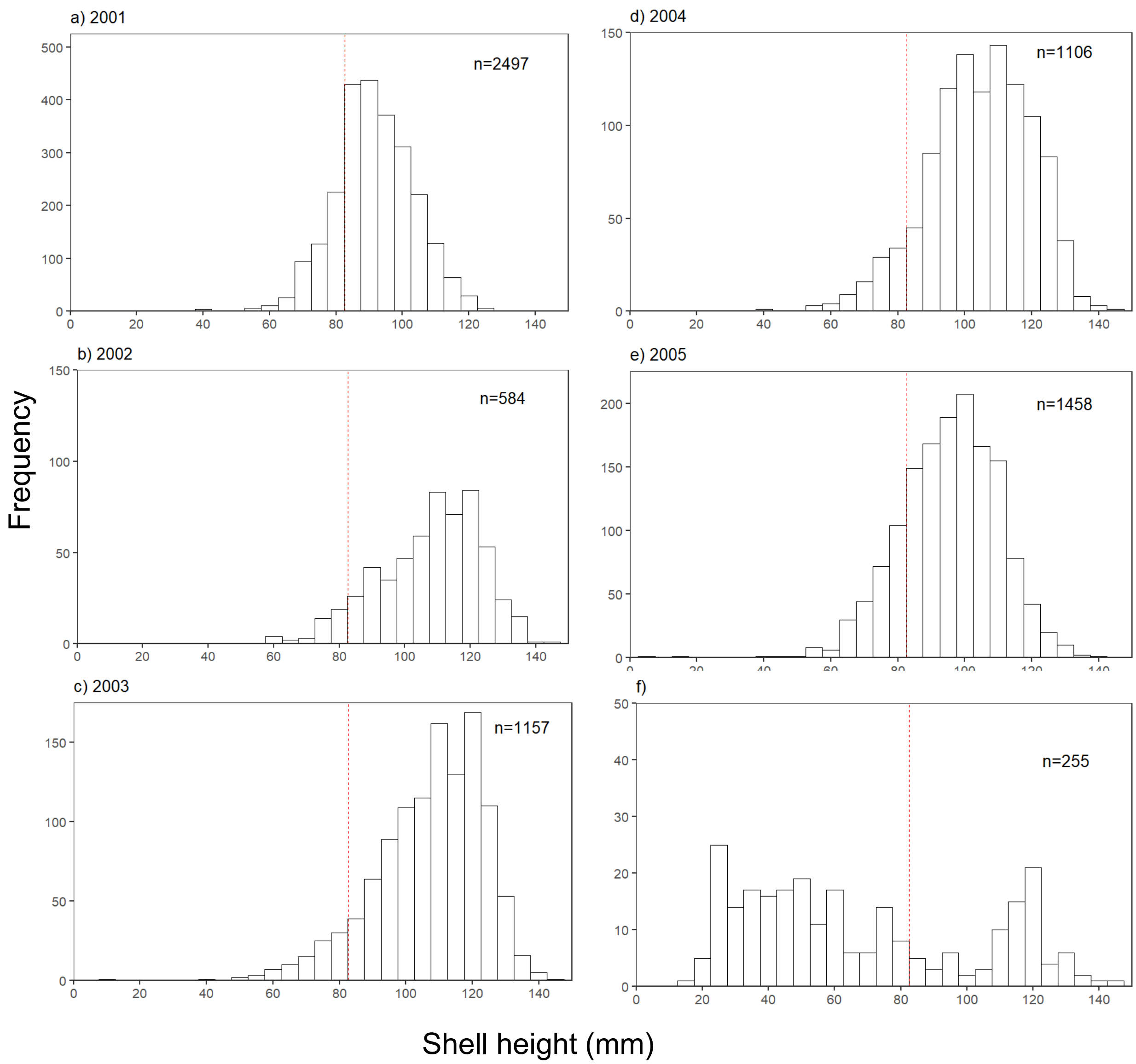

Figure 73. Shell height distribution of scallops from at-sea sampling on the SFA 21A bed from 2001 to 2005 (a to e) and from the research survey conducted in the high effort stratum in 2013 (f). The red vertical dashed line in each panel shows the 82.6 mm mark corresponding to regulatory ring size.

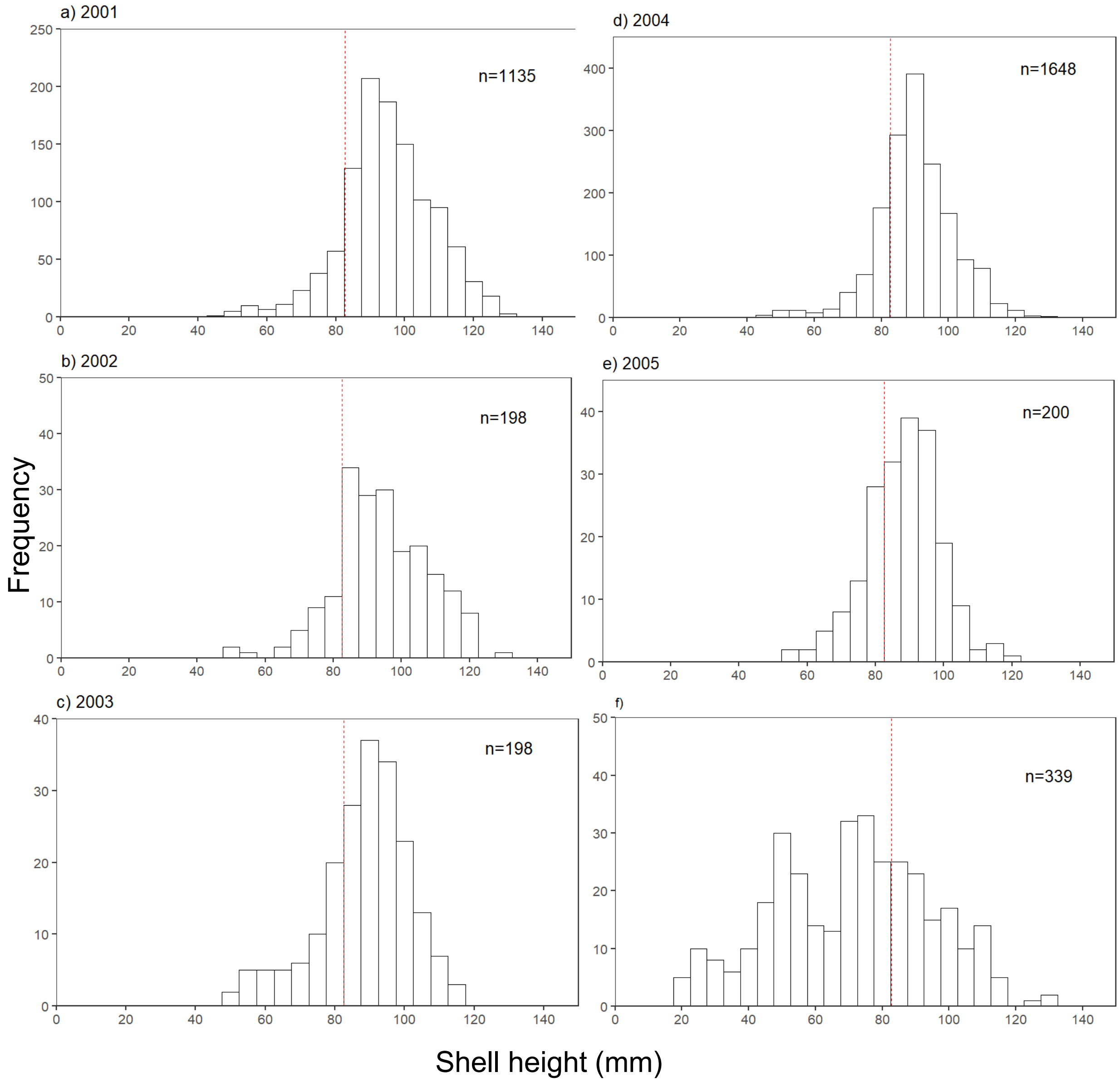

Figure 74. Shell height distribution of scallops from at-sea sampling on the West Point bed (SFA 22) from 2001 to 2005 (a to e) and from the research survey conducted in 2014 (f). The red vertical dashed line in each panel shows the 82.6 mm mark corresponding to regulatory ring size.

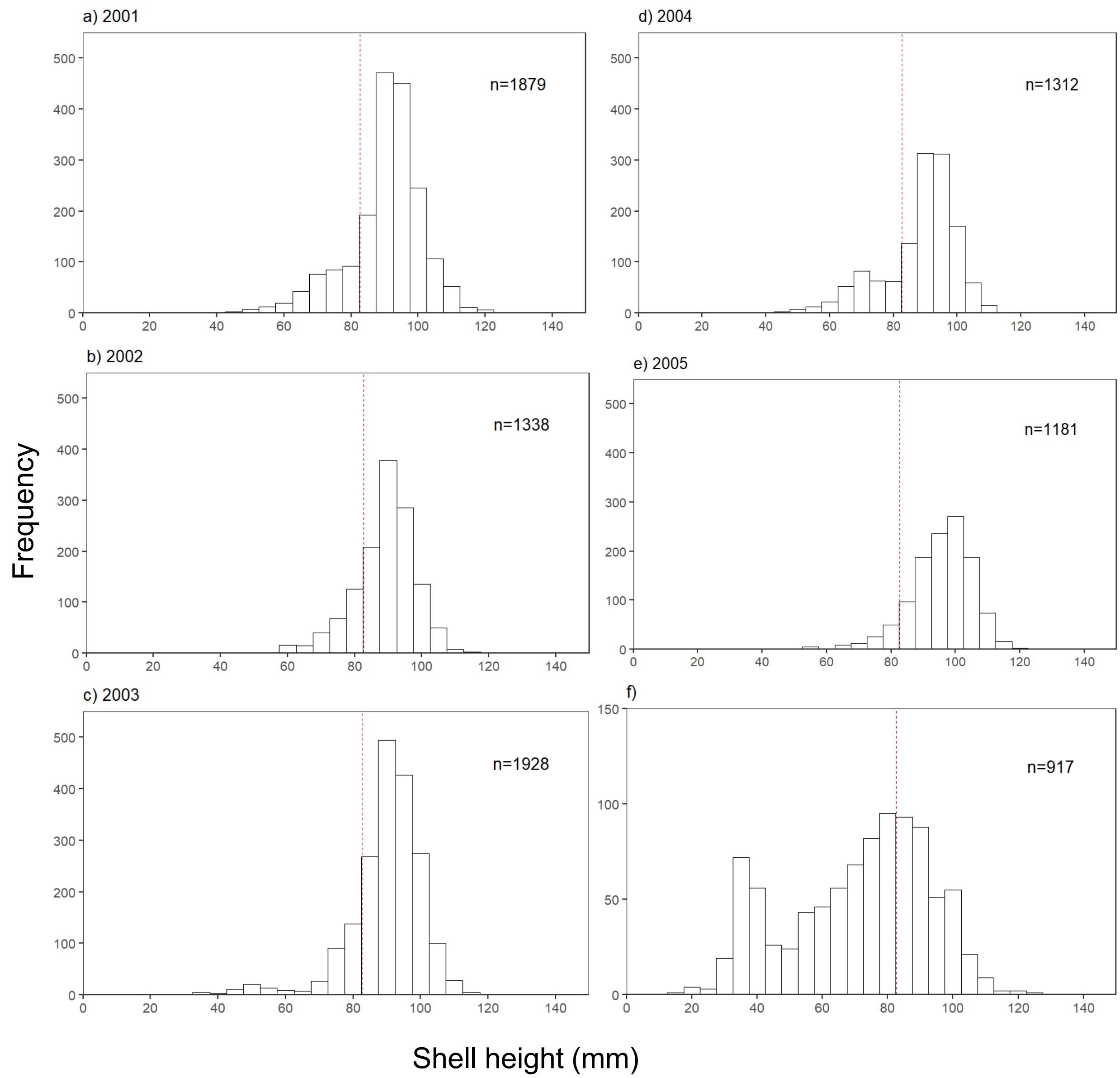

Figure 75. Shell height distribution of scallops from at-sea sampling on the Cape Tormentine bed (SFA 22) from 2001 to 2005 (a to e) and from the research survey conducted in 2012 (f). The red vertical dashed line in each panel shows the 82.6 mm mark corresponding to regulatory ring size.

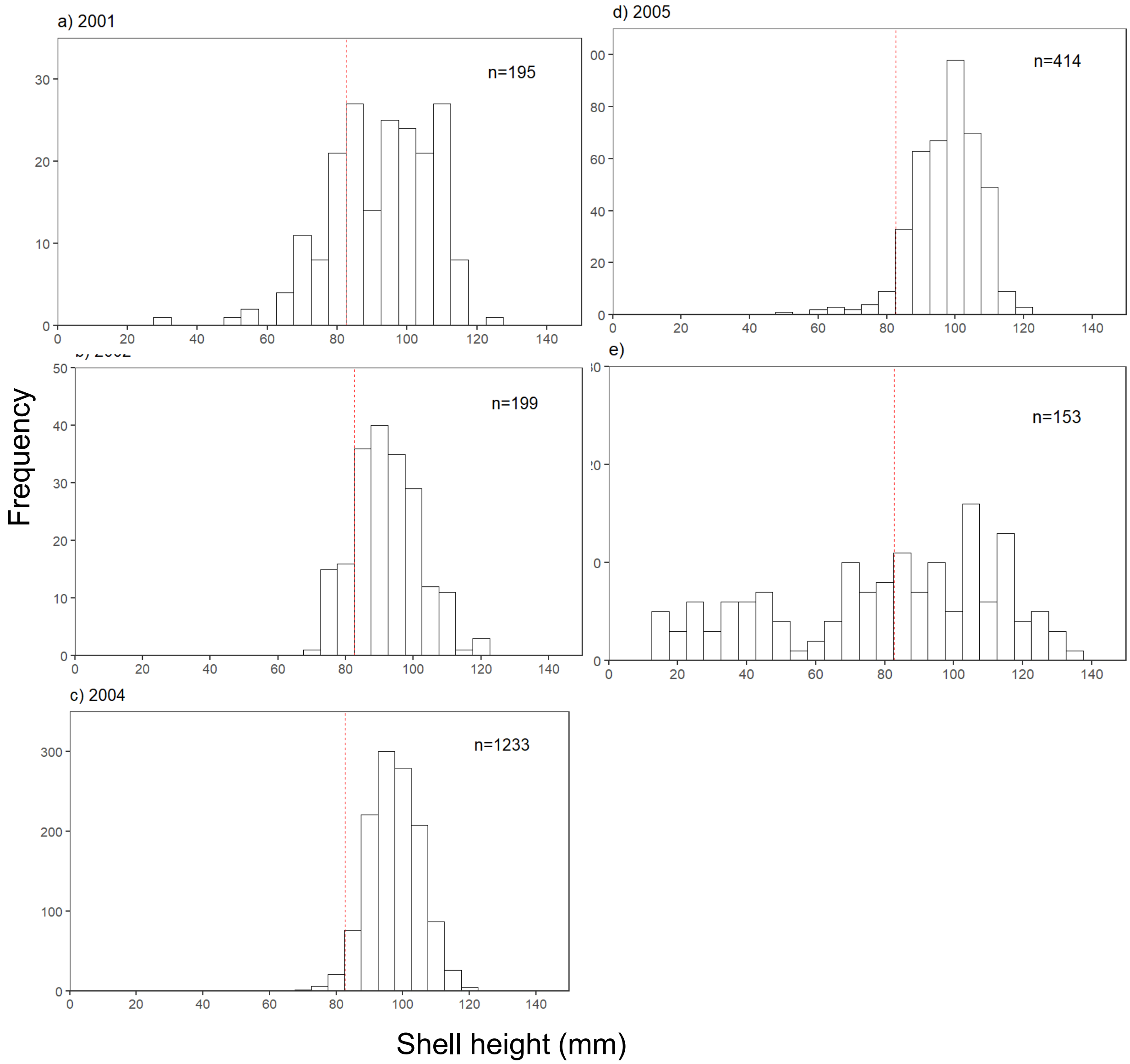

Figure 76. Shell height distribution of scallops from at-sea sampling on the Pictou bed (SFA 24) from 2001 to 2005 (a to d) and from the research survey conducted in 2015 (e). The red vertical dashed line in each panel shows the 82.6 mm mark corresponding to regulatory ring size.

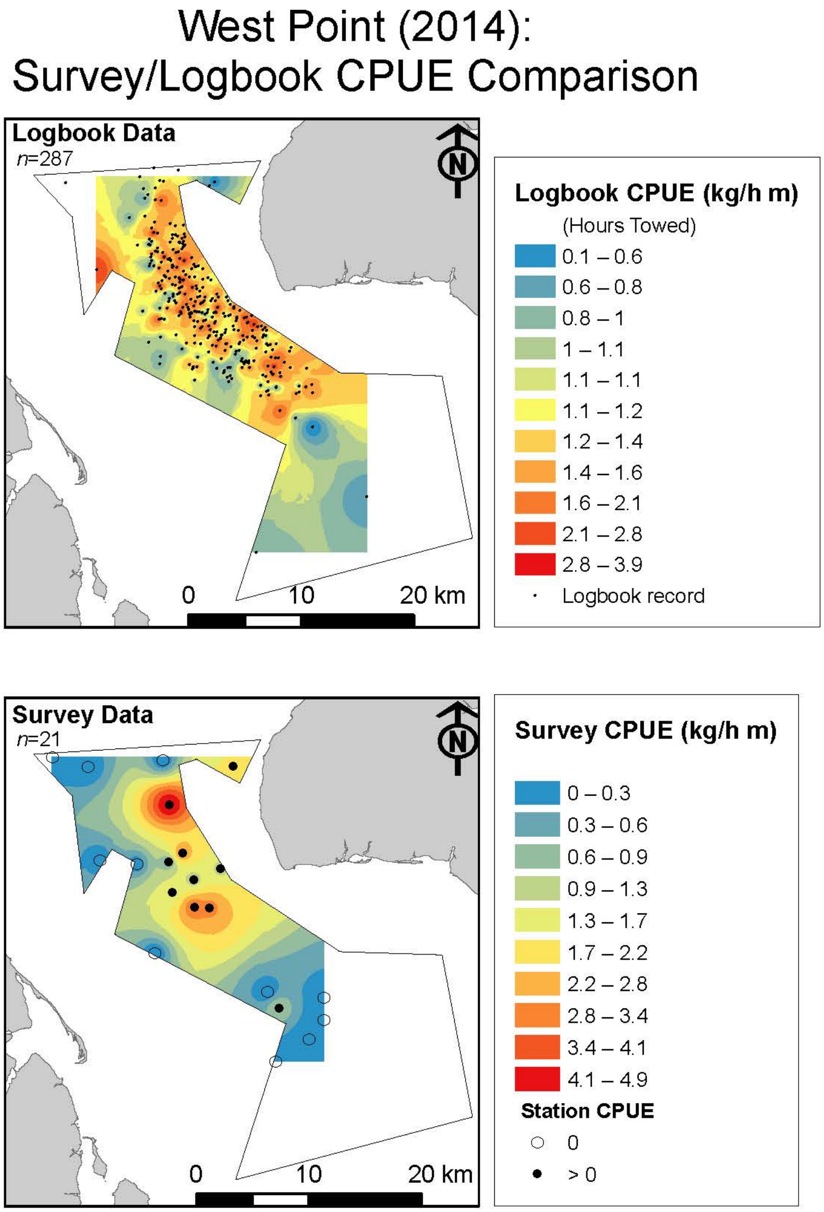

Figure 77. Spatial plot of average catch rate (kg $h^{-1}m^{-1}$) of the West Point bed from the 2014 commercial logbook data (upper panel) and from the 2014 research survey data (lower panel).

