B. STOCK ASSESSMENT FOR ATLANTIC SEA SCALLOPS IN 2014, UPDATED THROUGH 2013

Invertebrate Subcommittee[1]

B1. TERMS OF REFERENCE

1) Estimate removals from all sources including landings, discards, incidental mortality, and natural mortality. Describe the spatial and temporal distribution of landings, discards, and fishing effort. Characterize the uncertainty in these assumptions and sources of data. If possible using sensitivity analyses, consider the potential effects that changes in fishing gear, fishing behavior, and management may have on the assumptions.
2) Present the survey data being used in the assessment (e.g., regional indices of relative or absolute abundance, recruitment, size data, etc.). Characterize the uncertainty and any bias in these sources of data.
3) Investigate the role of environmental and ecological factors in determining recruitment success. If possible, integrate the results into the stock assessment.
4) Estimate annual fishing mortality, recruitment and stock biomass for the time series, and estimate their uncertainty. Report these elements for both the combined resource and by sub-region. Include a historical retrospective analysis to allow a comparison with previous assessment results and previous projections.
5) State the existing stock status definitions for "overfished" and "overfishing". Then update or redefine biological reference points (BRPs; point estimates or proxies for B_{MSY}, $B_{THRESHOLD}$, F_{MSY} and MSY) and provide estimates of their uncertainty. Comment on the scientific adequacy of existing BRPs and the "new" (i.e., updated, redefined, or alternative) BRPs.
6) Evaluate stock status with respect to the existing model (from previous peer reviewed accepted assessment) and with respect to a new model or model formulation developed for this peer review.
    a. Update the existing model with new data and evaluate stock status (overfished and overfishing) with respect to the existing BRP estimates.
    b. Then use the newly proposed model and evaluate stock status with respect to "new" BRPs and their estimates (from TOR-5).
7) Evaluate the realism of stock and catch projections and compute the statistical distribution (e.g., probability density function) of the OFL (overfishing level).
    a. Provide numerical annual projections (through 2016). Each projection should estimate and report annual probabilities of exceeding threshold BRPs for F, and probabilities of falling below threshold BRPs for biomass. Use a sensitivity analysis approach in which a range of assumptions about the most important uncertainties in the assessment are considered (e.g., terminal year abundance, variability in recruitment).
    b. Comment on the realism of the projections. Consider the major uncertainties in the assessment as well as sensitivity of the projections to various assumptions.

    Describe this stock's vulnerability (see "Appendix to the SAW TORs") to becoming overfished, and how this could affect the choice of ABC.

[1] See Appendix B1 for meetings and members of the Invertebrate Subcommittee who helped prepare this assessment.

8) Review, evaluate and report on the status of the SARC and Working Group research recommendations listed in most recent SARC reviewed assessment and review panel reports. Identify new research recommendations.

B2. EXECUTIVE SUMMARY

TOR-1 (Estimate removals from landings, discards, incidental mortality, and natural mortality…) U.S. sea scallop landings were high and stable during 2003-2012, averaging about 25,000 mt meats, almost three times higher than the long-term 1950-1999 mean. Landings in 2013 declined to 18,641 mt meats, the lowest since 2000, but still over twice the long-term mean. About 65% of landings during 2003-2012 were from the Mid-Atlantic region, 32% from Georges Bank, 2% from Southern New England and under 1% from the Gulf of Maine; the proportion from the Mid-Atlantic was higher than in earlier periods. A shift in the fishery towards Georges Bank occurred in 2013, when 64% of the landings were from Georges Bank, 32% from the Mid-Atlantic, 2% from Southern New England and 3% from the Gulf of Maine. Discards were highly variable with year and region. Maximum discards were 2553 mt meats in 2003. Discards have decreased since 2004, likely due to changes in gear regulations; estimated discards in 2013 were 437 mt meats. Incidental fishing mortality (mortality of scallops that interact with the gear but are not caught) is highly uncertain; based on two studies from the 1970s and 1980s, incidental fishing mortality on small scallops was estimated as 0.2 times fully recruited fishing mortality on Georges Bank, and 0.1 times fully recruited fishing mortality in the Mid-Atlantic. Natural mortality for all but the largest size group was estimated at 0.16 for Georges Bank and 0.2 for the Mid-Atlantic, an increase from 0.12 and 0.15, respectively, in the last assessment. Plus group natural mortality was estimated as 1.5 times that of smaller scallops.

TOR-2 (Survey data). A scallop survey using a lined scallop dredge and a random-stratified design has been conducted every year since 1979 on Georges Bank and the Mid-Atlantic Bight. Based on this survey, biomass and abundance remained relatively low from 1979-1995 on Georges Bank and 1979-1998 in the Mid-Atlantic. The indices rose dramatically starting in 1995 on Georges Bank and 1998 in the Mid-Atlantic, and were fairly stable from 2003-2009. Decreases have been observed in both regions in recent years, although the indices are still well above levels observed previous to 1995. Paired tows experiments that compared dredge catches to densities observed using the HabCam towed camera system estimated the efficiency of the dredge as 0.41 on sand and 0.27 on gravel/cobble habitat (Appendix B4).

A video drop camera survey was conducted between 2003 and 2012 on Georges Bank and the Mid-Atlantic, using a systematic grid design. This survey generally shows declining trends, with biomass and abundance somewhat less than the expanded dredge survey.

A towed camera ("HabCam") survey was used for the first time in this assessment (Appendix B6). The survey was conducted during 2011-2013 on Georges Bank and 2012-2013 in the Mid-Atlantic. HabCam is towed behind a vessel, taking rapid-fire photographs of the sea bottom. Estimates from HabCam were obtained using a model-based approach, using a zero-inflated generalized additive model combined with kriging of the residuals. Biomass and abundance estimates from HabCam were similar to those from the dredge.

TOR-3 (Environmental effects on recruitment). Two putative environmental factors were

explored as predictors of recruitment in the Mid-Atlantic Bight (Appendix B8). A tentative relationship was found between food supply (phytoplankton) and recruitment. Additionally, the spatio-temporal distribution of the sea star *Astropecten americanus*, a predator of small invertebrates, including juvenile sea scallops, appear to correlate to the spatio-temporal patterns of scallop recruitment in the southern Mid-Atlantic Bight.

TOR-4 (Estimation of F, Biomass, Recruitment). A forward projecting size-structured estimation model (CASA) was used for estimation of biomass, fishing mortality and recruitment. Growth in the model was based on growth increment data from shell growth ring analysis. Three models were used, one each for the open and closed portions of Georges Bank, and a model for the Mid-Atlantic. The models appeared to give good estimation for some years, but in the Georges Bank Closed and Mid-Atlantic models, estimates of abundance and biomass had poor diagnostics in years associated with very strong year classes. Model estimated biomass and abundance generally declined, and fishing mortality increased, during 1975-1995. The biomass in the Georges Bank closed areas increased rapidly after these areas were closed to fishing in 1994. Estimated biomass in Georges Bank open and the Mid-Atlantic increased more gradually as fishing mortality was slowly reduced starting around 1998. Estimated overall fully recruited fishing mortality in 2013 was 0.32, and biomass was estimated at 132,561 mt meats. This was slightly higher than direct expanded estimates from the dredge survey (129,113 mt meats) and HabCam (111,157 mt meats). Explorations were made in incorporating density-dependent mortality on juvenile scallops into the CASA model in order to better model the population dynamics of large year classes, and initial results appear to be promising.

TOR-5 (Stock status definition). The SYM (Stochastic Yield Model) was used to estimate reference points. This model explicitly takes into account parameter uncertainty, including key uncertainties in natural mortality and stock-recruit relationships, when estimating maximal sustainable yield (MSY) and the associated biomass and fishing mortality reference points B_{MSY} and F_{MSY}. Estimated whole stock MSY, F_{MSY} and B_{MSY} were 23,798 mt meats, 0.48 and 96,480 mt meats, respectively.

TOR-6 (Evaluate stock status). The estimated fishing mortality in 2013 was 0.32, which was below both the previous and new F_{MSY} estimates (0.38 and 0.48, respectively). The estimated biomass in 2013 is 132,561 mt meats. The stock is considered overfished if the biomass is less than half of B_{MSY}. B_{MSY} was estimated as 125,358 in the previous assessment and 96,480 mt meats in this assessment. Thus, the 2013 stock biomass was above both B_{MSY} estimates. Therefore, it can be concluded that the sea scallop stock was neither overfished nor was overfishing occurring in 2013, regardless of whether the previous or new reference points are used.

TOR-7 (Projections) Projections were conducted using the SAMS (Scallop Area Management Simulator), which models scallops on a relatively fine spatial scale in order to model effects such as closures and reopenings of areas. Example simulations, based on expected management during 2014-2016, predicts gradual increases in biomass and landings.

B3. INTRODUCTION AND LIFE HISTORY

The Atlantic sea scallop, *Placopecten magellanicus,* is a bivalve mollusk that occurs on the eastern North American continental shelf from Cape Hatteras to the Gulf of St. Lawrence and Newfoundland. Major aggregations in US waters occur in the Mid-Atlantic from Virginia to Long Island, on Georges Bank, in the Great South Channel, and, to a lesser extent, in the Gulf of Maine (Hart and Chute 2004). In Georges Bank and the Mid-Atlantic, sea scallops are harvested primarily at depths of 30 to 100 m, whereas the bulk of landings from the Gulf of Maine are from near-shore waters. This assessment focuses on the two main portions of the sea scallop stock and fishery, Georges Bank in the north and the Mid-Atlantic in the south (Figure B3.1). Results for Georges Bank and the Mid-Atlantic are combined to evaluate the stock as a whole.

US landings during 2003-2012 exceeded 24,000 mt each year, roughly twice the long-term mean, but declined to 18,641 mt in 2013.2 US ex-vessel sea scallop revenues were over $500 million in 2011-2012 and $465 million in 2013, making the sea scallop fishery the most valuable fishery in the US during these years. Unusually strong recruitment in the Mid-Atlantic Bight area and increased yield per recruit due to effort reduction, area rotation, and gear restrictions were the key contributors to high landings during the most recent period. The drop off in 2013 reflects weaker recruitment in the Mid-Atlantic during 2009-2011 (2007-2009 year classes). The mean meat weight of landed scallops was over 25 g after 2005 (when the Amendment 10 management plan went into effect), compared to less than 14 g during the early to mid 1990s.

Access area closures and openings used for rotational fishery management have had a strong influence on sea scallop population dynamics (Figure B3.1). Roughly 40% of the productive scallop grounds on Georges Bank and Nantucket Shoals were closed to both groundfish and scallop gear during most of the time since December 1994. Portions of the closed areas have been reopened to limited fishing during 1999-2000 and since 2004. In the Mid-Atlantic, there have been four rotational scallop areas. These areas are generally closed for two to three years, and then reopened to allow harvesting. The areas are closed again after observations of strong recruitment until the small scallops grow to fishable size.

Sea scallops in U.S. waters have been assessed using forward projecting size-structured models since 2007. Fishing mortality, biomass and recruitment are estimated using a version of the CASA (Catch-At-Size Analysis) model based loosely on Sullivan et al. (1990). Forecasts are done using the SAMS (Scallop Area Management Simulator) model, which models the scallop fishery and population on a relatively fine regional scale, in order to help understand the effects of area management such as closing and reopening areas to fishing. Reference points are calculated using the SYM model (Stochastic Yield Model, Hart 2013). All of these models were specifically developed for use with sea scallops.

2 In this assessment, landings and biomass are reported in metric tons (mt) of scallop meats, unless otherwise indicated.

Life History and Distribution

Sea scallops are found in the Northwest Atlantic Ocean from North Carolina to Newfoundland along the continental shelf typically on firm sand and gravel bottoms (Hart and Chute 2004). Sea scallops feed by filtering phytoplankton, microzooplankton, and detritus particles. Sea scallops are broadcast spawners with separate sexes. Sea scallops mature at about age 2 (~40-75 mm SH[3]), but gamete production is limited until age 4. Larvae are planktonic for 5-8 weeks before settling to the bottom. Scallops fully recruit to the NEFSC lined dredge survey at 40 mm SH, and to the current commercial fishery at around 90-105 mm SH, although sea scallops between 70-90 mm were common in landings prior to 2000.

According to Amendment 10 of the Atlantic Sea Scallop Fishery Management Plan, all sea scallops in the US EEZ belong to a single stock but there are two principal stock assessment regions (Mid-Atlantic and Georges Bank). The US sea scallop stock can be divided into Georges Bank, Mid-Atlantic, Southern New England, and Gulf of Maine regional components based on survey data, fishery patterns, and other information (NEFSC 2004, Figure B3.1). However, Southern New England is considered to be part of the Georges Bank region for assessment modeling purposes. Most of the scallops in the Gulf of Maine lie in state waters, and are managed by the states of Maine and Massachusetts. See Appendix B7 for an assessment of sea scallops in the Northern Gulf of Maine federal management area.

Growth

Sea scallop growth can be inferred using visible "rings" laid down on the shell. These rings have been confirmed as annual marks, although the year one ring is typically missing (Stephenson and Dickie 1954, Merrill et al. 1966, Hart and Chute 2009a, Chute et al. 2012). Studies in Canadian waters indicated that the rings are laid down during the winter (Stephenson and Dickie 1954, Tan et al. 1988) but a recent stable isotope study showed that the rings from scallops in US waters are laid down near the temperature maximum, likely coinciding with the fall spawn (Chute et al. 2012).

Obtaining absolute age from shell rings can be problematic for some scallops because the first few rings may be missing or obscure, especially on older scallops (Claereboudt and Himmelman, 1996). For this reason, Hart and Chute (2009b) treated the distance between rings as annual growth increments, with age unknown. They introduced a method to estimate von Bertalanffy growth parameters from such data which includes random effects on both L_∞ and K to take into account variation in growth among individuals. This method gives estimates of mean von Bertalanffy coefficients and the variance of these parameters among individuals in the population. These parameters and variances are used to estimate growth transition matrices for CASA. The von Bertalanffy parameter t_0 cannot be estimated using growth increments, but estimates of this parameter are not required in a size-structured assessment.

The growth estimates in Hart and Chute (2009b) were based on scallops collected between 2001 and 2007. NEFSC (2010) added additional data from shells collected in 2008. New data from

3 Scallop body size is measured as shell height (SH), the maximum distance between the umbo and shell margin.

shells collected during 1988, 1993 and 2009-2012 are used in this assessment (Table B3-1). Growth on Georges Bank showed little temporal variability during the 2001-2012 time period, but the shells collected in 2010-2012 in the Mid-Atlantic appear to growth slightly faster than those from 2001-2009 (Figure B3.2).

Scallop growth during 1988 and 1993 was substantially slower than in recent years (Figure B3.3). A comparison of the growth increments from these years to 2001-2012 indicate little difference between these periods for scallops less than 76 mm, the ring size for commercial dredge gear before 1994 (Figure B3.3). However, there appears to have been less and less fast growing scallops as shell height increased. This pattern is consistent with preferential removal of faster growing scallops by the fishery. In part, this may be due to a "Lee's effect", where the faster growing scallops recruit earlier to the fishery and die sooner. However, spatial fishery patterns likely also play a role because areas containing faster growing scallops were likely fished harder. Similarly, commercial-sized scallops in the Georges Bank closed areas grow faster and have a greater asymptotic size than in the areas opened to fishing (Table B3-1; Figure B3.2; Hart and Chute 2009b).

Maturity and fecundity

Scallops reach sexual maturity at about age 2. Sea scallops > 40 mm SH are reliably detected in surveys used in this assessment and are all considered mature individuals. Thus biomass estimates for scallops 40+ mm in this assessment are effectively spawning biomass estimates. However, individuals younger than 4 years may contribute little to total egg production because fecundity increases rapidly with age (MacDonald and Thompson 1985; NEFSC 1993).

Sea scallop spawning generally occurs in late summer or early autumn throughout their range. Spring spawns and minor "dribble" spawns may also occur at other times. The spring spawn is often strong in the Mid-Atlantic Bight (DuPaul et al. 1989). Spring spawns on Georges Bank are less substantial but may be increasing in strength with warmer winter water temperatures (Almeida et al. 1994, Dibacco et al. 1995, Thompson et al. 2014). Out of 14 scallops (6 from Georges Bank and 8 from the Mid-Atlantic) analyzed by stable isotopes, only one, from Delmarva in the southern Mid-Atlantic, was found to be spring-spawned, while the others were fall spawned (Chute et al. 2012). No assumption regarding timing of spawning is made in this assessment, as it is not required for size-structured models.

Shell height/meat weight relationships

Shell height-meat weight relationships allow conversion from numbers of scallops at a given size to meat weights. For sea scallops $W=\exp(\alpha+\beta\ln(H))$, where W is meat weight in grams and H is shell height in mm (Appendix B3). Meat weights depend on factors which affect feeding and metabolic rates, including depth and location. Meat weights decrease with depth, probably because of reduced food (phytoplankton) supply.

Shell height/meat weight data were collected during annual NEFSC sea scallop surveys during 2001-2013. Unlike previous studies, where meats were either frozen or brought in live and then weighed on land, meats were weighted at sea just after they were shucked (Hennen and Hart

2012). These data have been used in scallop assessments since 2007, and were updated for this assessment (Appendix B3).

Depth and subarea had a significant effect on the shell height/meat weight relationships (Appendix B3). In this assessment, covariate-adjusted shell height/meat weight relationships were used to calculate survey biomass, while simple relationships (depth omitted) were used in modeling (CASA, SAMS and SYM) where depth is not explicit (Table B3.2).

Meat weights for scallops in the commercial fishery may differ from those predicted from research survey data for a number of reasons. First, the shell height-meat weight relationship varies seasonally, in part due to the reproductive cycle, so that meat weights collected during the NEFSC survey in July and August may differ from those in the rest of year (Hennen and Hart 2012). Additionally, commercial fishers concentrate on speed, and often leave some meat on the shell during shucking (Naidu 1987, Kirkley and DuPaul 1989). On the other hand, meats in fishery catches may gain weight due to water uptake during storage on ice (DuPaul et al. 1990). Finally, fishers may target areas with relatively large meat weight at shell height, and thus may increase commercial meat weights compared to that collected on the research vessel.

Observer data were used to adjust predicted meat weights based on survey data for seasonal variation and for commercial fishing practices. Annual commercial meat weight anomalies were computed based on the seasonal patterns of landings together with the mean monthly commercial meat weight at shell height. The average annual meat weight anomalies are used in assessment modeling to calculate fishery meat weights.

Shell height/Meat weight relationships

	Mid-Atlantic		**Georges Bank**	
	a	B	a	b
NEFSC (2014)	-9.33	2.66	-8.79	2.55
NEFSC(2014) , open areas			-9.37	2.65
NEFSC (2014), closed areas			-8.26	2.45
Hennen Hart (2012)/NEFSC 2010	-10.8	2.97	10.25	2.85
Lai and Helser (2004)	-12.34	3.28	11.44	3.07
Serchuk and Rak (1983)	-12.16	3.25	-11.77	3.17
Haynes (1966)	-11.09	3.04	-10.84	2.95

Natural mortality

Assessments prior to 2010 assumed a natural mortality rate of $M = 0.1$ based on Merrill and Posgay (1964). A reanalysis of the Merrill and Posgay study indicated that an unbiased estimate for M was approximately 0.12 (NEFSC 2010), with a corresponding estimate in the Mid-Atlantic of 0.15. Hart et al. (2013) estimated M within the CASA stock assessment model as 0.16 in the Georges Bank closed areas.

No direct estimate of *M* is available for Mid-Atlantic sea scallops. The ratio of the growth coefficient *K* to *M* is generally regarded as a life history invariant that should be approximately constant for similar organisms (Beverton and Holt 1959, Chernov 1993). Applying this idea and using updated growth parameter estimates indicates that sea scallop natural mortality in the Mid-Atlantic should be about 0.53/0.44 that of Georges Bank (see the estimates of growth coefficients above). Using $M = 0.16$ in Georges Bank, *M* is about 0.2 in the Mid-Atlantic. These are the estimates used in this assessment for all but the largest size group (plus group).

MacDonald and Thompson (1986) directly observed sea scallop natural mortality in a near-shore population off of Newfoundland. They found that mortality was low from 60-130 mm SH, but increased substantially for scallops larger than 130 mm. A large cohort of 2 year old scallops (1997 cohort) was observed in 1999 at a station in the Nantucket Lightship Closed Area in an area where recruitment is rare and sporadic and which has been closed to scallop fishing since 1994. A second, smaller cohort of 2 year olds was observed there in the 2000 survey, but almost no recruitment has been observed at this site since. This station has been sampled using the NEFSC survey dredge every year since 2003. The catches at this station indicate low mortality until the dominant 1997 cohort reached 11 years old, after which numbers caught declined substantially. Both these studies thus suggest that natural mortality of very old scallops may be higher than younger ones. Likelihood profiles from the Georges Bank closed CASA model, discussed in section 6, suggest the mortality of the plus group is most likely about 1.5 times that of smaller scallops. Therefore, for this assessment, the plus group natural mortality was assumed to be 1.5 times that of smaller sizes, (0.24 on Georges Bank and 0.3 in the Mid-Atlantic).

MacDonald and Thompson (1986) observed scallops as old as 19 years. The oldest observed in the NEFSC age and growth program are at least 18 years old on Georges Bank and 15 years old in the Mid-Atlantic. These oldest ages are consistent with the natural mortality assumptions given above.

Table B3.1. Regional von Bertalanffy growth parameter estimates from mixed-effects models for sea scallops. SD L_∞ and SD K are the estimated standard deviation of these parameters among individuals in the population.

Source	Region	Years	L_∞	SE	K	SE	SD L_∞	SD K
NEFSC (2014)	Mid-Atlantic	2010-2012	138.0	0.5	0.522	0.005	12.7	0.05
	Mid-Atlantic	2001-2009	131.7	0.3	0.535	0.003	13.6	0.13
	Mid-Atlantic	1988,1993	118.9	2	0.551	0.02	20.8	0.15
	Georges Bank (All)	2001-2012	144.0	0.2	0.44	0.002	13.9	0.11
	Georges Bank (All)	1988,1993	133.4	1.4	0.498	0.013	9.2	0.09
	Georges Bank (Closed)	2001-2012	147.6	0.3	0.426	0.002	12.8	0.11
	Georges Bank (Open)	2001-2012	137.4	0.3	0.442	0.002	11.4	0.11
NEFSC (2010)	Mid-Atlantic	2001-2008	132.1	0.3	0.527	0.004	13.3	0.14
	Georges Bank	2001-2008	144.0	0.3	0.429	0.002	14.5	0.11
Hart & Chute (2009)	Mid-Atlantic	2001-2007	133.3	0.4	0.508	0.004	13.4	0.13
	Georges Bank (All)	2001-2007	143.9	0.3	0.427	0.002	14.8	0.11
	Georges Bank (Open)	2001-2007	136.3	0.5	0.457	0.004	15.1	0.12
	Georges Bank (Closed)	2001-2007	147.8	0.3	0.413	0.003	13.2	0.1
Serchuk et al (1979)	Mid-Atlantic	?	151.8		0.300			
	Georges Bank	?	152.5		0.337			

Table B3.2. Simple shell height-meat weight relationships $W=\exp(\alpha+\beta\ln(H))$ for sea scallops. W is meat weight in grams and H is shell height in mm.

	Mid-Atlantic		Georges Bank	
	a	b	a	b
NEFSC (2014)	-9.33	2.66	-7.46	2.61
NEFSC(2014) , open areas			-9.37	2.65
NEFSC (2014), closed areas			-8.26	2.45
Hennen & Hart (2012)/NEFSC 2010	-10.8	2.97	10.25	2.85
Lai and Helser (2004)	-12.34	3.28	11.44	3.07
Serchuk and Rak (1983)	-12.16	3.25	-11.77	3.17
Haynes (1966)	-11.09	3.04	-10.84	2.95

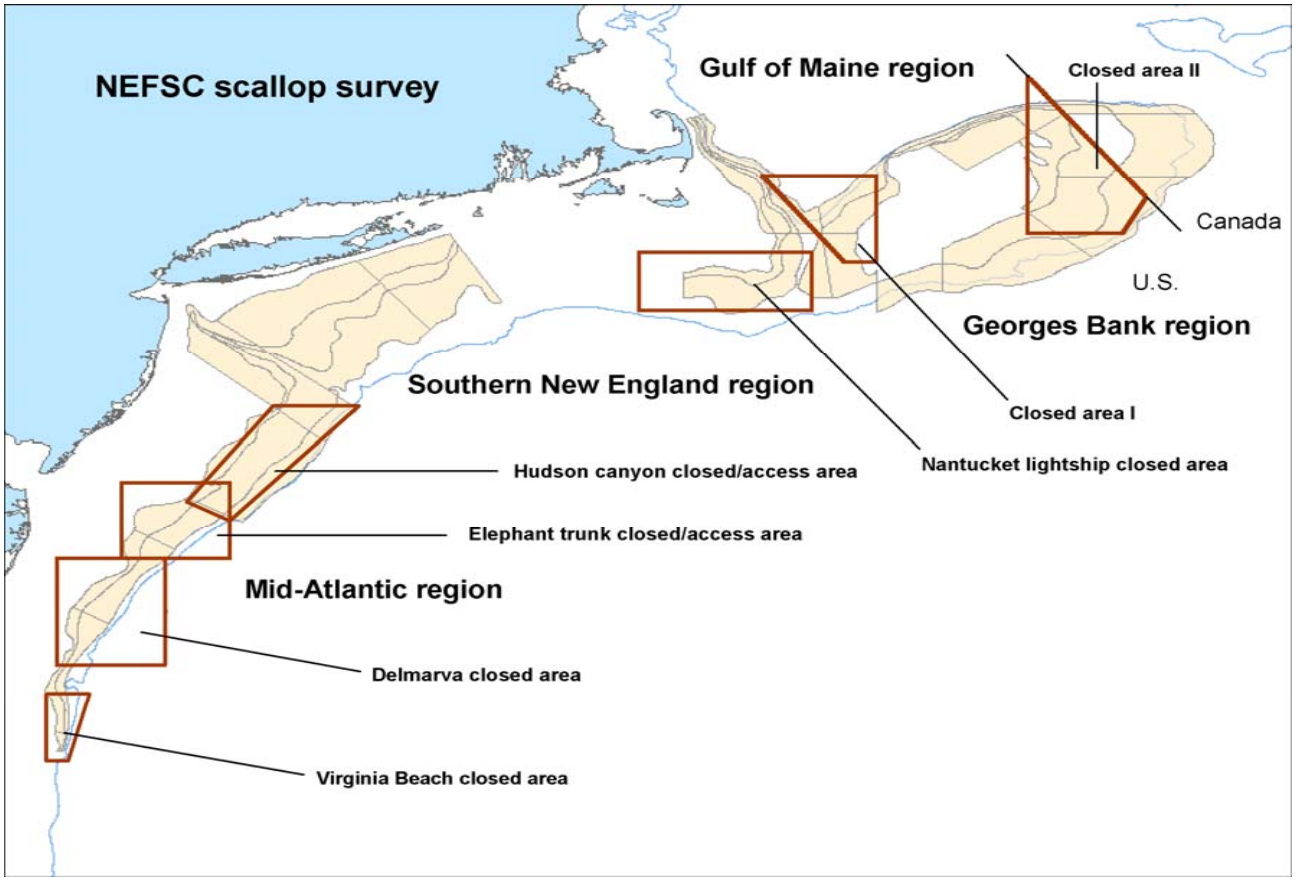


Figure B3.1 Stock assessment and management areas for sea scallops in US waters. The NEFSC scallop survey strata shown in yellow are the areas that are regularly surveyed by the NEFSC dredge survey, which have with appreciable scallop densities.

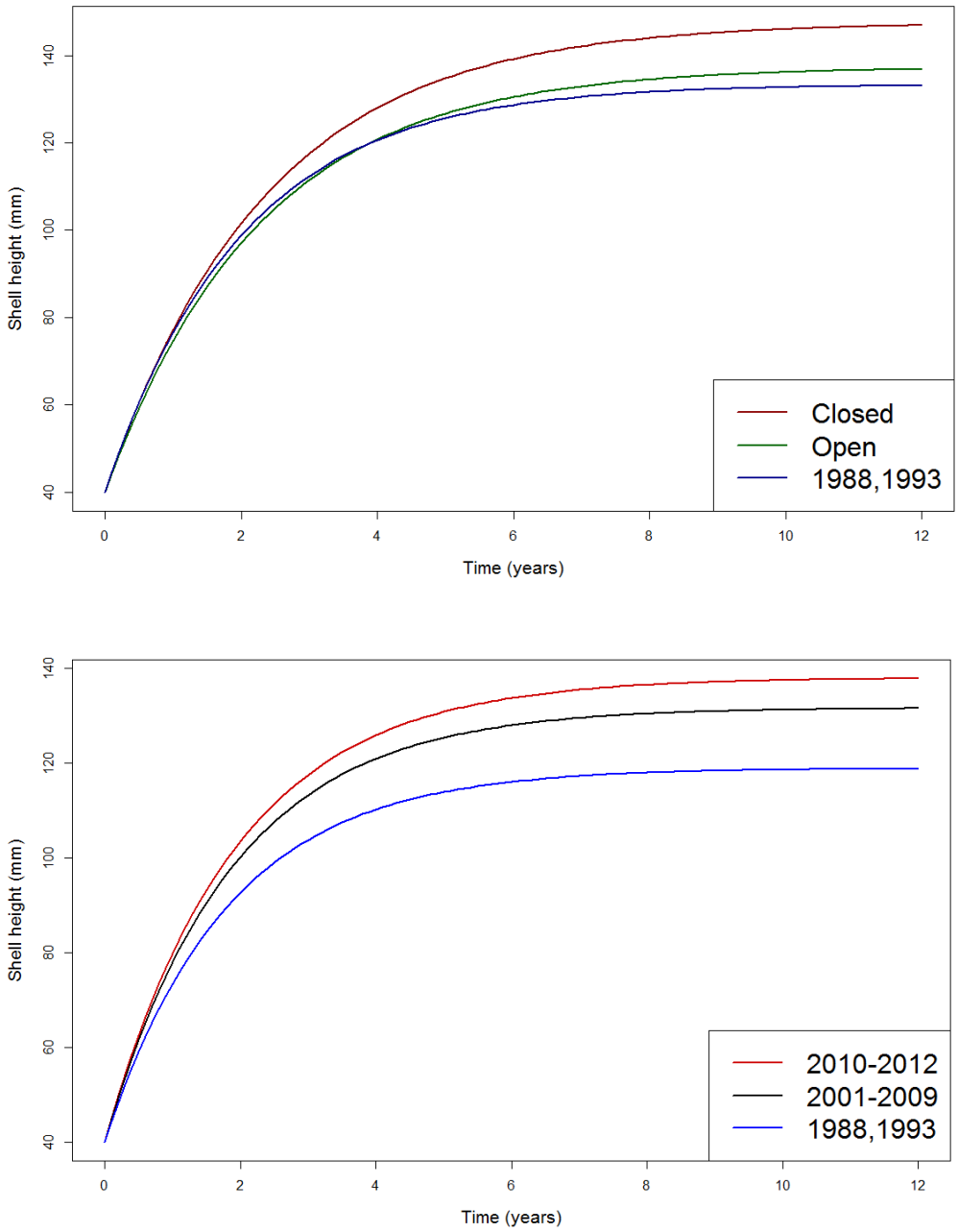


Figure B3.2. Growth curves for sea scallops in the Georges Bank (top) and Mid-Atlantic regions (bottom) for various areas and time periods. The Georges Bank open and closed area growth curves were based on shells collected between 2001-2012.

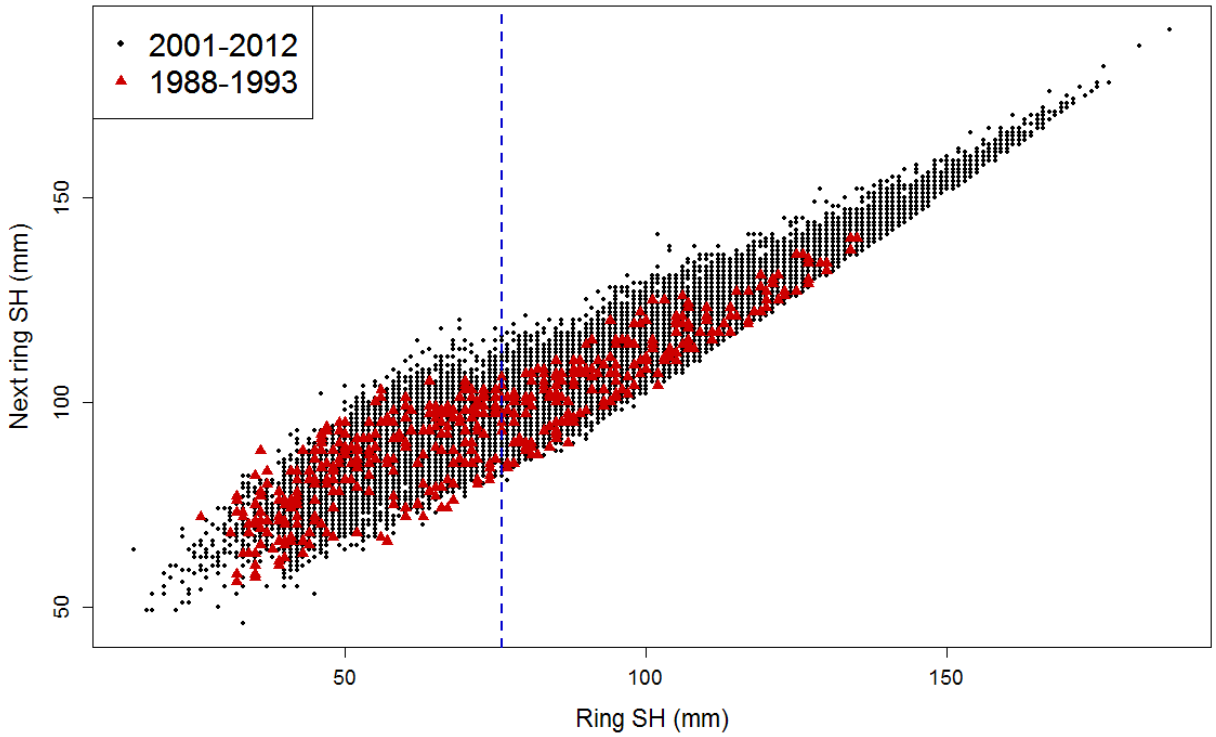


Figure B3.3. Comparison of growth increments from shells collected on Georges Bank between 2001 and 2012 and those collected which fishing effort was much higher (1988,1993). The dashed blue line is at 76 mm, the diameter of most commercial dredge rings prior to 1994.

B4. COMMERCIAL AND RECREATIONAL CATCH (TOR-1)

The US sea scallop fishery is conducted mainly by about 350 vessels with limited access permits. Two types of allocations are given to each limited access vessel. The first is a number of trips to rotational access areas that had been closed to scallop fishing in the past (with a trip limit, typically 12,000-18,000 lbs or 5,443-8,165 kg meats). The second is days at sea (DAS), which can be used in areas outside the closed and access areas. Vessels fishing under days at sea allocations are restricted to a 7 man crew and must shuck their scallops at sea in order to limit their processing power.

The remainder of landings come from vessels operating under "General Category" permits that are currently restricted to 272 kg meats (600 lbs) per trip, with a maximum of one trip per day. Landings from these vessels were less than 1% of total landings in the late 1990s, but increased to about 10% of landings during 2007-2009, and currently constitute about 6-7% of total landings. This type of permit had been open access, but was converted to an individual transferable quota (ITQ) fishery in March 2010.

Principal ports in the sea scallop fishery are New Bedford, MA, Cape May, NJ, and Hampton Roads, VA, but lesser amounts of scallops are landed in many ports from North Carolina to Maine. Toothless offshore (New Bedford style) scallop dredges are the main gear type in all regions, although some scallop fishing is done with otter trawls in the Mid-Atlantic, and a small fraction of the catch in the Gulf of Maine comes from divers. A typical limited access vessel tows two 4-4.6 m dredges, but some limited access vessels are restricted to a single 3.2 m dredge, and most general category vessels also use a single smaller dredge. Recreational catch is negligible.

Management history

The sea scallop fishery in the US EEZ is managed under the Atlantic Sea Scallop Fishery Management Plan (FMP) which was implemented on May 15, 1982. From 1982 to 1994, the primary management control was a minimum average meat weight requirement for landings. In 1984, Georges Bank was divided into US and Canadian EEZs; prior to this time, US and Canadian vessels fished on both sides of the current boundary.

FMP Amendment 4 (NEFMC 1993), implemented in 1994, changed the management strategy from meat count regulation to limited access combined with effort control and gear regulations. Limited access permits were issued to vessels with a history in the fishery; no new permits have been issued since. Incremental restrictions were made on days-at-sea (DAS), minimum ring size, and crew limits; DAS has been reduced from over 200 in 1994 to 31 in open areas in 2014. The minimum size of the rings in the dredge bag was gradually been increased from 76 mm in 1994 to 102 mm since December 2004. The minimum size of the twine top mesh has also been gradually increased from 6” to 10” since December 2004; while this measure was intended mainly to allow better escapement of finfish, it also likely improves the escapement of small scallops.

In addition to these measures, three large areas on Georges Bank and Nantucket Shoals were closed to groundfish and scallop fishing in December 1994 (Figure B3-1). Scallop biomass

rapidly increased in these areas between 1994-2004 (Hart and Rago 2006). Two areas in the Mid-Atlantic were closed to scallop fishing in April 1998 for three years in order to similarly increase scallop biomass and mean weight.

Sea scallops were formally declared overfished in 1997, and Amendment 7 was implemented during 1998 with more stringent days-at-sea limitations and a mortality schedule intended to rebuild the stocks within ten years. Subsequent analyses considering effects of closed areas indicated that the stocks would rebuild with less severe effort reductions than called for in Amendment 7, so the days at sea limitations were relaxed. A combination of the closures, effort reduction, gear and crew restrictions led to a rapid increase in biomass (Hart and Rago 2006), and sea scallops were rebuilt by 2001.

Prior to 2004, there were a number of ad hoc area management measures, including the Georges Bank and Mid-Atlantic closures in 1994 and 1998, limited reopenings of portions of the Georges Bank closed areas between June 1999 and January 2001, and reopening of the first Mid-Atlantic rotational areas in 2001. A new set of regulations was implemented as Amendment 10 during 2004. This amendment formalized an area based management system, with provisions and criteria for new rotational closures, and separate allocations (DAS or TACs) for reopening closed areas (rotational areas) and general open areas. The three Georges Bank closed areas have been divided into access areas, where fishing is periodically permitted, and long-term closures, where no scallop fishing is permitted (Figure B3.1). In most years, one or two of the three Georges Bank access areas are open to fishing, limited by a fixed number of trips and a trip limit.

Unlike the Georges Bank closed areas, which are generally closed to all scallop and groundfish fishing, the Mid-Atlantic rotational areas are specific to the scallop fishery (Figure B3.1). Two areas (Hudson Canyon South and Virginia Beach) were closed in 1998 and then reopened in 2001. Although the small Virginia Beach closure in the far south of the scallops' range was unsuccessful, scallop biomass built up in Hudson Canyon Closed Area while it was closed, and substantial landings were obtained from Hudson Canyon during 2001-2007. This area was again closed in 2008, reopened in 2011 and closed for a third time in 2014. A third rotational closure, the Elephant Trunk area east of Delaware Bay, was closed in 2004 after extremely high densities of small scallops were observed in surveys during 2002 and 2003. About 30,000 mt of scallops worth about $500 million were landed from that area after it was reopened in 2007. It was closed again in December 2012 after high numbers of small scallops were again observed in surveys. A fourth closed area, Delmarva, directly south of the Elephant Trunk area, was closed in 2007, reopened in 2009, closed in 2012 and reopened in 2014.

Landings

Sea scallop landings in the US increased substantially after the mid-1940's (Figure B4.1), with peaks occurring around 1960, 1978, 1990, and 2004. Maximum landings were 29,109 mt meats in 2004. Landings during 2001-2012 were all over 20,000 mt, whereas the maximum in the 20th century was 17,107 mt in 1990. Landings in 2013 were 18,641 mt, their lowest since 2000, but still higher than any year prior to 2001.

Landings from the Georges Bank and the Mid-Atlantic regions have dominated the fishery since 1964 (Table B4-1; Figure B4.2). Proration of total commercial sea scallop landings into Georges Bank, Mid-Atlantic, Southern New England, and Gulf of Maine used standard allocation procedures (Wigley et al. 2008).

US Georges Bank landings had peaks during the early 1960's, around 1980 and 1990, but declined precipitously during 1993 and remained low through 1998 (Figure B4-2). Landings in Georges Bank during 1999-2004 were fairly steady, averaging almost 5000 mt annually, and then increased in 2005-2006, primarily due to reopening of portions of the groundfish closed areas to scallop fishing. Georges Bank landings increased again in 2012-2013, mainly due to shift of "open" effort from the Mid-Atlantic to Georges Bank

Prior to the mid-1980s, Mid-Atlantic landings were generally lower than those on Georges Bank. Mid-Atlantic landings during 1962-1982 averaged less than 1800 mt per year (Figure B4.2). An upward trend in both recruitment and landings has been evident in the Mid-Atlantic since the mid-eighties. Landings peaked in 2004 at 24,494 mt. Mid-Atlantic landings declined after 2011, reflecting the poor 2007-2009 year classes there and concomitant effort shifts onto Georges Bank.

Landings from other areas (Gulf of Maine and Southern New England) are minor in comparison (Table B4-1). Most of the Gulf of Maine stock is assessed and managed by the State of Maine because it is primarily in state waters. However, the Nothern Gulf of Maine management area is managed by the New England Fishery Management Council with separate regulations (see Appendix B7 for an updated assessment). Gulf of Maine landings were less than 1% of the total US sea scallop landings in most recent years. Maximum landings in the Gulf of Maine were 1,614 mt during 1980.

Fishing effort and LPUE

Prior to 1994, landings and effort data were collected during port interviews by port agents which was combined with dealer data. Since 1994, commercial data are available in dealer reports (DR) and in vessel trip report (VTR) logbooks. DR give landings, but not area fished, and have reported landings by market category since 1998. VTR data contain information about area fished, fishing effort, and retained catches of sea scallops. Ability to link DR and VTR reports in data processing is reduced by incomplete data reports and other problems, although there have been significant improvements recently. A standardized method (Wigley et al. 2008) for matching DR to VTRs and assigning landings to fishing areas was used in this assessment for 1994-2013.

Landings per unit effort (LPUE, Figure B4.3) was computed as landings per day fished (days fished represent the time in days that gear was fishing). This was obtained from the port interview records for larger vessels prior to 1994 and from at-sea observers on limited access vessels afterwards. LPUE shows a general downward trend from the beginning of the time series to around 1998, with occasional spikes upward due to strong recruitment events. LPUE increased considerably since then as the stock recovered. Note the close correspondence in most years between the LPUE in the Mid-Atlantic and Georges Bank, probably reflecting the mobility of the scallop fishing fleet; if one area has higher catch rates, it is fished harder until the rates are equalized. Although comparisons of LPUE before and after the change in data collection procedures need to be made cautiously, there is no clear break in the LPUE trend in 1994.

Fishing effort (days fished) was computed as the product of LPUE and landings (Figure B4.4). This effort metric reflects the days fished that would have been required to obtain the reported total landings with limited access vessels. General category vessels, which usually fish with one small dredge would likely fish for several days to account for a single "day fished" of effort. Effort in the US sea scallop fishery generally increased from the mid-1970s to about 1991, and then decreased during the 1990s, first because of low catch rates, and later as a result of effort reduction measures. Effort increased in the Mid-Atlantic during 2000-2005, initially due to reactivation of latent effort among limited access vessels, and then to increases in general category effort. Total effort since 2005 has remained fairly stable, although there have been shifts between regions.

Discards and discard mortality

Sea scallops are sometimes discarded on directed scallop trips because they are too small to be economically profitable to shuck, or because of high-grading, particularly during access area trips (Figure B4.5). Ratios of discard to total catch (by weight) were recorded by sea samplers aboard commercial vessels since 1992 and used to estimate discarded scallops (Appendix B2). Sampling intensity on non-access area trips was low until 2003.

Discarded sea scallops may suffer mortality on deck due to crushing, high temperatures, or desiccation. There may also be mortality after they are thrown back into the water from physiological stress and shock, or from increased predation due to shock and inability to swim or shell damage (Veale et al. 2000, Jenkins and Brand 2001). Murawski and Serchuk (1989) estimated that about 90% of tagged scallops were still living several days after being tagged and placed back in the water. Total discard mortality of discarded scallops (including mortality on deck) is uncertain but has been estimated as 20% in previous assessments (e.g., NEFSC 2010). However, discard mortality may be higher during the Mid-Atlantic during the summer due to high water and deck temperatures, and likely strongly depends in both regions on fishing practices. Scallops returned to the water promptly have much higher chances of survival than ones left on deck for longer periods.

