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Assessment of the Arctic Surfclam (*Mactromeris polynyma*) Stocks on Banquereau and Grand Bank

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ABSTRACT

The offshore Arctic Surfclam fishery has traditionally been managed on the basis of bank-wide estimates of biomass and Total Allowable Catch (TAC). These biomass estimates resulted from scientific surveys, the most recent of which were in 2009 (Grand Bank) and 2010 (Banquereau). This bank-wide approach does not necessarily guarantee sustainability since biomass is estimated for areas where clam densities are too low to be commercially viable. Whole-bank biomass estimates and resulting TACs could result in areas of commercial density being fished down faster than they can be replenished. In addition, updated assessments using this approach require new survey data, which is not currently available for either bank. Here we apply an updated assessment approach that attempts to mitigate these issues by generating biomass estimates that are restricted to areas of commercially viable densities identified from historical Vessel Monitoring System (VMS) positional and Catch Per Unit Effort (CPUE) data. This approach generates estimates of biomass across each bank using Bayesian surplus production models to incorporate and quantify uncertainties associated with dredge efficiency. Given the sedentary nature of clams and the cyclical nature of the spatial footprint of fishing activity, we fit surplus production models to spatial disaggregated data. Five spatial assessment areas were constructed for Banquereau that were easily navigable; encompassed large scale contiguous clam beds, were approximately equal in total biomass, and included high and low density areas. The production model was fit to the CPUE index for each spatial assessment area with parameters such as dredge efficiency estimated across areas. Model results show trends of declining catch rates for all areas over the last 5 years. The summed biomass for the fished areas of Banquereau was 475,960 t (275,592–869,243 95% Bayesian Credible Interval).

We compared estimates generated for Banquereau in 2010 to estimates generated from survey observations. Density estimates from the 2010 survey were similar to the 2010 CPUE density estimates for overlapping locations despite different vessels, gear, and statistical approach. When these density estimates were expanded to the fished area, as identified from the VMS footprint, the resulting biomass estimates for 2010 were also similar between the survey (211,136 t) and CPUE (218,262 t). Biomass estimates from the last assessment were corrected for dredge efficiency, which was estimated to be 0.45 with considerable uncertainty (95% Confidence Interval 0.21–0.86). A Bayesian surplus production model incorporated and quantified the uncertainties associated with dredge efficiency, the resulting estimates of biomass, and provided estimates of process and observation error.

Reference points were calculated from biomass estimates of the surplus production model with F_{MSY} estimates near 0.1; however, phase plots indicate that catch rates decline when F is greater than 0.05. Advice based on aerial expansion from the fished areas to the entire bank is more risky than only considering the fished areas; exploitation rates near estimates of F_{MSY} are more risky than F reference levels below F_{MSY}.

INTRODUCTION

The Grand Bank and Banquereau Arctic Surfclam (*Mactromeris polynyma*) stock was last assessed in 2010 and 2011 (Roddick et al. 2011, 2012) using an assessment framework developed for Banquereau and Sable banks in 2007 (Roddick et al. 2007). This approach relied on interpolations of Surfclam density from the most recent surveys conducted on Grand Bank (2006, 2008, and 2009) and Banquereau (2010) to estimate the total biomass for each bank. Since that time, the need arose to reassess the status of the Surfclam resource despite the absence of updated fisheries-independent survey data. In 2016, a fisheries-dependent assessment methodology was developed for Banquereau using a spatially disaggregated surplus production model (Hubley and Heaslip 2018). This methodology was accepted as the new assessment approach at the 2016 assessment framework meeting (DFO 2016). The objective of this document is to provide information on the resource status of Banquereau and Grand Bank Arctic Surfclam using this revised assessment methodology, in support of decision-making for the 2018 fishery. Given that there has been relatively little fishing activity on Grand Bank since 2010, a full analysis can only be conducted for Banquereau at this time.

HISTORY OF THE ARCTIC SURFCLAM FISHERY

A fishery development plan was initiated in 1980 to determine the resource potential of the Ocean Quahog (*Arctica islandica*) and other underutilized clam species in the Scotia-Fundy Region. Commercial quantities of Arctic Surfclams were found on Banquereau during surveys conducted on the Scotian Shelf from 1980–1983 (Chaisson and Rowell 1985, Rowell and Chaisson 1983).

In 1986, a three-month test fishery took place with three companies participating. These companies chartered vessels from the United States that were equipped with a single hydraulic clam dredge (Amaratunga and Rowell 1986).

In 1987, a three-year Offshore Clam Enterprise Allocation (EA) Program was developed with industry consensus. Total Allowable Catches (TACs) and EAs were set for each of the three years of the program with three companies participating. The TACs and EAs were based on biological information provided by the surveys and test fishery and an economic break-even analysis on the resources necessary for a viable vessel and processor. The TACs were set at 30,000 t for Banquereau and 15,000 t for the rest of the Scotian Shelf.

The presence of Arctic Surfclam on the Grand Banks was reported as early as 1885 (Chamberlin and Stearns 1963), and Nesis (1963) mapped its distribution on parts of the Grand Banks. Following the development of the fishery for Arctic Surfclam on Banquereau in 1986, exploratory fishing on Grand Bank in 1987 and 1988 led to the expansion of the fishery to Grand Bank in 1989. Two exploratory licences and 2 exploratory permits were issued for one year for The Northwest Atlantic Fisheries Organization (NAFO) sub-divisions 3LNO (the Grand Banks), with a “precautionary” TAC of 20,000 t (DFO 1999b). The TAC was based on an economic break-even analysis, as there was little information on the available biomass in the area. With no biological advice on biomass and the TAC never being reached, the TAC for Grand Bank continued at the same level until after the 2010 Grand Bank assessment when the TAC was adjusted to 14,756 t in 2011.

Arctic Surfclam officially became a regulated species under the Atlantic Fishery regulations in February 1989 with the expansion of the fishery to Grand Bank. At this time, there were four licences with access to different areas under different EAs. In 1991, a new multi-year management plan was approved and an Offshore Clam Enterprise Allocation Program was approved for 1990–1994. The fisheries for the Scotia-Fundy and Newfoundland regions were combined under this single Integrated Fisheries Management Plan (IFMP). The TACs for Banquereau and Grand Bank did not change under this plan, but the EAs were revised so that all four permanent licences had equal access and allocations for all areas. The industry has consolidated over time, with a single enterprise currently controlling the three existing licences for four vessels.

The subsequent 1995-1997 Offshore Clam Fishery Multi-Year Harvesting Plan continued the EA program for 1995-1997 and maintained the same TACs for Banquereau and Grand Bank, but it prohibited permanent transfers of allocation. Commitments were made by the Industry and DFO to cost-share scientific studies over this period, and Industry committed to funding an economic study of the fishery and a dockside monitoring program. A second five year plan was approved for 1998-2002, the Offshore Surfclam IFMP; following the completion of DFO research in 1999, the TAC for Banquereau was reduced to 20,000 t in 2000. The 1998-2002 IFMP was extended for two years pending finalization of a long-term plan — the 2005-2009 Offshore Clams IFMP.

The current IFMP is a 5-year 'rolling' or ‘evergreen’ plan subject to amendment at the discretion of the Minister of Fisheries and Oceans Canada while respecting the applicable legislation, policies and regulations. The Offshore Clams IFMP remains in effect until replaced. At the end of each year the plan is to be reviewed and amended as required. Since the 2005–2009 Offshore Clams IFMP was approved, a technical update of a revised TAC for Grand Bank was made in 2011 with a reduction from 20,000 t to 14,756 t. Further amendments in 2014 included the addition of a precautionary approach framework and harvest control rules that were reviewed and established as a formal component of the Offshore Clams IFMP (DFO 2012b, 2014).

SURVEY AND ASSESSMENT HISTORY

Industry committed to funding a survey of Grand Bank and Banquereau in 1995–1997 under a multi-year Joint Project Agreement (JPA). Industry continued this commitment with a series of resource surveys to assess the biomass of Arctic Surfclam through multi-year JPAs with DFO. The intent was for the surveys to cycle through the fishing banks with a survey each year and individual banks surveyed every 3 to 5 years. The survey series started with a Quahog survey of Sable Bank in 2003, followed by surveys on Banquereau and Grand Bank. There were no surveys in 2005 and 2007; the last survey was conducted on Banquereau in 2010 (Roddick et al. 2012).

Since the start of the fishery, 3 Industry-DFO surveys of Banquereau have been conducted in 1996-1997, 2004, and 2010. Results from an assessment of the 1996-1997 survey of Banquereau (DFO 1999a) lead to a reduction of the TAC for Banquereau from 30,000 t to 24,000 t in 2000.

Two Industry-DFO surveys of Grand Bank have been conducted to date. Due to the size of the Bank, these surveys were split over multiple years in 1995-1997 and 2006, 2008, and 2009. The results of the Grand Bank portion of the 1995-1997 survey were not formally presented for review until 2010 when they were presented as part of an assessment that reviewed both surveys (Roddick et al. 2011). The results from this assessment resulted in a reduction of the TAC for Grand Bank from 20,000 t to 14,756 t in 2011.

Trend analyses of survey data from Banquereau and Grand Bank are complicated by vessel and gear changes between years and the Grand Bank survey being split over multiple years.

The Scotian Shelf and Grand Bank offshore clam fisheries continue to be managed under one plan (DFO 2014), with the license holders having equal access to quotas in both areas. Fishing activity has switched between Banquereau and Grand Bank through time, with the most recent focus on Banquereau until 2016 (Figure 1). The landings and TAC for the Banquereau fishery are shown in Figure 2; the landing and TAC for the Grand Bank fishery are show in Figure 3. Though landings have generally increased since the beginning of the fishery, they have never reached or approached the combined quota for both banks until 2016 (Table 1 and Figure 1). The landings for Banquereau have reached or approached the TAC for a number of years (i.e., 2009-12 and 2014-16; Figure 2 and Table 2).

The fishery has used large freezer processor vessels since 1992. There were 3 vessels active for most years, fishing on both Banquereau and Grand Bank, and the fleet currently consists of three freezer processors. The distribution of catch and effort data by watch, distribution of catch, and distribution of effort for the fishery on Banquereau for 2004-2016 is shown in Figure 4, Figure 5, and Figure 6, respectively. The annual distribution of effort for individual years (2004-2016) is shown in Figure 7 and the distribution of catch per unit effort (CPUE) for Banquereau is shown in Figure 8. The distribution of catch for the fishery on Grand Bank for 2004-2016 is shown in Figure 9. The majority of the fishing effort (95%) on Banquereau has focused on an area of approximately 20% across the bank (Figure 6), while the catches on Grand Bank have concentrated on a small portion of the bank to date (Figure 9).

An assessment framework for Arctic Surfclam on Banquereau and Sable banks was previously reviewed in 2007 (Roddick et al. 2007). A peer-reviewed stock assessment of Arctic Surfclam on Grand Bank was conducted in 2010 using an assessment approach similar to that developed for Banquereau (Roddick et al. 2011). The Banquereau Arctic Surfclam stock was last assessed in 2011 (Roddick et al. 2012). After the last assessment, there was a shift from the scheduled assessments to a multi-year indicator driven Precautionary Approach (PA) framework with formal stock assessments anticipated approximately every 10 years. The PA framework includes limit reference points with associated harvest control rules. Upper (URP) and Limit (LRP) reference points were established based on a B_{MSY} proxy of 1,015,059 t for Banquereau and 703,065 t for Grand Bank and calculated using fishable biomass per recruit and estimated average annual recruitment. The default 80% and 40% of the B_{MSY} for this stock were used for the reference points:

	Banquereau	**Grand Bank**
Upper Reference Point (URP)	812,047 t	562,452 t
Limit Reference Point (LRP)	406,024 t	281,226 t

The associated upper removal reference rate was F = 0.33M (0.0264) and was applied to the harvestable biomass >70 g/m2 while the stock is in the Healthy Zone. In the period between formal stock assessments, indicator reports were produced annually as interim-year updates. Indicator trigger levels were established to monitor changes in stock status and as a primary determinant of management adjustments related to fishing mortality, TAC, and the multi-year assessment schedule:

	Indicator Trigger Levels	
	Banquereau	**Grand Bank**
CPUE	70 g/m^2	50 g/m^2
Spatial Extent	253 km^2	128 km^2
Size Composition	<1% of catch >120 mm	<0.5% of catch >105 mm

Independent reviews of the management of the Arctic Surfclam fishery were conducted in 2015 by Hoenig (2015b[1]) and Orensanz (2015[2]). Recommendations from these reviews included changing from a TAC that is a fraction of the most recent bank wide biomass estimate to a TAC that is a fraction of the fishable area with a rotation time that matches recovery time (Hoenig 2015b). The fishable areas of high densities of clams could be identified and mapped with adapted survey designs and the spatial heterogeneity of fishing mortality, and recovery time could be explored with the use of Vessel Monitoring System (VMS) positional data in support of implementing spatially explicit harvest strategies. Both authors identified that estimates of the efficiency of the survey gear and the recovery time of exploited patches continues to be a major source of uncertainty requiring further attention. The 2016 framework meeting (DFO 2016) took these recommendations into consideration when developing the new methodology detailed in the analysis section below.

SURFCLAM LIFE HISTORY

The Arctic Surfclam, also commonly known as Stimpson's Surfclam or the Pink Neck Clam, is a large (up to 160 mm) long-lived bivalve that can reach more than 60 years of age. It is found in deep water of both the northern North Pacific and the northwestern Atlantic oceans (Chamberlin and Stearns 1963). Commercial quantities of Arctic Surfclam are found in the inshore areas off southwest Nova Scotia, in the Gulf of St. Lawrence, and in the offshore areas of the Eastern Scotian Shelf and Eastern Grand Banks (DFO 2012a). Arctic Surfclam are dioecious broadcast spawners that reach reproductive maturity between 5 and 8 years of age and spawn mainly in the summer or fall. The high dispersal potential of the pelagic larvae of Surfclam likely results in high gene flow throughout their range. Genetic surveys in the Northwest Atlantic found little genetic structure, which supports this prediction (Cassista and Hart 2007). Larval development and growth is temperature dependent (Davis and Shumway 1996); after a planktonic larval stage of 1-3 weeks, juveniles recruit to inshore or offshore sandy banks where their distribution is limited to benthic substrates with medium to large grain sediments and water temperatures of less than 15˚C. Growth rates for Arctic Surfclam diminish after approximately 50 mm shell length.

Growth

A length stratified, random sub-sample of clams processed for morphometric measurements was selected for ageing during the Banquereau and Grand Bank surveys (Roddick et al. 2011,

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[1] Hoenig, J.M. 2015b. Review of the Scientific Basis for Managing Stocks of Arctic Surfclam on Banquereau and Grand Bank: Data, Analysis, and Overall Inference. Unpublished report.

[2] Orensanz, J.M.L. 2015. Review of Arctic Surfclam Fishery Management. Unpublished report.

2012). There is more variability in the estimated ages for larger clams; therefore, the sampling consisted of 30 clams per 5 mm shell length interval up to 80 mm shell length and 150 clams per 5 mm interval for size intervals over 80 mm. Age was estimated using thin sections of the hinge area of the left valve and a microscope with transmitted light at 40 time magnification to count the annuli (Almeida and Sheehan 1997, see Roddick et al. (2011, 2012) for sectioning and ageing details). All personnel involved in ageing the clams went through training with a reference collection and group training sessions to ensure consistency in assignment of ages (Roddick et al. 2011, 2012).

The resulting age data were fit to a von Bertalanffy growth curve:

$$L_t = L_\infty(1 - e^{-k(t-t_0)})$$

where L_t is the length at age t; L is the asymptotic length; k is a growth coefficient; and t_0 is the theoretical age at zero length. Curves were fit to both the raw sample data and the sample weighted by the survey size frequency distribution in 5 mm (Figure 10; Figure 23 in Roddick et al. 2012).

Size and Age at Sexual Maturity

Samples to estimate size and age at maturity were collected during the Banquereau and Grand Bank surveys (Roddick et al. 2011, 2012). Morphometric measurements were taken for each clam before preservation in a 10% solution of formalin in seawater. The preserved samples were transported to the Bedford Institute of Oceanography (Dartmouth, NS) where the foot portion, which contains the gonad material, was separated for histological processing. Histology and gonadal staging was done by the Aquatic Diagnostic Services of the Atlantic Veterinary College at the University of Prince Edward Island (Charlottetown, PEI). Gonad sections were classified into six maturity stages (Ropes 1968, Rowell et al. 1990):

1. early active;
2. late active;
3. ripe;
4. spawning;
5. spent; and
6. immature.

The proportion of mature individuals was plotted against size. A Richard’s Curve (Millar and Fryer 1999) was fit to the data using maximum likelihood. The shells were retained and aged with the same techniques used for the morphometric samples, with the exception of very small shells, which were first coated with or embedded in epoxy to support them during sectioning and polishing. A Richard’s Curve was fit to the age at maturity data using the same method used for the size at maturity data.

For the 2010 Banquereau survey, a total of 87 Arctic Surfclams ranging in size from 23–99 mm were processed for maturity, size, and sex, 84 of which were aged. Ages from these samples ranged from 5 to 41 years (Roddick et al. 2012). The resulting maturity data were fit with a Richard’s Curve using maximum likelihood. The size at 50% maturity was 45.2 mm shell length (Figure 10; Figure 23 in Roddick et al. 2012), which is below the 62.24 mm size at 50% retention calculated for the 2010 Banquereau Survey (Figure 11 in Roddick et al. 2012), below the 87.4 mm estimate for the survey dredge used on Banquereau in 2004 (Figure 10 in Roddick et al. 2007), and below the 85.6 mm estimate for a commercial clam dredge (Figure 11 in Roddick et al. 2007). The age of 50% maturity was 8.3 years old (Figure 10; Figure 23 in

Roddick et al. 2012). These values are larger and older than survey samples aged using similar methods from the Grand Bank population, which were 39.9 mm and 5.3 years at 50% maturity (Figure 8 in Roddick et al. 2011).

Mortality

Since there has been a commercial fishery for clams on Banquereau, it is assumed that the Natural Mortality (M) rate is equivalent to the Total Mortality (Z) rate minus the Fishing Mortality (F) rate. The simplest mortality estimate examined has included the method used by Amaratunga and Rowell (1986):

$$Z = \frac{3}{T_{MAX}}$$

where T_{MAX} is the lifespan of the organism. The lifespan is usually described as the age at which 5% of the population remains alive. It is an approximation that requires very little data. Taking the estimated size of 50% recruitment (62 mm) and the growth curve gave a recruitment age of 9 for the 2010 Banquereau assessment (Roddick et al. 2012). From the estimated age distribution (Figure 10; Figure 23 in Roddick et al. 2012), the upper 5% cut off is 50 years of age, which produces a mortality estimate of $Z = 0.06$, lower than Amaratunga and Rowell's (1986) initial estimate for Banquereau of $Z = 0.075$. In that case, Z was considered to be equal to the Natural Mortality (M) rate since there was no fishery at the time. The commercial fishery on Banquereau has been operating since 1986, or about half the lifespan of Arctic Surfclams, thus M would be smaller than this estimate of Z.

Beverton and Holt's (1956) method takes the decline on the right hand side of the length frequency distribution and uses the von Bertalanffy growth parameters to estimate the time required for the animals to grow through a size range. Total mortality is estimated with the formula:

$$Z = \frac{(K(L_\infty - L_m))}{(L_m - L')}$$

where L' is the smallest length fully represented in the length frequency data, L_m, is the mean length of all clams ≥ L', and K and L_∞ are von Bertalanffy growth curve parameters. This method requires length frequency data and a growth curve, but does not require a large sample to be aged. The size at 95% selectivity for the 2010 Banquereau survey was 84 mm, producing an mortality estimate of $Z = 0.081912$ using Beverton and Holt's (1956) method.

The third method that has been used is the catch curve method (Chapman and Robson 1960, Ricker 1975), which takes a large aged sample and models the decline in numbers at age.

$$N_t = N_0 * e^{-Zt}$$

Where N_0 is the initial number of individuals, t is the period of time (years), and N_t is the number alive at time t. Z is estimated with a linear regression of the log transformed numbers at age and was estimated to be 0.07905 for the 2010 Banquereau Survey.

The fourth method that has been used is the Chapman Robson (C-R) estimate of Z (Chapman and Robson 1960). This method uses the mean age of animals above the recruitment age to estimate mortality: where $\bar{a}$ is the mean age above recruitment for those clams above the age of recruitment (a_r; i.e., mean of [a - a_r] for clams > a_r), and n is the sample size. Using a recruitment age of 25, the same used for the 2009 Grand Bank survey, the C-R mortality estimate for the Banquereau 2010 survey is $Z = 0.075501$.

The last three methods require a decision on which sizes/ages to include, as they require the analysis to be based on individuals that are selected by the sampling gear, and thus on the descending right limb of the length frequency curve. The selectivity curve from the survey was used as the basis for this decision.

For the methods that require age frequencies (catch curve and C-R), the survey age frequency for Banquereau was estimated from the length frequency data using an age-length key constructed from the aged sample (approximately 150 Arctic Surfclams from each 5 mm interval). This was to make sure the length-age key covered the full size range. The age-length key was used to convert the survey length frequencies into age frequencies. The resulting population age frequency was used for the catch curve estimate of Total Mortality (*Z)*. The biomass estimate and landings provide an estimate of F, and the resulting M was compared with that used in the 2004 Banquereau Arctic Surfclam stock assessment (M = 0.08; Roddick et al. 2007).

From the 2010 Banquereau assessment (Roddick et al. 2012), mortality estimates are in the range of 0.06 to 0.082 with Z including both natural (M) and fishing mortality (F). From the Grand Bank assessment (Roddick et al. 2011), mortality estimates were in the range of 0.06 to 0.10 (Roddick et al. 2011).

ECOSYSTEM CONSIDERATIONS AND IMPACTS OF DREDGING

Fisheries and Oceans Canada (DFO) is committed to an ecosystem approach to fisheries management. The Department also has responsibilities and mandates that include fish habitat, species at risk, conservation of biodiversity, and oceans planning and management.

Habitat

The clam dredges used in the offshore clam fishery have an immediate impact on the substrate and benthic organisms as they liquefy the sediment down to a minimum of 20 cm, remove many large macro-infaunal organisms, and cause sedimentation and displace organisms adjacent to the track. On Banquereau, the long term impacts of a hydraulic clam dredge on the habitat and benthic community have been studied at a deep site of 65-70 m depth and followed over a 10-year period (Gilkinson et al. 2015, Gilkinson et al. 2003, Gilkinson et al. 2005). The largest quantified species impact is the removal of clams and other non-target bivalves from the area, both from harvesting and from incidental mortality. Harvest efficiencies greater than 90% are not uncommon and, for the clams that remain, more than two-thirds can be damaged (Lambert and Goudreau 1996). Given the sedentary nature of clams and their slow growth rate, this is a long-term impact. The experiment demonstrated immediate impacts on both habitat and non-target organisms. Within the first 2 years following dredging, there was an increase in the abundance of non-target benthic species such as echinoderms, with a shift in relative abundance of the species present. Visual methods such as still photos and video recordings could not discern the tracks after one year; however, tracks were visible from the sidescan sonar imagery (Gilkinson et al. 2005). The species composition in the dredged sites seemed to be dominated by colonizing species three years after dredging. Definite conclusions were complicated by similar changes in the reference sites, suggesting that the effects of dredging could extend beyond the disturbed area, that variation in community composition observed in the dredged area was unrelated to the dredging itself, or some combination of the two (Gilkinson et al. 2005).

Results from sidescan sonar imaging infer that changes to the sediment structure caused by dredging can persist for 10 years or longer. There was low recruitment of large bivalve species to the experimental study site over 10 years post-dredging, and sidescan sonar was still able to detect some of the track locations 10 years after dredging. During the Sable Island Bank survey in 2003, out of 26 sampling sites that were surveyed with sidescan sonar one year later, only 6 deep sites still showed evidence of dredge tracks. Four commercial bivalve species (Arctic Surfclam; Northern Propellerclam, *Cyrtodaria silique*; Ocean Quahog, *Arctica islandica*; and Greenland Smoothcockle, *Serripes groenlandicus*) showed low recruitment at the experimental site over the 10-year post-dredging period, but a similar recruitment pattern was also observed in non-dredged areas suggesting that low recruitment is unlikely a result of dredging. The persistence of dredge tracks at deep sites suggests that water depth likely influences track persistence, with shallower areas having sediments that are more actively worked by waves and currents. Hydraulic clam dredge fisheries occur on fairly mobile, well-sorted sand, which may help mitigate the overall impact on some elements of the benthic community (NMFS 2002); however, there continues to be uncertainty about the long-term impacts of dredges on overall benthic productivity.

Although clam dredges have a large immediate impact on the bottom, the impact of the fishery is usually ranked lower than other bottom contact gear, due largely to its relatively small footprint. The footprint of the fishery can be estimated from the logbook data using the “area swept” (km^2) per year. This estimate is a maximum as there is no correction for overlapping tows. With three vessels currently active in the offshore clam fishery, the area swept is relatively small compared to the spatial extent of the target species and other mobile gear fisheries. Since 1986, approximately 3,898 km^2 have been swept on Banquereau with the highest annual areas swept in 1998-2000 and 2014-2016. Since the Grand Bank Arctic Surfclam fishery began in 1989, approximately 1,280 km^2 have been swept with the greatest activity in 1995, 2001-2003, and an increase in 2016 compared to previous years of little to no fishing on Grand Bank since 2006.

There is considerable spatial and temporal variation of area swept over the timeframe of the fishery with areas of high clam biomass fished more frequently and intensely than other sections and periods when the fishery has concentrated on Banquereau rather than Grand Bank. The average annual area swept during the last 13 years of the fishery (2004–2016) on Banquereau is approximately 160 km^2 and for Grand Bank is approximately 26 km^2. The footprint of the fishery over the last 13 years is shown in Figure 5 for Banquereau and Figure 9 for Grand Bank. Since the target species is one of the longer lived species in the benthos it will be one of the last species to recover from fishing. If an area fished is not returned to prior to the recovery time of the Arctic Surfclam, this should allow the shorter lived, faster growing species time to recover before the area is fished again.

