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Data Review and Assessment Framework of the Arctic Surfclam (*Mactromeris polynyma*) on Banquereau and Grand Bank

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

A review of life-history characteristics, impacts of dredging, habitat suitability, and survey and fishery information for Arctic Surfclam (*Mactromeris polynyma*) in Atlantic Canada was performed to provide a basis for a risk assessment framework to assess management options.

Since the last survey in 2010, fishing has occurred almost entirely on Banquereau with little effort directed towards Grand Bank, thus this review is focused on an analysis of fishery data from Banquereau. Issues associated with using the Catch Per Unit Effort (CPUE) data included changing efficiency, spatial variability, and a short time lag in the reporting of catch. Changes in efficiency over time was not accounted for; however, the time lag and spatial variability was partially mitigated through censoring and spatial aggregation of the data and the use of Vessel Monitoring System (VMS) positional data which provided more accurate and frequent information to identify areas of exploitation during 2004–2015.

Density estimates from the 2010 survey were similar to the 2010 CPUE density estimates for overlapping locations. 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 (209,261 t) and CPUE (217,604 t). Biomass estimates from the last assessment were corrected for dredge efficiency, which was estimated to be 0.45 with considerable uncertainty. 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.

In order to facilitate the discussion of a spatial management approach, five example areas were constructed considering the following criteria: easily navigable, encompass large scale contiguous clam beds, approximately equal in total biomass, and inclusion of both high and low density areas. The production model was fit to the CPUE index for each area with some parameters (e.g., dredge efficiency) estimated across areas. Model results show a trend of declining catch rates across all areas for the last five years. Maximum Sustainable Yield (MSY) reference points were calculated from the surplus production model with F_{MSY} estimates near 0.1; however, phase plots indicate that catch rates tend to decline when F (fishing mortality) is greater than 0.05. A qualitative risk assessment indicated that despite how the spatial management areas are divided, there is considerably more risk associated with setting Total Allowable Catch (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}.

Examen des données et cadre d'évaluation concernant la mactre de Stimpson (*Mactromeris polynyma*) du Banquereau et du Grand Banc

RÉSUMÉ

Un examen des caractéristiques du cycle biologique, des impacts du dragage, de la qualité de l'habitat, ainsi que des renseignements obtenus par relevé et des renseignements sur la pêche de la mactre de Stimpson (*Mactromeris polynyma*) au Canada Atlantique a été réalisé en vue de fournir une base pour l'établissement d'un cadre d'évaluation des risques afin d'évaluer les options de gestion.

Depuis le dernier relevé datant de 2010, la pêche a été pratiquée presque exclusivement sur le Banquereau, peu d'efforts ayant été déployés sur le Grand Banc; par conséquent, cet examen se concentre sur une analyse des données sur les pêches provenant du Banquereau. Les problèmes découlant de l'utilisation des données de capture par unité d'effort (CPUE) comprenaient l'efficacité fluctuante, la variabilité spatiale et un bref délai dans la déclaration des prises. Les variations de l'efficacité au fil du temps n'ont pas été prises en compte; cependant, le délai et la variabilité spatiale ont été partiellement atténués par la censure et la concentration spatiale des données ainsi que par l'utilisation des données de position du Système de surveillance des navires (SSN) qui fournissaient des renseignements plus précis et plus fréquents afin de déterminer les zones d'exploitation entre 2004 et 2015.

Les estimations de la densité tirées du relevé de 2010 étaient comparables aux estimations de la densité de CPUE de 2010 pour les emplacements qui se chevauchent. Lorsque ces estimations de la densité ont été étendues à la zone de récolte, telle qu'elle a été définie selon l'empreinte obtenue au moyen du SSN, les estimations de la biomasse qui en découlent pour 2010 étaient également semblables pour le relevé (209 261 tonnes) et les captures par unité d'effort (217 604 tonnes). Les estimations de la biomasse tirées de la dernière évaluation ont été corrigées pour tenir compte de l'efficacité de la drague, qui a été estimée à 0,45 avec une grande incertitude. Un modèle bayésien de production excédentaire a intégré et quantifié les incertitudes liées à l'efficacité de la drague, les estimations de la biomasse qui en découlent, et a fourni des estimations du processus et des erreurs d'observation.

Afin de faciliter la discussion quant à une approche de gestion spatiale, cinq zones ont été définies à titre d'exemple en tenant compte des critères suivants : zones facilement navigables, englobant des gisements de myes contigus à grande échelle, ayant une biomasse totale à peu près égale, et incluant des secteurs à densité élevée et des secteurs à densité faible.
Le modèle de production a été adapté à l'indice de CPUE pour chaque secteur, certains paramètres (comme l'efficacité de la drague) étant estimés sur plusieurs zones. Les résultats du modèle indiquent une tendance à la baisse des taux de prises dans toutes les zones pour les cinq dernières années. Les points de référence du rendement maximal soutenu ont été calculés à l'aide du modèle de production excédentaire, avec des estimations de F_{RMS} proches de 0,1; cependant, les diagrammes de phase montrent que les taux de prise ont tendance à diminuer lorsque la valeur de F (mortalité par pêche) est supérieure à 0,05. Une évaluation qualitative du risque a indiqué que quelle que soit la manière dont les zones d'évaluation spatiale sont divisées, il existe un risque beaucoup plus important associé à la formulation de recommandations quant au total autorisé des captures (TAC) basées sur des estimations de la biomasse résultant d'une expansion de la densité des populations dans des zones encore non exploitées. En outre, des taux d'exploitation proches des estimations de F_{RMS} comportent plus de risques que d'autres niveaux de référence de F se trouvant en deçà de F_{RMS}.

INTRODUCTION

The objective of this document is to compile and review the science information basis to conduct a preliminary risk assessment of spatial management options for Arctic Surfclam (*Mactromeris polynyma*) in Atlantic Canada. This document includes the reproduction of information presented in previous assessment documents as well as a review and analysis of available fishery, survey, biological, and ecological information. Given that there is little recent information available for Grand Bank and significant time constraints, this data review and analysis largely focuses on Banquereau.

DATA REVIEW

This data review includes content previously published by Roddick et al. (2011, 2012), as well as new information to 2015. Details on the development of the fishery up to 1989 can be found in Roddick and Kenchington (1990).

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 3-year Offshore Clam Enterprise Allocation (EA) Program was developed with industry consensus. Total Allowable Catches (TACs) and EAs were set for each of the 3 years of the program with three companies participating. The Total Allowable Catches (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 Surfclams 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 Surfclams on Banquereau in 1986, exploratory fishing on Grand Bank in 1987 and 1988 led to the expansion of the fishery to this area in 1989. Two exploratory licences and 2 exploratory permits were issued for 1 year for 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 Surfclams 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 EA 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.

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 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 5-year plan was approved for 1998–2002, the Offshore Surfclam IFMP, and 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 (DFO) 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. 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).

SURVEY AND ASSESSMENT HISTORY

Facing decisions on investment in the fishery and with DFO unable to obtain funding for surveys of the resource, 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 were to be 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. As a result of other financial commitments, there were no surveys in 2005 and 2007. The last survey was conducted on Banquereau in 2010 (Roddick et al. 2012).

Three Industry-DFO surveys of Banquereau have been conducted since the start of the fishery 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 since the start of the fishery in 1995–1997, with a second survey split over the years of 2006, 2008, and 2009 as a result of the size of the area involved. 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 (Figure 1). The landings and TAC for the Banquereau and Grand Bank fisheries are shown in Figure 2, and 3, respectively. Though landings have generally increased since the beginning of the fishery, they have never reached the combined quota for both banks (Table 1 and Figure 1). However, the landings for Banquereau have reached or approached the TAC for a number of years (i.e., 2009–12 and 2014–15; Figure 1, Figure 2, Table 1, 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 3 freezer processors. The distribution of catch, effort, and Catch Per Unit Effort (CPUE) for the fishery on Banquereau for 2004–2015 is shown in Figure 4, 5, and 6, respectively, and the distribution of effort for some individual years between 2004 and 2010 is shown in Figure 7. The distribution of catch for the fishery on Grand Bank for 2004 through 2015 is shown in Figure 8. The majority of the fishing effort (95%) on Banquereau has focused on an area of approximately 20% across the Bank (Figure 4), while the catches on Grand Bank have concentrated on a small portion of the Bank to date (Figure 8).

An assessment framework for Arctic Surfclam on Banquereau and Sable banks was 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 current PA framework includes limit reference points with associated harvest control rules. Upper and Limit 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 is $F = 0.33M$ (0.0264) and is applied to the harvestable biomass >75 g/m^2 while the stock is in the Healthy Zone. In the period between formal stock assessments, indicator trigger levels have been established to monitor changes in stock status and are a primary determinant of management adjustments related to fishing mortality, TAC, and the multi-year assessment schedule. Indicators developed to monitor changes in stock status between surveys include:

	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 (2015[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 with a rotation time that matches recovery time (Hoenig 2015, unpublished manuscript). 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 and require further attention.

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 Surfclams 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 geneflow 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), and 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, 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 40x magnification to count the annuli (Almeida and Sheehan 1997, see Roddick et al. 2011, Roddick et al. 2012 for sectioning and aging 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).

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

[2] Orensanz, J.M.L. 2015. Review of Arctic Surfclam fishery management. (unpublished manuscript)

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 increments (Figure 9; 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 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. 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 to 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 9; 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 9; 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 rate (M) is equivalent to the total mortality rate (*Z*) minus the fishing mortality rate (F). 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 9; Figure 23 in Roddick et al. 2012), the upper 5% cut off is 50 years of age that 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 rate (M) since there was no fishery at the time. The commercial fishery on Banquereau has been operating since 1986, or about half the lifespan of the 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 it 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 the number alive at time t. For the 2010 Banquereau survey, Z is estimated with a linear regression of the log transformed numbers at age and was estimated to be 0.07905.

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 ā 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 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 *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 total mortality (Z) including both natural mortality (*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 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.

The offshore clam fishery uses bottom contact gear that disturbs the seabed. This disturbance has a large immediate impact on the substrate and benthic organisms with the dredges liquefying the sediment down to a minimum of 20 cm, removing many large organisms, and causing sedimentation and displacement of organisms adjacent to the track. The long term impacts on the habitat and benthic community of areas fished specific to the use of a hydraulic clam dredge have been studied at a deep site of 65–70 m depth on Banquereau, with the site 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 two years following dredging. In this timeframe, there was an increase in the abundance of non-target benthic species, such as echinoderms, with a shift in relative abundance of the species that were present. Visual methods such as still photos and video recordings could not discern the tracks after one year; however, tracks were visible from the sonar imagery. 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, indicating an effect that extends beyond the disturbed area, variation unrelated to the dredging, or a combination of both (Gilkinson et al. 2005).

Results from sidescan sonar imaging infer that changes to the sediment structure caused by dredging can persist for ten 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, *M. polynyma*; 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.

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 3 vessels currently active in the offshore clam fishery, the area impacted is relatively small compared to the spatial extent of the target species and other fisheries. Since 1986, approximately 3,562 km^2 have been swept on Banquereau (Table 2), and since the Grand Bank Arctic Surfclam fishery began in 1989, approximately 1,176 km^2 have been swept, with most of this activity in 1990–2003 (Table 2). 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 12 years of the fishery (2004–2015) on Banquereau is approximately 152 km^2 and for Grand Bank is approximately 29 km^2. The footprint of the fishery for Banquereau over the last 12 years is shown in Figure 4 and for Grand Bank is shown in Figure 8. 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 a vessel does not return to an area fished 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

Commercial discards and bycatch data are available from:

1. the DFO Newfoundland Region and Maritimes Region At-Sea Observer Programs (International Observer Program (IOP), Newfoundland Region: 1995–1997, 2007, and 2009–2015; and Industry Surveys Database (ISDB), Maritimes Region: 1998–1992, 1994–1996, 1998–1999, and 2008);
2. industry on-board sampling program (1999-2009; see Tables 8a and 8b in Roddick et al. 2012 for Banquereau and Table 6 in Roddick et al. 2011 for Grand Bank); and
3. the Banquereau and Grand Bank surveys (Roddick et al. 2011, 2012, Roddick et al. 2007).

Updated data from the DFO At-Sea Observer Programs was not received in sufficient time to be presented in detail at the Canadian Science Advisory Secretariat (CSAS) meeting and will be presented in a future document.

SURVEY BYCATCH

Results from the most recent surveys for Banquereau and Grand Bank include a summary of bycatch data for those tows having a catch greater than 100 g/m^2, which represents areas that are likely to be targeted by the commercial fishery (See Table 9 in Roddick et al. 2012 for Banquereau and Table 4 in Roddick et al. 2011 for Grand Bank). Bycatch from the Banquereau and Grand Bank surveys was compared to data from the International Observer Program (IOP) sampling programs on the commercial vessels. The survey bycatch data is recorded in more detail with larger sample sizes than the IOP and on-board programs. For the 2010 Banquereau survey, the five bushel subsamples used for catch composition amounted to 38 t of catch. There are eight species that 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. This is much higher than either of the programs sampling the commercial vessels and so could be a function of spatial distribution or gear.

International Observer Program Sampling (IOP) data from Newfoundland and the Maritimes regions indicate that between 1995 and 2015, 19,071,355 kg of catch was observed on Banquereau and 5,559,462 kg was observed on Grand Bank, with no observer coverage during the years 2000–2006. The observers are instructed to obtain the best estimate possible, but the method used – i.e., sub-sampling or visual observation – is not specified or documented (Joe Firth, DFO Newfoundland, pers. comm.). Table 3 shows the catch composition by year. Overall, Arctic Surfclams accounted for 77.71% of the total observed catch, while Northern Propeller Clams, Greenland Cockles and Ocean Quahogs were 14.69%, 2.03%, and 0.11%, respectively. The most abundant non-bivalve species reported were sand dollars (3.76%), whelk (0.21%), and sea cucumbers (0.18%). The year 2007 stands out for the low number of species; stone and shell were recorded in 2010 and 2011, but not previously. There are a number of non-specified groupings that vary in their use between years, such as, skate (NS), sand lances (NS) and scallop (NS). Winter Skate were recorded in 1995 and 2015. The Committee on the Status of Endangered Wildlife in Canada (COSEWIC) designated the Eastern Scotian Shelf – Newfoundland population of Winter Skate as Endangered in 2015. Thorny Skate are the most common skate identified. Thorny and Smooth Skate, which was also only reported in 1995, under were both given statuses of Special Concern by COSEWIC in 2012.