Incidental mortality

Scallop dredges likely kill and injure some scallops that are contacted by the gear but not caught, primarily due to damage (e.g., crushing) to the shells by the dredge. Caddy (1973) estimated that

15-20% of the scallops remaining in the track of a dredge were killed. Murawski and Serchuk (1989) estimated that less than 5% of the scallops remaining in the track of a dredge suffered non-landed mortality. Caddy's study was done in a relatively hard bottom area in Canada, while the Murawski and Serchuk study was in sandy bottom off the coast of New Jersey. It is possible that the difference in indirect mortality estimated in these two studies was due to different bottom types (Murawski and Serchuk 1989).

In order to use these studies to relate landed and non-landed fishing mortality in stock assessment calculations, it is necessary to know the efficiency *e* of the dredge (the probability that a fully recruited scallop in the path of a dredge is captured). Denote by *c* the fraction of scallops that suffer mortality among sea scallops in the path of the dredge but not caught. The best available information indicates that $c = 0.15\text{-}0.2$ (Caddy 1973), and $c < 0.05$ (Murawski and Serchuk 1989). The ratio *R* of scallops in the path of the dredge that were caught, to those killed but not caught is:

$$R = e/[c(1-e)] \qquad (4.1)$$

If scallops suffer direct (i.e., landed) fishing mortality at rate F_L, then the rate of indirect (non-landed) fishing mortality will be (Hart 2003):

$$F_I = F_L / R = F_L\, c\, (1-e)/e. \qquad (4.2)$$

If, for example, the commercial dredge efficiency *e* is 50%, then $F_I = F_L\, c$, where F_L is the fully recruited fishing mortality rate for sea scallops. Assuming $c = 0.15$ to 0.2 (Caddy 1973) gives $F_I = 0.15\, F_L$ to $0.2\, F_L$. With $c < 0.05$ (Murawski and Serchuk 1989) $F_I < 0.05\, F_L$. For this assessment, incidental mortality was assumed to be $0.2\, F_L$ in Georges Bank and $0.1\, F_L$ in the Mid-Atlantic.

Prior assessments applied the incidental mortality F_I from equation (4.2) to all sizes of scallops. However, the observations of Caddy (1973) and Murawski and Serchuk (1989) were in terms of mortality of scallops remaining after a pass of a dredge. Thus, the incidental fishing mortality as a function of shell height h should be:

$$F_{Ih}(h) = F_I\,(1 - q(h)) \qquad (4.3)$$

where q(h) is the catchability of commercial gear on a scallop of shell height h. We took q(h) to be:

$$q(h) = q_0\, s(h) \qquad (4.4)$$

where q_0 is 0.5 on Georges Bank and 0.6 in the Mid-Atlantic (commercial gear is more efficient on large scallops than the survey dredge, see e.g., Yochum and DuPaul 2008), and s(h) is commercial size selectivity estimated by the CASA model. All of these calculations take place in the assessment model itself.

Commercial shell height data

Since most sea scallops are shucked at sea, it has sometimes been difficult to obtain reliable commercial size compositions. Port samples of shells brought in by scallopers have been collected, but there are questions about whether the samples were representative of the landings and catch. Port samples taken during the meat count era often appear to be selected for their size rather than being randomly sampled, and the size composition of port samples from 1992-1994 differed considerably from those collected by at-sea observers during this same period. For this reason, commercial size compositions from port samples after 1984 when meat count regulations were in force are not used in this assessment.

Sea samplers (observers) have collected shell heights of kept scallops from commercial vessels since 1992, and discarded scallops since 1994. Although these data are likely more reliable than that from port sampling, they still must be interpreted cautiously for years prior to 2003 due to limited observer coverage (except for the access area fisheries, which always have had good observer coverage). Except for 2006, observer coverage rates have been over 5% since 2003, and were over 10% during 2012-2013.

Shell heights from port and sea sampling data indicate that sea scallops between 70-90 mm often made up a considerable portion of the landings during 1975-1998, but sizes selected by the fishery have increased since then, so that scallops less than 90 mm were rarely taken since 2002 (Figure B4.6).

Dealer data (landings) have been reported by market categories (under 10 meats per pound, 10-20 meats per pound, 20-30 meats per pound etc) since 1998 (Figure B4.7). These data also indicate a trend towards larger sea scallops in landings in recent years. While nearly half the landings in 1998 were in the smaller market categories (more than 30 meats per pound), 75% or more of recent landings were below 20 count and about 99% were below 30 count.

Table B4.1. US scallop landings 1964-2013 (mt meats), by region and gear type. Dredge gear was recorded as "other" prior to 1978.

	Gulf of Maine				Georges Bank				S. New England				Mid Atlantic Bight				Total			
Year	dredge	trawl	other	sum	dredge	trawl	other	sum	dredge	trawl	other	sum	dredge	trawl	other	sum	dredge	trawl	other	sum
1964		0	208	208		0	6,241	6,241		52	3	55		0	137	137		52	6,590	6,642
1965		0	117	117		3	1,478	1,481		2	24	26		0	3,974	3,974		5	5,592	5,598
1966		0	102	102		0	883	884		0	8	8		0	4,061	4,061		1	5,055	5,056
1967		0	80	80		4	1,217	1,221		0	8	8		0	1,873	1,873		4	3,178	3,182
1968		0	113	113		0	993	994		0	56	56		0	2,437	2,437		0	3,599	3,599
1969		1	122	123		8	1,316	1,324		0	18	19		5	846	851		14	2,302	2,317
1970		0	132	132		5	1,410	1,415		0	6	6		14	459	473		19	2,006	2,026
1971		4	358	362		18	1,311	1,329		0	7	7		0	274	274		22	1,949	1,971
1972		1	524	525		5	816	821		0	2	2		5	653	658		11	1,995	2,006
1973		0	460	460		15	1,065	1,080		0	3	3		4	245	249		19	1,773	1,792
1974		0	223	223		15	911	926		0	4	5		0	937	938		16	2,076	2,091
1975		6	741	746		13	844	857		8	42	50		52	1,506	1,558		80	3,132	3,212
1976		3	364	366		38	1,723	1,761		4	3	7		819	2,972	3,791		361	5,061	5,422
1977		4	254	258		27	4,709	4,736		1	10	11		255	2,564	2,819		58	7,536	7,595
1978	242	1	0	243	5,532	37	0	5,569	25	2	0	27	4,435	207	0	4,642	10,234	247	0	10,481
1979	401	5	1	407	6,253	25	7	6,285	61	5	0	66	2,857	29	1	2,888	9,572	64	9	9,645
1980	1,489	122	3	1,614	5,382	34	2	5,419	130	3	0	133	2,202	85	79	2,366	9,204	245	83	9,532
1981	1,225	73	7	1,305	7,787	56	0	7,843	68	1	0	69	772	14	2	788	9,852	144	9	10,005
1982	631	28	5	664	6,204	119	0	6,322	126	0	0	126	1,602	6	2	1,610	8,562	153	7	8,723
1983	815	72	7	895	4,247	32	4	4,284	243	1	0	243	3,092	19	10	3,121	8,398	124	21	8,542
1984	651	18	10	678	3,011	29	3	3,043	161	3	0	164	3,695	53	2	3,750	7,518	103	14	7,635
1985	408	3	10	421	2,860	34	0	2,894	77	4	0	82	3,230	49	2	3,281	6,575	90	12	6,677
1986	308	2	6	316	4,428	10	0	4,438	76	2	0	78	3,407	386	6	3,799	8,218	400	12	8,631
1987	373	0	9	382	4,821	30	0	4,851	67	1	0	68	7,639	1,168	1	8,808	12,900	1,199	10	14,109
1988	506	7	13	526	6,036	18	0	6,054	65	4	0	68	6,071	938	8	7,017	12,678	966	21	13,666
1989	600	0	44	644	5,637	25	0	5,661	127	11	0	138	7,894	534	5	8,433	14,258	570	49	14,876
1990	545	0	28	574	9,972	10	0	9,982	110	6	0	116	6,364	541	10	6,915	16,991	558	38	17,587
1991	527	3	75	605	9,235	77	0	9,311	55	16	0	71	6,408	878	14	7,300	16,225	973	89	17,288
1992	676	2	45	722	8,230	7	0	8,238	119	5	0	124	4,562	570	5	5,137	13,587	584	50	14,221
1993	763	2	32	797	3,637	18	0	3,655	65	1	0	66	2,412	393	3	2,808	6,878	413	36	7,327
1994	410	6	9	425	1,182	7	0	1,189	29	1	0	30	5,211	754	0	5,965	6,832	768	9	7,609
1995	342	6	13	361	992	4	1	997	41	2	0	43	5,786	798	7	6,591	7,161	810	21	7,992
1996	544	5	12	561	2,126	7	4	2,137	59	5	0	64	4,467	653	4	5,124	7,196	670	20	7,886
1997	673	5	21	699	2,347	9	1	2,357	81	11	3	95	2,703	378	1	3,082	5,804	403	26	6,233
1998	392	5	15	412	2,045	19	1	2,065	103	3	0	106	2,411	564	6	2,981	4,951	591	22	5,564
1999	267	2	2	271	5,172	6	1	5,179	78	1	0	79	3,629	959	1	4,589	9,146	968	4	10,118
2000	162	21	43	226	4,910	40	5	4,955	85	3	1	89	8,139	1,210	2	9,351	13,296	1,274	51	14,621
2001	335	7	1	343	4,879	58	6	4,943	28	37	0	65	14,144	1,543	16	15,703	19,386	1,645	23	21,054
2002	386	18	1	405	5,967	33	11	6,011	20	12	0	32	15,981	1,426	36	17,443	22,354	1,489	48	23,891
2003	197	3	1	201	4,859	22	2	4,883	53	4	0	57	19,040	1,226	10	20,276	24,149	1,255	13	25,417
2004	165	12	0	177	4,249	146	11	4,406	830	151	11	992	22,313	1,194	26	23,533	27,557	1,503	48	29,108
2005	163	12	12	187	8,958	69	15	9,042	845	13	40	898	14,361	1,096	109	15,566	24,327	1,190	176	25,693
2006	147	3	5	155	15,688	51	21	15,760	2,029	10	8	2,047	7,944	782	46	8,772	25,808	846	80	26,734
2007	97	8	12	117	9,419	45	18	9,482	335	18	7	360	16,234	345	55	16,634	26,085	416	92	26,593
2008	103	12	5	120	6,405	24	11	6,440	303	6	16	325	16,819	556	13	17,388	23,630	598	45	24,273
2009	81	0	3	84	6,451	8	16	6,475	216	1	3	220	17,487	12	1,851	19,350	24,235	21	1,873	26,129
2010	148	13	6	168	5,826	18	47	5,890	254	9	26	290	19,172	281	97	19,550	25,400	321	177	25,898
2011	193	17	2	212	8,159	14	135	8,309	338	24	24	386	17,224	318	205	17,747	25,914	373	366	26,653
2012	392	22	3	417	13,671	37	16	13,724	118	4	32	154	11,172	272	176	11,620	25,353	334	228	25,915
2013	449	43	6	498	11,823	27	25	11,875	308	13	5	326	5,683	229	54	5,966	18,263	311	89	18,664

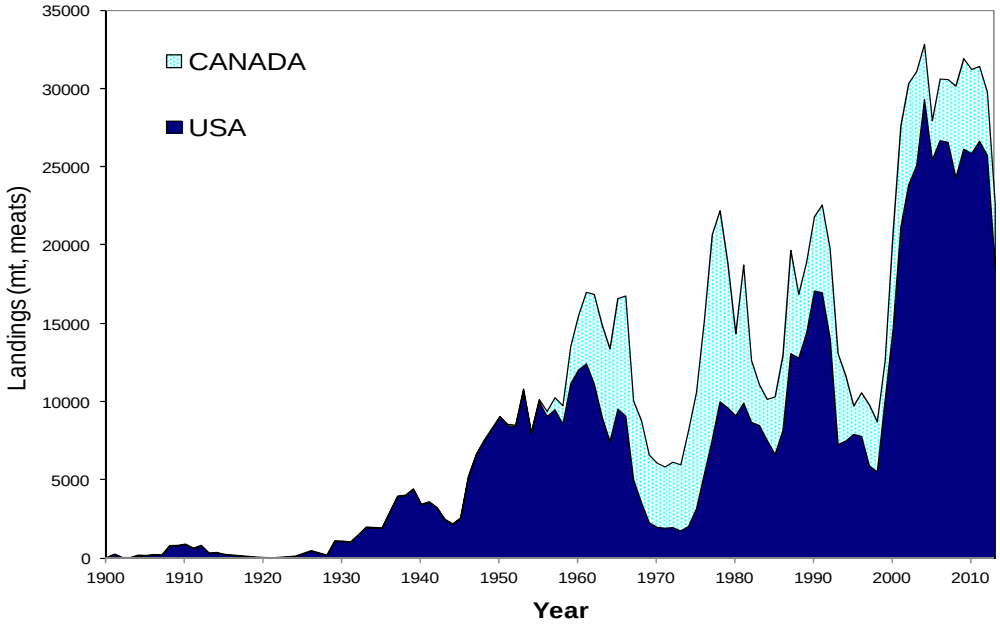


Figure B4.1. Sea scallop landings in NAFO areas 5-6 (North Carolina to Georges Bank).

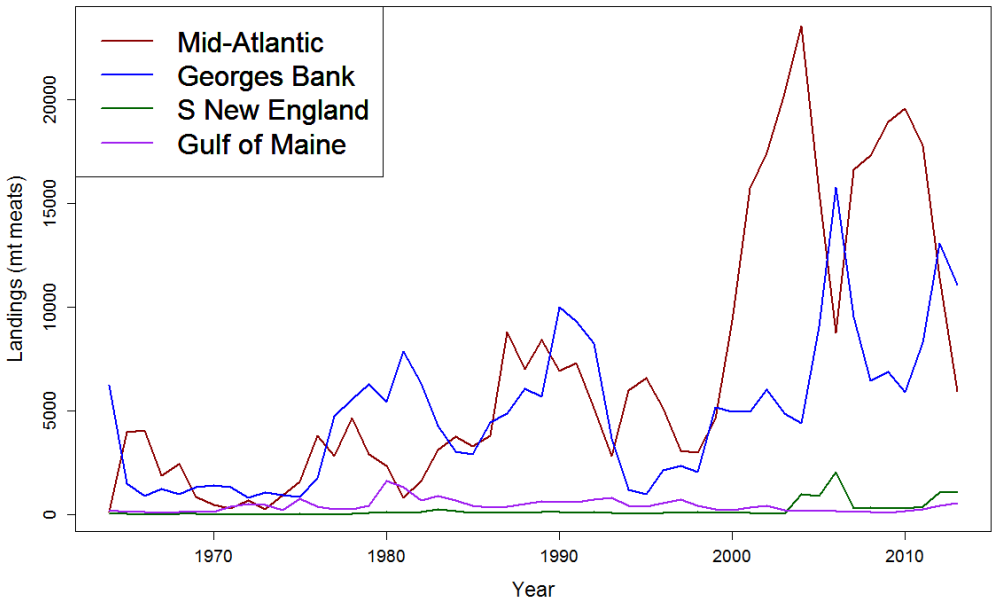


Figure B4.2. US sea scallop landings during 1964-2013, by region.

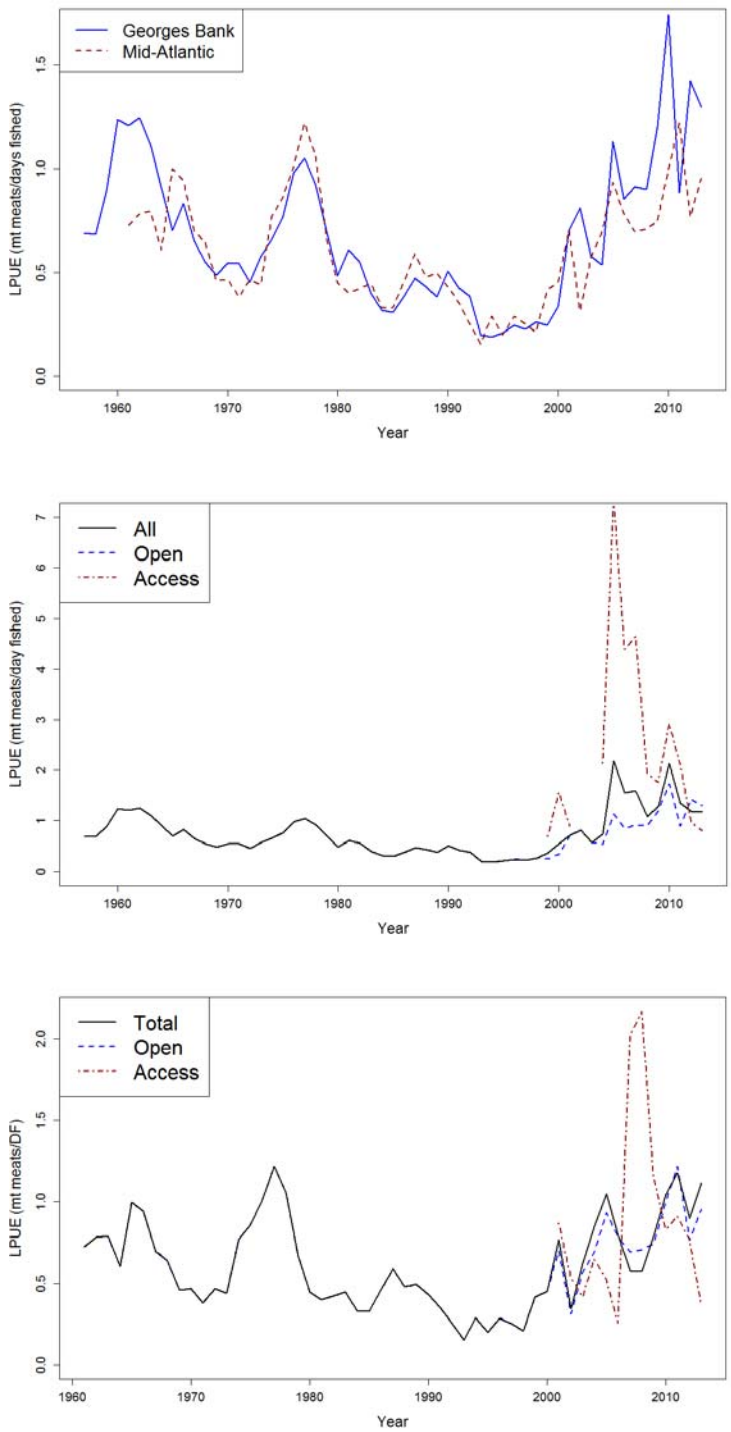


Figure B4.3 *Top*: landings per unit effort (LPUE) on Georges Bank and the Mid-Atlantic, excluding access area trips. *Middle:* LPUE on Georges Bank, separated into access and open areas and combined. *Bottom:* LPUE in the Mid-Atlantic, separated into access and open areas and combined.

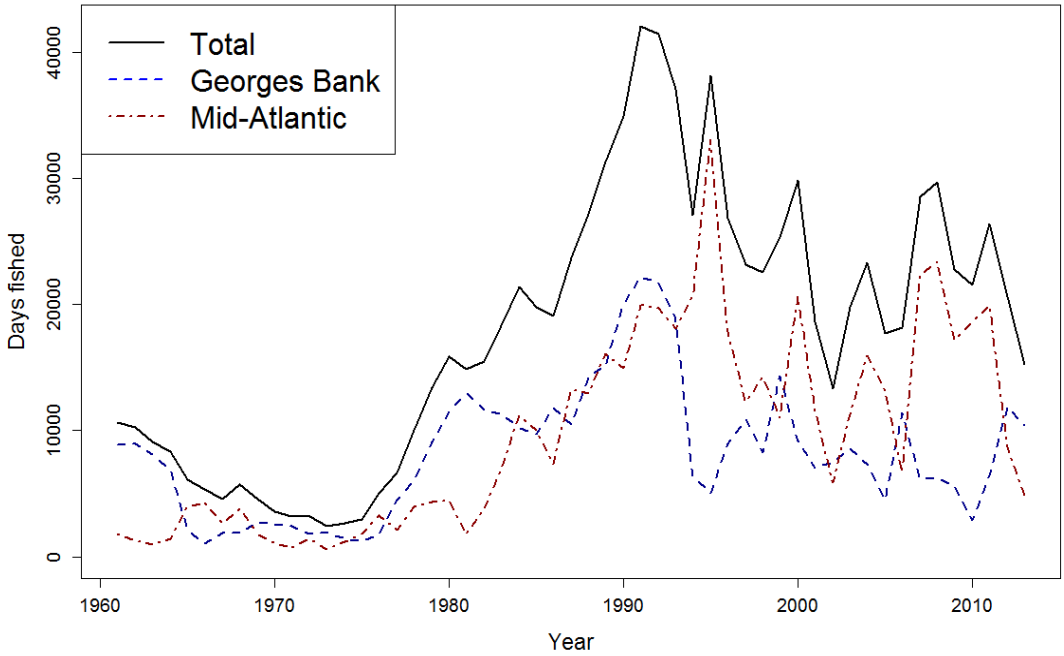


Figure B4.4 Sea scallop fishing effort in the US, 1961-2013.

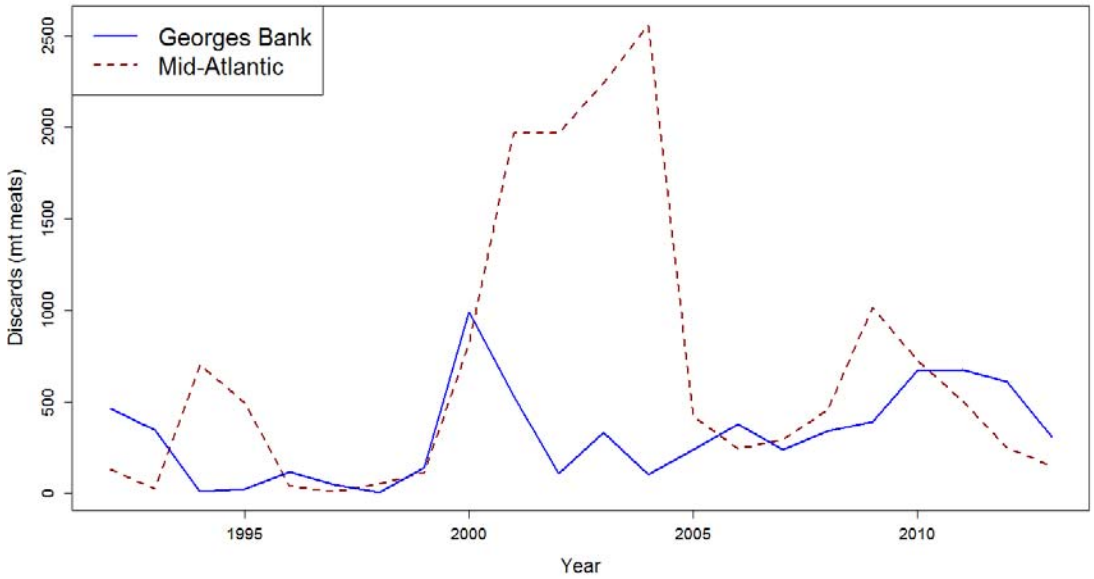


Figure B4.5. Estimated discards in the US scallop fishery, 1992-2013.

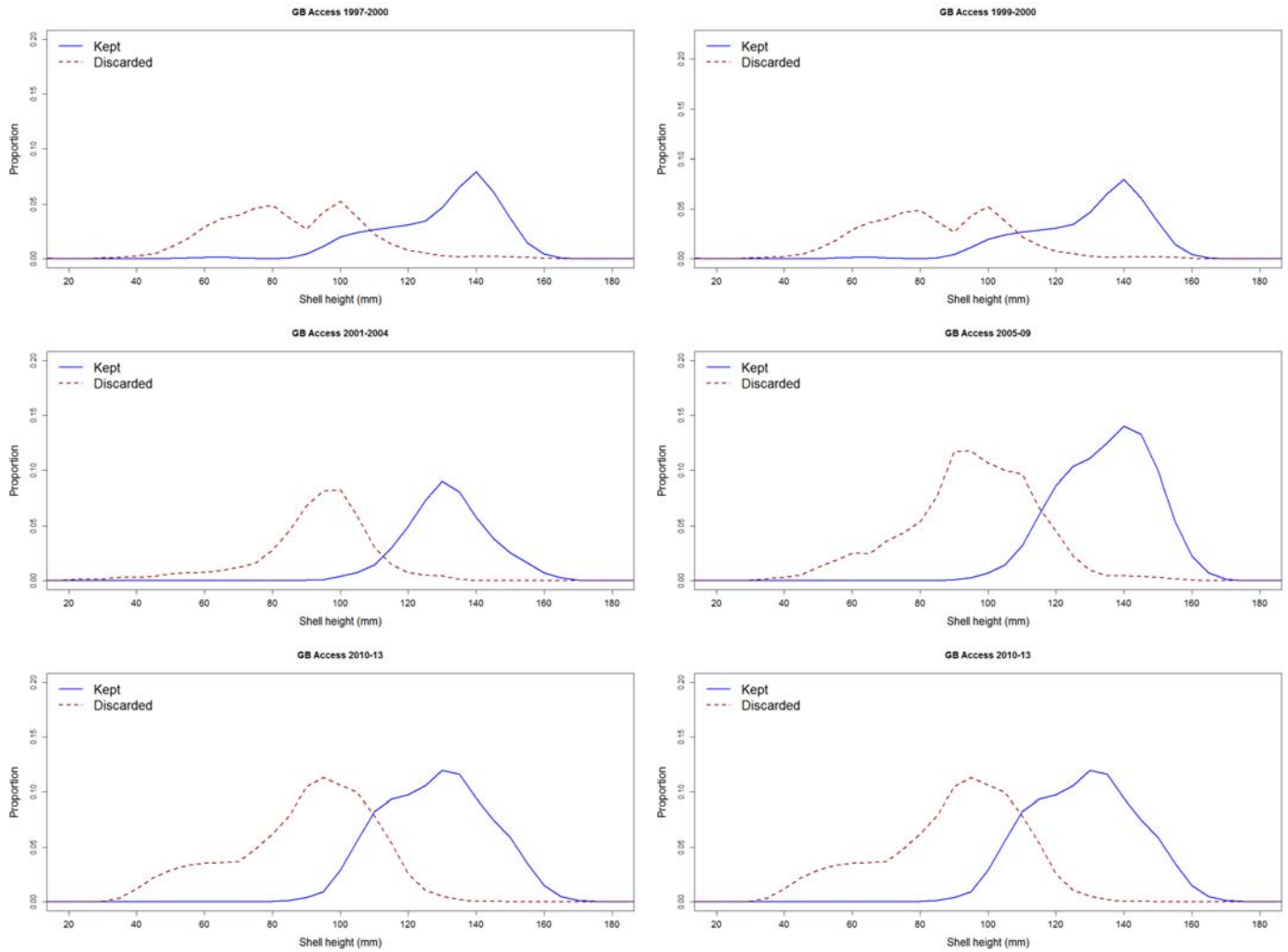


Figure B4.6. Shell heights of commercial kept (solid line) and discarded (dashed line) sea scallops from Georges Bank access areas, based on data from sea samplers.

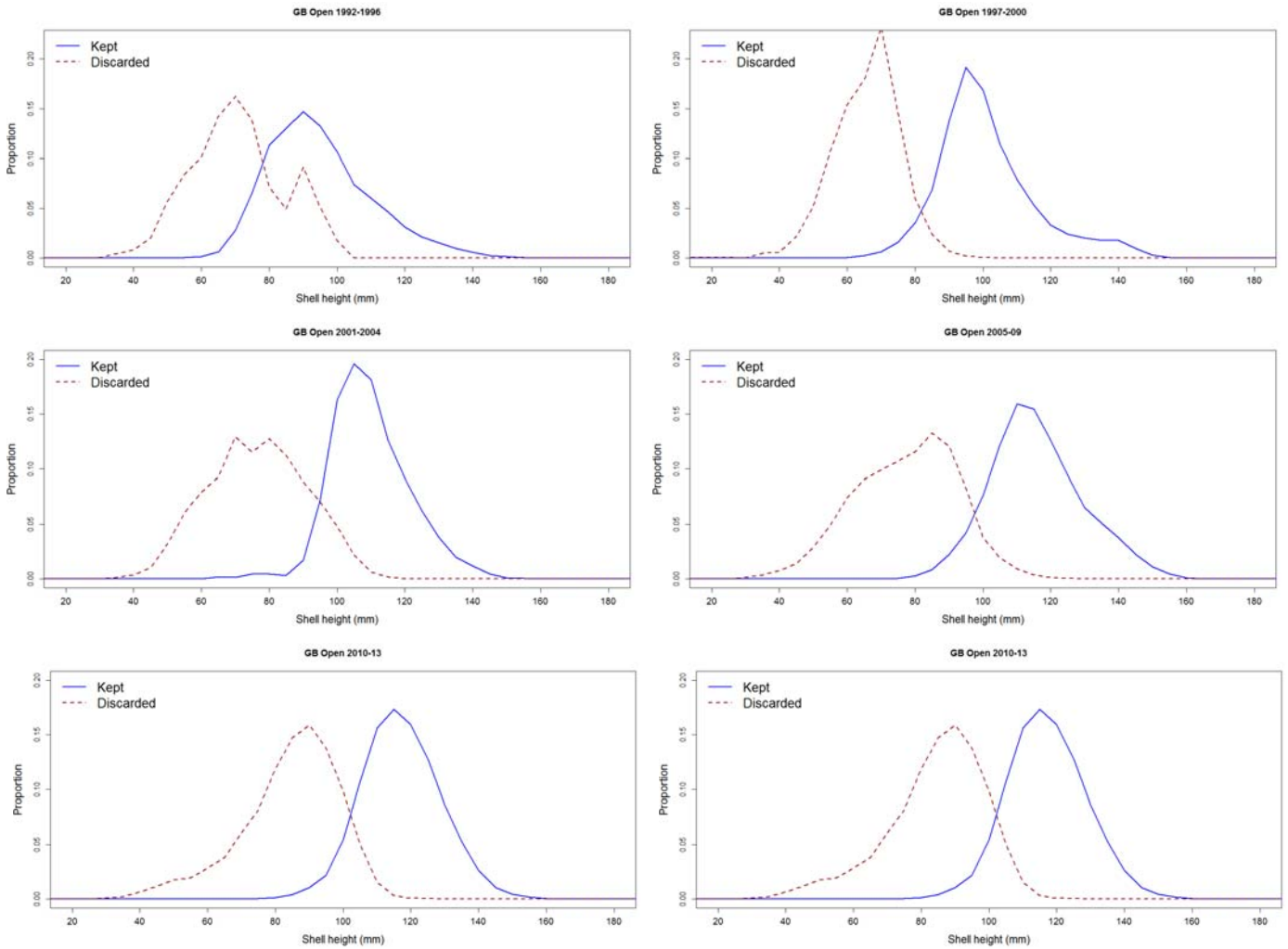


Figure B4.6 (cont). Shell heights of commercial kept (solid line) and discarded (dashed line) sea scallops from Georges Bank open areas.

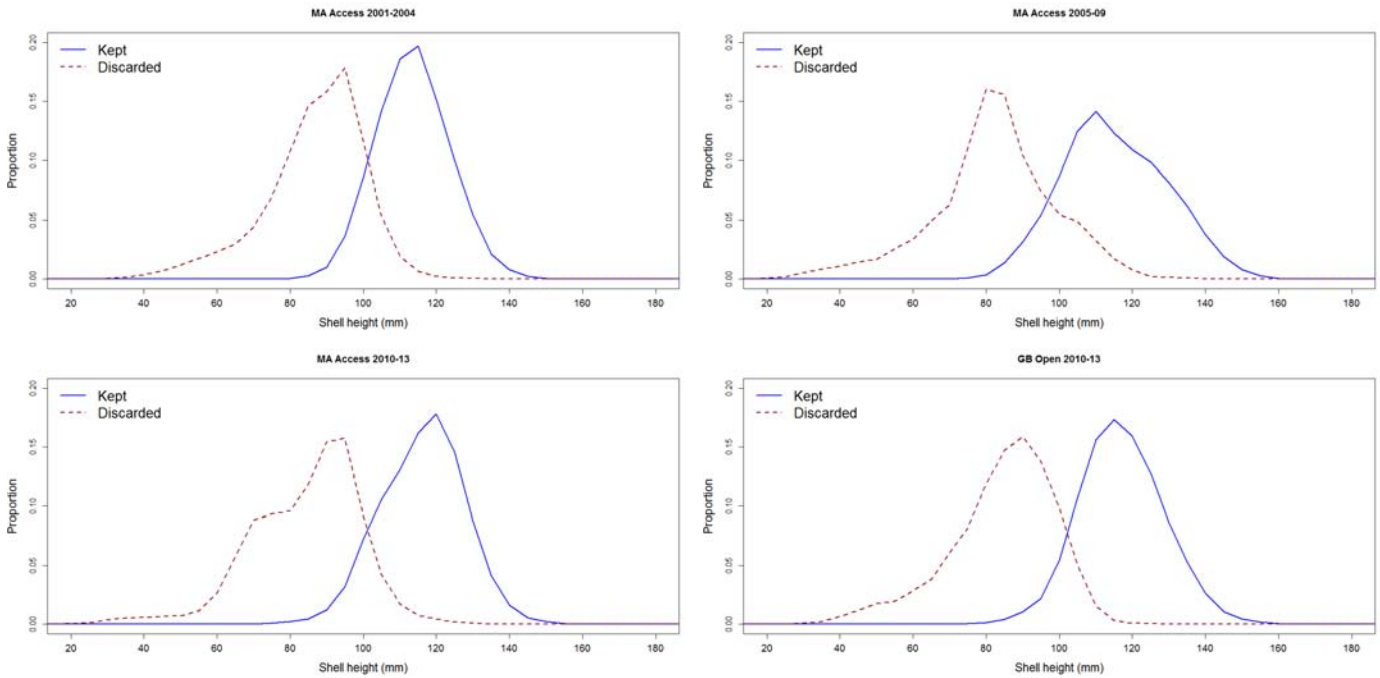


Figure B4.6 (cont.). Shell heights of commercial kept (solid line) and discarded (dashed line) sea scallops from Mid-Atlantic Bight access areas.

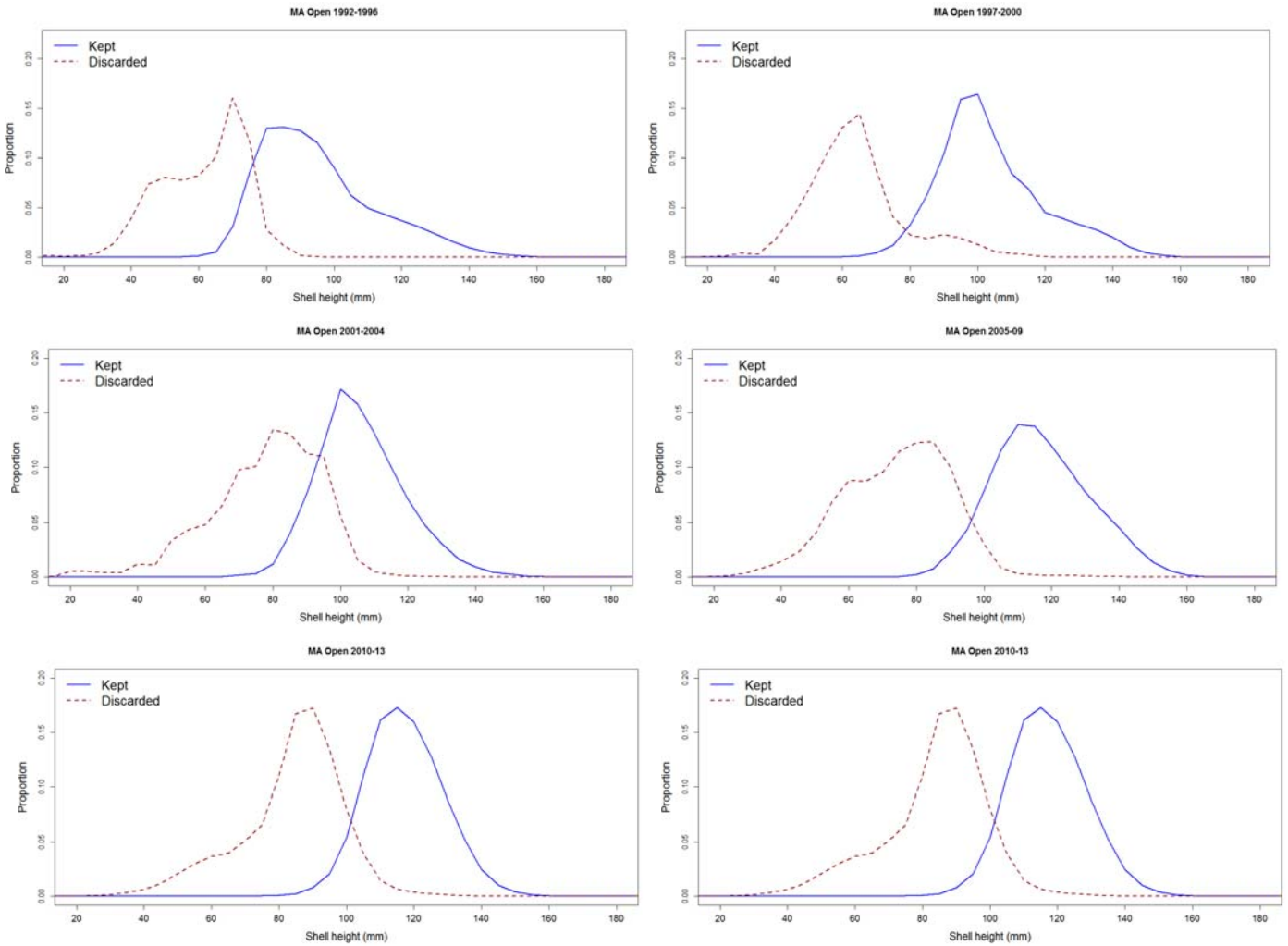


Figure B4.6 (cont.). Shell heights of commercial kept (solid line) and discarded (dashed line) sea scallops from Mid-Atlantic Bight open areas.

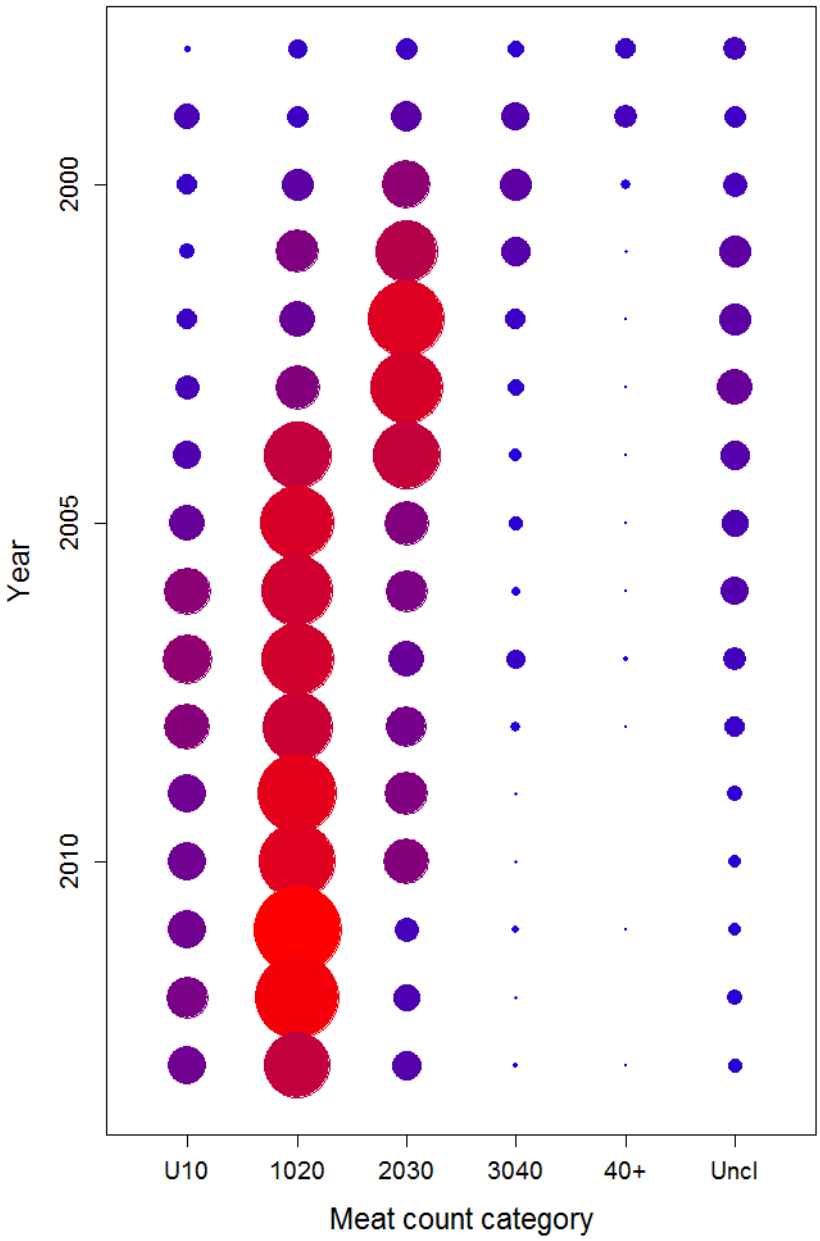


Figure B4.7. Landings by commercial meat count category (U10 = less than 10 meats per lb, 1020 = between 10-20 meats per pound, 2030 = between 20-30 meats per pound, 40+ = over 40 meats per pound, and Uncl = unclassified). The areas of the bubbles are proportional to landings.

B5. SURVEY DATA (TOR-2)

Dredge surveys

Sea scallop dredge surveys were conducted by NEFSC in 1975 and annually after 1977 to measure abundance and size composition of sea scallops in the Georges Bank and Mid-Atlantic regions (Figures B3-1 and B5-1). Means and standard errors were calculated using standard methods for stratified random surveys (Cochran 1977, Serchuk and Wigley 1989; Wigley and Serchuk 1996; Smith 1997).

The 1975-1978 surveys used a 3.08 m (10') unlined New Bedford scallop dredge with 54 mm rings. A 2.44 m New Bedford survey dredge with 54 mm rings and a 38 mm plastic liner has been used since 1979. Based on comparisons between camera and dredge data, scallops greater than 40 mm are considered fully selected by the lined survey dredge gear (NEFSC 2007). The survey covers Georges Bank and the Mid-Atlantic, using a random-stratified design. At each station, the dredge is deployed for 15 minutes. Caught scallops are counted and measured, and subsamples are weighed (meat weight, gonad weight, whole weight, see Hennen and Hart 2012). The shells from the subsamples are brought to shore for growth analysis.

The *R/V Albatross IV* was used for all NEFSC scallop surveys from 1975-2007, except during 1990-1993, when the *R/V Oregon* was used instead. Surveys by the *R/V Albatross IV* during 1989 and 1999 were incomplete on Georges Bank. In 1989, the *R/V Oregon* and *R/V Chapman* were used to sample the South Channel and a section of the Southeast Part of Georges Bank. Serchuk and Wigley (1989) did not find significant differences in catch rates between the *R/V Albatross IV*, *R/V Oregon* and *R/V Chapman.* The *F/V Tradition* was used to complete the 1999 survey on Georges Bank. NEFSC (2001) found no statistically significant differences in catch rates between the *F/V Tradition and R/V Albatross IV* from 21 comparison stations after adjustments were made for tow path length. Therefore, survey dredge tows from these other vessels were used without adjustment except for normalizing for tow distance as discussed below. The northern edge of Georges Bank was not covered by the NEFSC survey until 1982. Data from the Canadian scallop survey during 1979-1981, which used the same gear as the NEFSC survey, was used to cover the northern edge in those years (NEFSC 2010).

In 2008-2013, the NEFSC scallop survey was conducted on the *R/V Hugh Sharp*. Direct and indirect comparisons between the catches by the *R/V Hugh Sharp*, *R/V Albatross IV* and commercial vessels towing the lined survey dredge were not significantly different (NEFSC 2010). However, average catches were slightly greater (~5%) on the *R/V Hugh Sharp.* Comparison of tow distance data from dredge sensor data indicate that tow lengths from the *R/V Hugh Sharp* were about 8% longer on average than those on the *R/V Albatross IV* or commercial vessels (Figure B5.2).