Discards and Bycatch

Discards and bycatch data are available from:

1. the Banquereau and Grand Bank surveys (Roddick et al. 2011, 2012, 2007);
2. the industry on-board sampling program 1999–2012; and
3. the DFO Newfoundland Region and Maritimes Region At-Sea Observer Programs (International Observer Program [IOP], Newfoundland Region: 1995, 2007, and 2009–2015 for Banquereau and 1995–1997, 2007, and 2016 for Grand Bank; and Maritimes Region: 1988–1991, 1994, 1996, 1998–1999, and 2008 for Banquereau and 1989–1992 and 1995–1996 for Grand Bank).

Survey Bycatch

The last assessments for Banquereau (Roddick et al. 2012) and Grand Bank (Roddick et al. 2011) included bycatch data from scientific surveys. The survey bycatch data is recorded in more detail with larger sample sizes than the IOP and on-board programs. Bycatch for survey tows having a catch greater than 100 g/m^2 was compared to data from the sampling programs on commercial vessels, representing those areas likely to be fished commercially. The species compositions from the surveys are more extensive than the other sampling programs due to the detailed sampling and large sample size.

For the 2010 Banquereau survey, the five bushel subsamples used for catch composition amounted to 38 t of catch (Roddick et al. 2012). For survey tows with catches greater than 100 g/m^2 and only living material, eight species made up more than 1% of the catch. Sand dollars, sea mice, and sea cucumbers were the only non-bivalve species, with sand dollars making up 36% of the catch (Table 9 in Roddick et al. 2012). Over the three years of the last Grand Bank survey (2006, 2008, and 2009), 56.9 t of catch was processed for composition (Roddick et al. 2011). For survey tows with catches greater than 100 g/m^2 and only living material, five species made up more than 1% of the catch (Table 4 in Roddick et al. 2011). Sand dollars and sea cucumber were the only non-bivalve species, with sand dollars making up 26% of the catch (Table 4 in Roddick et al. 2011). The species compositions of the surveys are more extensive than the other sampling programs as a result of the detailed sampling and large sample size. For both surveys, the proportion of sand dollars is higher than either of the programs sampling the commercial vessels and could be a function of spatial distribution or gear.

On-board Sampling Program

The on-board sampling uses one bushel samples of unsorted catch. The samplers were provided with reference materials but have limited experience in species identification. Most of the components are at the genus level or higher, resulting in shorter list than from surveys, where samples can be frozen for later identification. The most recent analysis of on-board sampling of catch is presented in Table 8 of Roddick et al. (2012) for Banquereau and in Table 6 of Roddick et al. (2011) for Grand Bank. Arctic Surfclams were 60% of living material for Banquereau (1999-2009) and 29% of the living material for Grand Bank (2002-2009). Even when Arctic Surfclams and Greenland Cockles were combined, the on-board sampling showed only 54% Arctic Surfclam, which was similar to the survey data for potential commercial areas at 48%, but lower than the IOP sampling. Sand dollars were the only non-bivalve component making up more than 1% of the catch for both Banquereau and Grand Bank.

Commercial Bycatch

The IOP data reports from DFO Newfoundland Region indicate that since the last assessments (Roddick et al. 2011, 2012), observers were on board for trips to Banquereau in 2012-2015 and for one trip to Grand Bank in 2016. For these trips, 10,326,715 kg of catch was observed on Banquereau and 1,287,381 kg of catch was observed on Grand Bank (Table 3). The observers are instructed to obtain the best estimates possible, but the method used – i.e., sub-sampling or visual observation – is not specified or documented (Joe Firth, DFO Newfoundland, pers. comm.).

For Banquereau, Arctic Surfclams were 60.98% of the total observed catch along with 10.90% Northern Propeller Clams, 2.16% Greenland Smoothcockles, and 0.08% Ocean Quahogs (Table 3). The most abundant non-bivalve species reported for Banquereau making up more than 1% of the catch were sand dollars (9.42%) (Table 3). The relative proportions of bivalve species were comparable to those reported in the last assessment for Arctic Surfclam on Banquereau (Table 7 in Roddick et al. 2012). For non-bivalve species, there were relatively more sand dollars for 2012–2015 compared with the value reported in the last assessment for 1995 and 2009-2011 (9.42% vs. 3.76%).

For Grand Bank, Arctic Surfclams were 94.75% of the total observed catch along with 3.70% Greenland Smoothcockles, 0.13% Ocean Quahogs, and 0.08% Propeller Clams (Table 3). The most abundant non-bivalve species making up more than 1% of the catch for Grand Bank were sea cucumbers (1.25%). Compared to values reported for 2007 in the last assessment for Arctic Surfclam on Grand Bank (Table 7 in Roddick et al. 2011), the catch of Surfclams is higher for 2016 than the 2007 trip (94.75% vs. 20.00%) that targeted Greenland Smoothcockles (76.28% of the 2007 catch). For non-bivalve species, Sand dollars were present in 2007 (3.57%) and absent in 2016, whelks were absent in 2007 and present in 2016, and a number of crab and fish species were recorded in 2007 while there were no fish or crab species recorded in 2016.

As reported in the last assessments (Roddick et al. 2011, 2012), there is a higher percentage of Surfclams in the IOP data compared with the survey data, which may indicate that the fishery targeted areas with a higher catch of Surfclams than the 100 g/m2 used to delimit commercial grounds for the survey data, that the commercial dredges retain less by-catch than the survey dredges, and/or there was a bias in the sampling. The list of species encountered in the IOP data was much shorter than that from the surveys, and it contained more large, easily noticed organisms. The difference in number of species recorded was probably reflective of both a smaller sample size and a bias for larger species, while the higher proportion of clams was likely a function of the areas targeted and gear used.

There are a number of non-specified groupings that vary in their use between years, such as, skates (NS), sand lances (NS), and scallop (NS). Categories for shells, stone, and sand were not reported for Banquereau until 2010 and have not been reported to date for Grand Bank.

On Banquereau, the non-specified grouping for skates (skates [NS]; Family Rajidae) was the most abundant category for skates, and Thorny Skate (2012–2015, *Amblyraja radiata*) and Smooth Skate (2014-2015, *Malacoraja senta*) were the first and second most common skate species identified. These two species were both given statuses of Special Concern by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) in 2012 (COSEWIC 2012). For the previous assessment (Table 7 in Roddick et al. 2012), skates (NS) and Thorny Skate catch categories were reported for 1995 and 2009-2011, while Smooth Skate was previously reported once in 1995. Winter Skate was recorded in 2015 on Banquereau and was also previously reported once in 1995. COSEWIC designated the Eastern Scotian Shelf – Newfoundland population of Winter Skate as Endangered in May 2015. No skates were recorded on Grand Bank in 2016. For the years reported in the last assessment (1995-1997 and 2007; Roddick et al. 2011), Skates (NS) were reported in 1995 and 1997, skates were absent in 1996, and Thorny Skate was recorded in 2007 (Table 5, Roddick et al. 2011). In previous years, the relative proportion of the catch for skates on Grand Bank was low and comparable to that for Banquereau (≤ 0.04%). The skate by-catch is low for Banquereau and Grand Bank, but might become an issue.

Climate

The vulnerability of Arctic Surfclam to ocean warming and acidification has not specifically been studied to date; however, benthic invertebrates such as Ocean Quahog (*Arctica islandica*), Northern Quahog (*Mercenaria mercenaria*), and Atlantic Surfclam (*Spisula solidissima*) have been identified as exhibiting a high or very high degree of climate vulnerability in a broad examination of the relative vulnerability of fish and invertebrates on the Northeast United States Shelf (Hare 2016). With warming temperatures, we’d expect a bathymetric shift in the distribution of Arctic Surfclams, similar to the shift to deeper water observed for inshore Atlantic Surfclams off the Mid-Atlantic coast of the USA during a period of unusually warm water (Weinberg 2005). A latitudinal shift is also likely to occur, where depth (e.g., Laurentian Channel) and substrate (e.g., Grand Bank) does not limit suitable habitat. In addition to changes in latitude and depth of species related to bottom temperature, we would also expect changes in growth rate, tissue weight, and mortality rates. Basic knowledge of the life history of Arctic Surfclam are necessary to help us understand how spawning and recruitment may be impacted by changes in ocean temperature and the time scales at which such changes may impact the fishery.

FISHERY DATA

The main sources of data from the commercial fishery are the logbooks and a voluntary sampling program carried out on-board the vessels. There is also periodic coverage under the IOP, which puts independent observers on the vessels to monitor catch. The logbooks provide data on location, catch, and effort expressed as area swept calculated from reported towing time, vessel speed and gear width. The sampling programs provide data on length frequencies, bycatch, and conversion factors. Additionally, physical samples are sent to DFO additional morphometric analysis. Vessel Monitoring Systems (VMS) allow fishing vessel positions to be transmitted to DFO once an hour through a satellite communication system providing fine scale information on the spatial and temporal distribution of fishing activity.

The use of logbook data to estimate CPUE is complicated by the fact that Arctic Surfclams are sedentary, fishing effort varies in location over time, and the vessels are freezer processors. During fishing, catch from the dredges is fed into a hopper system that continuously feeds the processing line. Catch weights are recorded as processed product weight at the end of the processing line, so there is a lag in the reporting of catch that makes it difficult to accurately match catch to the effort that produced it for individual records.

The effect of mismatched catch and effort data is mitigated by censoring the data and spatially aggregating catch and effort individually over the Bank. Data filtering consisted of removing records that did not contain both catch and effort data, as well as records with extreme low and high values of catch and effort. Plots of the distribution of catch and effort data were used to inform the choice of threshold for including records (Figure 4). The analysis of CPUE data only includes records reporting more than 15,000 m^2 and less than 200,000 m^2 of effort per watch and more than 1500 kg and less than 30,000 kg of catch per watch. Outliers, likely attributable to data entry error and-or partial watches, were censored from the analysis. It was assumed that the remaining data were representative of the fishery performance.

The VMS data consists of precise positional information for fishing vessels on hourly intervals since 2004. These data were joined with their associated watch record from the log data. Log records are reported every six hour watch and several VMS records were linked to each watch based on whether the timestamp from the VMS fell within the given six hour period. The catch and effort data were then distributed evenly among the VMS position such that the data from a given watch now has accurate positional information for each hour as opposed to an average position for every six hours. This resulted in a far more accurate spatial representation on the distribution of catch and effort information.

Catch and effort information was aggregated to 1 km x 1 km square grid cells for the period where VMS data is available (2004-2016) in order to examine the spatial distribution of the fishery (Figure 5 and Figure 6). The gridded effort data is also presented annually in Figure 7 to show how the distribution of effort has changed over time. The fishery initially concentrated on an area along the south-east slope of the shoal on eastern Banquereau; as this area was fished down, the fleet moved out to the central and western portions of the Bank. The initial area had a large pulse of recruitment that was seen in the 2004 survey (Roddick et al. 2007). Fishing effort increased over time as the recruits grew, and this area has sustained large catches in recent years. The CPUE was calculated by taking the sum of total catch over the sum of total effort within each cell (Figure 8). This plot shows a large area near that south-east slope where densities are higher than elsewhere on the bank. When effort is expressed as area dredged and measured in km^2 the aggregated effort data also represents the proportion of area dredged in each cell (Figure 6). Approximations of local exploitation per cell can be made assuming 100% catchability (q = 1), an even distribution of clams, and no overlapping tows. Although these assumptions are oversimplified and potentially biased, they are the best available a proxy for local exploitation at this time.

Another advantage of expressing effort in terms of area dredged is that commercial CPUE is expressed as a density of clams on the bottom with convenient units for various scales (i.e., t/km^2 = g/m^2). Density estimates from the commercial CPUE can be expanded by area to produce biomass estimates that can be compared to estimates from the survey. However, there are many factors that could lead to uncertainty and bias in both catch rates and the survey. These include the catchability (q), which here is synonymous with dredge efficiency; selectivity differences; and other changes in efficiencies of the fishery over time. Grand Bank has seen much less fishing activity than Banquereau since 2004 (Figure 9), so minimal new fishery information since the last assessment was available (Roddick et al. 2011).

Catch composition is currently available at the resolution of a fishing trip, which is too coarse to describe the spatial variability in size composition across the bank. However, it does give an overall indication of the size composition of the catch in each year (Figure 13).

SURVEY DATA

Science surveys of Banquereau Arctic Surfclams were conducted in 2004 and 2010. Due to the large size of the Grand Bank, a scientific survey of Grand Bank Arctic Surfclam was conducted in three regions ending in 2009 (2006, 2008 and 2009) to assess the biomass of the stock in this area. A detailed description of the survey design and procedures is available in the previous research documents (Roddick et al. 2011, 2012).

The vessel and dredge used in the more recent surveys (2008–2010) differed from those used for the 2004 and earlier surveys. The vessel used for the 2010 survey of Banquereau was the *Tenacity 1*, a 36 m, 353 GT stern dragger that was built in 1967. It was equipped with a pump, stern ramp, and hydraulic clam dredge. The dredge was 226 cm wide and 445 cm long, with a 177 cm knife blade. The average bar spacing in the cage section was 23 mm on the top and sides, and 28 mm on the bottom. The depth of the knife was set to 14.3 cm below the runners.

For the 2010 survey, 260 stations were randomly assigned within the 100 m contours on Banquereau with a minimum spacing of 2.0 km between tows. An additional 35 stations from the 2004 survey were selected from areas where no fishing had occurred between the 2004 and 2010 surveys. These were to allow for comparisons between the surveys.

Towing and catch processing procedures are described in detail in Roddick et al. (2011, 2012). Tows were generally three minutes in duration and tow distance was measured so that the catch could be standardized for a given area towed. Subsampling was employed at various levels to effectively estimate the abundance and species composition of the catch at each station. Additional sampling included at least 100 clams measured for length frequency and a sample of up to three clams from each 5 mm interval collected for morphometric measurements and ageing.

Selectivity and dredge efficiency experiments were conducted during the 2010 survey in addition to the 35 repeated tows from the 2004 survey used to compare dredge efficiencies between surveys because of different gears. In 2010, the back of the dredge was a cage and door system rather than the chain bag and cod end used in 2004. This meant that the dredge used in 2010 had a lower capacity than that used in 2004, but it was felt that it would also retain less shell. The 35 tows were selected from areas where no fishing activity had taken place between the two surveys. A linear regression through the origin gives a slope of 0.634 (Standard error = 0.064 and $p < 0.001$). This indicates that the catch rate for the 2010 tows was only 63% of what it was in 2004. Roddick et al. (2012) concluded that the 2004 and 2010 survey biomass estimates are not directly comparable, and the estimates cannot be used to indicate a change in biomass between surveys. A comparison of survey catch rates with commercial CPUE in areas where they overlapped in 2004 and 2010 shows that density estimates from the commercial CPUE are more similar to the survey in 2010 than in 2004 (Figure 11). It might be that commercial dredges are more efficient than the survey, but the survey selects for a large size range of clams as indicated by a comparison of selectivity curves (Figure 12). However, the catch composition in the survey is similar to that of the fishery in 2009-2010 (Figures 10 and 13).

Survey dredge efficiency was estimated using the patch model, a depletion based approach that was developed specifically for estimating the sampling efficiency when dredging for sessile marine invertebrates (Rago et al. 2006, Roddick et al. 2012). The negative log likelihood profile for the efficiency estimate using clams larger than the 90% retention size is shown in Figure 14. The profile is rounded, rather than sharp, and that is reflected in the standard deviation for the estimate (0.48). The MLE estimate of dredge efficiency was 45% with a right skewed 95% confidence interval of 21-86% (Roddick et al. 2012, Figure 12). These results reflect considerable uncertainty in estimated dredge efficiency.

The length frequency for the total survey and ageing results are shown in Figure 10. There is a mode of small clams less than 50 mm shell length that was not observed in the 2004 survey. Due to the differences in gear selectivity between 2004 and 2010, the lack of smaller clams in 2004 does not indicate their absence from the population. There are a large number of age classes present in the larger sizes; therefore, the aged sample consisted of a length stratified random sample with approximately 30 clams per 5 mm shell length increment up to 80 mm and approximately 150 clams per 5 mm increment above 80 mm. Figure 10 displays the sample age versus length scatter plot, fitted with von Bertalanffy growth curves for both the aged sample and weighted by population numbers at length. The length frequency histograms of the aged sample and the survey size frequency distribution are to the left of the scatter plot, and the age frequency histograms for the sample and estimated for the population are shown below. The age frequency distributions indicate fluctuations in recruitment through time. The distribution of Surfclams across the Bank was estimated from the 2004 and 2010 surveys using inverse distance weighting interpolation (Figure 13, Pebesma 2004). Some of the patterns are consistent with the fishery information but, given the highly patchy nature of the resource, the density of sampling in the survey is insufficient to adequately describe the distribution of clams across the Bank. Higher densities in 2004 may just be the result of different catchabilities between surveys and not changes in abundance.

ANALYSIS

HABITAT SUITABILITY

The patchy nature of the Surfclam resource is a key factor for considering spatial management. This patchiness complicates the provision of harvest advice based on a presumed bank-wide biomass instead of areas actually harvested (Hoenig 2015a). Ideally, fine-scale habitat information could be used to predict Surfclam habitat using relevant covariates that are related with clam abundance and distribution. Currently, these types of data and associated predictive models are unavailable. In lieu of this information, we used high resolution VMS data to construct an approximation of clam habitat by assuming the fishery has targeted all areas with fishable concentrations over the past 12 years (since 2004). This assumption is likely more appropriate for Banquereau than for Grand Bank due to their relative size and cumulated effort during this period.

On Banquereau, the density of VMS locations was estimated from 2004-2016 (Figure 16). This image was produced using the kernel smoothed intensity function from the Spatstat package with a sigma of 0.2 (Baddeley et al. 2015). The VMS density is expressed as the number of transmissions per km^2, with the resolution set at 100 m^2, so that the number of transmissions per km^2 was estimated for every 100 m^2. A density level of 30 transmissions per km^2 was chosen to define the fished areas, and it was used to define the area considered clam habitat that can support a fishery. The estimated area of viable clam habitat is sensitive to this threshold (Table 4), and ongoing analysis comparing high resolution habitat suitability models should be used to refine or corroborate this level.

SPATIAL ASSESSMENT AREAS

Preliminary analyses presented at the 2016 assessment framework meeting suggested that, as a result of the sedentary nature of clams and the cyclic nature of where fishing effort was directed, surplus production models fit better to data that was spatial disaggregated. The following criteria were used to define spatial delineations:

1. easily navigable (made of straight lines);
2. encompass large scale contiguous clam beds;
3. be roughly equal in total biomass; and
4. include both high and low density areas.

Five proposed areas were selected based on these criteria (Figure 17) and used in further analyses. A summary of the available data by area is provided in Table 5, which includes the total amount of area, the area of commercial viable clam habitat as defined by the VMS density, the catch and the biomass from the 2010 survey and commercial CPUE.

BIOMASS ESTIMATION

The estimated survey biomass in the 2010 survey area was calculated by two methods:

1. Random sampling statistics:

$$B = \frac{A_s}{A_t} * C$$

where B = biomass, A_s = survey area, A_t = area of standard tow, and C is mean catch per standard tow.

2. Areal expansion using inverse distance weighting (Figure 15, Pebesma 2004).

These estimates were calculated for both the entire survey area as well as just within the fished area polygons and summarized by the spatial assessment areas (Figure 17, Table 5).

The only new data to inform the current status of the fishable biomass since the last survey (2010) comes from the CPUE index derived from the fishery information since. As discussed above in the fishery data section, CPUE expressed as density of Surfclams (t/km^2) can be scaled to the total fished area as an index of total fishable biomass. The annual CPUE index and associated standard errors were calculated using a jackknife estimator (Smith 1980).

$$CPUE_{-j} = n\left(\frac{\sum C}{\sum E}\right) - (n-1)R_{-j}$$

where *n* is the number of records in a given year, respectively, and

$$R_{-j} = \frac{\sum C_{i,-j}}{\sum E_{i,-j}}$$

with the j^{th} observation removed. The annual CPUE index with standard errors is shown for each area in Figure 18.

The biomass from the CPUE densities (assuming $q = 1$) expanded to the total fished area and the associated catches are shown for all five areas from 2004-2016 in Table 6 and Table 7, respectively. In 2010, the estimated biomass was 211,136 t and 218,262 t from the survey average and CPUE data, respectively, expanded to the fished area (Table 6). In 2016, the estimated biomass from CPUE decreased to 179,633 t.

SPATIAL PRODUCTION MODEL

The time series of catch and CPUE data can be used to incorporate biomass dynamics into this analysis in the form of logistic biomass dynamics or surplus production models (Schaefer 1954) fit simultaneously to each area (*j*). Implementing the model in a Bayesian state space framework gives us the ability to realistically propagate credible errors from both the data and previous analyses (e.g., efficiency estimates and standard error of the CPUE index).

$$B_{t+1,j} = B_{t,j} + r_j B_{t,j}\left(\frac{B_{t,j}}{K_j}\right) - C_{t,j}$$

This type of model is simpler to implement than a full age-structured model and estimates only a few parameters of interest: *B*, the fishable biomass; *K*, carrying capacity; *r*, intrinsic population growth rate; *q*, the commercial dredge efficiency; *σ*, process error; and *τ*, observation error. Dividing the Bank into 5 areas (Figure 17) introduces a spatial aspect to the model whereby parameters can be estimated across all areas or separately for each area. As there is no information to suggest that dredge efficiency would vary between areas, the *q* parameter was shared across areas:

$$O_{t,j} = B_{t,j} * q$$

where *O* is the area expanded biomass estimates from the CPUE analysis for each area (*j*) and year (*t*). Carrying capacity was assumed to be related to the habitat area within each area. This was implemented by scaling *K* by habitat for each area as:

$$K_j = \overline{K} * \left(\frac{H_j}{\overline{H}}\right)$$

Although the population growth rate parameter, *r*, maybe spatially variable, it was assumed to be similar across the stock area. As such, the *r* parameter was estimated for each area but was constrained by a hierarchical structure where the mean and standard deviation is estimated for all areas and then used to define the prior on individual *r(*s) for each area.

$$\bar{r} \sim unif(0,1)$$

$$\sigma_r^2 \sim LN(-0.35,0.08)$$

$$r_j \sim LN(\log(\bar{r}, \sigma_r^2)$$

The prior for catchability was informed by the dredge efficiency estimates. A beta distribution was assumed for the prior with a mean equal to the mean of the dredge efficiency estimates from the depletion experiments (0.45, Figure 14), and a variance that produced a similar 95% CI (Confidence Interval) of (0.20, 0.71).

$$q \sim beta(a = 6, b = 7.33)$$

The state space methods used to estimate the parameters of this model give it the ability to estimate unobserved states ("true" fishable biomass) and to simultaneously estimate model process errors and data observation errors. Process errors (σ_r^2) are the uncertainties that propagate into future states via the recursive form of the logistic equation (i.e., errors in B_{t+1} in the state space of B_t vs. B_{t+1}). Observation errors (σ_ε^2) refer to the uncertainties associated with measurement and observation (i.e., measurement/data-related errors of both variables in the state space of B_t vs. B_{t+1}). This former ability is particularly important as parameter estimates and forecasts based on observation-only errors provide unrealistically optimistic (small and constant) error bounds, and parameter estimates and forecasts based on process-only errors expand rapidly into the future, resulting in potentially unrealistically pessimistic (large and usually growing) error bounds (Choi et al. 2012). A uniform prior was selected for process error:

$$\sigma_\tau \sim unif(0{,}5),$$

whereas, the prior on the observation error was informed by the average coefficient of variation (CV) from the CPUE index (0.38). Assuming the CPUE index follows a log normal distribution, the relationship between the CV for CPUE and the variance of its logarithm can be used to estimate observation error directly (Hubley et al. 2014, Johnson and Kotz 1970).

$$\hat{\sigma}_\varepsilon^2 = \log(CV^2 + 1)$$

This value (0.134) was then used to construct an informative gamma prior on the observation precision (Hubley et al. 2014, Smith and Hubley 2014).

$$\frac{1}{\sigma_\varepsilon^2} \sim gamma(shape = 3, rate = 0.4)$$

The posterior distribution of the parameters of interest conditional upon the data were estimated using a Gibbs sampling algorithm (Markov chain Monte Carlo method) using the JAGS platform (Plummer 2003, 2013). Two Markov chains were followed to ensure convergence with the first 100,000 replicates discarded as a burn-in and then every tenth replicate of the next 500,000 were kept to describe the posterior distributions of the parameters.

The fit of predicted CPUE from the spatial production model to the CPUE index is shown in Figure 19 along with 50% and 95% credible intervals. Most areas show a declining trend in the 1990s and then increasing in the 2000s. The trend is more pronounced in area 5 where consistent recruitment has contributed to higher densities observed in this area. In more recent years, this area has seen a drop in CPUE indicating a depletion of the resource in this area.

Posterior densities of the estimated model parameters are shown in Figures 20-22. The posterior distributions for the shared parameters generally indicate that information in the data has updated the parameter estimates from the prior distributions. The exception being the posterior for the standard deviation of *r* where the hyperprior was intentionally informative to prevent the resulting priors on area specific *r(s)* from being too informative and give *r* the opportunity to vary between areas. The estimates of r varied only slightly between areas. The median estimate of dredge efficiency (0.39) was lower than the results of the survey dredge efficiency experiment (0.45). The prior on *q* could be modified if more research was conducted to inform dredge efficiency for commercial gear. The estimated observation error was also lower than the prior based on CPUE variance (Figure 20).

Exploitation rates have varied as the fishery shifted its focus between areas (Figure 23). Spikes in exploitation are typically followed by reduced exploitation in subsequent years and do not normally occur in multiple areas in the same year (e.g., Area 5 in Figure 23). Biomass estimates for each area are presented in Figure 24 and Table 8. Generally for these areas, biomass increased in the early 2000s and declined somewhat in recent years.