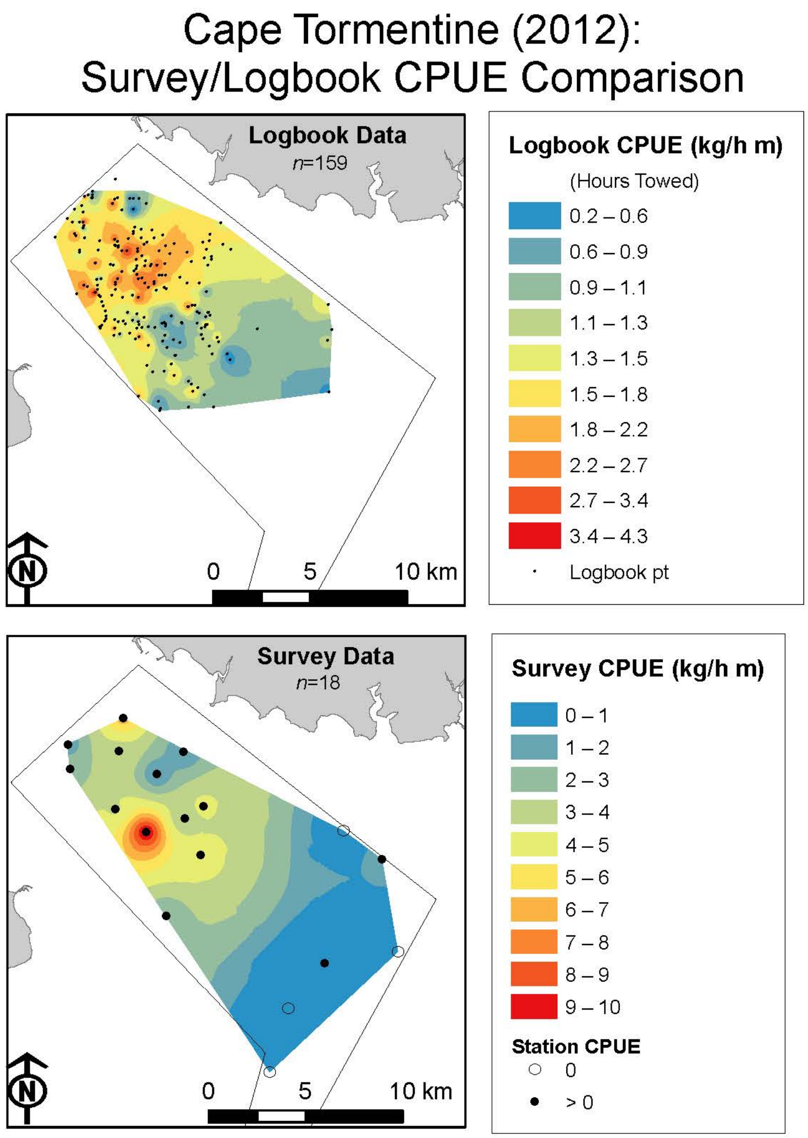

Figure 78. Spatial plot of average catch rate (kg $h^{-1}m^{-1}$) of the Cape Tormentine bed from the 2012 commercial logbook data (upper panel) and from the 2012 research survey data (lower panel).

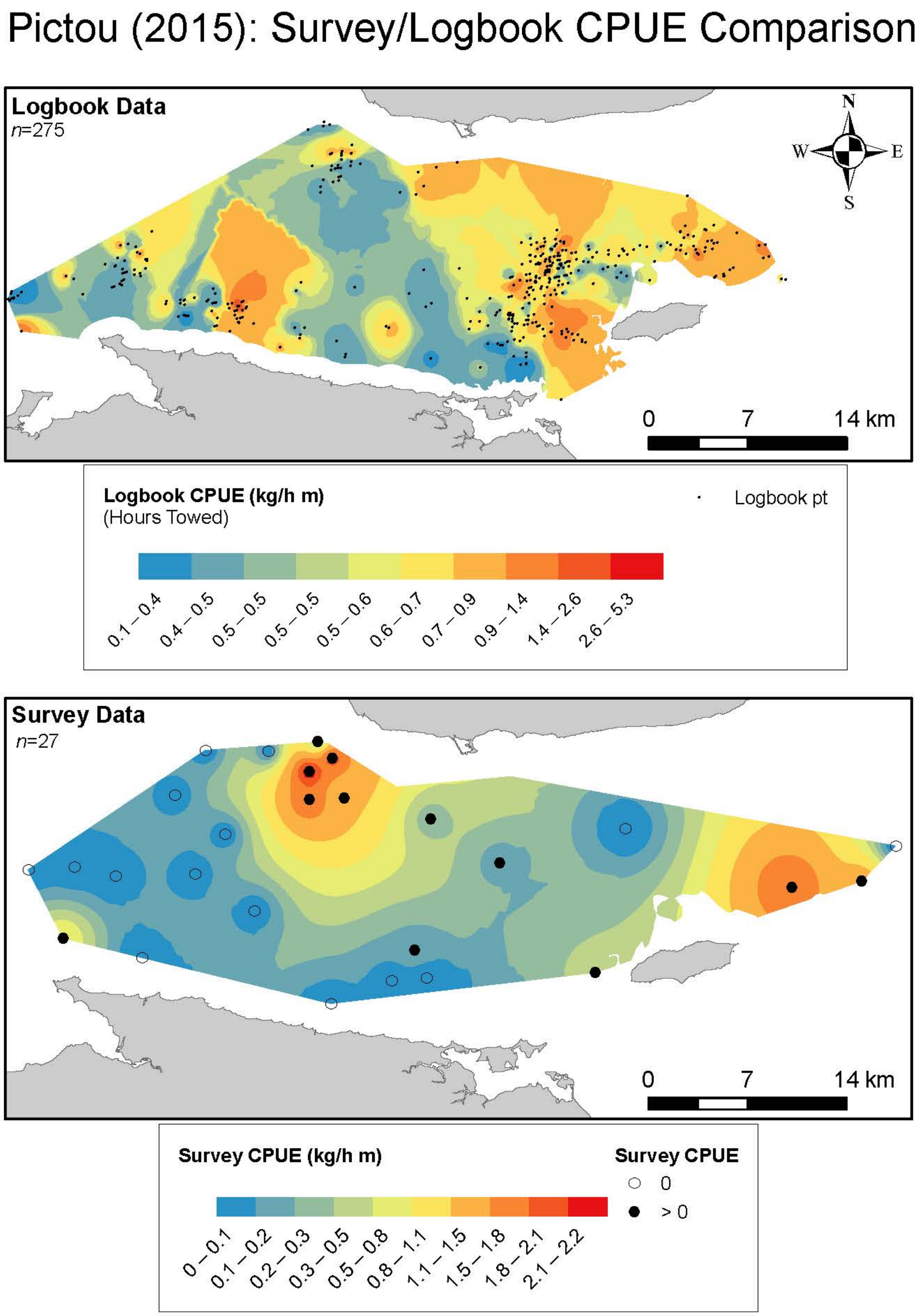

Figure 79. Spatial plot of average catch rate (kg $h^{-1}m^{-1}$) of the Pictou bed from the 2015 commercial logbook data (upper panel) and from the 2015 research survey data (lower panel).

ANNEXES

ANNEX 1

Table A1. Weekly proportion of scallop landings between the Cape Tormentine, West Point and Other beds in Scallop Fishing Area 22 from 2003 to 2016 logbook records based on daily fishing positions.

Year	Week	Cape Tormentine	West Point	*Other*	Year	Week	Cape Tormentine	West Point	Other
2003	1	0.37	0.43	0.20	2010	1	0.25	0.63	0.12
	2	0.21	0.51	0.28		2	0.16	0.51	0.33
	3	0.10	0.56	0.33		3	0.09	0.50	0.41
	4	0.07	0.46	0.47		4	0.11	0.36	0.53
	5	0.02	0.38	0.60		5	0.16	0.27	0.57
2004	1	0.47	0.23	0.30	2011	1	0.29	0.52	0.19
	2	0.51	0.20	0.29		2	0.36	0.35	0.29
	3	0.42	0.17	0.41		3	0.28	0.35	0.37
	4	0.28	0.17	0.55		4	0.23	0.39	0.38
	5	0.14	0.30	0.57		5	0.25	0.36	0.39
2005	1	0.18	0.49	0.33	2012	1	0.42	0.46	0.12
	2	0.11	0.51	0.39		2	0.39	0.35	0.25
	3	0.10	0.39	0.51		3	0.27	0.46	0.27
	4	0.03	0.26	0.71		4	0.20	0.46	0.34
	5	0.08	0.43	0.49		5	0.18	0.49	0.32
2006	1	0.32	0.43	0.25	2013	1	0.72	0.19	0.09
	2	0.21	0.48	0.30		2	0.89	0.04	0.07
	3	0.15	0.55	0.30		3	0.80	0.05	0.15
	4	0.10	0.53	0.37		4	0.50	0.25	0.25
	5	0.13	0.66	0.21		5	0.36	0.44	0.20

Year	Week	Cape Tormentine	West Point	*Other*	Year	Week	Cape Tormentine	West Point	Other
2007	1	0.21	0.67	0.12	2014	1	0.48	0.34	0.18
	2	0.22	0.69	0.09		2	0.34	0.48	0.18
	3	0.17	0.57	0.26		3	0.24	0.38	0.38
	4	0.16	0.40	0.44		4	0.31	0.43	0.27
	5	0.13	0.53	0.34		5	0.17	0.44	0.39
2008	1	0.43	0.43	0.15	2015	1	0.58	0.34	0.09
	2	0.46	0.25	0.30		2	0.60	0.26	0.14
	3	0.41	0.23	0.36		3	0.50	0.37	0.13
	4	0.40	0.18	0.42		4	0.43	0.22	0.35
	5	0.26	0.20	0.53		5	0.44	0.38	0.18
2009	1	0.41	0.45	0.14	2016	1	0.81	0.10	0.09
	2	0.43	0.32	0.25		2	0.81	0.04	0.15
	3	0.28	0.42	0.30		3	0.63	0.09	0.29
	4	0.20	0.46	0.35		4	0.62	0.07	0.30
	5	0.17	0.59	0.25		5	0.43	0.13	0.44

ANNEX 2

Table A2. Weekly proportion of scallop landings between the Pictou and Other beds in Scallop Fishing Area 24 from 2003 to 2016 logbook records based on daily fishing positions.

Year	Week	Pictou	Other	Year	Week	Pictou	Other	Year	Week	Pictou	Other
2003	1	0.32	0.68	2009	1	0.25	0.75	2015	1	0.43	0.57
	2	0.30	0.70		2	0.33	0.67		2	0.38	0.62
	3	0.26	0.74		3	0.45	0.55		3	0.38	0.62
	4	0.28	0.72		4	0.40	0.60		4	0.43	0.57
	5	0.36	0.64		5	0.24	0.76		5	0.38	0.62
	6	0.33	0.67		6	0.34	0.66		6	0.38	0.62
	7	0.34	0.66		7	0.20	0.80		-	-	-
2004	1	0.31	0.69	2010	1	0.34	0.66	2016	1	0.42	0.58
	2	0.37	0.63		2	0.33	0.67		2	0.45	0.55
	3	0.50	0.50		3	0.38	0.62		3	0.41	0.59
	4	0.45	0.55		4	0.36	0.64		4	0.38	0.62
	5	0.52	0.48		5	0.23	0.77		5	0.38	0.62
	6	0.46	0.54		6	0.16	0.84		6	0.42	0.58
	7	0.57	0.43		7	0.36	0.64		7	0.70	0.30
2005	1	0.25	0.75	2011	1	0.34	0.66	-			
	2	0.31	0.69		2	0.48	0.52				
	3	0.50	0.50		3	0.47	0.53				
	4	0.31	0.69		4	0.36	0.64				
	5	0.26	0.74		5	0.28	0.72				
	6	0.29	0.71		6	0.42	0.58				
	7	0.13	0.87		7	0.33	0.67				

Year	Week	Pictou	Other	Year	Week	Pictou	Other	Year	Week	Pictou	Other
2006	1	0.40	0.60	2012	1	0.48	0.52				
	2	0.62	0.38		2	0.46	0.54				
	3	0.46	0.54		3	0.45	0.55				
	4	0.30	0.70		4	0.35	0.65				
	5	0.34	0.66		5	0.25	0.75				
	6	0.37	0.63		6	0.18	0.82				
	7	0.24	0.76		7	0.20	0.80				
2007	1	0.12	0.88	2013	1	0.31	0.69				
	2	0.28	0.72		2	0.50	0.50				
	3	0.43	0.57		3	0.50	0.50				
	4	0.33	0.67		4	0.48	0.52				
	5	0.37	0.63		5	0.50	0.50				
	6	0.28	0.72		6	0.47	0.53				
	7	0.27	0.73		7	0.65	0.35				
2008	1	0.09	0.91	2014	1	0.31	0.69				
	2	0.38	0.62		2	0.49	0.51				
	3	0.42	0.58		3	0.35	0.65				
	4	0.36	0.64		4	0.43	0.57				
	5	0.28	0.72		5	0.22	0.78				
	6	0.37	0.63		6	0.37	0.63				
	-	-	-		7	0.36	0.64				

ANNEX 3

Table A3. Catch rates (kg h^{-1}) derived from the at-sea sampling program on commercial fishing vessels from 2001 to 2005 (Davidson et al 2012) and commercial catch rate from logbooks for that corresponding week of the season and bed, when available. Catch rate are not reported for at-port sampling.

Bed	Year	Date	Week	Tows (n)	Catch rate (kg h^{-1})	Comm. catch rate
21A bed	2001	17/07	2	9	6.81	-
	2002	01/08	5	7	3.55	-
	2003	03/07	1	10	4.02	4.28
	2004	21/07	3	9	4.87	4.32
	2005	07/07	1	10	7.14	7.11
Cape Tormentine	2001	16/05	2	20	6.89	-
	2002	09/05	1	10	6.58	-
	2003	05/05	1	16	9.96	6.26
	2004	14/05	2	9	4.54	6.94
	2005	06/05	1	14	4.29	3.96
West Point	2001	29/05	4	7	6.14	-
	2002	-	-	-	-	-
	2003	-	-	-	-	-
	2004	06/05	1	8	7.96	7.60
	2005	-	-	-	-	-
Pictou	2001	-	-	-	-	-
	2002	-	-	-	-	-
	2004	19/11	3	14	4.65	3.63
	2005	16/11	3	4	2.66	3.25

ANNEX 4

Table A4. Annual average catch rate (kg h^{-1}) per sea scallop bed from 2003 to 2016 reported in commercial fishery logbooks.

Catch rate (kg h^{-1})			
Year / Bed	West Point	Cape Tormentine	Pictou
2003	5.1	4.5	2.8
2004	6.2	6.1	3.9
2005	4.9	3.4	2.7
2006	4.7	4.3	3.2
2007	6.8	5.0	3.2
2008	6.6	7.1	3.1
2009	6.4	6.5	2.9
2010	6.0	5.2	3.8
2011	7.4	7.9	3.9
2012	6.5	7.6	3.8
2013	5.8	9.5	3.8
2014	6.5	7.3	3.3
2015	5.8	7.0	3.4
2016	3.7	5.6	4.4

ANNEX 5

Table A5. Specifications of the scallop research survey gear composed of an 8-gang scallop drag.

Drag Part	Measurements (2012-2013 drag)	Measurements (2014 + drag)
Drag total width	3.4 m	3.4 m
Drag inside width	2.84 m	2.84 m
Tow bar length	4.6 m	3.4 m
Tow bar hollow diameter	10 cm	10 cm
Outside bucket width	37.5 cm	37.5 cm
Inside bucket width	35.5 cm	35.5 cm
Inside bucket height	28 cm	28 cm
Bucket depth	54 cm	54 cm
Bucket teeth	5 cm	5 cm
Bucket ring diameter	9 cm	9 cm
Mesh size	1.4 cm	1.4 cm
Runner diameter	-	**32.6 cm X 30.5 cm**

ANNEX 6

Meat weight shell height relationship of scallops in the Gulf Region: A comparison to the Maritimes Region SPA 4 and Georges Bank 'a'

J.A. Sameoto (Maritimes), D. Keith (Maritimes) and M. Niles (Gulf)

Background:

An understanding of the relationship between scallop meat weight and shell height is required to sustainably manage scallop populations when landings are in terms of meat weight. This relationship is required to a) convert between biomass (meats) and scallop numbers, and b) quantify the spatial variability in meat weight for animals of a specified size (shell height); otherwise referred to as condition (Nasmith et al. 2016). An index of condition can provide insight into the relative productivity of an area since areas of higher condition will have greater yield of meat relative to areas of lower condition, all else being equal (e.g. scallop abundance, size, etc.). Further, since catch rates and landings data are in terms of scallop meat weight, an understanding of scallop condition allows for a more complete understanding of these commercial fishery indicators.

Methods:

Detailed shell height and meat weight data were collected from individual scallops during the Gulf scallop surveys in 2012, 2013, 2014, 2015, and 2016. Scallops were measured using digital calipers for shell height to the nearest 0.01 mm (maximum distance from the umbo to the outer shell margin). Weights were measured with a digital balance with an accuracy of 0.1 g. The spatial distribution of samples from these years is shown in Fig. A6-a. Sampling was conducted in distinct areas within Scallop Fishing Areas (SFAs) during each of these years (Table A6-a, Fig. A6-a) and sampling was conducted during the months of June, July and August.

Scallop Meat Weight Shell Height Modelling

In the Maritimes Region of DFO, detailed shell height and meat weight data for the sea scallop (*Placopecten magellanicus*) has been regularly collected from annual scallop surveys. For the Bay of Fundy region, these data are modeled using a generalized linear mixed effect model (GLMM) using a Gamma family with a log link, tow as the grouping variable, and depth as a covariate (Nasmith et al. 2016). To conduct meat weight shell height modelling of the Gulf data, and to enable the comparison of the results to two relatively productive scallop fishing areas in the DFO Maritimes Region (Scallop Production Area (SPA) 4 and Georges Bank area 'a'), the same modelling methods as in Nasmith et al. (2016) were applied to the Gulf data from 2012 to 2016. Sampling of SPA 4 and Georges Bank 'a' is conducted during July and August, respectively, whereas the Gulf data was collected in June, July, and August (Table A6-a). Although meat weight shell height relationships have been shown to vary temporally (Sarro and Stokesbury 2009, Nasmith and Smith 2017), exploratory analyses showed no significant differences between using the full Gulf dataset (June, July and August) and that subset to July and August. Therefore all data from June to August was used in the subsequent analyses.

The GLMM from Nasmith et al. (2016) was fit to the Gulf data for each year, and therefore by area: SFA 22 South (2012), SFA 21A (2013), SFA 22 North (2014), SFA 24 (2015), and SFA 21BC (2016). Model evaluation showed that depth was not significant for any of the individual areas (years); however, this is likely due to the low contrast in depth ranges within years and areas (Fig. A6-b). Depth was removed as a covariate and the final model formulation is shown in equation 1. The modelled meat weight shell height relationships by area (year) can be seen in Fig. A6-c and associated parameter estimates from the models by area (year) are in Table A6-b.

$$\log(W_{ij}) = (\beta_0 - b_{0,j}) + (\beta_1 - b_{1,j})\log(H_{ij}) \quad (1)$$

Where,

W_{ij} = Meat weight for shell i, from tow j

H_{ij}= Scallop shell height for shell i, from tow j

β_0, $b_{0,j}$ = Fixed and random effects for intercept

β_1, $b_{1,j}$ = Fixed and random effects for slope

The meat weight (g) of a 100 mm shell height scallop (here-after referred to as "condition") was then estimated for each area (year) using each area's (year's) parameter estimates (fixed effects only) and compared to the time series of condition from the Maritimes Regions SPA 4 and Georges Bank "a" (Fig. A6-d). Condition was predicted as being the highest in SFA 22 North (2014; 18.0 g), followed by SFA 21A (2013; 15.9 g), SFA 21BC (2016; 14.9 g), SFA 22 South (2012; 14.3 g), and SFA 24 (2015; 12.4 g), respectively (Table A6-b, Fig. A6-d). However, it is important to note that it is not possible to disentangle if these differences are due to spatial effects or due to temporal (e.g. year) differences.

There is often significant inter-annual variability in condition (Nasmith et al. 2016) which cannot be quantified given the limitations with the Gulf data; as a result the Gulf condition data should be treated with some caution. However, assuming the 2012 to 2016 Gulf data is representative, the condition of Gulf scallop is ≈ $\frac{1}{3}$ greater than in SPA 4 and is similar to the condition observed on Georges Bank "a" (Fig. A6-d; Gulf ≈15 g, SPA 4 ≈ 11 , Georges Bank "a" ≈ 16 g per 100 mm shell height). As a result, for the same catch rate in SPA 4 and the Gulf, the expectation would be that ≈33 % fewer animals would be caught in the Gulf (assuming similar abundances, size distributions harvested, etc.). For example, a 1 kg $h^{-1}m^{-1}$ catch rate from the Gulf targeting 100 mm scallop of average condition (15 g) would result in ≈ 67 individuals being harvested; whereas in SPA 4 a 1 kg $h^{-1}m^{-1}$ catch rate would harvest ≈91 individuals, all else being equal. Therefore, condition should be considered whenever interpreting trends in catch rate, particularly when catch rate is used as an index of abundance.

Previous relationships of meat weight and shell height for SFAs in the Gulf Region were reported in Davidson et al. (2012) from sampling conducted in 2001 through 2005. However, direct comparison of the results in Davidson et al. (2012) with these results is not possible due to the spatial grouping of beds within SFA, aggregation of years within SFA, and temporal differences of when samples were collected during this earlier time period (Davidson et al. 2012).

References:

Davidson, L.-A., Biron, M., and Niles, M. 2012. Scallop Fishery Assessment of the Southern Gulf of St. Lawrence in 2010: Commercial Fishery Data. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/007. vi + 40 p.

Nasmith, L., and Smith, S.J. 2017. Seasonal monitoring surveys of scallop (*Placopecten magellanicus*) in Scallop Production Areas 1 and 4 from 2000-2005. Can. Tech. Rep. Fish. Aquat. Sci. 3216; v + 38 p.