When the rock and shell categories are removed for the Banquereau data, sand dollars are the only non-bivalves that make up more than 1% of the catch. Arctic Surfclams make up 79% of the living catch overall, and range from 66 to 93% within years.

ON-BOARD SAMPLING PROGRAM

The on-board sampling of the catch is shown in Table 8 in Roddick et al. (2012). The number of items is between that of the IOP program and the survey sampling. The sampling is done by taking a 1 bushel sample of the catch and separating the components. The samplers are provided with reference materials but have limited experience in species identification. Most of the components are at the genus level or higher, accounting for the shorter list than from the survey, where samples can be frozen for later identification. Arctic Surfclams were 49% of the catch or 60% of living material. Sand dollars were 14% of the living material, the only non-bivalve component making up more than 1% of the catch.

CLIMATE

The vulnerability of Arctic Surfclam to ocean warming and acidification have 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 et al. 2016). With warming temperatures, a bathymetric shift in the distribution of Arctic Surfclams would be expected, similar to the shift to deeper water observed for inshore Atlantic Surfclams (*Spisula solidissima solidissima*) 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, it would also be expected that changes in growth rate, tissue weight, and mortality rates would occur. 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, conversion factors. Additionally, physical samples are sent to DFO for processing morphometric details. Vessel Monitoring Systems 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 data has been 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 10). 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 1,500 kg and less than 30,000 kg of catch per watch. Most of the outliers are the result of errors and partial watches, and 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 a 1 square km grid for the period where VMS data is available (2004–2015) in order to examine the spatial distribution of the fishery (Figures 4–8). 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. CPUE was calculated by taking the sum of total catch over the sum of total effort within each cell (Figure 6). 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 4). 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 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; synonymous here with dredge efficiency), selectivity differences and other changes in the efficiency of the fishery over time. Grand Bank has seen much less fishing activity than Banquereau since 2004 so minimal new fishery information since the last assessment was available (Roddick et al. 2011) and is sparse for this area (Figure 7).

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 11).

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 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 (SE) = 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 that 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 12). 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 13); however, the catch composition in the survey is similar to that of the fishery in 2009–2010 (Figures 9 and 11).

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 12. The profile is rounded, rather than sharp, and that is reflected in the standard deviation for the estimate (0.48). The maximum likelihood estimate of dredge efficiency was 45% with a right skewed 95% confidence interval of 21–86% (Roddick et al. 2012, Figure 14). These results reflect considerable uncertainty in estimates of dredge efficiency.

The length frequency for the total survey and ageing results are shown in Figure 9. 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 9 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 15, 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. Reviews of the previous research documents indicated concern over providing harvest advice for the bank wide biomass instead of just the fished areas (Hoenig 2015, unpublished manuscript). The challenge was to identify which areas containing harvestable densities. Ideally, fine scale habitat information could be used to predict Surfclam habitat using relevant covariates that are related with clam abundance and distribution. Until these types of data are available, the high resolution VMS data can be used to construct an approximation of clam habitat by assuming in recent years (since 2004) the fishery has targeted all areas with fishable concentrations. This assumption may hold true for Banquereau but not for Grand Bank.

On Banqureau, the density of VMS locations was estimated from 2004-2015 (Figure 16). This image was produced using the kernel smoothed intensity function from the Spatstat package with a sigma of 0.2 (Baddely et al. 2015). 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 was used to define the area would be considered clam habitat that can support a fishery. The area of viable clam habitat is sensitive to the threshold used to define it and this level was chosen somewhat arbitrarily.

SPATIAL MANAGEMENT AREAS

In order to facilitate the discussion of spatial management, a test case defining a small number of areas were delineated. The criteria for defining the areas were:

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.

An example set of five areas were proposed for consideration of spatial management (Figure 17). A summary of the available data by area is provided in Table 4 that 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, As = survey area, At = 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 management areas (Figure 17, Table 4).

Whereas the survey data is now six years out of date, the only new information to inform the current status of the fishable biomass comes from the CPUE index derived from the fishery information. As discussed above in the fishery data section, CPUE expressed as density of Surfclams (t/km2) 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 jth observation removed. The annual CPUE index with standard errors is shown for each area along with the daily CPUE (Figure 18). The daily CPUE was shown to see if depletion effects are apparent at these spatial and temporal scales.

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 2004–2015 in Tables 5 and 6, respectively. In 2010 the estimated total fishable biomass for all areas was 209,261 t from the survey data and was 217,604 t from the CPUE data. The biomass estimate from the CPUE density for 2015 is 137,008 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 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:

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

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 for 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 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 (στ2) are the uncertainties that propagate into future states via the recursive form of the logistic equation (i.e., errors in Bt+1 in the state space of Bt vs Bt+1). Observation errors (σε2) refer to the uncertainties associated with measurement and observation (i.e., measurement/data-related errors of both variables in the state space of Bt vs Bt+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; 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 its CV 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 Just Another Gibbs Sampler (JAGS) platform (Plummer 2003, Plummer 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 (0.38) was lower than the results of the 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).

Biomass estimates, presented in Figure 23, reveal a general trend across areas where biomass increased in the early 2000s and declined somewhat in recent years. Exploitation rates have varied as the fishery shifted its focus between areas (Figure 24). Exploitation rates were high in Area 5 in 2015 as catches have remained high and catch rates have declined. Spikes in exploitation are typically followed by reduced exploitation in subsequent years and do not normally occur in multiple areas in the same year.

INDICATORS AND REFERENCE POINTS

The logistic biomass dynamic model also provides parameter estimates which allow for the estimation of Maximum Sustainable Yield (MSY) reference points where MSY = $0.25rK$, $B_{MSY} = 0.5K$ and $F_{MSY} = 0.5r$. 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).

Maximum Sustainable Yield calculations have been used before by Chaisson and Rowell (1985) to estimate yield for Arctic Surfclams on Banquereau, but these approaches have fallen out of favour as stocks have collapsed when their fisheries were managed at MSY. It is currently used as an upper limit that triggers corrective action if this level is reached. Lower yield levels such as 2/3MSY and $F_{0.1}$ are more common in recent literature, but some stocks have declined using these as well. More conservative equations such as Maximum Constant Yield (MCY) = xMB_0 (Annala 1993) are more recent, and based on a strategy of setting a yield that is low enough to be sustainable at all probable biomass levels. The "*x*" in xMB_0 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, 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).

DISCUSSION

Hoenig (2015, unpublished manuscript) characterises DFO's initial management of the fishery as adequate for the time but also states that this management...

> *"...does not guarantee sustainability of the fishery. This is because much of the biomass is present at densities too low to make harvest commercially viable. Thus, a total allowable catch (TAC) calculated from the total (bank-wide) biomass may lead to the patches with commercial quantities of resource being fished down faster than they can be renewed through recruitment and growth of new biomass."*

With this criticism in mind, the new analysis presented in this document seeks to estimate biomass in only the fished areas. Future analyses could evaluate habitat suitability in areas outside of those identified here, but 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, CPUE is the only source of information in regards to current stock status. It is also the only information that is available as a time series of abundance. For these reasons, the data CPUE was relied upon fairly heavily in the new analyses presented in this document 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 to the entire Bank, for which much of the associated uncertainty has not been captured in the estimates of abundance. By expanding average density across all tows to the total area of the Bank without accounting for the variability in in selectivity or dredge efficiencies leads to considerable uncertainty in these biomass estimates. By not propagating the errors associated with these processes, more uncertainty is presented in the biomass estimates provided in 2010, but they were not incorporated into the final estimate for Banquereau. The selectivity adjustment involved differencing two selectivity curves that were estimated from different methods. This was acknowledged as being problematic, and the confidence interval for the dredge efficiency estimate was very wide. The selectivity adjustment was not necessary when examining commercial CPUE data. In order to address uncertainty in dredge efficiency, it is useful to consider the conservative scenario where $q = 1$ (Biomass = 137,008 t, in 2015; Table 5). Alternatively, the spatial production model provides a context where the uncertainties in dredge efficiency are captured in the posteriors of the estimated parameters (Biomass = 404,880 t, in 2015; Table 7).

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 areas presented here were intended to include contiguous beds that are more likely to exhibit similar dynamics while still satisfying the other criteria mentioned above and in the Spatial Management Areas section.

The MSY based reference points presented in Figures 25 to 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 provides 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., hyper stability). 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.

QUALITATIVE RISK ASSESSMENT

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) versus low F (MCY) 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)	Medium	Extreme
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 reference points were calculated from the surplus production model with F_{MSY} estimates near 0.1; however, phase plots (Figure 28) indicate that catch rates tend to decline when F is greater than 0.5. Despite how the spatial management 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}.

RESEARCH RECOMMENDATIONS

Catch Per Unit Effort (CPUE) data are the main source of abundance information since recent fishery-independent data (e.g., scientific survey data) are not currently available. Analyses should be undertaken to identify and correct for potential biases of CPUE.

The bias of improving efficiency over time could be partially addressed by further experiments to improve estimates of commercial dredge efficiency. Efficiency is also expected to increase as knowledge of suitable clam habitat is acquired and new technologies are implemented. Regular communication between industry and science staff with respect to changes in fishing techniques is necessary as an input to the interpretation and standardization of CPUE data.

With high resolution track data of fishing vessels, the patch model or similar depletion approaches could be implemented to look at depletion rates and vessel return rates. A spatial depletion analysis of the fishery data could also be investigated to assess recovery times.

Further evaluation of potential assessment/management areas on Banquereau including the criteria that could be used to delineate the boundaries of these areas is recommended.

A potential strategy to ensure the long-term viability of the resource is the use of closed broodstock areas. It is not known if the biomasses outside of high density areas can act as a source of recruitment into exploited areas.

Further investigation of Arctic Surfclam dispersal, connectivity, and source-sink dynamics is warranted, including the role of biomass outside of fishing areas and the remaining biomass within depleted areas. To inform the work of establishing protected reproductive areas, improved knowledge of larval recruitment dynamics and interconnectivity among Arctic Surfclam patches within Banquereau is essential. Biophysical simulations and genomic analyses could be used to investigate these processes and population characteristics.

An improved estimate of biomass is needed for Grand Bank. Exploration of the application of methods used for Banquereau is not feasible given that fishery related data are limited since the fishery has concentrated on Banquereau to date.

Since the Arctic Surfclam fishery is managed by a quota based on round weight, every effort should be made to ensure accurate conversion values are used to estimate round weight from processed weight. Conversion factor data has not been collected since 2012 and conversions can vary by year, season, and location. Further experiments are needed to calculate conversion factors for individual products and species. Data for each species should be collected under processing conditions for each of the products that are landed.

Differences in biological characteristics between beds could be investigated. If significant differences exist, there is a potential for the management strategy to be tailored to each location.

If a new fishery independent survey is recommended, the survey design should incorporate habitat suitability similar to the scallop survey in SFA 29 (Smith et al. 2014).

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TABLES

Table 1. Landings 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

Note: Discard data and any Surfclam caught as bycatch from inshore fisheries are not included. Data for the years 2014 and 2015 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 the logbook records.

Year Caught	Grand Bank			Banquereau		
	Catch (t)	Effort (km^2)	CPUE (g/m^2)	Catch (t)	Effort (km^2)	CPUE (g/m^2)
1986	34	n/a	n/a	29	0.841	34.962
1987	1	n/a	n/a	1,210	16.090	75.222
1988	5	n/a	n/a	2,474	24.533	100.854
1989	373	3.369	110.793	9,159	84.935	107.837
1990	6,049	23.645	255.835	6,158	68.198	90.291
1991	2,094	11.339	184.688	714	9.702	73.593
1992	5,161	27.083	190.573	0	0	n/a
1993	13,100	92.840	141.097	64	2.174	29.361
1994	10,979	95.229	115.295	5,313	39.800	133.483
1995	14,907	128.366	116.131	11,425	84.102	135.848
1996	5,772	53.564	107.755	19,262	156.394	123.166
1997	7,492	79.979	93.671	19,517	157.164	124.183
1998	931	11.370	81.864	24,456	237.333	103.047
1999	1,472	18.599	79.159	24,138	254.184	94.961
2000	3,289	45.954	71.572	20,248	233.277	86.797
2001	8,026	110.382	72.714	11,014	158.942	69.298
2002	6,077	120.271	50.531	12,506	148.990	83.939
2003	8,727	120.985	72.130	16,960	147.036	115.343
2004	6,437	66.867	96.259	16,493	149.498	110.321
2005	3,967	51.762	76.646	14,327	141.499	101.249
2006	4,990	75.200	66.360	15,932	116.700	136.522
2007	215	7.480	28.776	17,931	115.435	155.332
2008	0	0	n/a	19,301	130.580	147.808
2009	437	7.520	58.149	24,158	180.480	133.852
2010	296	9.322	31.771	22,558	160.258	140.763
2011	112	9.015	12.372	20,858	130.991	159.234
2012	0	0	n/a	20,214	135.920	148.720
2013	199	6.065	32.851	19,271	149.874	128.582
2014	0	0	n/a	23,657	200.191	118.170
2015	0	0	n/a	20,244	217.353	93.141

Table 3. International Observer Program (IOP) data on species caught for the Arctic Surfclam fishery by year for Banquereau and Grand Bank.