In NEFSC (2010), tows on the *R/V Hugh Sharp* were reduced by 5% to compensate for the apparent differences among survey vessels. For this assessment, each tow was normalized to a tow length of 1 nm. Because dredge sensor data is only available for a subset of the tows, regression equations were developed based on tows where the sensor data is available to predict tow distance using nominal tow distance and depth as predictors. Nominal tow distance is the

nominal tow time (i.e., the time elapsed after the winch is locked at the beginning of the tow to the time when haul back begins) times the mean vessel speed between these times. Separate relationships were developed for the *R/V Albatross IV* (which was assumed to also apply to the other vessels used from 1989-1999), and the *R/V Hugh Sharp:*

Tow length = -0.0388 + 0.001484*Depth + 1.061*Nominal length (*R/V Hugh Sharp)*
Tow length = 0.0864 – 0.000444*Depth + 0.972*Nominal length (*R/V Albatross IV)*

where tow length is in nautical miles and depth is in meters.
Rock excluder chains have been used on NEFSC sea scallop survey dredge since 2004 in certain hard bottom strata to enhance safety at sea and increase reliability (NEFSC 2004). Based on paired tow trials with and without excluders, the best overall estimate was that rock chains increased survey catches on hard grounds by a factor of 1.31 (CV = 0.2). To accommodate rock chain effects in hard bottom areas, survey data collected prior to 2004 from strata 49-52 and in the portions of strata 651, 661, 71 and 74 within Closed Area II were multiplied by 1.31 prior to calculating stratified random means for larger areas. Variance calculations in these strata include a term to account for the uncertainty in the adjustment factor (NEFSC 2007).

The survey area on Georges Bank used in conducting the survey and to tabulate survey data for assessment purposes was modified in this assessment to eliminate marginal scallop habitat. The modified survey area was used to calculate stratified mean catch per tow for the dredge in all years in this assessment. Stratum 72 comprises a shallow area on the northern portion of Georges Bank (Figure B5-3). Most of this stratum has few scallops, but there is a small deep portion where larger catches are often observed. Using the entire stratum induces high variability in the mean number in this stratum, depending primarily on how many tows were in the productive portion. For this reason, stratum 72 was reduced to contain the productive portion of the stratum only (Figure B5-3). Similarly, scallops are more abundant in the northern portion of stratum 74 than in the southern portion. Therefore, only the northern portion of Stratum 74 was used in the survey index. Finally, stratum 631, where the density of scallops is very low, was eliminated from the Georges Bank survey index completely. These changes resulted in a reduction in the total surveyed area on Georges Bank from 7,281 nm^2 to 6,416 nm^2.

Relatively high abundance of sea scallops in closed areas makes it necessary to further post-stratify survey data by splitting NEFSC shellfish strata that cross open/closed area boundaries. After re-stratification, the original and new strata were combined into open, closed or other areas as required for assessment and management purposes (NEFSC 1999, Figures B3-1 and B5-1).

The Virginia Institute of Marine Science (VIMS) has conducted intensive dredge surveys of selected regions on commercial vessels since 2005, using partially randomized grid designs (Figure B5.1). These surveys use two dredges fished side-by-side; the NEFSC lined survey dredge is deployed on one side while a commercial dredge is used on the other side. Comparisons between commercial vessels and the *R/V Albatross IV* indicate suggest that the survey dredge has the same fishing power on these vessels (NEFSC 2010). In the last several years, VIMS has conducted several hundred tows per year.

All VIMS data for fully covered strata (original or post-stratified) were treated in the same way

as NEFSC tows. The partially randomized grid design was treated as random when calculating variances. This likely slightly overstates the true sample variance.

A relatively small number of unsurveyed strata were filled by imputation. Imputation procedures were similar to those in NEFSC (2010). In brief, GAM models were fit to estimate trends in average catch rates over time for individual survey strata with strata nested within subregions. Length composition data for such strata was estimated by the stratified mean length composition for other strata in the same region.

Capture efficiency of the survey dredge was estimated by comparing dredge catches to densities observed by the HabCam system towed at the same location (Appendix B4). The best estimates of dredge efficiency were 0.41 on sand substrates, and 0.27 on rougher gravel/cobble substrates. These, together with estimates of tow path length and stock area (see above) were used to expand mean catch per tow and estimate stock size in absolute terms. For these purposes, the South Channel and northern portion of Closed Area II are considered to have gravel/cobble bottom while the northern edge of Georges Bank, west of Closed Area II are considered mixed sand with gravel/cobble, where dredge efficiency average 0.34. All other areas, including all of the Mid-Atlantic are assumed to be predominately sand and are expanded assuming a survey dredge efficiency of 0.41.

Dredge survey stock size was increased by 10% in the Mid-Atlantic and 4% on Georges Bank to account for scallops at low densities outside the survey strata set used to calculate mean catch per tow. NEFSC (2010) estimated that about 10% of the scallops in the Mid-Atlantic and 3% of the scallops on Georges Bank lie outside the regular dredge survey strata. The new adjustment for Georges Bank was increased from 3% to 4% to also account for scallops in the areas that were dropped from the survey strata set.

Dredge survey results

Biomass and abundance trends for the dredge survey are presented in Table B5-1 and Figure B5-4. Based on dredge survey estimates, biomass and abundance on Georges Bank were generally low until around 1995. Very large increases were observed during 1995-2000 after implementation of closures and effort reduction measures. Biomass has remained high since, although some decreases have occurred during the last several years.

In the Mid-Atlantic Bight, dredge abundance and biomass indices were at low levels during 1979-1997, and then increased rapidly during 1998-2003 due to area closures, reduced fishing mortality, changes in fishery selectivity, and strong recruitment. Biomass was relatively stable during 2003-2008, but then declined, in part due to poor recruitment and fishing down of rotational areas. A slight increase was observed in 2013 due to growth of the large 2010 year class. Survey shell height frequencies show a trend to larger shell heights in both regions since 1995.

SMAST Video Survey

Video survey data was collected by the School for Marine Sciences and Technology (SMAST), University of Massachusetts, Dartmouth between 2003 and 2012 (Table B5-2, Stokesbury et al. 2004). This survey is conducted using drop video cameras; each station consists of clusters of

four drops, and stations are placed on a grid generally 3 nm apart. Although there are several cameras on the camera pyramid, the survey index is based on the "large" camera, a standard definition video camera which was mounted 1.575 m above the bottom in the center of the sampling frame. Each drop quadrat covers about 2.8 m^2.

The precision of measurements must be considered in interpreting shell height data from video. Based on tank experiments, Jacobson et al. (2010) estimated the error associated with shell height measurements from the large video camera had a standard deviation of 6.1 mm. Field measurements are likely less precise than in a tank. For this reason, measurement error was estimated in this assessment by fitting SMAST shell heights to dredge shell heights from the same year and region that were convolved with a Gaussian kernel with mean 0 and standard deviation σ. The standard deviation that best fit the SMAST shell heights over all years and regions was 11 mm. This is the value used in modeling for this assessment.

Video survey data are expressed as densities (number m^{-2}). Variances for estimated densities are approximated using the estimator for a simple random survey applied to station means. There was some variability in the areas covered during each year.

HabCam Towed Camera Survey

HabCam is an underwater towed digital camera system (Appendix B6). The camera(s) take rapid-fire still photos of the sea floor (typically 6/sec) as it is towed at typical speeds between 5-7 knots at roughly 2 m above the bottom. Camera output is sent to the vessel using a fiber optic cable, where it is recorded on hard disk together with related metadata.

Two HabCam vehicles are in operation (Figure B5-5). The first, known as "v2", carries a single camera, and has been in operation since 2005. The second, known as "v4" carries two cameras to allow 3D viewing and more precise measurements, as well as a side-scan sonar and a full array of oceanographic sensors (e.g., CTD, chlorophyll, dissolved oxygen, pH, CDOM, water spectrometer, etc.), and was first deployed in 2012. "v1" and "v3" were prototypes that have not seen routine use.

Region-scale HabCam surveys were conducted on Georges Bank in 2011 using the v2 system, and on both Georges Bank and the Mid-Atlantic in 2012 and 2013 using the v4 system. All broadscale HabCam survey were conducted on the *R/V Hugh Sharp*. The broadscale survey was supplemented in all three years by intensive surveys of selected areas using the v2 system deployed on the *F/V Kathy Marie*. Because of the large number of images collected, only subsets were examined for sea scallop measurements and counts; typically between 1/50 to 1/200 photographs were analyzed, corresponding to about one every 25 to 100 meters. These were expanded to large scales using a zero-inflated generalized additive model followed by ordinary kriging of the residuals (Table B5-3; Figure B5-6; Appendix B6). An alternative method, taking stratified means of the main transects, gave similar results. More details on the HabCam survey and the associated geostatistical methodologies can be found in Appendix B6.

Measurement error was estimated for HabCam by comparing the shell heights to dredge data, as was done for the SMAST survey. Best fit occurred at a standard deviation of 12.7 mm, which is

what was used in the modeling.

The expanded dredge survey time series together with the two optical surveys are shown in Figures B5-7 and B5-8.

Table B5.1. Dredge survey data for sea scallops on Georges Bank (below), in the Mid-Atlantic (next page) and whole stock (3rd page).

Year	Abundance (mean N/tow)	CV	Biomass index (kg/tow meats)	CV	Number of tows	Proportion positive tows	Mean meat weight (g)	Expanded abundance (millions)	Expanded biomass (mt meats)
1979	87.4	0.41	1.697	0.34	108	0.89	19.4	1,269	24,628
1980	75.8	0.24	0.920	0.16	118	0.81	12.1	1,031	12,498
1981	61.2	0.13	1.079	0.13	82	0.83	17.6	753	13,272
1982	132.9	0.46	1.080	0.32	118	0.83	8.1	2,076	16,876
1983	61.2	0.22	0.810	0.21	126	0.88	13.2	890	11,785
1984	39.3	0.11	0.577	0.10	128	0.85	14.7	536	7,887
1985	61.8	0.15	0.731	0.16	154	0.90	11.8	830	9,816
1986	116.8	0.13	1.070	0.10	153	0.90	9.2	1,445	13,237
1987	120.1	0.17	1.173	0.16	170	0.86	9.8	1,619	15,815
1988	98.7	0.16	0.993	0.14	175	0.80	10.1	1,289	12,967
1989	63.6	0.11	0.631	0.08	120	0.78	9.9	806	7,999
1990	184.1	0.24	1.511	0.22	175	0.81	8.2	2,415	19,823
1991	257.9	0.37	1.633	0.25	176	0.89	6.3	3,678	23,292
1992	232.0	0.44	2.020	0.43	171	0.89	8.7	3,300	28,737
1993	61.8	0.24	0.577	0.16	164	0.87	9.3	753	7,027
1994	46.7	0.20	0.518	0.16	177	0.84	11.1	561	6,217
1995	111.8	0.20	0.873	0.16	176	0.88	7.8	1,637	12,774
1996	133.6	0.20	1.617	0.19	171	0.90	12.1	1,855	22,458
1997	89.4	0.15	1.606	0.17	190	0.88	18.0	1,292	23,212
1998	283.0	0.26	4.003	0.32	195	0.87	14.1	3,646	51,566
1999	193.5	0.15	3.391	0.16	173	0.98	17.5	2,663	46,663
2000	766.7	0.29	8.198	0.22	164	0.91	10.7	9,996	106,882
2001	408.9	0.13	6.761	0.13	208	0.95	16.5	5,560	91,938
2002	334.5	0.14	7.195	0.14	214	0.93	21.5	4,498	96,764
2003	277.9	0.12	6.749	0.13	207	0.94	24.3	3,839	93,236
2004	291.5	0.11	8.301	0.12	218	0.94	28.5	3,959	112,749
2005	265.6	0.12	6.792	0.09	343	0.95	25.6	3,888	99,436
2006	221.3	0.13	6.123	0.13	236	0.94	27.7	3,258	90,145
2007	224.8	0.10	4.722	0.07	363	0.97	21.0	3,453	72,533
2008	321.8	0.10	6.460	0.08	239	0.97	20.1	4,805	96,444
2009	362.7	0.15	6.151	0.11	214	0.97	17.0	5,497	93,229
2010	413.1	0.21	7.652	0.09	268	0.97	18.5	6,407	118,682
2011	279.4	0.12	6.971	0.08	225	0.96	25.0	3,946	98,469
2012	225.3	0.13	5.034	0.08	224	0.97	22.3	3,488	77,936
2013	336.5	0.23	4.856	0.14	213	0.94	14.4	4,416	63,723

Table B5.1. (continued – dredge survey data for the Mid Atlantic region)

Year	Abundance (mean N/tow)	CV	Biomass index (kg/tow meats)	CV	Number of tows	Proportion positive tows	Mean meat weight (g)	Expanded abundance (millions)	Expanded biomass (mt meats)
1979	34.7	0.10	0.665	0.10	166	0.92	19.2	590	11,329
1980	42.8	0.12	0.577	0.08	167	0.94	13.5	755	9,829
1981	32.1	0.16	0.457	0.13	167	0.91	14.3	565	7,791
1982	33.5	0.11	0.497	0.08	185	0.91	14.8	591	8,458
1983	32.3	0.10	0.458	0.08	193	0.89	14.2	569	7,794
1984	32.2	0.11	0.444	0.09	204	0.91	13.8	567	7,560
1985	74.1	0.12	0.739	0.09	201	0.94	10.0	1,307	12,582
1986	129.6	0.09	1.295	0.08	226	0.93	10.0	2,285	22,057
1987	131.9	0.08	1.177	0.07	226	0.93	8.9	2,326	20,054
1988	147.8	0.10	1.738	0.08	227	0.91	11.8	2,606	29,610
1989	172.8	0.09	1.553	0.07	244	0.93	9.0	3,047	26,452
1990	215.2	0.22	1.789	0.18	216	0.89	8.3	3,794	30,463
1991	81.0	0.10	0.945	0.10	228	0.92	11.7	1,428	16,100
1992	43.5	0.11	0.526	0.07	229	0.87	12.1	767	8,956
1993	135.6	0.10	0.852	0.08	214	0.96	6.3	2,391	14,513
1994	145.1	0.13	1.141	0.09	227	0.94	7.9	2,558	19,430
1995	173.4	0.13	1.605	0.11	227	0.96	9.3	3,057	27,333
1996	58.8	0.08	0.747	0.07	211	0.89	12.7	1,037	12,718
1997	43.2	0.13	0.504	0.06	225	0.93	11.7	762	8,590
1998	168.4	0.15	1.343	0.12	215	0.92	8.0	2,969	22,872
1999	238.3	0.24	2.239	0.20	226	0.92	9.4	4,202	38,143
2000	292.1	0.14	3.719	0.13	229	0.88	12.7	5,152	63,348
2001	308.4	0.11	4.124	0.12	227	0.90	13.4	5,438	70,236
2002	284.0	0.10	4.224	0.11	206	0.89	14.9	5,009	71,952
2003	654.5	0.16	7.007	0.10	201	0.90	10.7	11,541	119,339
2004	471.0	0.12	6.093	0.08	248	0.89	12.9	8,305	103,772
2005	344.6	0.08	6.048	0.07	278	0.94	17.5	6,077	103,005
2006	386.6	0.09	6.917	0.07	302	0.95	17.9	6,818	117,810
2007	314.6	0.06	6.097	0.06	304	0.94	19.4	5,549	103,852
2008	373.7	0.09	6.258	0.08	259	0.97	16.7	6,591	106,586
2009	370.5	0.12	7.007	0.10	196	0.92	18.9	6,533	119,343
2010	250.3	0.08	5.115	0.07	281	0.94	20.4	4,414	87,126
2011	172.7	0.10	3.840	0.10	298	0.96	22.2	3,045	65,396
2012	260.2	0.12	3.194	0.06	269	0.94	12.3	4,589	54,407
2013	256.1	0.10	3.746	0.08	309	0.98	14.6	4,517	63,796

Table B5.1. (continued – dredge survey data for the whole stock)

Year	Abundance (mean N/tow)	CV	Biomass index (kg/tow meats)	CV	Number of tows	Proportion positive tows	Mean meat weight (g)	Expanded abundance (millions)	Expanded biomass (mt meats)
1979	57.6	0.27	1.113	0.23	274	0.91	19.3	1,859	35,957
1980	57.2	0.15	0.726	0.09	285	0.89	12.6	1,786	22,327
1981	44.7	0.10	0.727	0.09	249	0.88	16.4	1,318	21,063
1982	76.7	0.35	0.750	0.20	303	0.88	9.6	2,667	25,334
1983	44.8	0.14	0.611	0.13	319	0.88	13.6	1,459	19,579
1984	35.3	0.08	0.502	0.07	332	0.89	14.3	1,103	15,447
1985	68.8	0.09	0.735	0.08	355	0.92	10.8	2,137	22,398
1986	124.0	0.08	1.197	0.06	379	0.92	9.6	3,730	35,294
1987	126.8	0.09	1.176	0.08	396	0.90	9.3	3,945	35,869
1988	126.5	0.08	1.415	0.07	402	0.86	11.1	3,895	42,577
1989	125.3	0.07	1.153	0.06	364	0.88	9.2	3,853	34,451
1990	201.7	0.16	1.668	0.14	391	0.85	8.3	6,209	50,286
1991	157.8	0.27	1.244	0.15	404	0.91	7.7	5,106	39,392
1992	125.4	0.35	1.175	0.32	400	0.88	9.3	4,067	37,693
1993	103.6	0.10	0.733	0.08	378	0.92	7.2	3,144	21,540
1994	102.4	0.11	0.870	0.08	404	0.90	8.6	3,119	25,647
1995	146.6	0.11	1.287	0.09	403	0.92	8.7	4,694	40,107
1996	91.3	0.13	1.125	0.12	382	0.90	12.3	2,892	35,176
1997	63.3	0.10	0.983	0.12	415	0.91	15.8	2,054	31,802
1998	218.2	0.16	2.498	0.22	410	0.90	11.7	6,615	74,438
1999	218.8	0.16	2.739	0.13	399	0.95	12.8	6,865	84,806
2000	498.2	0.20	5.664	0.15	393	0.89	11.3	15,148	170,230
2001	352.0	0.09	5.269	0.09	435	0.93	15.1	10,998	162,174
2002	305.9	0.08	5.514	0.09	420	0.91	18.3	9,507	168,716
2003	490.9	0.12	6.895	0.08	408	0.92	14.5	15,380	212,575
2004	393.0	0.09	7.051	0.07	466	0.91	18.5	12,264	216,521
2005	310.3	0.07	6.371	0.05	621	0.95	20.8	9,965	202,441
2006	314.8	0.08	6.572	0.06	538	0.95	21.2	10,076	207,955
2007	275.6	0.05	5.500	0.04	667	0.95	20.0	9,002	176,385
2008	351.2	0.07	6.346	0.06	498	0.97	18.2	11,396	203,030
2009	367.1	0.09	6.635	0.08	410	0.95	18.0	12,030	212,572
2010	321.0	0.12	6.217	0.06	549	0.95	19.3	10,821	205,808
2011	219.0	0.08	5.199	0.06	523	0.96	23.8	6,991	163,865
2012	245.0	0.09	3.993	0.05	493	0.96	16.7	8,077	132,343
2013	291.0	0.12	4.228	0.08	522	0.96	14.5	8,933	127,519

Table B5.2. SMAST Large Camera survey data for sea scallops on Georges Bank, the Mid-Atlantic and combined.

Year	Density (N/m^2)	CV	N stations	Survey area (km^2)	Number (millions)	Mean wt (g)	Biomass (mt)
				Georges Bank			
2003	0.147	0.08	929	28,677	4,213	21.9	92,343
2004	0.122	0.12	935	28,863	3,513	26.6	93,341
2005	0.116	0.11	902	27,844	3,235	24.5	79,370
2006	0.110	0.11	939	28,986	3,177	20.9	66,527
2007	0.142	0.11	912	28,153	3,989	17.8	70,858
2008	0.098	0.09	910	28,091	2,744	13.9	38,113
2009	0.157	0.11	899	27,751	4,351	12.1	52,779
2010	0.116	0.10	939	27,937	3,241	18.1	58,682
2011	0.147	0.12	918	28,338	4,169	15.6	64,885
2012	0.129	0.14	892	27,535	3,555	14.7	52,184
				Mid-Atlantic			
2003	0.483	0.17	804	24,819	11,995	8.7	103,889
2004	0.224	0.10	840	25,930	5,801	12.9	75,032
2005	0.210	0.12	864	26,671	5,598	14.0	78,141
2006	0.191	0.10	897	27,690	5,292	13.7	72,312
2007	0.179	0.09	941	29,048	5,202	14.5	75,227
2008	0.184	0.10	931	28,739	5,288	14.3	75,356
2009	0.134	0.06	928	28,647	3,844	15.1	57,904
2010	0.109	0.08	988	30,499	3,324	20.6	68,363
2011	0.066	0.06	1,359	41,951	2,756	23.3	64,305
2012	0.111	0.08	1,168	35,999	3,996	9.3	37,187
				Whole stock			
2003	0.303	0.12	1,733	53,496	16,208	12.1	196,232
2004	0.170	0.08	1,775	54,793	9,313	18.1	168,374
2005	0.162	0.08	1,766	54,515	8,834	17.8	157,512
2006	0.149	0.07	1,836	56,676	8,468	16.4	138,839
2007	0.161	0.07	1,853	57,201	9,192	15.9	146,085
2008	0.141	0.07	1,841	56,830	8,032	14.1	113,469
2009	0.145	0.06	1,827	56,398	8,196	13.5	110,683
2010	0.112	0.07	1,927	58,436	6,565	19.4	127,045
2011	0.099	0.08	2,277	70,289	6,925	18.7	129,189
2012	0.119	0.08	2,060	63,534	7,551	11.8	89,372

Table B5.3. Summary of HabCam abundance and biomass data for sea scallops used in this assessment. "Images" is the number of images annotated. "Images w/scallops" is the number of images in which scallops were observed. "GAM + kriging" results were estimated using the preferred approach (zero-inflated GAM models with ordinary kriging of residuals). Alternative stratified mean estimates are also shown. See Appendix B6 for further details.

Stock	Year	Annotated Images	Images w/scallops	Number (millions)				Biomass (mt)			
				Stratified random	CV	GAM + kriging	CV	Stratified random	CV	GAM + kriging	CV
GB	2011	202,257	21,428	3,992	0.02	3,832	0.31	110,204	0.02	102,819	0.12
	2012	36,304	7,189	4,003	0.03	4,642	0.14	94,025	0.03	94,040	0.08
	2013	33,864	4,671	3,562	0.03	4,049	0.09	54,683	0.03	49,671	0.29
MAB	2012	20,969	2,095	4,166	0.03	4,902	0.13	50,574	0.04	49,196	0.12
	2013	42,213	3,627	5,064	0.05	4,611	0.07	62,315	0.04	61,485	0.13
Total	2012	57,273	9,284	8,169	0.02	9,545	0.10	144,598	0.02	143,236	0.07
	2013	76,077	8,298	8,627	0.03	8,659	0.06	116,998	0.03	111,157	0.15

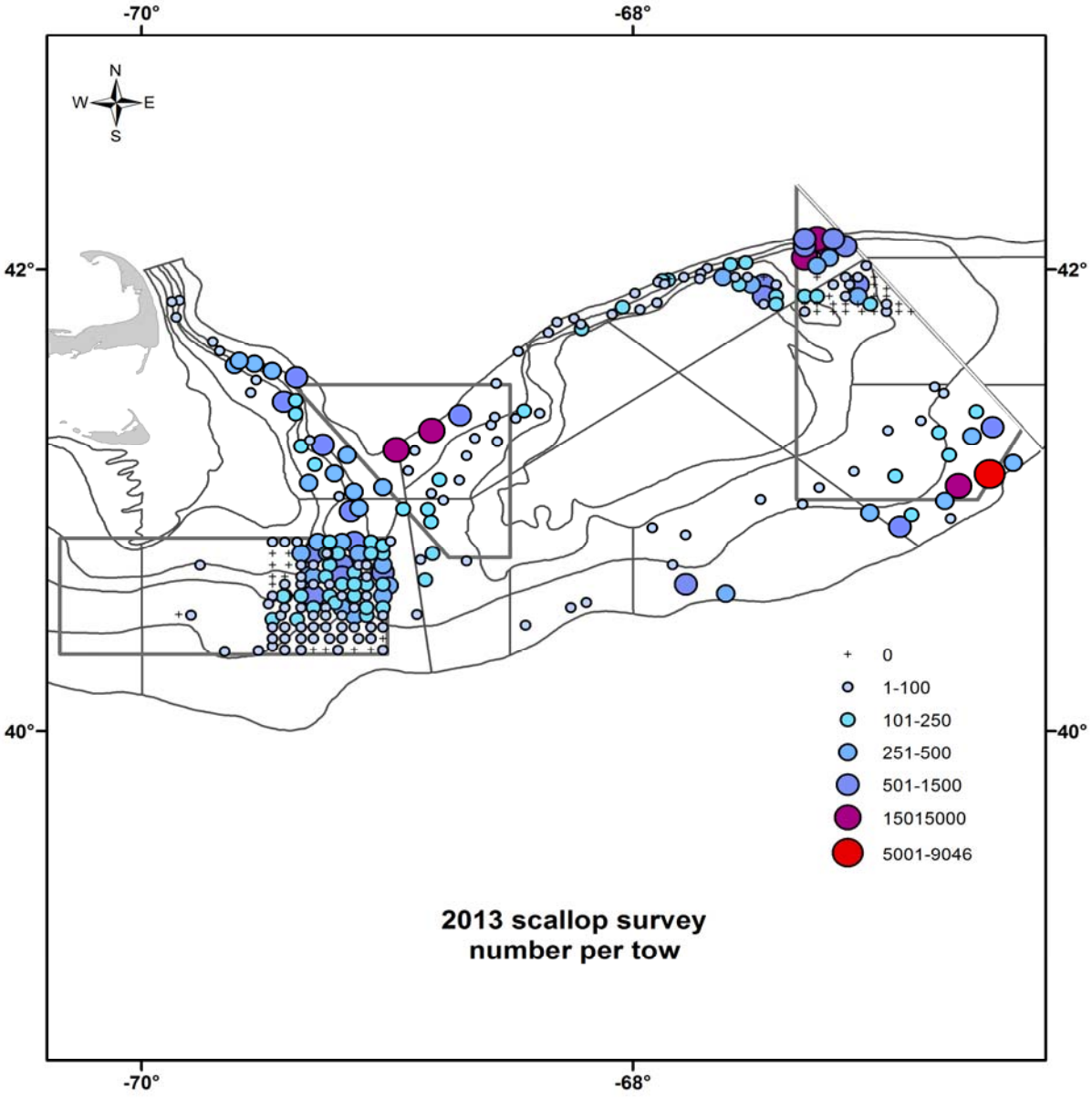


Figure B5.1(a). Dredge survey (NEFSC and VIMS) scallop dredge survey catch number in numbers per tow for Georges Bank.

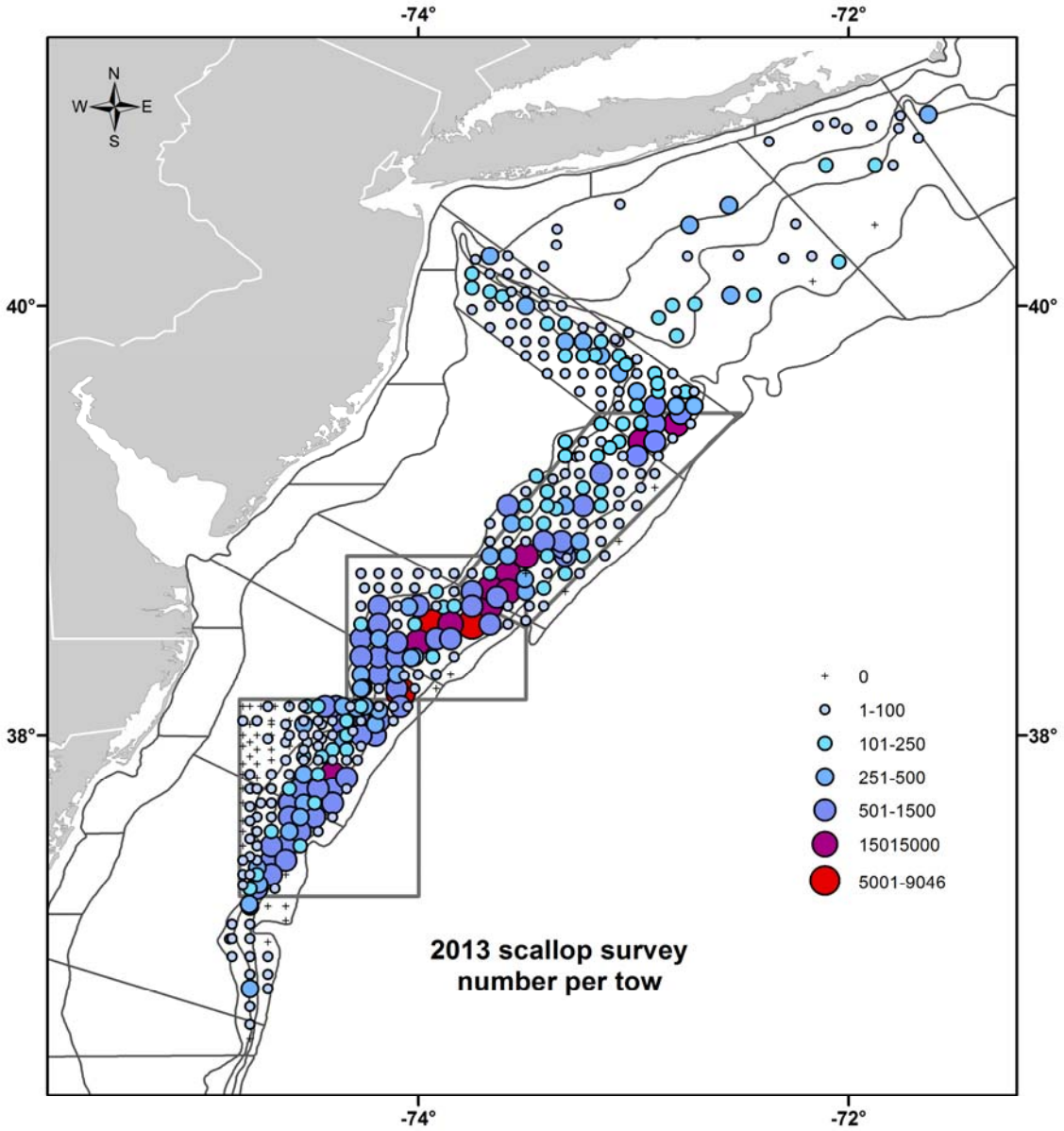


Figure B5.1(b). Dredge survey (NEFSC and VIMS) scallop catch number in numbers per tow for the Mid-Atlantic Bight.

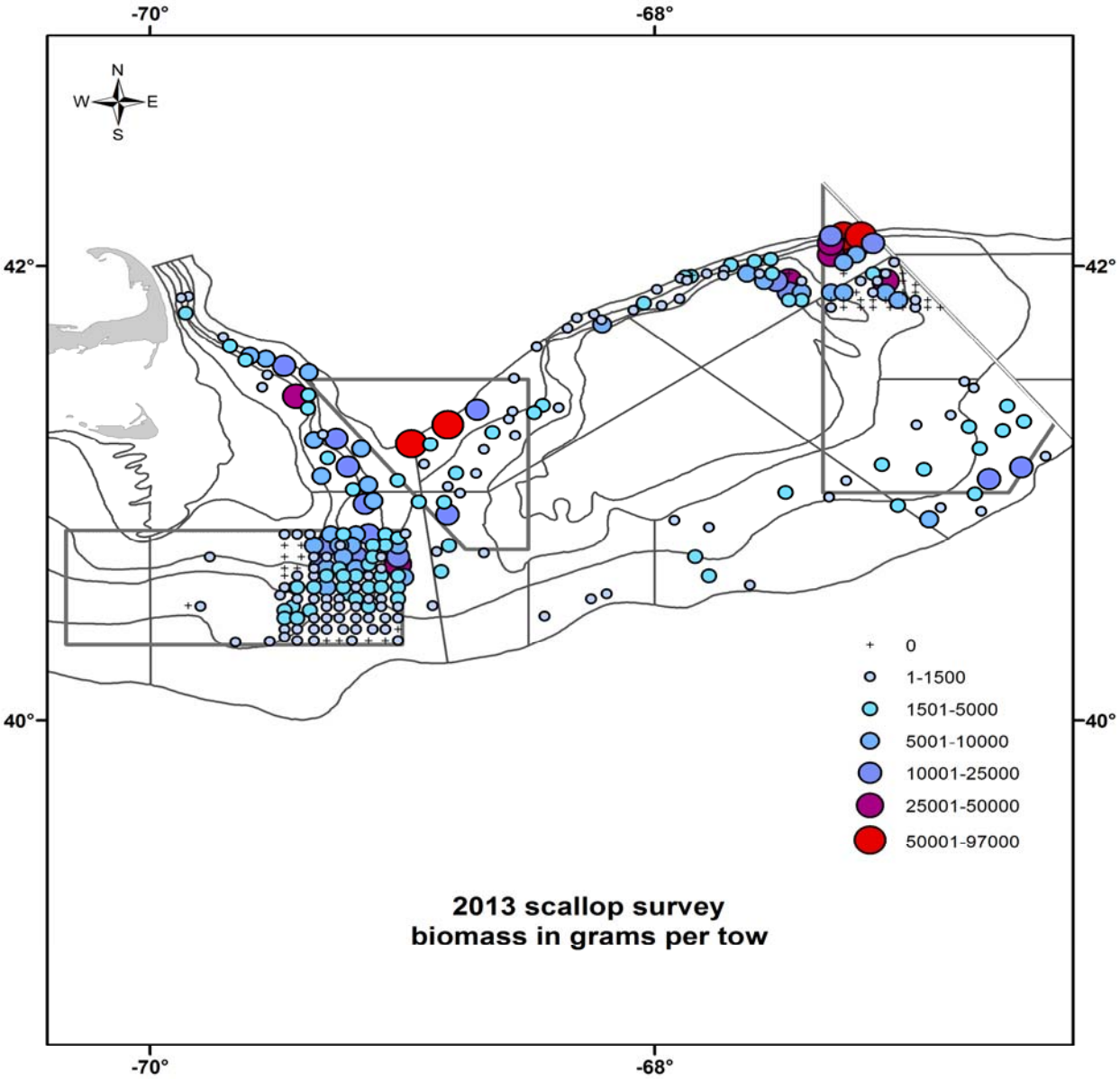


Figure B5.1(c). . Dredge survey (NEFSC and VIMS) scallop catch biomass in grams meats per tow for biomass in grams meat per tow, Georges Bank.

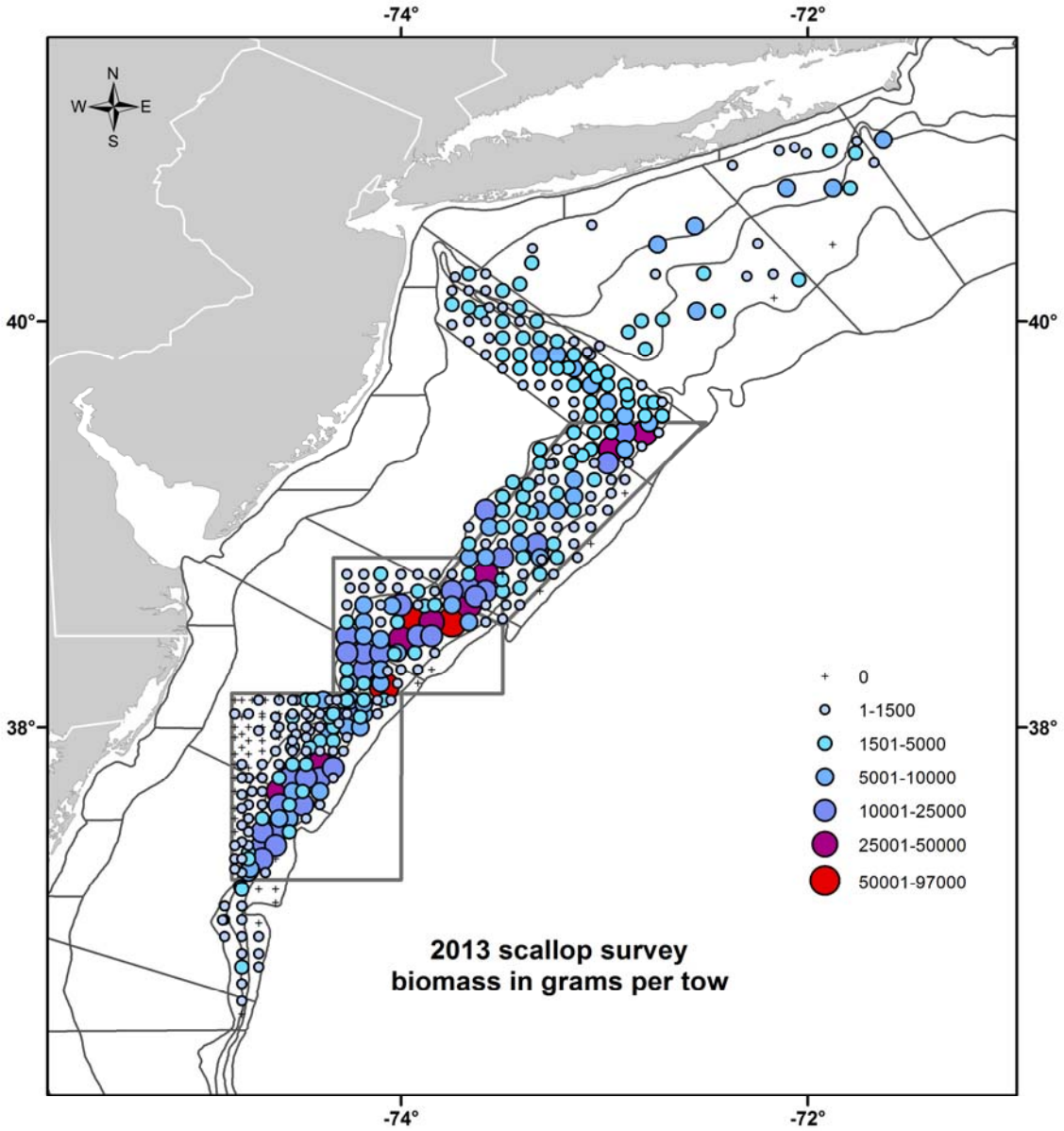


Figure B5.1 (d). Dredge survey (NEFSC and VIMS) scallop catch biomass in grams meats per tow for the Mid-Atlantic Bight.

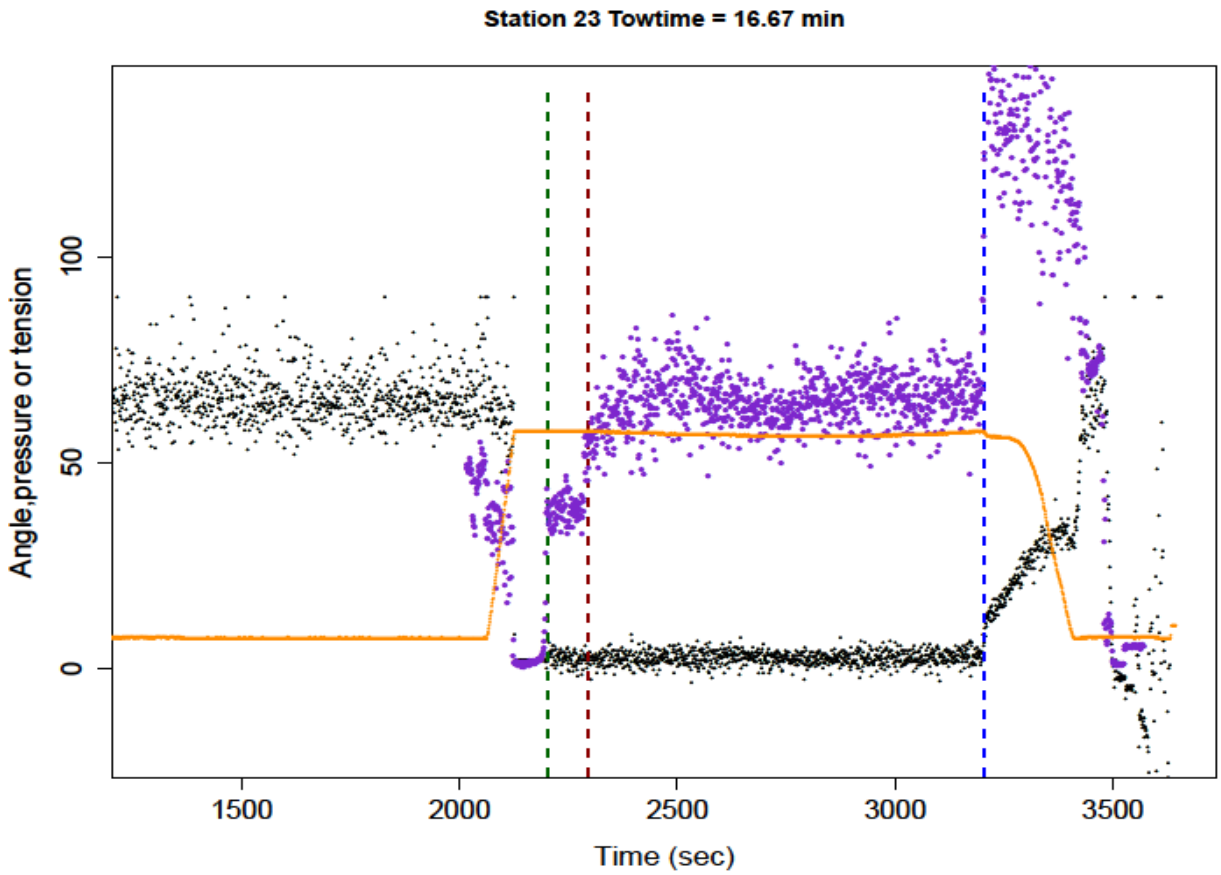


Figure B5.2. Dredge sensor data for an example tow on the *R/V Hugh Sharp* in 2013. The small black dots represent dredge angle, the orange line is pressure (a surrogate for water depth), and the purple dots are cable tension. When the dredge first hits the bottom, cable tension is zero, indicating that the dredge is not moving. The sudden increase in cable tension occurs when the tow has begun (green line), which typically is before the winch is locked (nominal tow start, red line). At tow end (blue line), sudden changes are seen in dredge angle, cable tension, and pressure.

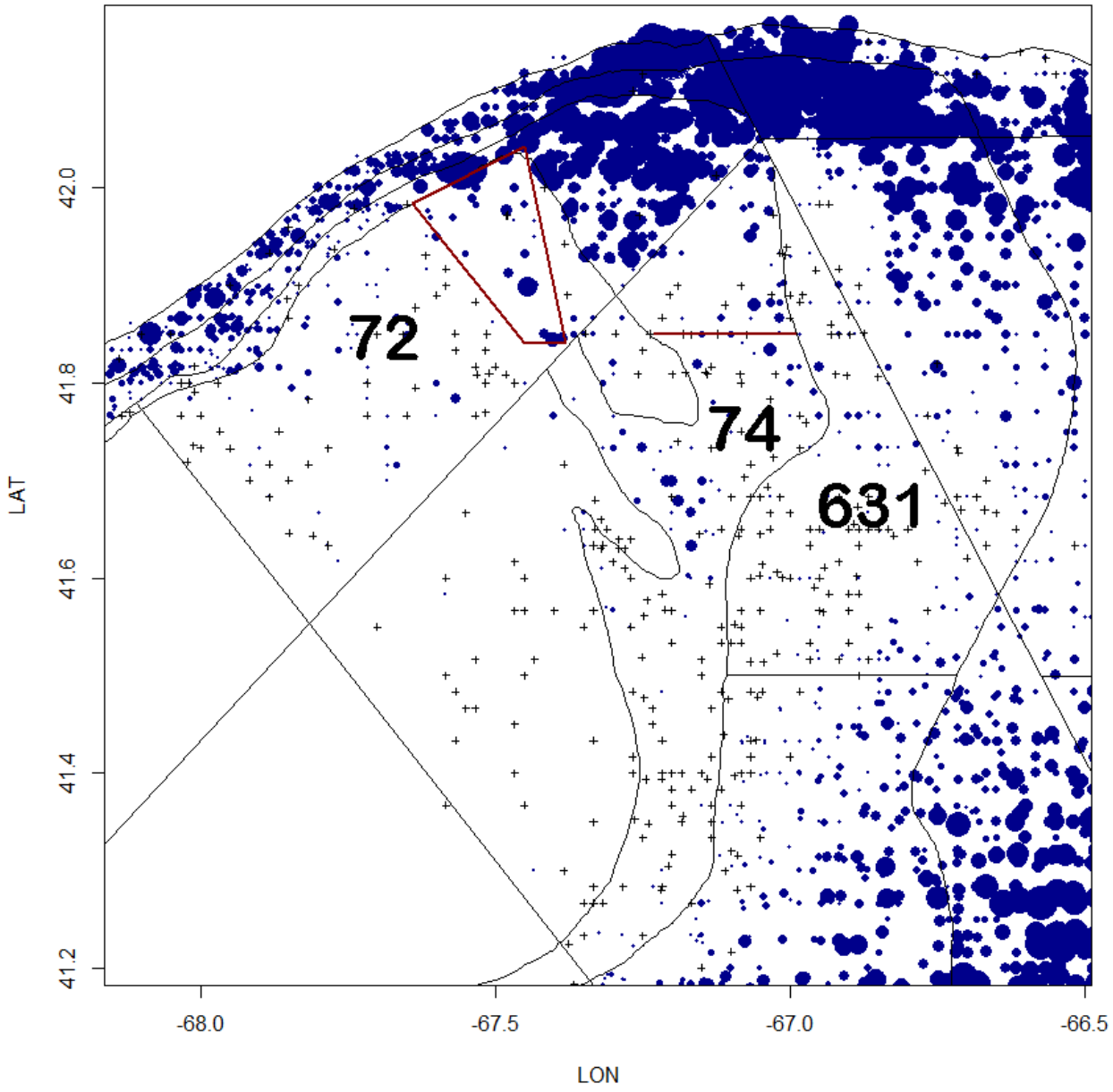


Figure B5.3 Scallop catches (in weight per tow) for all NEFSC dredge tows 1979-2013 in the northeast portion of Georges Bank, showing the two strata (72 and 74) whose areas were modified and the stratum (631) that was dropped. The red polygon in stratum 72 shows the portion of the stratum that is retained in the survey index. The portion of stratum 74 retained in the survey index is the area north of the red line. Catches with zero scallops are shown by plus marks.