INDICATORS AND REFERENCE POINTS

The logistic biomass dynamic model also provides parameter estimates that allow for the estimation of Maximum Sustainable Yield (MSY) reference points where $MSY = 0.25rK$, $B_{MSY} = 0.5K$ and $FMSY = 0.5r$. In a state space model framework, the estimates of process error can be incorporated to provide stochastic MSY reference points (Bousquet et al. 2008). Applying deterministic MSY rules to stochastic environments may lead to increased probability of decreasing stock sizes and productivity (Bousquet et al. 2008). The inclusion of process error has previously been shown to decrease the MSY reference points, making them more precautionary and, dependent on the level of process error or non-stationarity in the system, these decreases may be significant (Bousquet et al. 2008, Cadigan 2012). The posterior densities for the MSY-based reference points along with the median and stochastic medians are presented in Figures 25-27.

MSY calculations have been used before by Chaisson and Rowell (1985) to estimate yield for Arctic Surfclams on Banquereau, but these have fallen out of favour as other invertebrate stocks have collapsed when their fisheries were managed at MSY. The MSY is currently used as an upper limit that triggers corrective action if this level is reached. Lower yield levels such as 2/3MSY and $F_{0.1}$ have also been used but with varying success. More conservative equations such as Maximum Constant Yield (MCY) = $xMB0$ (Annala 1993) have been used to set yield levels that are highly probable to remain sustainable at all biomass levels. The “x” in $xMB0$ is often set in the range of 0.2 to 0.3 for fisheries that will have little or no monitoring and so can be very conservative. For inshore Ocean Quahogs in Nova Scotia, a DFO Expert Opinion (DFO 2005) recommended that a constant mortality rate based on the MCY approach be used. An F of $0.33M$, slightly higher than MCY, was recommended in the last assessment, as most Canadian fisheries have some level of monitoring (Roddick et al. 2012). The 2007 Banquereau assessment meeting recommended that with the lack of a time series of data, uncertainties with recruitment levels, and concerns over habitat impacts, that a TAC based on this fishing mortality applied to the most recent fishable biomass estimate was appropriate for Arctic Surfclams on Banquereau (DFO 2007a, b).

In the interim between full assessments of stock biomass, secondary indicators were developed to help identify significant changes in resource status (Roddick 2013). These indicators are derived from fishery dependent data and are used to provide an evaluation of stock status relative to Limit Reference Points (LRPs). The LRPs are based on CPUE, fisheries spatial footprint, stock densities, and the frequency of older clams in catch composition (age structure). Since 2013, annual reports on stock status have been produced using these indicators. All indicators have indicated positive stock status relative to their limit reference points since 2011 (Appendix 1).

Studies documenting the recovery of benthic habitat, sedimentary communities, and target species (*Mactromeris polynyma*) suggest that it could take up to 10 years post-dredging for the communities to recover to a state reflecting undisturbed conditions (Gilkinson et al. 2015). Mirroring this observation, it has been an industry practice to fallow for approximately 10 years post-dredging to allow for re-establishment through recruitment and time to reach sexual maturity estimated between 5 and 9 years in Atlantic Canada. Currently, this decadal lag period is likely the best available estimate of recovery time for the stock until new estimates are available. Though the fisheries footprint provides a spatial index relative to the size of the Bank, it does not consider that the impacts of fishing activity are likely cumulative since Surfclam are sessile and recruitment probably occurs at a decadal time scale (Gilkinson et al. 2015). To account for this cumulative impact, we calculated a cumulative footprint for the fishery as a function of 5 and 10 year time lags. In any year, fisheries footprints generally do not exceed prescribed yearly LRPs (250 km^2 for Banquereau and 125 km^2 for Grand Bank); however, cumulative footprints for both banks have reached 1,750 km^2 (approximately 18% of the estimated 10,110 km^2 size of the bank) but have declined in recent years (Figure 28). Cumulative fisheries footprints have plateaued near the estimated available fished area for Banquereau (based on an estimated fishing area of 1,601 km^2; Table 5), suggesting that estimates of fishable area and a recovery period of 10 years are likely appropriate for this stock.

The biological reference points B_{MSY} and F_{MSY} were used to calculate the default 0.8 and 0.4 B_{MSY} normally used to define the Limit Reference Point (LRP) and Upper Stock Reference (USR). These were compared to the CPUE reference point of 70 g/m^2 from the indicators report by adjusting how 70 g/m^2 would translate into modeled biomass estimates for each area. These levels along with removal reference levels of 0.5 F_{MSY} and 0.33M (0.0264) are shown on the phase plots (Figure 29). The removal reference level of 0.5 F_{MSY} was proposed as an intermediate value between 0.33M, which was developed for a larger less productive stock area, and F_{MSY}, which appears to be overestimated and is greater than any observed F levels.

DISCUSSION

The management of the Arctic Surfclam fishery has traditionally-based TAC and metrics of stock status on entire bank estimates of biomass. Whereas this approach has generally been considered adequate for the fishery, it does not necessarily guarantee sustainability. Estimates of biomass based on entire bank surveys assume that fishing effort will be evenly or randomly distributed across all habitats and densities. However, not all densities are commercially viable and, thus, TACs that integrate across a density spectrum could lead to areas of commercial density being fished down faster than they can be replenished (Hoenig 2015a). The analysis presented in this document seeks to mitigate this issue by estimating biomass for only those areas characterized by fishable densities. Future analyses could further refine this approach by evaluating habitat suitability in areas that have not been fished since 2004. It is important to restrict exploitation in the fished areas to levels that have been determined sustainable for only those areas (i.e., biomass from outside the areas is not considered).

There have been no new fishery-independent surveys since 2010; therefore, fishery-dependent CPUE data are the only source of information related to current stock status. CPUE is also the only information that is available that provides a time series of abundance. For these reasons, CPUE data are relied upon in this assessment despite inherent issues present in commercial catch rate data.

The estimated total biomass for Banquereau from the previous assessment (1,150,585 t in 2010) is the result of extrapolation of the average survey density to the entire bank, and it did not capture much of the associated uncertainties. Expanding average density across all tows to the total area of the bank, without accounting for the uncertainty in the dredge efficiency estimates, leads to considerable underestimate of uncertainty in the overall biomass estimate. By not propagating the errors associated with these processes, uncertainty is not captured in the advice, potentially leading to a false sense of confidence in the estimates of total biomass. The revised assessment approach used here deals with these issues explicitly. In order to address uncertainty in dredge efficiency, it is useful to consider the conservative scenario where $q = 1$ (fished area biomass in 2016: 179,633 t; Table 6). Alternatively, the spatial production model provides a context where the uncertainties in dredge efficiency are captured in the posteriors of the estimated parameters (fished area biomass in 2016: 475,960 t; Table 8).

The stock-recruitment relationship and larval dispersal are the primary determinates of Surfclam distribution given the sedentary nature of adults. Biomass dynamics can be estimated at virtually any scale by dividing the stock by as many areas as desired subject only to limitations in data availability and analytical practicality (e.g., computer speed). The proposed areas used here include contiguous beds that are more likely to exhibit similar dynamics while still satisfying the other criteria mentioned above and in the Spatial Assessment Areas section.

The MSY-based reference points presented in Figures 25-27 are calculated from the estimates of r and K from the spatial production model. There is potential for these parameters to be confounded in surplus production models and this should be considered in the interpretation of the reference points. A scenario where the population growth rate, r, is estimated high and the carrying capacity, K, is estimated low gives the model more flexibility in fitting the data but could provide overly optimistic reference points (higher F_{MSY} and lower B_{MSY}).

SOURCES OF UNCERTAINTY

This section is meant to capture uncertainties that are not already accounted for in the analysis. The time lag in relating catch and the associated effort introduces some noise to the fishery data, as some portions of the catch reported in the log should be attributed to the effort of the previous watch. Dredge efficiency estimates are known to be highly variable and contribute to significant uncertainty when used to extrapolate total biomass from the survey. The dredge efficiency estimates from the spatial production model were similar, and similarly variable, to previous estimates. Increasing investment in technologies aimed at improving efficiency has likely resulted in the CPUE index remaining high as beds are depleted (e.g., hyperstability). The commercial CPUE is the main data source for this analysis, so it is important to consider this uncertainty when setting catch limits for these areas.

CONCLUSIONS AND ADVICE

A qualitative risk assessment is meant to consider the risks of various assessment and management strategies. Here we consider the risks of high F (MSY), medium F (0.5_{MSY}) and low F (0.33M) management strategies and whether they are applied to biomass estimates based on only the fished areas versus the total bank area.

F level	**Fished Area**	**Total Area**
High (approximately 0.1)	High	Extreme
Medium (approximately 0.05)	Medium	Very High
Low (approximately 0.025)	Low	High

Fishing strategies based on estimated biomass of the whole bank are more risky than estimated biomass for just the fished areas because there is less information available for the areas that have not previously supported fisheries. Using biomass estimates and dredge efficiency estimates from the production model is more risky than assuming $q = 1$, but it also permits the uncertainties and risks to be quantified.

Maximum sustainable yield (MSY) reference points were calculated from the surplus production model with F_{MSY} estimates near 0.09; however, phase plots (Figure 29) indicate that catch rates tend to decline when F is greater than 0.05. Despite how the spatial assessment areas are divided, there is considerably more risk associated with setting TAC recommendations based on biomass estimates that result from areal expansion to areas that have not previously been fished. In addition, exploitation rates near the estimates of F_{MSY} are more risky than alternative F reference levels that are below F_{MSY}.

The Banquereau Arctic Surfclams stock is healthy, as the median modelled biomass estimates are above all of the biomass reference levels (LRP, USR, $CPUE_{70}$) for all the areas (Figure 24). However, the CPUE indicates biomass has decreased since the last assessment in 2010 especially in Area 5 (Figure 24). It is recommended that potential harvest levels be applied to only the identified fished areas as these are the only areas where we have recent information to base advice. Of the three potential F removal references, F_{MSY} is considered high risk since declines in CPUE were observed under F levels that were significantly lower. The medium risk F level would result in TACs that are comparable to the current TAC, while the low risk F level would result in much lower TACs when it is applied to the fished area biomasses (Figure 30).

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TABLES

Table 1. Landings (tonnes) for the offshore Arctic Surfclam fishery in Atlantic Canada by year landed.

Year Landed	Grand Bank	Banquereau	Scotian Shelf	Total
1987	0	883	0	883
1988	0	2,929	0	2,929
1989	1,485	8,565	0	10,050
1990	10,501	5,673	686	16,859
1991	7,162	684	0	7,845
1992	11,609	0	0	11,609
1993	19,871	56	0	19,927
1994	15,879	4,590	0	20,468
1995	13,465	10,256	9	23,731
1996	6,459	18,913	12	25,384
1997	7,406	19,695	7	27,107
1998	958	24,712	5	25,676
1999	1,487	24,949	0	26,436
2000	3,246	20,715	0	23,961
2001	8,389	11,375	0	19,765
2002	6,928	12,559	10	19,497
2003	10,150	16,295	0	26,445
2004	6,331	16,855	0	23,187
2005	4,006	14,414	0	18,420
2006	5,156	15,877	0	21,033
2007	217	17,982	0	18,198
2008	10	19,326	0	19,336
2009	127	24,565	0	24,692
2010	287	22,558	0	22,845
2011	76	22,140	0	22,216
2012	0	21,228	0	21,228
2013	268	19,663	0	19,931
2014	0	20,258	3	20,260
2015	0	24,430	0	24,430
2016	14,350	22,328	7	36,685

Note: Discard data and any Arctic Surfclam caught as bycatch from inshore fisheries are not included. Data for the years 2014-2016 are preliminary and, as such, may be incomplete and/or subject to change without notice. Data sources: Commercial Data Division, Policy and Economics Branch, Maritimes Region, and Newfoundland Region.

Table 2. Estimated catch, effort, and catch per unit effort (CPUE) for Banquereau and Grand Bank from logbook records. Hyphen denotes value not calculated.

	Grand Bank			**Banquereau**		
Year Caught	**Catch (t)**	**Effort (km^2)**	**CPUE (g/m^2)**	**Catch (t)**	**Effort (km^2)**	**CPUE (g/m^2)**
1986	34	-	-	29	0.841	34.96
1987	1	0.052	10.18	1,210	16.090	75.22
1988	5	-	-	2,474	24.533	100.85
1989	373	3.369	110.79	9,159	84.935	107.84
1990	6,049	23.645	255.84	6,158	68.198	90.29
1991	2,094	11.339	184.69	714	9.702	73.59
1992	5,161	27.083	190.57	0	-	-
1993	13,100	92.840	141.10	64	2.174	29.36
1994	10,979	95.229	115.29	5,313	39.800	133.48
1995	14,907	128.366	116.13	11,425	84.102	135.85
1996	5,772	53.564	107.76	19,262	156.394	123.17
1997	7,492	79.979	93.67	19,517	157.164	124.18
1998	931	11.370	81.86	24,456	237.333	103.05
1999	1,472	18.599	79.16	24,138	254.184	94.96
2000	3,289	45.954	71.57	20,248	233.277	86.80
2001	8,026	110.382	72.71	11,014	158.942	69.30
2002	6,077	120.271	50.53	12,506	148.990	83.94
2003	8,727	120.985	72.13	16,960	147.036	115.34
2004	6,437	66.867	96.26	16,493	149.498	110.32
2005	3,967	51.762	76.65	14,327	141.499	101.25
2006	4,990	75.200	66.36	15,932	116.700	136.52
2007	215	7.480	28.78	17,931	115.435	155.33
2008	0	-	-	19,301	130.580	147.81
2009	437	7.520	58.15	24,158	180.48	133.85
2010	296	9.322	31.77	22,558	160.258	140.76
2011	112	9.015	12.37	20,858	130.991	159.23
2012	0	-	-	20,214	135.92	148.72
2013	199	6.065	32.85	19,270	149.874	128.58
2014	0	-	-	23,640	200.918	117.66
2015	730	7.546	96.76	23,287	241.993	96.23
2016	13,560	95.414	142.12	24,154	220.065	109.76

Table 3. International Observer Program (IOP) data on species caught for the Arctic Surfclam fishery by year for Banquereau (2012-2015) and Grand Bank (2016). Hyphen denotes species not present.

Species	**Banquereau**				**Grand Bank**	**Total (kg)**
	2012	**2013**	**2014**	**2015**	**2016**	
Arctic Surfclam	1,659,254	1,626,283	1,087,833	1,924,209	1,219,836	7,517,415
Northern Propeller Clam	421,955	467,940	51,458	183,973	1,085	1,126,411
Sand Dollars (NS)	312,802	360,892	89,540	209,925	-	973,159
Shells	81,212	364,802	98,105	259,781	-	803,900
Stone	170,208	129,391	174,375	259,986	-	733,960
Greenland Smoothcockle	97,204	110,118	4,930	10,392	47,590	270,234
Whelk	15,508	27,533	13,090	16,079	1,085	73,295
Sea Cucumber (*C. frondosa*)	650	337	11,565	5,185	-	17,737
Sea Cucumber (NS)	122	4,388	-	2,197	16,120	22,827
Sea Cucumber (*P. fabricii*)	-	1	7	-	-	8
Sea Urchin (NS)	2,465	2,090	6,715	1,961	-	13,231
Ocean Quahog	3,539	1,153	97	3,928	1,635	10,352
Sea Stars (NS)	1,702	1,344	4,380	2,563	-	9,989
Sand	5,953	432	-	-	-	6,385
Annelid (Segmented Worms)	201	-	-	5,514	-	5,715
Hermit Crab (NS)	1,216	1,686	1,243	1,534	-	5,679
Bristle Worms	731	4,294	-	-	-	5,025
Mussels (NS)	-	571	234	1,789	30	2,624
Blue Mussel	390	-	-	-	-	390
Snow Crab or Queen Crab	842	959	135	487	-	2,423
Sand Lances (NS)	1,179	-	622	506	-	2,307
Yellowtail Flounder	862	921	4	26	-	1,813
Skates (NS)	753	828	-	-	-	1,581
Scallop (NS)	-	1,264	-	180	-	1,444
Iceland Scallop	145	332	235	181	-	893
Sea Scallop	63	48	257	140	-	508
Thorny Skate	128	37	688	520	-	1,373
Toad Crab (NS)	315	793	86	130	-	1,324
Longhorn Sculpin	115	440	182	109	-	846
American Plaice	291	276	1	10	-	578
Smooth Skate	-	-	134	95	-	229
Sea Anemone	-	-	-	161	-	161
Sponges	14	57	-	57	-	128
Brittle Stars	59	-	-	-	-	59
Moonsnail	27	-	-	-	-	27
Winter Skate	-	-	-	23	-	23
Cancer Crab	-	-	-	16	-	16
Soft Coral	-	7	-	-	-	7
Clam (NS)	6	-	-	-	-	6
Sea Raven	-	5	-	-	-	5
Witch Flounder	-	-	-	4	-	4
Silver Hake	-	-	1	2	-	3
Atlantic Cod	-	-	2	-	-	2
Total Weight Observed (kg)	2,779,911	3,109,222	1,545,919	2,891,663	1,287,381	11,614,096

Table 4. Sensitivity analysis of area fished to Vessel Monitoring System (VMS) threshold (number of pings per km^2 since 2004).

VMS Threshold	Fished Area (km^2)
10	2,255
15	2,033
20	1,867
25	1,727
30	1,601
35	1,481
40	1,367
45	1,259
50	1,159

Table 5. Total area, fished area (area of commercial viable clam habitat as defined by the Vessel Monitoring System (VMS) density), mean annual catch, and total catch since 2004 for the five spatial assessment areas on Banquereau (see Figure 17). Biomass estimates using the 2010 survey data expanded to the total area (entire Bank), 2010 survey data expanded to the fished area, and catch per unit effort (CPUE, g/m^2) expanded to the fished area for 2010 and 2016 are listed.

Area ID	Total Area (km^2)	Fished Area (km^2)	Mean Aannual Catch (t)	Total Catch Since 2004 (t)	Biomass Estimates (t)			
					2010 Survey Total Area	2010 Survey Fished Area	2010 CPUE Fished Area	2016 CPUE Fished Srea
1	3,008	315	3,510	45,628	192,448	24,934	56,127	32,888
2	2,008	436	5,221	67,879	182,519	43,281	55,914	48,582
3	3,251	442	4,081	53,054	338,452	75,693	49,354	52,571
4	1,555	220	2,406	31,281	31,892	10,509	24,703	20,092
5	2,078	189	4,945	64,280	138,773	56,719	32,163	25,500
Total	11,900	1,601	20,163	262,122	884,085	211,136	218,262	179,634

Table 6. Biomass estimates (tonnes) from catch per unit effort data expanded to the fished area for the five spatial assessment areas on Banquereau (see Figure 17).

Year	Area 1	Area 2	Area 3	Area 4	Area 5	Total
2004	42,721	30,405	48,455	22,354	23,082	167,018
2005	31,269	39,786	46,337	25,363	50,853	193,608
2006	40,587	37,030	54,144	28,662	43,438	203,861
2007	35,467	57,431	60,400	31,185	42,666	227,150
2008	42,492	61,142	49,657	32,698	42,533	228,523
2009	37,728	45,084	54,281	29,043	31,868	198,003
2010	56,127	55,914	49,354	24,703	32,163	218,262
2011	44,850	59,094	66,947	39,419	36,191	246,500
2012	36,332	57,088	60,280	31,472	37,949	223,121
2013	44,056	42,641	62,062	26,989	26,193	201,940
2014	34,571	55,034	47,538	25,443	23,673	186,259
2015	24,447	41,505	31,827	18,611	22,420	138,811
2016	32,888	48,582	52,571	20,092	25,500	179,634
Mean	38,733	48,518	52,604	27,387	33,733	200,976

Table 7. Catch (tonnes) in the five spatial assessment areas on Banquereau (see Figure 17).

Year	Area 1	Area 2	Area 3	Area 4	Area 5	Total
2004	6,245	1,683	8,023	521	20	16,493
2005	3,943	3,584	3,320	3,456	24	14,327
2006	1,490	1,615	7,089	729	5,009	15,932
2007	556	3,511	5,764	1,645	6,455	17,931
2008	863	3,709	6,084	2,369	6,275	19,301
2009	1,837	2,561	8,110	2,730	8,920	24,158
2010	2,664	9,574	2,682	393	7,245	22,558
2011	4,399	3,953	3,326	5,101	4,079	20,858
2012	2,973	4,416	1,333	6,771	4,720	20,214
2013	6,213	1,766	865	5,535	4,891	19,270
2014	7,744	11,395	230	787	3,483	23,640
2015	2,896	7,230	1,766	519	10,876	23,287
2016	3,804	12,880	4,461	724	2,284	24,154
Mean	3,510	5,221	4,081	2,406	4,945	20,163

Table 8. Biomass estimates (tonnes) from the spatial production model in the five spatial assessment areas on Banquereau (see Figure 17).

Year	Area 1	Area 2	Area 3	Area 4	Area 5	Total
2004	101,906	108,162	132,004	57,748	68,944	468,764
2005	94,156	120,234	133,667	65,154	102,188	515,399
2006	99,963	126,972	146,879	70,014	114,286	558,114
2007	100,916	154,261	152,079	75,808	114,622	597,686
2008	108,695	162,739	146,549	77,816	110,362	606,161
2009	111,659	153,923	148,978	75,040	99,774	589,374
2010	123,966	164,725	147,533	72,839	94,772	603,835
2011	116,653	164,424	162,810	83,547	95,132	622,566
2012	105,688	160,248	160,312	76,792	93,167	596,207
2013	105,230	145,994	154,263	67,725	80,173	553,385
2014	91,811	152,498	134,693	60,144	72,519	511,665
2015	78,023	137,511	117,572	54,002	70,552	457,660
2016	84,091	139,978	132,869	54,377	64,632	475,947
Mean	101,751	145,513	143,862	68,539	90,856	550,520

FIGURES

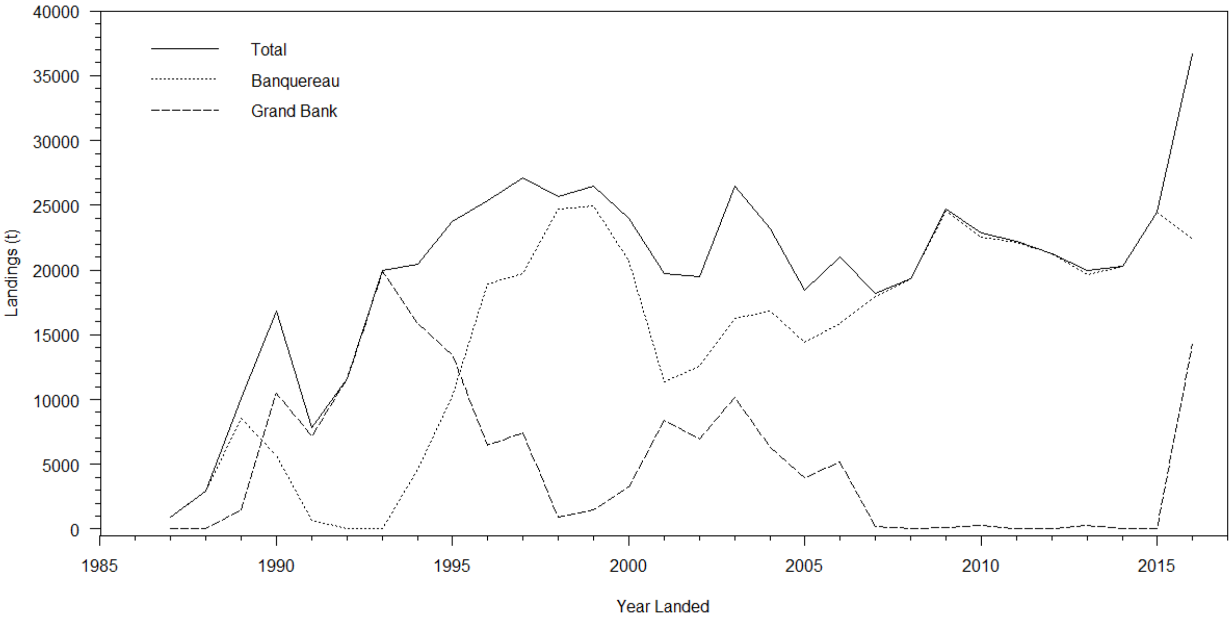


Figure 1. Landings (tonnes) of Arctic Surfclams from the Banquereau and Grand Bank fisheries.

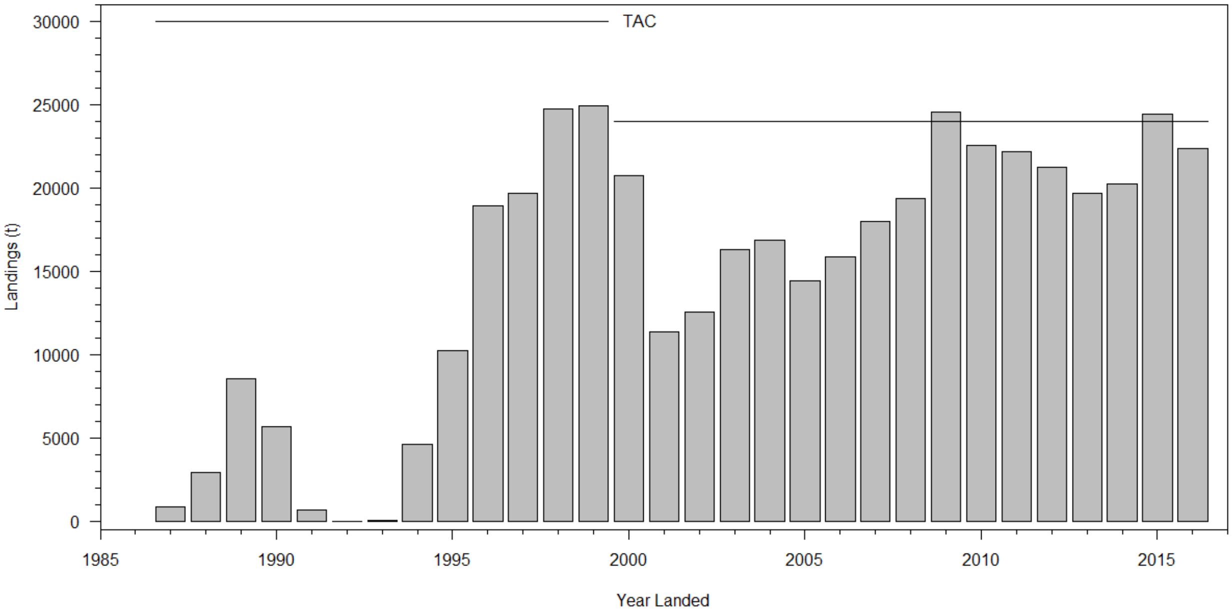


Figure 2. Landings (tonnes) and total allowable catch (TAC; tonnes) for the Banquereau Arctic Surfclam fishery.