Nasmith, L., J. Sameoto, and A. Glass. 2016. Scallop Production Areas in the Bay of Fundy: Stock Status for 2015 and Forecast for 2016. DFO Can. Sci. Advis. Sec. Res. Doc. 2016/021. vi + 140 p.

Sarro, C.L., and K.E. Stokesbury. 2009. Spatial and temporal variability in the shell height/meat weight relationship of sea scallop *Placopecten magellanicus* in the Georges Bank Fishery. J. Shellfish Res. 28: 497-503

Tables A6

Table A6-a. Distribution of Gulf Region meat weight shell height scallop data by month from 2012 to 2016.

Area (Year)	Month		
	June	July	August
SFA 22 South (2012)	389	379	-
SFA 21A (2013)	25	55	-
SFA 22 North (2014)	176	-	-
SFA 24 (2015)	-	-	515
SFA 21BC (2016)	-	-	488

Table A6-b. Meat weight shell height parameters for mixed effect gamma models of Gulf Region data. Parameters β_0 and β_1 are as defined for equation 1 in the text.

Area (Year)	Fixed Effects		Random Effects		Residual	Meat weight (g) of 100 mm Shell Height
	β_o	β_1	σ_{b0}	σ_{b1}	σ_R	
SFA 22 South (2012)	2.15	2.85	0.00177	0.00425	0.0199	14.3
SFA 21A (2013)	3.10	3.01	0.00235	0.125	0.0114	15.9
SFA 22 North (2014)	2.86	2.90	0.00272	0.0448	0.0206	18.0
SFA 24 (2015)	1.88	2.93	0.00753	0.0243	0.0293	12.4
SFA 21BC (2016)	1.91	3.12	0.00243	0.00833	0.0221	14.9

Figures A6

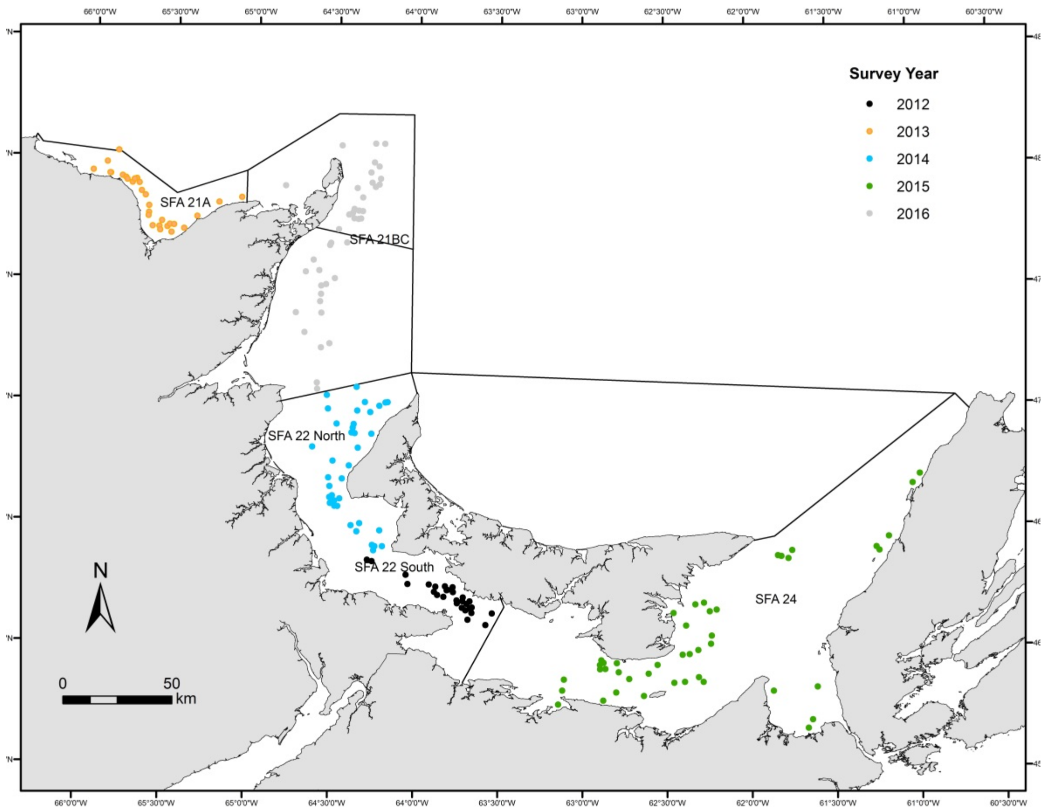

Figure A6-a. Spatial distribution of meat weight - shell height tows in the Gulf Region from 2012 to 2016 surveys.

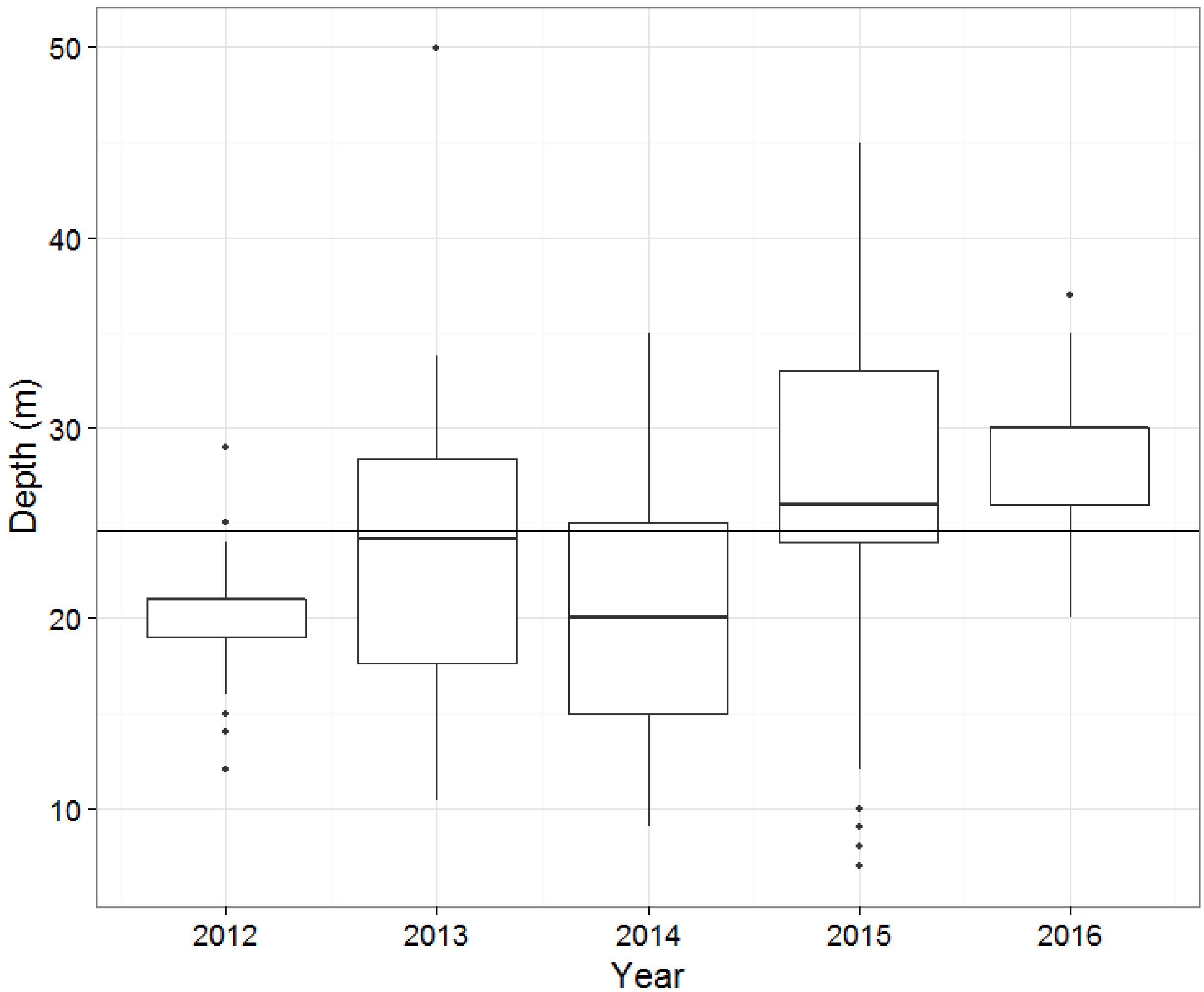

Figure A6-b. Depth distribution of meat weight shell height samples from the Gulf Region from 2012 to 2016. Note the spatial distribution of samples was different each year; 2012 samples were in SFA 22 South, 2013 samples were in SFA 21A, 2014 samples were in SFA 22 North, 2015 samples were in SFA 24, and 2016 samples were in SFA 21BC.

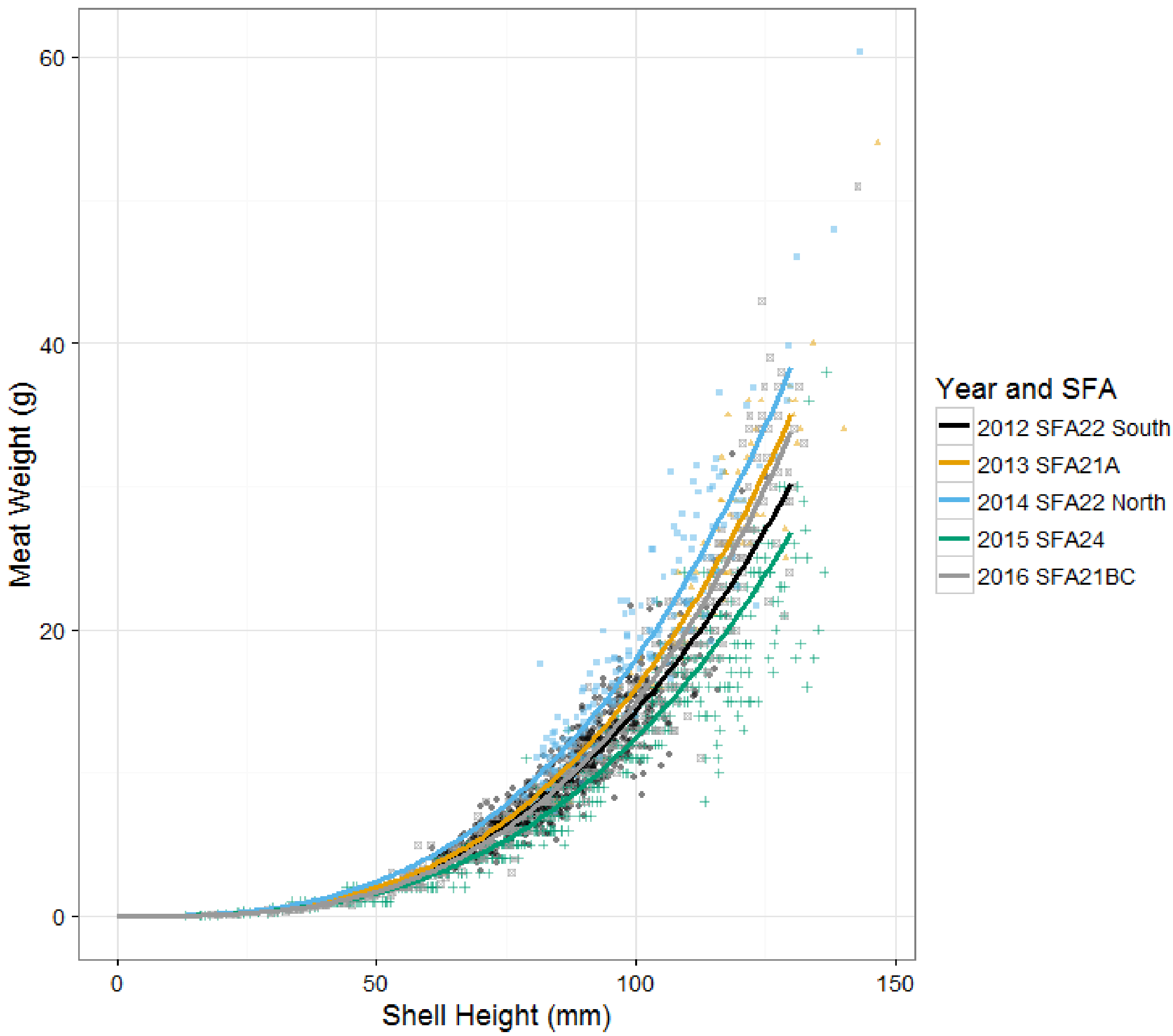

Figure A6-c. Meat weight shell height relationships from 2012 to 2016 for 5 separate areas in the Gulf Region.

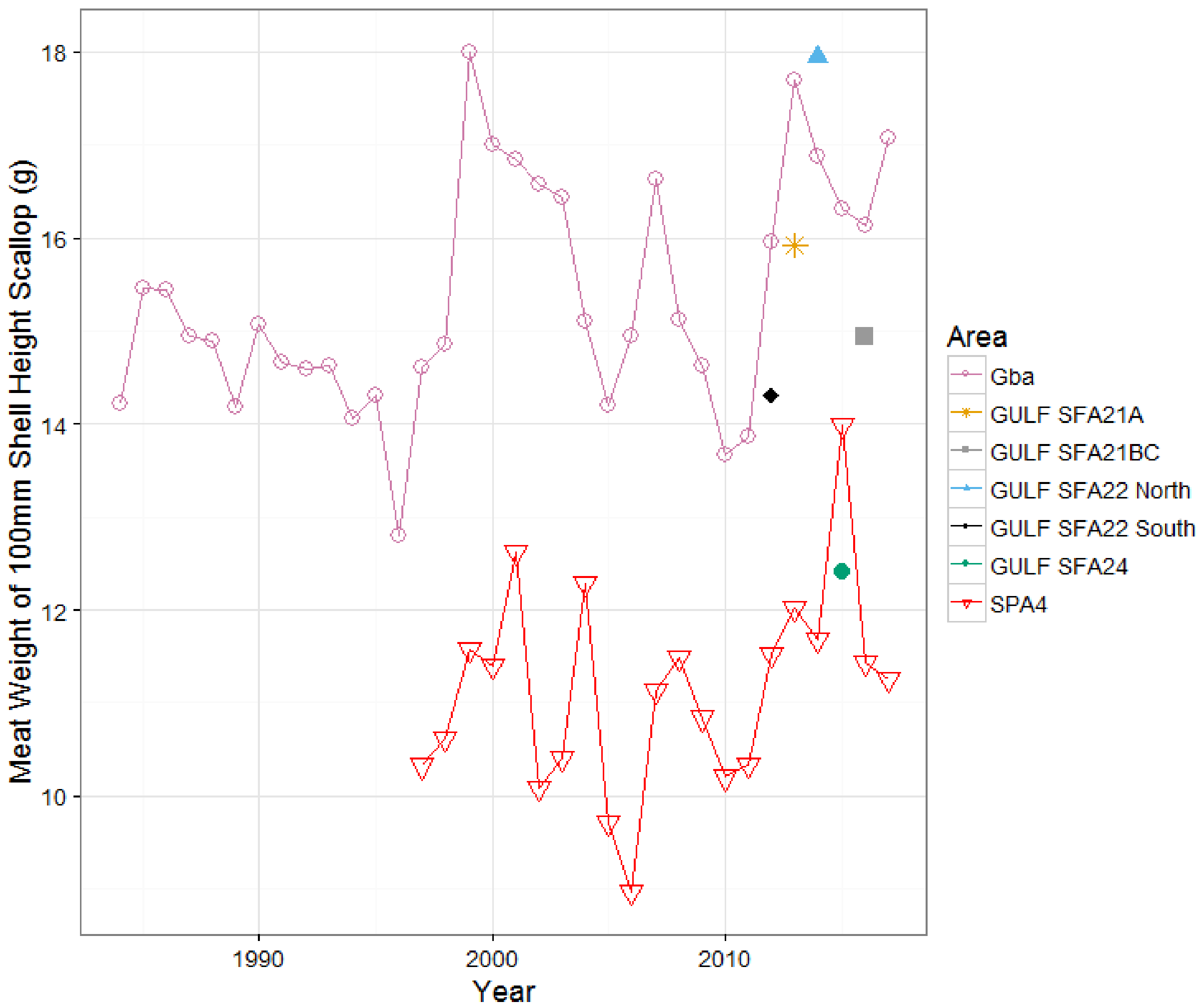

Figure A6-d. Time series of scallop condition (meat weight of a 100 mm shell height scallop) for Scallop Production Area 4 (SPA4), Georges Bank "a" (Gba), Scallop Fishing Area (SFA) 21A, SFA 21BC, SFA 22 North, SFA 22 South, and SFA 24.

ANNEX 7

Table A7. Research survey abundance indices of scallop as number of scallops per standard tow of 437.27 m^2 (mean and standard error (SE)) and density (number m^{-2}) for each survey by stratum and for three size classes (all sizes, < 80 mm and ≥ 80 mm shell height). Not corrected for dredge efficiency.

SFA	Stratum No. / Name		All sizes			< 80 mm			≥ 80 mm		
			Number per standard tow		Density	Number per standard tow		Density	Number per standard tow		Density
			Mean	SE	Mean (/m2)	Mean	SE	Mean (/m2)	Mean	SE	Mean (/m2)
21A	1	Buffer	13.37	5.57	0.031	9.28	4.04	0.021	4.09	1.55	0.009
	2	Moderate effort	1.90	0.66	0.004	1.29	0.54	0.003	0.61	0.21	0.001
	3	Low effort	2.10	1.62	0.005	0.27	0.17	0.001	1.83	1.62	0.004
	4	No effort	0.00	0.00	0.000	0.00	0.00	0.000	0.00	0.00	0.000
21BC	1	Moderate effort	14.79	6.16	0.034	7.59	3.95	0.016	7.20	2.36	0.016
	2	Low effort	2.88	1.17	0.007	0.99	0.53	0.002	1.89	0.67	0.004
	3	No effort	0.00	0.00	0.000	0.00	0.00	0.000	0.00	0.00	0.000
	4	Buffer	0.39	0.29	0.000	0.35	0.27	0.000	0.05	0.05	0.000
22 north	1	Low effort	0.91	0.53	0.002	0.07	0.07	0.000	0.84	0.47	0.002
	2	Moderate effort	1.46	0.41	0.003	0.22	0.10	0.001	1.24	0.39	0.003
	3	High effort	8.72	3.10	0.020	5.75	2.19	0.013	2.96	1.07	0.007
	4	Buffer	0.00	0.00	0.000	0	0	0	0	0	0
22 south	1	Very low or no effort	2.38	1.74	0.005	1.40	0.88	0.003	0.98	0.88	0.002
	2	Low effort	13.13	4.88	0.030	5.73	2.16	0.013	7.40	2.83	0.017
	3	High effort	49.66	13.71	0.114	29.96	8.96	0.069	19.70	5.29	0.045
	4	Buffer (18m) - NB	0.00	0.00	0.000	0	0	0.000	0.00	0.00	0.000
	5	Buffer (18m) - PEI	0.00	0.00	0.000	0	0	0.000	0.00	0.00	0.000

SFA	Stratum No. / Name		All sizes			< 80 mm			≥ 80 mm		
			Number per standard tow		Density	Number per standard tow		Density	Number per standard tow		Density
			Mean	SE	Mean (/m2)	Mean	SE	Mean (/m2)	Mean	SE	Mean (/m2)
24	1	High effort	3.31	0.97	0.008	1.42	0.43	0.003	1.83	0.58	0.004
	2	Moderate effort	7.05	6.21	0.002	4.12	3.86	0.000	2.94	2.35	0.001
	3	Low effort	5.06	2.94	0.012	2.07	1.56	0.005	2.99	1.48	0.007
	4	No effort	0.00	0.00	0.000	0.00	0.00	0.000	0.00	0.00	0.000
	5	Buffer	7.23	3.02	0.027	1.54	0.72	0.011	5.69	2.45	0.016

ANNEX 8

Table A8. Research survey abundance indices of scallop as live weight (kg) of scallops per standard tow of 437.27 m^2 (mean and standard error (SE)) and density (g m^{-2}) for each survey by stratum and for three size classes (all sizes, < 80 mm and ≥ 80 mm shell height). Not corrected for dredge efficiency.