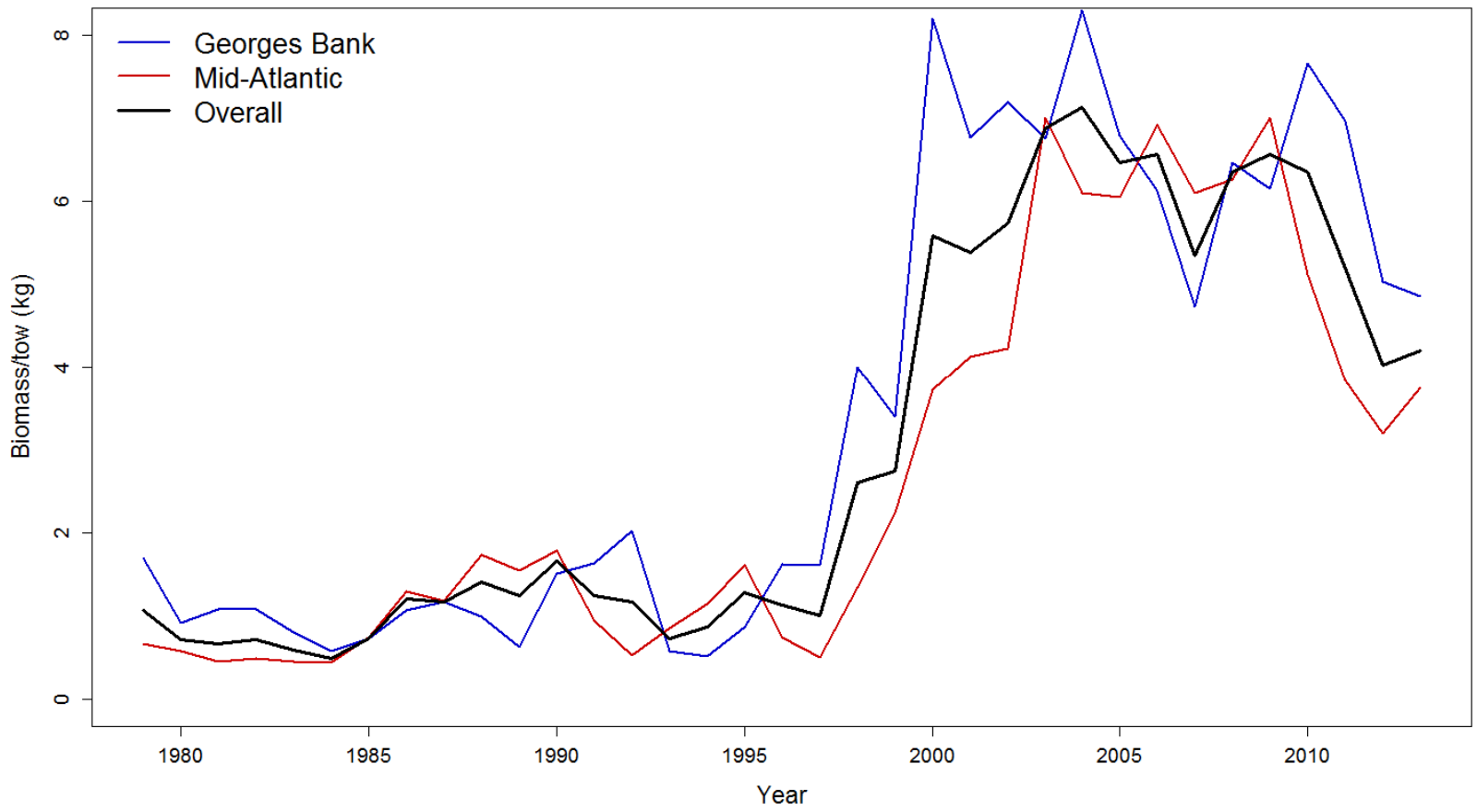


Figure B5.4. Mean stratified biomass from dredge surveys on Georges Bank, the Mid-Atlantic, and overall, 1979-2013.

Figure B5.5. The “v2” (top left) and “v4” (top right) HabCam systems, with an example image taken by v4 in the Elephant Trunk area of the Mid-Atlantic in 2013.

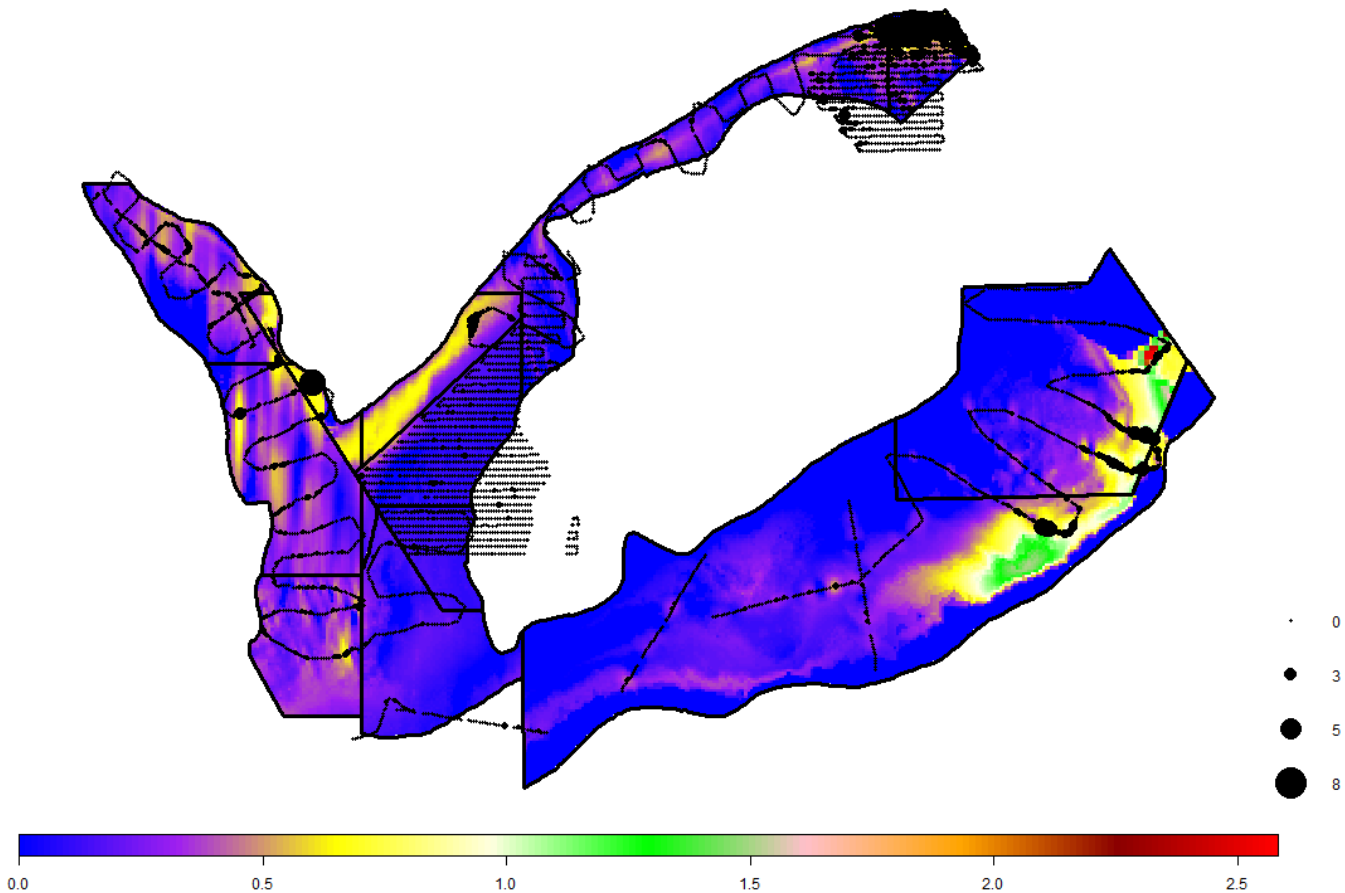


Figure B5.6(a). Estimated scallop densities (# m^2) on Georges Bank in 2013 based on HabCam data using the GAM plus ordinary kriging method. The survey trackline (black line) together with observations of scallops (black dots) are also shown.

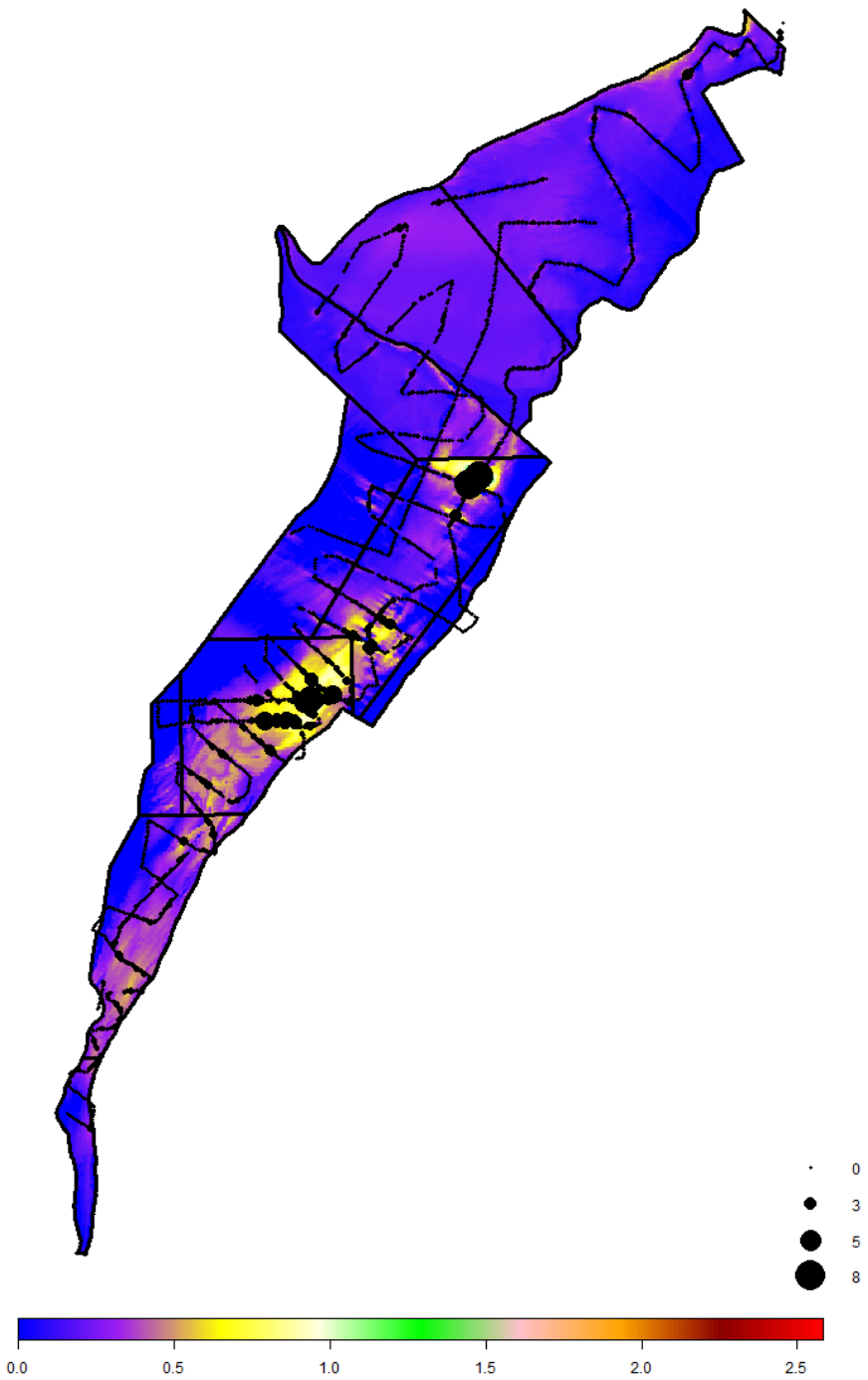


Figure B5.6(b). Estimated scallop densities (# m^2) in the Mid-Atlantic in 2013 based on HabCam data using the GAM plus ordinary kriging method. The survey trackline (black line) together with observations of scallops (black dots) are also shown.

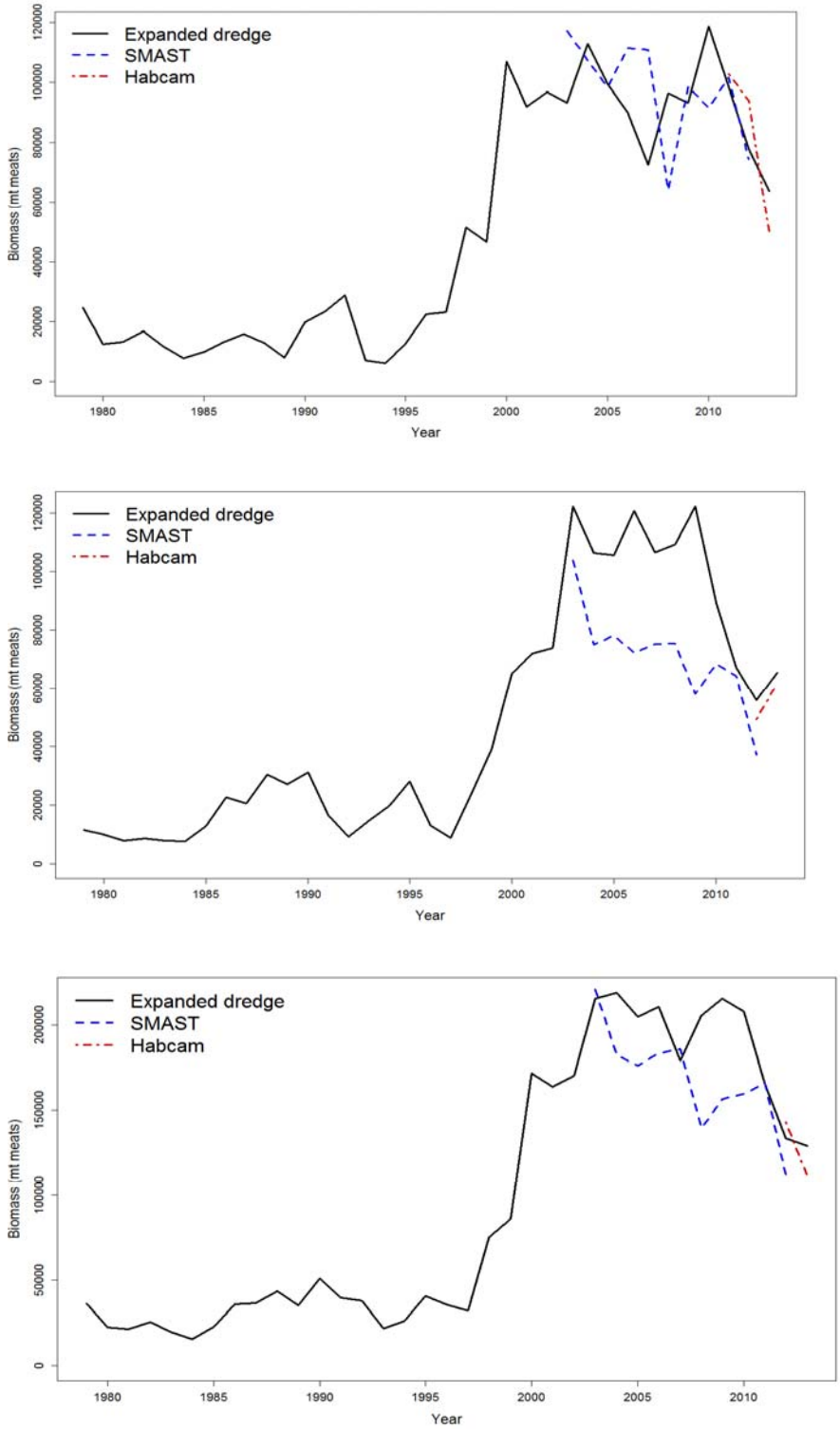


Figure B5.7. Comparison of dredge, SMAST video and HabCam survey biomass estimates for Georges Bank (top), Mid-Atlantic (middle), and combined stock (bottom).

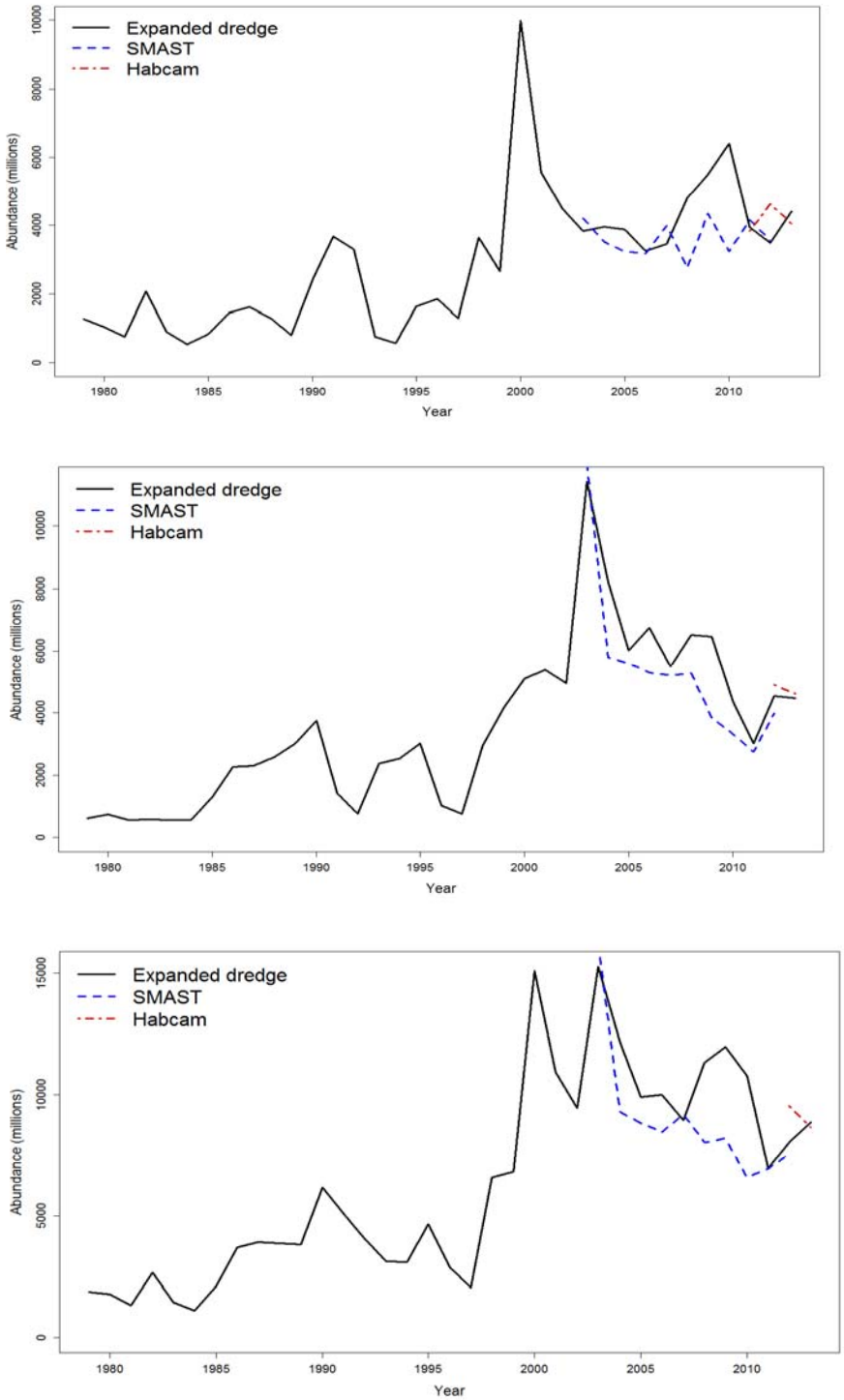


Figure B5.8. Comparison of dredge, SMAST video and HabCam survey abundance estimates for Georges Bank (top), Mid-Atlantic (middle), and combined stock (bottom).

B6. FISHING MORTALITY, BIOMASS, AND RECRUITMENT ESTIMATES (TOR 4)

A catch-at-size-analysis (CASA, Sullivan et al 1990) was used as the primary assessment estimation model. This model has been used for US sea scallop assessments since 2007 (NEFSC 2007, 2010). It performed well in simulation testing using the SAMS model as the operating model (NEFSC 2007; Hart et al. 2013). An additional and simpler "empirical" modeling approach was used for comparison to CASA results (see below and Appendix B9).

For the first time in this assessment, Georges Bank sea scallops were assessed using separate CASA models for open and closed areas. In previous sea scallop assessments, Georges Bank was modeled as a single region containing open, closed and rotational areas. Domed fishery selectivity patterns were used for the Georges Bank stock when there was no fishing in closed areas because large scallops are most common in the closed areas and thus experience less fishing mortality on average than smaller commercial-sized scallops. Using simulated and real data, Hart et al. (2013) concluded that splitting Georges Bank into open and closed areas gave more stable and likely more precise results, probably due to problems modeling complicated and ephemeral domed selectivity patterns. Separating the open and closed areas allows the use of simple logistic selectivity models for fishery size data, rather than domes. As in previous assessments, scallops in the Mid-Atlantic were assessed using single CASA model.

All three CASA models (Georges Bank open, Georges Bank closed and Mid-Atlantic Bight) were run from 1975-2013. Shell heights were modeled with 5mm shell height bins starting at 20mm, but only scallops larger than 40mm were used in tuning because smaller scallops are not fully selected in any of the surveys. The lined dredge and HabCam surveys were assumed to have flat selectivity for scallops 40+ mm. Selectivity of the SMAST large camera and unlined dredge surveys was fixed at experimentally determined values (NEFSC 2007). Selectivity of the winter trawl survey, used in the Mid-Atlantic model only, was assumed logistic with parameters estimated by the model.

Population shell height/meat weight conversions used parameters estimated from 2001-2013 research vessel survey data. Fishery meat weights were adjusted based on estimated seasonal anomalies and the seasonal distribution of landings in that year (see Appendix B3). Commercial shell height (size composition) data for 1975-1984 was from port samples, and 1992-2013 data were from sea samples (observers). The final (plus) group included L_∞. The meat weights for the plus group bin in a given year were the mean observed weight of scallops in the plus group in the dredge survey (for the population) or in port or sea samples (for the fishery, Figure B6.1).

CASA models growth using stochastic growth transition matrices that describe the probabilities for each starting size group of reaching new size groups after one year of growth. In previous assessments, transition matrices were derived directly from shell increment data, and a single transition matrix was used for the entire time series (Hart and Chute 2009a). Several growth transition matrices were used in this assessment to represent growth in different time periods because of new evidence indicating that apparent growth has changed over time. The fishery tends to select large, fast growing individuals so that smaller and relatively slow growing individuals are over-represented in the residual population; the extent of the reduced growth depends on the level of fishing effort.

The growth matrices were based on von Bertalanfy growth parameters and their variances (that measure variability among individual scallops) estimated from growth increment data

using mixed-effects models (Hart and Chute 2009b, see life history section). The matrix was constructed by drawing L_∞ and K values from independent normal distributions with means and variances among individuals estimated by the mixed-effect model. One thousand parameters were drawn for each 0.05 mm interval within each 5 mm starting size bin and used to simulate one year of growth. The resulting binned scallop shell heights were converted to proportions that estimate the desired transition probabilities. Transition matrices constructed in this way were smoother, but similar, to matrices derived directly from growth increments in past assessments.

Prior probabilities (also known as likelihood constraints) are used to incorporate knowledge regarding absolute scale from the surveys. Priors on survey catchability were used for the lined dredge, the SMAST large camera, and HabCam surveys. Priors were calculated assuming that catchability parameters for these surveys have a beta distribution with specified mean and coefficient of variation (CV). The assumed CVs for catchability priors were 0.15 for SMAST and the dredge survey and 0.1 for HabCam. The CV for HabCam is smaller because it is expected to give the most accurate scaling.

For use with priors, the dredge survey was expanded to an absolute scale assuming flat selectivity, experimentally derived estimates of capture efficiency and best estimates of stock area and areas swept by the dredge tows (Appendix B4). SMAST large camera data were expanded after using the experimentally derived selectivity curve to adjust for reduced selectivity of small scallops. After this adjustment, SMAST abundance and size data were expanded assuming flat selectivity and 100% capture efficiency. Expansion of the HabCam survey assumed 100% detectability of scallops > 40mm by the camera.

The estimated catchability parameters from CASA are useful diagnostics when compared to their priors. In the CASA model, I=qN where I is a survey abundance observation, N is abundance available to the survey and q (with expected value 1.0) is the catchability parameter. Relatively high estimates of q indicate relatively low estimated abundance and *vice-versa* because abundance N=I/q.

The catchability parameters estimates described above could, in principal, be larger or smaller than one but beta distributions in CASA do not allow values larger than one. Moreover, we wanted to use a symmetrical beta distribution so that the probability of being slightly larger or smaller than the expected value was the same. We met these objectives in a convenient fashion and without additional programming by multiplying the survey abundance data in the model by 0.5 so that the mean of the prior distributions and expected catchability values were 0.5. This rescaling is simply for convenience; it replaces the target 1.0 for catchability by 0.5 with no other effect on model estimates.

CVs for survey data and effective samples sizes for length data were tuned in preliminary model runs so that the median of assumed values used in tuning were similar to expected values based on goodness of fit. Asymptotic delta method variances calculated in CASA with AD-Model Builder software were used to compute variances and CVs. Sensitivity and profile analyses were also used to describe uncertainty.

CASA model for Georges Bank Open

The model was tuned to the lined dredge survey (1979-2013), the SMAST large video camera survey (2003-2012), the HabCam survey (2011-2013) and the unlined dredge survey (1975

and 1977). The commercial fishery selectivity periods were 1975-1998, 1999-2004, and 2005-2013 so that there was separate fishery selectivity curve during each period.

Two growth matrices were used: one derived from shells collected from the Georges Bank open areas from 2001-2012, and the other from shells collected from all of Georges Bank during 1988 and 1993. The first growth matrix is from a period of moderate fishing pressure while the second is from a period of high fishing pressure. The first transition matrix was used during 1975-1985 and 1999-2013 when fishing effort was moderate and the second matrix was used from 1986-1998, when fishing effort was the highest. Natural mortality was set at $M = 0.16$ ($M = 0.24$ on the plus group) and incidental fishing mortality was set at 0.2 times fully recruited fishing mortality for the smallest size group as described elsewhere in this report. Results are shown in Figures B6.2 to B6.15.

The resulting basecase model fit survey abundance, trends and size data reasonably well (Figures B6.2 to B6.5). Mean estimated posterior efficiencies for the dredge, SMAST and HabCam surveys ranged from 0.53-0.66 (compared to the prior mean 0.5), indicating that CASA abundance estimates were slightly lower than the survey abundance data on average (Figure B6.7). Model estimates of fishing mortality were consistent in scale with the Beverton-Holt (1956) length-based equilibrium estimator (Figure B6.13).

Fishery selectivity strongly shifted over time toward larger shell heights, reflecting changes in gear and targeting practices (Figure B6.8). The size at 50% selectivity moved from about 75 mm before 1999, to 90 mm during 1999-2004, and 100 mm since 2005.

Biomass and abundance generally declined and fishing mortality increased during 1975-1995, with these trends reversing themselves after 1995. As a result of the changes in selectivity and fully recruited fishing mortality, survival to large shell heights has increased substantially in recent years (Figures B6.10-11).

The Georges Bank Open runs show very little retrospective pattern with a seven year peel (Figure B6.15). However, over the last three years, there has been a tendency for the model to overestimate biomass and underestimate fishing mortality.

CASA model for Georges Bank Closed

The model was tuned to the same surveys as used for Georges Bank open areas. There were three growth periods in the model. The first, from 1975-1986, used data from shells collected in the open areas during 2001-2012 that reflected moderate fishing pressure. The second 1987-1995 used data from shells collected from all of Georges Bank during 1988 and 1993 when fishing pressure was high. The third period 1996-2013 is based on shells from the Georges Bank Closed Areas during 2001-2012 when fishing was low or zero. Natural and incidental fishing mortality assumptions were the same as the open area model (i.e., $M = 0.16$ and $M = 0.24$ on the plus group). Incidental fishing mortality was set at 0.2 times fully recruited fishing mortality for the smallest size group. Results are shown in Figures B6-16 to B6-25.

Model abundance estimates generally track dredge survey abundance data well during 1979-1997, but are below survey abundance for 1998-2010. Mean posterior efficiencies for catchability were 0.68 for the dredge, 0.74 for SMAST and 0.39 for HabCam so that the dredge and SMAST surveys were above the prior mean of 0.5 while HabCam was below

(Figure B6.21). The discrepancy between the surveys is likely due to the fact that the HabCam survey was only conducted in 2011-2013, when estimated abundance tended to be above the surveys, whereas there were years that the model was well below expanded estimates from both the other surveys. The model estimated abundance and biomass for 2013 above both the dredge and HabCam surveys.

The model generally fit shell height data and survey data, except for years with very strong recruitment events, when the model tended to be below the survey data (Figures B6.17 to B6.19). CASA model estimates of fishing mortality about the same scale as Beverton-Holt estimates (Figure B6.27).

Estimated fishing mortality increased from 1975-1993 (Figures B6.23 and B6.25) and were low or zero afterward. This resulted in a dramatic increase in biomass during 1994-2004, and a build-up of large scallops (Figure B6.23 and B6.24). Fishery selectivity since 1999 shifted strongly to large scallops (Figure B6.22), even more so than in the open areas, because scallop fishermen tend to select the largest market category (U-10s, i.e., over 45 g meat weight) which usually commands a premium price.

The model for Georges Bank closed areas has a moderate retrospective pattern (Figure B6.29, Mohn's $\rho = 0.33$), where estimates of biomass decrease, and fishing mortality increase, as more years of data are added.

When 6 or 7 years of data are removed, the model fits the survey data well (Figure B6.28). However, the declines in biomass observed in surveys in recent years cannot be fully explained by fishery removals and the assumed natural mortality, so that the model lowers the biomass for previous years as more years of data are added.

<u>CASA model for combined Georges Bank open and closed areas</u>
Biomass and fishing mortality estimates for Georges Bank open and closed combined (Figure B6.30) show generally decreasing biomass and increasing fishing mortality from 1975-1992, with peak fishing mortality of 1.69 in 1992, and minimum biomass of 5,903 mt in 1993. Fishing mortality since 1995 has generally been between 0.2 and 0.4, and biomass increased substantially between 1994 and 2003. Estimated 2013 biomass and fishing mortality for Georges Bank combined is 86,460 mt and F = 0.30, respectively. Retrospective scores for the entire Georges Bank region fell between the scores for the open and closed portions only (Figure B6.30b).

CASA Model for the Mid-Atlantic

The Mid-Atlantic CASA model uses the surveys also used for Georges Bank plus the NEFSC winter bottom trawl survey which was conducted between 1992 and 2007. The winter survey used flatfish trawl gear similar to commercial scallop trawls and should have caught scallops fairly reliably. Preliminary runs with potentially domed selectivity for the winter trawl survey did not indicate that selectivity was reduced for large scallops, so selectivity was modeled using a logistic curve with parameters estimated by the model. Survey efficiency priors and selectivity assumptions for the other three surveys were the same as for Georges Bank. The fishery selectivity periods were 1975-1979, 1980-1997, 1998-2001, 2002-2004 and 2005-2013. The first period was modeled as domed (double logistic) selectivity, due to indications in the data of higher mortality on intermediate sized scallops. This was likely caused by fishing effort that was concentrated in only a portion of the stock, so that most large scallops

were in areas outside the intensively fished area where densities were lower. All the other periods were assumed to have logistic selectivity. Natural mortality was set at $M = 0.2$ with $M = 0.3$ for the plus group, and incidental fishing mortality was set at 0.1 times fully recruited fishing mortality for the smallest size group.

Three growth periods were used: the 1975-1985 and 1998-2008 periods were modeled based on shells collected during 2001-2009 when fishing pressure was moderate. Growth during 1986-1997 was based on shells collected in 1988 and 1993 when fishing effort was high. Growth during 2009-2013 was based on shells collected during 2010-2012 when growth was apparently somewhat faster than during 2001-2009.

Preliminary runs using the effective sample size tuned to match model fits for the dredge survey gave unrealistic results with the model estimating lower fishing mortality in the early 1990s, when fishing effort was the highest, than ten years later. In addition, the model predicted a build-up of scallops in the plus group during the early 1990s contrary to dredge survey shell heights. Estimated fishing mortalities conflicted with those from the Beverton-Holt equilibrium estimator.

For these reasons, the effective sample size of the dredge shell heights was increased to an average of about 800 so that the dredge size data fit the model more closely (Figures B6-31 to B6-43). This resulted in much more realistic fishing mortality and shell height estimates (Figure B6.40). The increased effective sample size is ad-hoc but corresponds to an effective sample size of about 4 scallops per tow which is not unreasonable. Results are shown in Figures B6.33 to B6-44.

The final model fit survey abundance data well for some years, but was often below survey estimates during and after strong recruitment events (Figures B6.31). This was especially apparent starting in 2003, when a very strong year class was observed in both the dredge and SMAST surveys. Because of this conflict, posterior efficiencies were high and near the upper bounds of their priors (over 0.8 for the dredge and SMAST surveys and over 0.6 for HabCam relative to the prior target 0.5, Figure B6.37). Model estimates of shell heights generally fit the data well, except the model estimates of some strong year classes were below those of surveys (Figures B6.32 to B6.35).

Fishery selectivity was strongly domed during 1975-1979 but shifted to a logistic shape and moved father to the right during subsequent periods as would be expected based on management and fishery changes (Figure B6.38). By 2005-2013, only the plus group was fully selected. Model estimated fishing mortality on larger scallops generally increased during 1975-1995, reaching a maximum fully recruited fishing mortality of about 1.5 in 1995, and then declined (Figure B6.39 and B6.41). This decline was much greater for small scallops, which were affected by the shifting selectivity as well as the decline in fully recruited fishing mortality. Abundance and biomass were relatively low during 1975-1998, and then rapidly increased from 1998-2003 (Figures B6.39). Biomass and abundance declined during 2009-2012, primarily as a result of poor recruitment. Recruitment appears to have been substantially stronger since 1998 (Figure B6.39).

The model for sea scallops in the Mid-Atlantic Bight showed a fairly strong retrospective pattern for the earliest three years, with biomass decreasing and fishing mortality increasing as more years of data were added (Figure B6.44). However, this pattern has disappeared during the last several years and has reversed directions slightly.

Whole stock biomass, abundance and mortality

Biomass, egg production, abundance, recruitment and fishable mean abundance were estimated for the whole stock and for Georges Bank as a whole by adding estimates for the Mid-Atlantic Bight and Georges Bank Open and Closed (Table B6.1). For example, whole stock fishing mortality rates for each year were calculated: $F = (C_M + C_{Go} + C_{Gc})/(\overline{N}_M + \overline{N}_{Go} + \overline{N}_{Gc})$ where C_M, C_{Go} , C_{Gc} are catch numbers for the Mid-Atlantic Bight, Georges Open and Georges Closed areas. Terms in the denominator are average fishable abundances during each year calculated in the CASA model as $\overline{N} = \sum_L \frac{N_L\left(1-e^{-Z_L}\right)}{Z_L}$. The simple ratio formula used to calculate whole stock F is an "exact" solution because the catch equation can be written $C = F\overline{N}$.

Whole stock variances were calculated assuming that estimation errors for Georges Bank open and closed, and the Mid-Atlantic Bight were independent. In particular, variances for biomass, abundance and catch estimates were the sum of the variances for Georges Bank open and closed and the Mid-Atlantic Bight. CVs for the ratios estimating whole stock F were approximated $CV_F = \sqrt{CV_C^2 + CV_{\overline{N}}^2}$, which is exact if catch number C_N and average abundance $\overline{N}$ are independent and lognormally distributed (Deming 1960). The CV for measurement errors in catch for each region CV_C=0.05 is the same as assumed in fitting the CASA model. Variances for the stock as a whole depend on the assumption that model errors in Georges Bank and the Mid-Atlantic are independent. These variances would be higher if a positive correlation between model errors exists, and lower if they are negatively correlated.

Like the trends for smaller areas, whole-stock fishing mortality generally increased from 1975-1992 and then declined (Table B6.1 and Figure B6.45). Whole stock biomass, abundance and fishing mortality in 2013 were respectively 132,561 mt meats, 8014 million and 0.32. The biomass and abundance in 2013 were the highest in the 1975-2013 time series. Retrospective scores for the entire sea scallops stock were in the same range as scores for individual regions (Figure B.45b).

The standard errors estimated by the CASA model in this assessment are too small and do not capture all of the underlying uncertainties. The long time series of relatively precise dredge survey data and recent optical survey data, assumptions that survey selectivity is known and prior information on survey efficiencies likely contribute to the underestimation of uncertainty. It is also possible that the survey catchability estimates near the bounds of their priors artificially reduce variance. Comparisons with expanded survey data, retrospective and sensitivity analyses as well as likelihood profiles shown below better describe the uncertainties in the assessment.

Historical retrospective analysis

The current CASA model estimates can be compared to those from the last two benchmark assessments (SARC-45/NEFSC 2007 and SARC-50/NEFSC 2010), and also updates of the SARC-50 model configurations through 2011 and 2012 (Figures B6.46). While the estimates have been fairly stable, there has been a tendency for biomass and recruitment to be revised downward, and fishing mortality upward over time.

It is also of interest to compare the SARC-50 configuration updated through 2013 to the present model. There is a more substantial difference in the Georges Bank models, where the stock was assessed as a whole in the SARC-50 and using separate models for open and closed areas in the current assessment (Hart et al. 2013). The biomass plots indicate modest differences between the two configurations (Figure B6.47). Fishing mortality estimates for the two models are not completely comparable because of differences in estimated selectivity between the models.

Likelihood profile analysis

Likelihood profiles were constructed for natural mortality (Figure B6.48) with plus group natural mortality was fixed at 1.5x that of smaller scallops. For both Georges Bank open and closed, total -log likelihood was minimized at about M = 0.22. For the open areas, the survey trend component of the likelihood (sum over all surveys) was smallest at lower M values, whereas the likelihood for the size data (sum of fishery and all surveys) and Q priors were minimized at larger M values. There was a similar pattern for Georges Bank closed, although the survey trend likelihood component was minimized at about M = 0.18. For Mid-Atlantic sea scallops, the total –log likelihood was minimized near the assumed M = 0.2. The likelihood component for size composition was minimized at a lower natural mortality, whereas the component for the Q prior was minimized at higher M. Effects on stock estimates were evaluated by sensitivity analysis (see below).

Another likelihood profile analysis was constructed for natural mortality of the plus group. Because of the limited number of scallops in the plus groups in the other two models, this was conducted for the Georges Bank closed area model only. Natural mortality for the smaller size groups was fixed at M = 0.16 as in the basecase model. The size composition data component of the likelihood was minimized at low plus group mortality, whereas the –log likelihood of the survey trends and q priors decreased and fit improved as plus group mortality increased (Figure B6.49). Total –log likelihood was minimized at a plus group M of about 0.24, or 1.5 times that of smaller size groups. The latter is the assumption of natural mortality on the plus group made in all the models.

Profiles over dredge survey catchability
A final set of likelihood profile analyses were used to explore differences between CASA model abundance estimates and survey swept-area abundance data as well as the tendency for dredge, SMAST and HabCam survey catchability estimates to fall near the upper bound of their prior distributions (Tables B6-2 to B6-4).

Models for the Mid-Atlantic Bight, Georges Bank closed and Georges Bank open areas were run with the catchability parameter (Q) for the dredge survey fixed at a range of values between 0.4 and 1.2. Goodness of fit (unweighted negative log likelihood) for each type of data as well as measures of stock biomass and fishing mortality were recorded after each run. The profiles were run with catchability priors turned off so that they would not interfere with fit to any of the data in the model.

If the survey swept-area abundance data and model agree about stock size, then the CASA model's catchability estimates for the dredge, SMAST and HabCam data should be in the lower end of the range (Q=0.4-0.6) because of the way the survey data in CASA are scaled. At higher values of Q, the model estimates stock sizes lower than the swept-area abundance

data and *vice-versa*.

Results indicate that the most of the data for all three areas fit best when dredge survey Q is higher than its expected value and estimated abundance is lower on average than indicated by the survey swept-area abundance data (Tables B6-2 to B6-4). This tendency is most pronounced in the Mid-Atlantic Bight area. The cause of these discrepancies is not clear.

Sensitivity analysis

To test the sensitivity of the model outputs to key assumptions, CASA model runs were conducted with alternative assumptions regarding natural mortality, survey priors and incidental mortality. Alternative assumptions about natural mortality on Georges Bank were M = 0.12 (as in SARC-50) and M = 0.20, and M = 0.15 (SARC-50) and M = 0.25 in the Mid-Atlantic. Runs were conducted with the survey priors turned off, at twice the assumed CVs ("loose priors": 0.3 for dredge and SMAST, and 0.2 for HabCam) and at half the assumed CVs ("tight priors": 0.075 for the dredge and SMAST, and 0.05 for HabCam). Alternative assumptions for incidental mortality were either zero or twice the assumed value (0.4 for Georges Bank and 0.2 for the Mid-Atlantic).

Variations in the assumed natural mortality had little effect on Georges Bank Open runs. Assumptions about survey priors had modest effects only in the last several years (Figure B6.50). The assumed value of natural mortality had a stronger effect on Georges Bank Closed runs, especially in the first 15 years after the closures. The higher natural mortality rate allowed the model to estimate a biomass closer to that estimated by the surveys during the 1998-2008 period. However, the value of natural mortality had little influence on the 2013 estimated biomass. Tighter survey priors induced higher biomass estimates, mainly from 2002-2013, whereas loose or no priors induced lower estimates.

The assumed natural mortality rate also had limited effects in the Mid-Atlantic Bight runs, and primarily affected the estimated biomass during 2000-2010. Loose or no survey priors decreased biomass estimates in the Mid-Atlantic, mainly in the last 5 years of the time series. Effects on fishing mortality were generally modest and in the reverse direction of effects on biomass (Figure B6.51). The assumed level of incidental mortality had little effect on model estimates of biomass (Figure B6.52).

Experimental runs with density-dependent natural mortality on juvenile scallops

Scallop abundance estimates from the CASA model were typically below those of the surveys when strong recruitment was observed in the surveys. This suggests that natural mortality of juveniles may increase at high density. If this is the case, CASA models would be below the surveys for those years because observations of the strong year class in subsequent years would indicate less scallops than would be expected based on the initial survey observations and assumptions regarding natural and incidental mortality. High natural mortality on large year classes of juveniles ignored in modeling would induce retrospective patterns like that observed, where estimates of strong year classes and abundance would decline as more years of data were added.

There is also experimental evidence of density-dependent natural mortality on juvenile sea scallops. Wong et al. (2005) seeded juvenile scallops in experimental plots at densities of 1, 6

or 69 m^{-2}. Scallop density in the high-density sites declined markedly due to both predation (and in particular predation by *Cancer* spp. crabs) and dispersal, resulting in final densities of about 1 m^{-2} regardless of treatment. Predation rates of *Cancer* crabs on juvenile sea scallops appear to be greater when scallops are more common than alternative prey species, and increase with increasing scallop density (Barbeau et al. 1998, Wong and Barbeau 2005). Thus, *Cancer* crabs are potential agents of density dependence in juvenile sea scallops; they primarily consume scallops less than 70 mm, and almost all less than 90 mm (Elner and Jamieson 1979, Lake et al. 1987).