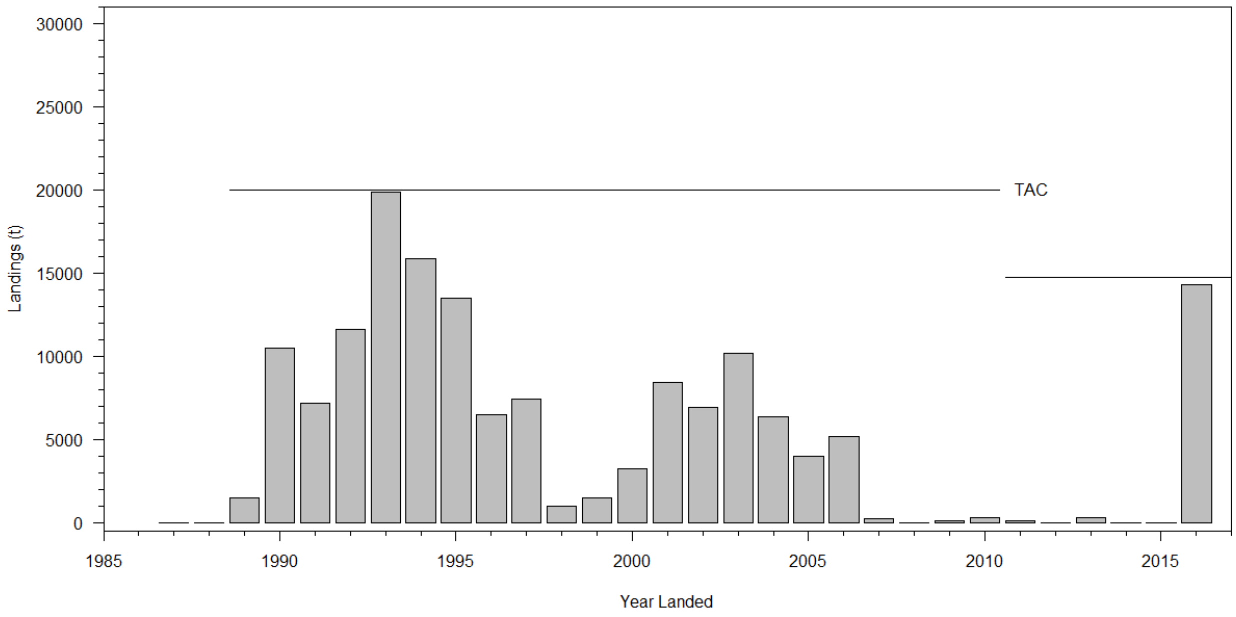


Figure 3. Landings (tonnes) and total allowable catch (TAC; tonnes) for the Grand Bank Arctic Surfclam fishery.

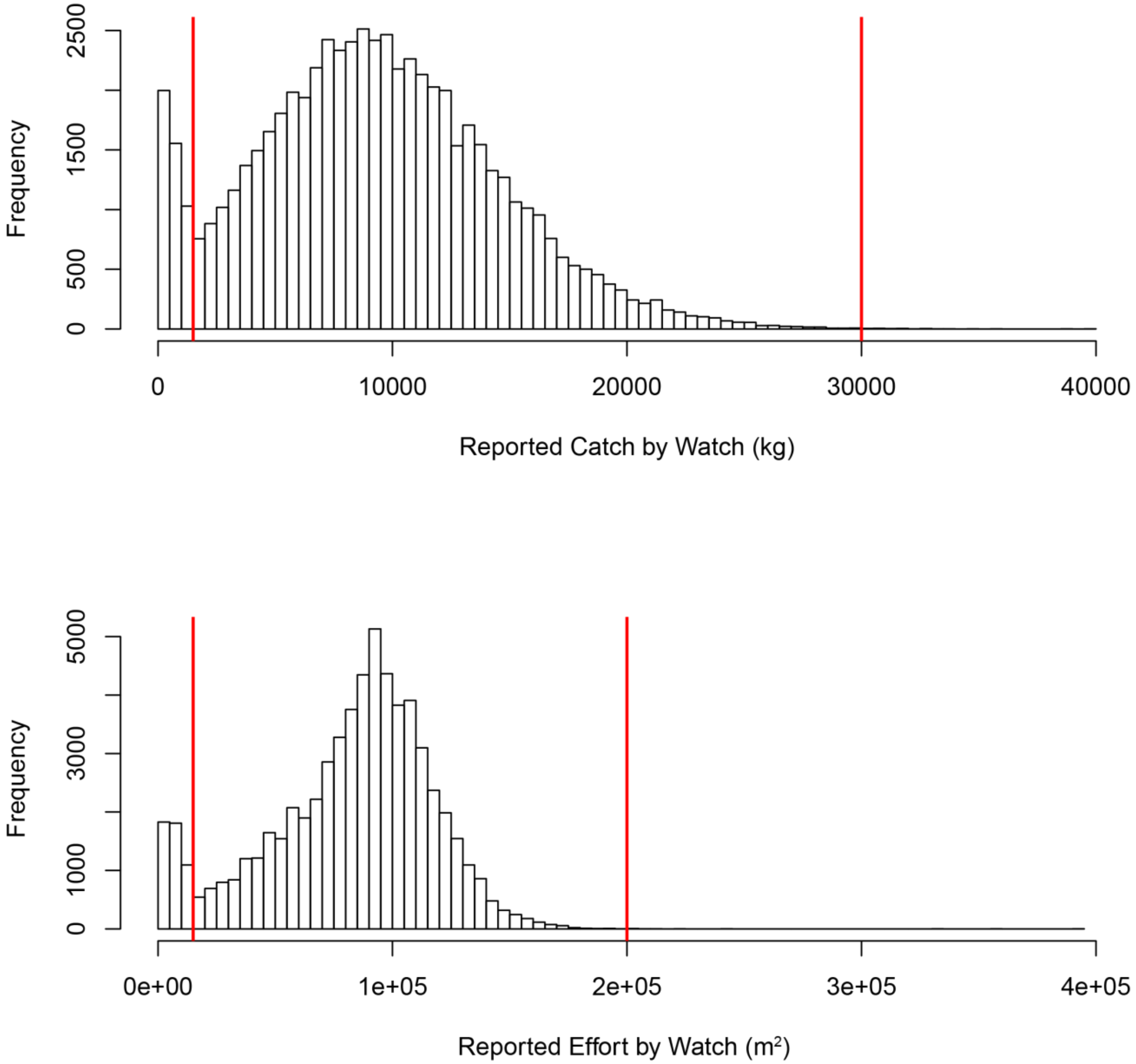


Figure 4. Distribution of catch (kg) and effort (m^2) data by watch from the log records for 2004 through 2016. Red lines indicate where data were censored for catch per unit effort (CPUE) analysis.

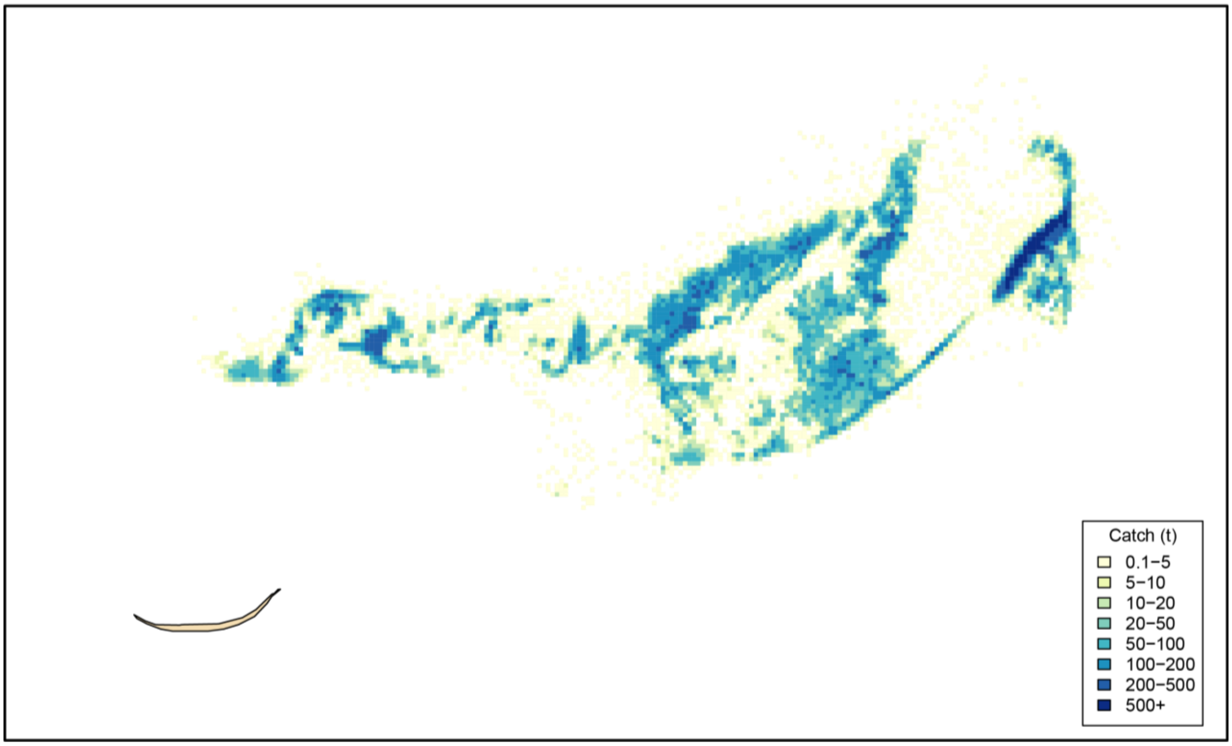


Figure 5. Distribution of Arctic Surfclam catches (tonnes) from logbook and Vessel Monitoring System (VMS) data for Banquereau. Catch is aggregated by 1 km x 1 km cells for 2004 through 2016.

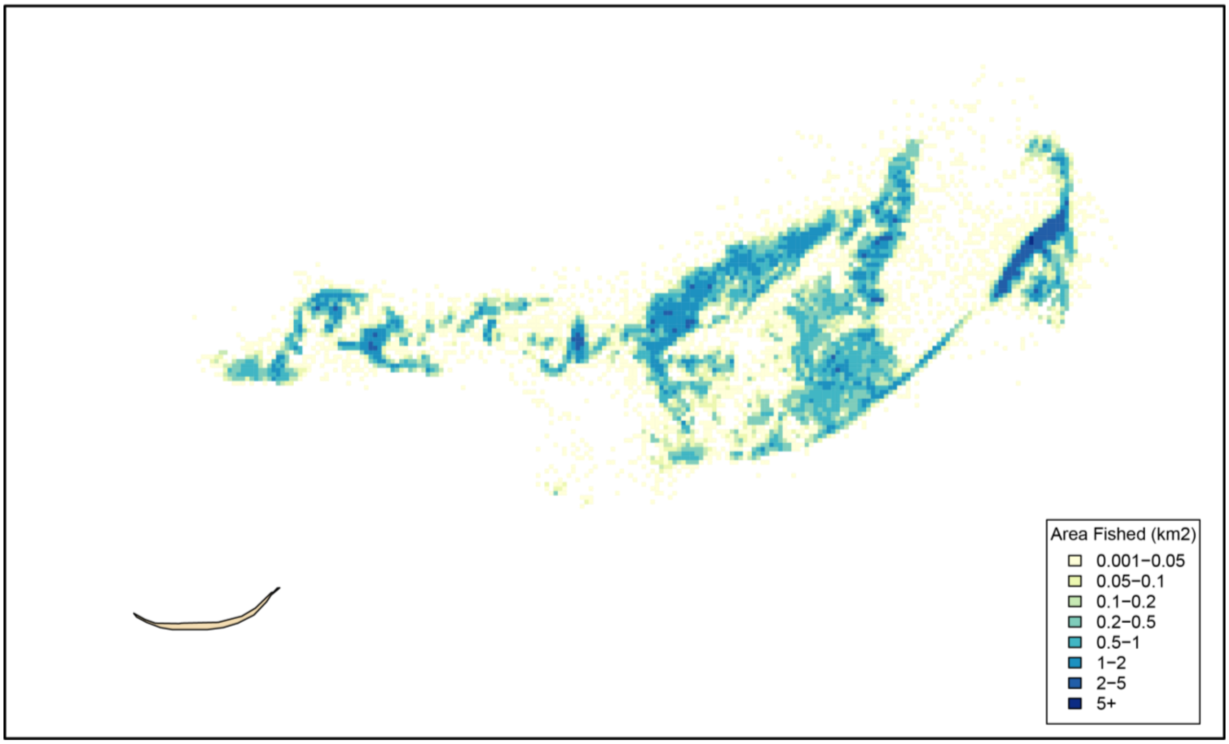


Figure 6. Distribution of Arctic Surfclam effort (km2) from logbook and VMS data for Banquereau. Effort is aggregated by 1 km x 1 km cells for 2004 through 2016.

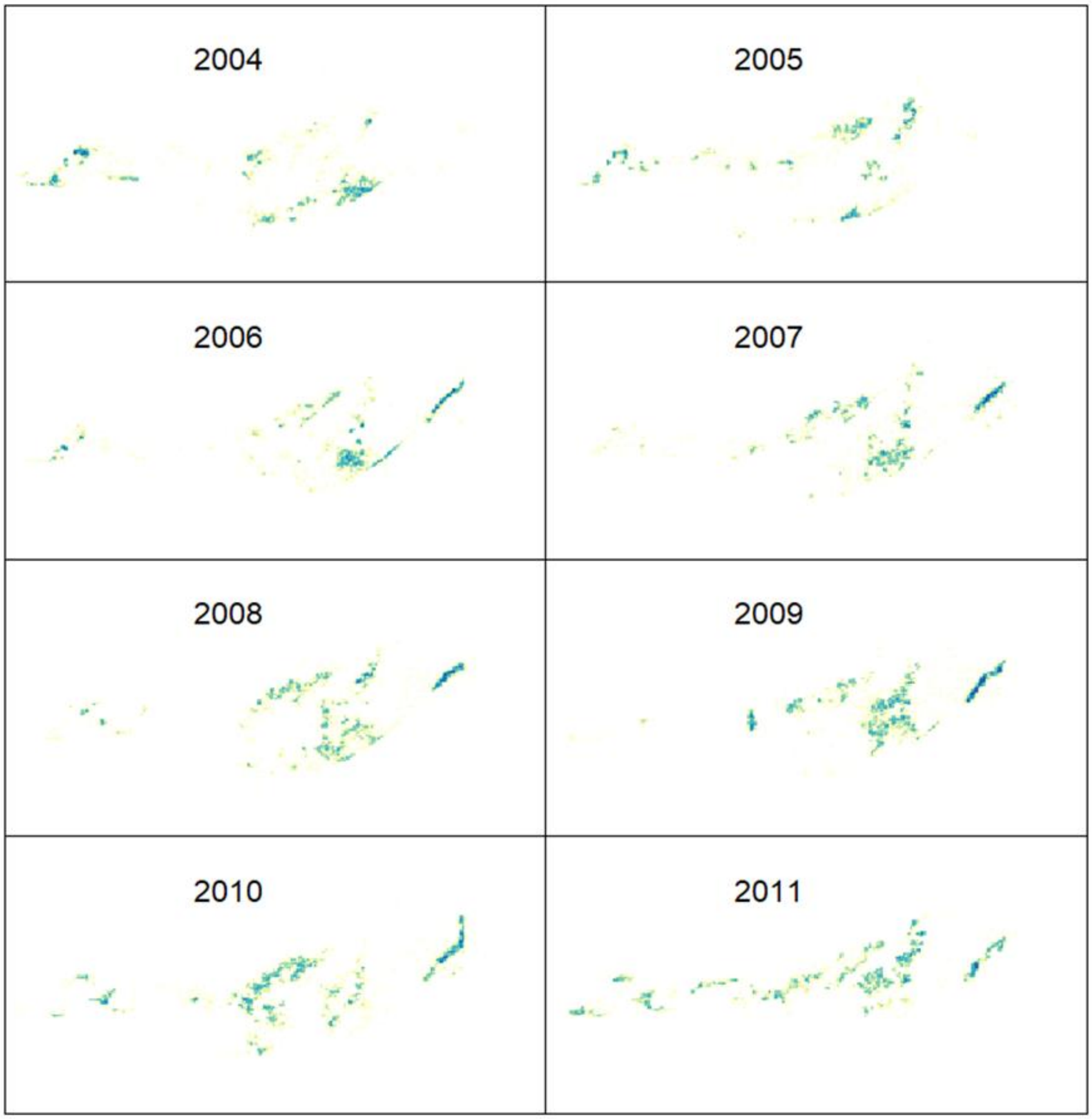


Figure 7. Annual distribution of Arctic Surfclam effort (km^2) from logbook and Vessel Monitoring System (VMS) data for Banquereau. Catch is aggregated by 1 km x 1 km cells. Example years from 2004 through 2011 are shown.

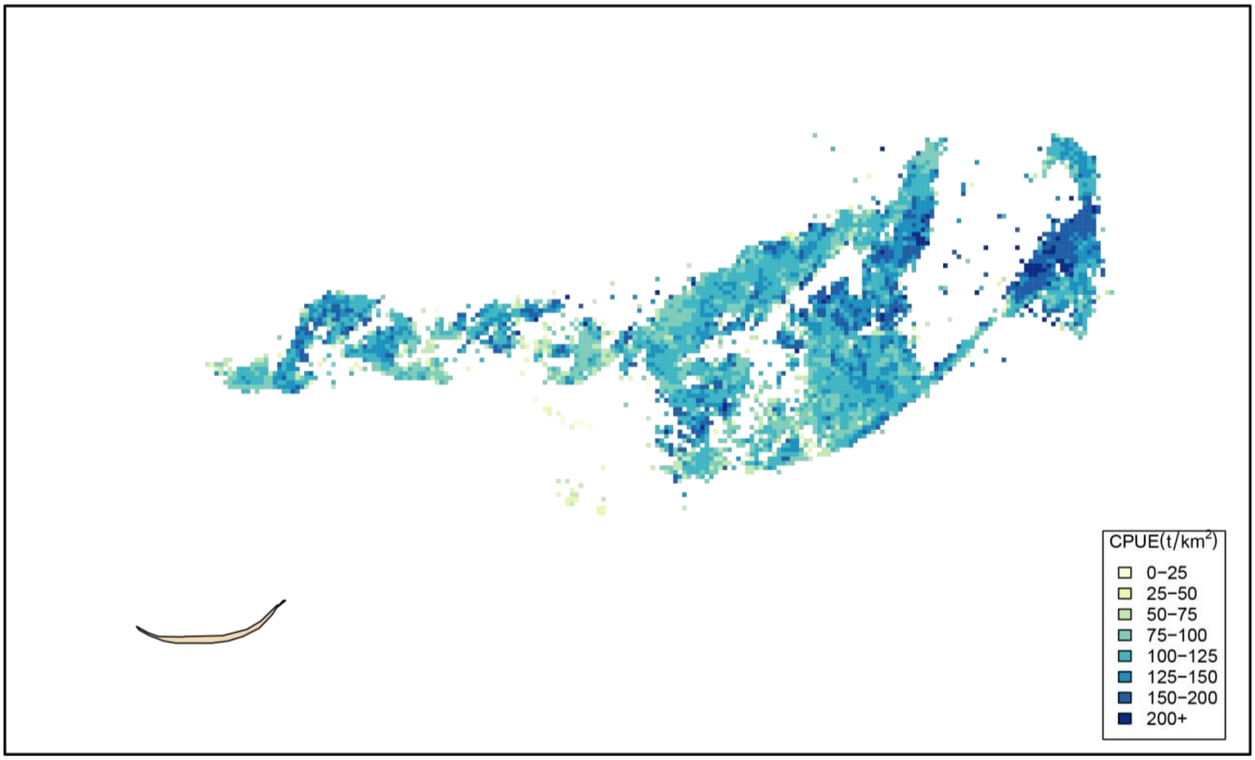


Figure 8. Distribution of Arctic Surfclam catch per unit effort (CPUE; t/km^2) from logbook and Vessel Monitoring System (VMS) data for Banquereau. Catch is aggregated by 1 km x 1 km cells for 2004 through 2016.

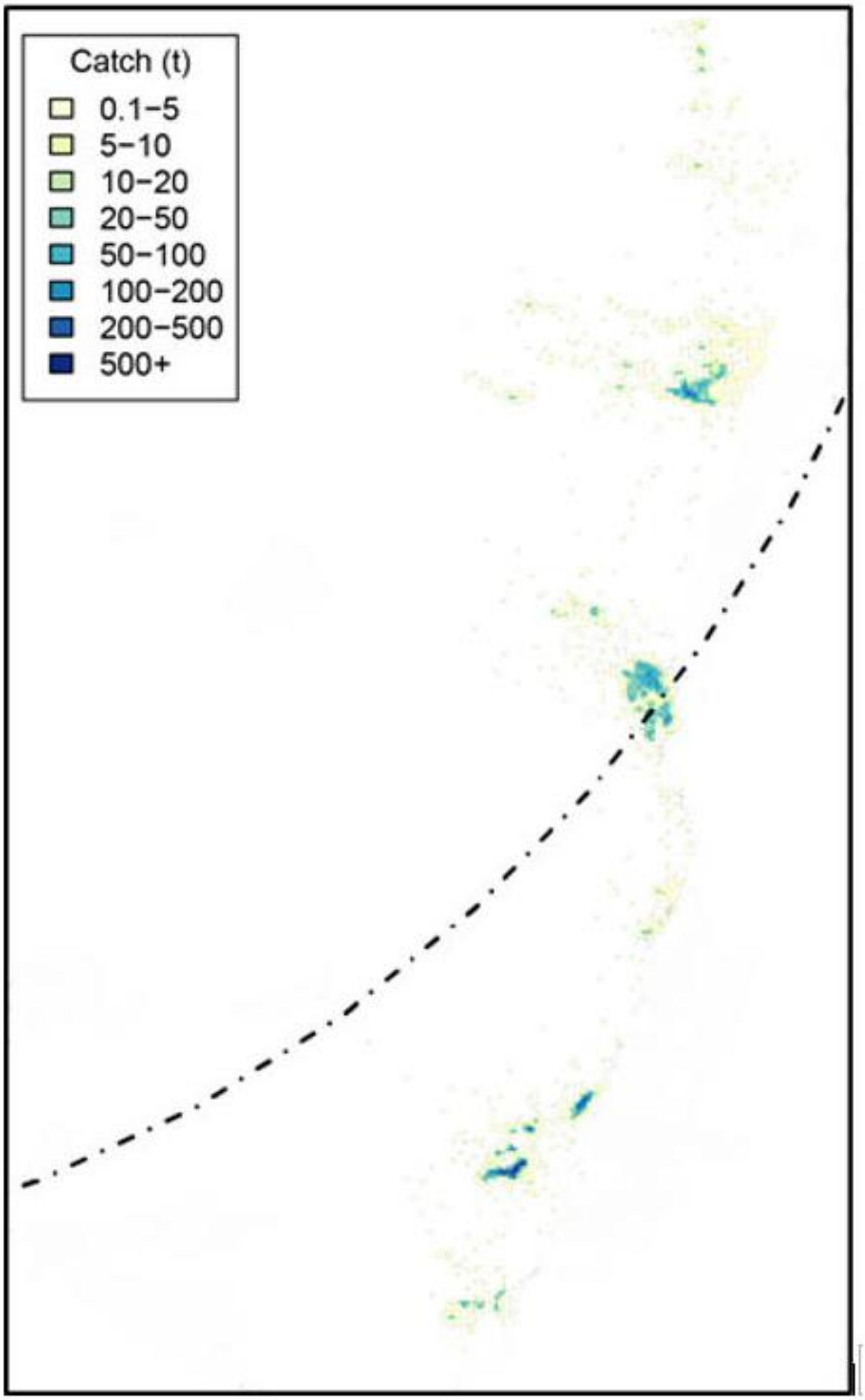


Figure 9. Distribution of Arctic Surfclam catches (tonnes) from logbook and Vessel Monitoring System (VMS) data for Grand Bank. Catch is aggregated by 1 km x 1 km cells for 2004 through 2016. The dashed line denotes the boundary for Canada's Exclusive Economic Zone.