Common Name	**Weight (kg)**					
	2011	**2010**	**2009**	**2007**	**1995**	**Total**
Arctic Surfclam	535,352	1,010,002	1,894,933	1,390,114	1,964,746	6,795,147
Northern Propeller Clam	128,150	28,089	707,588	238,313	182,521	1,284,661
Sand Dollars	60,445	36,810	227,994	3,795	0	329,044
Greenland Smooth Cockle	9,194	129	61,257	99,488	7,493	177,561
Shells	53,310	8,260	0	0	0	61,570
Stone	33,975	4,600	0	0	0	38,575
Whelk	6,625	1,052	10,891	0	0	18,568
Sea Cucumber (*C. frondosa*)	430	5,345	910	0	5,516	12,201
Sea Cucumber NS (Holothuroidea)	0	0	3,221	0	0	3,221
Ocean Quahog	28	70	7,011	0	2,150	9,259
Snow Crab	112	0	2,937	58	0	3,107
Thorny Skate	25	1,046	87	0	1,788	2,946
Skates (NS)	2	1	961	0	104	1,068
Sea Star	19	0	1,286	0	0	1,305
Sea Star (*Leptasterias polaris*)	0	341	41	0	0	382
Blue Mussel	0	0	1,045	0	174	1,219
Mussel	0	37	0	0	0	37
Green Sea Urchin	406	240	43	0	299	988
Seasnail (NS)	0	0	0	0	659	659
Sea Scallop	5	2	230	0	0	237
Scallop (NS)	0	416	33	0	113	562
Iceland Scallop	95	10	406	0	35	546
Atlantic Lyre Crab	0	0	0	0	253	253
Lyre Crab NS	15	0	72	0	0	87
Hermit Crab	106	16	102	0	0	224

Common Name	Weight (kg)					
	2011	2010	2009	2007	1995	Total
Sand Lances (NS)	100	48	0	0	0	148
Yellowtail Flounder	8	45	97	0	41	191
Offshore Sand Lance	0	0	104	0	13	117
American Plaice	0	1	123	0	95	219
Winter Skate	0	0	0	0	112	112
Longhorn Sculpin	0	3	113	0	0	116
Witch Flounder	0	0	107	0	0	107
Atlantic Surfclam	0	100	0	0	0	100
Atlantic Cod	0	0	2	0	35	37
Monkfish	0	0	0	0	31	31
Soft Coral	4	7	1	0	0	12
Spiny Dogfish	0	0	0	0	7	7
Sculpins (NS)	0	0	0	0	6	6
Smooth Skate	0	0	0	0	3	3
Jonah Crab	0	0	3	0	0	3
Haddock	0	0	0	0	2	2
White Hake	0	0	0	0	1	1
Total Weight Observed	**828,406**	**1,096,670**	**2,921,598**	**1,731,768**	**2,166,197**	**8,744,639**

Table 4. Area summary.

					Biomass Estimates			
Area ID	**Total Area (km^2)**	**Fished Area (km^2)**	**Mean Annual Catch (t)**	**Total Catch Since 2004 (t)**	**2010 Survey Total Area**	**2010 Survey Fished Area**	**2010 CPUE Fished Area**	**2015 CPUE Fished Area**
1	3,008	315	3,488	41,853	192,448	25,268	56,081	24,497
2	2,008	436	4,587	55,041	182,519	41,485	55,906	41,482
3	3,251	442	4,051	48,608	338,452	75,118	49,258	31,824
4	1,555	220	2,546	30,552	31,892	10,520	24,870	18,546
5	2,078	185	4,907	58,889	138,773	56,870	31,490	20,658
Total	11,900	1,597	19,579	234,943	884,085	209,261	217,604	137,008

Table 5. Biomass estimates (tonnes) from catch per unit effort (CPUE).

Year	**Area 1**	**Area 2**	**Area 3**	**Area 4**	**Area 5**	**Total**
2004	42,726	30,356	48,459	22,296	22,705	166,542
2005	31,260	39,751	46,346	25,334	48,161	190,852
2006	40,558	37,148	54,123	28,634	42,519	202,981
2007	35,587	57,543	60,441	30,943	41,751	226,265
2008	42,491	61,109	49,664	32,702	41,659	227,625
2009	37,696	45,133	54,312	29,042	31,172	197,355
2010	56,081	55,906	49,258	24,870	31,490	217,604
2011	44,801	59,077	66,908	39,353	35,420	245,559
2012	36,316	57,041	60,258	31,421	37,212	222,247
2013	44,100	42,578	62,087	26,942	25,640	201,348
2014	34,723	55,168	47,630	25,378	23,197	186,096
2015	24,497	41,482	31,824	18,546	20,658	137,008
Mean	39,236	48,524	52,609	27,955	33,465	201,790

Table 6. Catch by area (tonnes).

Year	Area 1	Area 2	Area 3	Area 4	Area 5	Total
2004	6,247	1,687	8,021	518	20	16,493
2005	3,939	3,582	3,320	3,465	21	14,327
2006	1,488	1,616	7,090	726	5,012	15,932
2007	556	3,516	5,781	1,627	6,451	17,931
2008	865	3,701	6,087	2,378	6,270	19,301
2009	1,839	2,567	8,111	2,733	8,909	24,158
2010	2,663	9,592	2,669	392	7,243	22,558
2011	4,390	3,952	3,327	5,100	4,089	20,858
2012	2,973	4,416	1,337	6,777	4,711	20,214
2013	6,226	1,762	866	5,532	4,885	19,271
2014	7,775	11,416	231	787	3,448	23,657
2015	2,892	7,235	1,769	518	7,831	20,244
Mean	3,488	4,587	4,051	2,546	4,907	19,579

Table 7. Biomass estimates (tonnes) from spatial production model.

Year	Area 1	Area 2	Area 3	Area 4	Area 5	Total
2004	98,994	92,229	122,855	58,514	62,121	434,714
2005	90,914	103,075	124,382	66,353	93,170	477,894
2006	96,868	108,245	136,900	71,430	103,748	517,192
2007	97,695	132,881	141,787	77,410	103,754	553,527
2008	105,254	140,128	136,069	79,579	99,624	560,655
2009	108,091	132,022	138,638	76,320	89,746	544,817
2010	120,909	141,898	137,022	73,932	85,163	558,924
2011	113,119	141,172	152,366	85,514	85,283	577,454
2012	102,068	137,234	149,457	78,507	83,293	550,560
2013	101,847	124,522	143,625	69,323	70,509	509,826
2014	88,110	129,915	124,370	61,655	61,709	465,759
2015	73,378	114,116	104,974	55,587	56,825	404,880
Mean	99,771	124,786	134,371	71,177	82,912	513,017

FIGURES

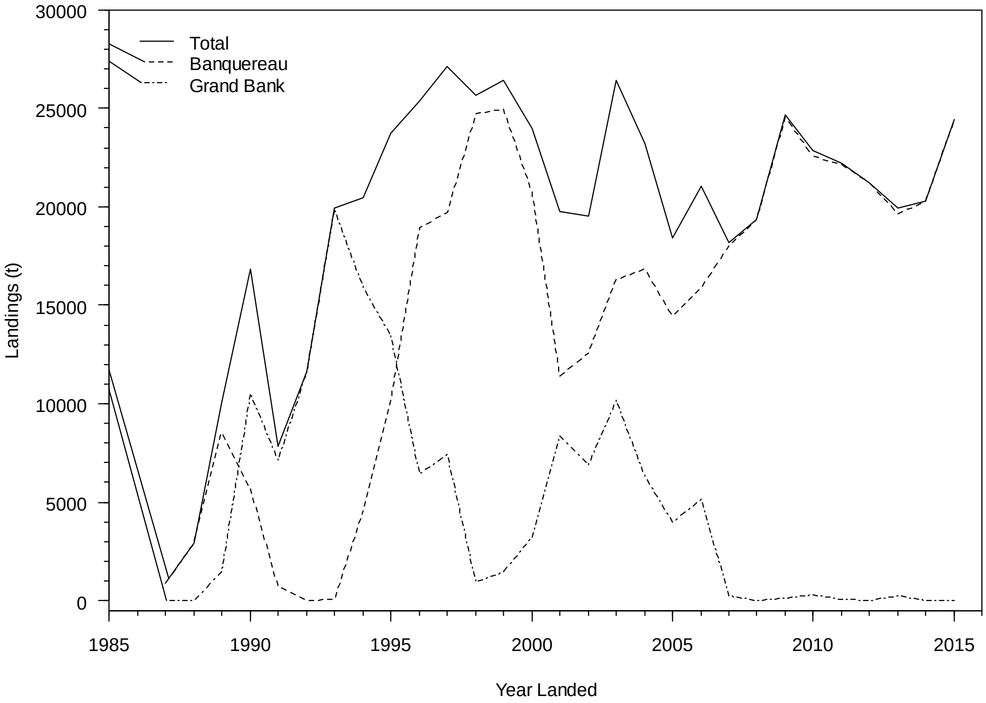


Figure 1. Landings (tonnes) of Arctic Surfclams from the Banquereau and Grand Bank fisheries.

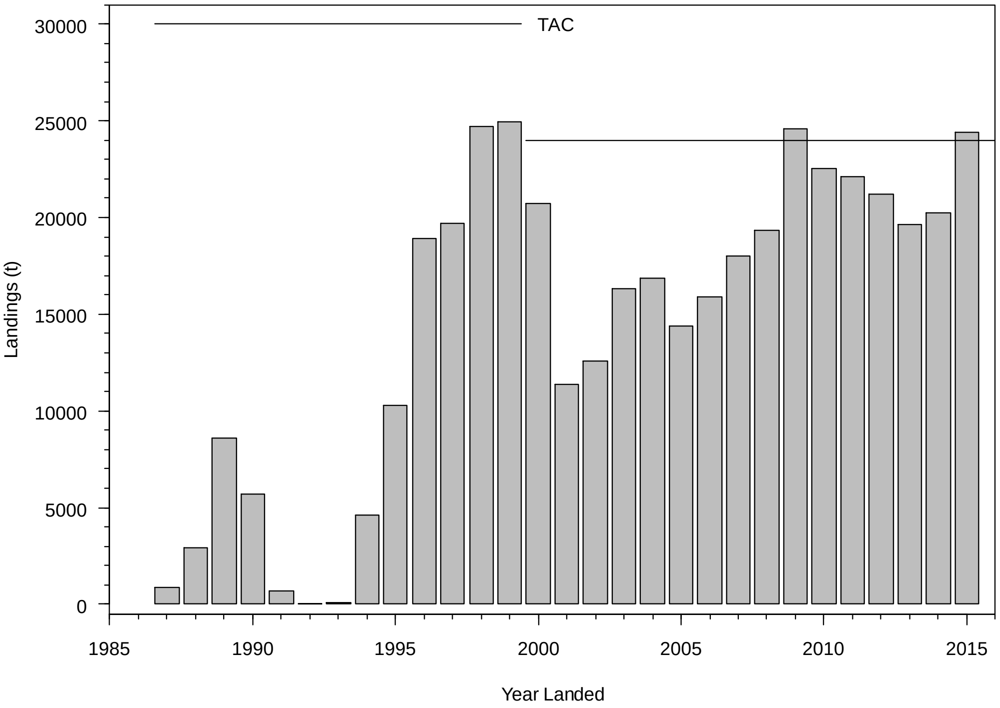


Figure 2. Landings (tonnes) and total allowable catch (TAC; tonnes) for the Banquereau Arctic Surfclam fishery.

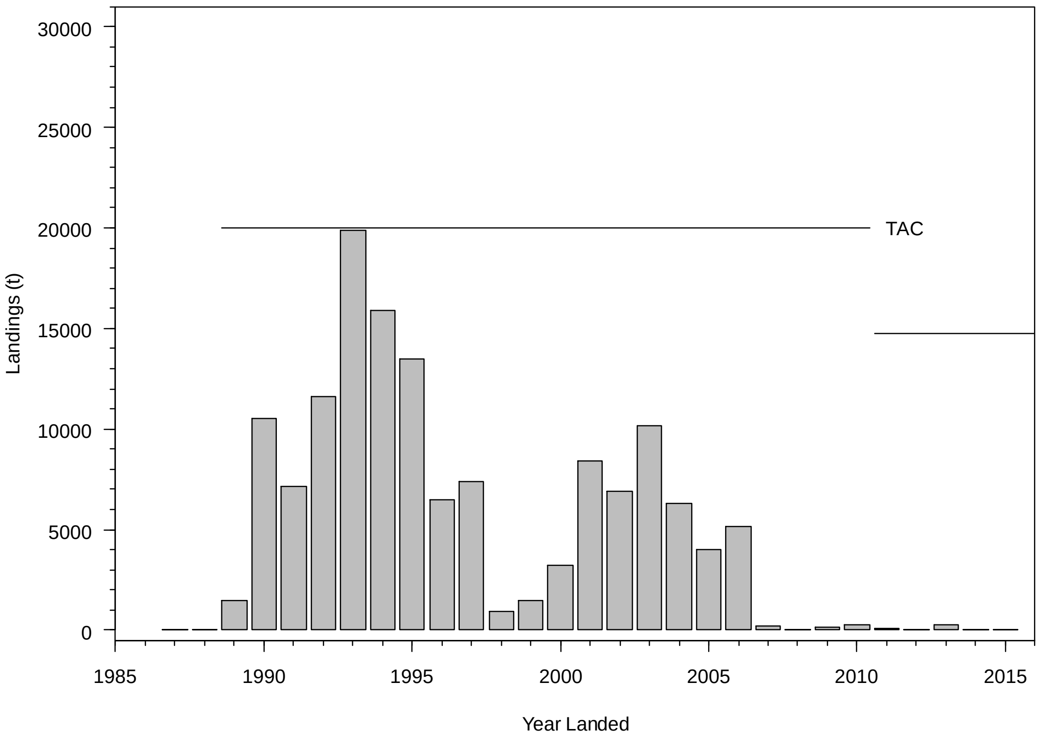


Figure 3. Landings (tonnes) and total allowable catch (TAC; tonnes) for the Grand Bank Arctic Surfclam fishery.

(Figure 4) This figure contains third party information that is not available for publication under *Privacy Act* guidelines.

Figure 4. 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 2015.

(Figure 5) This figure contains third party information that is not available for publication under *Privacy Act* guidelines.

Figure 5. 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 for 2004 through 2015.

(Figure 6) This figure contains third party information that is not available for publication under *Privacy Act* guidelines.

Figure 6. 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 2015.

(Figure 7) This figure contains third party information that is not available for publication under *Privacy Act* guidelines.

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) This figure contains third party information that is not available for publication under *Privacy Act* guidelines.

Figure 8. 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 2015. The dashed line denotes the boundary for Canada’s Exclusive Economic Zone.