In order to model density-dependent juvenile mortality, we defined the number of juveniles as the J = L(H), where H is scallop numbers at shell height and L is a declining logistic function. For this initial exploration, the inflection point L_{50} of the logistic function was set at 80 mm, and the slope of the logistic function was also fixed (Figure B6.53). Natural mortality of juveniles of shell height H was assumed to be M_0 (H) + kL(H)J, where M_0 is a fixed constant and k is a parameter estimated by the model. For this preliminary work, M_0 was set at half of the adult natural mortality (i.e., 0.08 for Georges Bank and 0.1 for the Mid-Atlantic) at small sizes, and increases to full adult natural mortality at large sizes (i.e., $M_0(H) = M[2-L(H)]/2$, where M is the natural mortality on adults).

Example runs are shown here for Georges Bank Open and Closed; density-dependence in the Mid-Atlantic model was difficult to estimate. Both Georges Bank models showed improved fits to the survey data, especially Gerorges Bank Closed (Figures B6.53 and B6.54). Estimated natural mortality of juveniles ranged between about 0.15 and 1. The working group thought these preliminary model runs were promising and recommended further development of this approach.

Empirical Assessment

The empirical assessment used simple techniques to estimate sea scallop stock abundance, biomass and fishing mortality in the Mid-Atlantic, Georges Bank and combined stock areas without using a stock assessment model (Appendix B5). The purpose was to evaluate the accuracy of CASA estimates as independently as possible by taking advantage of the three surveys (dredge, SMAST and HabCam) that can be used to estimate stock size directly. However, empirical results could be used in place of CASA model estimates if the later were unavailable. The data and various parameters used in the empirical analysis are a subset of those also used in the CASA model and were all obtained independently in field studies or other analyses rather than from a stock assessment model.

Empirical and CASA model estimates of abundance and fishing mortality show similar trends in all regions (Tables 3-4 and Figure 7 all in Appendix B5). However, empirical abundance estimates were usually higher reflecting the tension in CASA models between matching the scale of the abundance data (matching the prior on Q) versus fitting the survey and fishery data which was evident in likelihood profile analysis over a ranges of dredge survey catchability (Tables B6-2 to B6-4). As expected, fishing mortality estimates show the inverse pattern with empirical generally lower than CASA estimates.

Table B6.1. CASA model estimates and standard errors for July 1 abundance and biomass (40+mm SH), and fully recruited fishing mortality for George Bank open, closed, and total. (See following pages).

	Georges Bank Open						Georges Bank Closed						Georges Bank Total					
Year	Abund	SE	Biomass	SE	F	SE	Abund	SE	Biomass	SE	F	SE	Abund	SE	Biomass	SE	F	SE
	(millions)		(mt)				(millions)		(mt)				(millions)		(mt)			
1975	969	37	16322	622	0.08	0.01	537	23	10625	461	0.09	0.01	1507	623	26946	622	0.09	0.01
1976	1023	35	17449	666	0.19	0.01	601	23	11952	478	0.14	0.01	1624	667	29401	666	0.17	0.01
1977	859	32	16389	634	0.30	0.02	502	20	11651	464	0.28	0.02	1361	635	28040	634	0.29	0.02
1978	752	27	14047	567	0.34	0.02	460	18	10155	412	0.34	0.02	1212	568	24202	567	0.34	0.03
1979	602	24	11299	482	0.45	0.03	312	15	7504	353	0.58	0.04	914	483	18803	482	0.50	0.04
1980	678	25	9484	394	0.43	0.03	359	17	5948	291	0.49	0.04	1037	395	15432	394	0.45	0.03
1981	575	22	8118	313	0.63	0.04	299	15	5160	265	0.58	0.04	875	314	13279	313	0.61	0.05
1982	500	19	6080	249	0.87	0.06	241	15	4371	276	0.49	0.04	741	250	10451	249	0.73	0.06
1983	358	17	4632	230	0.74	0.05	206	18	3667	314	0.56	0.04	565	231	8298	230	0.67	0.05
1984	314	18	3978	244	0.54	0.03	230	21	3682	352	0.26	0.02	543	245	7660	244	0.43	0.04
1985	334	21	3792	257	0.61	0.04	265	26	4034	408	0.47	0.03	598	258	7827	257	0.54	0.05
1986	490	26	3676	239	1.19	0.08	392	35	4551	433	0.72	0.05	883	240	8227	239	0.95	0.09
1987	524	25	4389	239	0.84	0.05	440	45	5005	541	0.89	0.06	964	240	9394	239	0.86	0.08
1988	393	23	4233	270	0.95	0.06	804	62	7335	605	0.87	0.06	1197	271	11568	270	0.91	0.14
1989	451	26	3803	266	0.98	0.06	816	57	10092	728	0.52	0.04	1268	267	13895	266	0.65	0.09
1990	535	26	4033	229	1.21	0.08	674	44	9074	570	1.10	0.08	1209	230	13108	229	1.13	0.13
1991	634	26	4293	188	1.49	0.10	583	30	6445	313	1.44	0.10	1217	190	10738	188	1.46	0.14
1992	376	15	3366	135	1.69	0.11	352	24	4070	269	1.70	0.12	728	136	7435	135	1.69	0.16
1993	222	11	2270	119	1.13	0.07	343	34	3633	368	0.92	0.07	564	120	5903	119	1.02	0.13
1994	220	14	2200	143	0.53	0.03	351	37	4890	546	0.13	0.01	571	143	7090	143	0.26	0.04
1995	440	19	3278	166	0.55	0.04	522	44	7743	726	0.00	0.00	962	167	11022	166	0.17	0.04
1996	466	20	4369	196	0.77	0.05	629	48	11235	905	0.00	0.00	1095	197	15603	196	0.26	0.05
1997	451	22	4456	225	0.81	0.05	691	52	15342	1142	0.00	0.00	1142	226	19798	225	0.24	0.05
1998	637	33	5260	259	0.67	0.04	1014	64	20416	1347	0.00	0.00	1651	261	25676	259	0.30	0.04
1999	1015	44	7770	325	0.90	0.06	988	65	23875	1552	0.20	0.01	2003	328	31645	325	0.44	0.06
2000	1306	45	11600	404	0.60	0.04	1687	86	29443	1689	0.15	0.01	2993	406	41043	404	0.35	0.04
2001	1328	42	14741	468	0.59	0.04	1900	84	38707	1881	0.03	0.002	3229	469	53448	468	0.31	0.04
2002	1174	39	15006	478	0.65	0.04	1918	80	47889	2063	0.00	0.00	3092	480	62895	478	0.29	0.04
2003	1210	37	14775	481	0.53	0.03	2058	79	55666	2216	0.00	0.00	3268	482	70441	481	0.19	0.03
2004	1149	37	16192	521	0.27	0.02	1860	72	58707	2292	0.07	0.005	3008	523	74899	521	0.14	0.02
2005	1257	43	18019	576	0.34	0.02	1676	70	55653	2303	0.15	0.01	2933	577	73672	576	0.21	0.03
2006	1213	47	16459	558	0.85	0.05	1380	66	47466	2251	0.25	0.02	2593	560	63925	558	0.44	0.06
2007	1562	61	16564	605	0.60	0.04	1359	72	41169	2219	0.16	0.01	2921	608	57733	605	0.30	0.04
2008	1694	73	19653	800	0.57	0.04	1376	77	39837	2245	0.07	0.005	3070	803	59489	800	0.25	0.04
2009	1838	91	22826	1101	0.48	0.03	1565	89	41774	2358	0.05	0.004	3403	1105	64600	1101	0.24	0.03
2010	1862	105	26747	1485	0.24	0.01	1689	101	44361	2558	0.09	0.01	3551	1488	71109	1485	0.16	0.02
2011	1994	127	31320	1924	0.17	0.01	1928	127	46717	2908	0.18	0.01	3923	1928	78037	1924	0.17	0.02
2012	1871	140	32374	2400	0.36	0.02	2077	154	48792	3423	0.21	0.02	3948	2404	81166	2400	0.29	0.03
2013	2006	211	29533	2834	0.54	0.03	2756	251	56926	4275	0.06	0.00	4762	2842	86460	2834	0.30	0.04

Figure B6.1 continued. CASA model estimates and standard errors for July 1 abundance and biomass (40+mm SH), and fully recruited fishing mortality for Mid-Atlantic and Total (GB and MA combined).

		Mid-Atlantic							Total			
Year	Abund	SE	Biomass	SE	F	SE	Abund	SE	Biomass	SE	F	SE
	(millions)		(mt)				(millions)		(mt)			
1975	516	26	5890	305	0.56	0.05	2023	50	32837	832	0.17	0.02
1976	632	22	6709	355	1.02	0.10	2256	47	36110	893	0.31	0.03
1977	644	21	8372	307	0.53	0.05	2004	43	36412	844	0.35	0.03
1978	496	15	7821	246	1.07	0.10	1708	36	32023	743	0.49	0.04
1979	328	10	6108	194	0.97	0.09	1241	30	24911	628	0.59	0.04
1980	318	10	4820	172	0.46	0.04	1355	32	20252	519	0.45	0.03
1981	417	12	5601	192	0.17	0.02	1292	30	18880	453	0.50	0.04
1982	473	14	6912	226	0.29	0.03	1215	28	17363	435	0.56	0.04
1983	528	15	7093	236	0.56	0.05	1092	29	15391	455	0.62	0.05
1984	573	18	7021	249	0.68	0.07	1116	33	14681	496	0.54	0.05
1985	799	24	8002	286	0.61	0.06	1397	41	15829	561	0.58	0.05
1986	1087	32	11482	382	0.44	0.04	1969	54	19708	625	0.65	0.05
1987	1270	37	12113	393	0.93	0.09	2234	63	21506	711	0.90	0.08
1988	1230	40	12613	445	0.77	0.07	2427	77	24181	798	0.84	0.07
1989	1212	35	11149	368	1.20	0.12	2480	72	25044	858	0.87	0.08
1990	1097	30	10541	326	1.06	0.10	2306	60	23649	695	1.10	0.09
1991	735	21	8520	263	1.10	0.11	1952	45	19258	450	1.30	0.10
1992	515	18	5733	213	1.12	0.11	1242	34	13168	369	1.47	0.11
1993	941	35	6381	257	0.90	0.09	1505	50	12284	464	0.97	0.08
1994	1405	59	9885	465	1.38	0.13	1976	71	16975	731	0.78	0.10
1995	1044	30	10031	306	1.51	0.15	2007	57	21052	805	0.81	0.11
1996	583	18	7737	246	0.81	0.08	1678	55	23340	958	0.46	0.05
1997	649	25	6606	257	0.61	0.06	1790	62	26404	1191	0.33	0.03
1998	1484	49	9934	364	1.08	0.10	3135	87	35610	1419	0.46	0.04
1999	2655	74	22092	691	0.80	0.08	4658	108	53736	1730	0.57	0.05
2000	3275	84	36301	1025	0.66	0.06	6268	128	77344	2016	0.51	0.06
2001	3355	80	43631	1155	0.69	0.07	6583	123	97079	2257	0.51	0.06
2002	3076	73	44862	1165	0.68	0.07	6168	115	107757	2417	0.47	0.05
2003	3991	87	45517	1109	0.75	0.07	7259	124	115958	2524	0.43	0.05
2004	3801	88	50849	1198	0.93	0.09	6809	120	125748	2638	0.43	0.06
2005	3790	92	52694	1334	0.80	0.08	6723	123	126366	2723	0.41	0.04
2006	3856	99	61284	1650	0.35	0.03	6449	128	125209	2846	0.40	0.03
2007	3681	92	62298	1673	0.62	0.06	6602	132	120031	2844	0.46	0.05
2008	3879	88	58561	1504	0.70	0.07	6948	138	118050	2818	0.47	0.06
2009	3209	74	54706	1272	0.82	0.08	6612	147	119306	2897	0.49	0.06
2010	2343	61	44283	1215	0.85	0.08	5894	158	115392	3197	0.43	0.05
2011	1675	57	33973	1159	0.87	0.08	5598	188	112010	3674	0.39	0.05
2012	2808	134	30516	1468	0.74	0.07	6756	248	111682	4431	0.40	0.03
2013	3253	182	46101	2649	0.39	0.04	8014	375	132561	5772	0.32	0.03

Table B6.2. CASA model likelihood profile analysis over a range of values for dredge survey catchability (Q) in the MAB region. Catchability priors were turned off in profile runs. The basecase run (with priors turned on) is colored yellow, runs with Q in the 0.4-0.6 expected range based on swept-area abundance are blue, and the run with the best fit to the data are salmon in color. The best fit occurs where the likelihood is zero (bold face).

Dredge survey Q	0.40	0.50	0.60	0.70	0.80	0.87	1.00	1.09	1.19
Total unweighted	618.500	480.800	264.000	137.200	48.800	166.600	**0.000**	200.100	336.100
Catch weight	208.349	194.825	183.041	153.940	44.222	2.902	**0.000**	37.589	124.802
Recruitment deviations	15.023	10.032	6.819	3.128	**0.000**	0.054	0.145	0.275	0.981
Survey trends-all	133.689	73.315	34.576	14.634	**0.000**	0.036	4.412	8.122	13.144
Length data-all	295.900	237.100	74.000	**0.000**	39.100	43.600	29.900	188.600	231.600
Survey trends									
Dredge	116.668	61.413	27.035	10.436	0.238	**0.000**	3.760	6.556	10.062
SMAST.LrgCam	3.447	2.008	1.269	1.253	**0.000**	0.135	2.860	4.160	5.381
Winter.BTS	11.039	7.668	5.160	3.130	0.366	0.372	0.124	0.070	**0.000**
Unlined.Dredge	**0.000**	0.001	0.216	0.265	0.260	0.286	0.314	0.118	0.176
HabCam	5.317	5.007	3.677	2.333	1.918	2.025	0.137	**0.000**	0.307
Length data									
Commercial.Fishery	152.900	152.930	35.200	**0.000**	11.880	24.840	29.840	190.150	211.040
Dredge	144.700	87.300	42.700	4.700	37.600	28.600	3.600	**0.000**	15.000
SMAST.LrgCam	10.061	9.551	8.364	6.129	0.110	**0.000**	6.562	11.919	16.906
Winter.BTS	**0.000**	0.080	0.750	1.200	1.960	1.860	2.150	2.030	2.280
Unlined.Dredge	0.297	0.299	2.289	5.140	5.039	5.258	5.197	0.093	**0.000**
HabCam	5.450	4.350	2.190	0.290	**0.000**	0.420	0.020	1.860	3.870
Mean 2011-2014 biomass (mt)	434,402	218,487	105,529	60,996	54,785	49,710	28,262	23,758	20,395
Mean 2011-2014 abun. wtd. F	0.01	0.02	0.06	0.12	0.14	0.15	0.31	0.38	0.45

Table B6.3 CASA model likelihood profile analysis over a range of values for dredge survey catchability (Q) in the GBK-open region. Catchability priors were turned off in profile runs. The basecase run (with priors turned on) is colored yellow, runs with Q in the 0.4-0.6 expected range based on swept-area abundance are blue, and the run with the best fit to the data are salmon in color. The best fit occurs where the likelihood is zero (bold face).

Dredge survey Q	0.40	0.50	0.60	0.66	0.75	0.84	0.98	1.09	1.09
Total unweighted	146.13	56.34	6.89	122.74	**0.00**	37.65	140.49	195.09	236.24
Catch weight	9.32	5.35	1.20	**0.00**	1.78	11.45	16.86	10.53	11.29
Recruitment deviations	20.90	13.53	6.54	3.36	**0.00**	0.08	4.44	7.02	8.19
Survey trends-all	116.68	49.64	11.75	1.74	**0.00**	6.88	3.63	0.92	3.91
Length data-all	11.83	0.41	**0.00**	2.43	10.82	31.84	128.17	189.19	224.95
Survey trends									
Dredge	89.48	35.27	7.60	0.94	0.25	4.54	1.07	**0.00**	2.89
SMAST.LrgCam	28.16	15.34	5.11	1.66	**0.00**	0.57	0.45	0.24	0.27
Unl.10ft.Dredge.40+mm	0.88	0.89	0.90	0.91	0.92	0.89	0.47	0.14	**0.00**
HabCam	0.02	**0.00**	0.01	0.09	0.70	2.75	3.51	2.42	2.61
Length data									
Commercial.Fishery	1.59	**0.00**	3.40	7.49	13.81	27.06	48.45	62.18	72.65
Dredge	15.04	8.82	4.18	1.25	**0.00**	4.28	64.41	99.38	118.23
SMAST.LrgCam	3.04	**0.00**	1.16	2.75	6.27	9.52	22.83	33.86	39.59
Unl.10ft.Dredge.40+mm	0.05	0.07	0.09	0.09	0.08	**0.00**	0.29	1.06	1.36
HabCam	1.44	0.86	0.51	0.18	**0.00**	0.31	1.52	2.03	2.44
Mean 2011-2014 biomass (mt)	181,251	97,471	53,744	38,653	25,051	19,297	18,282	18,897	18,377
Mean 2011-2014 abun. wtd. F	0.03	0.05	0.10	0.15	0.27	0.46	0.53	0.49	0.52

Table B6.4. CASA model likelihood profile analysis over a range of values for dredge survey catchability (Q) in the GBK-closed region. Catchability priors were turned off in profile runs. The basecase run (with priors turned on) is colored yellow, runs with Q in the 0.4-0.6 expected range based on swept-area abundance are blue, and the run with the best fit to the data are salmon in color. The best fit occurs where the likelihood is zero (bold face).

Dredge survey Q	**0.40**	**0.50**	**0.60**	**0.68**	**0.75**	**0.85**	**1.00**	**1.10**	**1.20**
Total unweighted	36.04	22.05	11.81	142.32	2.40	**0.00**	2.50	8.54	18.41
Catch weight	0.01	0.02	0.02	0.10	**0.00**	0.05	0.47	1.15	2.32
Recruitment deviations	14.95	11.32	8.32	5.56	4.77	2.96	1.04	0.30	**0.00**
Survey trends-all	14.33	7.22	3.06	**0.00**	1.19	2.59	8.51	14.94	23.17
Length data-all	14.60	11.33	8.26	8.96	4.30	2.26	0.33	**0.00**	0.77
Survey trends									
Dredge	8.53	3.90	1.53	**0.00**	0.58	1.13	3.28	5.48	8.25
SMAST.LrgCam	5.35	2.93	1.20	**0.00**	0.41	1.37	5.35	9.73	15.33
Unl.10ft.Dredge.40+mm	**0.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HabCam	0.85	0.80	0.73	0.40	0.60	0.49	0.28	0.13	**0.00**
Length data									
Commercial.Fishery	1.06	1.22	1.18	2.51	0.89	0.61	0.17	**0.00**	0.21
Dredge	10.72	8.59	6.68	4.52	4.22	2.87	1.31	0.55	**0.00**
SMAST.LrgCam	5.82	4.37	3.05	4.95	1.44	0.66	0.02	**0.00**	0.42
Unl.10ft.Dredge.40+mm	0.08	0.10	0.12	0.14	0.13	0.12	0.09	0.05	**0.00**
HabCam	0.08	0.22	0.40	**0.00**	0.79	1.16	1.91	2.57	3.31
Mean 2011-2014 biomass (mt)	125,498	88,137	64,526	50,812	42,317	32,537	22,304	17,508	13,888
Mean 2011-2014 abun. wtd. F	0.06	0.08	0.12	0.15	0.19	0.25	0.37	0.49	0.62

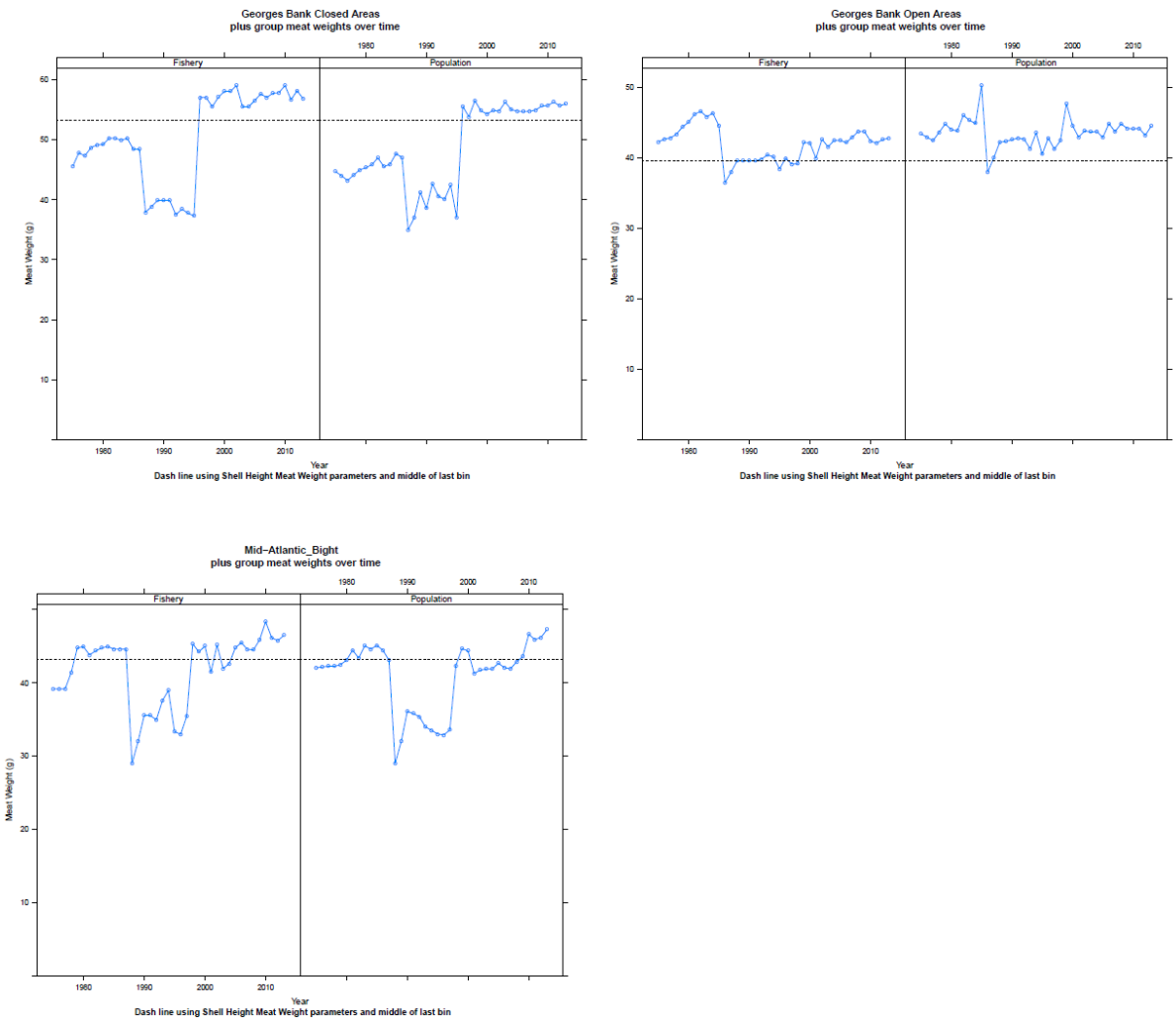


Figure B6.1. Estimated plus group meat weights for the population and the fishery in the open and closed portions of Georges Bank, and in the Mid-Atlantic Bight. The plus group represents scallops in the largest bin which contained L_∞.

(A) (B)

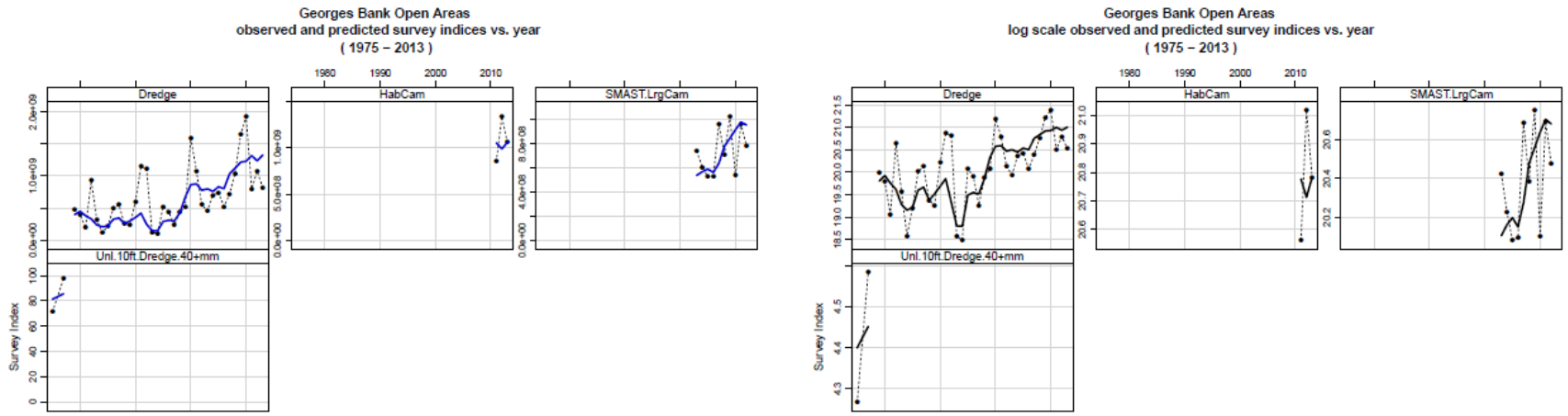


Figure B6.2. Observed survey trend (solid circles) and corresponding model estimates (lines) for the NEFSC lined dredge survey, the HabCam survey, the SMAST large camera survey and the NEFSC unlined dredge survey on Georges Bank open areas. Results are shown on a linear scale (A) and a log scale (B).

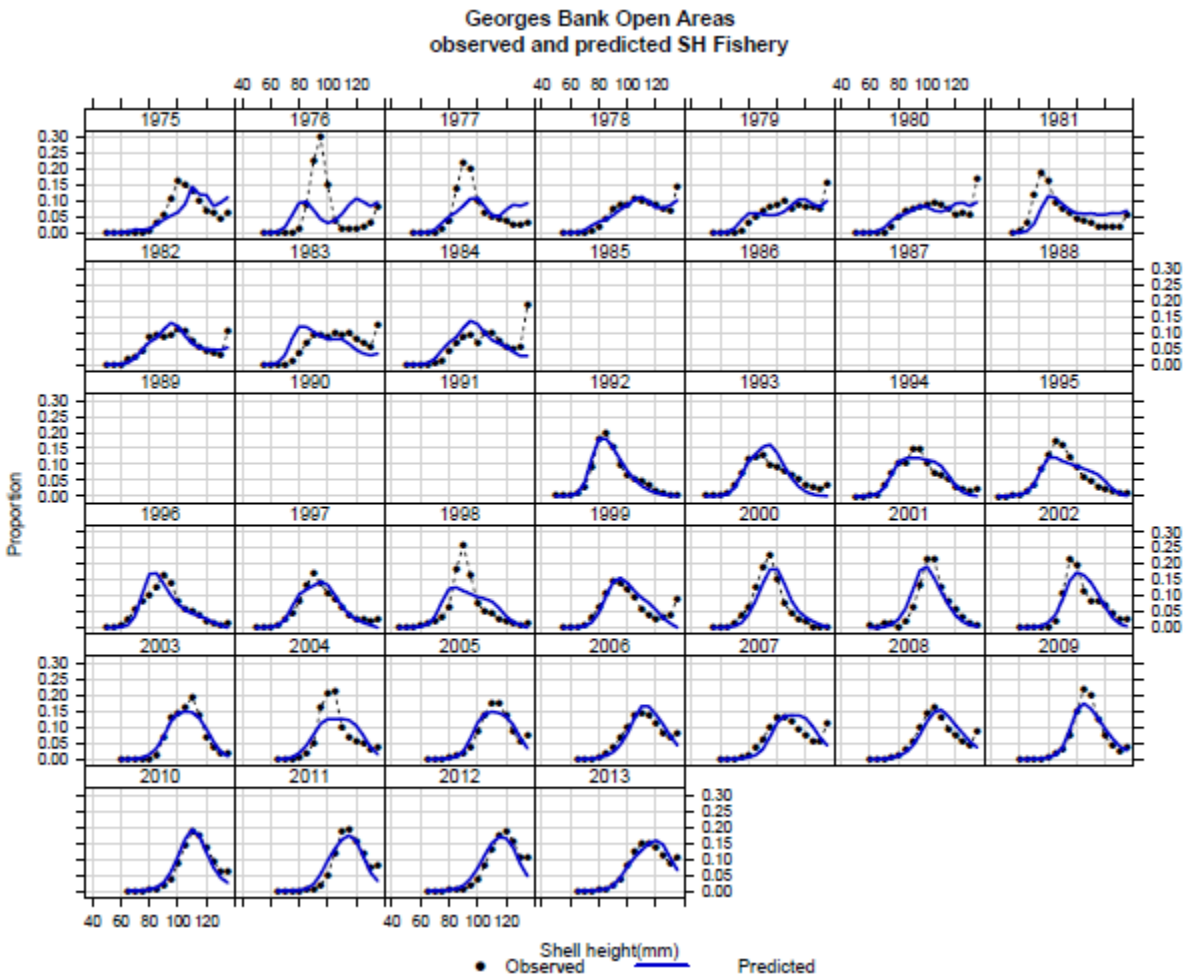


Figure B6.3. Comparison of observed fishery shell height proportions (solid circles) and model estimated fishery shell height proportions (lines) for Georges Bank open areas.

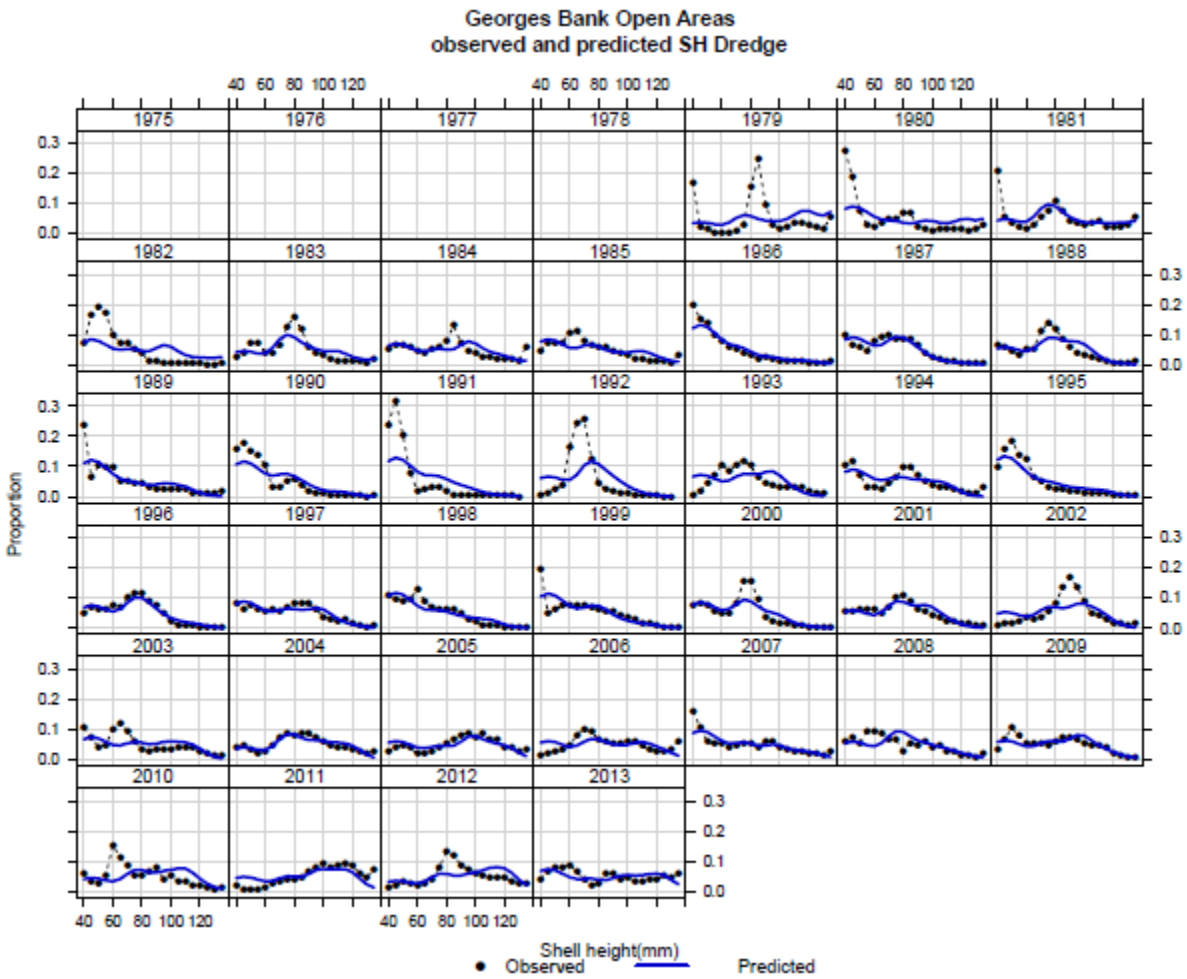


Figure B6.4. NEFSC lined dredge survey shell height proportions (solid circles) and model estimated shell height proportions (lines) for Georges Bank open areas.

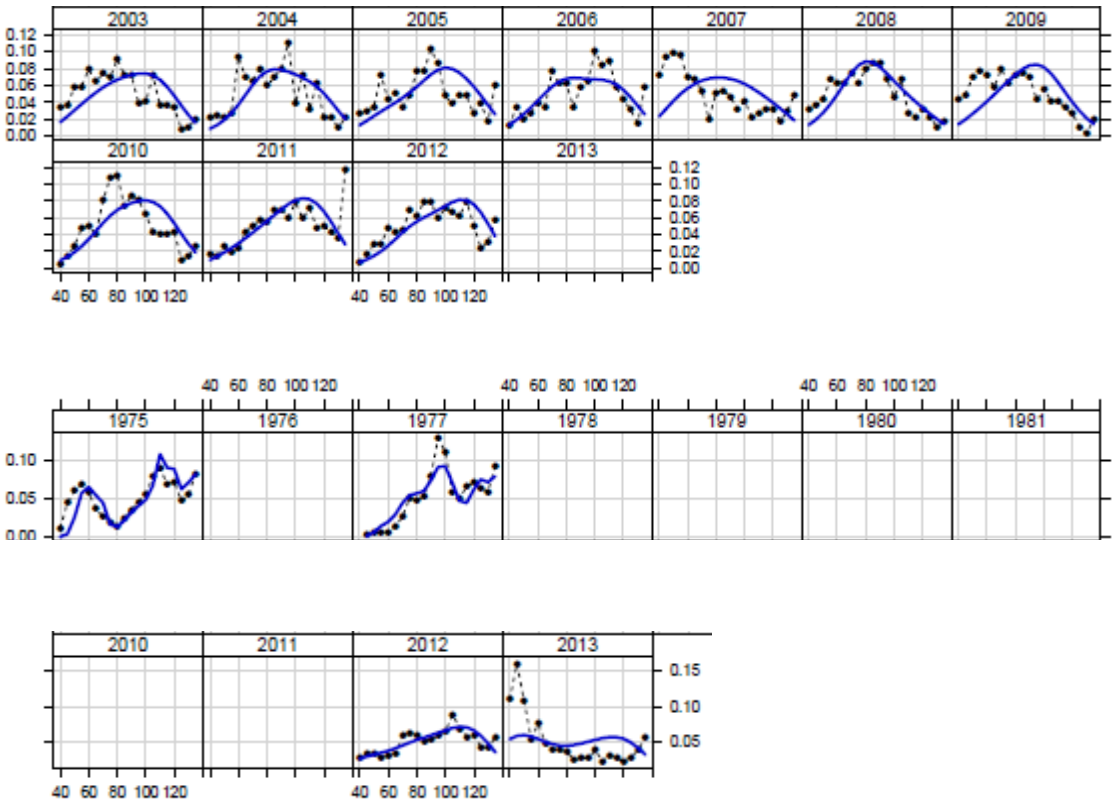


Figure B6.5. Shell height proportions for the SMAST large camera survey (top), the NEFSC unlined dredge survey (middle) and the HabCam survey (bottom) with model predicted proportions (lines) for Georges Bank.

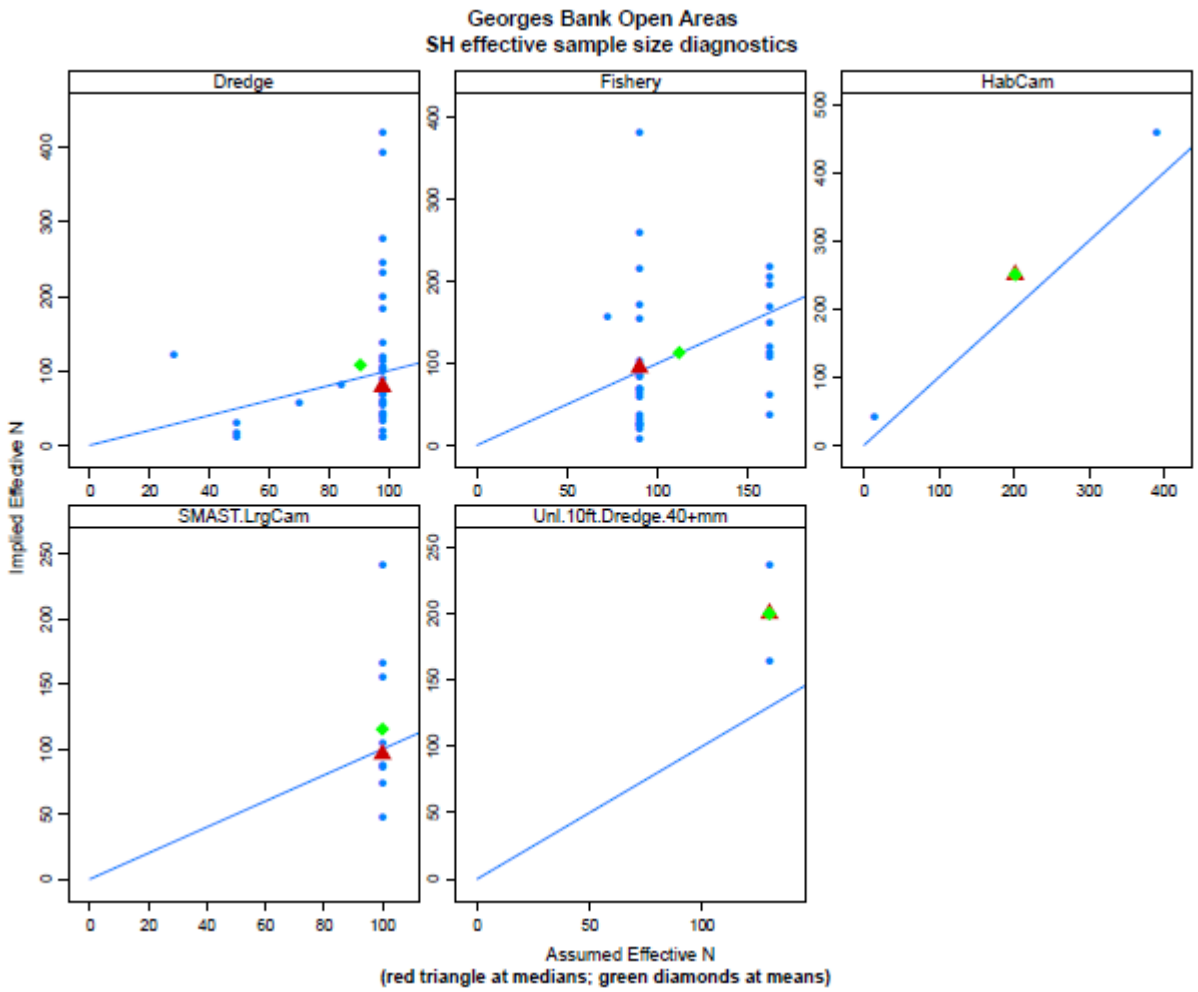


Figure B6.6. Assumed and model implied effective sample sizes for the four surveys (NEFSC unlined dredge, HabCam, SMAST large camera, NEFSC unlined dredge) and the fishery shell height compositions for Georges Bank open areas. The triangle is the median and the diamond is the mean.

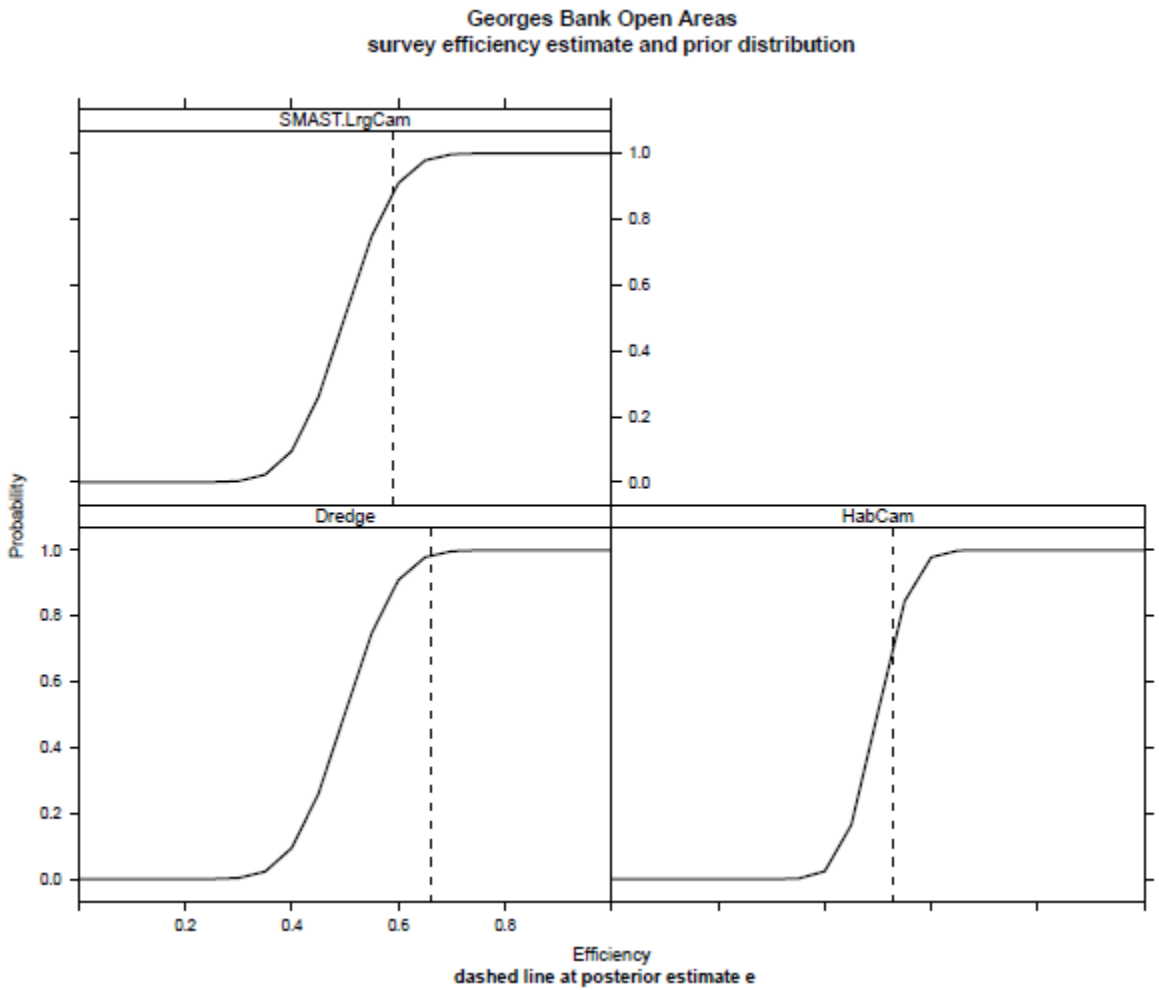


Figure B6.7. Prior cumulative distributions for catchability of the large camera video survey (top) lined dredge survey (bottom left) and HabCam survey (bottom right) for Georges Bank open areas. The dashed lines are the mean posterior estimate for survey catchability. For the purposes of this plot, the surveys were adjusted to have a mean prior catchability of 0.5

(A) (B)

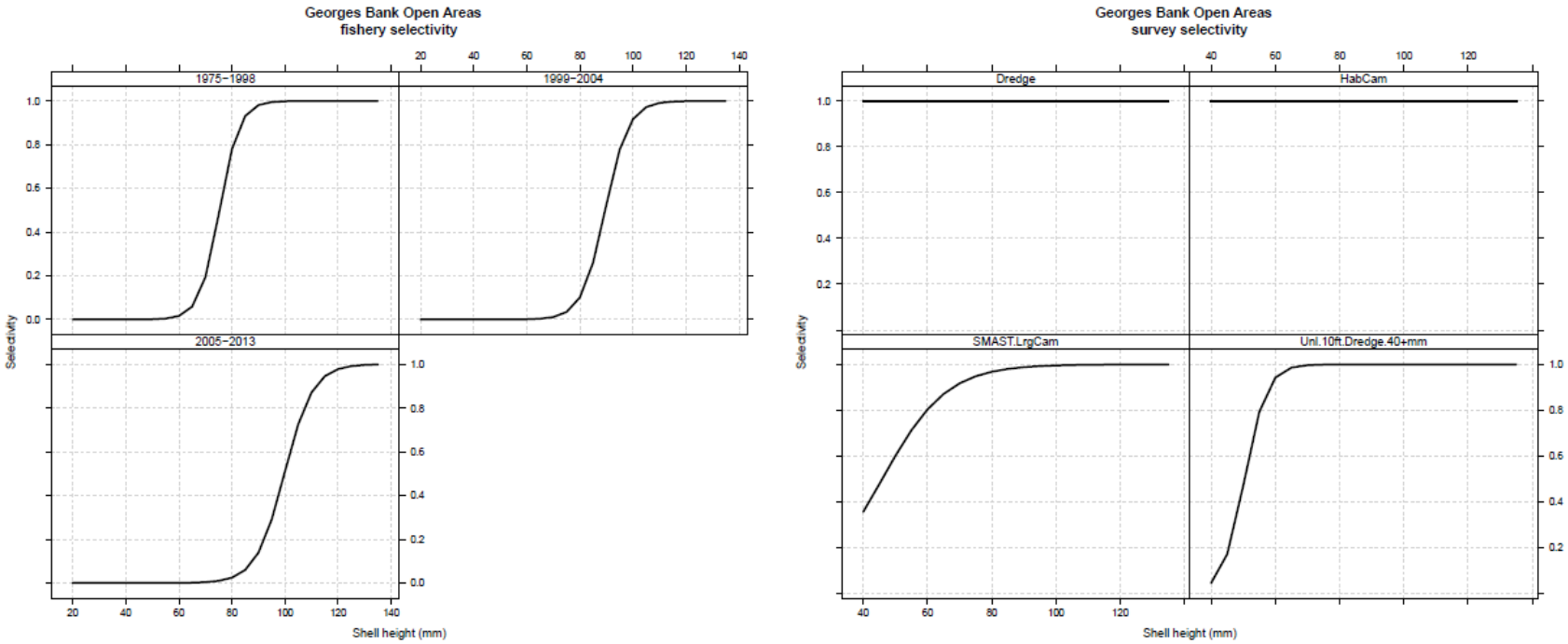


Figure B6.8. (A) Estimated fishery selectivity curves and (B) assumed survey selectivity curves (lined dredge top left, HabCam top right, large camera bottom left, and unlined dredge bottom right) for Georges Bank open areas.