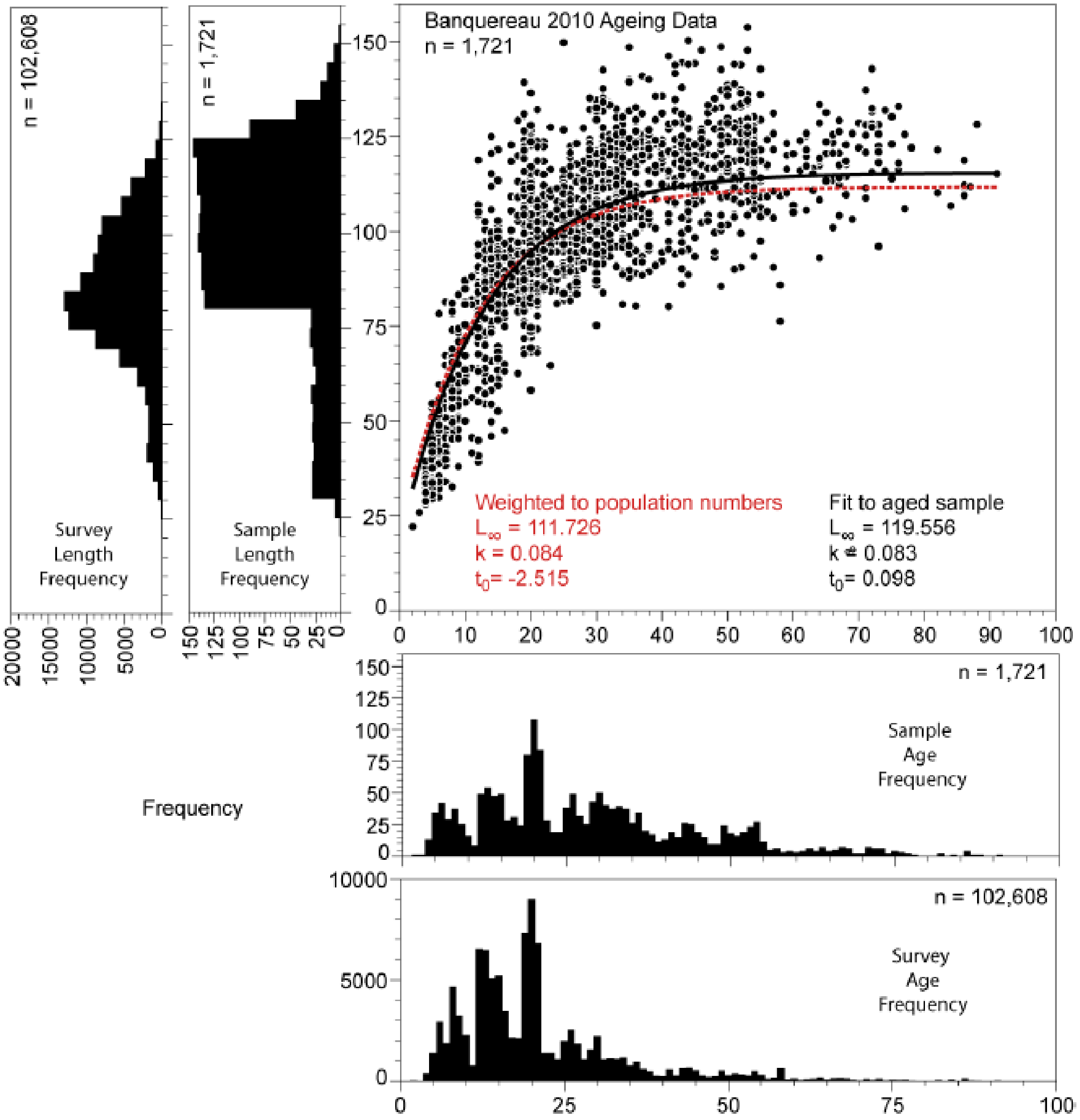
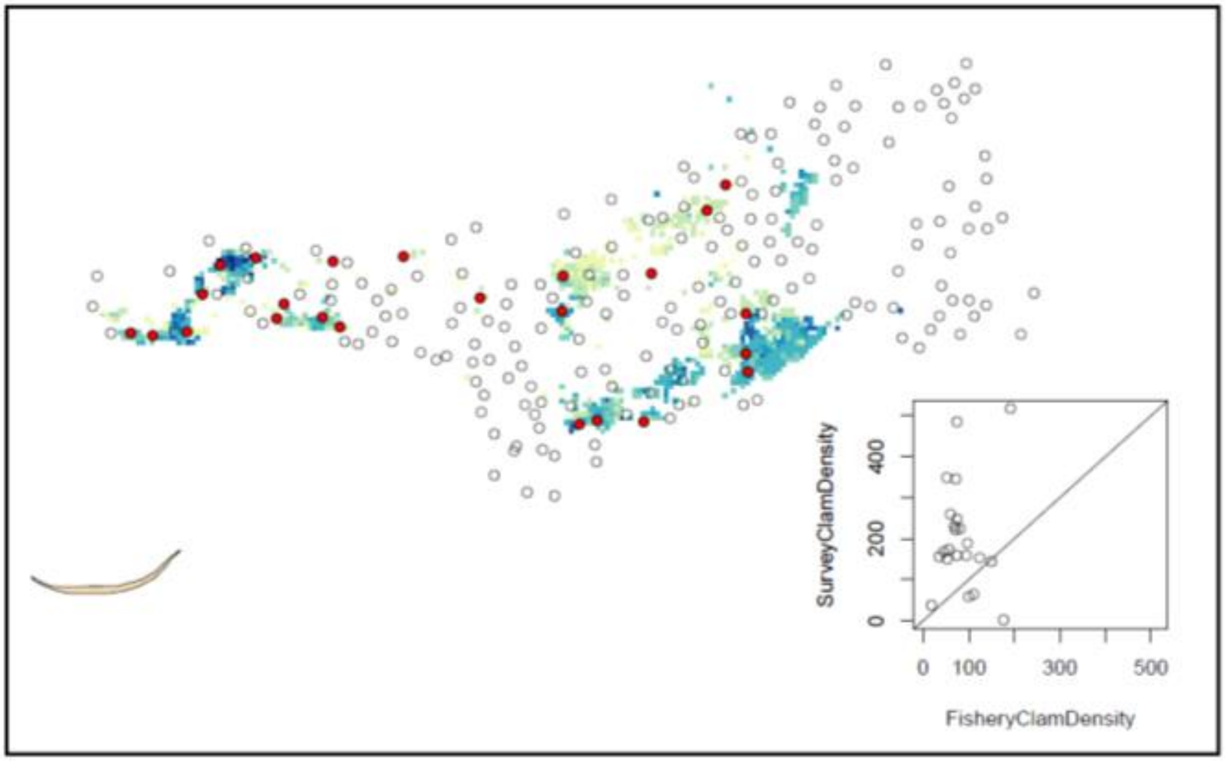


Figure 10. Survey and sample length frequency, ageing results and sample and estimated survey age frequency results from the ageing of a random sample of 1,721 Arctic Surfclams from the 2010 Banquereau offshore clam survey. (Reproduced from Roddick et al. 2012.)



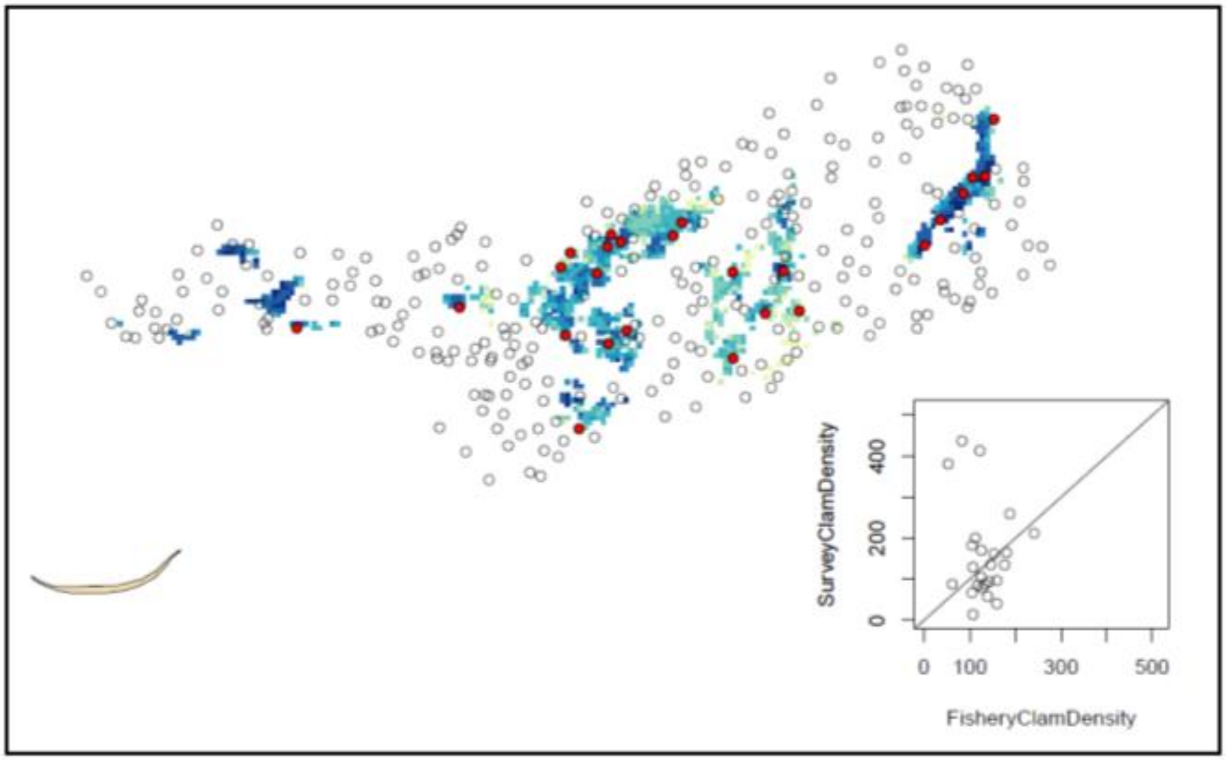


Figure 11. Comparison of survey station locations for the 2010 Banquereau Arctic Surfclam survey and fishery catch per unit effort (CPUE; g/m^2) for 2004 (top) and 2010 (bottom). Circles represent survey stations and the red circles showing locations of overlap between the survey and fishery effort. Density estimates from these locations are included in the inset plot of clam density estimated from the fishery versus density estimated from the survey.

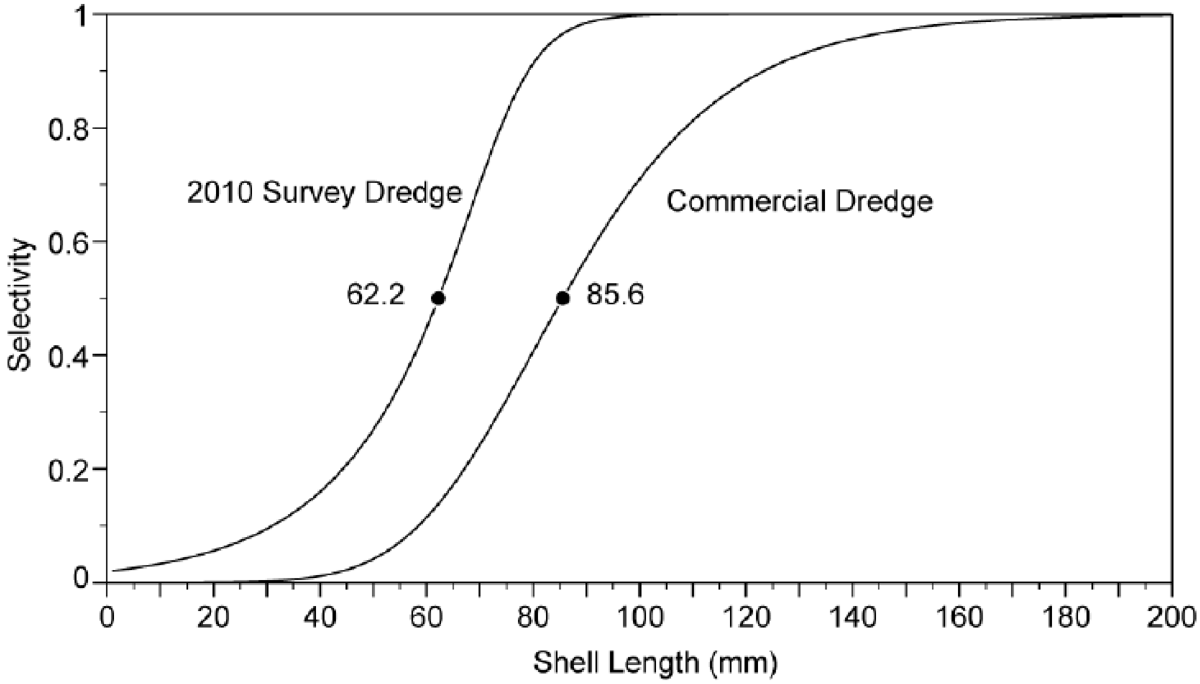


Figure 12. Selectivity curves for the 2010 survey dredge and commercial clam dredge. Sizes at 50% retention are shown (Roddick et al. 2012).

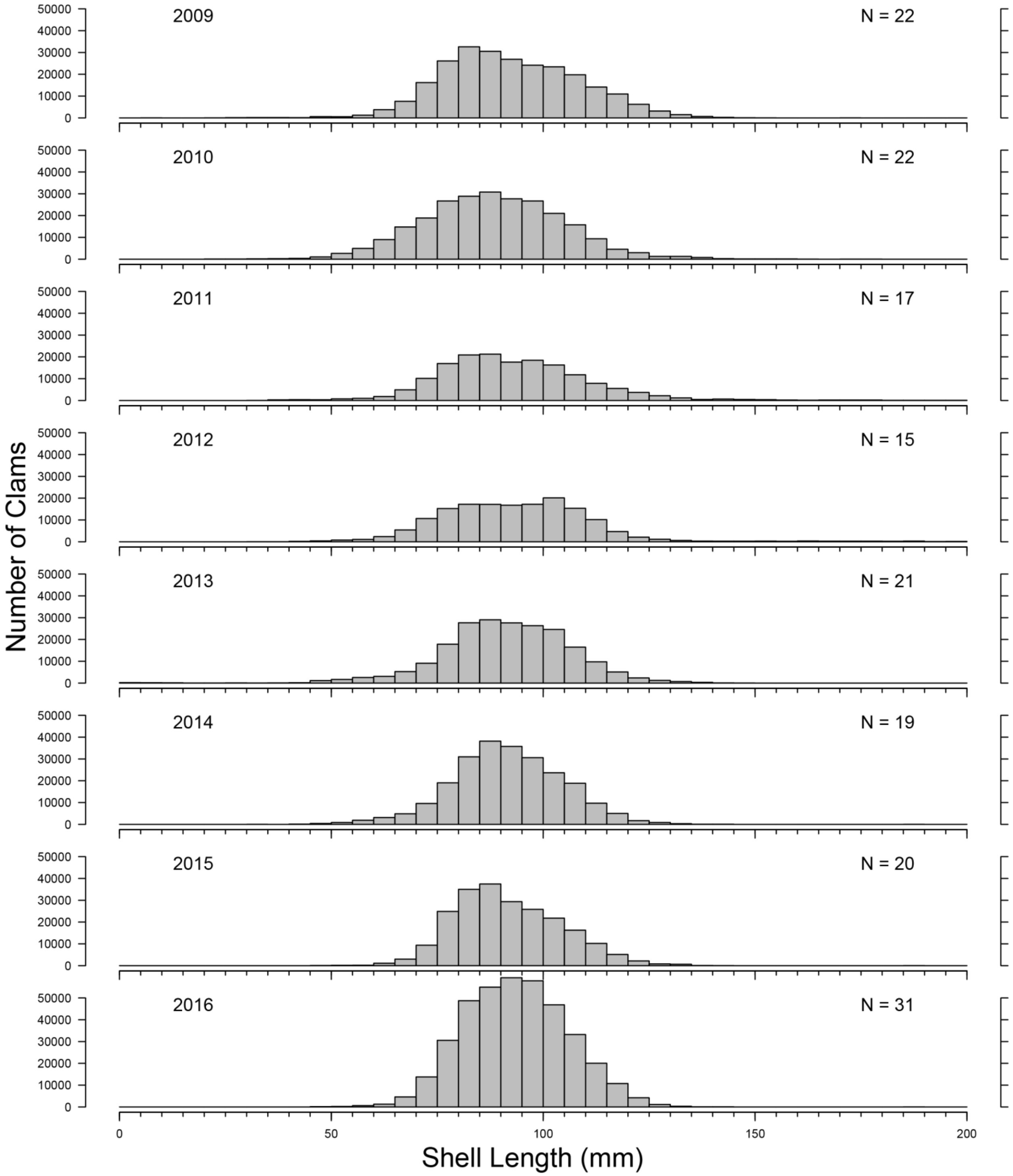


Figure 13. Length frequency distributions for Arctic Surfclams caught in the commercial fishery for 2009 through 2016.

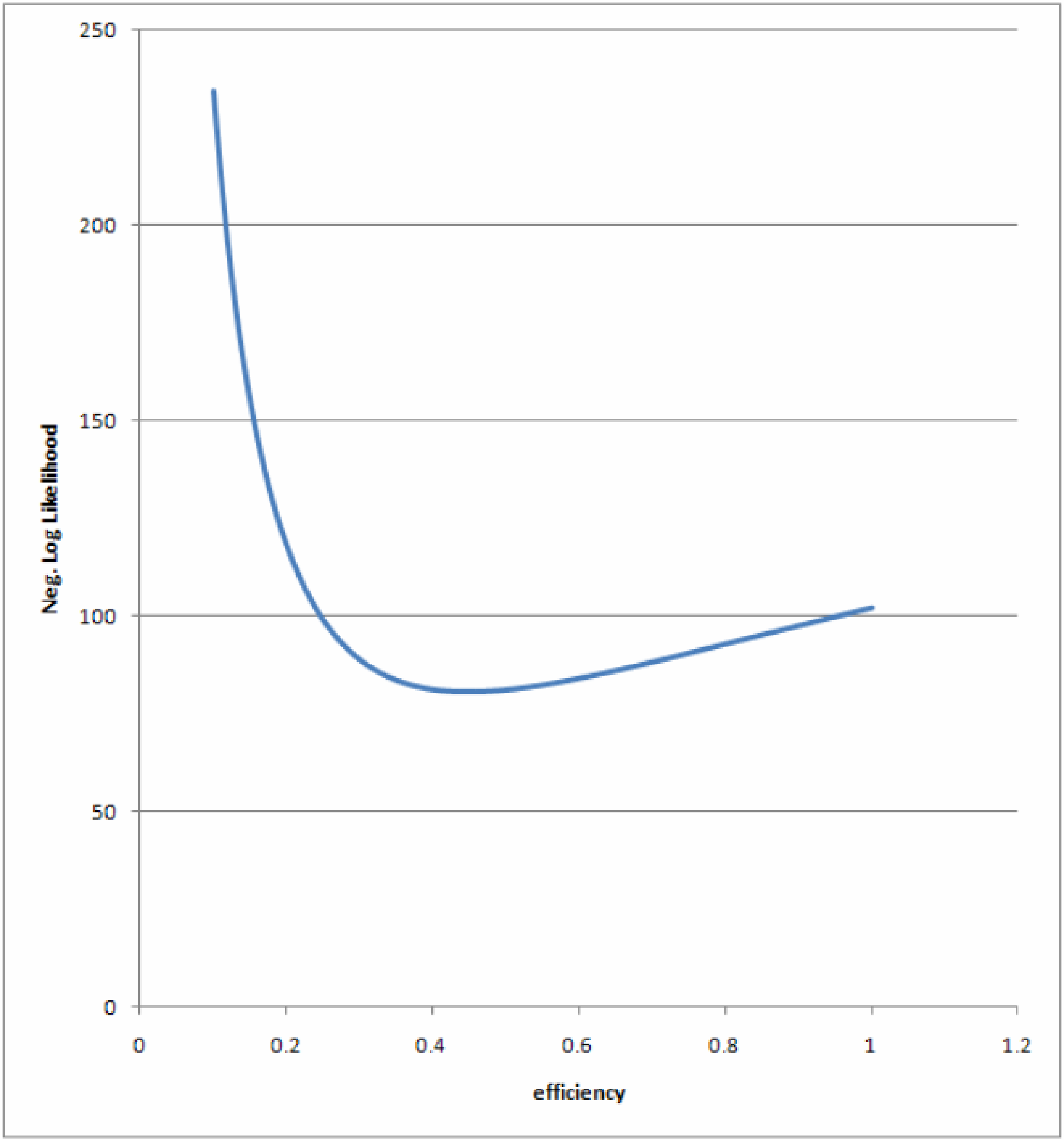


Figure 14. Likelihood profile for estimate of dredge efficiency from patch model. (Reproduced from Roddick et al. 2012.)

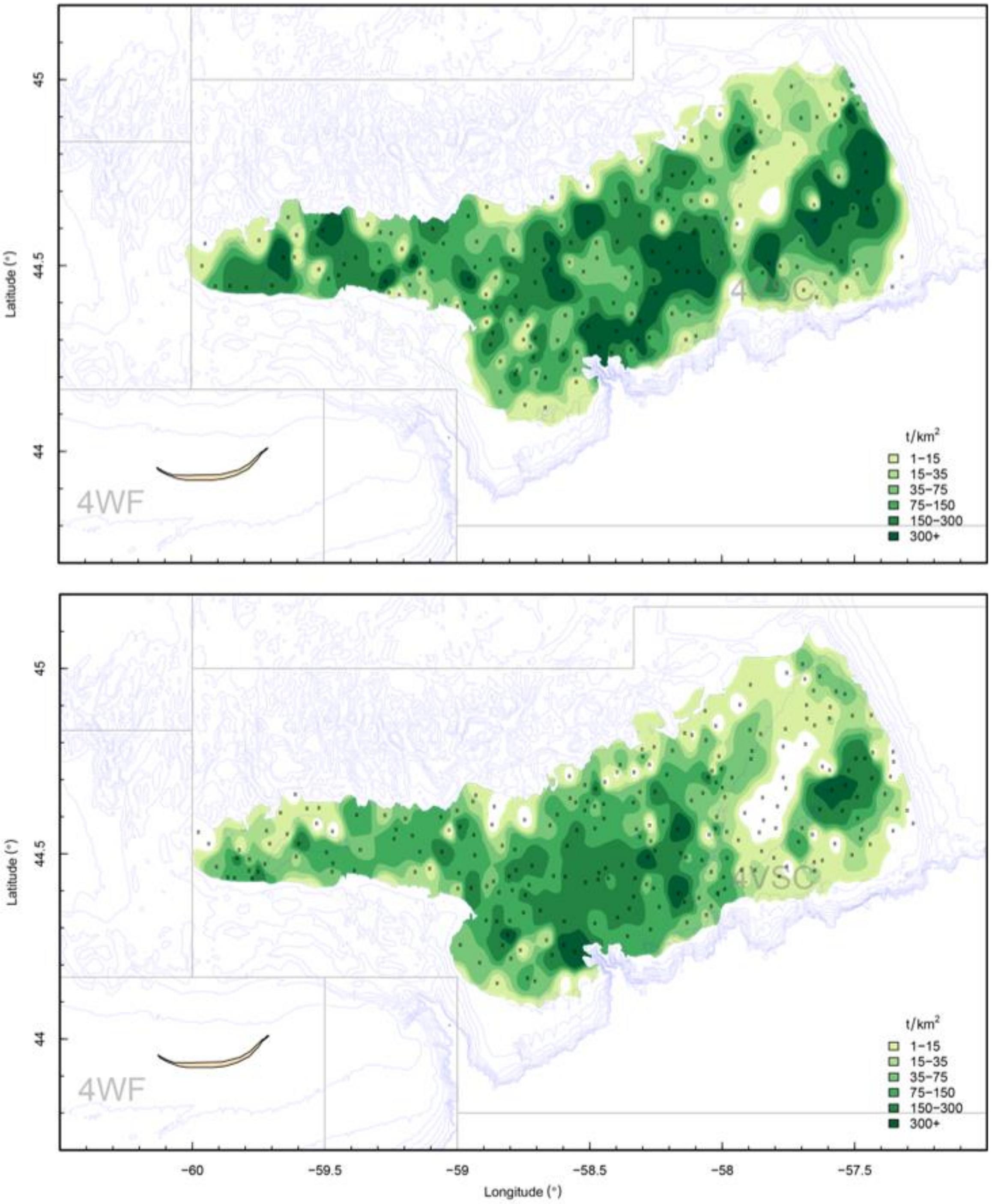


Figure 15. Contour plot of the estimated biomass density of Arctic Surfclam (tonnes/km^2) from the 2004 (upper panel) and 2010 (lower panel) Banquereau offshore survey.

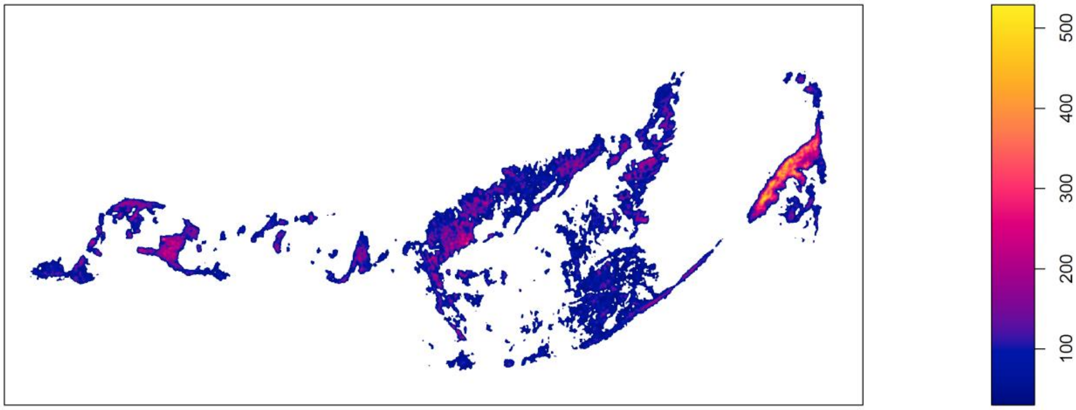


Figure 16. Vessel Monitoring System (VMS) density estimated from a kernel smoothed intensity function with a standard deviation of 0.2 on a 100 m^2 resolution. The scale bar shows VMS intensity expressed as the number of transmissions per km^2 for 2004-2016. The colored region shows the area where VMS intensity is greater than 30.