SFA	Stratum No. and Name		All sizes			< 80 mm			≥ 80 mm		
			Weight per standard tow		Densit y	Weight per standard tow		Density	Weight per standard tow		Density
			Mean	SE	Mean (g m^{-2})	Mean	SE	Mean (g m^{-2})	Mean	SE	Mean (g m^{-2})
21	1	Buffer	1.19	0.47	2.714	0.28	0.12	0.642	0.91	0.36	2.073
	2	Moderate effort	0.17	0.05	0.382	0.05	0.02	0.108	0.12	0.05	0.274
	3	Low effort	0.32	0.27	0.722	0.00	0.00	0.006	0.31	0.27	0.716
	4	No effort	0.00	0.00	0.000	0.00	0.00	0.000	0.00	0.00	0.000
21BC	1	Moderate effort	1.36	0.44	3.108	0.20	0.12	0.466	1.16	0.34	2.317
	2	Low effort	0.39	0.14	0.845	0.03	0.02	0.110	0.36	0.13	0.681
	3	No effort	0.00	0.00	0.000	0.00	0.00	0.000	0.00	0.00	0.000
	4	Buffer	0.01	0.01	0.000	0.01	0.01	0.000	0.01	0.01	0.000
22 north	1	Low effort	0.14	0.07	0.327	0.00	0.00	0.001	0.14	0.07	0.326
	2	Moderate effort	0.26	0.07	0.588	0.02	0.02	0.047	0.24	0.07	0.542
	3	High effort	0.76	0.25	1.740	0.26	0.11	0.603	0.50	0.17	1.136
	4	Buffer	0.00	0.00	0.000	0.00	0.00	0.000	0.00	0.00	0.000
22 south	1	Very low or no effort	0.31	0.27	0.703	0.14	0.12	0.321	0.17	0.15	0.381
	2	Low effort	1.36	0.56	3.118	0.27	0.13	0.613	1.07	0.44	2.439
	3	High effort	3.95	1.02	9.033	0.94	0.26	2.156	3.01	0.76	6.878
	4	Buffer (18m) – NB	0.00	0.00	0.000	0.00	0.00	0.000	0.00	0.00	0.000
	5	Buffer (18m) – PEI	0.00	0.00	0.000	0.00	0.00	0.000	0.00	0.00	0.000

SFA	Stratum No. and Name		All sizes			< 80 mm			≥ 80 mm		
			Weight per standard tow		Densit y	Weight per standard tow		Density	Weight per standard tow		Density
			Mean	SE	Mean (g m^{-2})	Mean	SE	Mean (g m^{-2})	Mean	SE	Mean (g m^{-2})
24	1	High effort	0.44	0.14	1.002	0.04	0.02	0.087	0.40	0.13	0.914
	2	Moderate effort	0.61	0.51	0.207	0.14	0.14	0.016	0.46	0.37	0.169
	3	Low effort	0.69	0.33	1.584	0.07	0.05	0.167	0.62	0.29	1.064
	4	No effort	0.00	0.00	0.000	0.00	0.00	0.000	0.00	0.00	0.000
	5	Buffer	1.46	0.69	3.914	0.04	0.02	0.372	1.42	0.68	2.651

ANNEX 9

Table A9. Total number caught of most common and key species or groups of species during the scallop research surveys from 2012 to 2016 in the Gulf region.

Total number caught of most common and key species or groups of species over five years of surveys in the Gulf region.	
Species name	number caught
Asterias vulgaris	7746
Cancer irroratus	3657
Other sea stars	2993
Placopecten magellanicus	2797
Other fish	1661
Homarus americanus	465
Pseudopleuronectes americanus	452
Hippoglossoides platessoides	265
Myoxocephalus sp.	237
Tautogolabrus adspersus	180
Scophthalmus aquosus	24
Urophycis tenuis	5

ANNEX 10

Table A10. Common name and Latin name of other species caught during the scallop research surveys from 2012 to 2016 in the Gulf region.

Common Name	Latin Name
Alligatorfish	*Aspidophoroides monopterygius*
American oyster	*Crassostrea virginica*
American plaice	*Hippoglossoides platessoides*
Arctic shanny	*Stichaeus punctatus*
Arctic staghorn sculpin	*Gymnocanthus tricuspis*
Astarte	*Astarte sp.*
Atlantic cod	*Gadus morhua*
Atlantic hooker sculpin	*Artediellus atlanticus*
Atlantic rock crab	*Cancer irroratus*
Atlantic sea poacher	*Leptagonus decagonus*
Atlantic tomcod	*Microgadus tomcod*
Bank clam	*Cyrtodaria siliqua*
Basket star	*Gorgonocephalidae,asteronychidae*
Black mussel	*Musculus niger*
Blood star	*Henricia sp.*
Blue mussel	*Mytilus edulis*
Brittle star	*unspecified*
Brittle star	*Stegophiura nodosa*
common Atlantic slippersnail	*Crepidule fornicata*
Cunner	*Tautogolabrus adspersus*
Daubed shanny	*Leptoclinus maculatus*
Diplopteraster multipes	*Diplopteraster multipes*

Common Name	**Latin Name**
Dusky seasnail	*Liparis gibbus*
Eyed sponge	*Polymastia mammilaris*
Fig sponge	*Suberites ficus*
Fish doctor	*Gymnelis viridis*
Fourbeard rockling	*Enchelyopus cimbrius*
Fourline snake blenny	*Eumesogrammus praecisus*
Sea scallop	*Placopecten magellanicus*
Grubby	*Myoxocephalus aeneus*
Heart urchin	*Brisaster fragilis*
Horse mussel	*Modiolus*
Horse star	*Hippasteria phrygiana*
Hyrdrozoa	*unspecified*
Iceland cockle	*Clinocardium ciliatum*
Iceland scallop	*Chlamys islandicus*
Inornate Pandora	*Pandora sp.*
Jellyfish	*Aurelias sp.*
Lady crab	*Ovalipes ocellatus*
lampshell	*Brachiopoda (phy.)*
Lebbeus groenlandicus	*Lebbeus groenlandicus*
Limpet	*Archaeogastropoda o.*
Longhorn sculpin	*Myoxocephalus octodecimspinosus*
Lumpsih	*Cyclopterus lumpus*
Mailed sculpin	*Triglops murrayi*
Margarites costalis	*Margarites costalis*

Common Name	**Latin Name**
Molpadia (sea cucumber)	*Molpadia*
Mud crab	*Unspecified*
New England Neptune	*Neptunea despecta*
Ocean pout	*Zoarces americanus*
Ocean Quahaug	*Arctica islandica*
Ophelia	*Ophelia sp*
Ophiura sarsi	*Ophiura sarsi*
Shrimp Pandalus borealis	*Pandalus borealis*
Pandalus montagui	*Pandalus montagui*
Pandora gouldiana	*Pandora gouldiana*
Pargurus arcuatus	*Pargurus arcuatus*
Pelican foot	*APORRHAIS sp.*
Periwinkle	*Littorina littorea*
Polar star	*Leptasterias polaris*
Polychaete worm	*Nereis sp.*
Psolus phantapus	*Psolus phantapus*
Pteraster militaris	*Pteraster militaris*
Purple sunstar	*Solaster endeca*
Quahaug	*Mercenaria mercenaria*
Red northern chiton	*Tonicella rubra*
Rock gunnel	*Pholis gunnellus*
Sand dollar	*Echinarachnius parma*
Sand lance	*Ammodytes sp.*
Sand shrimp	*Crangon septemspinosa*

Common Name	**Latin Name**
Scarlett psolus	*Psolus fabricii*
Sclerocrangon boreas	*Sclerocrangon boreas*
sea anemone	*Hormathia nodosa*
Sea anemone	*unspecified*
Sea cucumber	*Holothuroidea (cl.)*
Sea grapes	*Molgula manhattensis*
Sea mouse	*Aphrodita hastata*
Sea peach	*Halocynthia pyriformis*
Sea potato	*BOLTENIA sp.*
Sea raven	*Hemitripterus americanus*
Sea star	*Asterias sp.*
Sea strawberries	*Gersemia rubiformis*
Sea urchin	*Strongylocentrotus droebachiensis*
Seeweed	*unspecified*
Shorthorn sculpin	*Myoxocephalus scorpius*
Shrimp	*unidentified specie*
shrimp	*Argis dentata*
Slender eelbenny	*Lumpenus fabricii*
Slipper shell	*Margarites groenlandica*
Smooth skate	*Malacoraja senta*
Snakeblenny	*Lumpenus lampretaeformis*
Snow crab	*Chionoecetes opilio*
Soft-shell clam	*Mya arenaria*
Spindle shell	*Colus sp.*

Common Name	Latin Name
Spiny sunstar	*Crossaster papposus*
Sponge	*unspecified*
Stimpson surf clam	*Spisula polynyma*
Surf clam	*Spisula solidissima*
Terebratulina sp.	*Terebratulina sp.*
Thorny skate	*Amblyraja radiata*
Three spine stickleback	*Gasterosteus aculeatus aculeatus*
Toad crab	*Hyas sp.*
Vahl eelpout	*Lycodes vahlii*
White hake	*Urophycis tenuis*
Windowpane	*Scophthalmus aquosus*
Winter flounder	*Pseudopleuronectes americanus*
Yellowtail flounder	*Limanda ferruginea*
Yoldia	*Yoldia sp.*

ANNEX 11

Depletion model and survey estimates at the bed level.

Table A11-a. Depletion model results for each major scallop bed corresponding to the 20 trips km^{-2} density contour from 2003 to 2016 showing number of logbook records (n), catchability coefficient (q), cumulative catch in tons of meat (C), estimated Biomass before the fishery ($B_{0\ (t)}$) and estimated exploitation rate ($\hat{E}$). Italic text means non-significant model (P > 0.05).

Year	Area	n (logs)	q	C (t)	$B_{0\ (t)}$	E
2003	Cape Tormentine bed	191	0.282	11	22.95	0.50
2004	Cape Tormentine bed	263	0.188	31	51.71	0.61
2005	Cape Tormentine bed	64	0.337	7	12.74	0.53
2006	Cape Tormentine bed	144	0.269	12	22.07	0.56
2007	Cape Tormentine bed	148	0.255	15	28.49	0.54
2008	Cape Tormentine bed	182	0.169	32	59.64	0.54
2009	Cape Tormentine bed	215	0.195	28	47.63	0.59
2010	Cape Tormentine bed	118	0.337	10	21.43	0.48
2011	Cape Tormentine bed	260	0.202	25	53.10	0.47
2012	Cape Tormentine bed	294	0.226	30	50.51	0.60
2013	Cape Tormentine bed	520	0.125	64	112.91	0.57
2014	Cape Tormentine bed	226	0.208	25	48.44	0.51
2015	Cape Tormentine bed	266	0.212	27	48.74	0.55
2016	Cape Tormentine bed	311	0.206	25	41.68	0.60
2003	West Point bed	391	0.169	27	45.69	0.60
2004	West Point bed	90	0.196	16	38.97	0.40
2005	West Point bed	326	0.123	25	53.81	0.46
2006	West Point bed	412	0.141	26	48.10	0.54
2007	West Point bed	414	0.148	49	75.49	0.65
2008	West Point bed	212	0.237	24	42.34	0.56

Year	Area	n (logs)	q	C (t)	$B_{0\ (t)}$	E
2009	West Point bed	311	0.114	34	75.35	0.45
2010	West Point bed	338	0.187	30	48.06	0.62
2011	West Point bed	403	0.144	37	71.53	0.52
2012	West Point bed	386	0.138	37	68.07	0.54
2013	West Point bed	206	0.078	15	82.00	0.18
2014	West Point bed	327	0.220	28	46.58	0.61
2015	West Point bed	200	0.302	16	28.23	0.56
2016	West Point bed	57	0.796	3	6.20	0.42
2003	Pictou bed	70	0.126	8	27.65	0.29
2004	*Pictou bed*	*120*	*0.060*	*12*	*-60.30*	*-0.20*
2005	*Pictou bed*	*171*	*0.009*	*8*	*-277.08*	*-0.03*
2006	*Pictou bed*	*222*	*0.038*	*12*	*86.93*	*0.13*
2007	*Pictou bed*	*92*	*0.104*	*7*	*33.32*	*0.20*
2008	*Pictou bed*	*95*	*0.054*	*5*	*-57.25*	*-0.09*
2009	*Pictou bed*	*117*	*0.022*	*7*	*139.74*	*0.05*
2010	*Pictou bed*	*147*	*0.027*	*8*	*-136.12*	*-0.06*
2011	Pictou bed	223	0.109	12	41.74	0.28
2012	*Pictou bed*	*192*	*0.138*	*12*	*32.64*	*0.36*
2013	*Pictou bed*	*217*	*0.033*	*12*	*118.96*	*0.10*
2014	Pictou bed	181	0.096	7	36.39	0.19
2015	*Pictou bed*	*159*	*0.047*	*7*	*74.72*	*0.09*
2016	*Pictou bed*	*143*	*0.049*	*10*	*91.02*	*0.11*

Table A11-b. SFA specific research vessel scallop survey commercial size (≥ 80 mm shell height) biomass indices (not corrected for drag efficiency) of scallop as meat weight (kg per standard tow of 437.27 m^2; mean, standard error (SE)), density (g m^{-2}), corresponding area for the bed (km^2) according to the 20 pts km^{-2} contour, estimated biomass (meat weight, t), pro-rated landings to the bed, and exploitation rate.

Characteristic	SFA 21A	SFA 22 north	SFA 22 south
Bed	21A	West Point	Cape Tormentine
Year	2013	2014	2012
Abundance (kg per standard tow)			
Mean	0.153	0.177	0.344
Standard error	0.095	0.051	0.068
Density (g per m^{-2})	0.35	0.41	0.79
Surface area of the bed (km^2)	22	137	92
Biomass (t) before the fishery	7.7	87	102
Landings (t)	4.7	28	30
Exploitation rate	61%	34%	29%

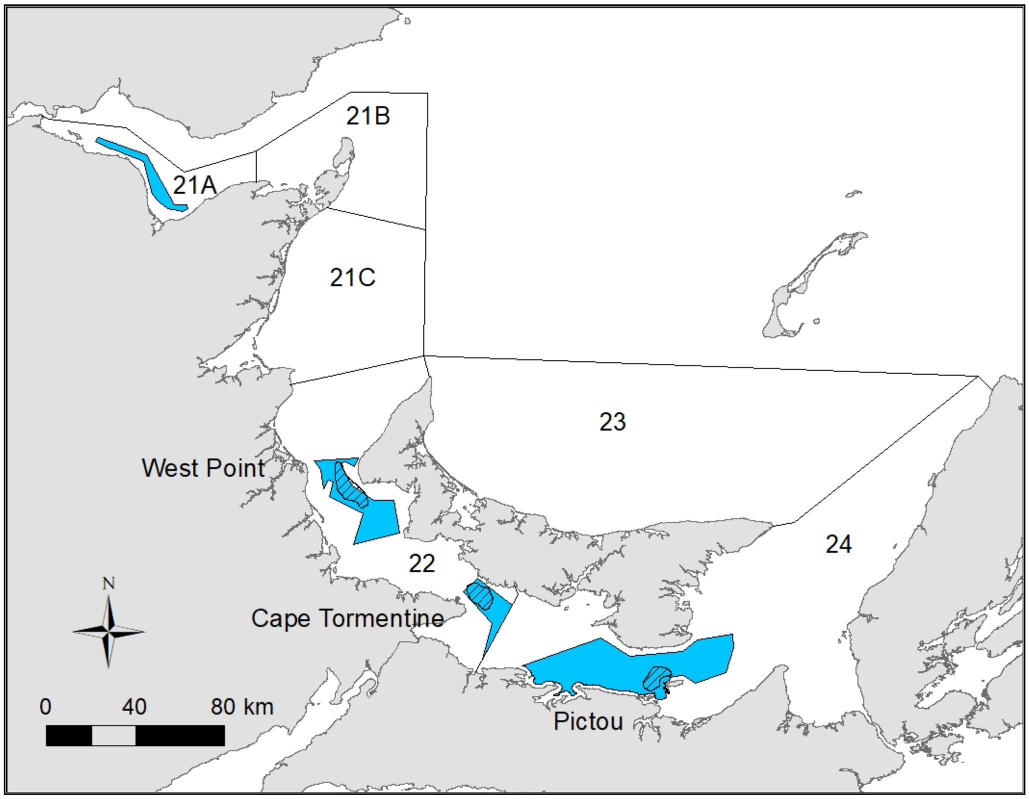

Figure A11-a. Major scallop beds as defined from the kernel density contour of 20 trips km² (hashed area), for the southern Gulf of St. Lawrence commercial scallop fishery, summed over years 2001 to 2016 used for catch rate and depletion model estimates (hashed area); in contrast to beds defined from the survey strata (blue shaded area).

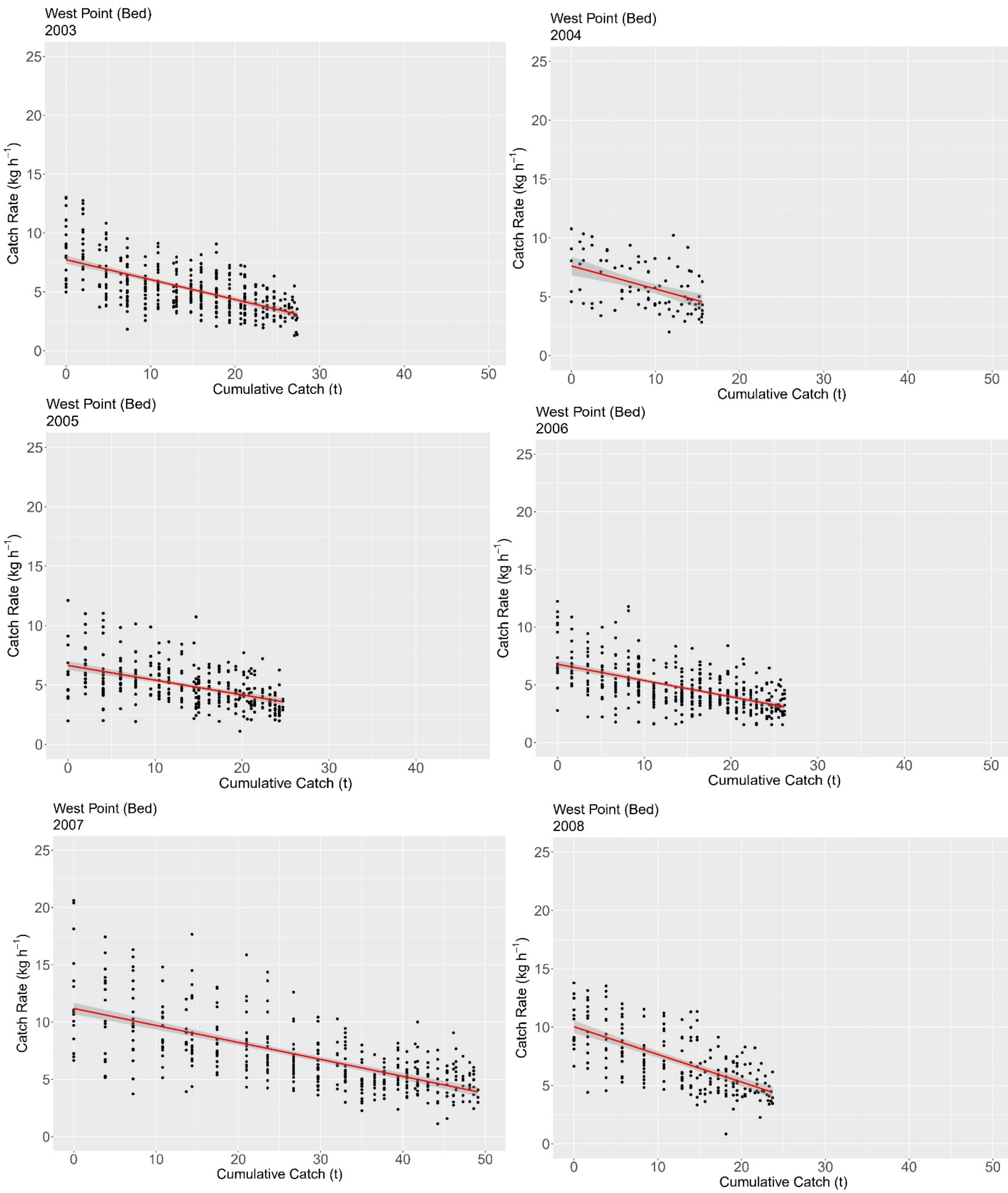

Figure A11-b. Plot of daily catch rates against the cumulative catch of scallops and the best-fit line (for years in which the model was statistically significant) of the Leslie depletion model for the West Point bed data as defined by the kernel density contour of 20 trips km^{-2} for each year from 2003 to 2008.