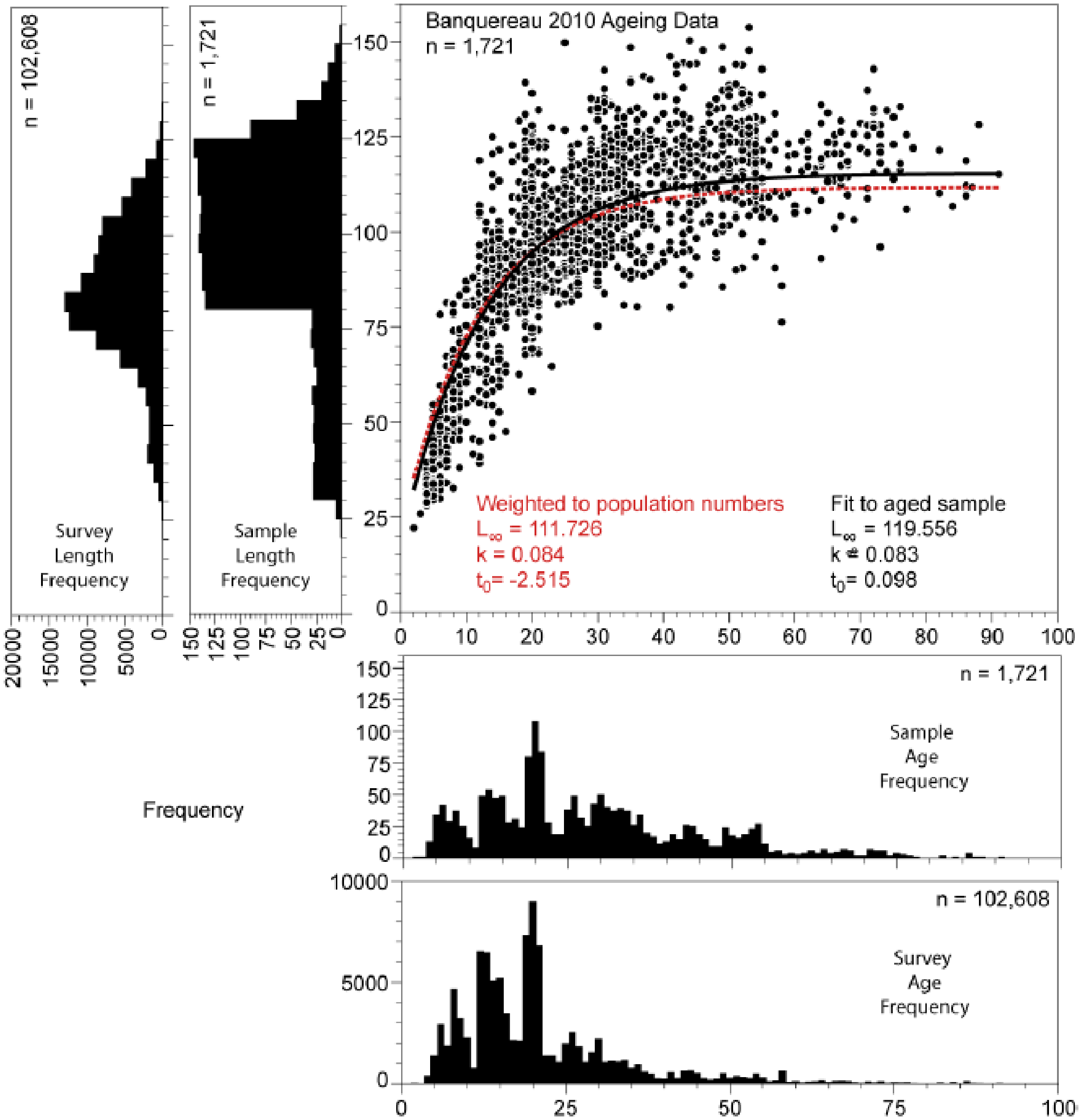


Figure 9. Survey and sample length frequency, ageing results and sample and estimated survey age frequency results from the ageing of a random sample of 1,721 Arctic Surfclams from the 2010 Banquereau offshore clam survey (Reproduced from Roddick et al. 2012).

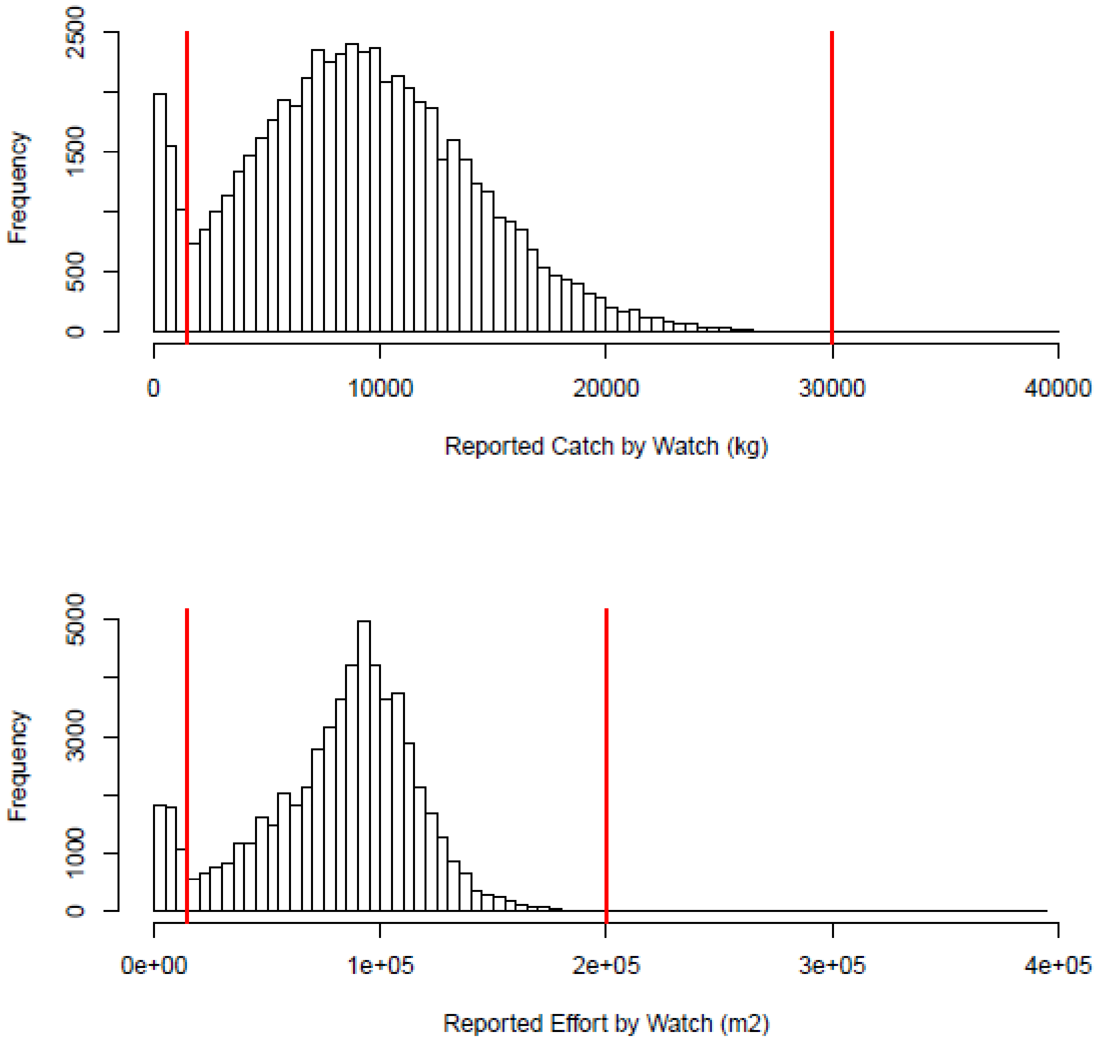


Figure 10. Distribution of catch (kg) and effort (m^2) data by watch from the log records for 2004 through 2015. The red vertical lines indicate where data were censored for catch per unit effort (CPUE) analysis.

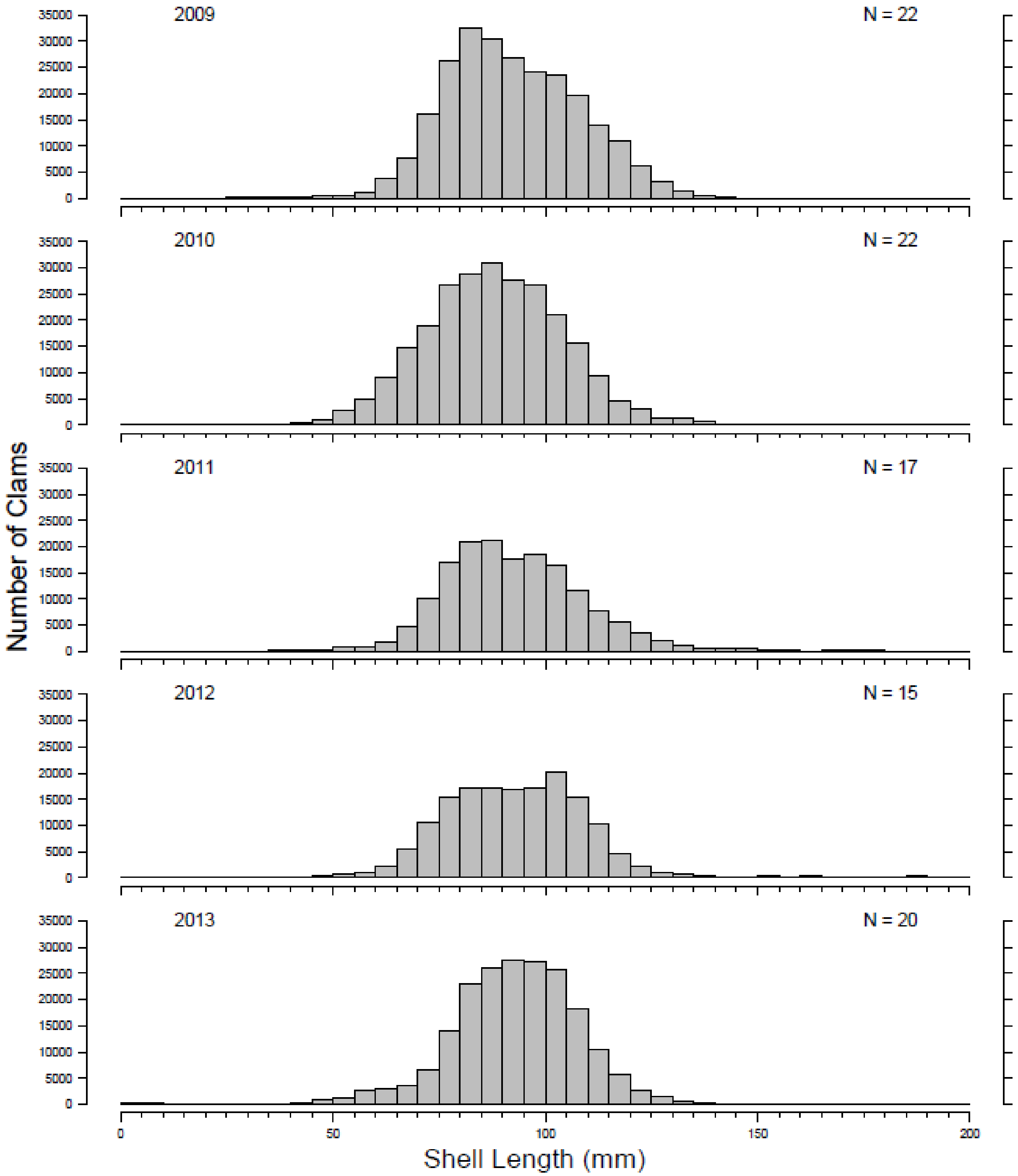


Figure 11. Length frequency distributions for Arctic Surfclams caught in the commercial fishery for 2009 through 2013.

(Figure 12) This figure contains third party information that is not available for publication under *Privacy Act* guidelines.

Figure 12. Comparison of survey station locations for the 2010 Banquereau Arctic Surfclam survey and fishery catch per unit effort (CPUE; g/m2) 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.

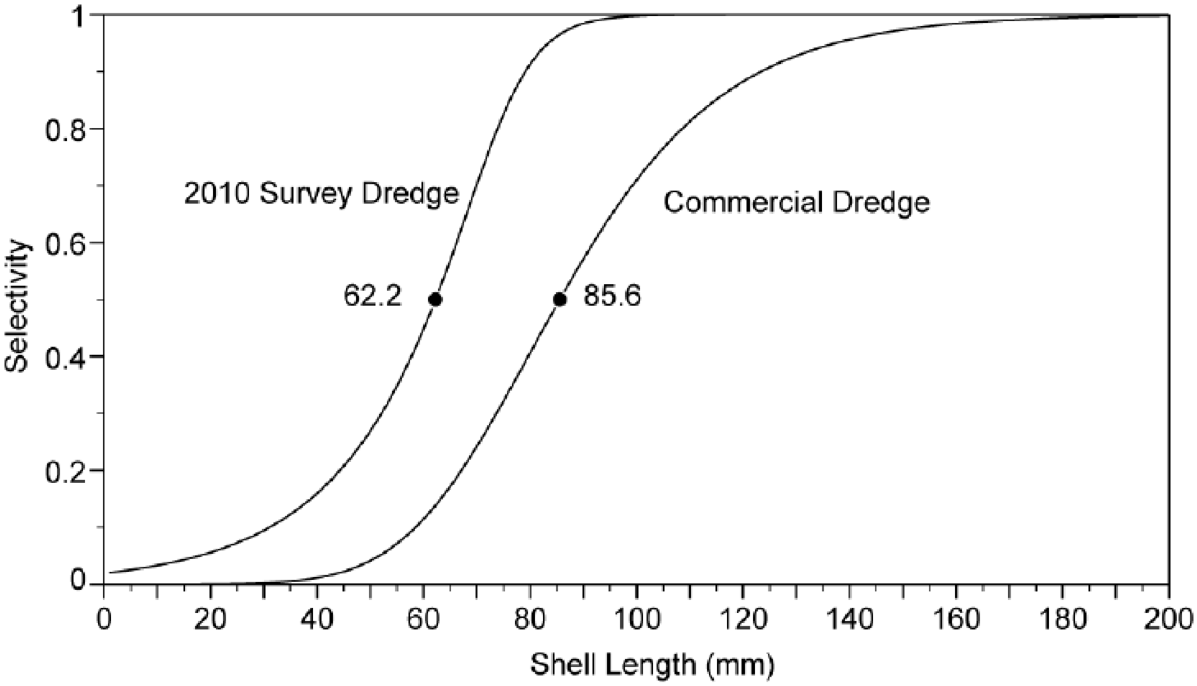


Figure 13. Selectivity curves for the 2010 survey dredge and commercial clam dredge. Sizes at 50% retention are shown (Roddick et al. 2012).