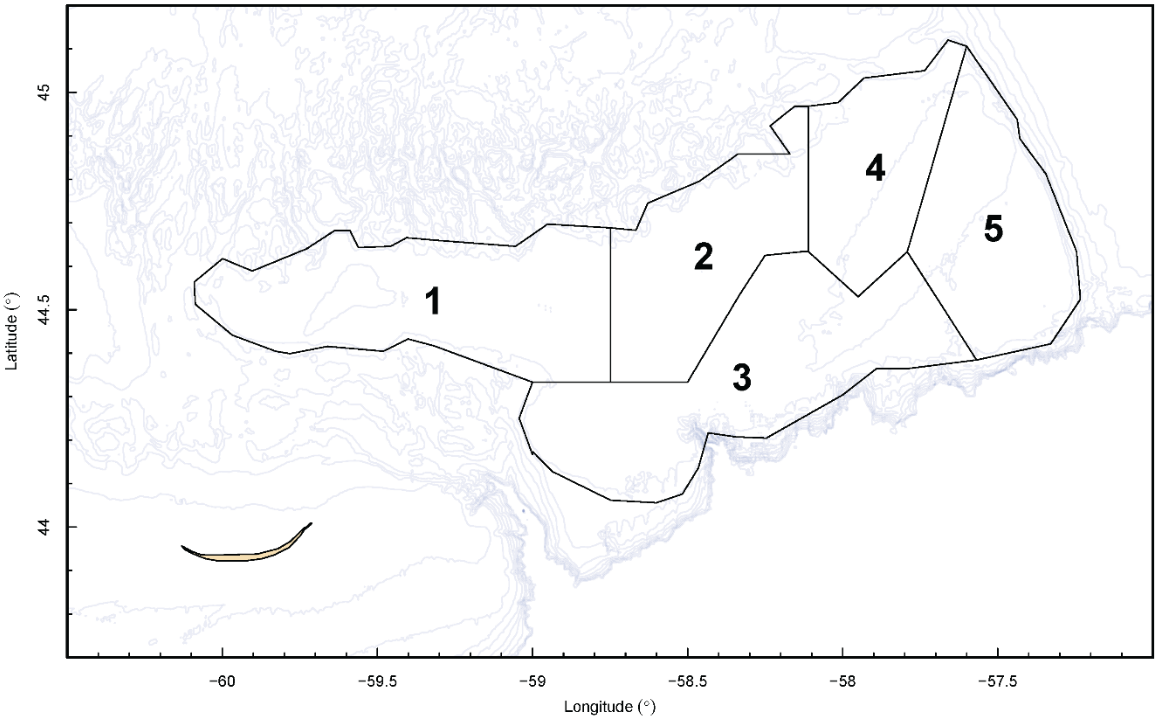


Figure 17. Five spatial assessment areas used for the analyses.

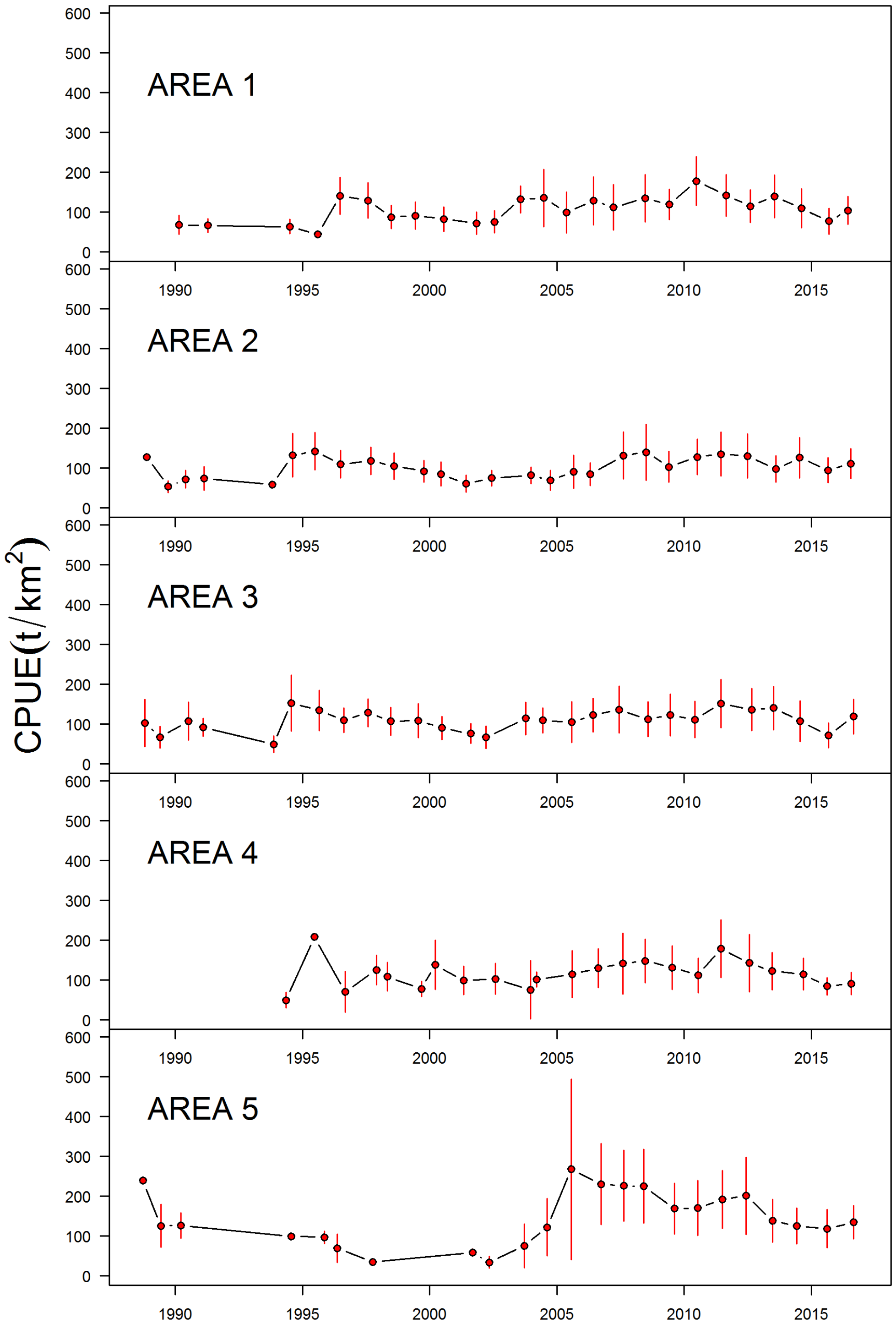


Figure 18. Catch Per Unit Effort (CPUE) by area showing the annual mean values (red points) ±1 standard error (red lines) for 1989–2016.

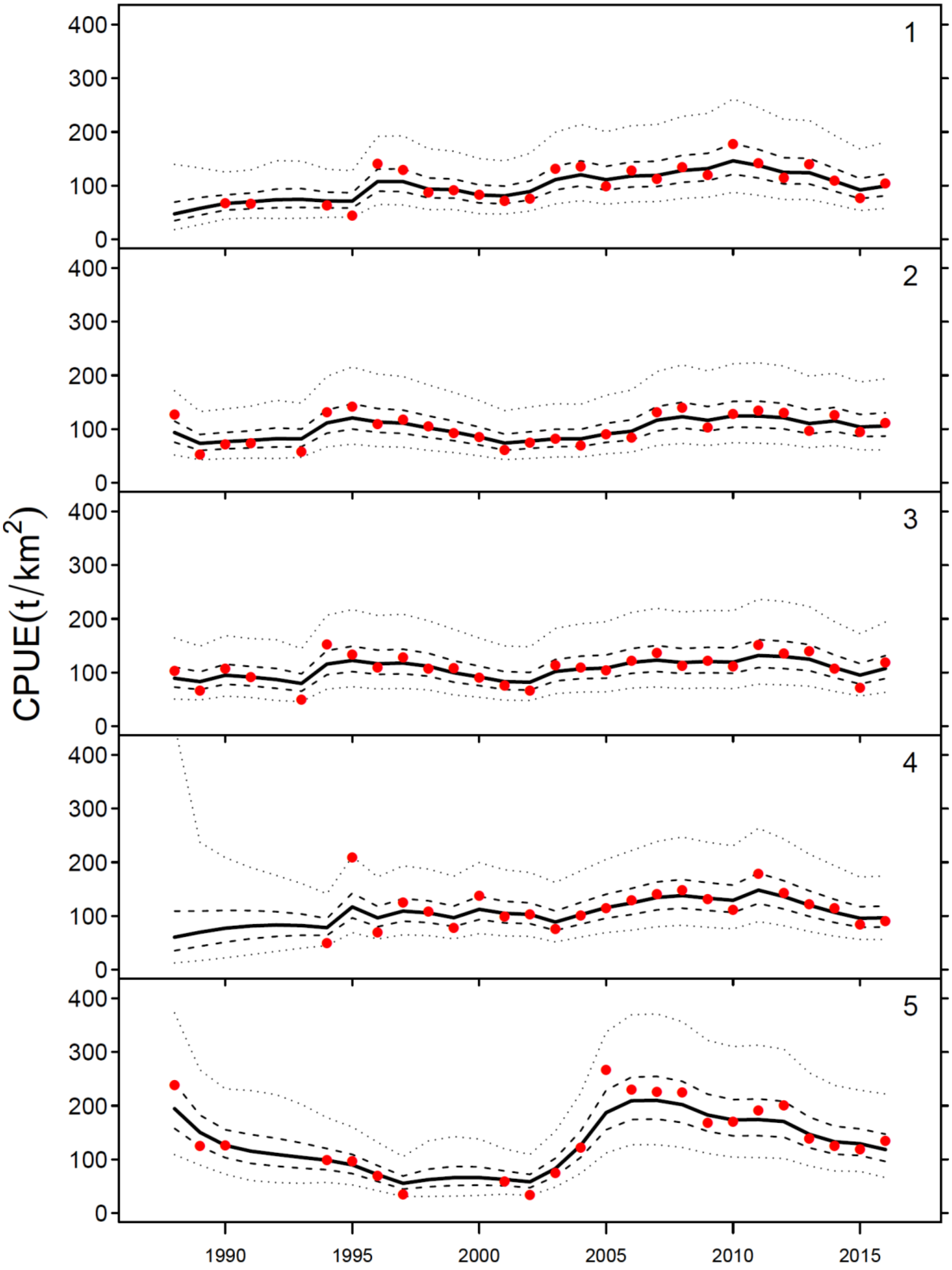


Figure 19. Spatial production model fit to the annual Catch Per Unit Effort (CPUE) index (red points) for each area (1-5) for 1988-2016. Lines indicate the median (solid), 50% credible interval (dashed), and 95% credible interval (dotted).

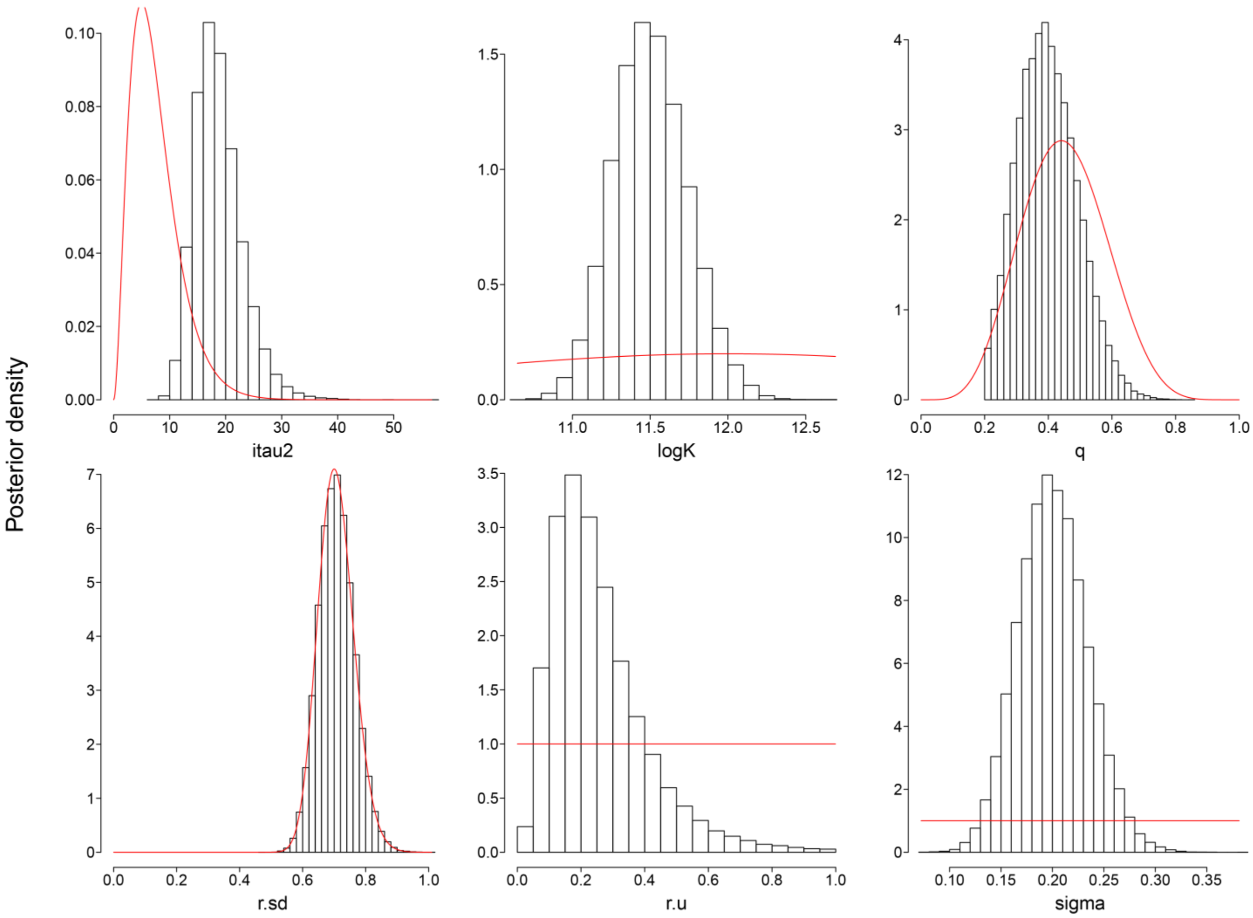


Figure 20. Histograms showing the marginal posterior density values for the shared parameter estimates included in the spatial production model. Top, left to right: observation precision (itau2), log of mean carrying capacity (logK), and dredge efficiency (q). Bottom, left to right: standard deviation of the population growth rate (r.sd), mean population growth rate (r.u), and process standard deviation (sigma). The red lines indicate the prior density distributions.

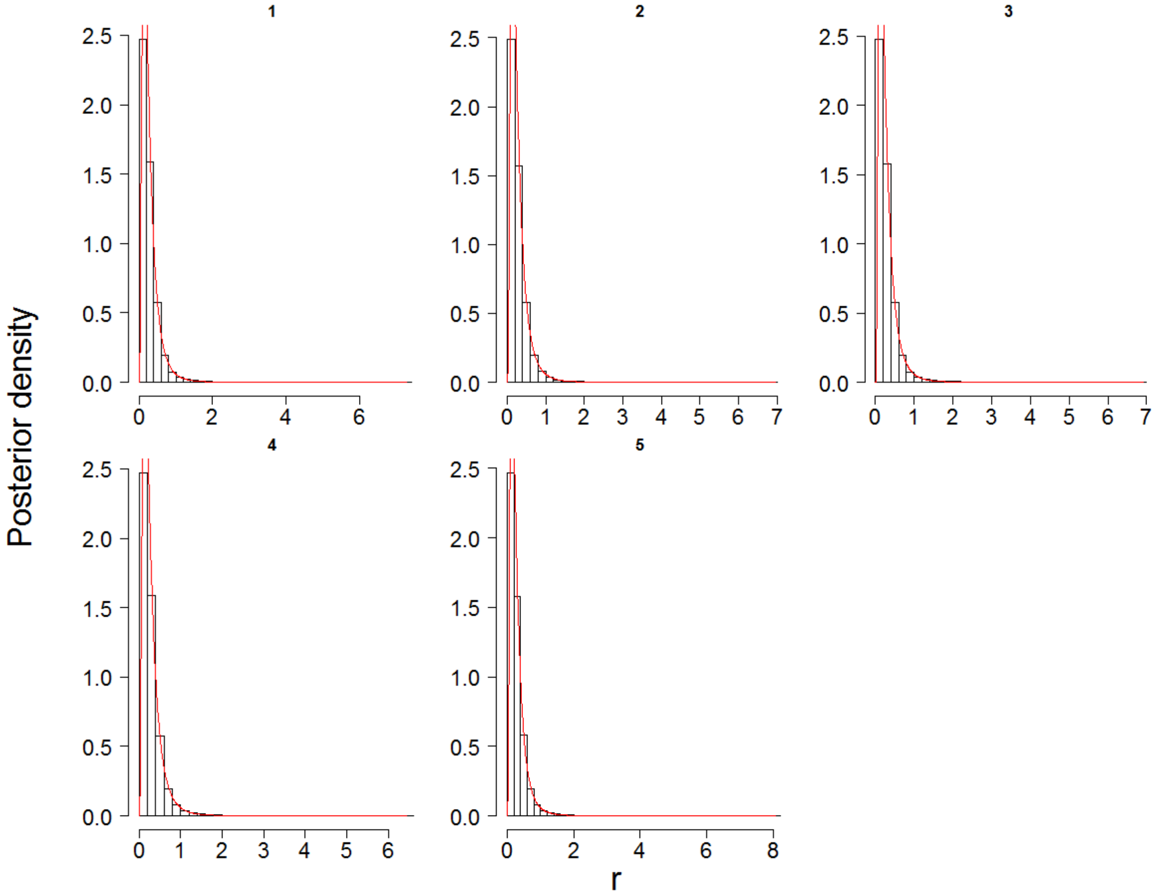


Figure 21. Histograms showing the marginal posterior density values for the estimates of population growth rate (r) for each area (1-5) from the spatial production model. The red lines indicate the prior density distributions of these estimates defined by the mean and standard deviation of the parameters shown in Figure 20.

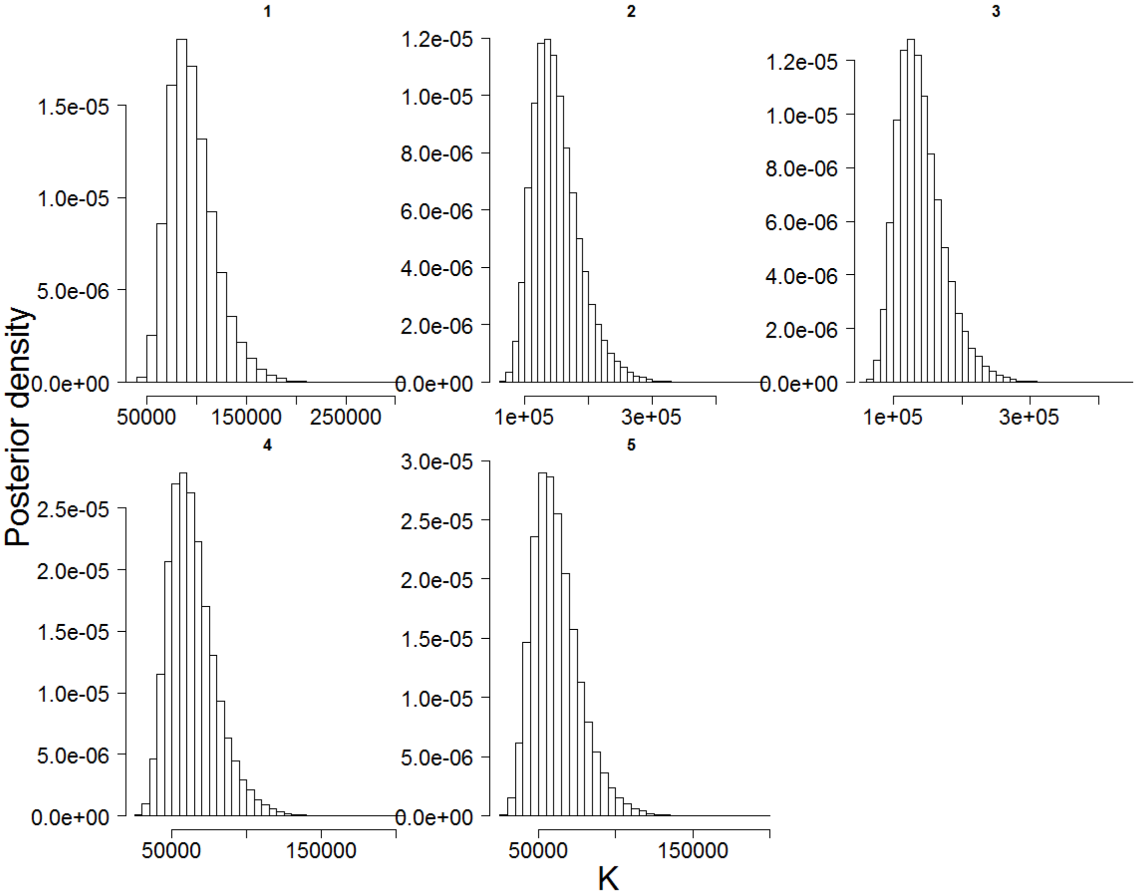


Figure 22. Histograms showing the marginal posterior density values for the estimates of carrying capacity (K) for each area (1-5) from the spatial production model.

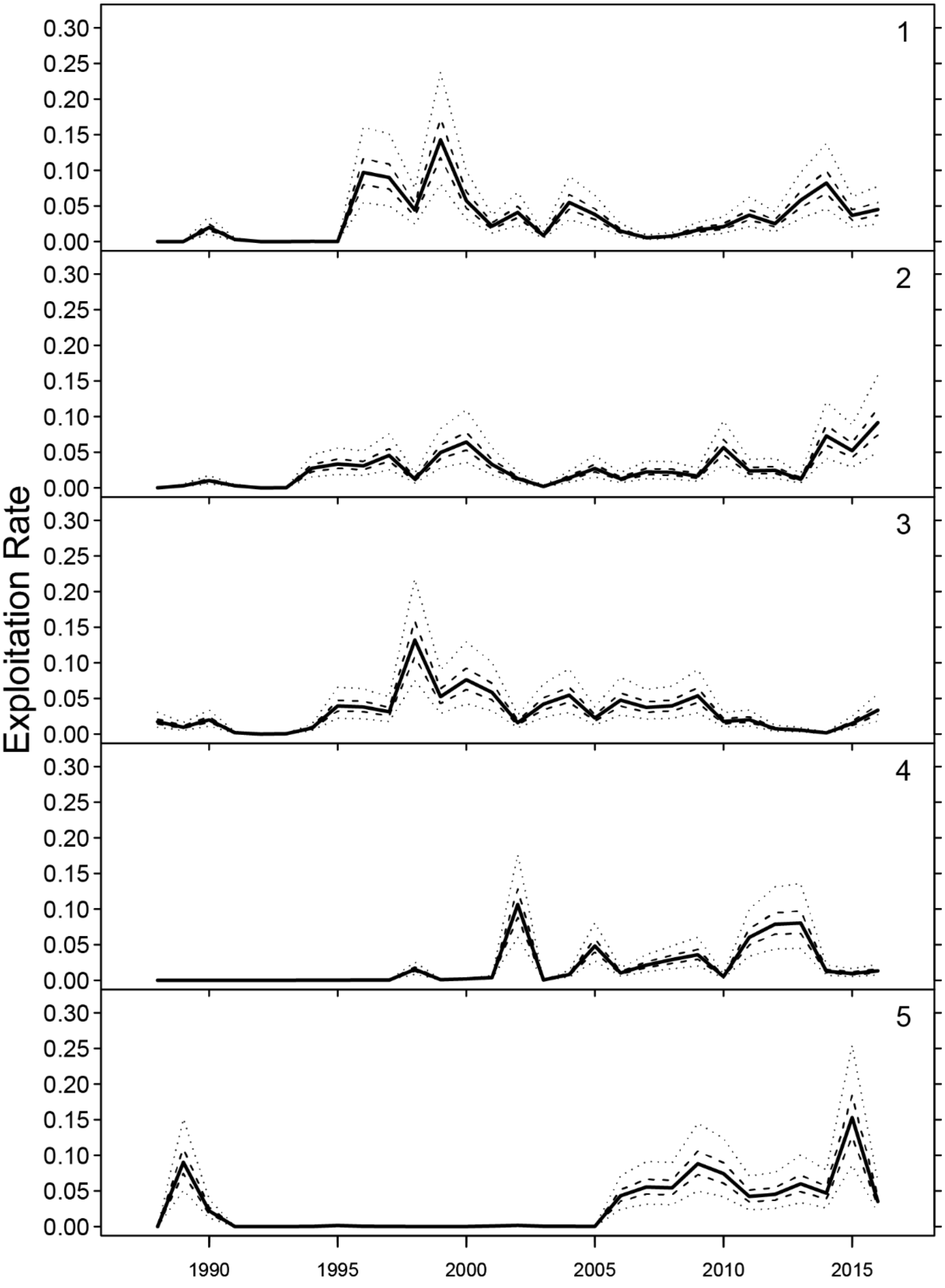


Figure 23. Estimates of exploitation rate for 1988-2016 from the spatial production model by area. Lines denote the median (solid), 50% credible interval (dashed), and 95% credible interval (dotted).