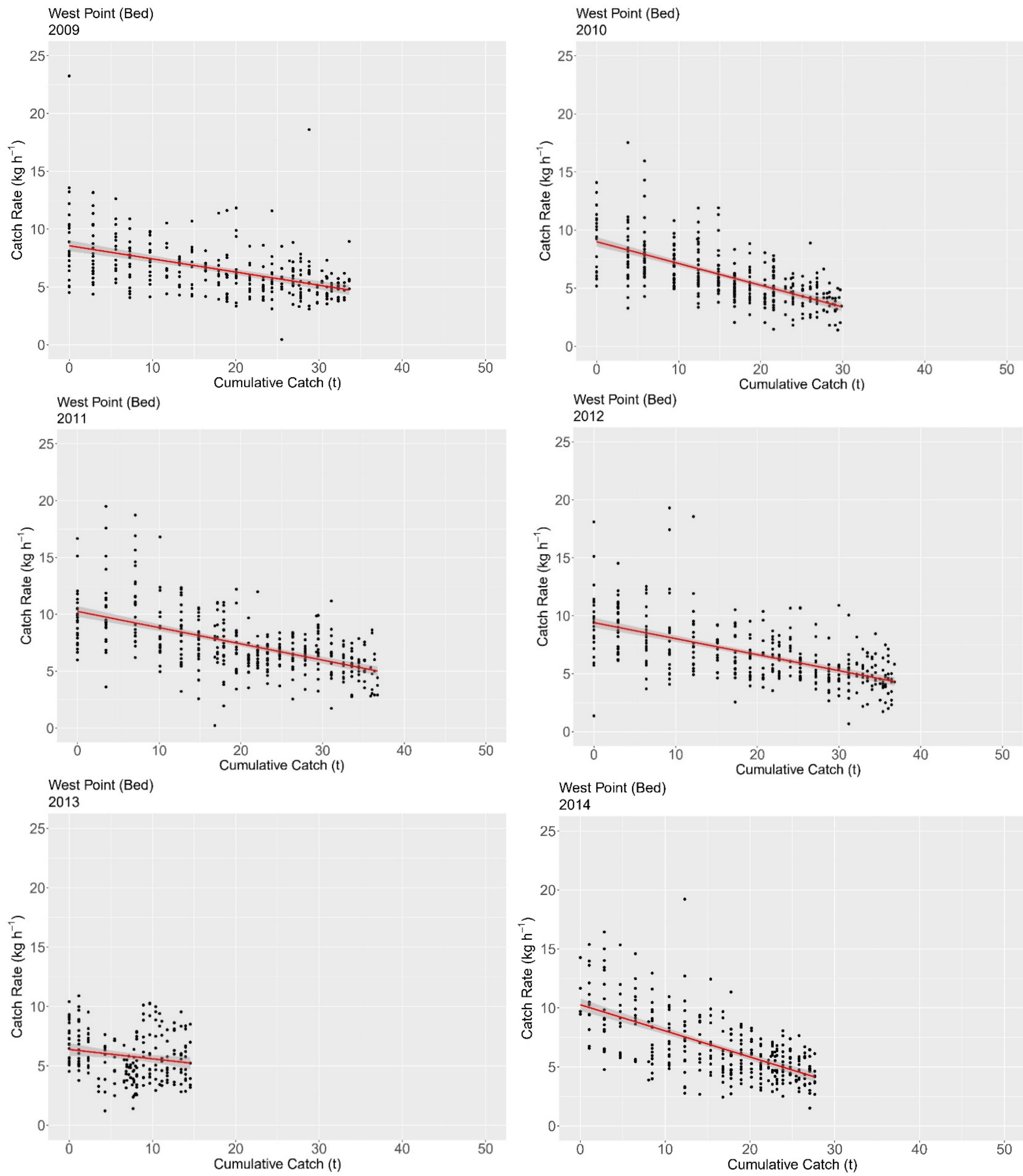

Figure A11-c. Plot of daily catch rates against the cumulative catch of scallops and the best-fit line (for years in which the model was statistically significant) of the Leslie depletion model for the West Point bed data as defined by the kernel density contour of 20 trips km^{-2} for each year from 2009 to 2014.

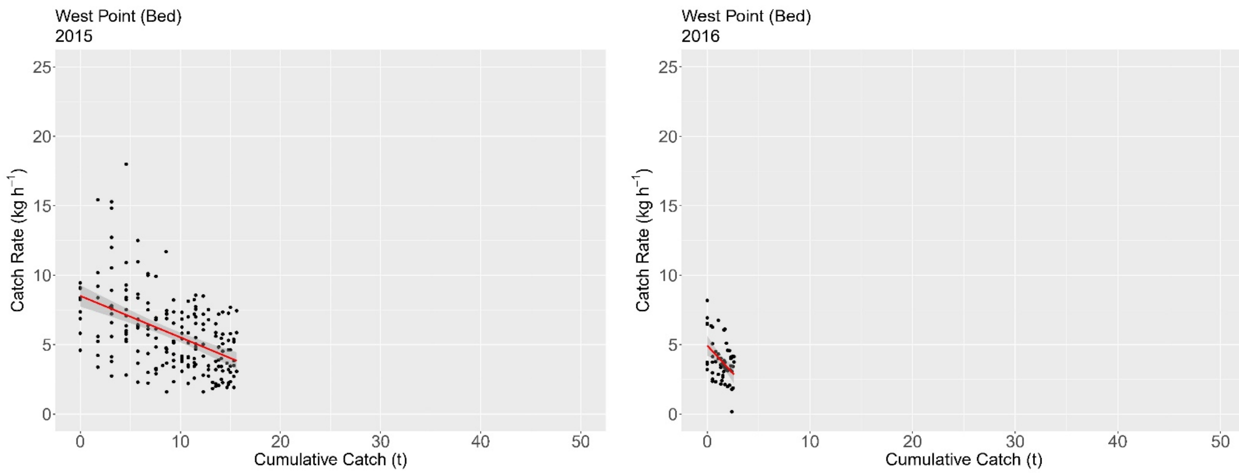

Figure A11-d. Plot of daily catch rates against the cumulative catch of scallops and the best-fit line (for years in which the model was statistically significant) of the Leslie depletion model for the West Point bed data as defined by the kernel density contour of 20 trips km^{-2} for each year from 2015 to 2016.

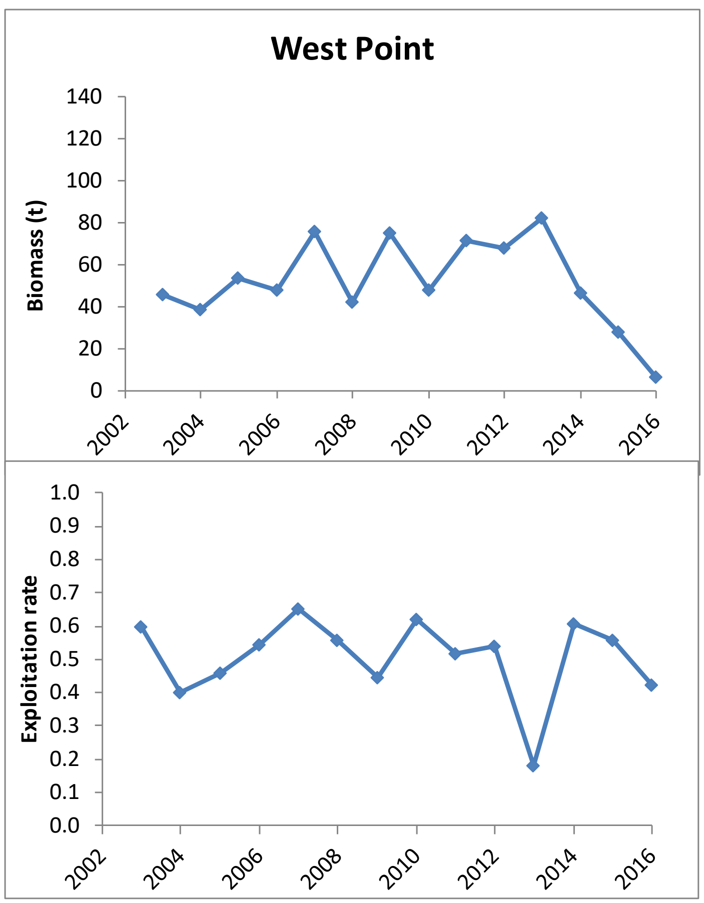

Figure A11-e. Depletion model estimates of Biomass (B_0) at the start of the fishery an d exploitation rate ($\hat{E}$) from 2003 to 2016 for the West Point bed (kernel density contour of 20 pts km^{-2}), in Scallop Fishing Area 22.

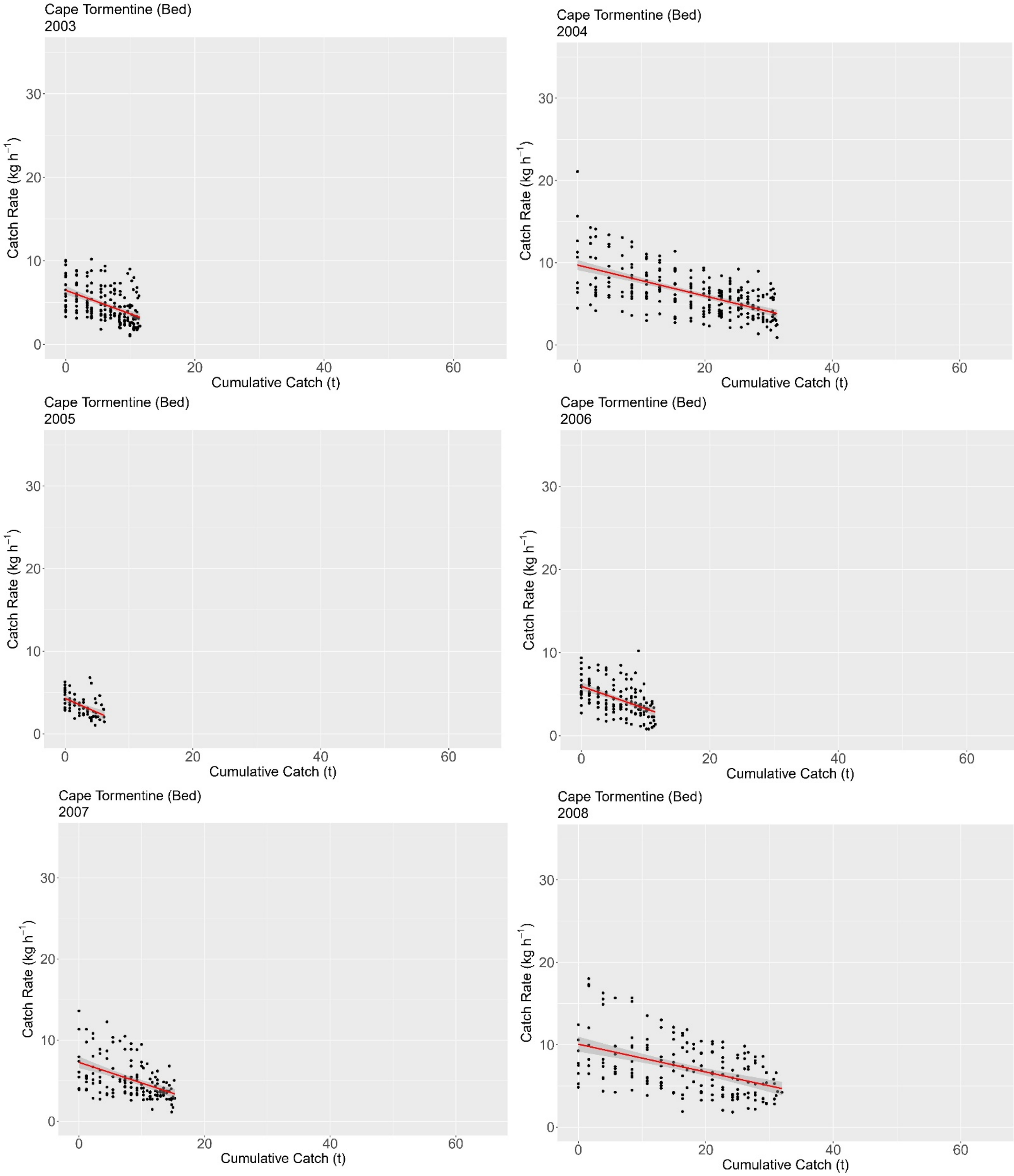

Figure A11-f. Plot of daily catch rates against the cumulative catch of scallops and the best-fit line (for years in which the model was statistically significant) of the Leslie depletion model for the Cape Tormentine bed data as defined by the kernel density contour of 20 trips km^{-2} for each year from 2003 to 2008.

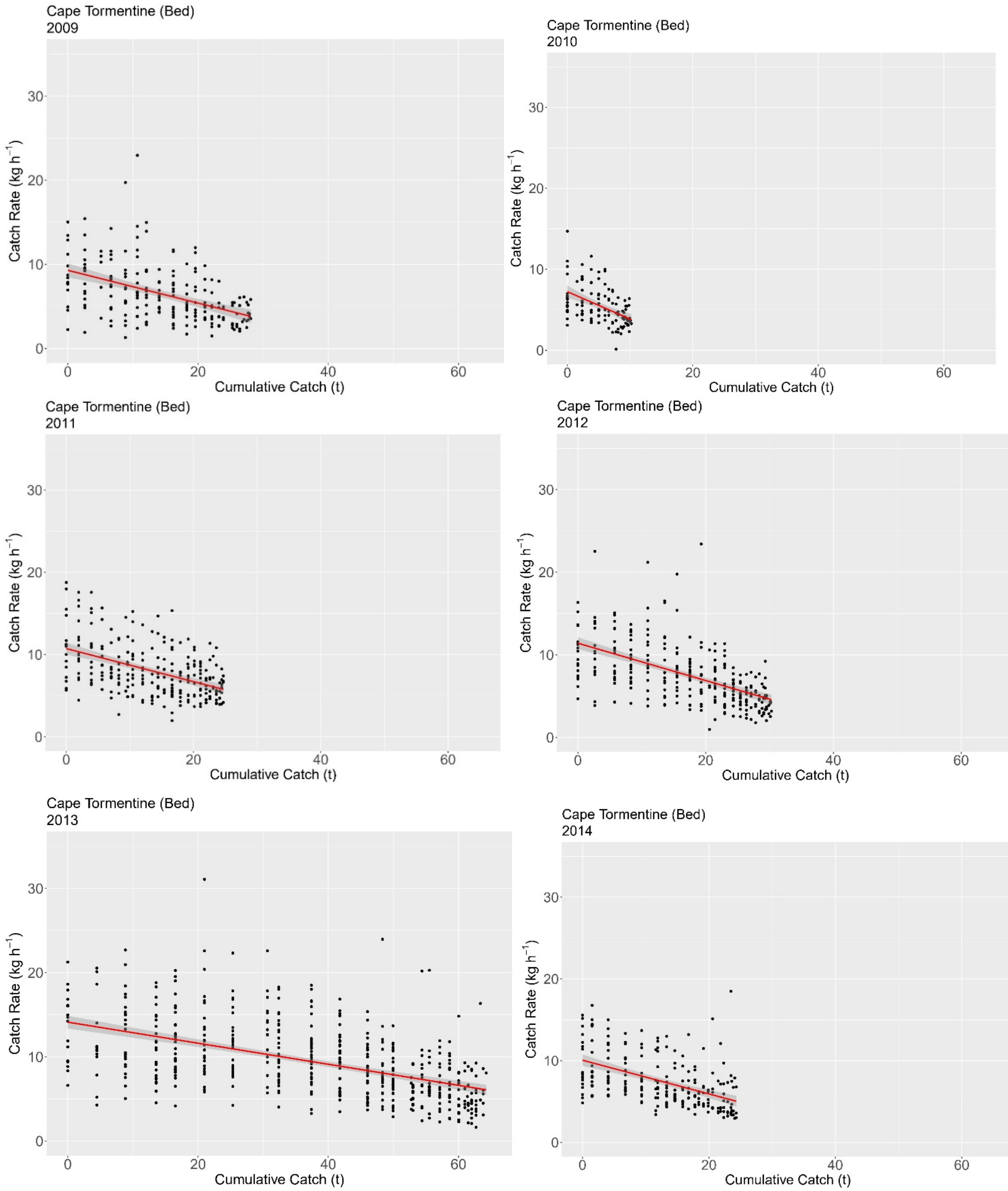

Figure A11-g. Plot of daily catch rates against the cumulative catch of scallops and the best-fit line (for years in which the model was statistically significant) of the Leslie depletion model for the Cape Tormentine bed data as defined by the kernel density contour of 20 trips km^{-2} for each year from 2009 to 2014.

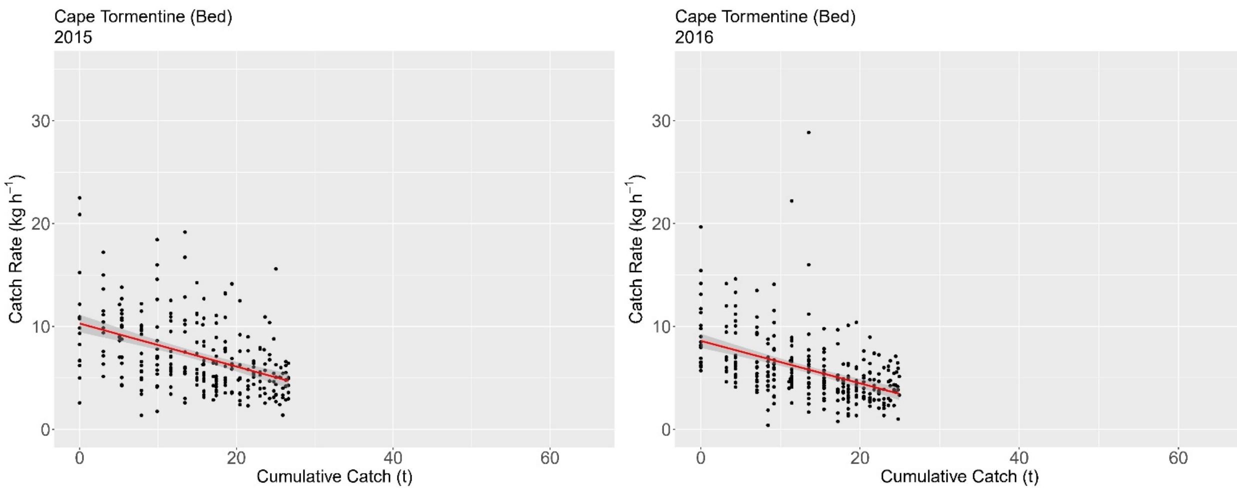

Figure A11-h. Plot of daily catch rates against the cumulative catch of scallops and the best-fit line (for years in which the model was statistically significant) of the Leslie depletion model for the Cape Tormentine bed data as defined by the kernel density contour of 20 trips km^{-2} for each year from 2015 to 2016.

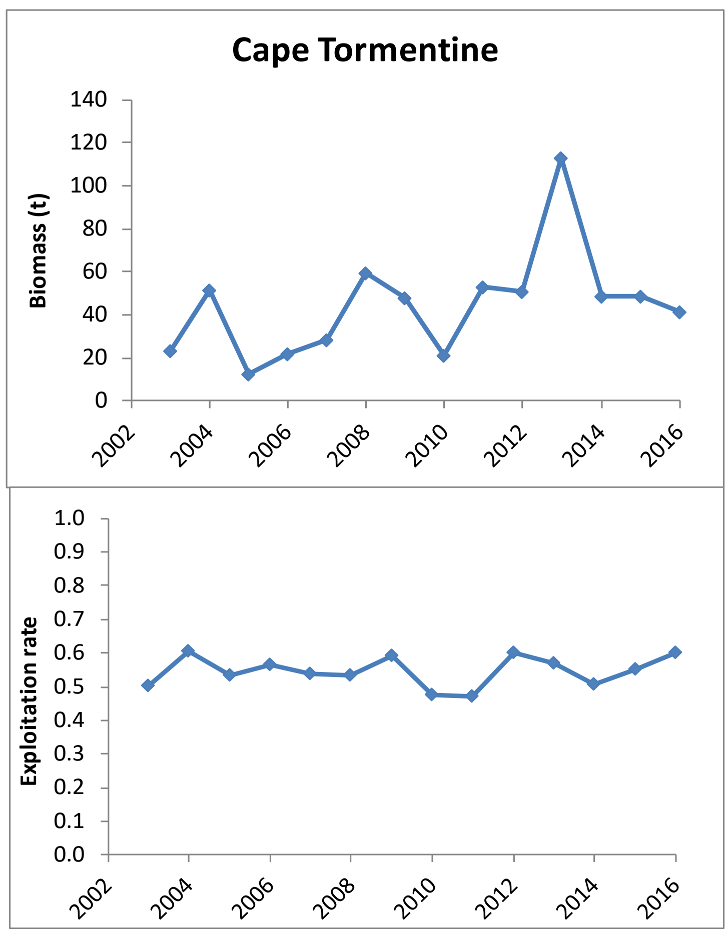

Figure A11-i. Depletion model estimates of Biomass (B_0) at the start of the fishery an d exploitation rate ($\hat{E}$) from 2003 to 2016 for the West Point bed (based on kernel density contour of 20 pts km^{-2}), in Scallop Fishing Area 22.