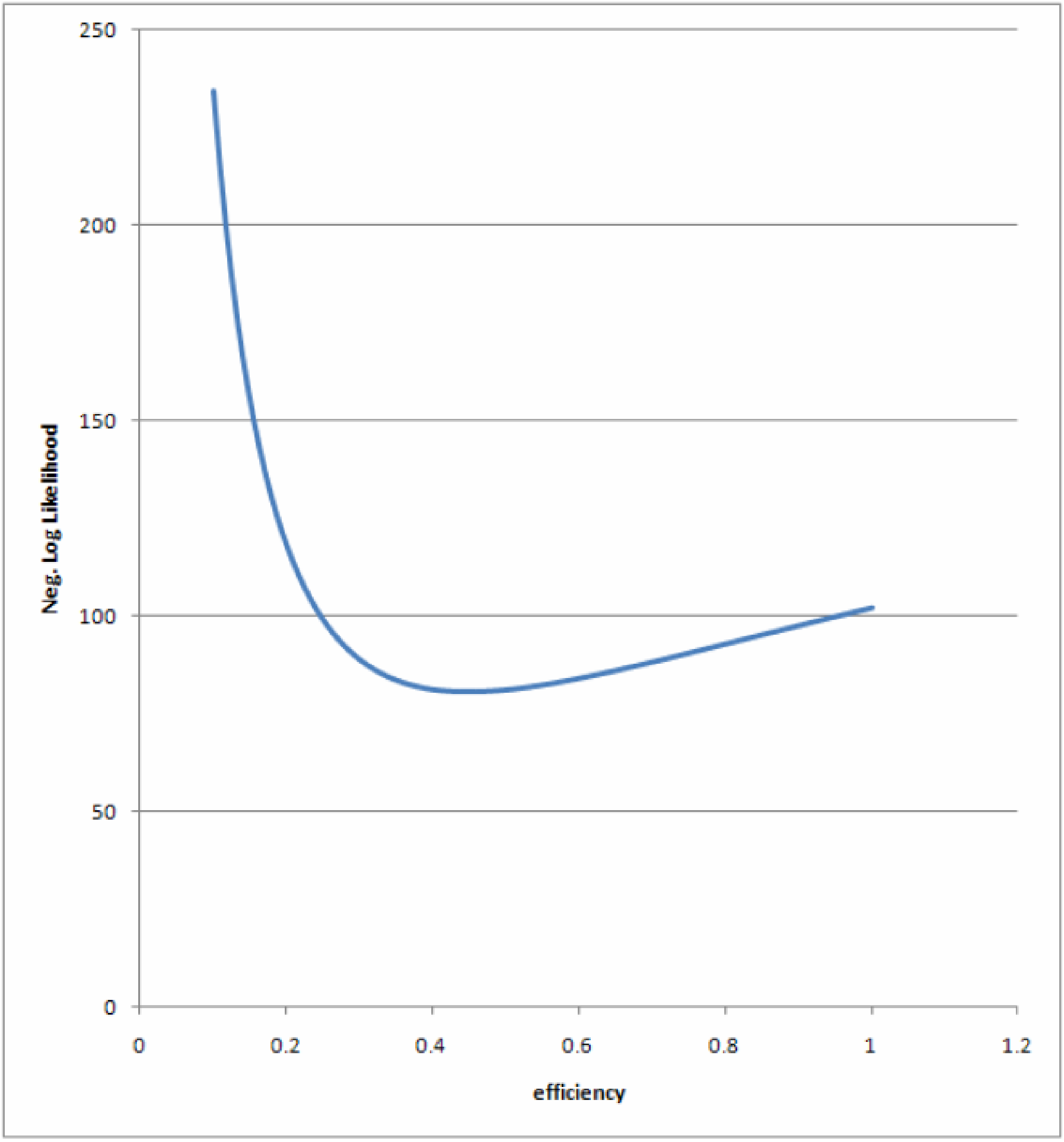
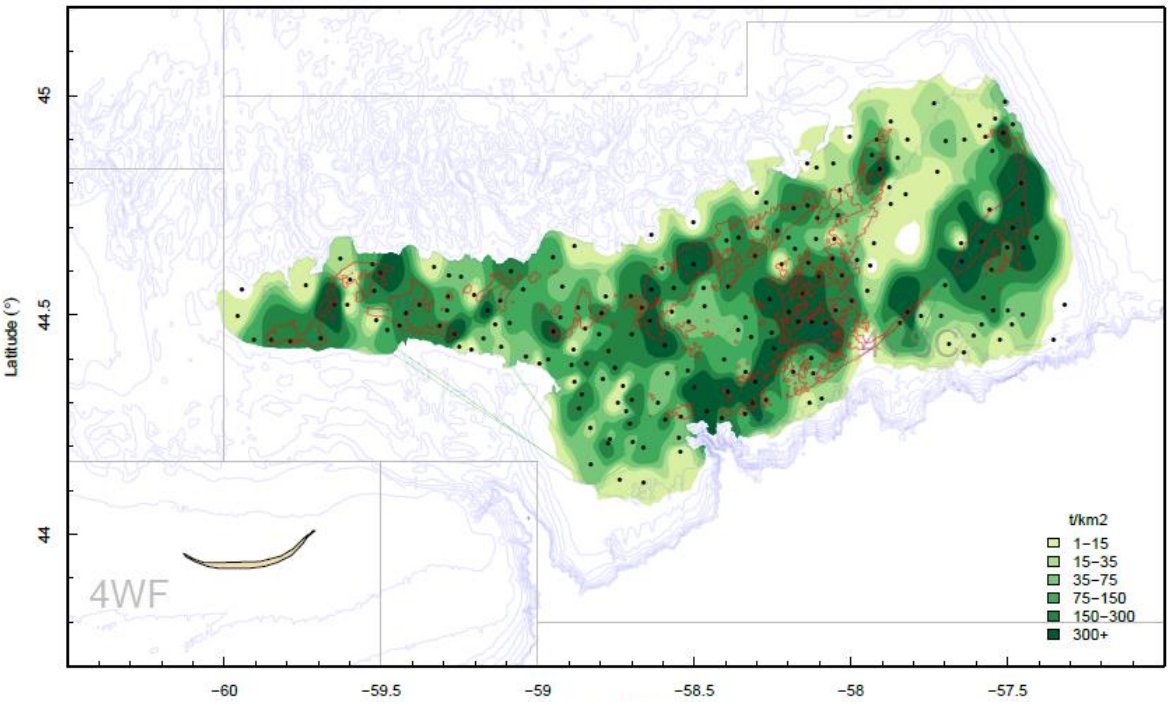


Figure 14. Likelihood profile for estimate of dredge efficiency from patch model (Reproduced from Roddick et al. 2012).

Banqureau Surf Clam Survey Density 2004



Banqureau Surf Clam Survey Density 2010

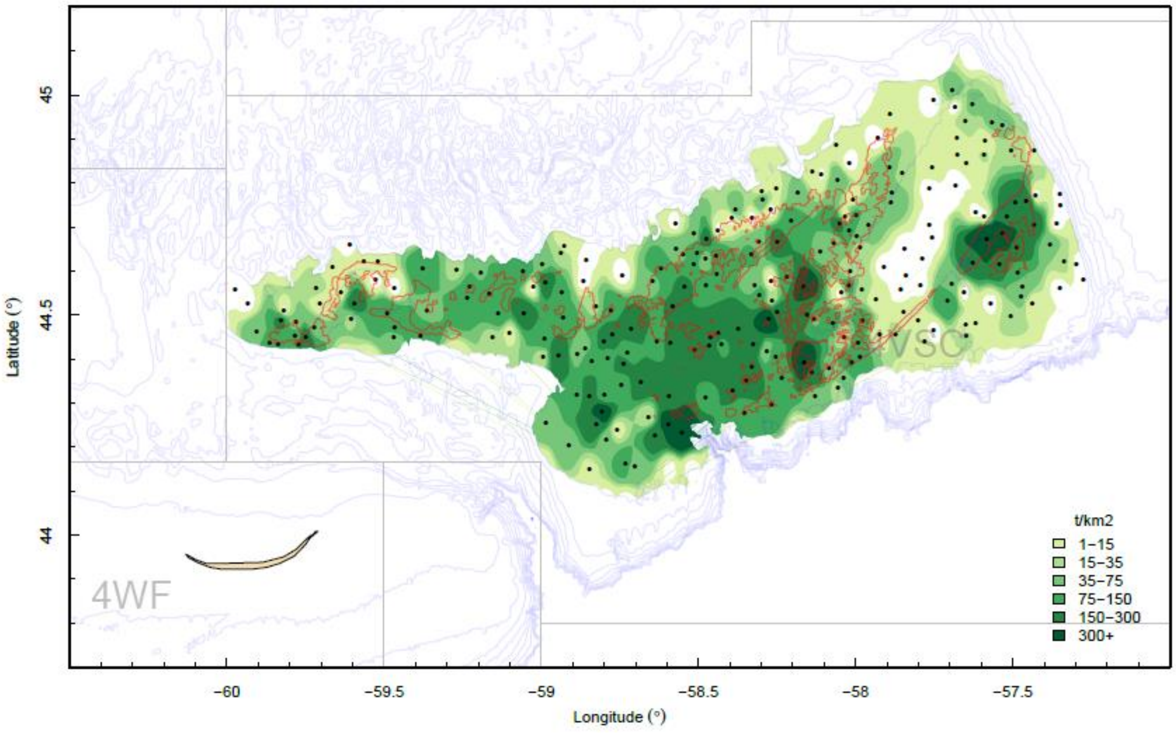


Figure 15. Contour plot of the estimated biomass density of Arctic Surfclam (tonnes/km2) from the 2004 (top) and 2010 (bottom) Banquereau offshore survey. Overlayed with the fished areas from the VMS analysis (red line).

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Figure 16. Vessel Monitoring System (VMS) density estimated from a kernel smoothed intensity function with a standard deviation of 0.2 on a 100m2 resolution. The scale bar shows VMS intensity expressed as the number of transmissions per km2 for 2004–2015.

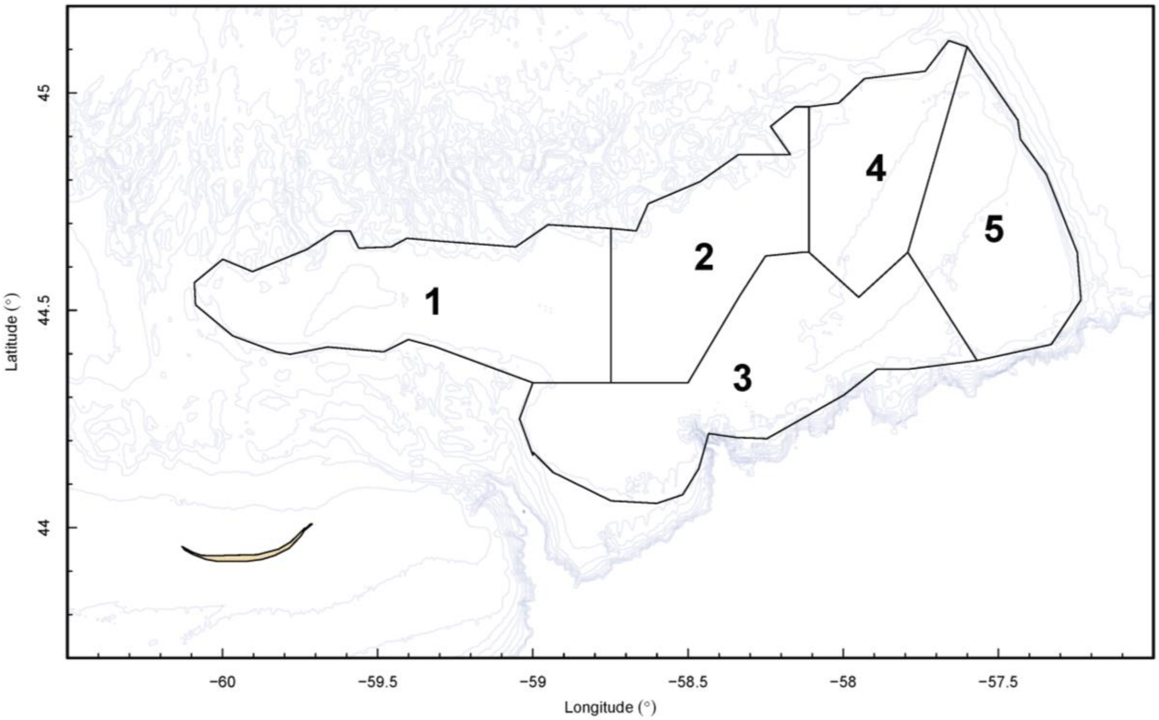

Figure 17. Potential areas for spatial management used for the analyses.