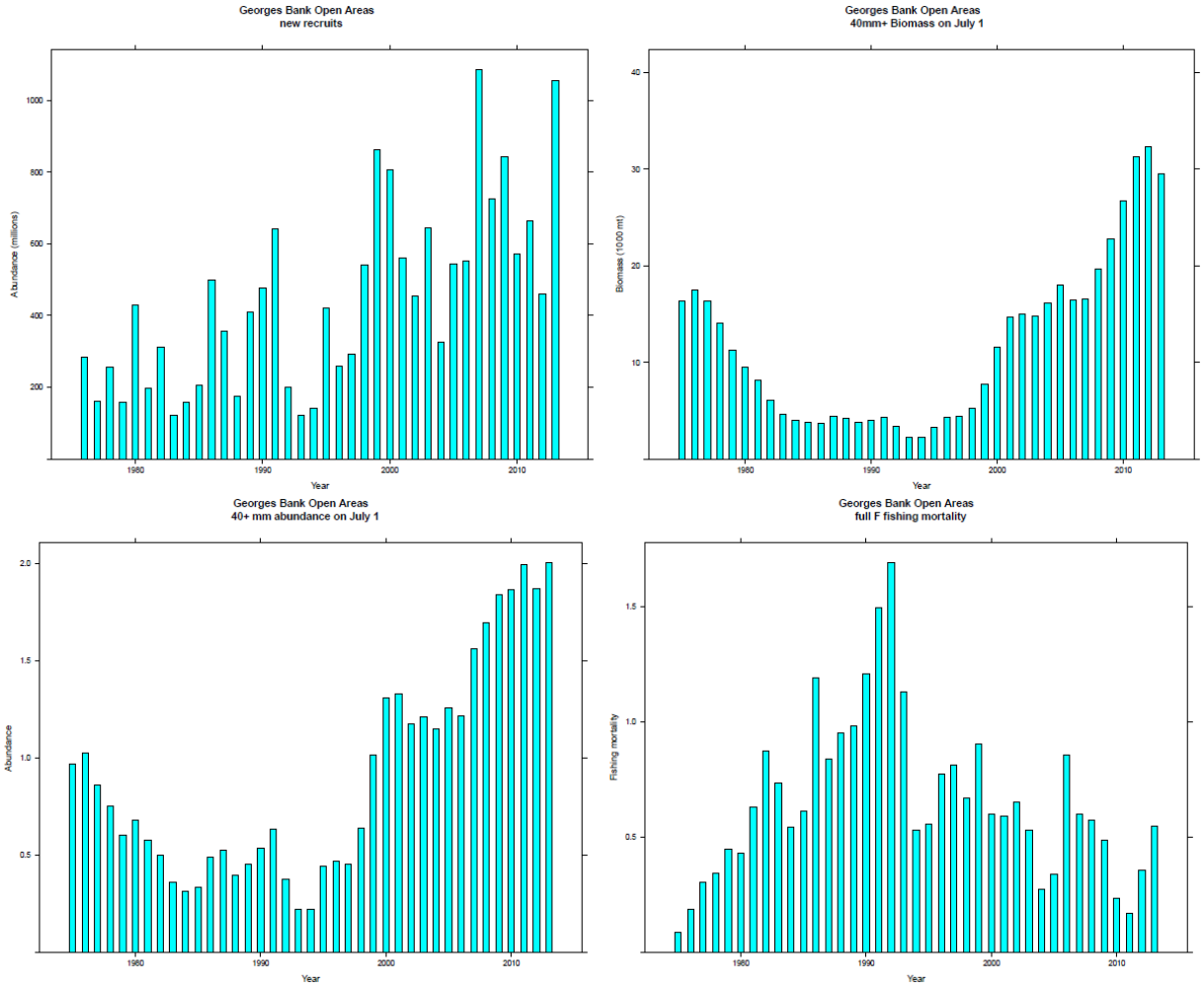


Figure B6.9. CASA model estimated recruitment (top left), July 1 biomass (top right), July 1 abundance (bottom left) and fully recruited fishing mortality (bottom right) for Georges Bank open areas.

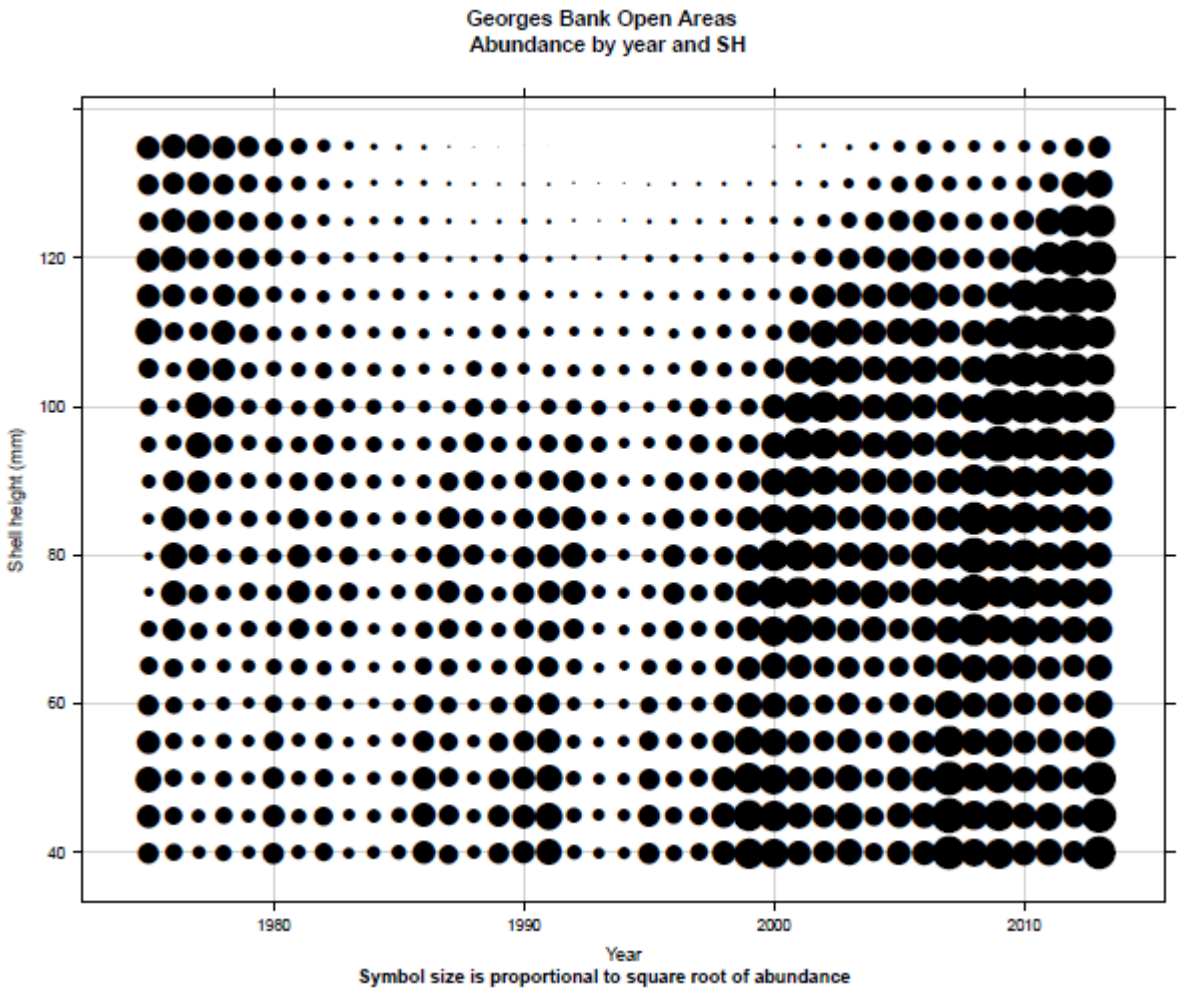


Figure B6.10. Model estimated abundances at shell height for Georges Bank open areas. Symbol areas are proportional to abundance.

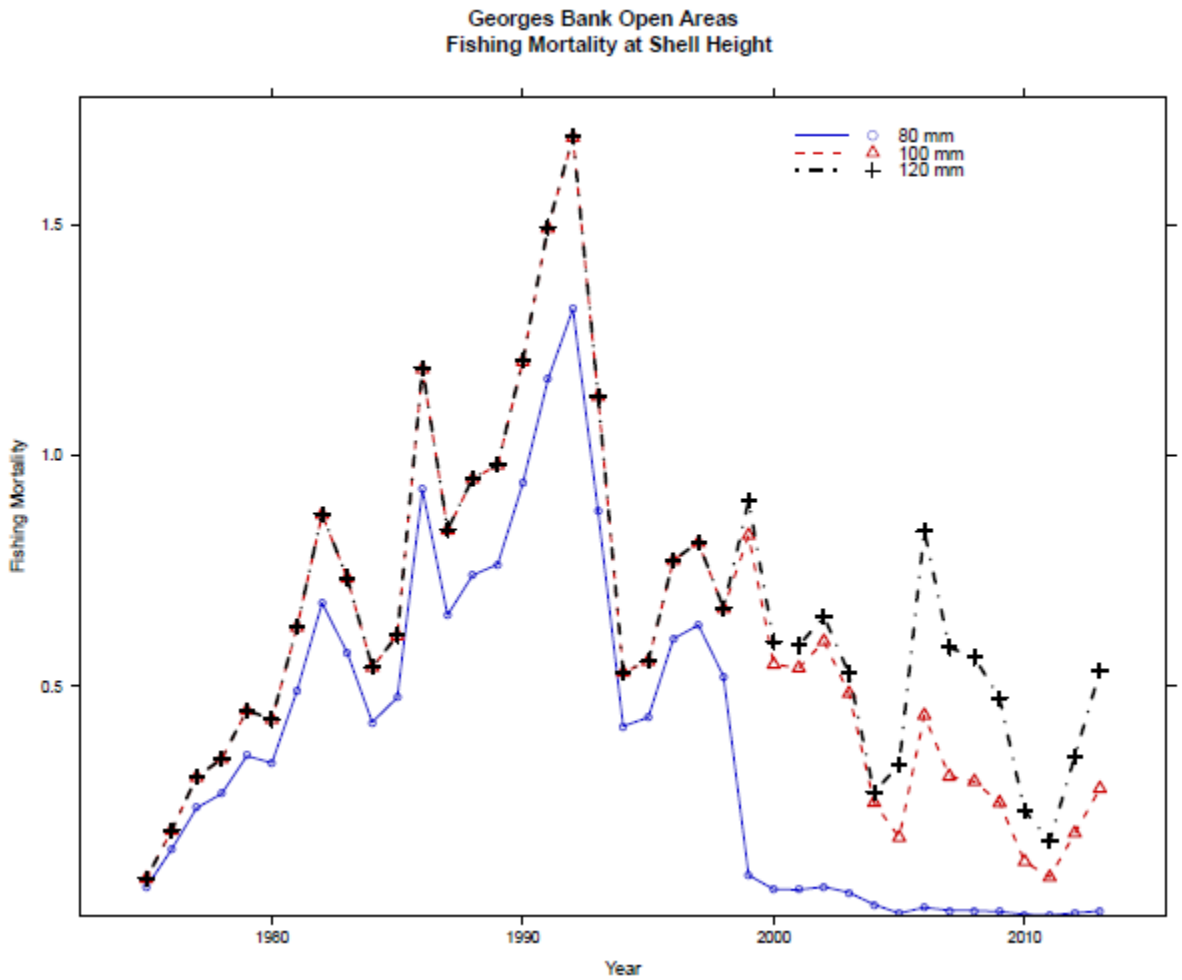


Figure B6.11. CASA model estimated fishing mortality at 80 mm (solid line with circles), 100 mm (dashed line with triangles) and 120 mm SH (dashed line with crosses) for Georges Bank open areas.

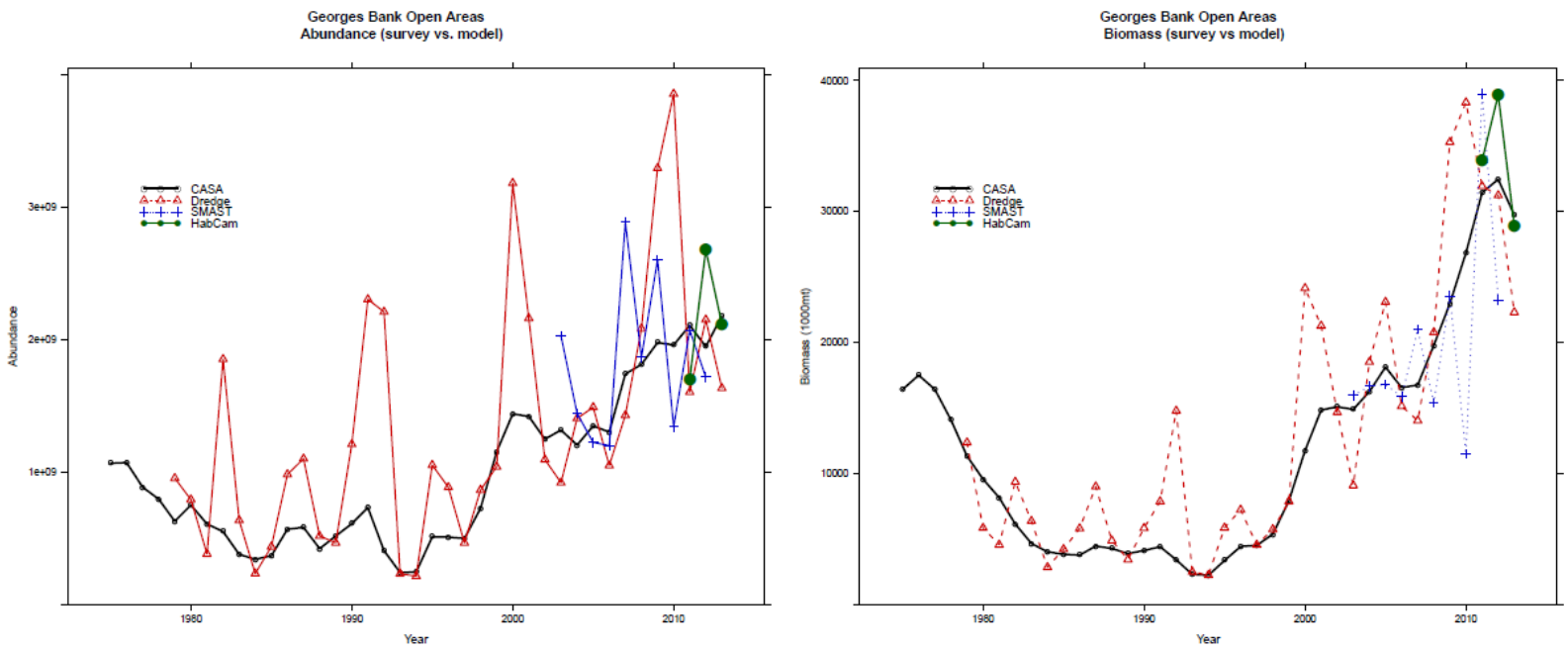


Figure B6.12. Comparison of CASA model estimated abundance (left) and biomass (right) with expanded estimates from the lined dredge survey (dashed red line with triangles), SMAST large camera survey (dotted blue line with crosses) and HabCam (solid line with circles) for Georges Bank open areas.

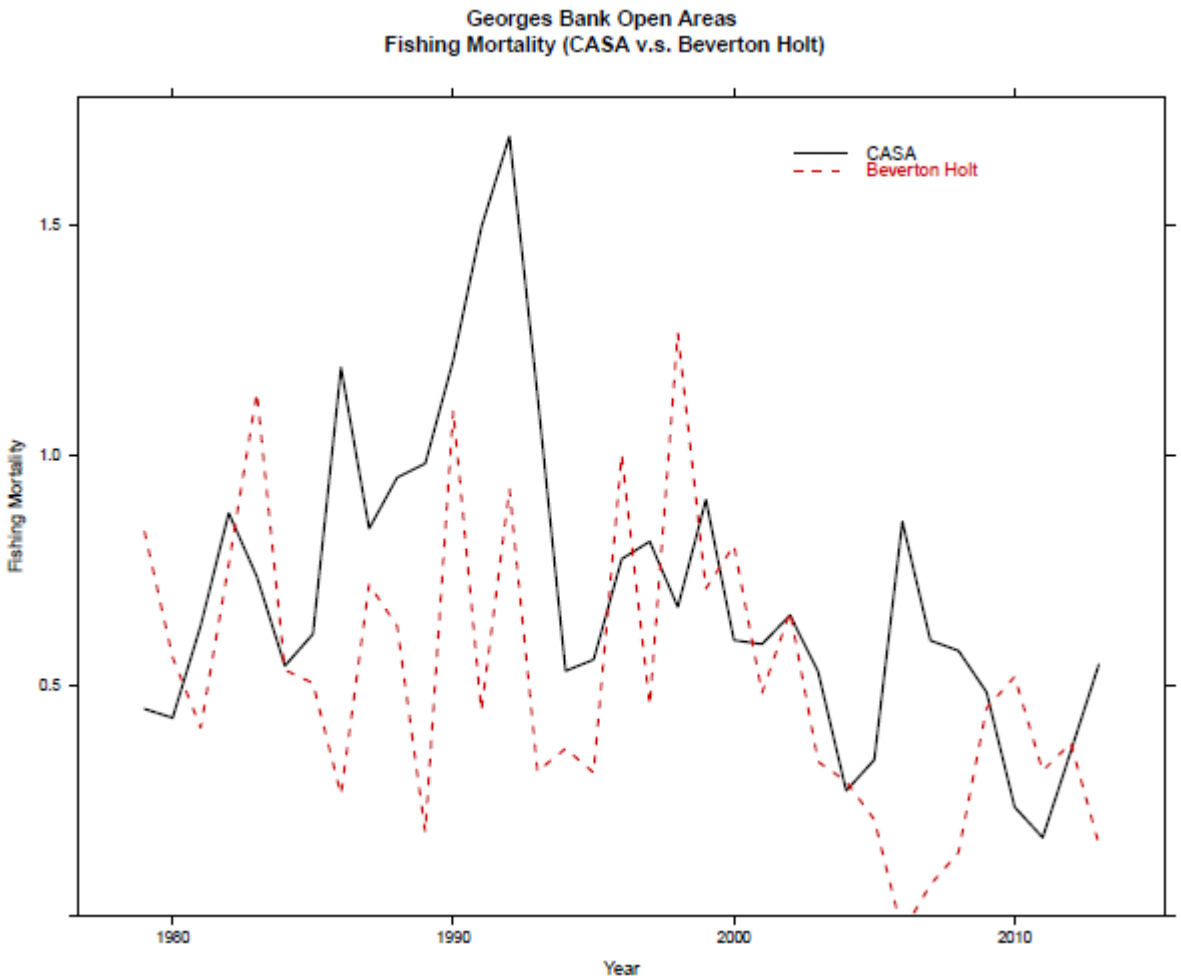


Figure B6.13. Comparison of fully recruited CASA fishing mortality with those calculated from the Beverton-Holt equilibrium length-based estimator for Georges Bank open areas.

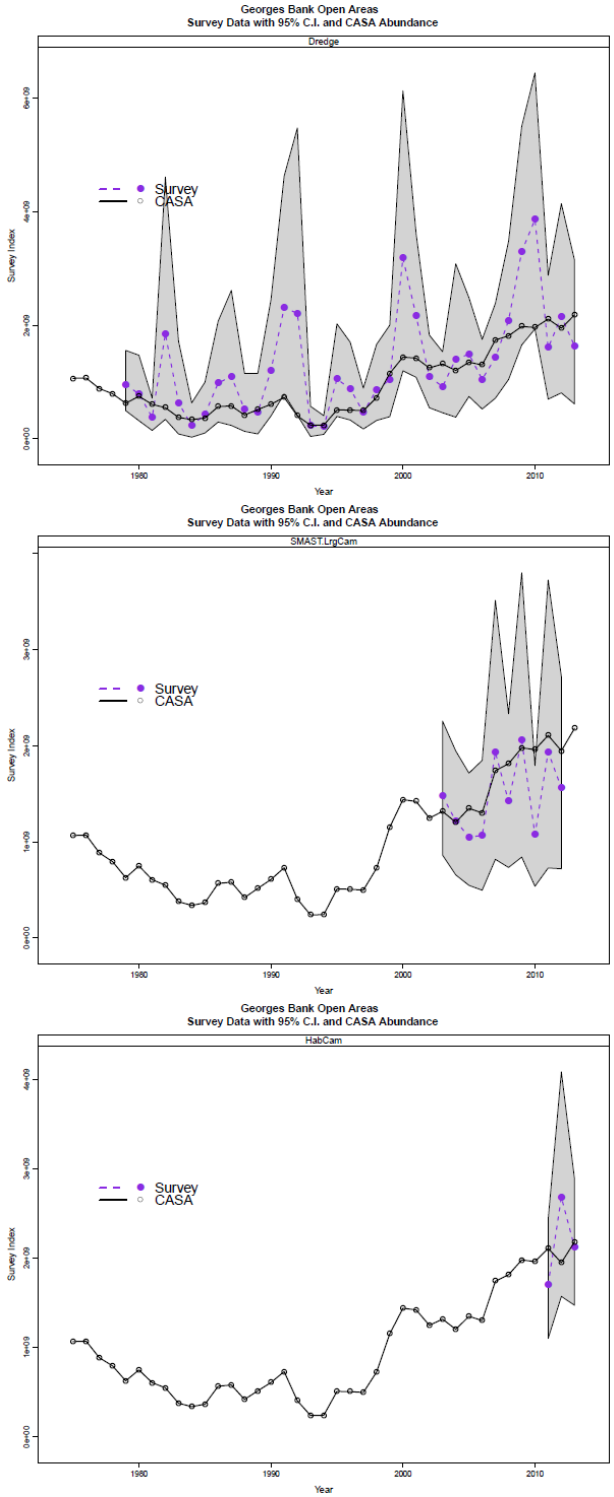


Figure B6.14. CASA model (black line with solid circles) for Georges Bank open areas compared to expanded survey estimates with their 95% C.I.s: dredge (top), SMAST (middle), and HabCam (lower)

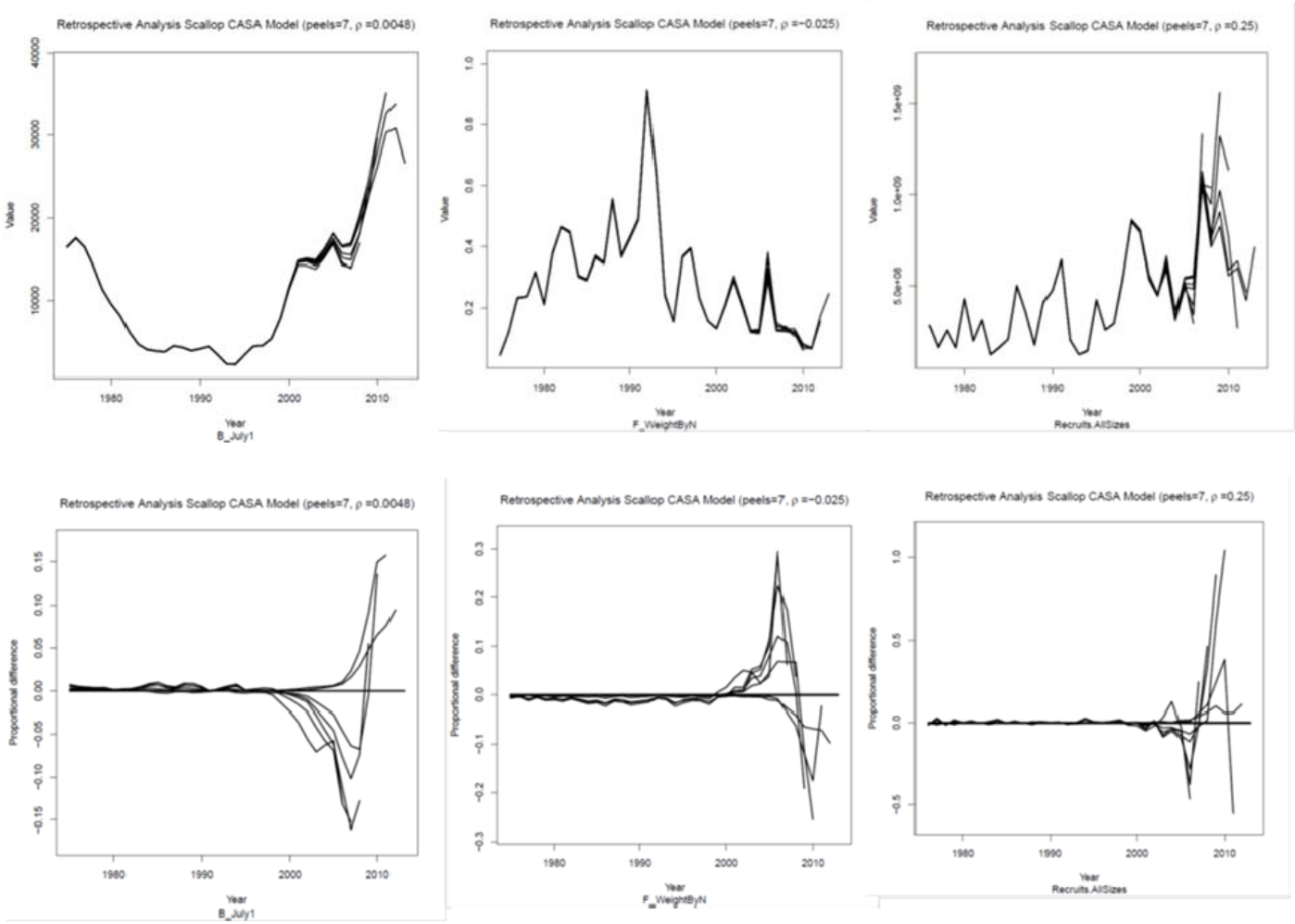


Figure B6.15. Retrospective plots for biomass, fishing mortality and recruitment, shown both on absolute and relative scales for Georges Bank open areas.

(A) (B)

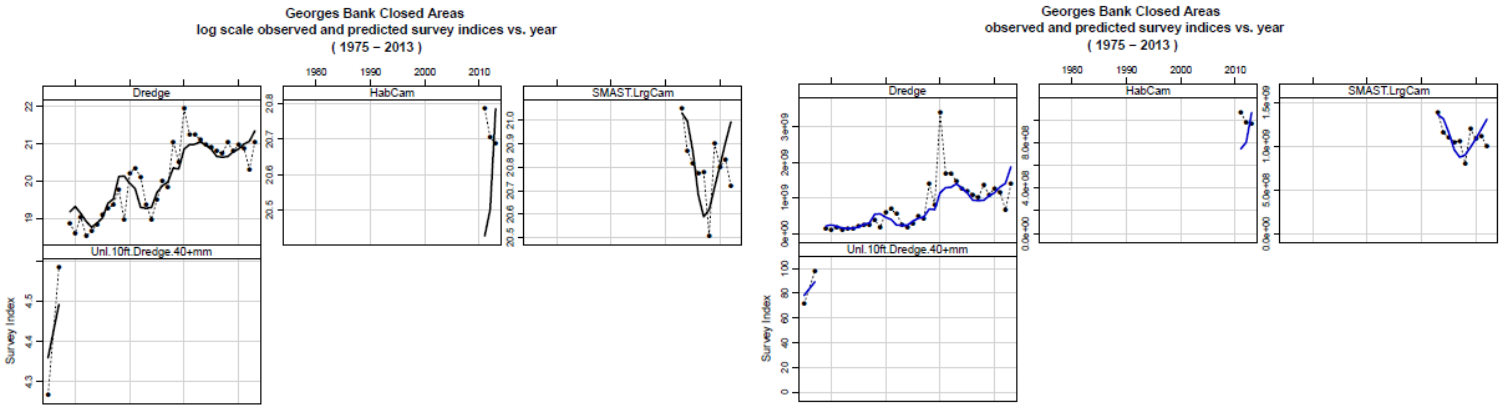


Figure B6.16. Comparison between survey trend (solid circles) and corresponding model estimates (lines) for the NEFSC lined dredge survey, the HabCam survey, The SMAST large camera survey and the NEFSC unlined dredge survey in the Georges Bank closed areas. Results are shown on a linear scale (A) and a log scale (B).

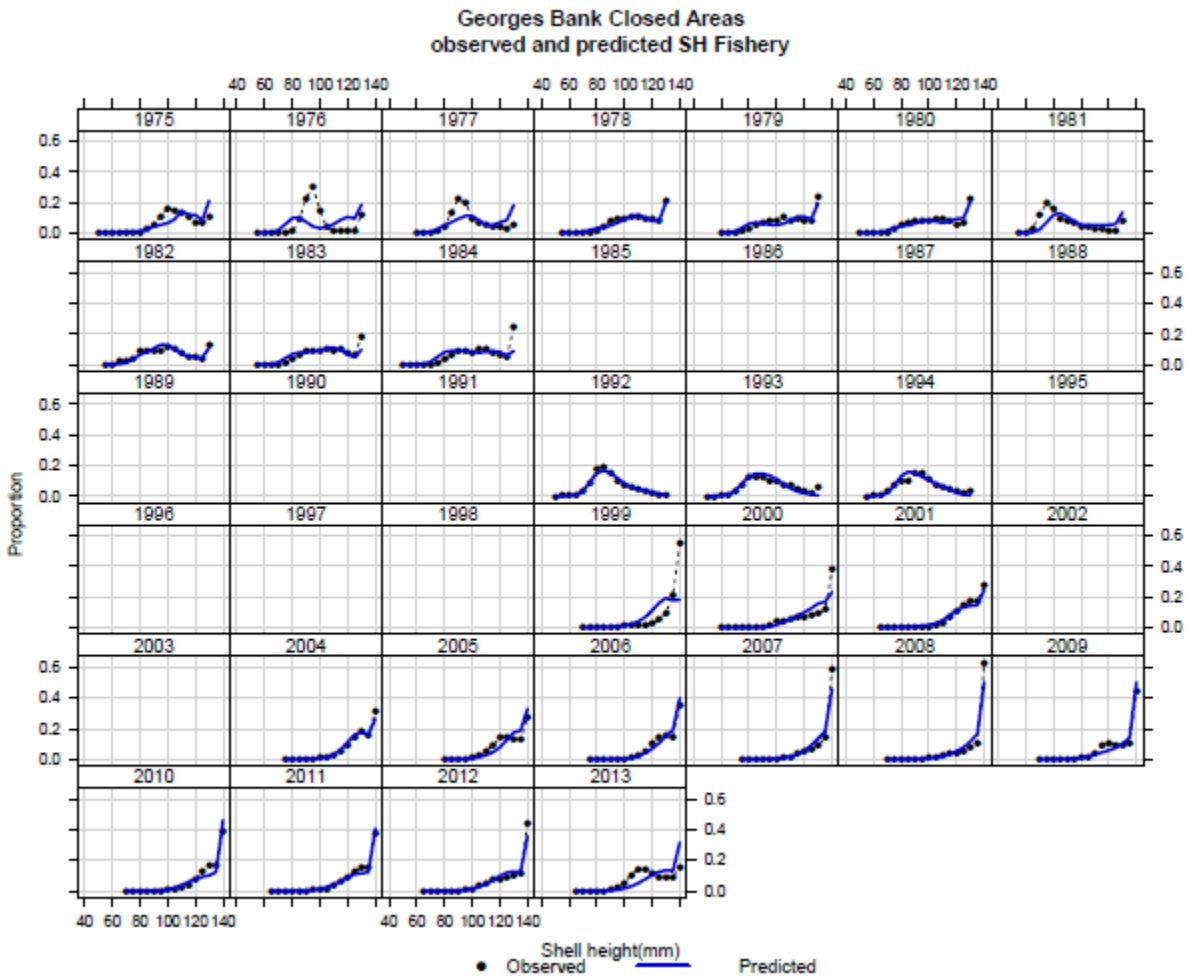


Figure B6.17. Comparison of fishery shell height proportions (solid circles) and model estimated fishery shell height proportions (lines) for Georges Bank closed areas.

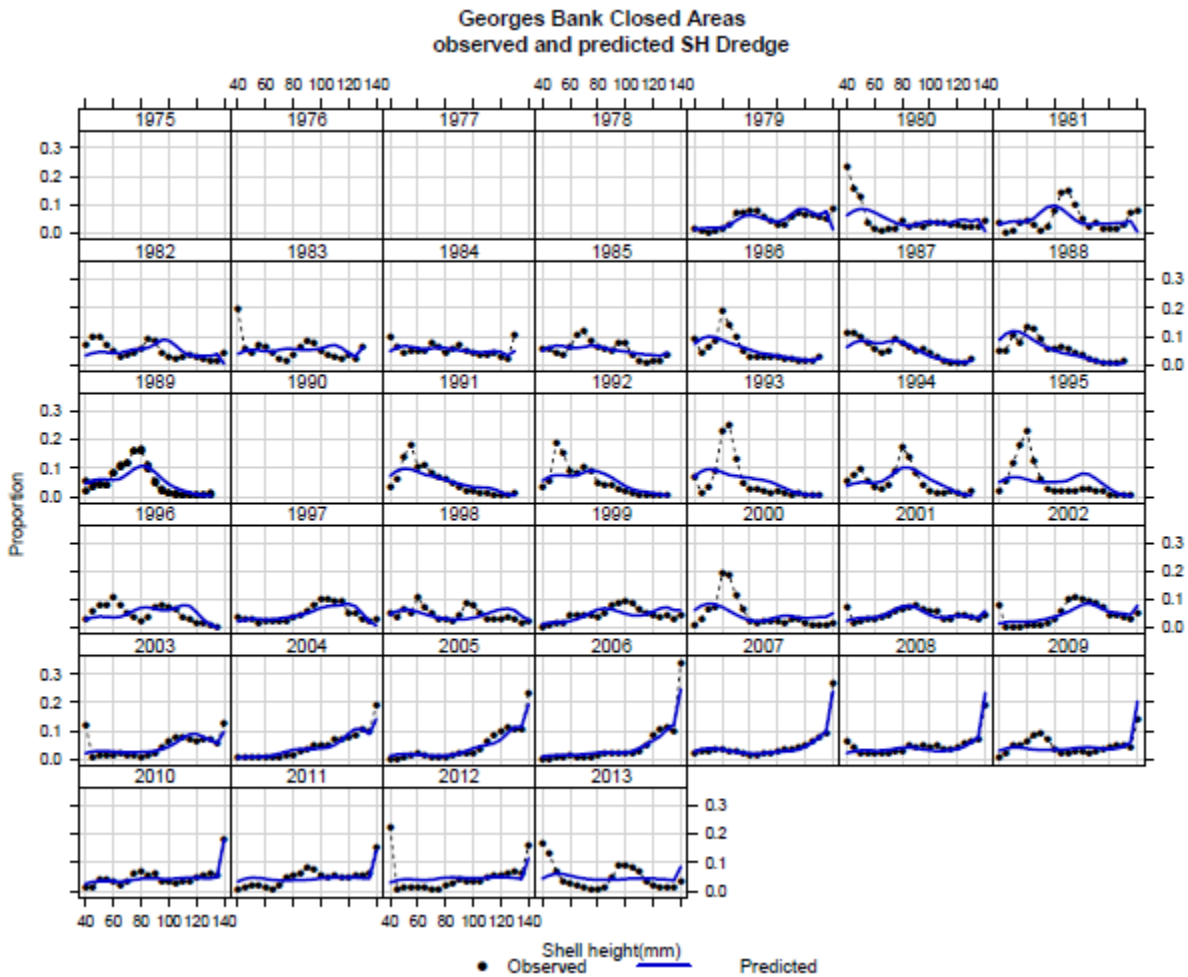


Figure B6.18. NEFSC lined dredge survey shell height proportions (solid circles) and model estimated shell height proportions (lines) for Georges Bank closed areas.

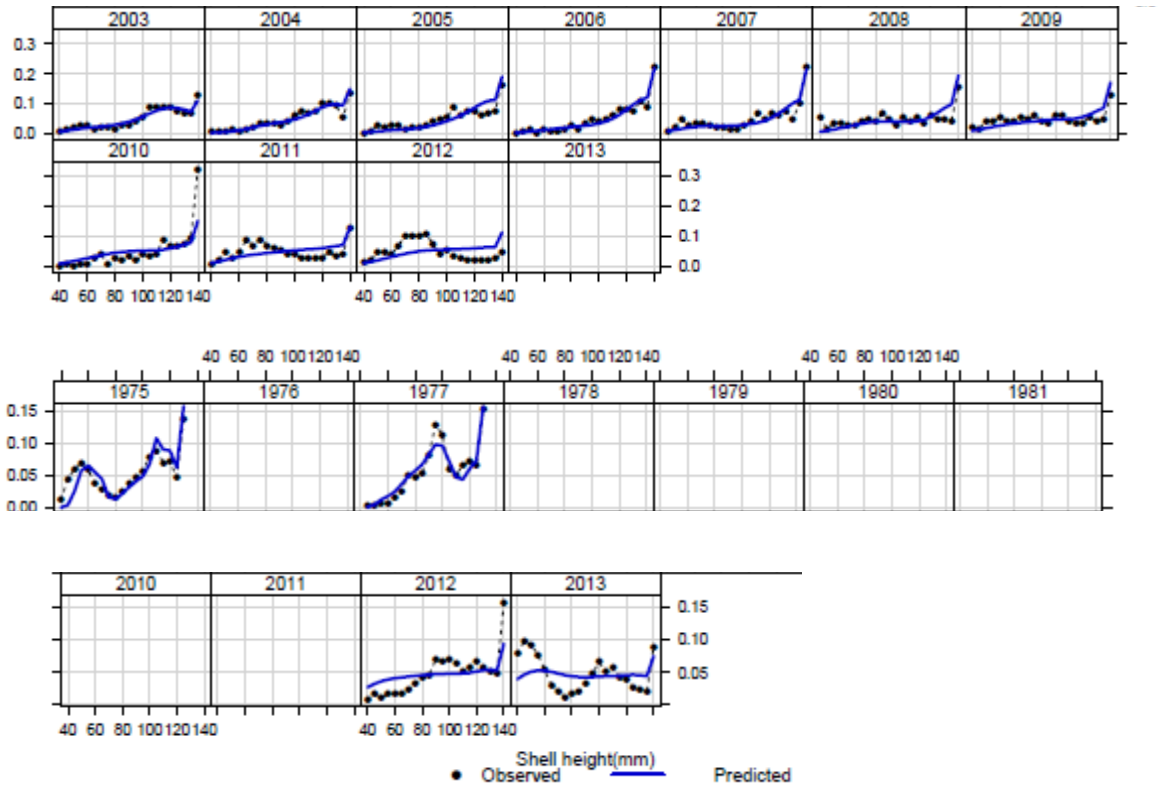


Figure B6.19. Shell height proportions for the SMAST large camera survey (top), the NEFSC unlined dredge survey (middle) and the HabCam survey (bottom) with model predicted proportions (lines) for Georges Bank closed areas.

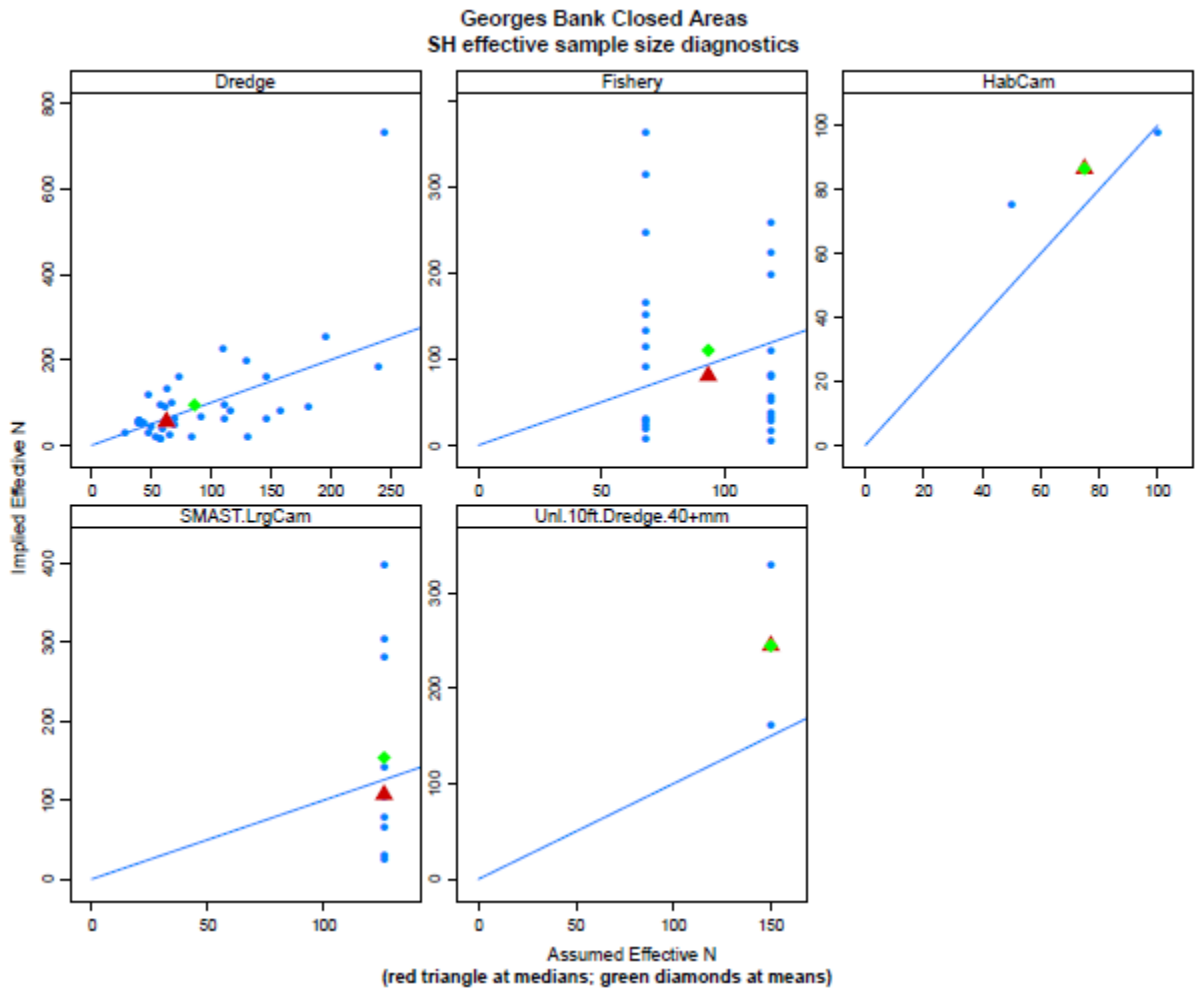


Figure B6.20. Assumed and model implied effective sample sizes for the four surveys (NEFSC unlined dredge, HabCam, SMAST large camera, NEFSC unlined dredge) and the fishery shell height compositions for Georges Bank closed areas. The triangle is the median and the diamond is the mean.