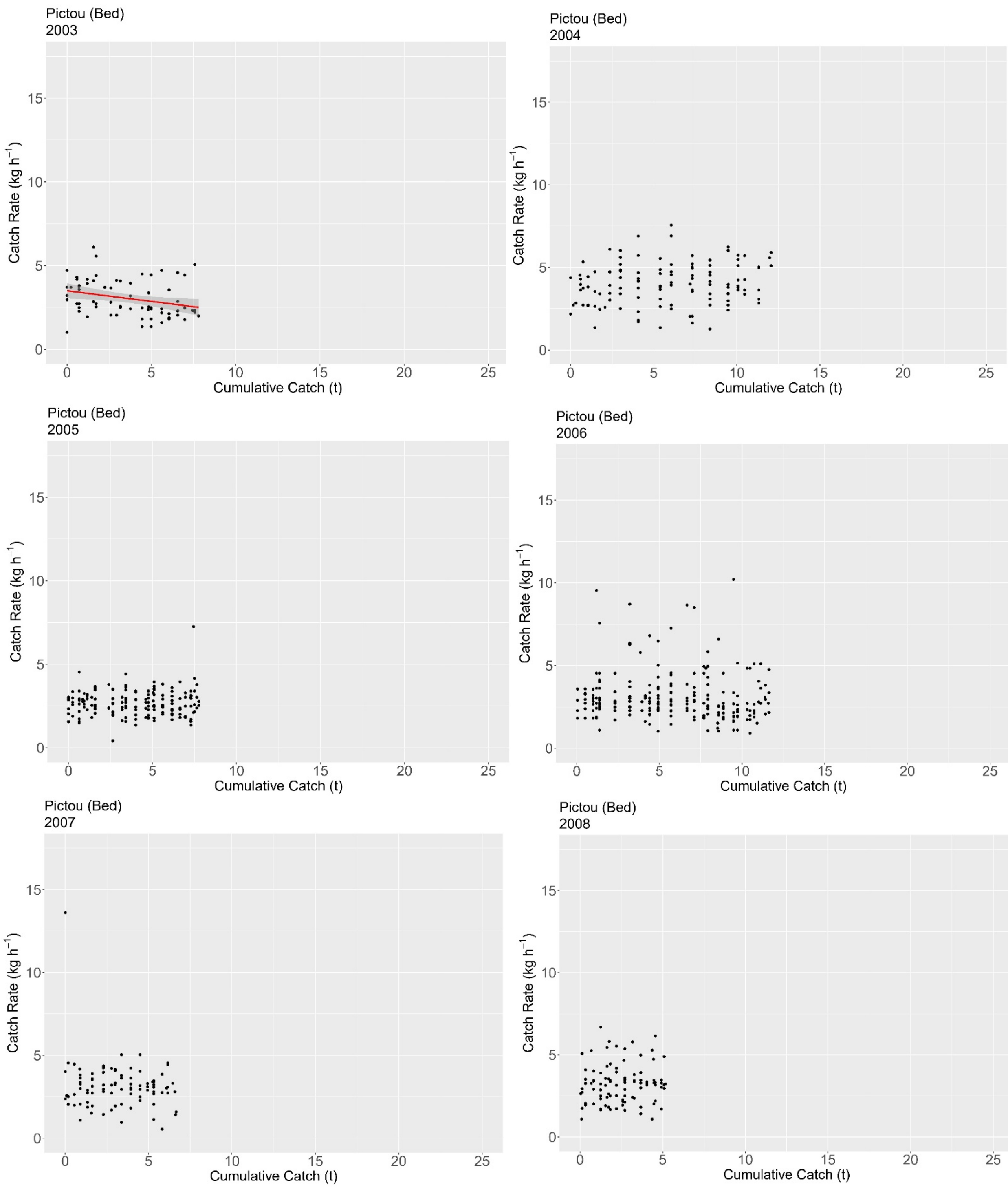

Figure A11-j. Plot of daily catch rates against the cumulative catch of scallops and the best-fit line (for years in which the model was statistically significant) of the Leslie depletion model for Pictou bed data as defined by the kernel density contour of 20 trips km^{-2} for each year from 2003 to 2008.

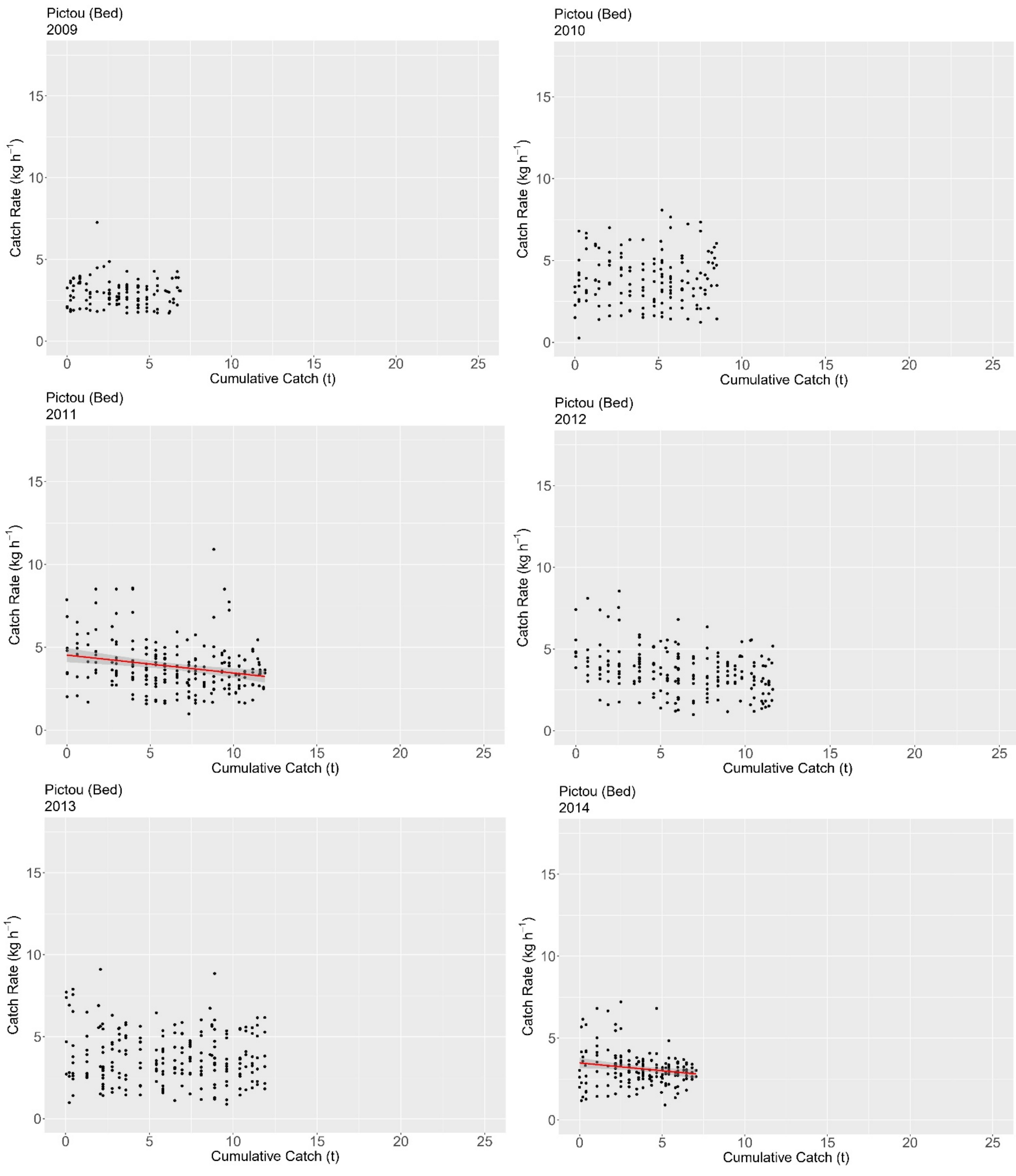

Figure A11-k. Plot of daily catch rates against the cumulative catch of scallops and the best-fit line (for years in which the model was statistically significant) of the Leslie depletion model for Pictou bed data as defined by the kernel density contour of 20 trips km^{-2} for each year from 2009 to 2014.

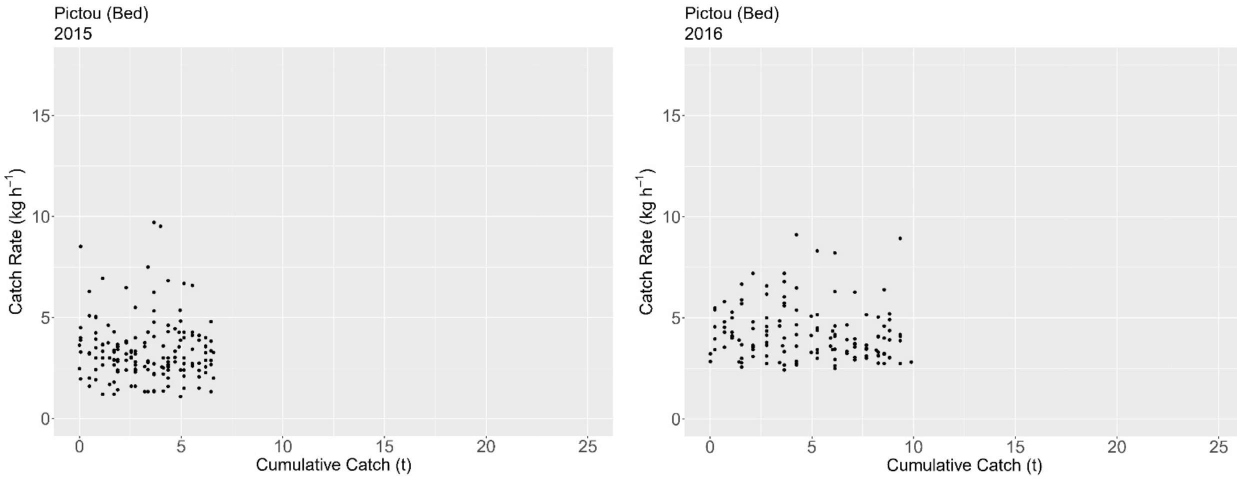

Figure A11-l. Plot of daily catch rates against the cumulative catch of scallops and the best-fit line (for years in which the model was statistically significant) of the Leslie depletion model for Pictou bed data as defined by the kernel density contour of 20 trips km^{-2} for each year from 2015 to 2016.

ANNEX 11

R script for depletion model.

```
################################################################################
#
#### Scallop Fishery - Depletion Modeling - Southern Gulf of St Lawrence ####
################################################################################
#

# Prepared by: Jeff Barrell, DFO-Gulf, 18 Oct 2018 #
# This is a compilation of code from several scripts used to analyzed data for the 2018 CSAS meeting #
# Models were applied for beds in 3 SFAs: 21A, 22, and 24; and 4 beds in total (SFA21A, Cape Tormentine, West Point, and Pictou) #
# Models were run at 2 spatial levels: 1) "bed" as defined by kernel density mapping of fishing effort, and 2) survey strata #
# Models were run for the years 2003 - 2016, corresponding to years with appropriate/valid data #
# All input data should be present in the working directory #

# First, load required packages #

library(dplyr)
library(lubridate)
library(ggplot2)

##########################################
#### Preparation of Sales Slip data ####
##########################################
setwd("D:/depletion/r script V4")

# Import data from .csv, subset to necessary variables/columns, and rename columns
slips <- read.csv("slips_2001_2016.csv", stringsAsFactors = F)
slips.sub <- subset(slips, select=c("Year","Fishing.Area.sub.place.landed","CFV",
                    "Scallop.Date.Fished","Landed.Weight..Kg"))
names(slips.sub) <- c("year","sfa","cfv","datefished","catchkg")
slips.sub$datefished <- as.Date(strptime(slips.sub$datefished, "%d/%m/%Y", tz=""))
slips.sub <- filter(slips.sub, year > 2002)

# Next, aggregate catch data from slips by sfa and year
```

```
slips.by.date <- aggregate(slips.sub$catchkg, by=list(slips.sub$year,slips.sub$sfa,slips.sub$datefished), FUN="sum")

names(slips.by.date) <- c("year","sfa","datefished","catchkg")

slips.by.date$week.yr <- week(slips.by.date$datefished)


# Remove bad dates, subset to SFAs of interest:

slips.22 <- filter(slips.by.date, sfa==22 & week.yr > 16 & week.yr < 25) ##between April 19 and June 14

slips.24 <- filter(slips.by.date, sfa==24 & week.yr > 42) ##after october 18

slips.21a <- filter(slips.by.date, sfa=="21a" & year > 2002)


# Set week of season for each SFA (inelegantly looped...)

years <- 2003:2016

num.years <- length(years)


# SFA 22

for(i in 1:num.years)

{

  slips.22$week.season[slips.22$year==years[i]] <- (interval(min(slips.22$datefished[slips.22$year==years[i]]), slips.22$datefished[slips.22$year==years[i]], tzone=tz(start)) %/% weeks(1)) + 1

}


# SFA 24

for(i in 1:num.years)

{

  slips.24$week.season[slips.24$year==years[i]] <- (interval(min(slips.24$datefished[slips.24$year==years[i]]), slips.24$datefished[slips.24$year==years[i]], tzone=tz(start)) %/% weeks(1)) + 1

}


# SFA 21a

years.21a <- c(2003:2009,2013:2015)

num.years.21a <- length(years.21a)


for(i in 1:num.years.21a)

{

  slips.21a$week.season[slips.21a$year==years.21a[i]] <-
(interval(min(slips.21a$datefished[slips.21a$year==years.21a[i]]),
slips.21a$datefished[slips.21a$year==years.21a[i]], tzone=tz(start)) %/% weeks(1)) + 1

}
```

```
######################################
#### Preparation of Logbook Data ####
######################################

# In the input data file, the column "bed" refers to the survey strata; "bed_20" refers to the beds determined by kernel density analysis (20 trips per sq. km). "sfa_latlong" is the best SFA dataset based on geolocation, though without the letter identifiers for SFA 21; "sfa_sub_latlong" includes the letter (e.g. 21B); "SFA" is the original SFA reported in logbooks, and is unreliable; was retained for debugging and identification of erroneous points.

data <- read.csv("logs_2001_2016.csv",stringsAsFactors = F)
data$bed_20[data$bed2=="SFA21Abed"] <- "sfa21a bed"

data.sub <- subset(data, select=c("Year_", "week_year", "date_", "total_landed_kg","catch_rate_tows_kgh","bed", "bed_20", "sfa_latlong", "sfa_sub_latlong", "SFA"))
names(data.sub) <- c("year","week","datefished","landed.kg","catchrate","strata","bed.20","sfa","sfa.sub", "sfa.old")
data.sub$datefished <- as.Date(strptime(data.sub$datefished, "%d/%m/%Y", tz=""))
data.sub <- data.sub %>% filter(!is.na(landed.kg) & !is.na(sfa)) # Removes 14 NAs from landings, 16 from sfa
data.sub$bed.20 <- sub("_"," ",data.sub$bed.20) # Remove underscores in bed name, replace with space

# ---- Landings Ratios ----
# Next, determine ratio of landings both PER BED (as defined by 20 trips per sq. km) and PER STRATUM.
# For both 22 & 24, there are some orphans in certain weeks, since we're going by week of year rather than week of season; this is adjusted below to week of season

##################
#---- SFA 22 ----#
##################

#---- SFA22 by BED: ------------

# Removes mislabeled points with bad times, wrong years
landed.22 <- data.sub[data.sub$sfa==22 & data.sub$week<29,]
```

```
landed.22 <- filter(landed.22, year > 2002)

# For use later when merging with slips:
logs.22 <- landed.22

# Loop to set week of season, output pdf graph and .csv of ratios:
years <- 2003:2016
num.years <- length(years)
landed.22.season <- NULL
landed.week.sum.22 <- NULL
ratio.22 <- NULL
p2 <- NULL

pdf("landings_ratio_SFA22_bed20.pdf",onefile=T,width=11,height=8.5)
for(i in 1:num.years)
{
  ID <- paste(years[i],"SFA 22", sep="_")
  XX <- landed.22[landed.22$year==years[i],]
  XX$week.season <- (interval(min(XX$datefished), XX$datefished, tzone=tz(start)) %/% weeks(1)) + 1
  landed.22.season[[ID]] <- XX

  landed.yr.22 <- aggregate(XX$landed.kg, by=list(XX$week.season,XX$bed.20), FUN="sum")
  names(landed.yr.22) <- c("week", "bed.20", "landed.sum")
  ratio.week.22 <- aggregate(landed.yr.22$landed.sum, by=list(landed.yr.22$week), FUN="sum")
  names(ratio.week.22) <- c("week", "week.sum")
  num.data.22 <- aggregate(XX$landed.kg, by=list(XX$week.season,XX$bed.20), FUN="length")
  names(num.data.22) <- c("week","bed.20","num.data")
  landed.yr.22 <- merge(landed.yr.22, ratio.week.22, by="week")
  landed.yr.22 <- merge(landed.yr.22,num.data.22,by=c("week","bed.20"))
  landed.yr.22$week.ratio <- landed.yr.22$landed.sum / landed.yr.22$week.sum
  landed.yr.22$year <- years[i]
  season <- ifelse(years[i]==2008,7,6)
  landed.yr.22 <- landed.yr.22[landed.yr.22$week < season,]
  landed.week.sum.22[[ID]] <- landed.yr.22

  # Plotting:
```

```
 p <- ggplot(landed.yr.22)+
   aes(x = week, y = week.ratio, shape=factor(bed.20))+
   geom_point(aes(colour = factor(bed.20)), size=3)+
   ggtitle("SFA 22", years[i])+
   xlab("Week of Season")+ ylab("Proportion of Landings")+
   scale_color_discrete(name="bed.20", breaks=c("cape tormentine","west point","sfa22 other"),
                  labels=c("Cape Tormentine","West Point","Other SFA22"))+
   scale_shape_discrete(name="bed.20", breaks=c("cape tormentine","west point","sfa22 other"),
                  labels=c("Cape Tormentine","West Point","Other SFA22"))+
   ylim(0,1)+
   theme(axis.text.x = element_text(face="plain", size=18),
       axis.text.y = element_text(face="plain", size=18),
       axis.title=element_text(size=18),
       plot.title = element_text(size=18),
       plot.subtitle = element_text(size=18))
 print(p)
 p2[[ID]] <- p
}
dev.off()

sfa22 <- as.data.frame(do.call("rbind",landed.22.season))
SFA22.bed20 <- as.data.frame(do.call("rbind",landed.week.sum.22))
write.csv(SFA22.bed20,"SFA22_bed20_ratio.csv")

SFA22.bed20$week.season <- SFA22.bed20$week
SFA22.bed.sub <- subset(SFA22.bed20, select=c(year,week.season,bed.20,week.ratio))



#---- SFA 22 by STRATUM: ------------

beds.22 <- unique(sfa22$strata)
num.beds.22 <- length(beds.22)
sfa22.week.sum <- NULL
a2 <- NULL
ZZ.week.sum <- NULL
```

```
pdf("landings_ratio_SFA22_strata.pdf",onefile=T,width=11,height=8.5)
for(i in 1:num.years)
{
 ID <- paste(years[i],"SFA 22", sep="_")
 ZZ <- sfa22[sfa22$year==years[i],]

 ZZ.week <- aggregate(ZZ$landed.kg, by=list(ZZ$week.season,ZZ$strata), FUN="sum")
 names(ZZ.week) <- c("week", "strata", "landed.sum")
 ZZ.ratio <- aggregate(ZZ.week$landed.sum, by=list(ZZ.week$week), FUN="sum")
 names(ZZ.ratio) <- c("week", "week.sum")
 ZZ.num.data <- aggregate(ZZ$landed.kg, by=list(ZZ$week.season,ZZ$strata), FUN="length")
 names(ZZ.num.data) <- c("week","strata","num.data")
 ZZ.week <- merge(ZZ.week, ZZ.ratio, by="week")
 ZZ.week <- merge(ZZ.week,ZZ.num.data,by=c("week","strata"))
 ZZ.week$week.ratio <- ZZ.week$landed.sum / ZZ.week$week.sum
 ZZ.week$year <- years[i]
 season <- ifelse(years[i]==2008,7,6)