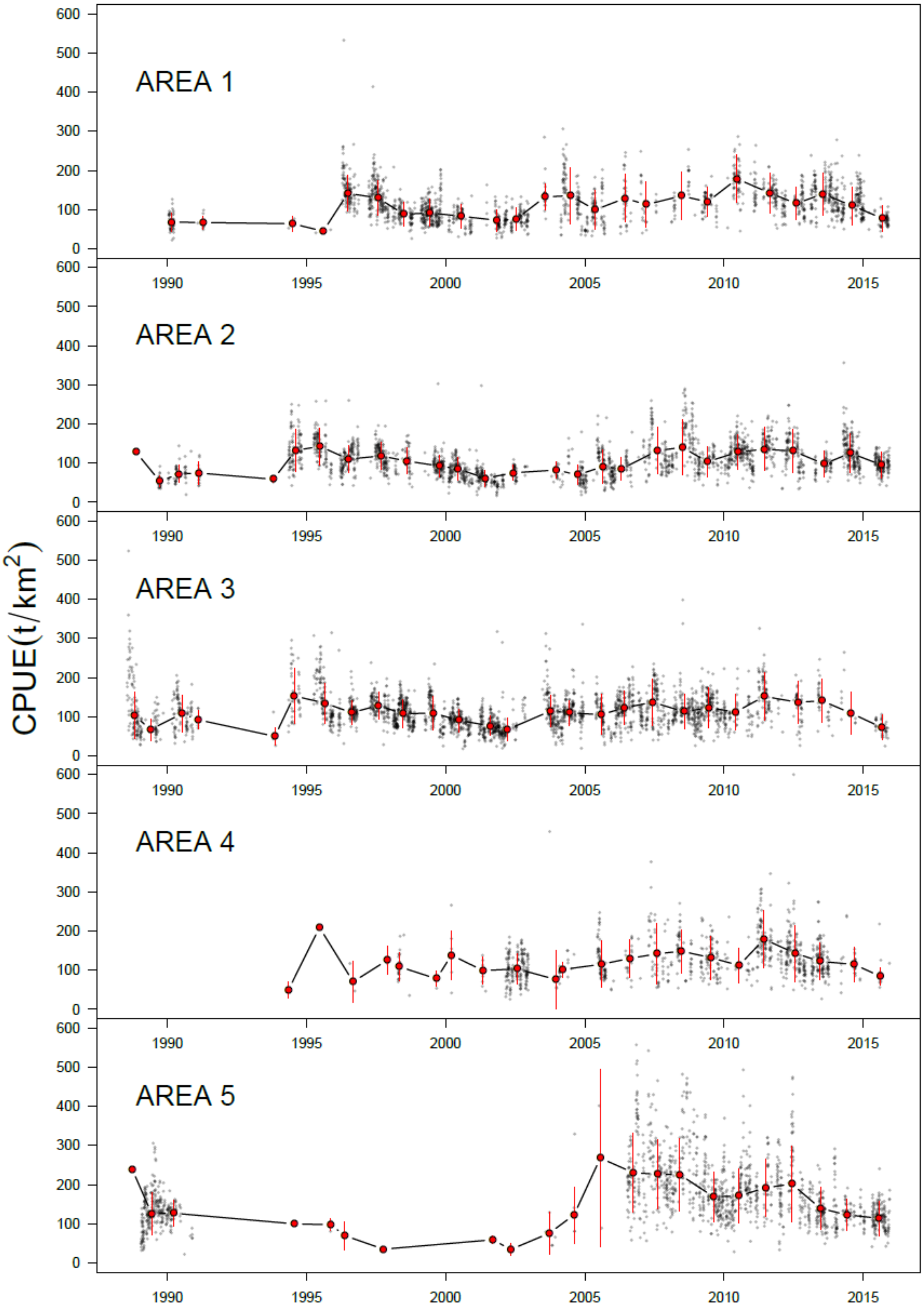

Figure 18. Catch per unit effort (CPUE) by area showing the annual mean values (red points) ±1 standard error and daily values (smaller grey dots) for 1989–2015.

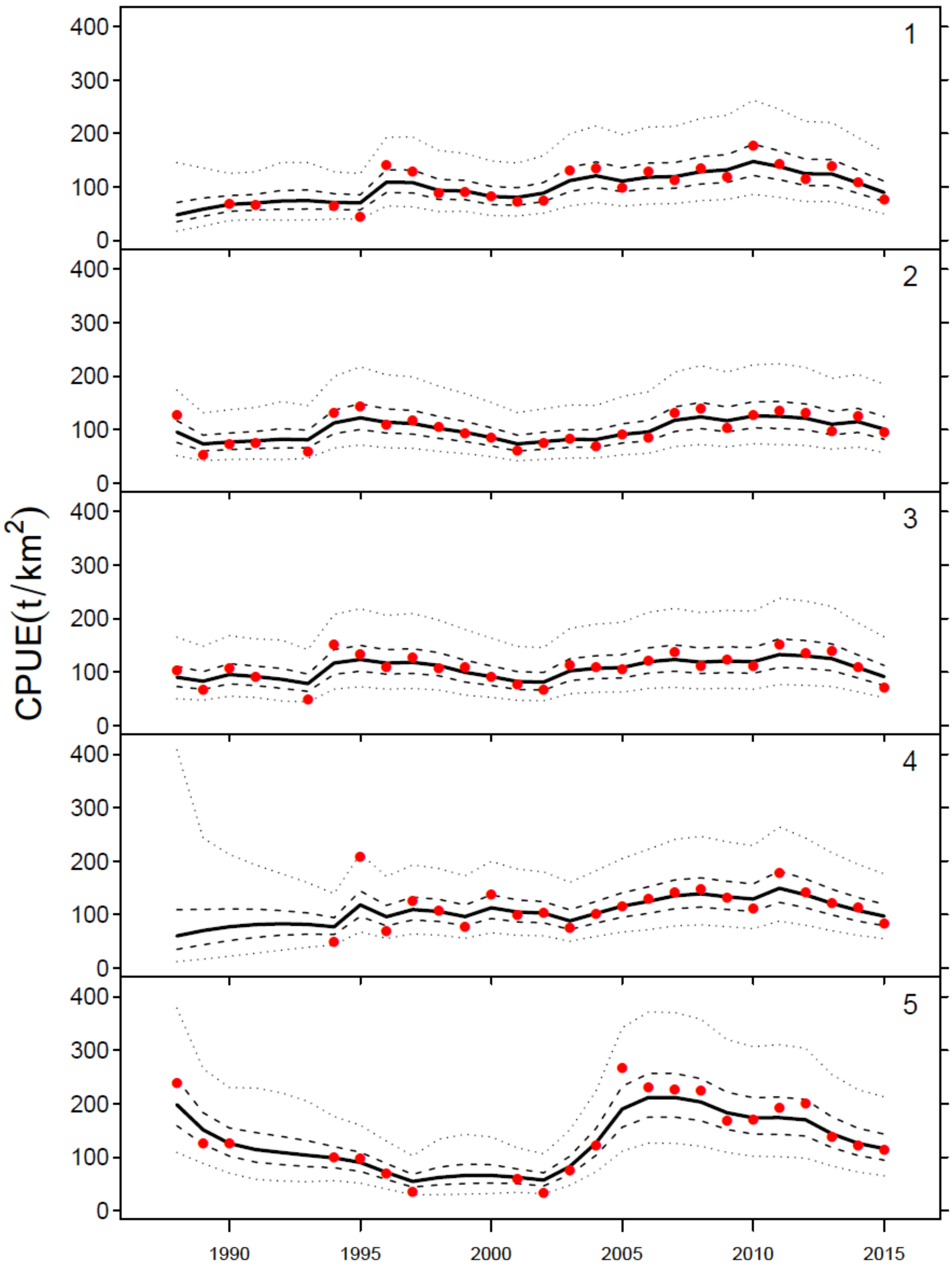

Figure 19. Spatial production model fit to the annual catch per unit effort (CPUE) index (red points) for each area for 1989–2015. Lines indicate the median (solid), 50% credible interval (dashed), and 95% credible interval (dotted).

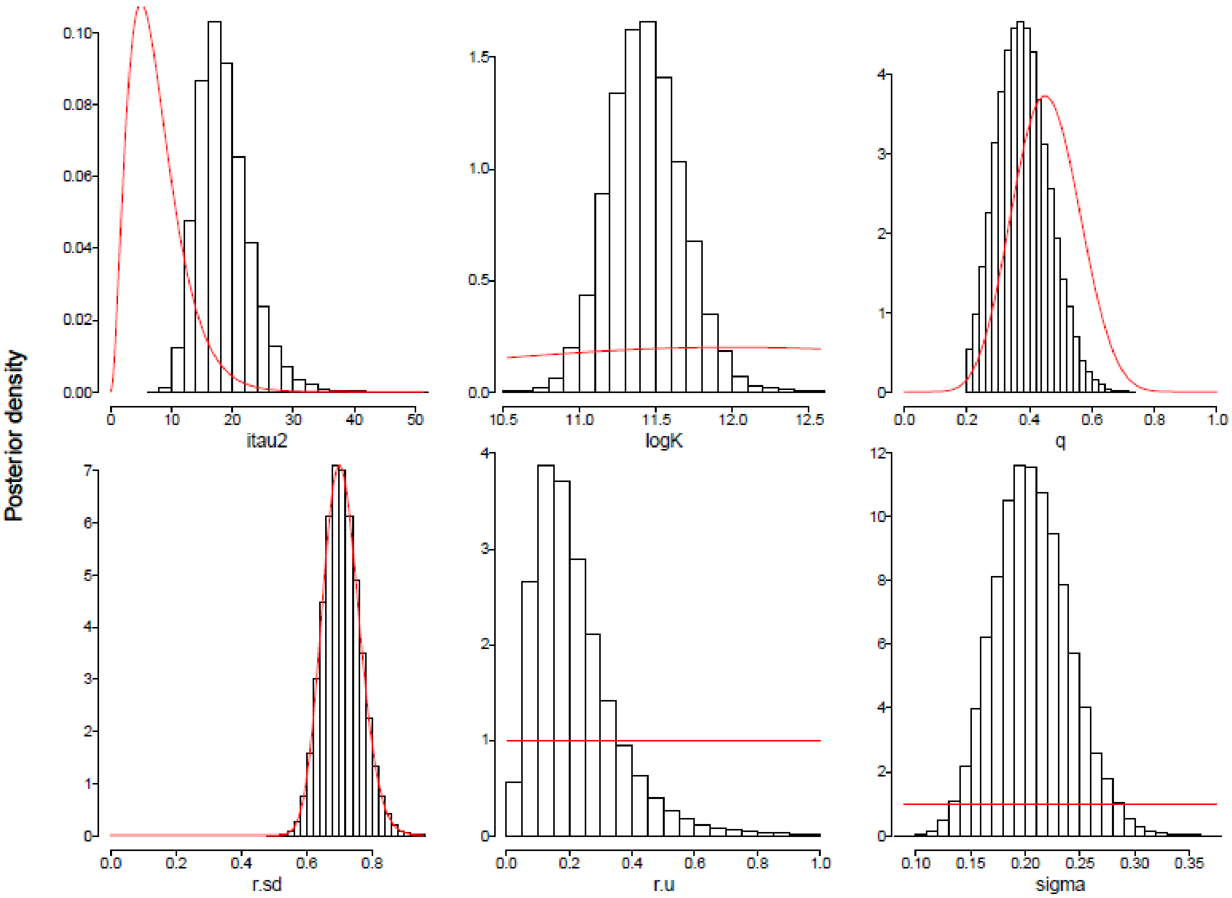

Figure 20. Histograms showing the marginal posterior density values for the shared parameter estimates included in the spatial production model. Top, left to right: observation precision (itau2), log of mean carrying capacity (logK), and dredge efficiency (q). Bottom, left to right: standard deviation 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.

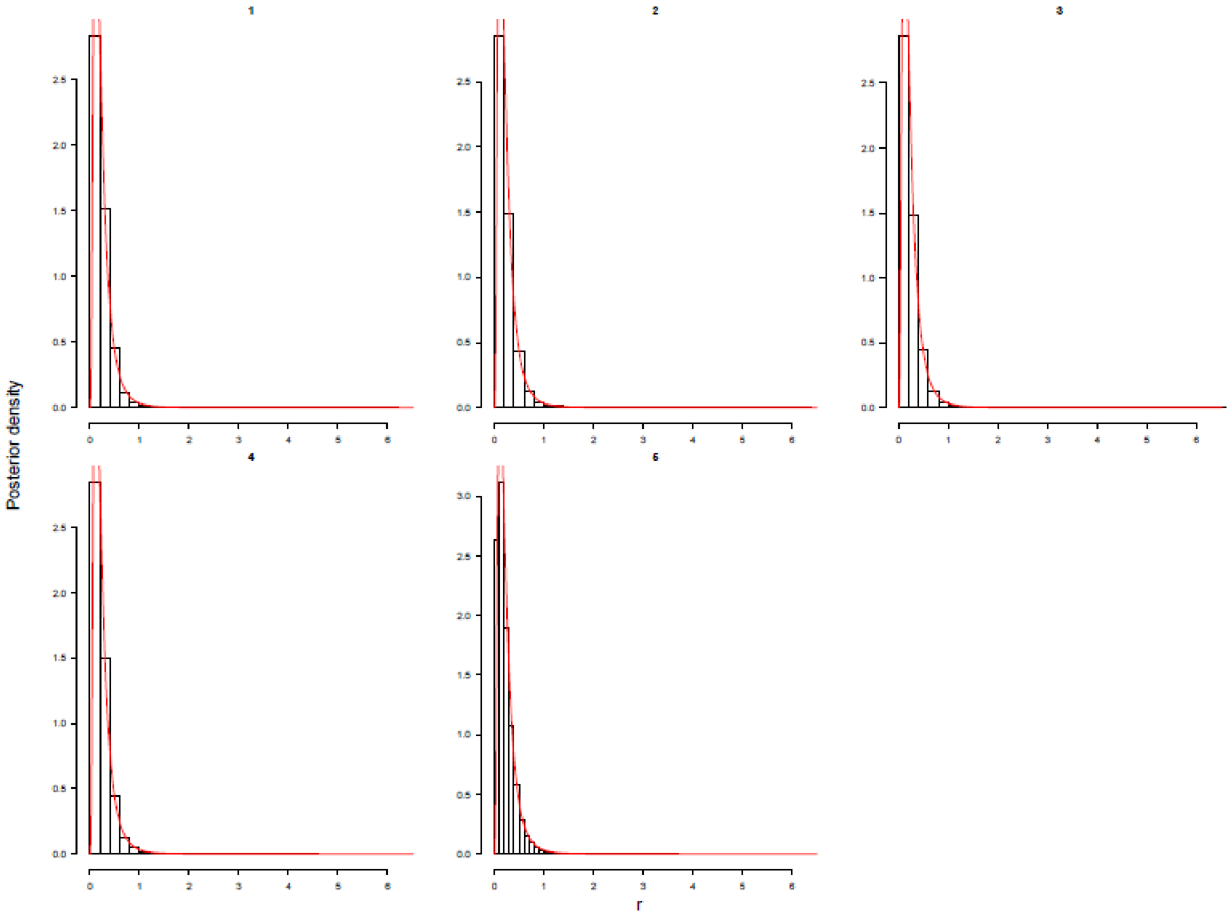

Figure 21. Histograms showing the marginal posterior density values for the estimates of population growth rate (r) for each area from the spatial production model. The red lines indicate the prior density distributions of these estimates defined by the mean and standard deviation of the parameters shown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