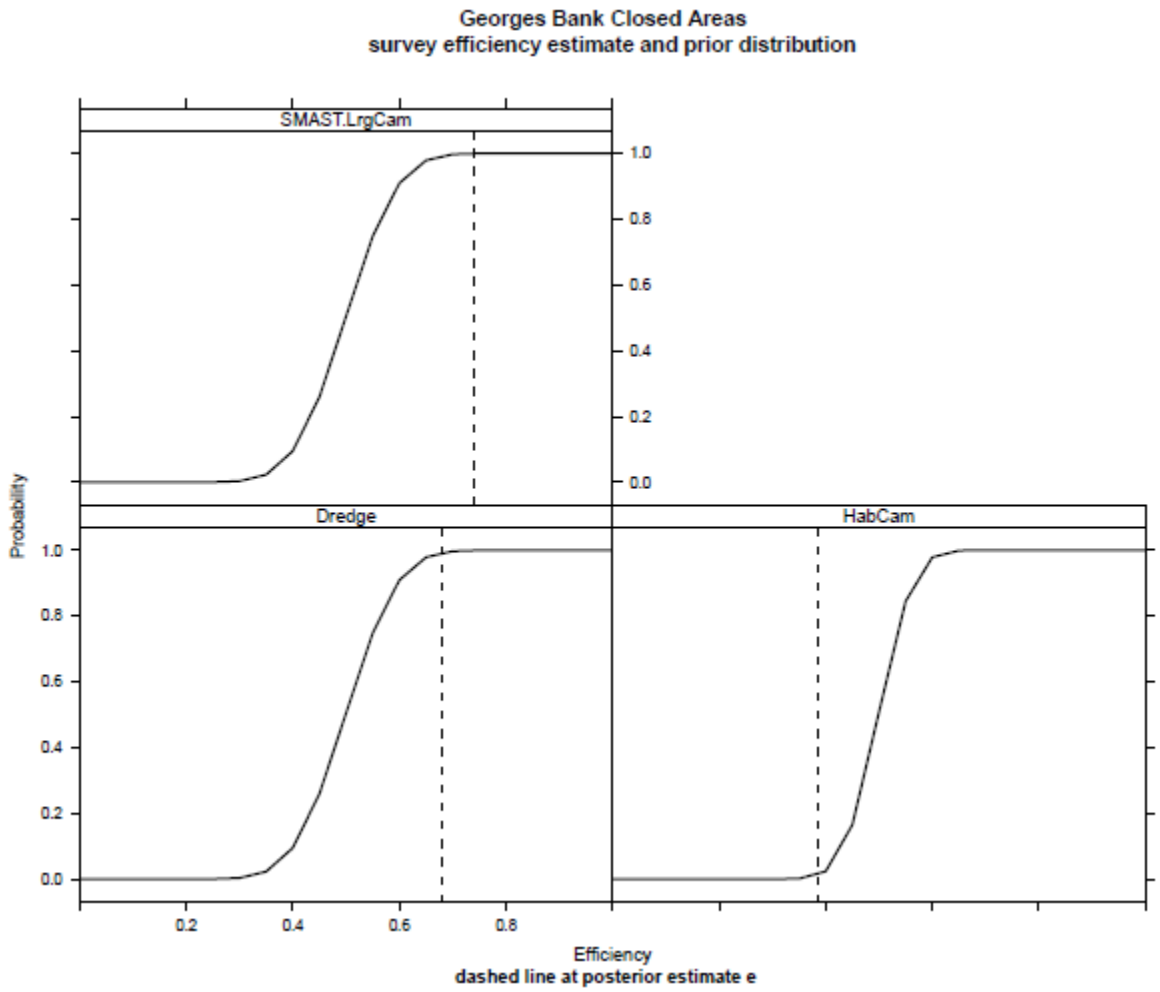


Figure B6.21. Prior cumulative distributions for catchability of the large camera video survey (top) lined dredge survey (bottom left) and HabCam survey (bottom right) for Georges Bank closed areas. The dashed lines are the mean posterior estimate for survey catchability. For the purposes of this plot, the surveys were adjusted to have a mean prior catchability of 0.5

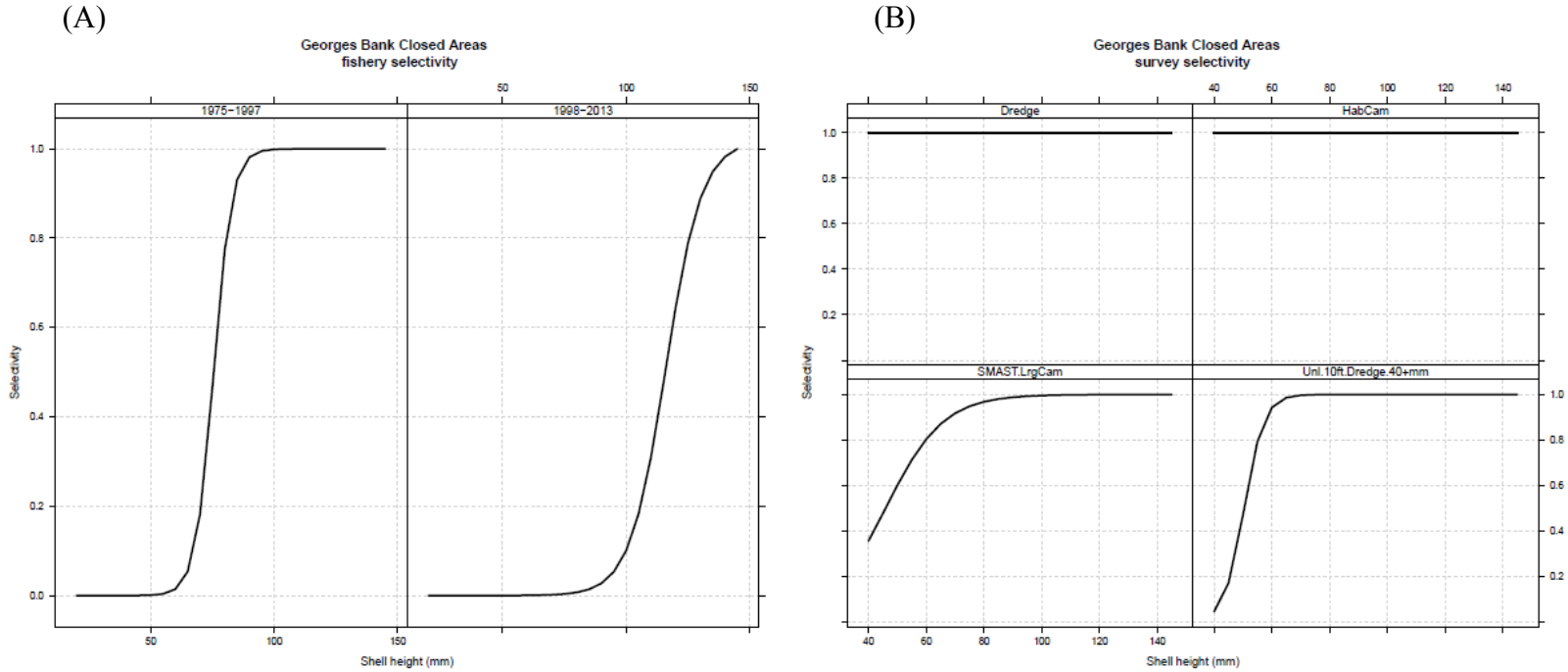


Figure B6.22. (A) Estimated fishery selectivity curves and (B) assumed survey selectivity curves (lined dredge top left, HabCam top right, large camera bottom left, and unlined dredge bottom right) for Georges Bank closed areas.

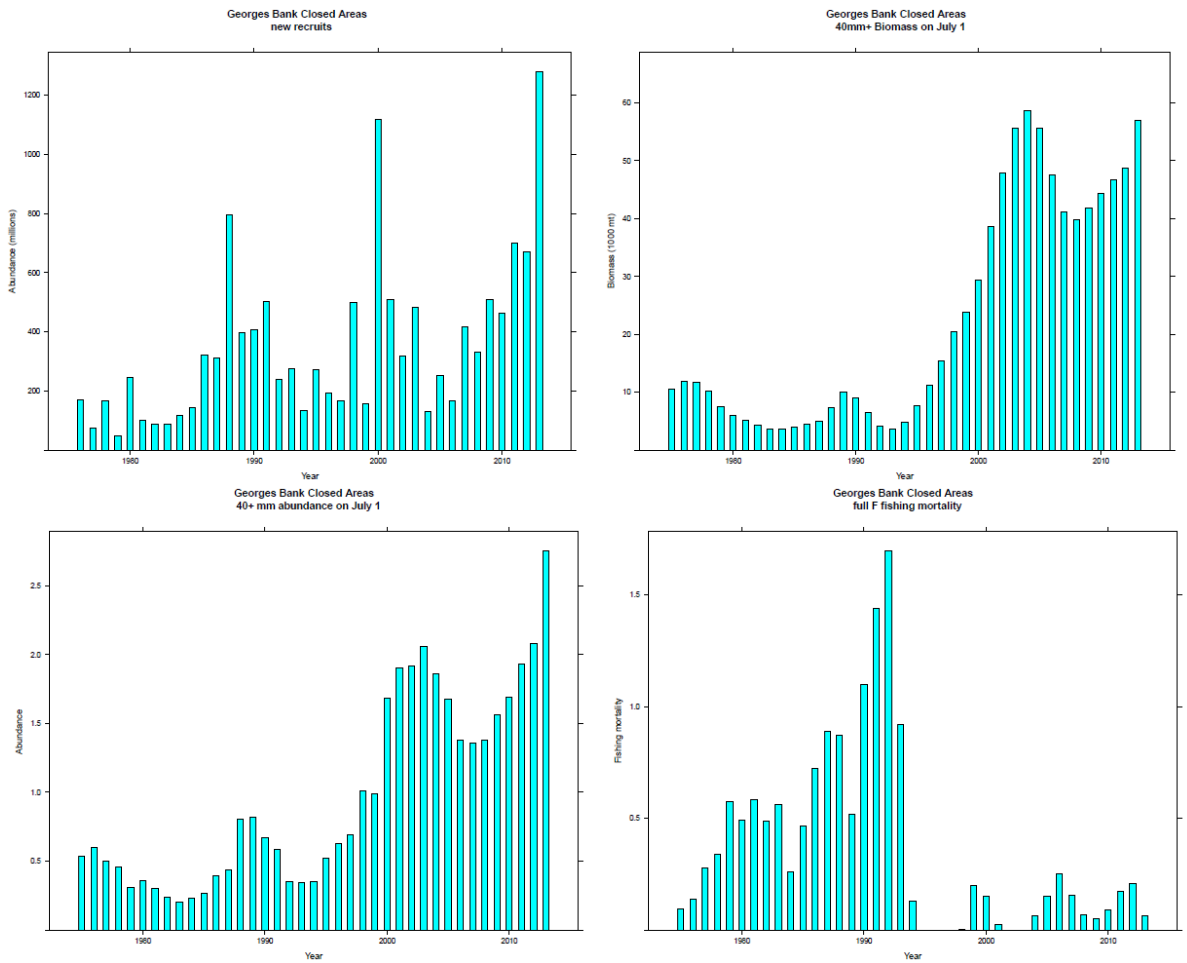


Figure B6.23. CASA model estimated recruitment (top left), July 1 biomass (top right), July 1 abundance (bottom left) and fully recruited fishing mortality (bottom right) for Georges Bank closed areas.

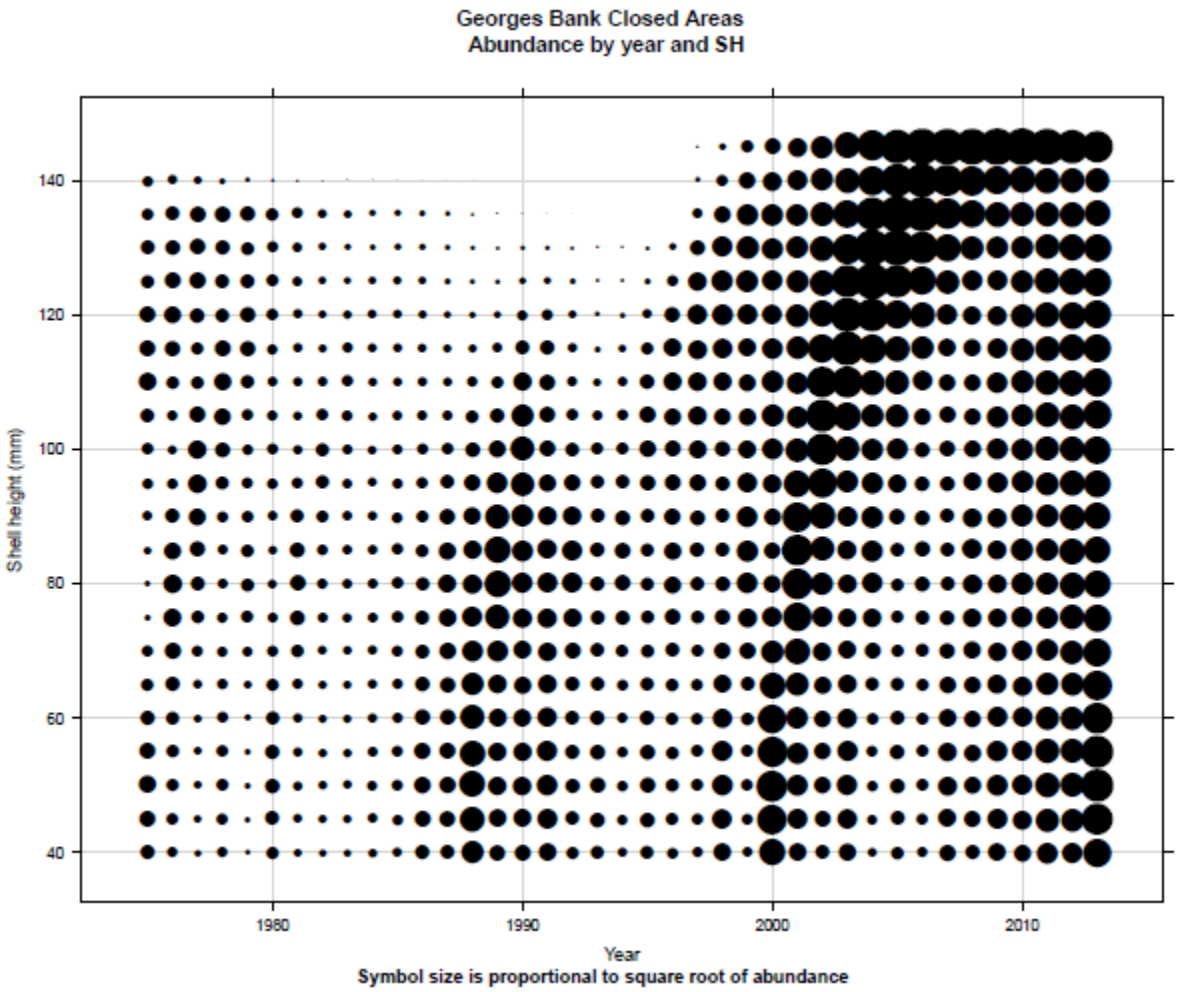


Figure B6.24. Model estimated abundances at shell height for Georges Bank closed areas. Symbol areas are proportional abundance.

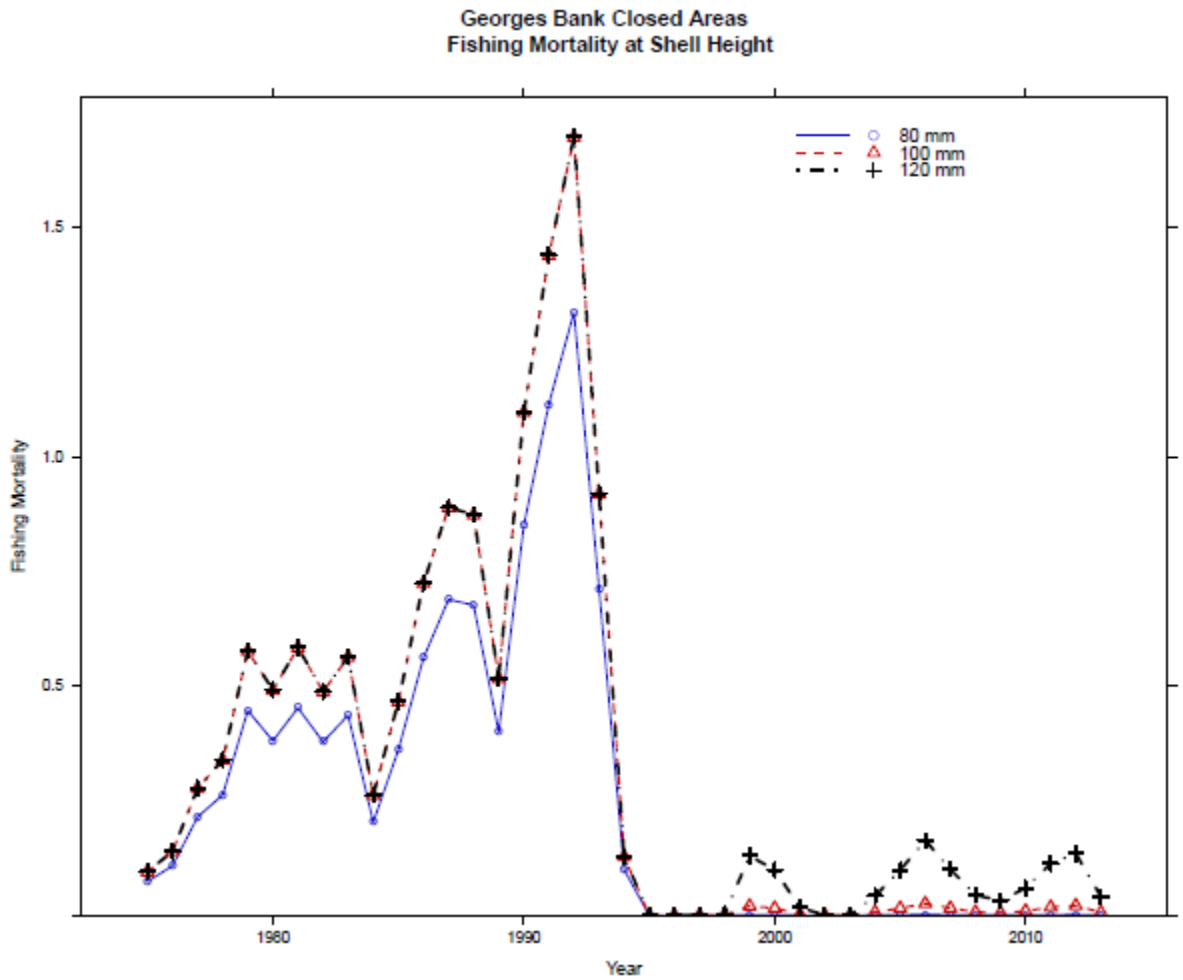


Figure B6.25. CASA model estimated fishing mortality at 80 mm (solid line with circles), 100 mm (dashed line with triangles) and 120 mm SH (dashed line with crosses) for Georges Bank closed areas.

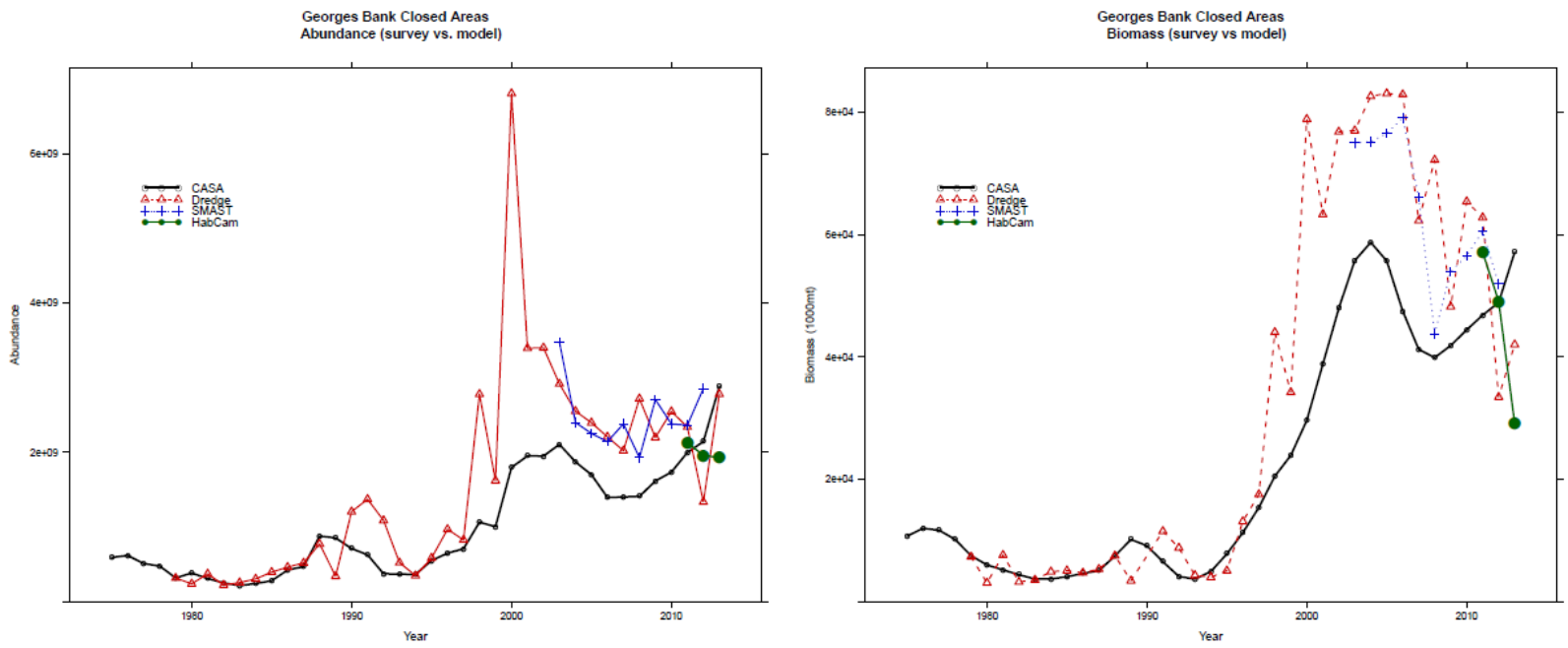


Figure B6.26. Comparison of CASA model estimated abundance (left) and biomass (right) with estimates from the lined dredge survey (dashed line with triangles), SMAST large camera survey (dotted line with crosses) and HabCam (solid line with circles) for Georges Bank closed areas. The dredge survey was expanded assuming an efficiency of 0.41 on sand and 0.27 on gravel/cobble.

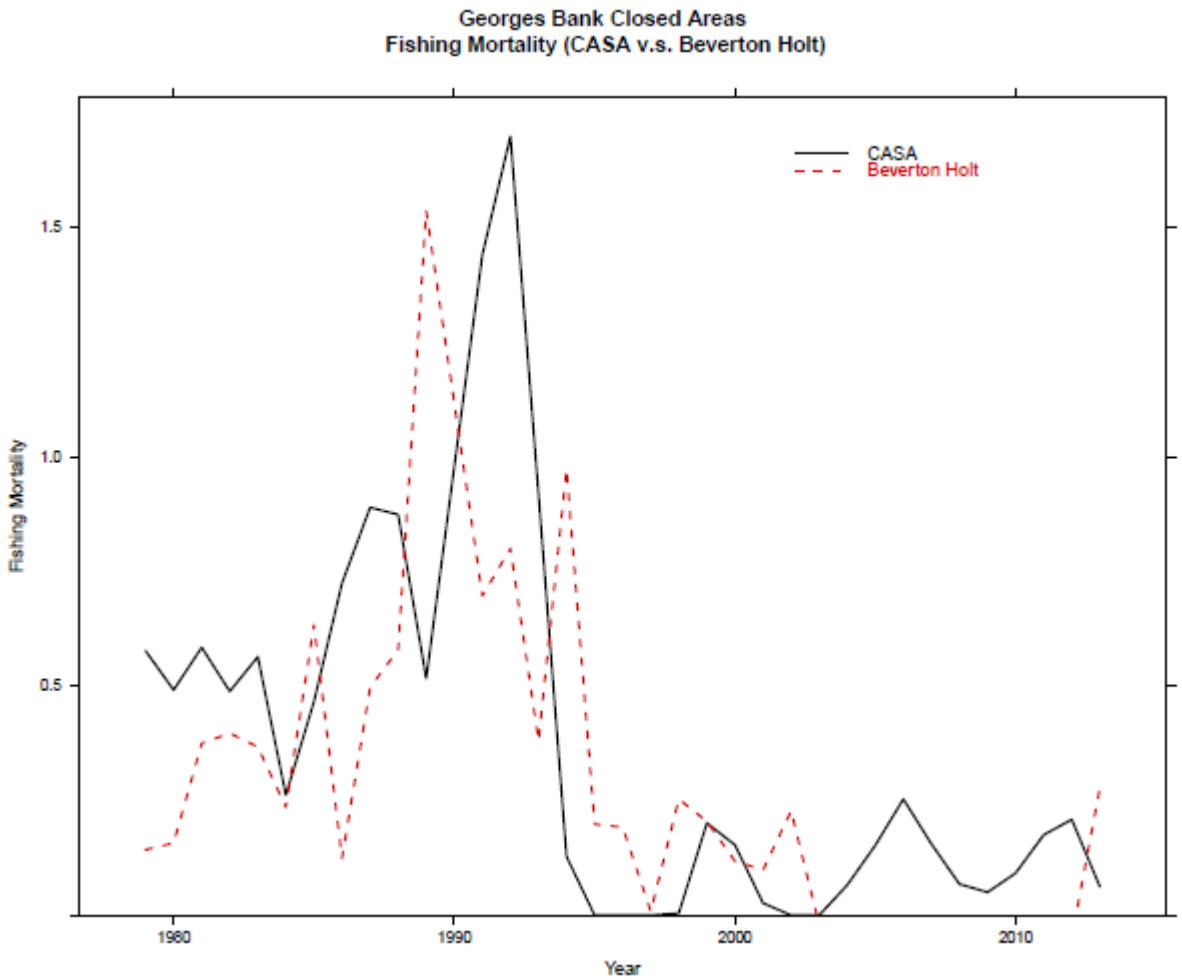


Figure B6.27. Comparison of fully recruited CASA fishing mortality with those calculated from the Beverton-Holt equilibrium estimator for the Georges Bank closed areas.

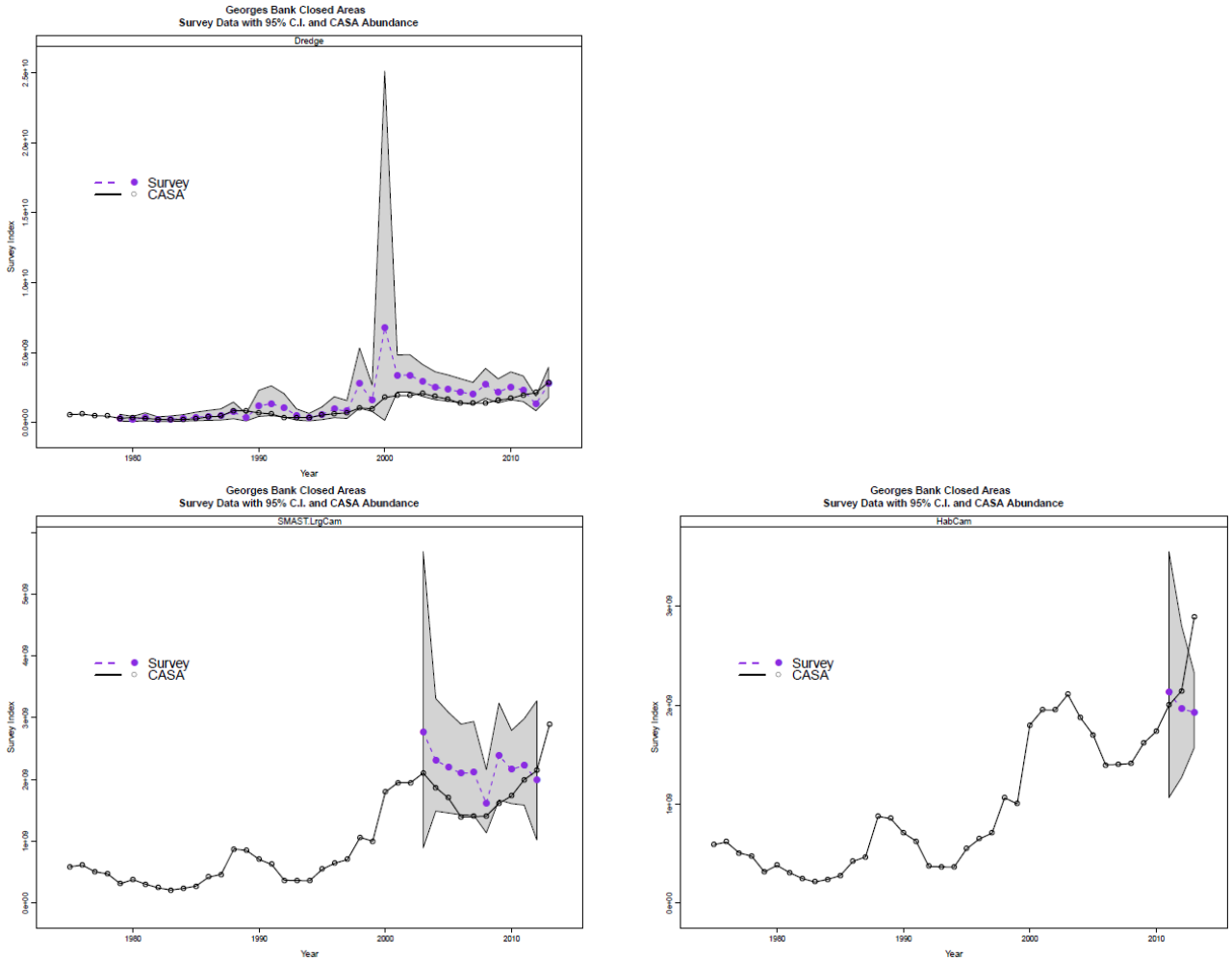


Figure B6.28. CASA estimated abundance compared to that from the dredge survey (top), the SMAST survey (left bottom), and the HabCam survey (right bottom), for Georges Bank closed areas.

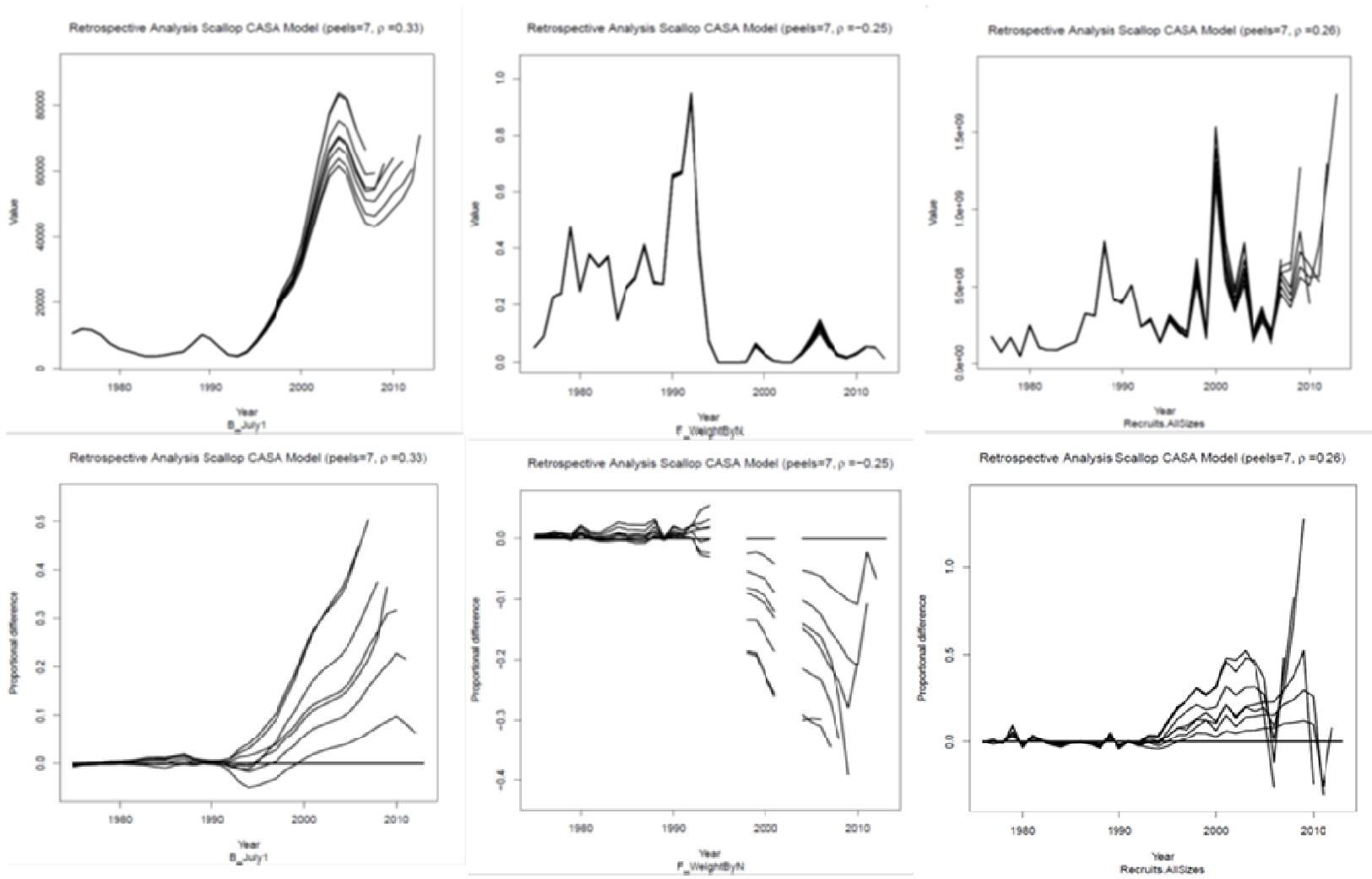


Figure B6.29. Retrospective plots for biomass, fishing mortality and recruitment for Georges Bank closed areas. Retrospectives are shown on both absolute and relative scales.

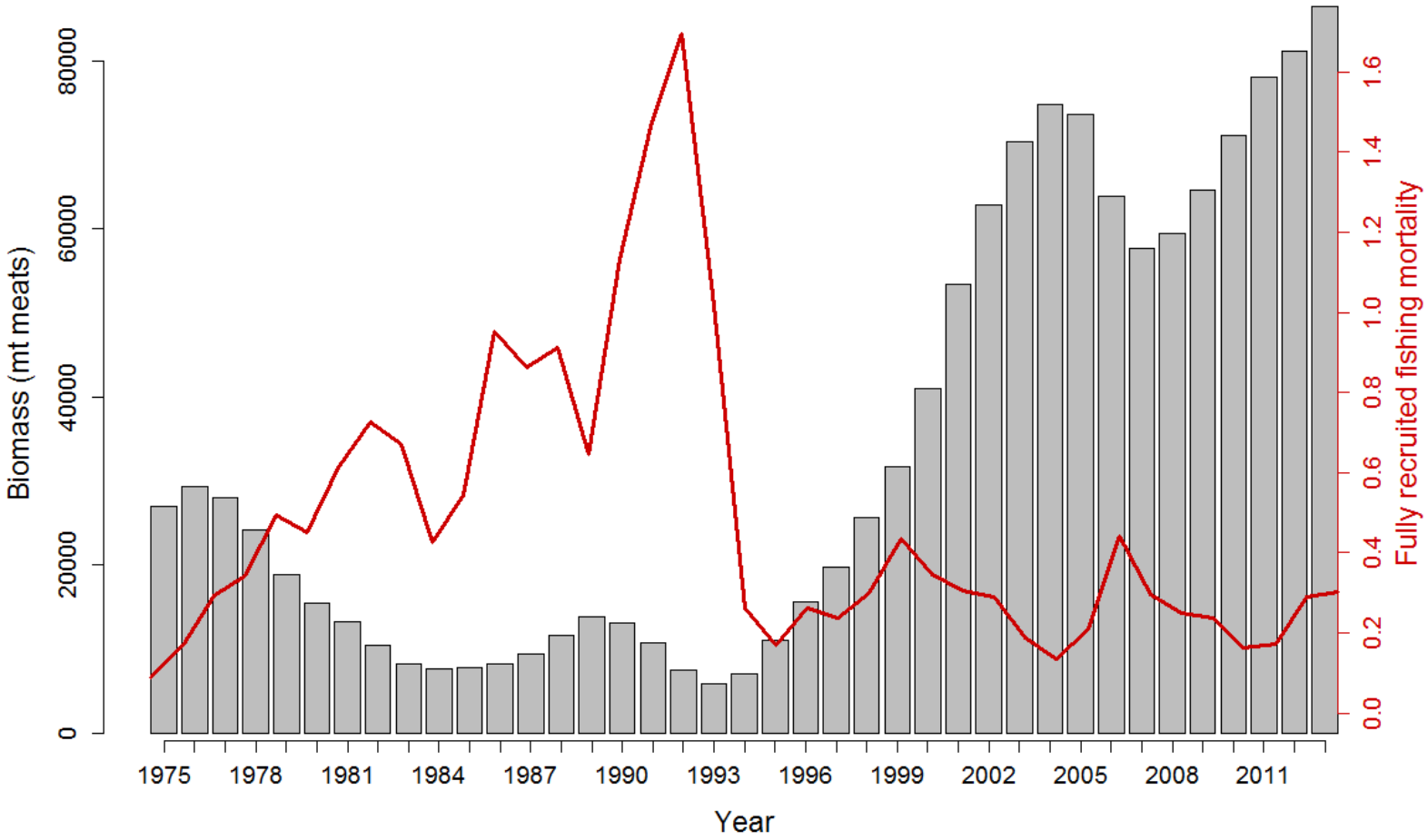


Figure B6.30. Estimated biomass and fully recruited fishing mortality for Georges Bank sea scallops (open and closed combined).

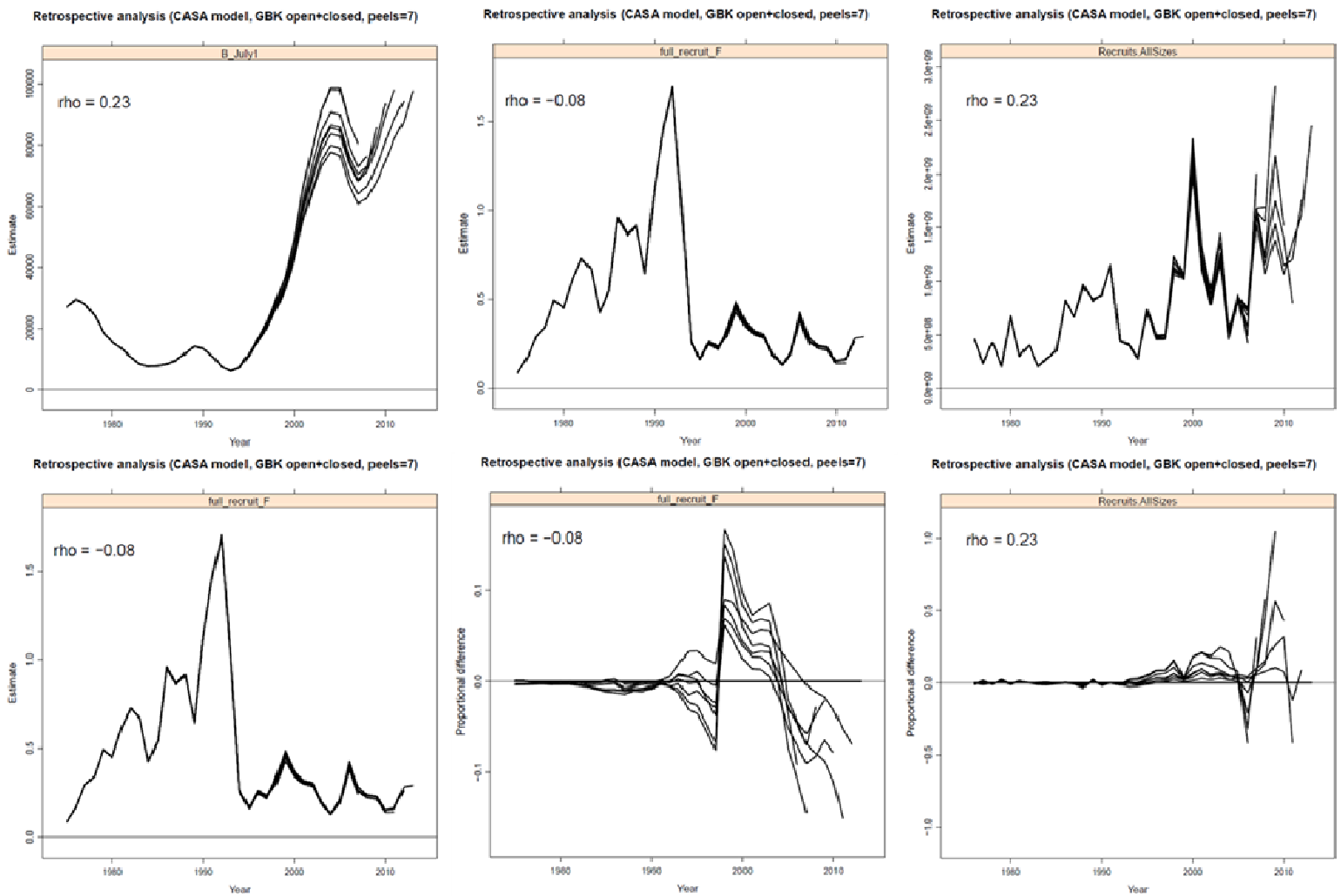


Figure B6.30b. Retrospective plots for the combined Georges Bank open and closed areas.

(A) (B)

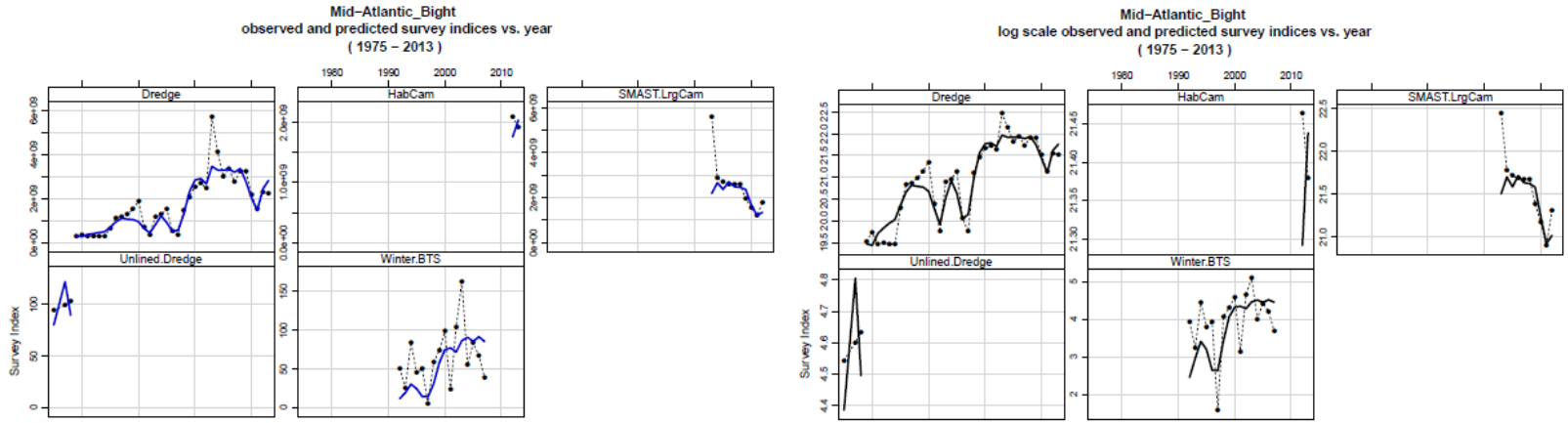


Figure B6.31. Survey trend (solid circles) and corresponding model estimates (lines) for the NEFSC lined dredge survey, the HabCam survey, The SMAST large camera survey, the NEFSC unlined dredge survey, and the NEFSC winter bottom trawl survey in the Mid-Atlantic Bight. Results are shown on a linear scale (A) and a log scale (B).