 ZZ.week <- ZZ.week[ZZ.week$week < season,]
 ZZ.week.sum[[ID]] <- ZZ.week

 # Plotting:
 cols <- c("cape tormentine"="red","west point"="darkgreen","w cape tormentine"="blue", "cap st
louis"="orange",
      "miminegash"="magenta","SFA22other"="purple")
 shapes <- c("cape tormentine"=15,"west point"=17,"w cape tormentine"=4, "cap st louis"=6,
       "miminegash"=3,"SFA22other"=16)
 p <- ggplot(ZZ.week)+
  aes(x = week, y = week.ratio)+
  geom_point(aes(colour = factor(strata), shape=factor(strata)), size=3)+
  ggtitle("SFA 22", years[i])+
  xlab("Week of Season")+ ylab("Proportion of Landings")+
  scale_discrete_manual(name="Stratum", values=cols, drop=F, aesthetics="colour",
             limits=c("cape tormentine","west point","w cape tormentine","cap st
louis","miminegash","SFA22other"),
             breaks=c("cape tormentine","west point","w cape tormentine","cap st
louis","miminegash","SFA22other"),
             labels=c("Cape Tormentine","West Point","West Cape Tormentine","Cap St
Louis","Miminegash","Other SFA22"))+
```

```
  scale_shape_manual(name="Stratum", values=shapes, drop=F,
                limits=c("cape tormentine","west point","w cape tormentine","cap st
louis","miminegash","SFA22other"),
                breaks=c("cape tormentine","west point","w cape tormentine","cap st
louis","miminegash","SFA22other"),
                labels=c("Cape Tormentine","West Point","West Cape Tormentine","Cap St
Louis","Miminegash","Other SFA22"))+

  ylim(0,1)+
  theme(axis.text.x = element_text(face="plain", size=18),
     axis.text.y = element_text(face="plain", size=18),
     axis.title=element_text(size=18),
     plot.title = element_text(size=18),
     plot.subtitle = element_text(size=18))
 print(p)
 a2[[ID]] <- p
}
dev.off()

SFA22.strata <- as.data.frame(do.call("rbind",ZZ.week.sum))
write.csv(SFA22.strata,"SFA22_strata_ratio.csv")

SFA22.strata$week.season <- SFA22.strata$week
SFA22.strata.sub <- subset(SFA22.strata, select=c(year,week.season,strata,week.ratio))


##################
#---- SFA 24 ----#
##################

#---- SFA24 by BED: ------------

# Clean data; Note the 'orphans' as in SFA 22; also, one odd point in 2002 occurs in week 26?
landed.24 <- data.sub[data.sub$sfa==24 & data.sub$week>43,] # Removes mislabeled points with bad times
landed.24 <- landed.24[!landed.24$sfa.old == 23,] # Remove a few more odd ducks
landed.24 <- filter(landed.24, year > 2002)
```

```
#table(landed.24$year,landed.24$week)

# For use later when merging with slips:
logs.24 <- landed.24

# Loop to set week of season, output pdf graph and .csv of ratios:
landed.24.season <- NULL
landed.week.sum.24 <- NULL
ratio.24 <- NULL
p2 <- NULL

pdf("landings_ratio_SFA24_bed20.pdf",onefile=T,width=11,height=8.5)
for(i in 1:num.years)
{
 ID <- paste(years[i],"SFA 24", sep="_")
 XX <- landed.24[landed.24$year==years[i],]
 XX$week.season <- (interval(min(XX$datefished), XX$datefished, tzone=tz(start)) %/% weeks(1)) + 1
 landed.24.season[[ID]] <- XX

 landed.yr.24 <- aggregate(XX$landed.kg, by=list(XX$week.season,XX$bed.20), FUN="sum")
 names(landed.yr.24) <- c("week", "bed.20", "landed.sum")
 ratio.week.24 <- aggregate(landed.yr.24$landed.sum, by=list(landed.yr.24$week), FUN="sum")
 names(ratio.week.24) <- c("week", "week.sum")
 num.data.24 <- aggregate(XX$landed.kg, by=list(XX$week.season,XX$bed.20), FUN="length")
 names(num.data.24) <- c("week","bed.20","num.data")
 landed.yr.24 <- merge(landed.yr.24, ratio.week.24, by="week")
 landed.yr.24$week.ratio <- landed.yr.24$landed.sum / landed.yr.24$week.sum
 landed.yr.24 <- merge(landed.yr.24,num.data.24,by=c("week","bed.20"))
 landed.yr.24$year <- years[i]
 landed.week.sum.24[[ID]] <- landed.yr.24

 # Plotting:
 p <- ggplot(landed.yr.24)+
  aes(x = week, y = week.ratio, shape=factor(bed.20))+
  geom_point(aes(colour = factor(bed.20)), size=3)+
  ggtitle("SFA 24", years[i])+
```

```
  xlab("Week of Season")+ ylab("Proportion of Landings")+
  scale_color_discrete(name="bed.20", labels=c("Pictou","Other SFA 24"))+
scale_shape_discrete(name="bed.20", labels=c("Pictou","Other SFA 24"))+
  ylim(0,1)+ xlim(1,7)+
  theme(axis.text.x = element_text(face="plain", size=18),
     axis.text.y = element_text(face="plain", size=18),
     axis.title=element_text(size=18),
     plot.title = element_text(size=18),
     plot.subtitle = element_text(size=18))
 print(p)
 p2[[ID]] <- p
}
dev.off()

sfa24 <- as.data.frame(do.call("rbind",landed.24.season))
SFA24.bed20 <- as.data.frame(do.call("rbind",landed.week.sum.24))
write.csv(SFA24.bed20,"SFA24_bed20_ratio.csv")

SFA24.bed20$week.season <- SFA24.bed20$week
SFA24.bed.sub <- subset(SFA24.bed20, select=c(year,week.season,bed.20,week.ratio))



#---- SFA24 by STRATUM: ------------

sfa24.week.sum <- NULL
b2 <- NULL
WW.week.sum <- NULL

pdf("landings_ratio_SFA24_strata.pdf",onefile=T,width=11,height=8.5)
for(i in 1:num.years)
{
 ID <- paste(years[i],"SFA 24", sep="_")
 WW <- sfa24[sfa24$year==years[i],]

 WW.week <- aggregate(WW$landed.kg, by=list(WW$week.season,WW$strata), FUN="sum")
 names(WW.week) <- c("week", "strata", "landed.sum")
 WW.ratio <- aggregate(WW.week$landed.sum, by=list(WW.week$week), FUN="sum")
```

```
  names(WW.ratio) <- c("week", "week.sum")
  WW.num.data <- aggregate(WW$landed.kg, by=list(WW$week.season,WW$strata), FUN="length")
  names(WW.num.data) <- c("week","strata","num.data")
  WW.week <- merge(WW.week, WW.ratio, by="week")
  WW.week <- merge(WW.week,WW.num.data,by=c("week","strata"))
  WW.week$week.ratio <- WW.week$landed.sum / WW.week$week.sum
  WW.week$year <- years[i]
  WW.week.sum[[ID]] <- WW.week

  # Plotting:
  p <- ggplot(WW.week)+
    aes(x = week, y = week.ratio)+
    geom_point(aes(colour = factor(strata), shape=factor(strata)), size=3)+
    ggtitle("SFA 24", years[i])+
    xlab("Week of Season")+ ylab("Proportion of Landings")+
    scale_color_discrete(name="Stratum", labels=c("Pictou","Other SFA 24"))+
    scale_shape_discrete(name="Stratum", labels=c("Pictou","Other SFA 24"))+

    ylim(0,1)+ xlim(1,7)+
    theme(axis.text.x = element_text(face="plain", size=18),
          axis.text.y = element_text(face="plain", size=18),
          axis.title=element_text(size=18),
          plot.title = element_text(size=18),
          plot.subtitle = element_text(size=18))
  print(p)
  b2[[ID]] <- p
}
dev.off()

SFA24.strata <- as.data.frame(do.call("rbind",WW.week.sum))
write.csv(SFA24.strata,"SFA24_strata_ratio.csv")

SFA24.strata$week.season <- SFA24.strata$week
SFA24.strata.sub <- subset(SFA24.strata, select=c(year,week.season,strata,week.ratio))

#################
```

```
#### SFA 21A ####
#################

#For SFA21A, there was no separate bed delineation beyond that ID'd by stratum.

logs.21a <- filter(data.sub, strata == "SFA21A" & year %in% years.21a)
logs.21a$bed.20 <- ifelse(logs.21a$bed.20 =="sfa21a bed","sfa21a bed","sfa21a other")

logs.21a.season <- NULL
logs.21a.week.sum <- NULL
ratio.21a <- NULL
d2 <- NULL

pdf("landings_ratio_SFA21A_bed20.pdf",onefile=T,width=11,height=8.5)
for(i in 1:num.years.21a)
{
 ID <- paste(years[i],"SFA 21A", sep="_")
 YY <- logs.21a[logs.21a$year==years.21a[i],]
 YY$week.season <- (interval(min(YY$datefished), YY$datefished, tzone=tz(start)) %/% weeks(1)) + 1
 logs.21a.season[[ID]] <- YY

 landed.yr.21a <- aggregate(YY$landed.kg, by=list(YY$week.season,YY$bed.20), FUN="sum")
 names(landed.yr.21a) <- c("week", "bed.20", "landed.sum")
 ratio.week.21a <- aggregate(landed.yr.21a$landed.sum, by=list(landed.yr.21a$week), FUN="sum")
 names(ratio.week.21a) <- c("week", "week.sum")
 num.data.21a <- aggregate(YY$landed.kg, by=list(YY$week.season,YY$bed.20), FUN="length")
 names(num.data.21a) <- c("week","bed.20","num.data")
 landed.yr.21a <- merge(landed.yr.21a, ratio.week.21a, by="week")
 landed.yr.21a <- merge(landed.yr.21a,num.data.21a,by=c("week","bed.20"))
 landed.yr.21a$week.ratio <- landed.yr.21a$landed.sum / landed.yr.21a$week.sum
 landed.yr.21a$year <- years.21a[i]
 #season <- ifelse(years[i]==2008,7,6)
 #landed.yr.21a <- landed.yr.21a[landed.yr.21a$week < season,]
 logs.21a.week.sum[[ID]] <- landed.yr.21a

 # Plotting:
```

```
 p <- ggplot(landed.yr.21a)+
  aes(x = week, y = week.ratio, shape=factor(bed.20))+
  geom_point(aes(colour = factor(bed.20)), size=3)+
  ggtitle("SFA 21A", years.21a[i])+
  xlab("Week of Season")+ ylab("Proportion of Landings")+
  scale_color_discrete(name="bed.20", breaks=c("sfa21a bed","sfa21a other"),
             labels=c("SFA21A Bed","SFA21A Other"))+
  scale_shape_discrete(name="bed.20", breaks=c("sfa21a bed","sfa21a other"),
             labels=c("SFA21A Bed","SFA21A Other"))+
  ylim(0,1)+
  theme(axis.text.x = element_text(face="plain", size=18),
     axis.text.y = element_text(face="plain", size=18),
     axis.title=element_text(size=18),
     plot.title = element_text(size=18),
     plot.subtitle = element_text(size=18))
 print(p)
 d2[[ID]] <- p
}
dev.off()


sfa21a <- as.data.frame(do.call("rbind",logs.21a.season))
SFA21A.strata <- as.data.frame(do.call("rbind",logs.21a.week.sum))
write.csv(SFA21A.strata,"SFA21A_strata_ratio.csv")

SFA21A.strata$week.season <- SFA21A.strata$week
SFA21A.strata.sub <- subset(SFA21A.strata, select=c(year,week.season,bed.20,week.ratio))



###############################
#### Merge Logs and Slips ####
###############################

# Here, the proportion of slips allocated to each bed are combined with logbook data. A check is done to see if all
rows are incorporated (logs.slips vs. logs.slips.alt); if not, the discrepancy indicates fishing for which there is a
```