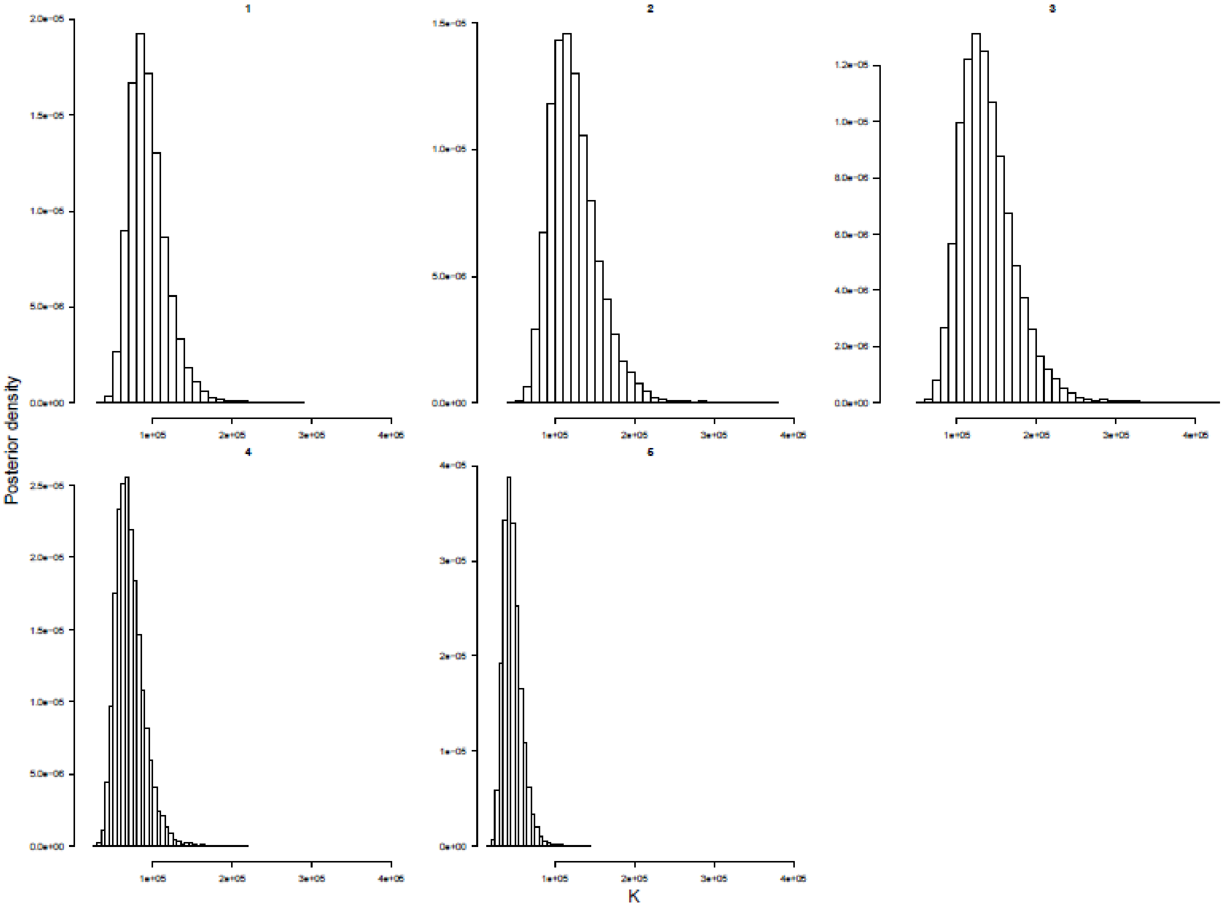

Figure 22. Histograms showing the marginal posterior density values for the estimates of carrying capacity (K) for each area from the spatial production model.

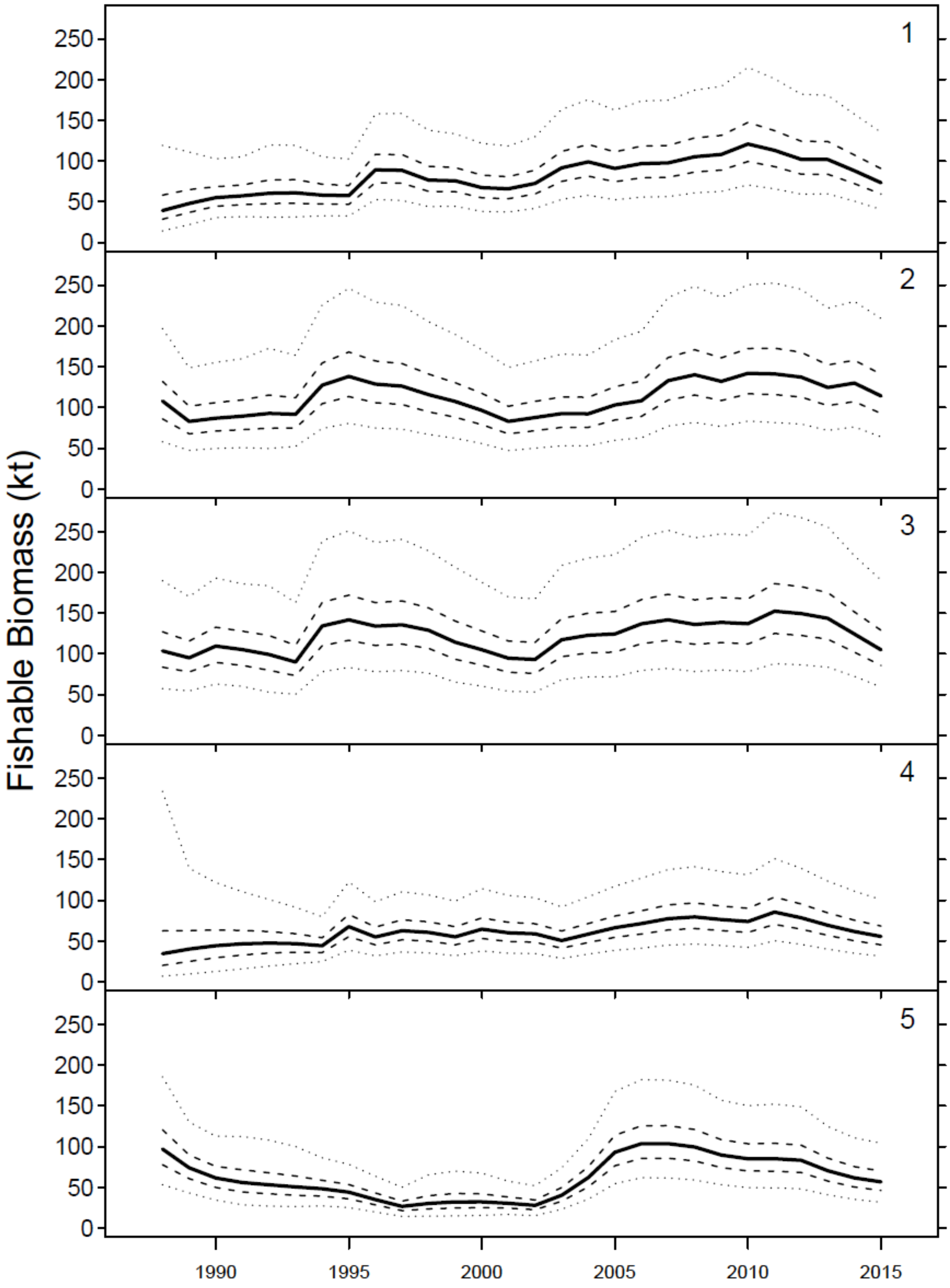

Figure 23. Estimates of biomass (fishable biomass in kilotonnes) from 1998–2015 from the spatial production model by area. Lines denote the median (solid), 50% credible interval (dashed), and 95% credible interval (dotted).

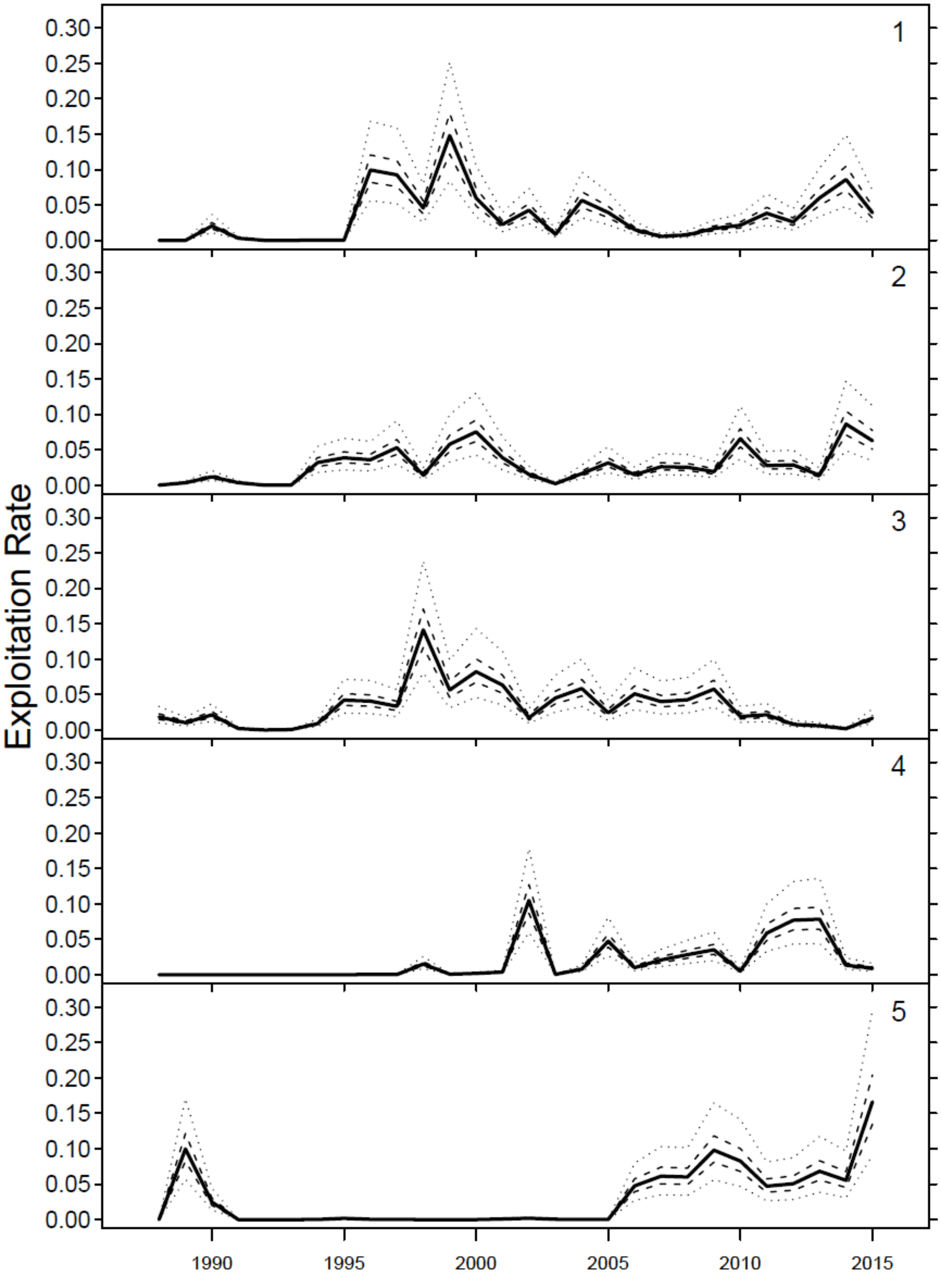

Figure 24. Estimates of exploitation rate for 1988–2015 from the spatial production model by area. Lines denote the median (solid), 50% credible interval (dashed), and 95% credible interval (dotted).