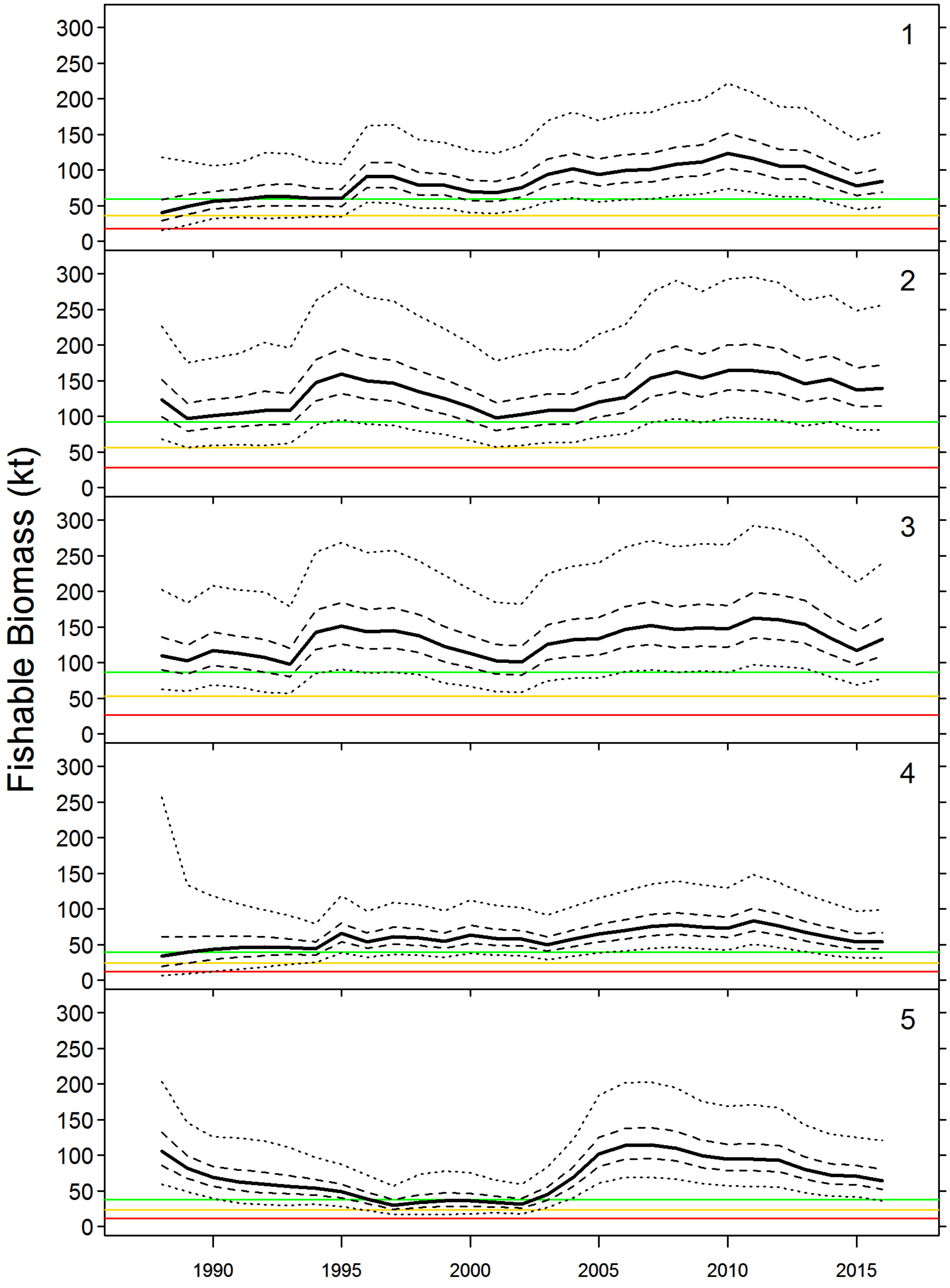


Figure 24. Estimates of biomass (fishable biomass in kilotonnes) from 1988-2016 from the spatial production model by area (1-5). Lines denote the median (solid), 50% credible interval (dashed), and 95% credible interval (dotted). The colored lines represent the LRP (red), USR (yellow) and CPUE (green) reference points.

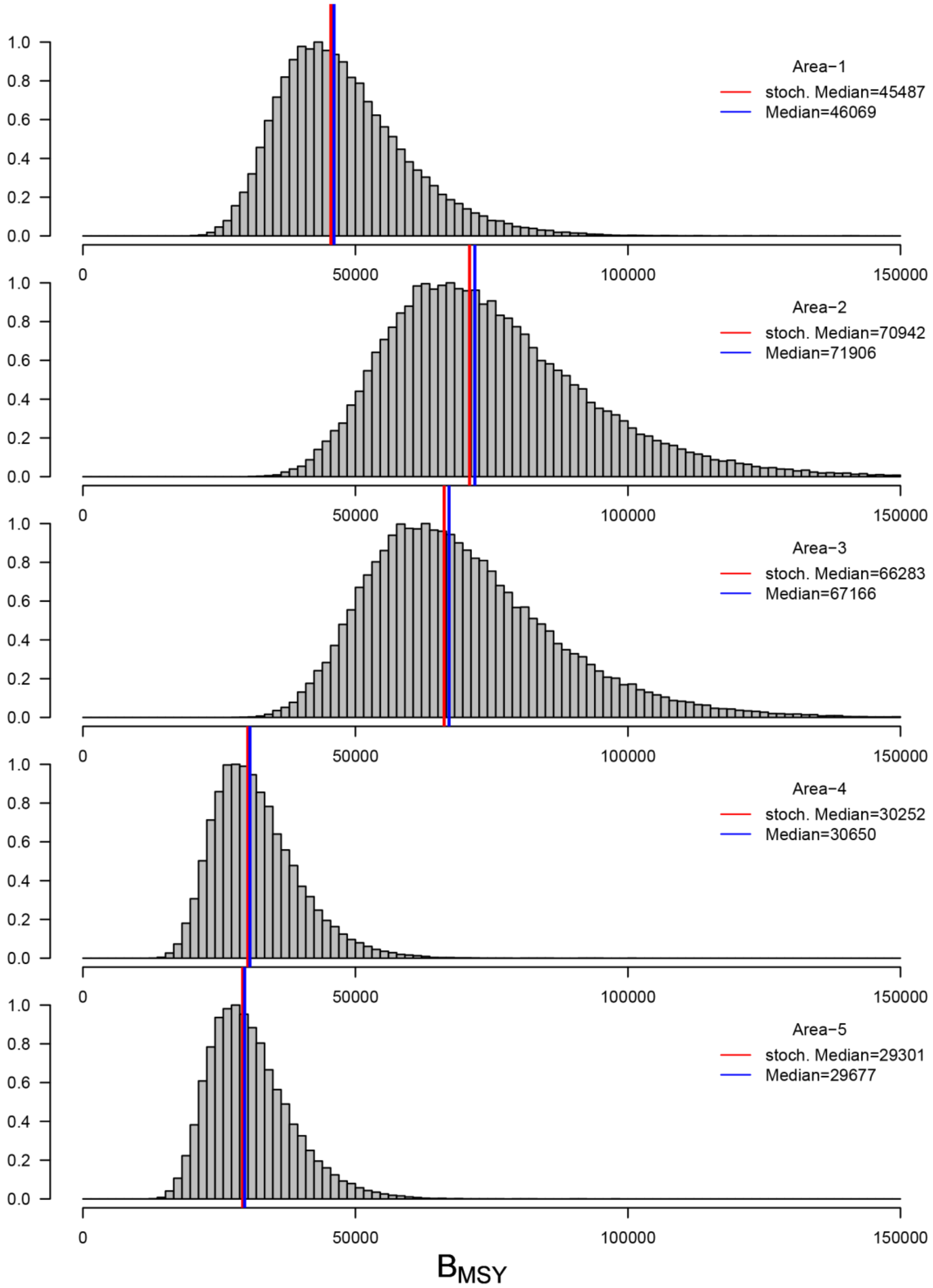


Figure 25. Posterior densities of B_{MSY} reference points by area with the median (blue) and stochastic median (red) of the estimates indicated.

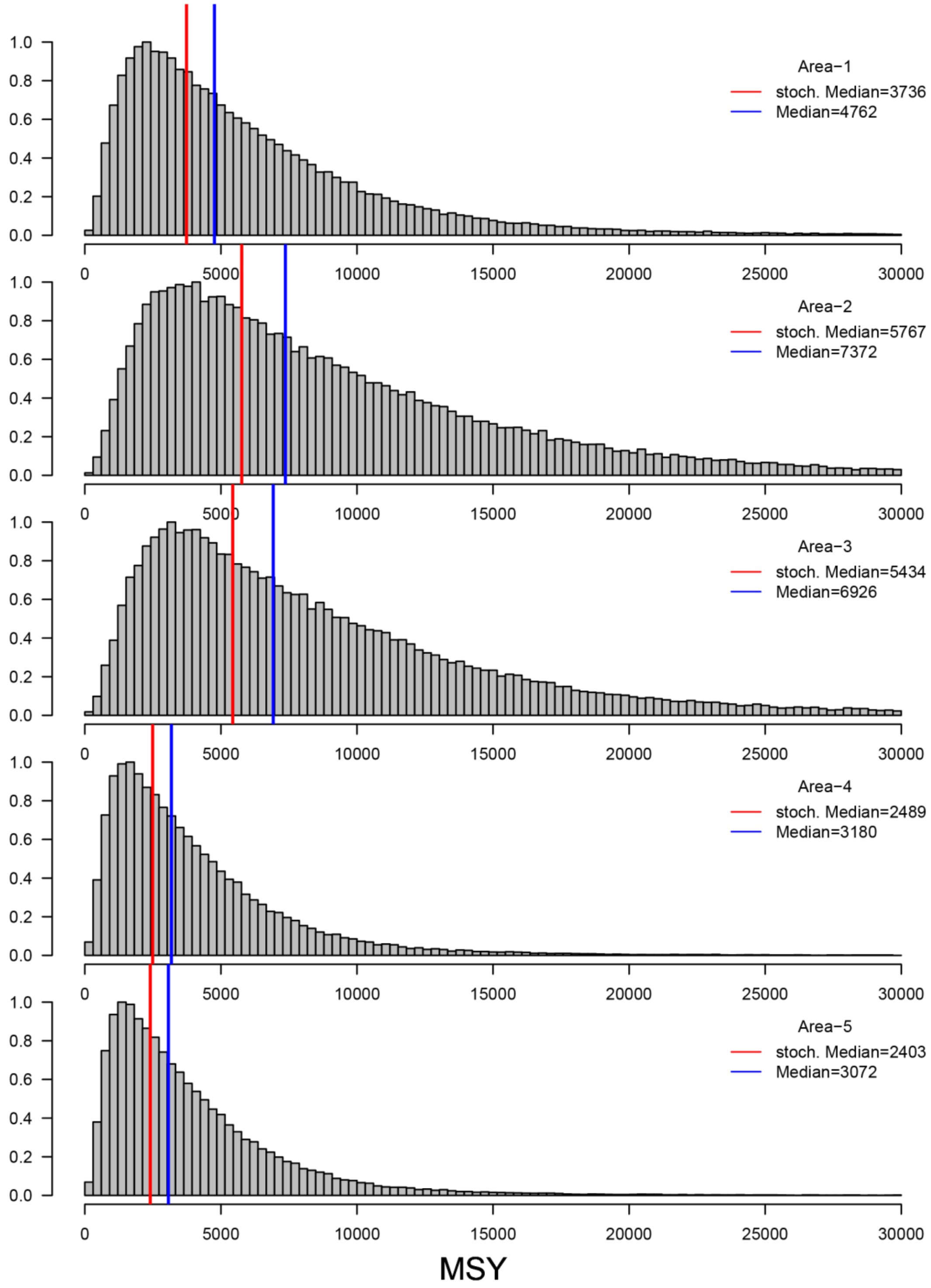


Figure 26. Posterior distribution of MSY reference points by area with the median (blue) and stochastic median (red) of the estimates indicated.

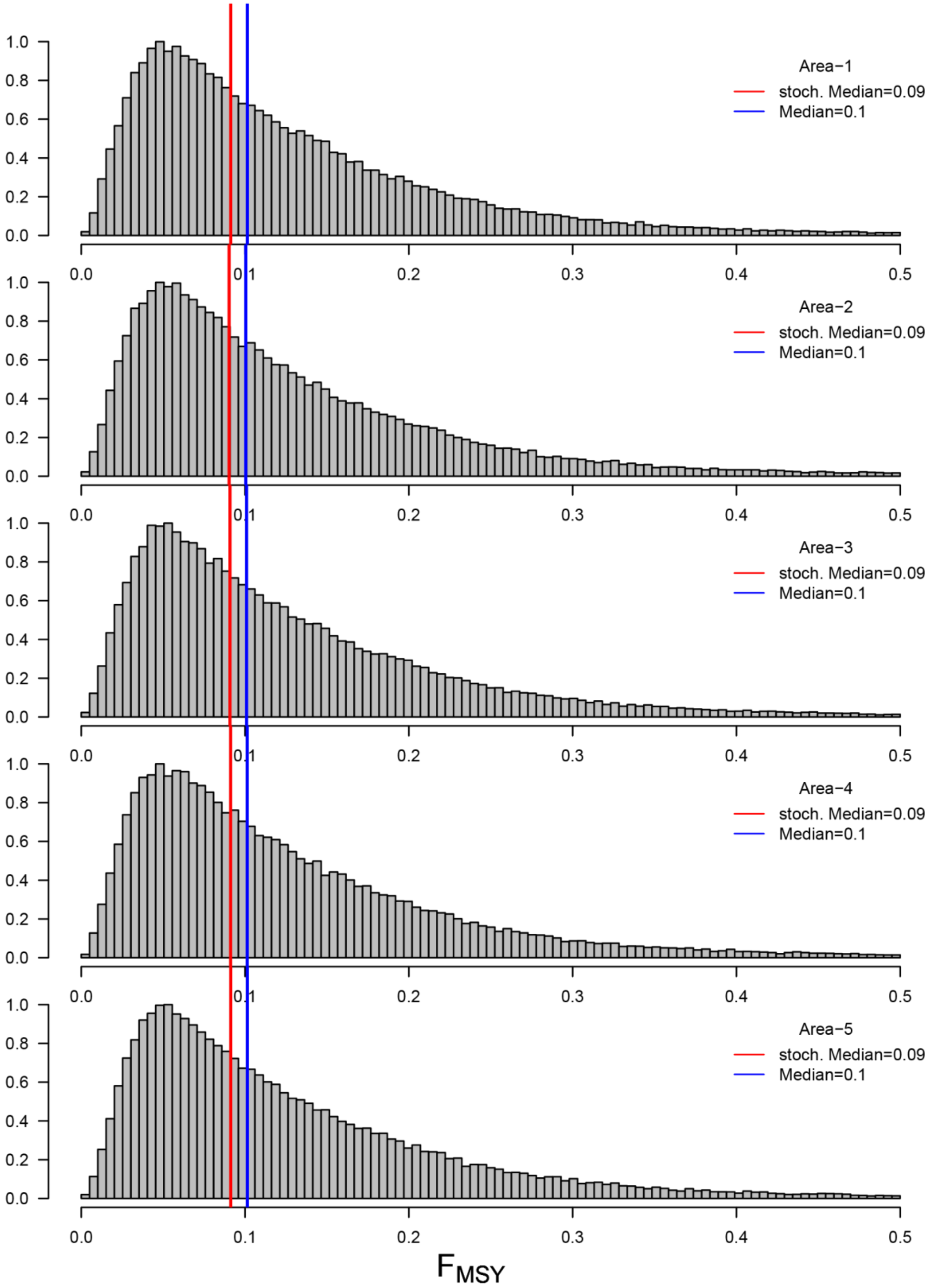


Figure 27. Posterior distribution of F_{MSY} reference points by area with median (blue) and stochastic median (red) of the estimates indicated.

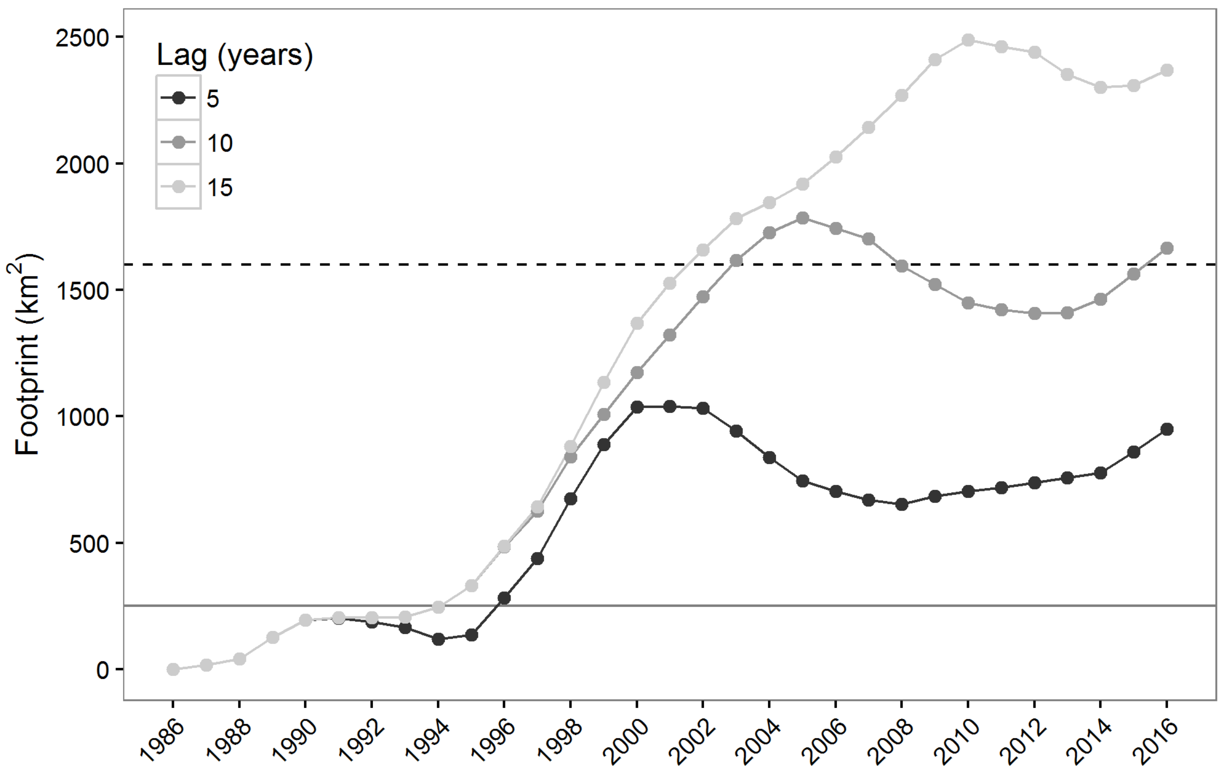


Figure 28. Cumulative fisheries footprint at 5, 10, and 15 year time lags for Banquereau. Solid line represents the threshold footprint level of 250 km^2 and dashed line denotes the estimated fished area estimated up to 2016 (1601.2 km^2).

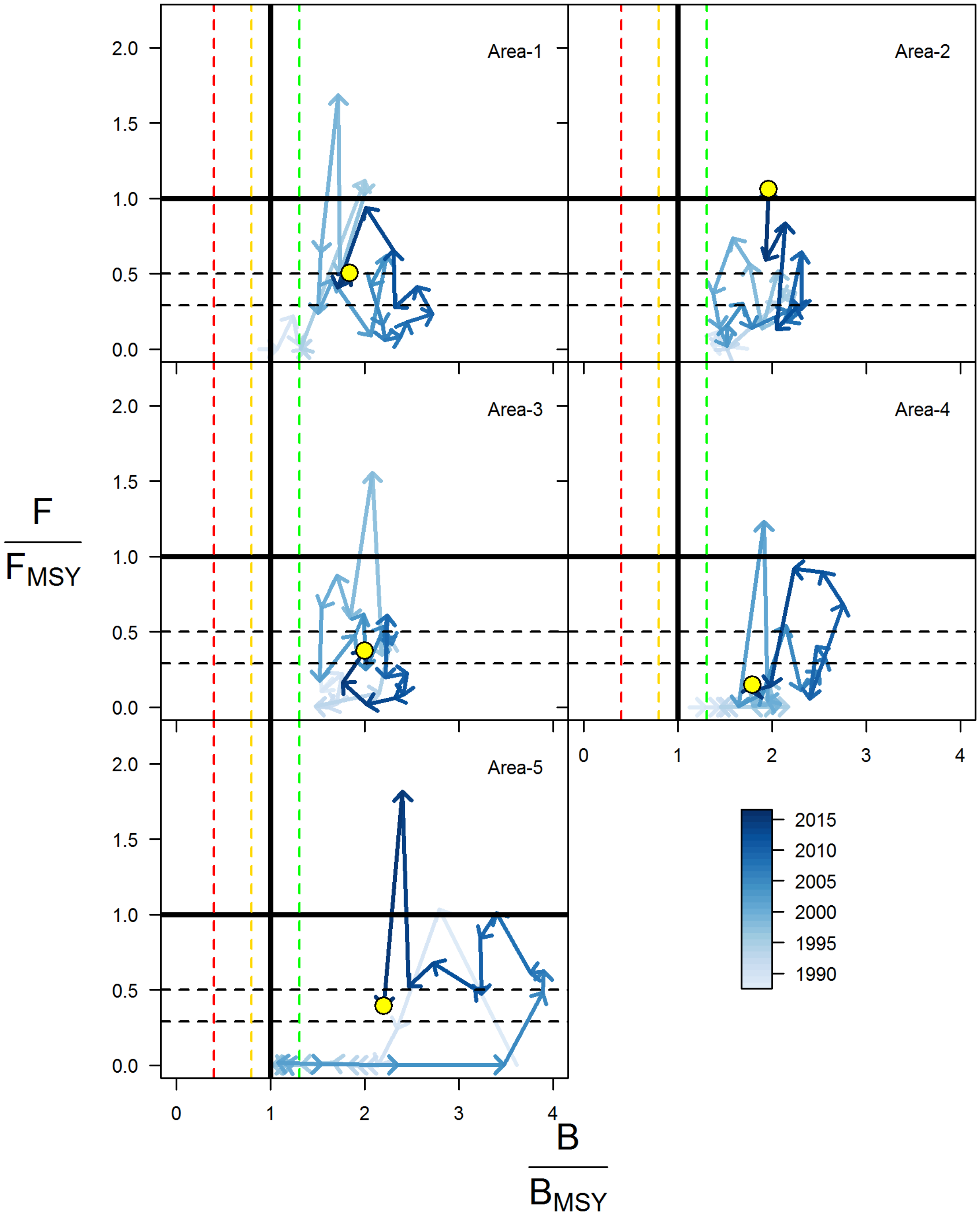


Figure 29. Phase plots showing spawning biomass relative to B_{MSY} (B/B_{MSY}) along the x-axis and fishing mortality relative to FMSY (F/F_{MSY}) along the y-axis. The biomass reference levels are shown by the thick vertical line ($B/B_{MSY} = 1$), and colored dashed lines for the LRP (red), USR (yellow) and CPUE (green). The fishery mortality reference levels are shown by the thick horizontal line ($F/F_{MSY} = 1$) and dashed lines for $0.5F_{MSY}$ and 0.33M (0.0264). The colored arrows denote data for each year (1988-2016). The yellow circle denotes the 2016 estimates of relative biomass and fishing mortality.

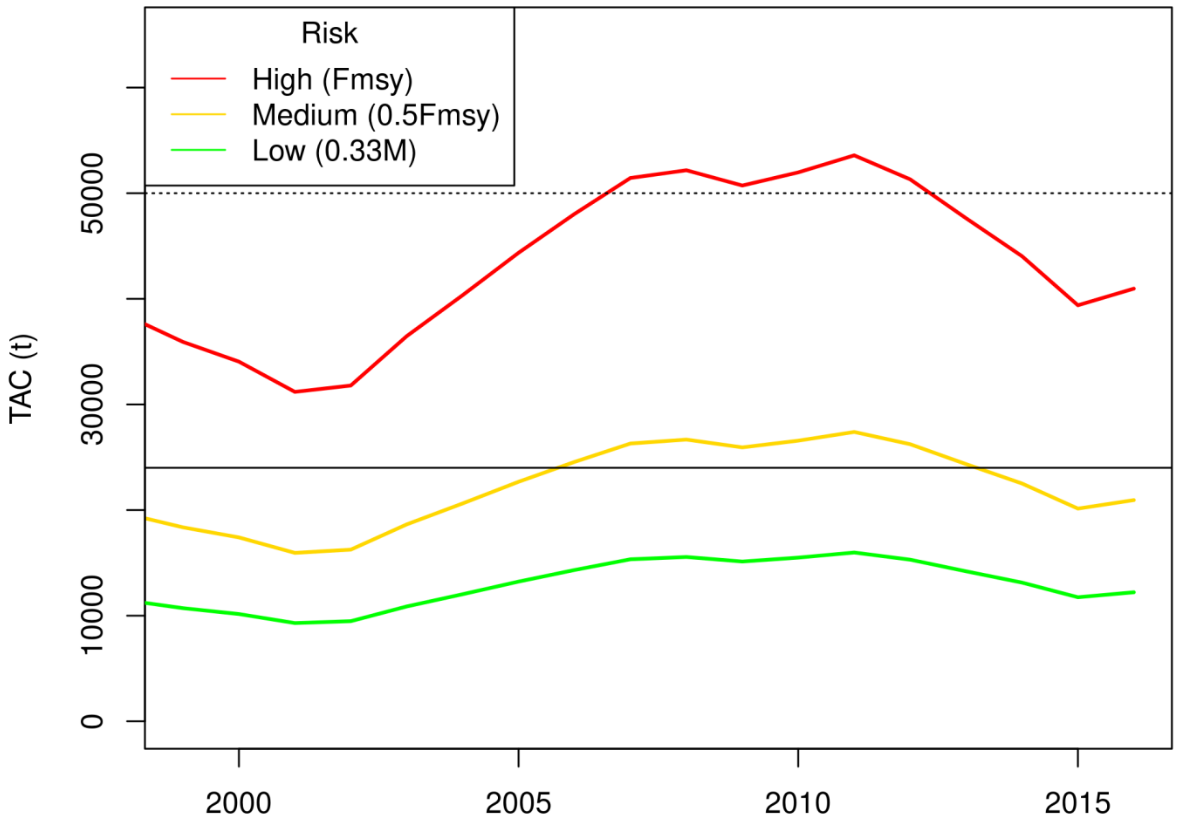


Figure 30. Illustration of what potential Total Allowable Catches (TACs) could have been under the various removal references identified in the risk scenarios. Solid horizontal line indicates the actual TAC.