sales slip but no logbook record. In most cases, this is due to a mismatch in dates, where the slip is filed with a sales date after the season is over. Rows are corrected where possible, ignored where not.

```
#---- SFA 22 ----
years <- 2003:2016
num.years <- length(years)

# First by strata:
temp.22.strata <- merge(slips.22, SFA22.strata.sub, by=c("year", "week.season"))
temp.22.strata$catchkg.bed <- temp.22.strata$catchkg * temp.22.strata$week.ratio

## STRATA: Cape Tormentine (cumsum)
ct.s <- temp.22.strata[temp.22.strata$strata == "cape tormentine",]
ct.s <- ct.s[order(ct.s$datefished),]
for(i in 1:num.years)
{
  ct.s$cumsum[ct.s$year==years[i]] <- (cumsum(ct.s$catchkg.bed[ct.s$year == years[i]]) -
ct.s$catchkg.bed[ct.s$year == years[i]])
}
logs.ct.s <- filter(logs.22, strata=="cape tormentine")

logs.slips.ct.s <- merge(logs.ct.s, ct.s, by=c("year", "strata", "datefished"), all.x=TRUE)
logs.slips.ct.s.alt <- merge(logs.ct.s, ct.s, by=c("year", "strata", "datefished"))
logs.slips.ct.s <- logs.slips.ct.s.alt

## STRATA: West Point (cumsum)
wp.s <- temp.22.strata[temp.22.strata$strata == "west point",]
wp.s <- wp.s[order(wp.s$datefished),]
for(i in 1:num.years)
{
  wp.s$cumsum[wp.s$year==years[i]] <- (cumsum(wp.s$catchkg.bed[wp.s$year == years[i]]) -
wp.s$catchkg.bed[wp.s$year == years[i]])
}
logs.wp.s <- filter(logs.22, strata=="west point")

logs.slips.wp.s <- merge(logs.wp.s, wp.s, by=c("year", "strata", "datefished"), all.x=TRUE)
logs.slips.wp.s.alt <- merge(logs.wp.s, wp.s, by=c("year", "strata", "datefished"))
```

```
logs.slips.wp.s <- logs.slips.wp.s.alt


# Then by bed:
temp.22.bed <- merge(slips.22, SFA22.bed.sub, by=c("year", "week.season"))
temp.22.bed$catchkg.bed <- temp.22.bed$catchkg * temp.22.bed$week.ratio


## BED: Cape Tormentine (cumsum)
ct.b <- temp.22.bed[temp.22.bed$bed.20 == "cape tormentine",]
ct.b <- ct.b[order(ct.b$datefished),]
for(i in 1:num.years)
{
  ct.b$cumsum[ct.b$year==years[i]] <- (cumsum(ct.b$catchkg.bed[ct.b$year == years[i]]) -
ct.b$catchkg.bed[ct.b$year == years[i]])
}
logs.ct.b <- filter(logs.22, bed.20 == "cape tormentine")


logs.slips.ct.b <- merge(logs.ct.b, ct.b, by=c("year", "bed.20", "datefished"), all.x=TRUE)
logs.slips.ct.b.alt <- merge(logs.ct.b, ct.b, by=c("year", "bed.20", "datefished"))
logs.slips.ct.b <- logs.slips.ct.b.alt


## BED: West Point (cumsum)
wp.b <- temp.22.bed[temp.22.bed$bed.20 == "west point",]
wp.b <- wp.b[order(wp.b$datefished),]
for(i in 1:num.years)
{
  wp.b$cumsum[wp.b$year==years[i]] <- (cumsum(wp.b$catchkg.bed[wp.b$year == years[i]]) -
wp.b$catchkg.bed[wp.b$year == years[i]])
}
logs.wp.b <- filter(logs.22, bed.20 == "west point")


logs.slips.wp.b <- merge(logs.wp.b, wp.b, by=c("year", "bed.20", "datefished"), all.x=TRUE)
logs.slips.wp.b.alt <- merge(logs.wp.b, wp.b, by=c("year", "bed.20", "datefished"))
logs.slips.wp.b <- logs.slips.wp.b.alt


#---- SFA 24 ----
# Only one bed/stratum to worry about
# First by strata:
```

```
temp.24.strata <- merge(slips.24, SFA24.strata.sub, by=c("year", "week.season"))
temp.24.strata$catchkg.bed <- temp.24.strata$catchkg * temp.24.strata$week.ratio

pic.s <- temp.24.strata[temp.24.strata$strata == "pictou",]
pic.s <- pic.s[order(pic.s$datefished),]
for(i in 1:num.years)
{
  pic.s$cumsum[pic.s$year==years[i]] <- (cumsum(pic.s$catchkg.bed[pic.s$year == years[i]]) -
pic.s$catchkg.bed[pic.s$year == years[i]])
}
logs.pic.s <- filter(logs.24, strata=="pictou")

logs.slips.pic.s <- merge(logs.pic.s, pic.s, by=c("year", "strata", "datefished"), all.x=TRUE)
logs.slips.pic.s.alt <- merge(logs.pic.s, pic.s, by=c("year", "strata", "datefished"))

# Then by bed:
temp.24.bed <- merge(slips.24, SFA24.bed.sub, by=c("year", "week.season"))
temp.24.bed$catchkg.bed <- temp.24.bed$catchkg * temp.24.bed$week.ratio

pic.b <- temp.24.bed[temp.24.bed$bed.20 == "pictou",]
pic.b <- pic.b[order(pic.b$datefished),]
for(i in 1:num.years)
{
  pic.b$cumsum[pic.b$year==years[i]] <- (cumsum(pic.b$catchkg.bed[pic.b$year == years[i]]) -
pic.b$catchkg.bed[pic.b$year == years[i]])
}
logs.pic.b <- filter(logs.24, bed.20=="pictou")

logs.slips.pic.b <- merge(logs.pic.b, pic.b, by=c("year", "bed.20", "datefished"), all.x=TRUE)
logs.slips.pic.b.alt <- merge(logs.pic.b, pic.b, by=c("year", "bed.20", "datefished"))

##########
# SFA21A #
##########

# For 21a, only concerned with stratum, no bed, so fewer calculations:
```

```
temp.21a.strata <- merge(slips.21a, SFA21A.strata.sub, by=c("year", "week.season"))
temp.21a.strata$catchkg.bed <- temp.21a.strata$catchkg * temp.21a.strata$week.ratio

SFA21A.s <- temp.21a.strata[temp.21a.strata$bed.20 == "sfa21a bed",]
SFA21A.s <- SFA21A.s[order(SFA21A.s$datefished),]
for(i in 1:num.years.21a)
{
  SFA21A.s$cumsum[SFA21A.s$year==years.21a[i]] <- (cumsum(SFA21A.s$catchkg.bed[SFA21A.s$year == years.21a[i]]) - SFA21A.s$catchkg.bed[SFA21A.s$year == years.21a[i]])
}
logs.21a.s <- filter(logs.21a, bed.20 == "sfa21a bed")

logs.slips.21a <- merge(logs.21a.s, SFA21A.s, by=c("year", "datefished"), all.x=TRUE)
logs.slips.alt.21a <- merge(logs.21a.s, SFA21A.s, by=c("year","datefished"))
logs.slips.21a <- logs.slips.alt.21a

#------------------------------------------------------------------------------------------------------------#


# Lastly, add a column with catch converted to metric tonnes for plotting purposes:
logs.slips.ct.s$cumsum_t <- logs.slips.ct.s$cumsum / 1000
logs.slips.ct.b$cumsum_t <- logs.slips.ct.b$cumsum / 1000
logs.slips.wp.s$cumsum_t <- logs.slips.wp.s$cumsum / 1000
logs.slips.wp.b$cumsum_t <- logs.slips.wp.b$cumsum / 1000
logs.slips.pic.s$cumsum_t <- logs.slips.pic.s$cumsum / 1000
logs.slips.pic.b$cumsum_t <- logs.slips.pic.b$cumsum / 1000
logs.slips.21a$cumsum_t <- logs.slips.21a$cumsum / 1000


##########################################
#### DEPLETION MODELS ##################
##########################################

lin.mod.ct.s <- NULL
lin.mod.ct.b <- NULL
```

```
lin.mod.wp.s <- NULL
lin.mod.wp.b <- NULL
lin.mod.pic.s <- NULL
lin.mod.pic.b <- NULL
lin.mod.21a <- NULL
out.ct.s <- NULL
out.ct.b <- NULL
out.wp.s <- NULL
out.wp.b <- NULL
out.pic.s <- NULL
out.pic.b <- NULL
out.21a <- NULL
p2 <- NULL

#---- Cape Tormentine (Stratum) ----

pdf("depletion_plots_strata_CT.pdf",onefile=T,width=11,height=8.5)
for(i in 1:num.years)
{
 XX <- logs.slips.ct.s[logs.slips.ct.s$year==years[i],]
 ID <- paste(years[i],"Cape Tormentine", sep="_")
 # plot(catchrate~cumsum, data=XX)
 # title(main=ID)

 lin.mod.ct.s[[ID]]<- lm(catchrate~cumsum_t, data=XX)

 len <- length(lin.mod.ct.s[[ID]]$model$cumsum_t)
 max.cumsum_t <- max(XX$cumsum_t)
 lm_coef <- c(lin.mod.ct.s[[ID]]$coefficients)

 #p-values
 temp <- summary(lin.mod.ct.s[[ID]])
 p_int <- temp$coefficients[1,4]
 p_cumsum_t <-temp$coefficients[2,4]

 #confidence intervals
```

```
  df.ci <- as.data.frame(confint(lin.mod.ct.s[[ID]]))
  q.hat.lwr <- -df.ci[2,1]
  B0.hat.lwr <- df.ci[1,1]/q.hat.lwr
  q.hat.up <- -df.ci[2,2]
  B0.hat.up <- df.ci[1,2]/q.hat.up

  #plots
  p <- ggplot(XX)+
   aes(x = cumsum_t, y = catchrate)+
   geom_point()+
   stat_smooth(method="lm",se=TRUE,col="red",size=1)+
   #geom_smooth(data=depletion.data.YR , aes(x=cpue_kg, y=K), se=TRUE, col="red") +
   xlab("Cumulative Catch (t)")+ylab(bquote("Catch Rate ("*kg~ h^-1*")"))+
   ggtitle("Cape Tormentine (Stratum)", years[i]) + ylim(0,35) + xlim(0,65)+
   theme(axis.text.x = element_text(face="plain", size=18),
      axis.text.y = element_text(face="plain", size=18),
      axis.title=element_text(size=18),
      plot.title = element_text(size=18),
      plot.subtitle = element_text(size=18))
  p2[[ID]] <- p
  print(p)

  #prepare for export
  out.ct.s[[ID]] <- c(len, lm_coef, max.cumsum_t, p_int, p_cumsum_t, q.hat.lwr, B0.hat.lwr, q.hat.up, B0.hat.up,
use.names=F)
  names(out.ct.s[[ID]]) <- c("number of data", "y_intercept", "coef_cumsum_t", "max_cumsum_t", "p_intercept",
"p_cumsum_t", "q_lower_ci", "B0_lower_ci", "q_upper_ci", "B0_upper_ci")
}

#additional derived variables and exporting
out.ct.s.df <- as.data.frame(do.call("rbind",out.ct.s))
out.ct.s.df$B0 <- (out.ct.s.df$y_intercept/out.ct.s.df$coef_cumsum_t)* -1
out.ct.s.df$exploitation <- out.ct.s.df$max_cumsum_t/out.ct.s.df$B0
out.ct.s.df$exploitation_lower_ci <- out.ct.s.df$max_cumsum_t/out.ct.s.df$B0_lower_ci
out.ct.s.df$exploitation_upper_ci <- out.ct.s.df$max_cumsum_t/out.ct.s.df$B0_upper_ci
write.csv(out.ct.s.df, "outct_strata_t.csv")
dev.off()
```

```
#---- Cape Tormentine (Bed) ----

pdf("depletion_plots_bed_CT.pdf",onefile=T,width=11,height=8.5)
for(i in 1:num.years)
{
 XX <- logs.slips.ct.b[logs.slips.ct.b$year==years[i],]
 ID <- paste(years[i],"Cape Tormentine", sep="_")
 # plot(catchrate~cumsum, data=XX)
 # title(main=ID)

 lin.mod.ct.b[[ID]]<- lm(catchrate~cumsum_t, data=XX)

 len <- length(lin.mod.ct.b[[ID]]$model$cumsum_t)
 max.cumsum_t <- max(XX$cumsum_t)
 lm_coef <- c(lin.mod.ct.b[[ID]]$coefficients)

 #p-values
 temp <- summary(lin.mod.ct.b[[ID]])
 p_int <- temp$coefficients[1,4]
 p_cumsum_t <-temp$coefficients[2,4]

 #confidence intervals
 df.ci <- as.data.frame(confint(lin.mod.ct.b[[ID]]))
 q.hat.lwr <- -df.ci[2,1]
 B0.hat.lwr <- df.ci[1,1]/q.hat.lwr
 q.hat.up <- -df.ci[2,2]
 B0.hat.up <- df.ci[1,2]/q.hat.up

 #plots
 p <- ggplot(XX)+
  aes(x = cumsum_t, y = catchrate)+
  geom_point()+
  stat_smooth(method="lm",se=TRUE,col="red",size=1)+
```

```
  #geom_smooth(data=depletion.data.YR , aes(x=cpue_kg, y=K), se=TRUE, col="red") +
  xlab("Cumulative Catch (t)")+ylab(bquote("Catch Rate ("*kg~ h^-1*")"))+
  ggtitle("Cape Tormentine (Bed)", years[i]) + ylim(0,35) + xlim(0,65)+
  theme(axis.text.x = element_text(face="plain", size=18),
        axis.text.y = element_text(face="plain", size=18),
        axis.title=element_text(size=18),
        plot.title = element_text(size=18),
        plot.subtitle = element_text(size=18))
 p2[[ID]] <- p
 print(p)

 #prepare for export
 out.ct.b[[ID]] <- c(len, lm_coef, max.cumsum_t, p_int, p_cumsum_t, q.hat.lwr, B0.hat.lwr, q.hat.up, B0.hat.up,
use.names=F)
 names(out.ct.b[[ID]]) <- c("number of data", "y_intercept", "coef_cumsum_t", "max_cumsum_t", "p_intercept",
"p_cumsum_t", "q_lower_ci", "B0_lower_ci", "q_upper_ci", "B0_upper_ci")
}

#additional derived variables and exporting
out.ct.b.df <- as.data.frame(do.call("rbind",out.ct.b))
out.ct.b.df$B0 <- (out.ct.b.df$y_intercept/out.ct.b.df$coef_cumsum_t)* -1
out.ct.b.df$exploitation <- out.ct.b.df$max_cumsum_t/out.ct.b.df$B0
out.ct.b.df$exploitation_lower_ci <- out.ct.b.df$max_cumsum_t/out.ct.b.df$B0_lower_ci
out.ct.b.df$exploitation_upper_ci <- out.ct.b.df$max_cumsum_t/out.ct.b.df$B0_upper_ci
write.csv(out.ct.b.df, "outct_bed_t.csv")
dev.off()




#---- West Point (Stratum) ----

pdf("depletion_plots_strata_WP.pdf",onefile=T,width=11,height=8.5)
for(i in 1:num.years)
{
 XX <- logs.slips.wp.s[logs.slips.wp.s$year==years[i],]
 ID <- paste(years[i],"West Point", sep="_")
 # plot(catchrate~cumsum, data=XX)
```

```
# title(main=ID)

lin.mod.wp.s[[ID]]<- lm(catchrate~cumsum_t, data=XX)

len <- length(lin.mod.wp.s[[ID]]$model$cumsum_t)
max.cumsum_t <- max(XX$cumsum_t)
lm_coef <- c(lin.mod.wp.s[[ID]]$coefficients)

#p-values
temp <- summary(lin.mod.wp.s[[ID]])
p_int <- temp$coefficients[1,4]
p_cumsum_t <-temp$coefficients[2,4]

#confidence intervals
df.ci <- as.data.frame(confint(lin.mod.wp.s[[ID]]))
q.hat.lwr <- -df.ci[2,1]
B0.hat.lwr <- df.ci[1,1]/q.hat.lwr
q.hat.up <- -df.ci[2,2]
B0.hat.up <- df.ci[1,2]/q.hat.up

#plots
p <- ggplot(XX)+
  aes(x = cumsum_t, y = catchrate)+
  geom_point()+
  stat_smooth(method="lm",se=TRUE,col="red",size=1)+
  #geom_smooth(data=depletion.data.YR , aes(x=cpue_kg, y=K), se=TRUE, col="red") +
  xlab("Cumulative Catch (t)")+ylab(bquote("Catch Rate ("*kg~ h^-1*")"))+
  ggtitle("West Point (Stratum)", years[i]) + ylim(0,25) + xlim(0,50)+
  theme(axis.text.x = element_text(face="plain", size=18),
       axis.text.y = element_text(face="plain", size=18),
       axis.title=element_text(size=18),
       plot.title = element_text(size=18),
       plot.subtitle = element_text(size=18))
p2[[ID]] <- p
print(p)
```

```
 #prepare for export
 out.wp.s[[ID]] <- c(len, lm_coef, max.cumsum_t, p_int, p_cumsum_t, q.hat.lwr, B0.hat.lwr, q.hat.up, B0.hat.up,
use.names=F)
 names(out.wp.s[[ID]]) <- c("number of data", "y_intercept", "coef_cumsum_t", "max_cumsum_t", "p_intercept",
"p_cumsum_t", "q_lower_ci", "B0_lower_ci", "q_upper_ci", "B0_upper_ci")
}

#additional derived variables and exporting
out.wp.s.df <- as.data.frame(do.call("rbind",out.wp.s))
out.wp.s.df$B0 <- (out.wp.s.df$y_intercept/out.wp.s.df$coef_cumsum_t)* -1
out.wp.s.df$exploitation <- out.wp.s.df$max_cumsum_t/out.wp.s.df$B0
out.wp.s.df$exploitation_lower_ci <- out.wp.s.df$max_cumsum_t/out.wp.s.df$B0_lower_ci
out.wp.s.df$exploitation_upper_ci <- out.wp.s.df$max_cumsum_t/out.wp.s.df$B0_upper_ci
write.csv(out.wp.s.df, "outwp_strata_t.csv")
dev.off()


#---- West Point (Bed) ----

pdf("depletion_plots_bed_WP.pdf",onefile=T,width=11,height=8.5)
for(i in 1:num.years)
{
 XX <- logs.slips.wp.b[logs.slips.wp.b$year==years[i],]
 ID <- paste(years[i],"West Point", sep="_")
 # plot(catchrate~cumsum, data=XX)
 # title(main=ID)

 lin.mod.wp.b[[ID]]<- lm(catchrate~cumsum_t, data=XX)

 len <- length(lin.mod.wp.b[[ID]]$model$cumsum_t)
 max.cumsum_t <- max(XX$cumsum_t)
 lm_coef <- c(lin.mod.wp.b[[ID]]$coefficients)

 #p-values
 temp <- summary(lin.mod.wp.b[[ID]])
 p_int <- temp$coefficients[1,4]
 p_cumsum_t <-temp$coefficients[2,4]
```

```
 #confidence intervals
 df.ci <- as.data.frame(confint(lin.mod.wp.b[[ID]]))
 q.hat.lwr <- -df.ci[2,1]
 B0.hat.lwr <- df.ci[1,1]/q.hat.lwr
 q.hat.up <- -df.ci[2,2]
 B0.hat.up <- df.ci[1,2]/q.hat.up

 #plots
 p <- ggplot(XX)+
  aes(x = cumsum_t, y = catchrate)+
  geom_point()+
  stat_smooth(method="lm",se=TRUE,col="red",size=1)+
  #geom_smooth(data=depletion.data.YR , aes(x=cpue_kg, y=K), se=TRUE, col="red") +
  xlab("Cumulative Catch (t)")+ylab(bquote("Catch Rate ("*kg~ h^-1*")"))+
  ggtitle("West Point (Bed)", years[i]) + ylim(0,25) + xlim(0,50)+
  theme(axis.text.x = element_text(face="plain", size=18),
     axis.text.y = element_text(face="plain", size=18),
     axis.title=element_text(size=18),
     plot.title = element_text(size=18),
     plot.subtitle = element_text(size=18))
 p2[[ID]] <- p
 print(p)

 #prepare for export
 out.wp.b[[ID]] <- c(len, lm_coef, max.cumsum_t, p_int, p_cumsum_t, q.hat.lwr, B0.hat.lwr, q.hat.up, B0.hat.up,
use.names=F)
 names(out.wp.b[[ID]]) <- c("number of data", "y_intercept", "coef_cumsum_t", "max_cumsum_t", "p_intercept",
"p_cumsum_t", "q_lower_ci", "B0_lower_ci", "q_upper_ci", "B0_upper_ci")
}

#additional derived variables and exporting
out.wp.b.df <- as.data.frame(do.call("rbind",out.wp.b))
out.wp.b.df$B0 <- (out.wp.b.df$y_intercept/out.wp.b.df$coef_cumsum_t)* -1
out.wp.b.df$exploitation <- out.wp.b.df$max_cumsum_t/out.wp.b.df$B0
out.wp.b.df$exploitation_lower_ci <- out.wp.b.df$max_cumsum_t/out.wp.b.df$B0_lower_ci
out.wp.b.df$exploitation_upper_ci <- out.wp.b.df$max_cumsum_t/out.wp.b.df$B0_upper_ci
```

```
write.csv(out.wp.b.df, "outwp_bed_t.csv")
dev.off()


#---- Pictou (Stratum) ----

pdf("depletion_plots_strata_Pic.pdf",onefile=T,width=11,height=8.5)
for(i in 1:num.years)
{
 XX <- logs.slips.pic.s[logs.slips.pic.s$year==years[i],]
 ID <- paste(years[i],"Pictou", sep="_")
 # plot(catchrate~cumsum, data=XX)
 # title(main=ID)

 lin.mod.pic.s[[ID]] <-lm(catchrate~cumsum_t, data=XX)

 len <- length(lin.mod.pic.s[[ID]]$model$cumsum_t)
 max.cumsum_t <- max(XX$cumsum_t)
 lm_coef <- c(lin.mod.pic.s[[ID]]$coefficients)

 #p-values
 temp <- summary(lin.mod.pic.s[[ID]])
 p_int <- temp$coefficients[1,4]
 p_cumsum_t <-temp$coefficients[2,4]

 #confidence intervals
 df.ci <- as.data.frame(confint(lin.mod.pic.s[[ID]]))
 q.hat.lwr <- -df.ci[2,1]
 B0.hat.lwr <- df.ci[1,1]/q.hat.lwr
 q.hat.up <- -df.ci[2,2]
 B0.hat.up <- df.ci[1,2]/q.hat.up

 #plots
 p <- ggplot(XX)+
  aes(x = cumsum_t, y = catchrate)+
  geom_point()+
```

```
  stat_smooth(method="lm",se=TRUE,col="red",size=1)+
  #geom_smooth(data=depletion.data.YR , aes(x=cpue_kg, y=K), se=TRUE, col="red") +
  xlab("Cumulative Catch (t)")+ylab(bquote("Catch Rate ("*kg~ h^-1*")"))+
  ggtitle("Pictou (Stratum)", years[i]) + ylim(0,17.5) + xlim(0,25)+
  theme(axis.text.x = element_text(face="plain", size=18),
        axis.text.y = element_text(face="plain", size=18),
        axis.title=element_text(size=18),
        plot.title = element_text(size=18),
        plot.subtitle = element_text(size=18))
 p2[[ID]] <- p
 print(p)

 #prepare for export
 out.pic.s[[ID]] <- c(len, lm_coef, max.cumsum_t, p_int, p_cumsum_t, q.hat.lwr, B0.hat.lwr, q.hat.up, B0.hat.up,
use.names=F)
 names(out.pic.s[[ID]]) <- c("number of data", "y_intercept", "coef_cumsum_t", "max_cumsum_t", "p_intercept",
"p_cumsum_t", "q_lower_ci", "B0_lower_ci", "q_upper_ci", "B0_upper_ci")
}

#additional derived variables and exporting
out.pic.s.df <- as.data.frame(do.call("rbind",out.pic.s))
out.pic.s.df$B0 <- (out.pic.s.df$y_intercept/out.pic.s.df$coef_cumsum_t)* -1
out.pic.s.df$exploitation <- out.pic.s.df$max_cumsum_t/out.pic.s.df$B0
out.pic.s.df$exploitation_lower_ci <- out.pic.s.df$max_cumsum_t/out.pic.s.df$B0_lower_ci
out.pic.s.df$exploitation_upper_ci <- out.pic.s.df$max_cumsum_t/out.pic.s.df$B0_upper_ci
write.csv(out.pic.s.df, "outpic_strata_t.csv")
dev.off()


#---- Pictou (Bed) ----

pdf("depletion_plots_bed_Pic.pdf",onefile=T,width=11,height=8.5)
for(i in 1:num.years)
{
 XX <- logs.slips.pic.b[logs.slips.pic.b$year==years[i],]
 ID <- paste(years[i],"Pictou", sep="_")
 # plot(catchrate~cumsum, data=XX)
```

```
# title(main=ID)

lin.mod.pic.b[[ID]] <-lm(catchrate~cumsum_t, data=XX)

len <- length(lin.mod.pic.b[[ID]]$model$cumsum_t)
max.cumsum_t <- max(XX$cumsum_t)
lm_coef <- c(lin.mod.pic.b[[ID]]$coefficients)

#p-values
temp <- summary(lin.mod.pic.b[[ID]])
p_int <- temp$coefficients[1,4]
p_cumsum_t <-temp$coefficients[2,4]

#confidence intervals
df.ci <- as.data.frame(confint(lin.mod.pic.b[[ID]]))
q.hat.lwr <- -df.ci[2,1]
B0.hat.lwr <- df.ci[1,1]/q.hat.lwr
q.hat.up <- -df.ci[2,2]
B0.hat.up <- df.ci[1,2]/q.hat.up

#plots
p <- ggplot(XX)+
  aes(x = cumsum_t, y = catchrate)+
  geom_point()+
  stat_smooth(method="lm",se=TRUE,col="red",size=1)+
  #geom_smooth(data=depletion.data.YR , aes(x=cpue_kg, y=K), se=TRUE, col="red") +
  xlab("Cumulative Catch (t)")+ylab(bquote("Catch Rate ("*kg~ h^-1*")"))+
  ggtitle("Pictou (Bed)", years[i]) + ylim(0,17.5) + xlim(0,25)+
  theme(axis.text.x = element_text(face="plain", size=18),
        axis.text.y = element_text(face="plain", size=18),
        axis.title=element_text(size=18),
        plot.title = element_text(size=18),
        plot.subtitle = element_text(size=18))
p2[[ID]] <- p
print(p)
```

```
  #prepare for export
  out.pic.b[[ID]] <- c(len, lm_coef, max.cumsum_t, p_int, p_cumsum_t, q.hat.lwr, B0.hat.lwr, q.hat.up, B0.hat.up,
use.names=F)
  names(out.pic.b[[ID]]) <- c("number of data", "y_intercept", "coef_cumsum_t", "max_cumsum_t", "p_intercept",
"p_cumsum_t", "q_lower_ci", "B0_lower_ci", "q_upper_ci", "B0_upper_ci")
}

#additional derived variables and exporting
out.pic.b.df <- as.data.frame(do.call("rbind",out.pic.b))
out.pic.b.df$B0 <- (out.pic.b.df$y_intercept/out.pic.b.df$coef_cumsum_t)* -1
out.pic.b.df$exploitation <- out.pic.b.df$max_cumsum_t/out.pic.b.df$B0
out.pic.b.df$exploitation_lower_ci <- out.pic.b.df$max_cumsum_t/out.pic.b.df$B0_lower_ci
out.pic.b.df$exploitation_upper_ci <- out.pic.b.df$max_cumsum_t/out.pic.b.df$B0_upper_ci
write.csv(out.pic.b.df, "outpic_bed_t.csv")
dev.off()


#---- SFA21A (Stratum only) ----

pdf("depletion_plots_21a.pdf",onefile=T,width=11,height=8.5)
for(i in 1:num.years.21a)
{
  XX <- logs.slips.21a[logs.slips.21a$year==years.21a[i],]
  ID <- paste(years.21a[i],"SFA 21A (Stratum)", sep="_")

  lin.mod.21a[[ID]]<- lm(catchrate~cumsum_t, data=XX)

  len <- length(lin.mod.21a[[ID]]$model$cumsum_t)
  max.cumsum_t <- max(XX$cumsum_t)
  lm_coef <- c(lin.mod.21a[[ID]]$coefficients)
```

```
 #p-values
 temp <- summary(lin.mod.21a[[ID]])
 p_int <- temp$coefficients[1,4]
 p_cumsum_t <-temp$coefficients[2,4]

 #confidence intervals
 df.ci <- as.data.frame(confint(lin.mod.21a[[ID]]))
 q.hat.lwr <- -df.ci[2,1]
 B0.hat.lwr <- df.ci[1,1]/q.hat.lwr
 q.hat.up <- -df.ci[2,2]
 B0.hat.up <- df.ci[1,2]/q.hat.up

 #plots
 p <- ggplot(XX)+
  aes(x = cumsum_t, y = catchrate)+
  geom_point()+
  stat_smooth(method="lm",se=TRUE,col="red",size=1)+
  #geom_smooth(data=depletion.data.YR , aes(x=cpue_kg, y=K), se=TRUE, col="red") +
  xlab("Cumulative Catch (t)")+ylab(bquote("Catch Rate ("*kg~ h^-1*")"))+
  ggtitle("SFA 21A (Stratum)", years.21a[i]) + ylim(0,17.5) + xlim(0,10)+
  theme(axis.text.x = element_text(face="plain", size=18),
     axis.text.y = element_text(face="plain", size=18),
     axis.title=element_text(size=18),
     plot.title = element_text(size=18),
     plot.subtitle = element_text(size=18))
 p2[[ID]] <- p
 print(p)

 #prepare for export
 out.21a[[ID]] <- c(len, lm_coef, max.cumsum_t, p_int, p_cumsum_t, q.hat.lwr, B0.hat.lwr, q.hat.up, B0.hat.up,
use.names=F)
 names(out.21a[[ID]]) <- c("number of data", "y_intercept", "coef_cumsum_t", "max_cumsum_t", "p_intercept",
"p_cumsum_t", "q_lower_ci", "B0_lower_ci", "q_upper_ci", "B0_upper_ci")
}

#additional derived variables and exporting
out.21a.df <- as.data.frame(do.call("rbind",out.21a))
```

```
out.21a.df$B0 <- (out.21a.df$y_intercept/out.21a.df$coef_cumsum_t)* -1
out.21a.df$exploitation <- out.21a.df$max_cumsum_t/out.21a.df$B0
out.21a.df$exploitation_lower_ci <- out.21a.df$max_cumsum_t/out.21a.df$B0_lower_ci
out.21a.df$exploitation_upper_ci <- out.21a.df$max_cumsum_t/out.21a.df$B0_upper_ci
write.csv(out.21a.df, "out21a_bed_t.csv")
dev.off()
```