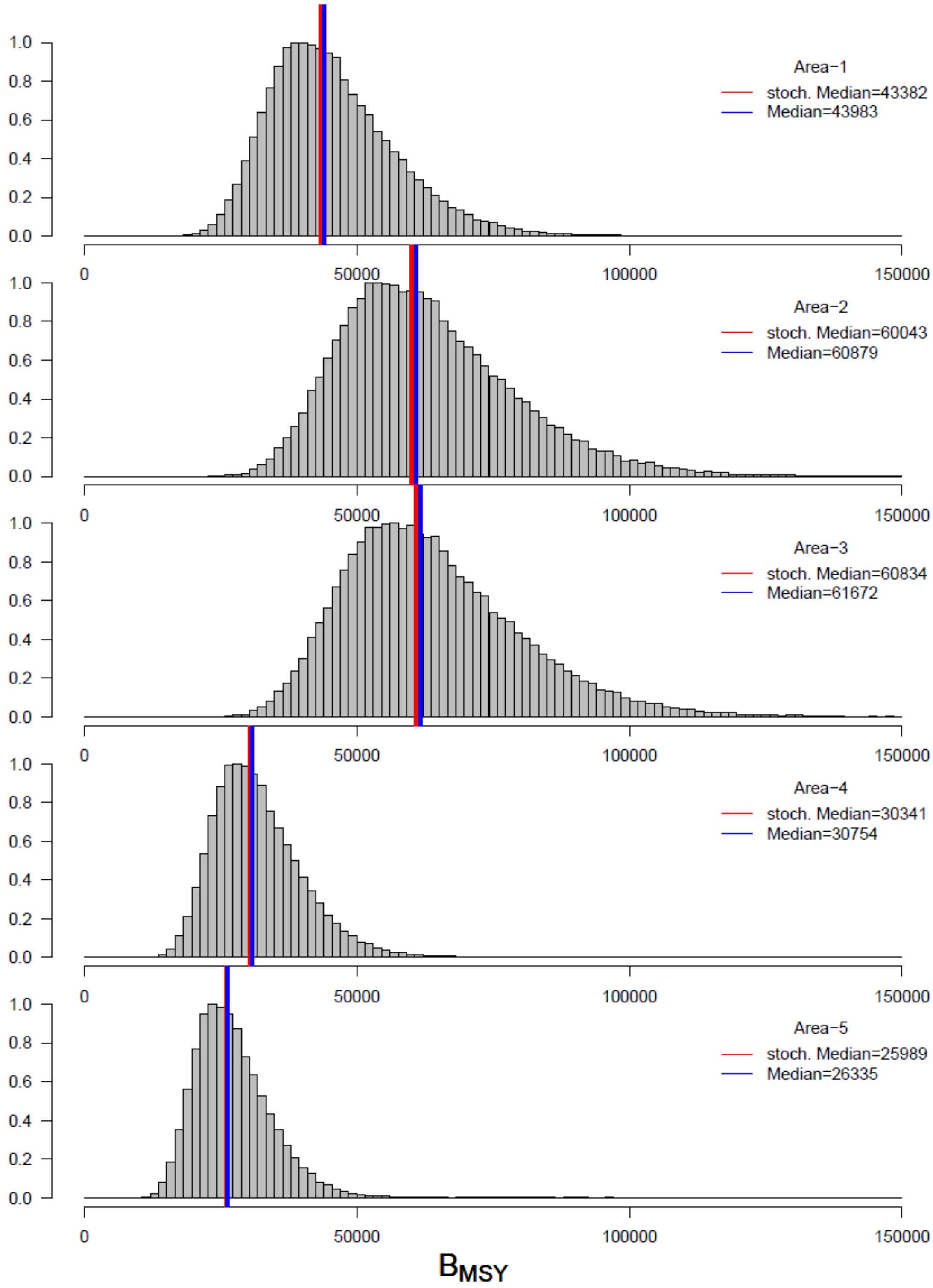

Figure 25. Posterior densities of BMSY reference points by area with the median (blue) and stochastic median (red) of the estimates indicated.

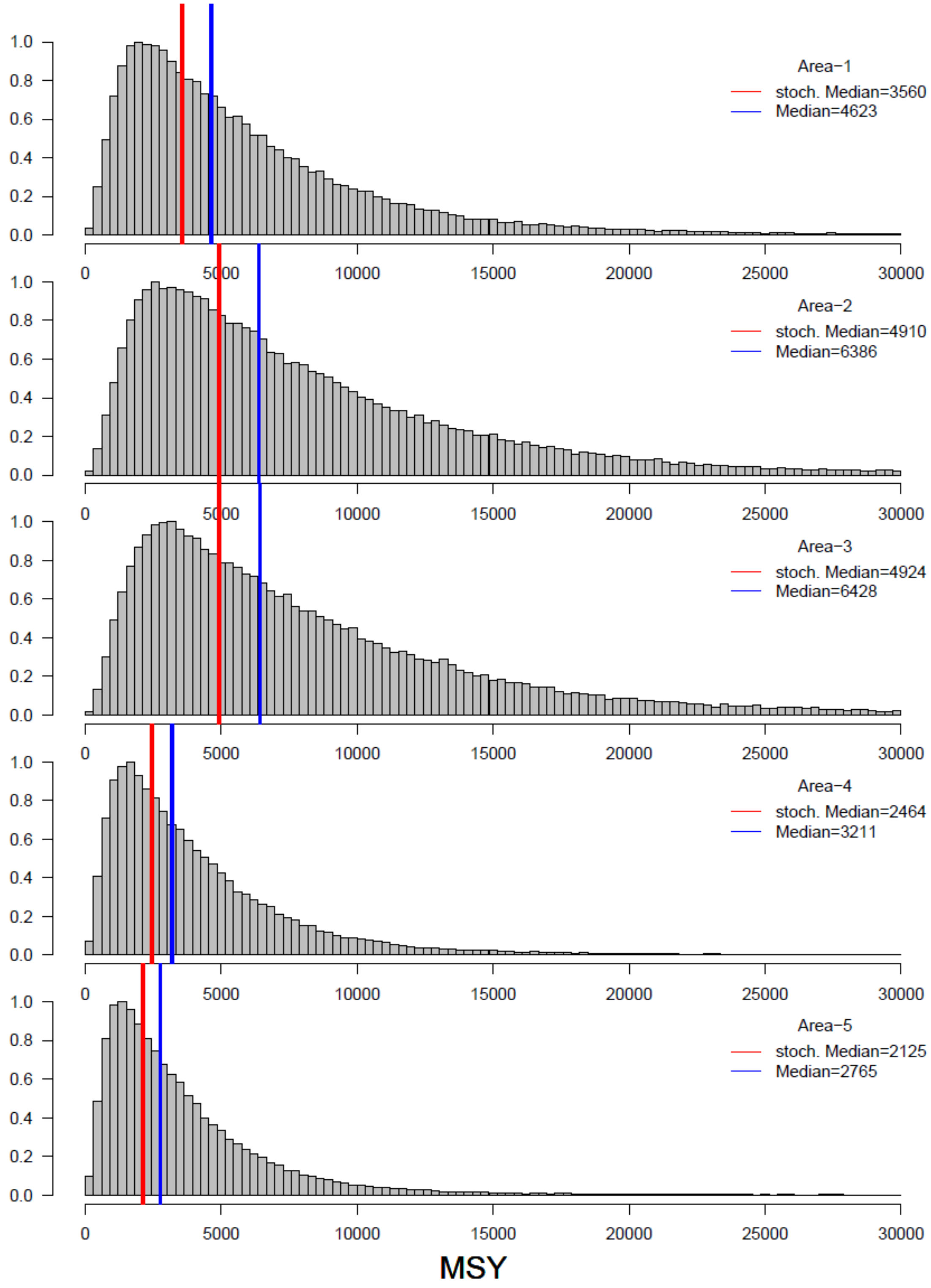

Figure 26. Posterior distribution of MSY reference points by area with the median (blue) and stochastic median (red) of the estimates indicated.

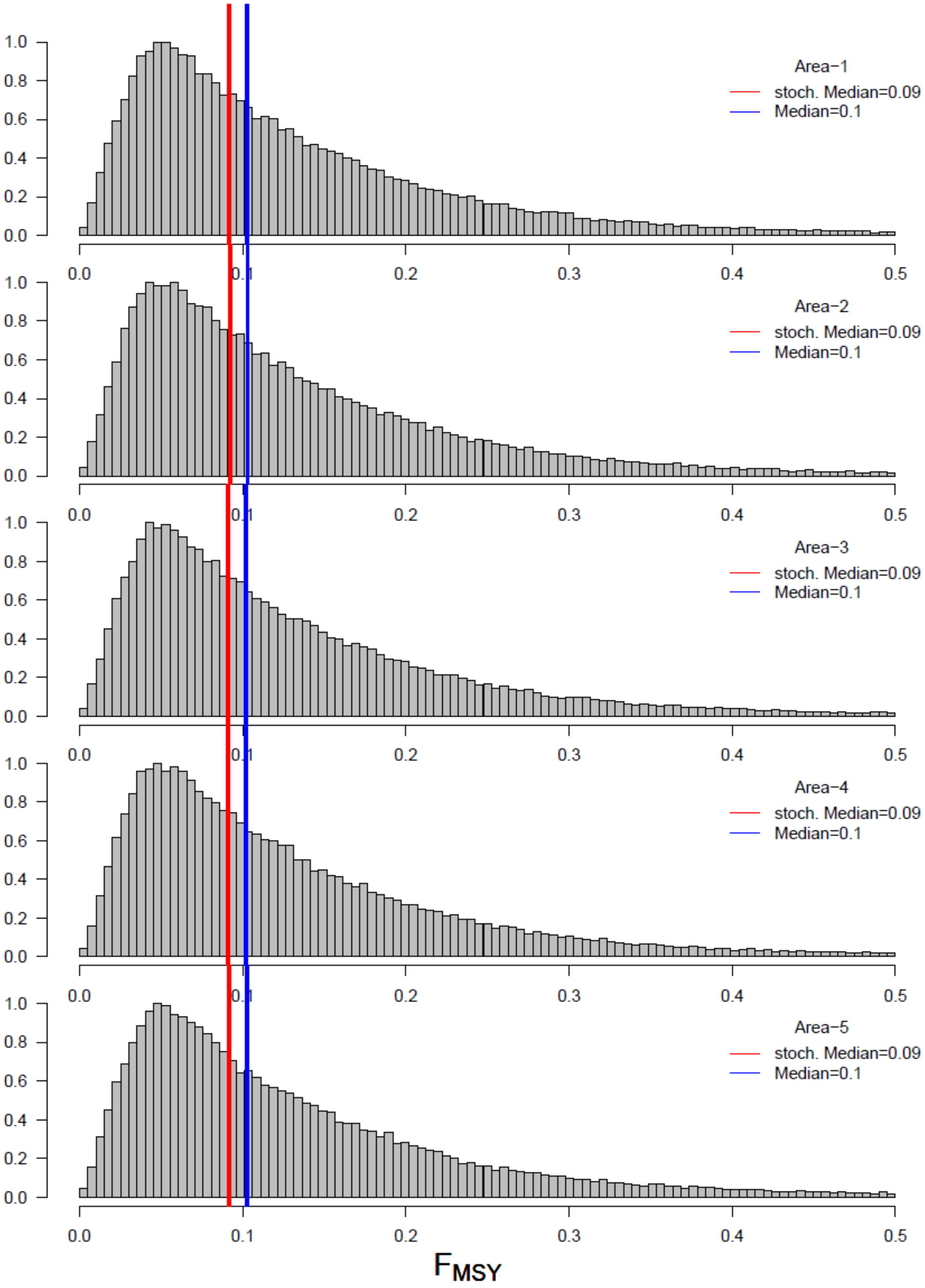

Figure 27. Posterior distribution of FMSY reference points by area with median (blue) and stochastic median (red) of the estimates indicated.

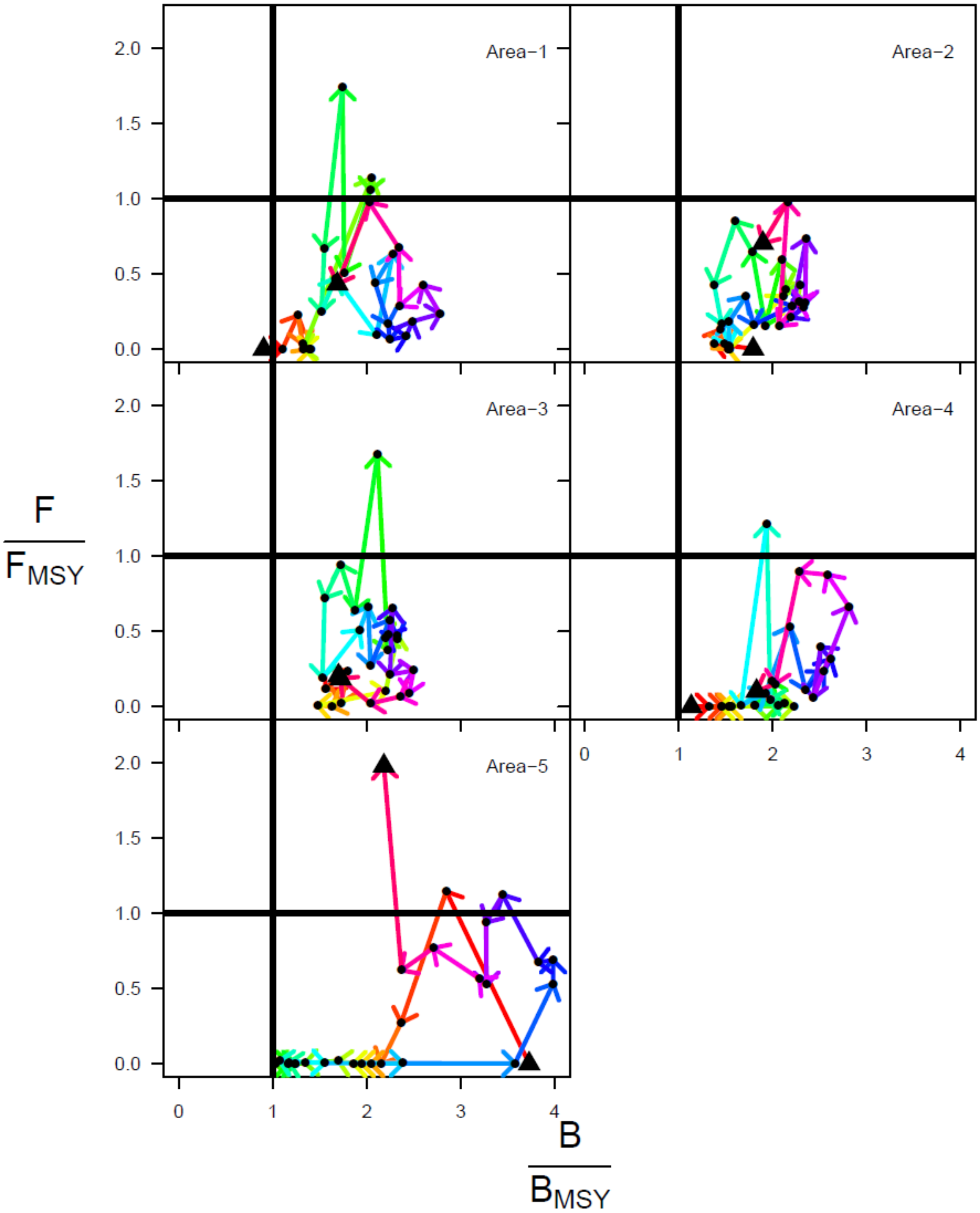

Figure 28. Phase plots showing spawning biomass relative to B_{MSY} (B/B_{MSY}) along the x-axis and fishery mortality relative to F_{MSY} (F/F_{MSY}) along the y-axis. The biomass reference level is shown by the thick vertical line ($B/B_{MSY} = 0$) and the fishery mortality reference level is shown by the thick horizontal line ($F/F_{MSY} = 0$). Points denote data for each year (1998–2015), triangles denote the start and end of the time series, and the colours of the lines denote time.