APPENDIX

APPENDIX 1. OFFSHORE ARCTIC SURFCLAM (*MACTROMERIS POLYNYMA*) SCIENCE MONITORING PROGRAM: COMMERCIAL STOCK STATUS INDICATORS FOR ARCTIC SURFCLAM ON BANQUEREAU AND GRAND BANK

Status of the fishery for Arctic Surfclam in Atlantic Canada in 2016

The annual monitoring program for the status of the fishery for Arctic Surfclam in Atlantic Canada is described in the document "Offshore Surfclam Science Monitoring Program". Three indicators are used to monitor the fishery: Catch Per Unit Effort (CPUE); the spatial extent or footprint of the fishery; and the abundance of older/larger clams in the catch.

Banquereau

Landings of Arctic Surfclam from the fishery on Banquereau in 2016, as indicated by the logbook data provided by industry to DFO Science, were 24,154 t, relative to a quota of 24,000 t (Table A1).

CPUE calculated from logbook data provided by industry for the fishery on Banquereau in 2016 indicates an annual average CPUE of 110 g/m^2 (Table A1, Figure A1). This value is greater than the value of 96 g/m^2 for 2015 and above the trigger level of 70 g/m^2.

The spatial extent or footprint of the fishery on Banquereau in 2016 was 220 km^2 (Table A1, Figure A2. This value is lower than the value of 242 km^2 for 2015 and is below the threshold level of 253 km^2.

The proportion of older/larger Arctic Surfclam in the unsorted catch from the fishery on Banquereau in 2016, as indicated by onboard sampling data provided by industry, was 2.31% of catch ≥120 mm (Table A2, Figure A3). This value is above the trigger level of 1.0% ≥120 mm and is higher than 2015 (1.55%).

Grand Bank

Landings of Arctic Surfclam from the fishery on Grand Bank in 2016, as indicated by the logbook data provided by industry to DFO Science, were 13,560 t relative to a quota of 14,756 t (Table A3).

The CPUE calculated from logbook data provided by industry for the fishery on Grand Bank in 2016 indicates an annual average CPUE of 142 g/m^2 (Table A3, Figure A4). This value is greater than the value of 97 g/m^2 for 2015 and above the trigger level of 50 g/m^2.

The spatial extent or footprint of the fishery on Grand Bank in 2016 was 95.4 km^2 (Table A3, Figure A5). This value is higher than the value of 7.5 km^2 for 2015 and is below the threshold level of 128 km^2.

The proportion of older/larger Arctic Surfclam in the unsorted catch from the fishery on Grand Bank in 2016, as indicated by onboard sampling data provided by industry, was 15.48% of catch ≥105 mm (Table A4, Figure A6). This value is above the trigger level of 1.0% of catch ≥105 mm and has decreased since 2015 (19.17%).

Table A1. Catch (t), effort (km^2), and Catch Per Unit Effort (CPUE) by year for the Arctic Surfclam fishery on Banquereau.

Year	Logged Catch (t)	Area Dredged (km²)	CPUE
1986	29	0.8	36
1987	1,210	16.1	75
1988	2,474	24.5	101
1989	9,159	84.9	108
1990	6,158	68.2	90
1991	714	9.7	74
1992	0	0.0	0
1993	64	2.2	29
1994	5,313	39.8	133
1995	11,425	84.1	136
1996	19,262	156.4	123
1997	19,517	157.2	124
1998	24,456	237.3	103
1999	24,138	254.2	95
2000	20,248	233.3	87
2001	11,014	158.9	69
2002	12,506	149.0	84
2003	16,960	147.0	115
2004	16,493	149.5	110
2005	14,327	141.5	101
2006	15,932	116.7	137
2007	17,931	115.4	155
2008	19,301	130.6	148
2009	24,158	180.5	134
2010	22,558	160.3	141
2011	20,858	131.0	159
2012	20,214	135.9	149
2013	19,270	149.9	129
2014	23,640	200.9	118
2015	23,287	242.0	96
2016	24,154	220.1	110

Table A2. Percent of large (>120 mm) Arctic Surfclams in unsorted catch on Banquereau.

Year	% Large	Number Unsorted
1999	6.00	6,997
2000	4.29	5,343
2001	4.75	1,517
2002	6.31	2,597
2003	1.66	2,533
2004	1.36	3,318
2005	0.85	828
2006	1.14	528
2007	5.10	804
2008	2.24	7,416
2009	3.87	17,940
2010	3.64	16,683
2011	7.31	10,841
2012	4.50	12,129
2013	2.76	21,290
2014	1.57	14,127
2015	1.55	13,741
2016	2.31	18,967

Table A3. Catch (t), footprint (km2), and Catch Per Unit Effort (CPUE) by year for the Arctic Surfclam fishery on Grand Bank.

Year	Logged Catch (t)	Area Dredged (km²)	CPUE
1987	1	0.1	10
1988	5	0.0	0
1989	373	3.4	110
1990	6,049	23.6	256
1991	2,094	11.3	185
1992	5,161	27.1	190
1993	13,100	92.8	141
1994	10,979	95.2	115
1995	14,907	128.4	116
1996	5,772	53.6	108
1997	7,492	80.0	94
1998	931	11.4	82
1999	1,472	18.6	79
2000	3,289	46.0	72
2001	8,026	110.4	73
2002	6,077	120.3	51
2003	8,727	121.0	72
2004	6,437	66.9	96
2005	3,967	51.8	77
2006	4,990	75.2	66
2007	215	7.5	29
2008	0	0.0	0
2009	437	7.5	58
2010	296	9.3	32
2011	112	9.0	12
2012	0	0.0	0
2013	99	6.1	33
2014	0	0.0	0
2015	730	7.5	97
2016	13,560	95.4	142

Table A4. Percent of large (>105 mm) Arctic Surfclams in unsorted catch on Grand Bank.

Year	% Large	Number Unsorted
2000	22.54	1,393
2001	39.19	1,697
2002	7.84	714
2003	10.79	621
2004	3.06	1,243
2005	1.16	172
2006	0.45	662
2010	1.34	224
2011	0.00	251
2013	6.67	180
2015	19.17	600
2016	15.48	8,300

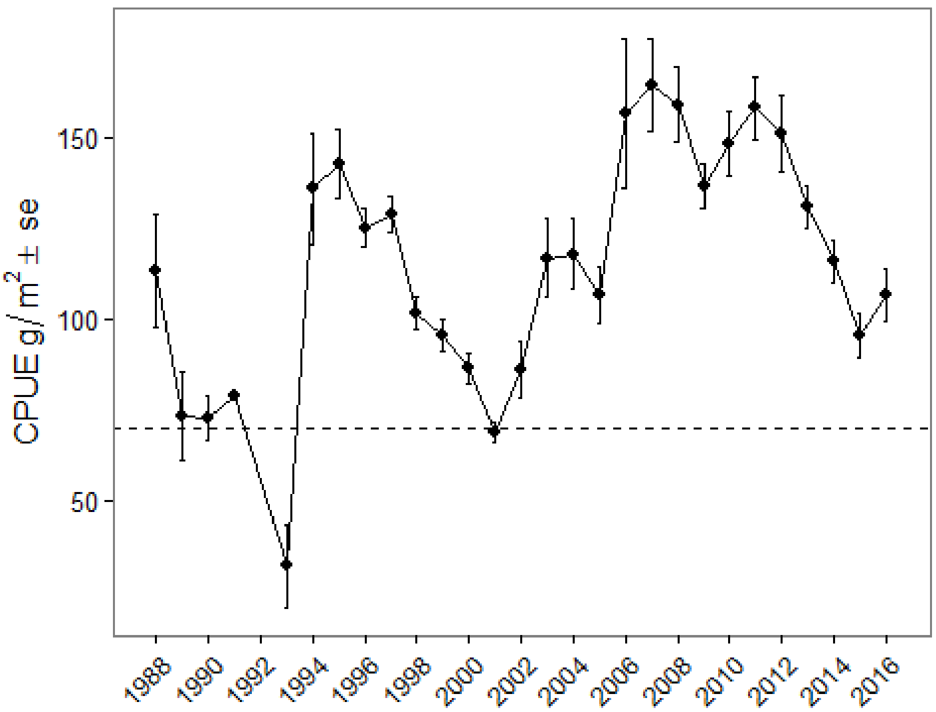


Figure A1. Average annual CPUE and standard error for the last five active vessels in the Arctic Surfclam fishery on Banquereau. Horizontal dashed line denotes trigger level for Banquereau of 70 g/m^2 Catch Per Unit Effort (CPUE).

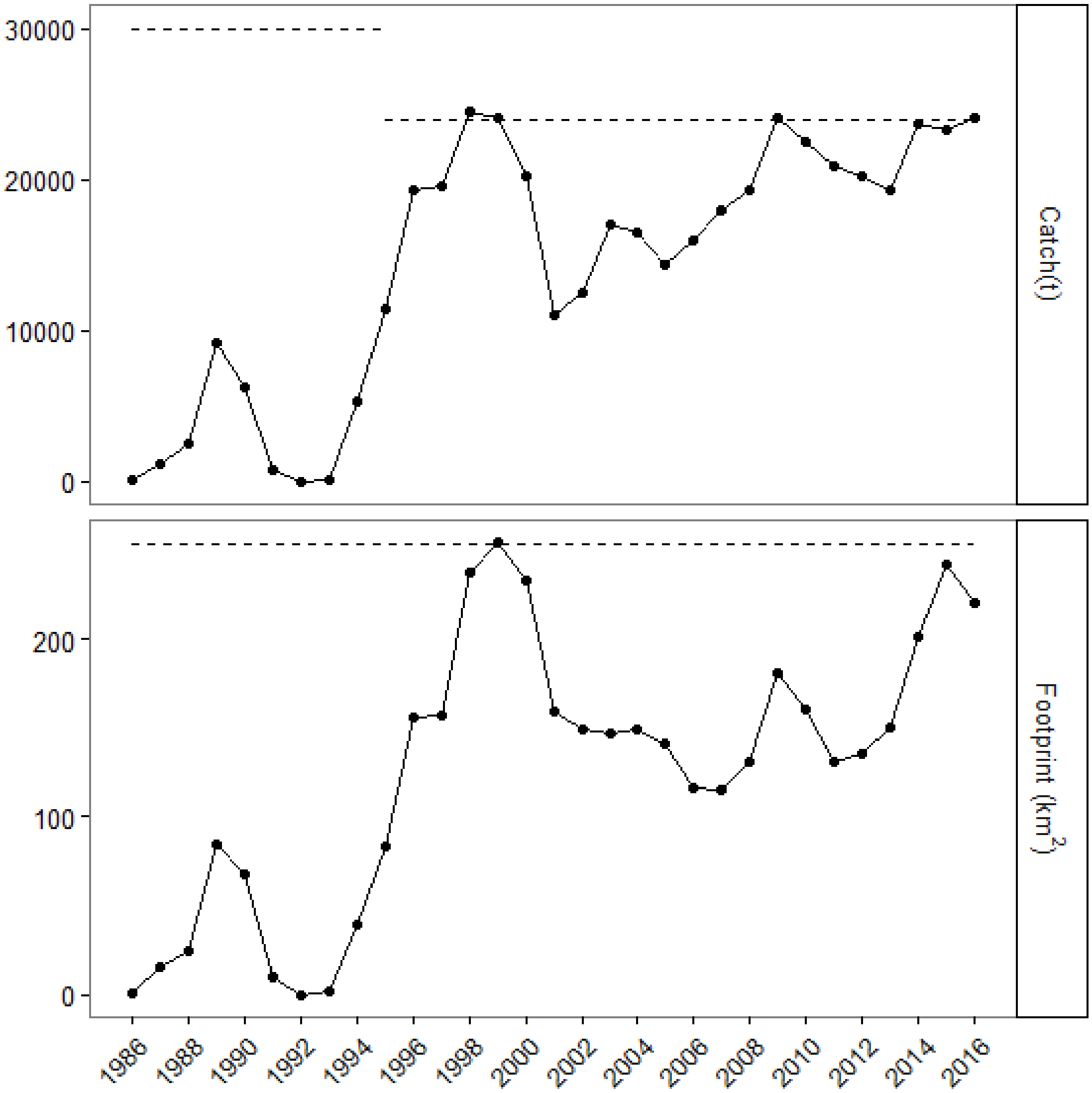


Figure A2. Catch (tonnes) and footprint (km^2) of the offshore Arctic Surfclam fishery by year on Banquereau. Horizontal dashed lines denote threshold levels for catch (Total Allowable Catch (TAC) of 30,000 t and 24,000 t) and fisheries footprint (253 km^2) for Banquereau.

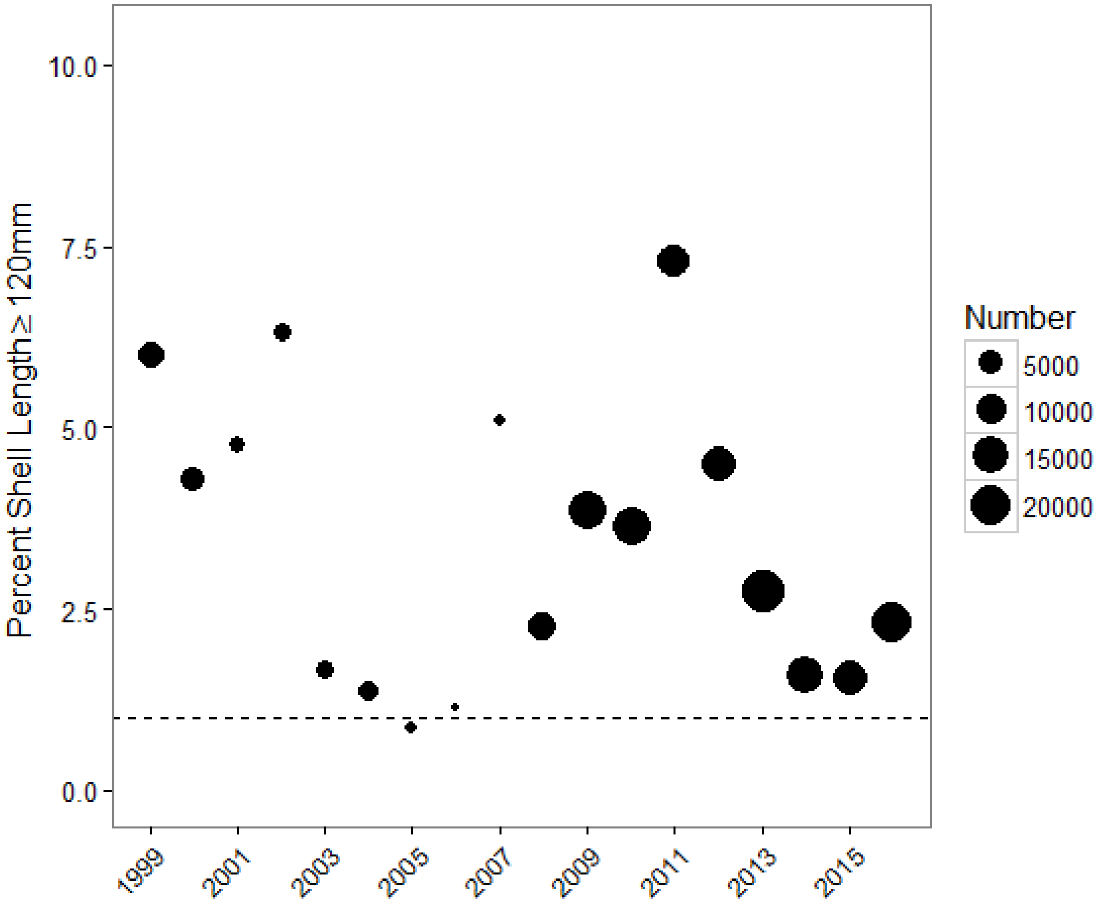


Figure A3. Percent of large (>120 mm) Arctic Surfclams in the unsorted commercial catch on Banquereau. Horizontal dashed line denotes trigger level for Banquereau of one percent.

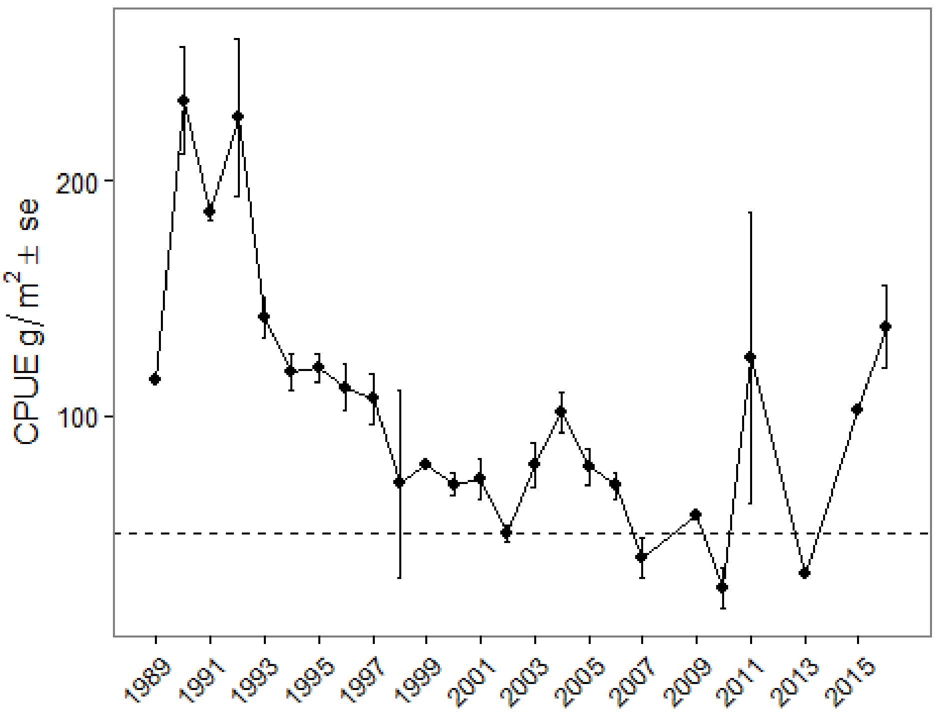


Figure A4. Average annual Catch Per Unit Effort (CPUE) and standard error for the last 5 active vessels in the Arctic Surfclam fishery on Grand Bank. Horizontal dashed line denotes trigger level for Grand Bank of 50 g/m^2 CPUE.

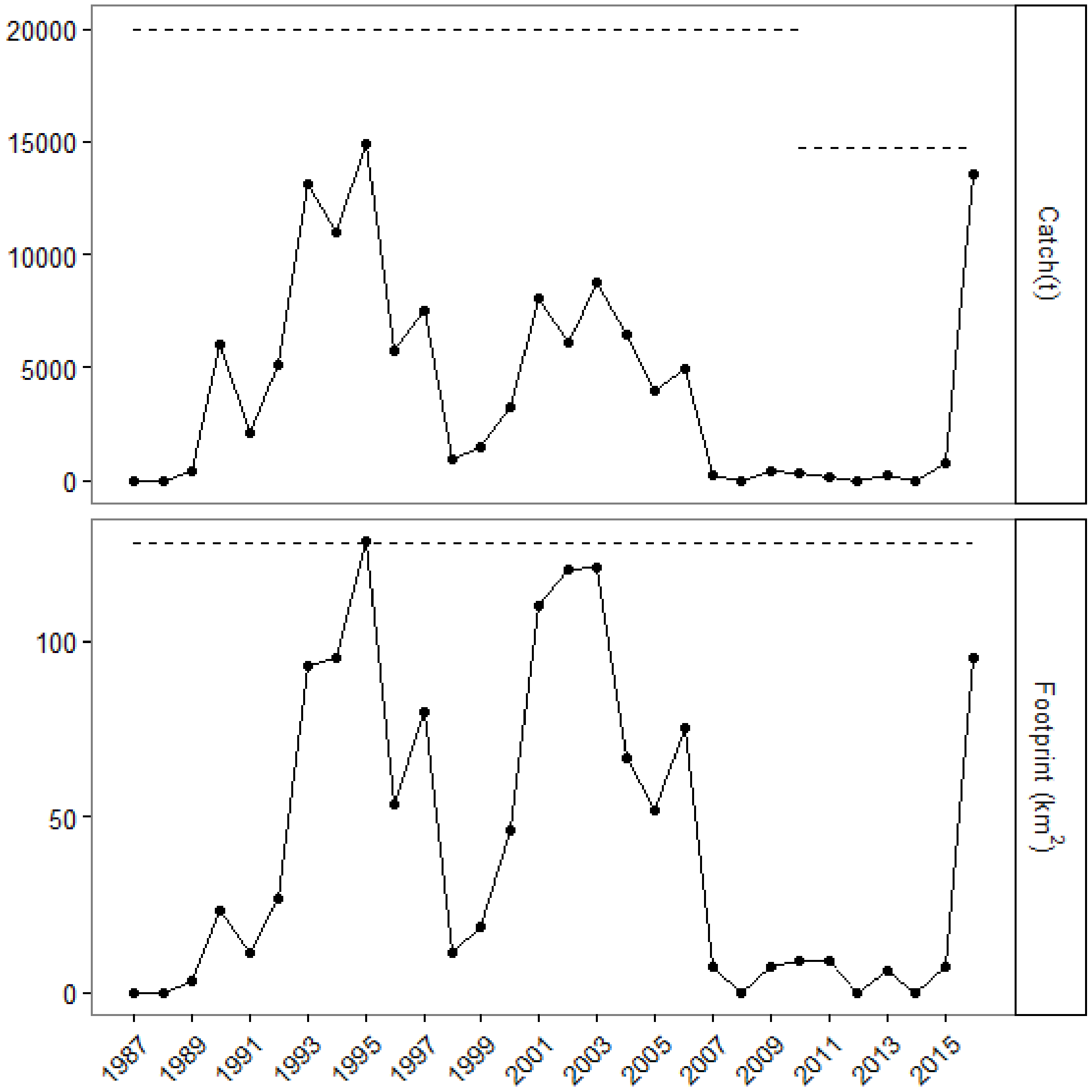


Figure A5. Catch (t) and footprint (km^2) of the offshore Arctic Surfclam fishery by year on Grand Bank. Horizontal dashed lines denote threshold levels for catch (TAC of 20,000 t and 14,756 t) and fisheries footprint (128 km^2) for Grand Bank.

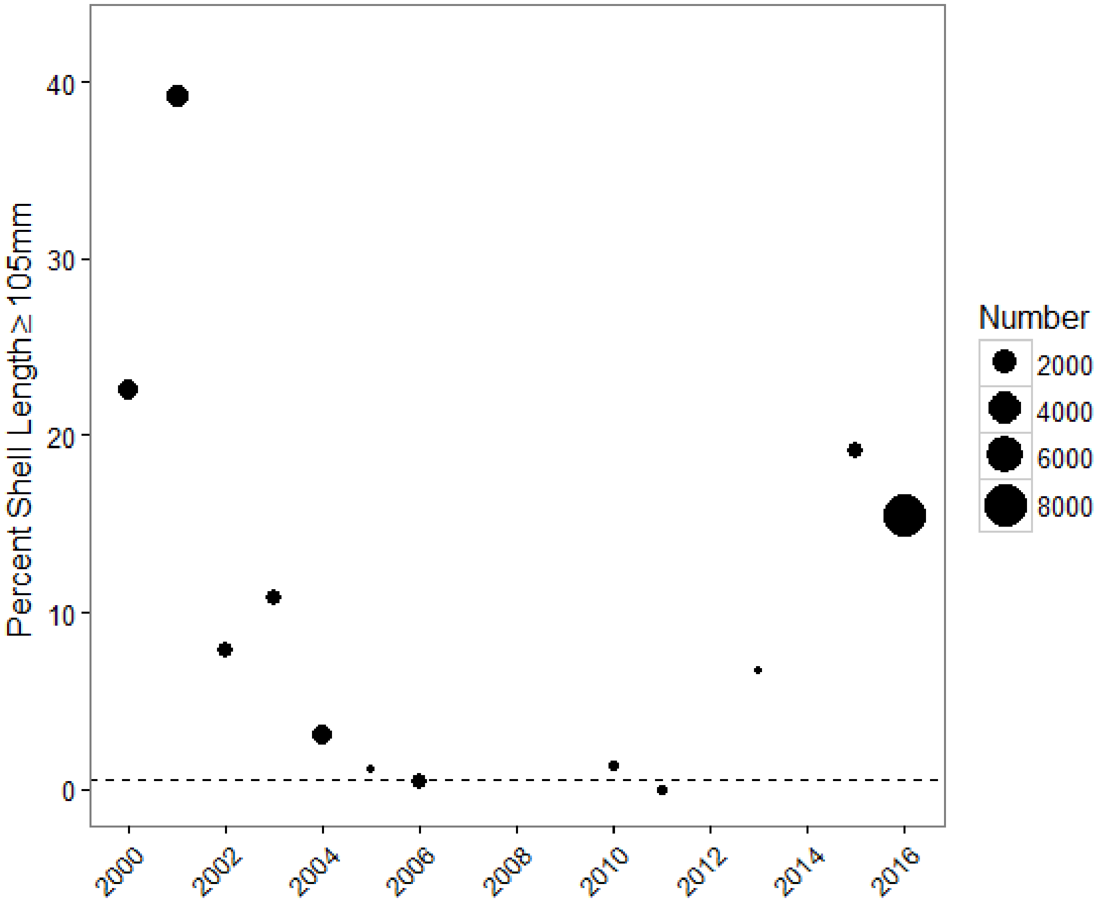


Figure A6. Percent of large (>105 mm) Arctic Surfclams in the unsorted commercial catch on Grand Bank. Horizontal dashed line denotes trigger level for Grand Bank of 0.5%.