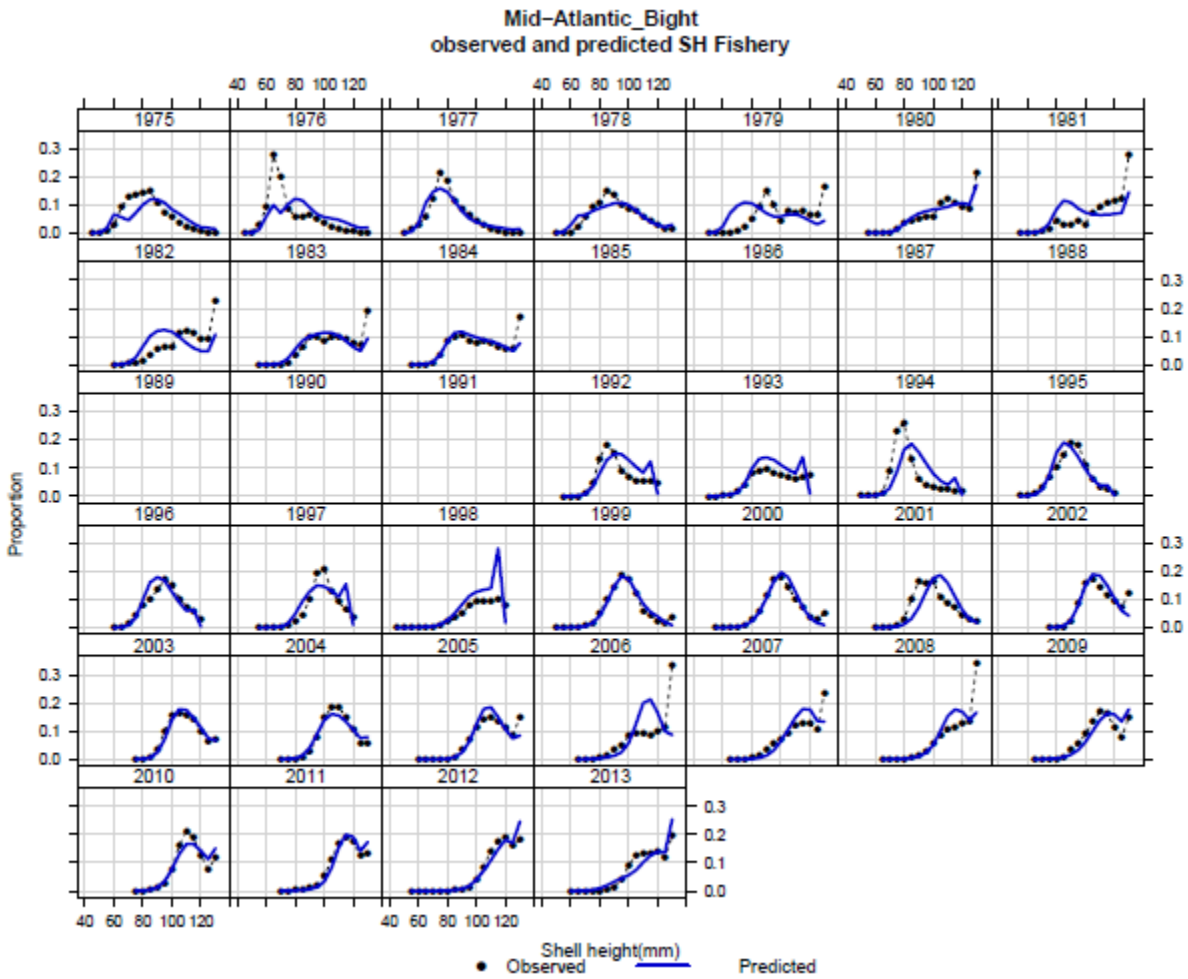


Figure B6.32. Comparison of fishery shell height proportions (solid circles) and model estimated fishery shell height proportions (lines) for the Mid-Atlantic Bight.

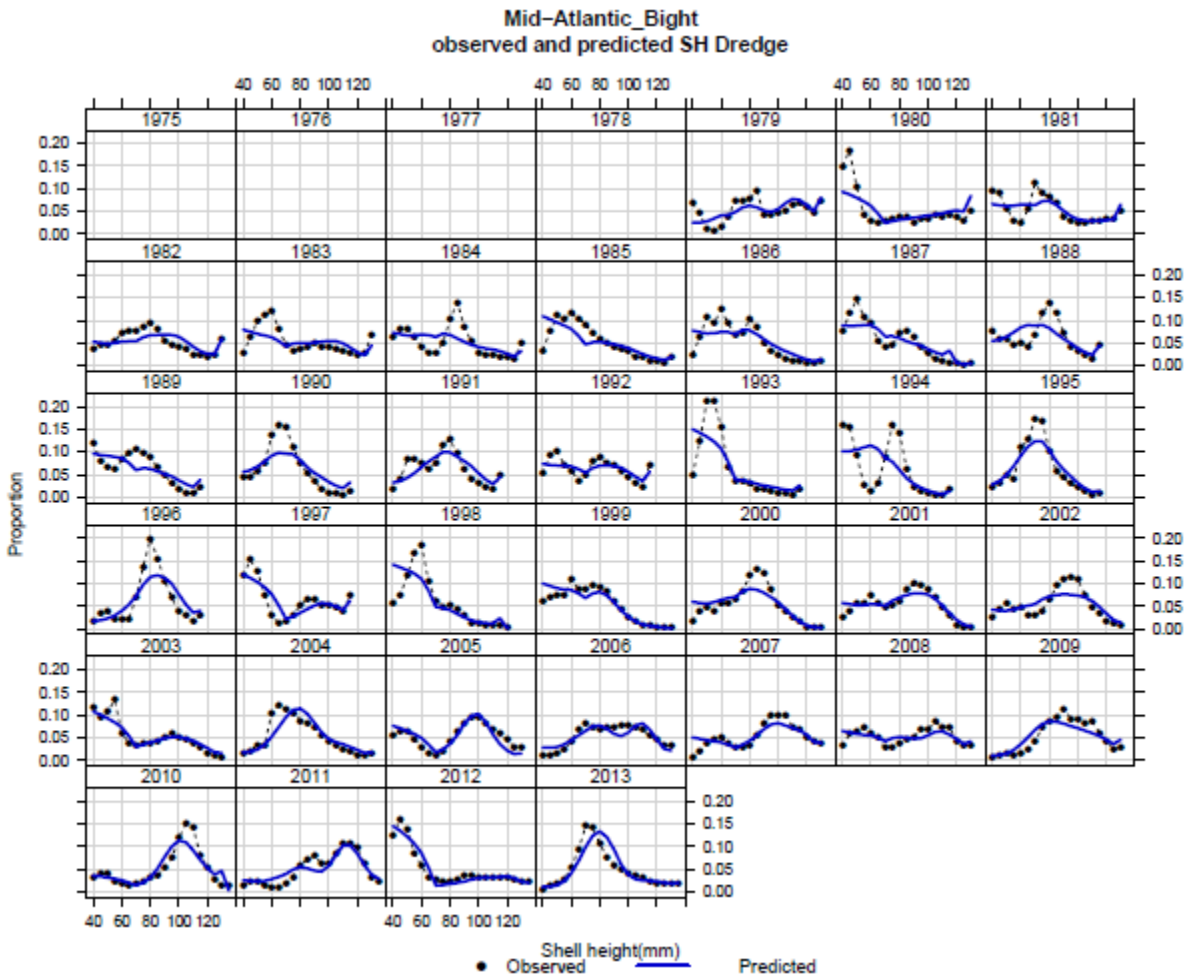


Figure B6.33. NEFSC lined dredge survey shell height proportions (solid circles) and model estimated shell height proportions (lines) for the Mid-Atlantic Bight.

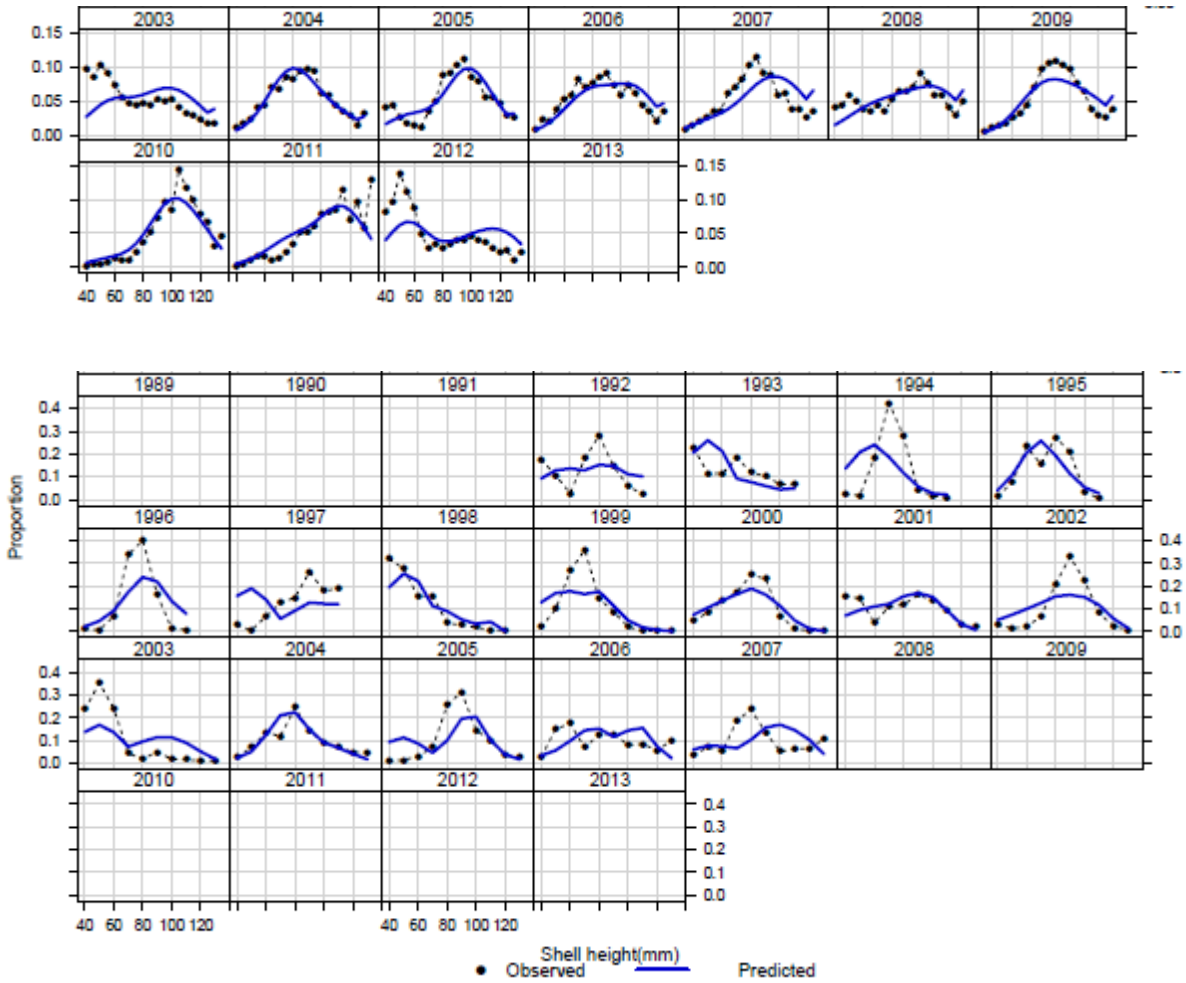


Figure B6.34. Shell height proportions for the SMAST large camera survey (top), and the NEFSC winter bottom trawl survey (bottom) with model predicted proportions (lines) for the Mid-Atlantic Bight.

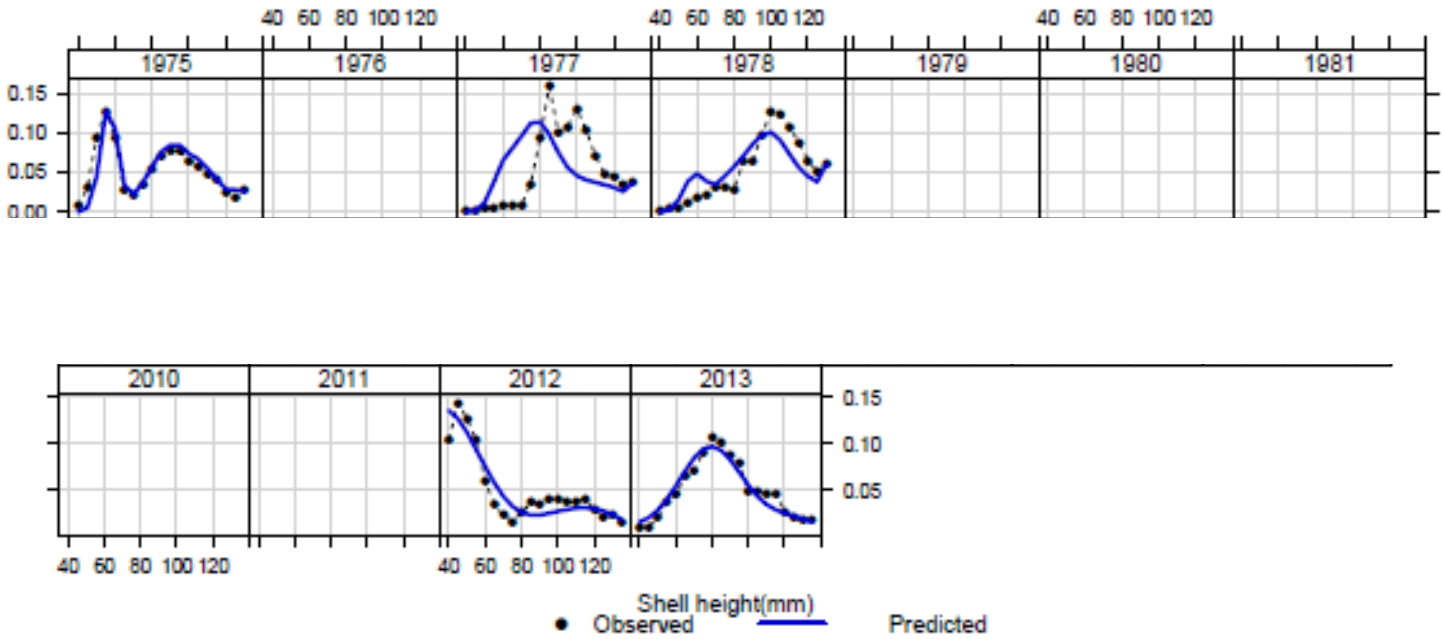


Figure B6.35. Shell height proportions for the NEFSC unlined dredge survey (top) and the HabCam survey (bottom) with model predicted proportions (lines) for the Mid-Atlantic Bight.

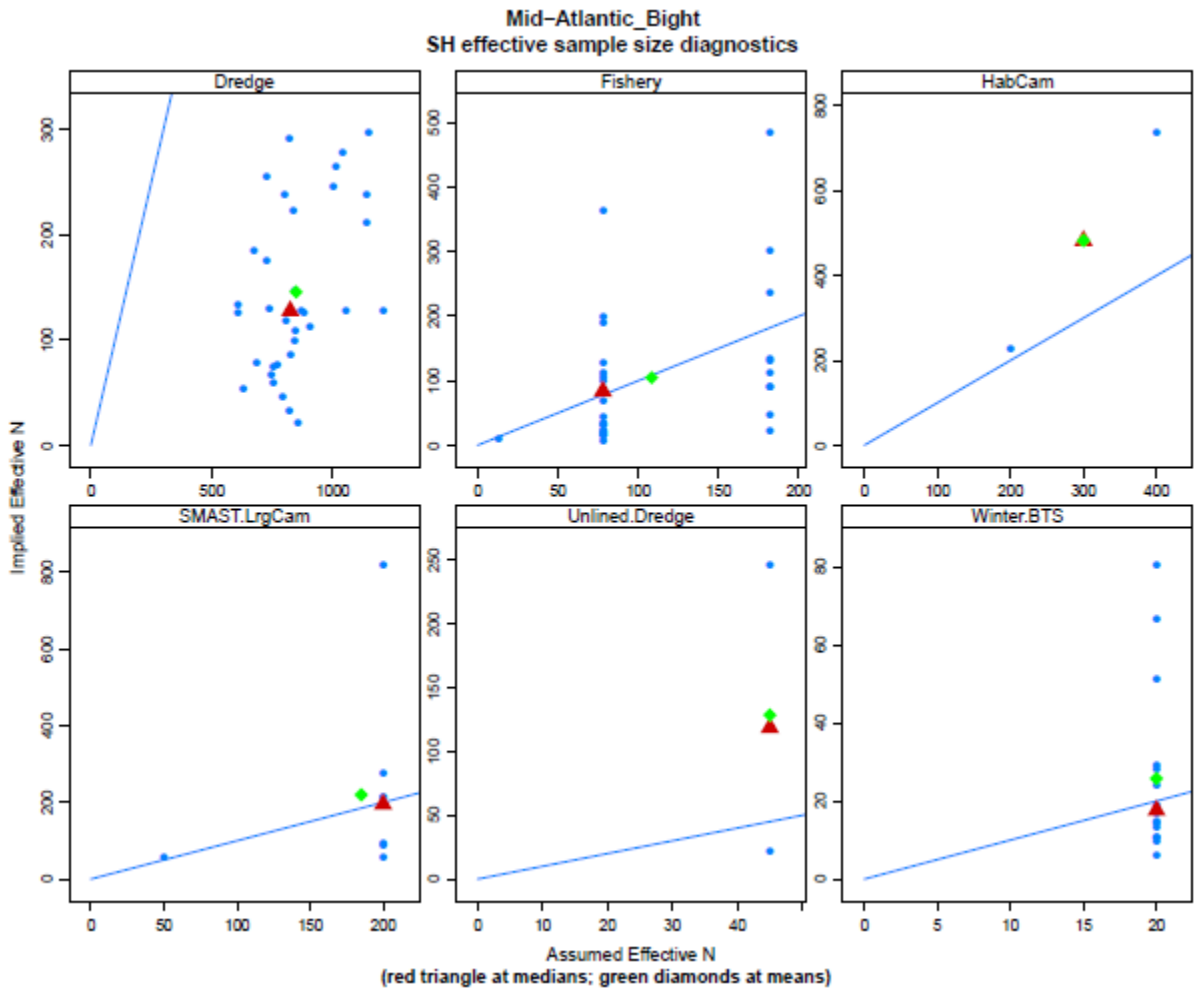


Figure B6.36 Assumed and implied effective sample sizes for the five surveys (NEFSC unlined dredge, HabCam, SMAST large camera, NEFSC unlined dredge, winter bottom trawl survey) and the fishery shell height compositions for the Mid-Atlantic Bight. The triangle is the median and the diamond is the mean.

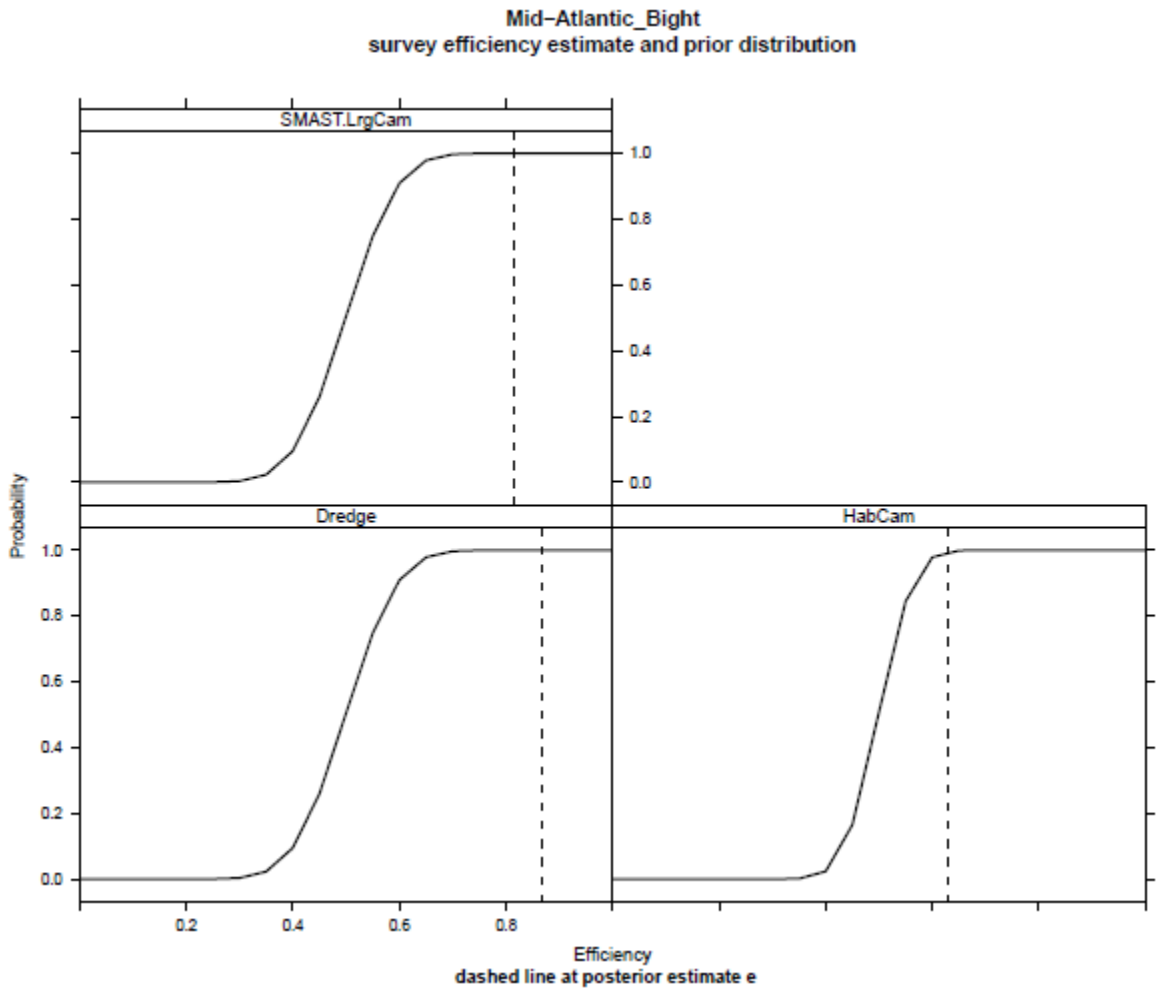


Figure B6.37. Prior cumulative distributions for catchability of the large camera video survey (top) lined dredge survey (bottom left) and HabCam survey (bottom right) for the Mid-Atlantic Bight. The dashed lines are the mean posterior estimate for survey efficiency. For the purposes of this plot, the surveys were adjusted to have a mean prior catchability of 0.5

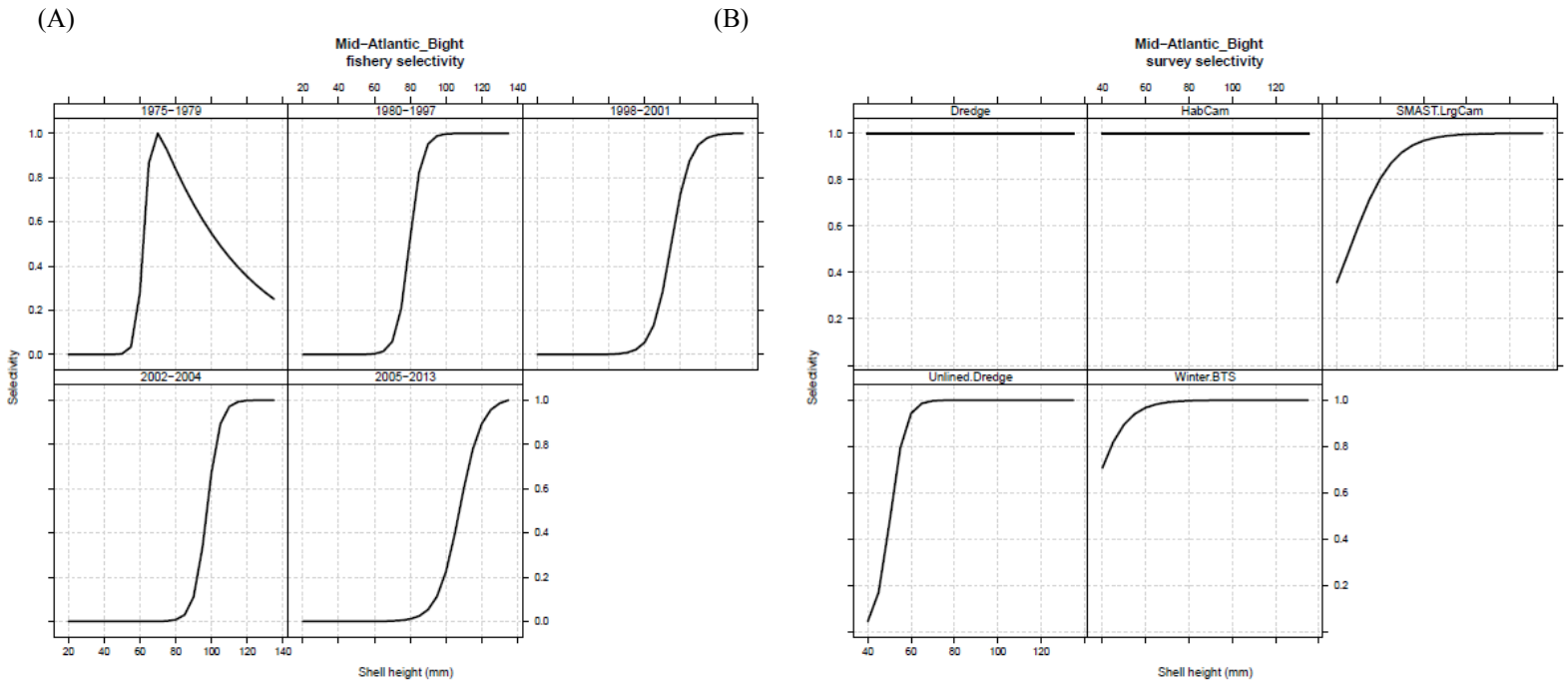


Figure B6.38. (A) Estimated fishery selectivity curves and (B) survey selectivity curves (lined dredge top left, HabCam top middle, large camera top right, unlined dredge bottom left, and winter bottom trawl bottom middle) for the Mid-Atlantic Bight.

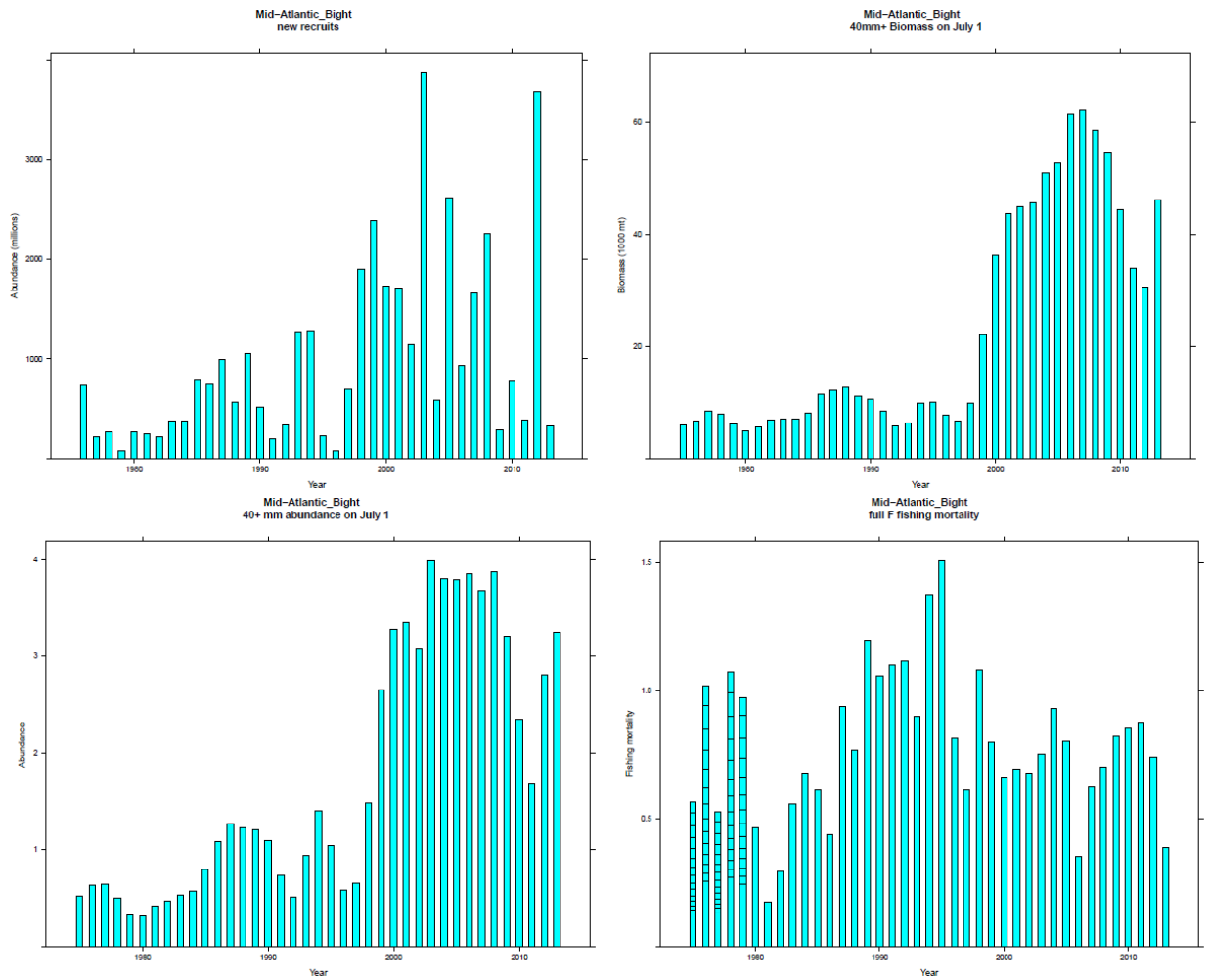


Figure B6.39. CASA model estimated recruitment (top left), July 1 biomass (top right), July 1 abundance (bottom left), and fully recruited fishing mortality (bottom right) for the Mid-Atlantic Bight.

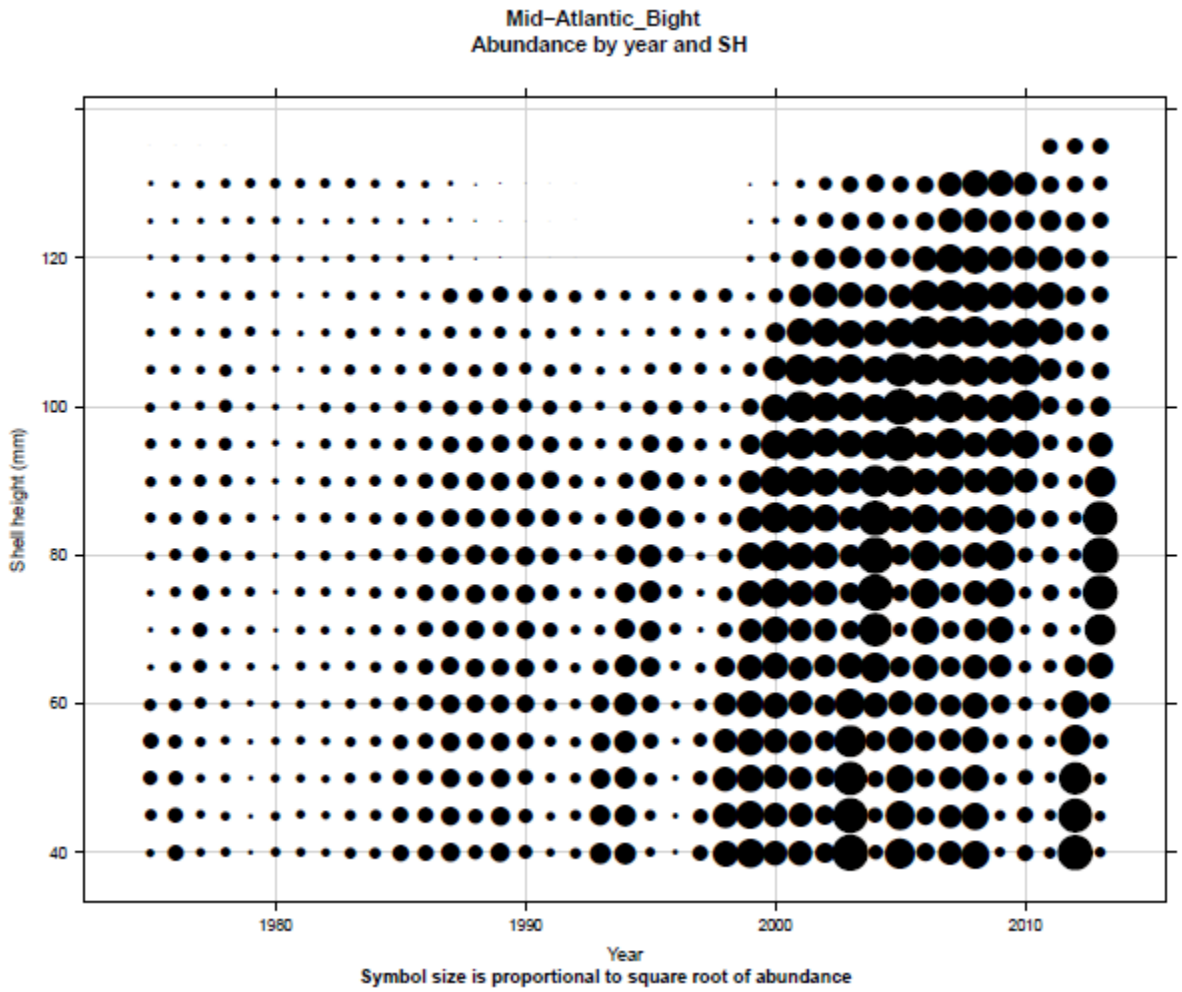


Figure B6.40. Model estimated abundances at shell height for the Mid-Atlantic Bight. Symbol areas are proportional to abundance.

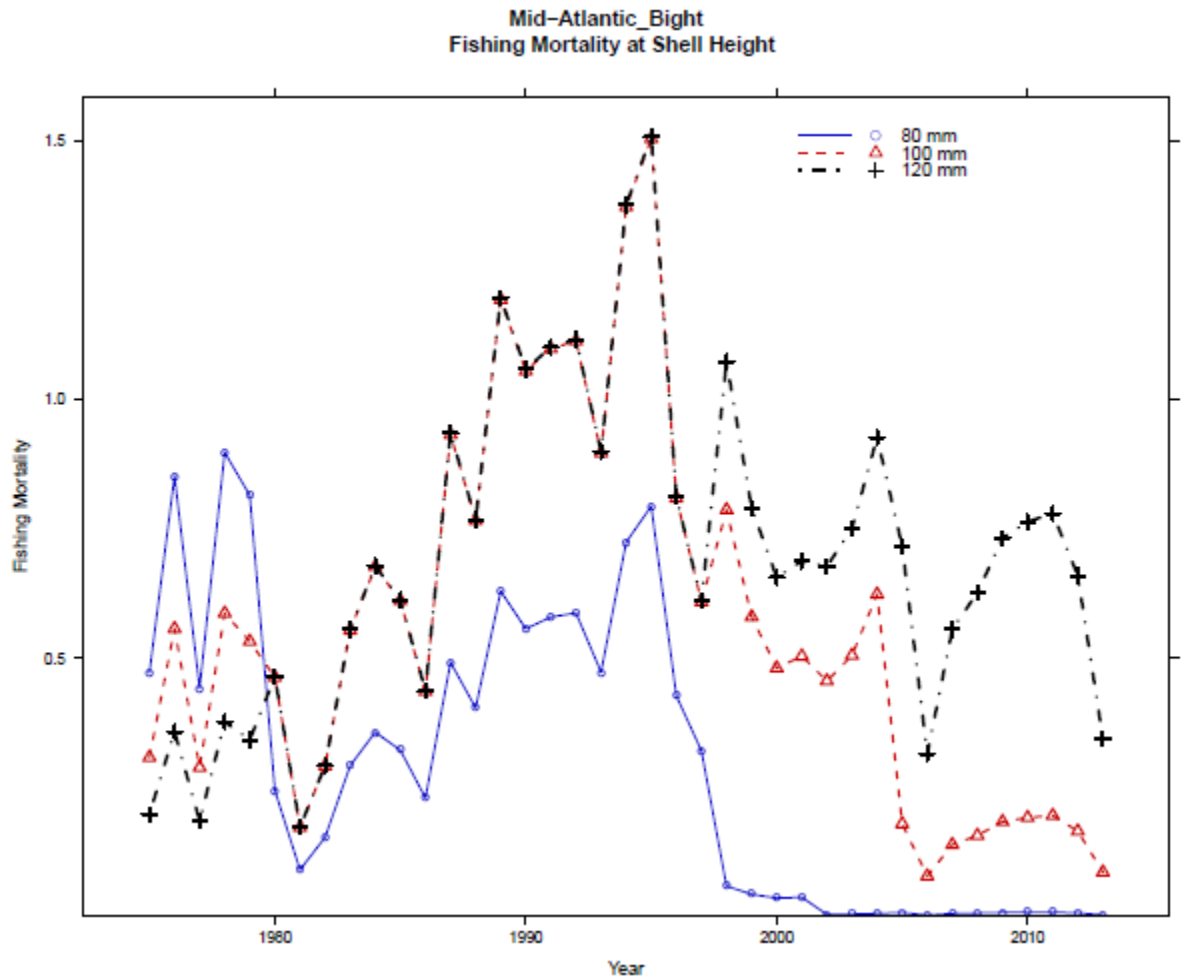


Figure B6.41. CASA model estimated fishing mortality at 80 mm (solid line with circles), 100 mm (dashed line with triangles) and 120 mm SH (dashed line with crosses) for the Mid-Atlantic Bight.

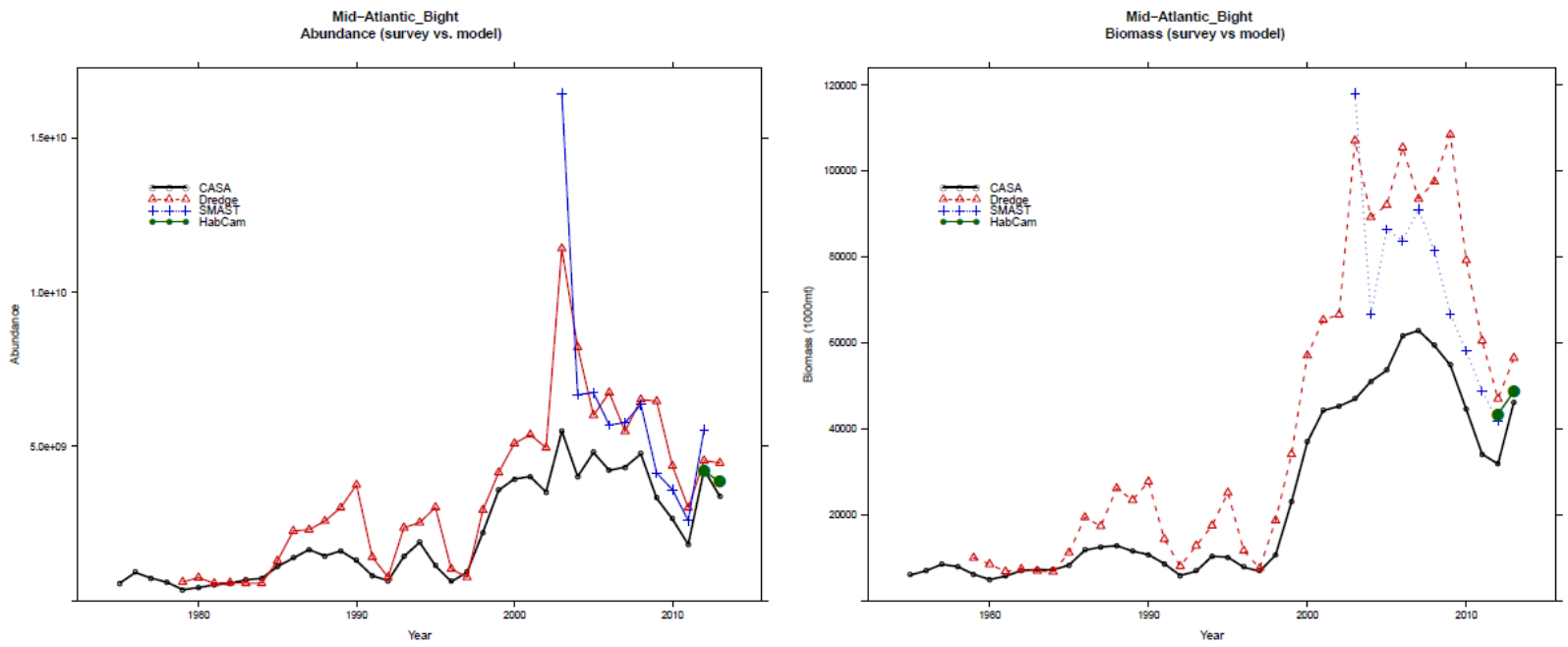


Figure B6.42. Comparison of CASA model estimated abundance (left) and biomass (right) with estimates from the lined dredge survey (dashed line with triangles), SMAST large camera survey (dotted line with crosses) and HabCam (solid line with circles) for the Mid-Atlantic Bight. The dredge survey was expanded assuming an efficiency of 0.41.

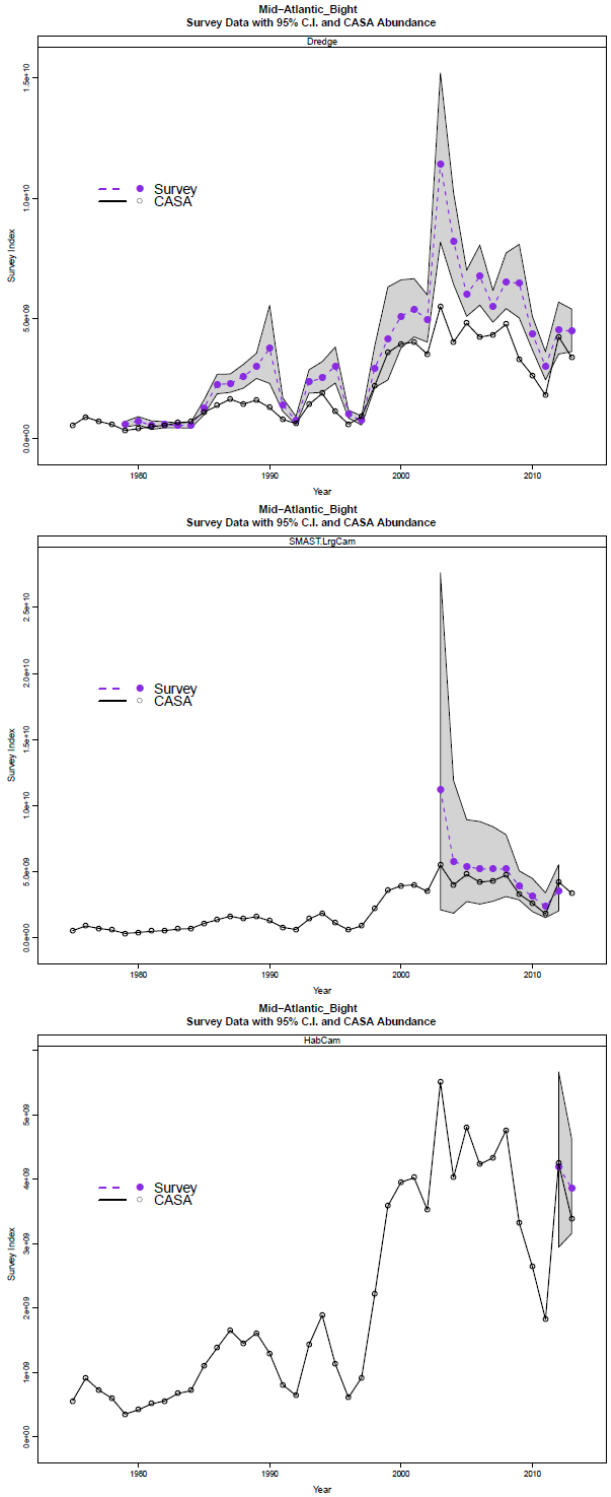


Figure B6.42b. CASA estimated abundance compared to that from the dredge survey (top), the SMAST survey (middle), and the HabCam survey (bottom), for the mid-Atlantic bight.

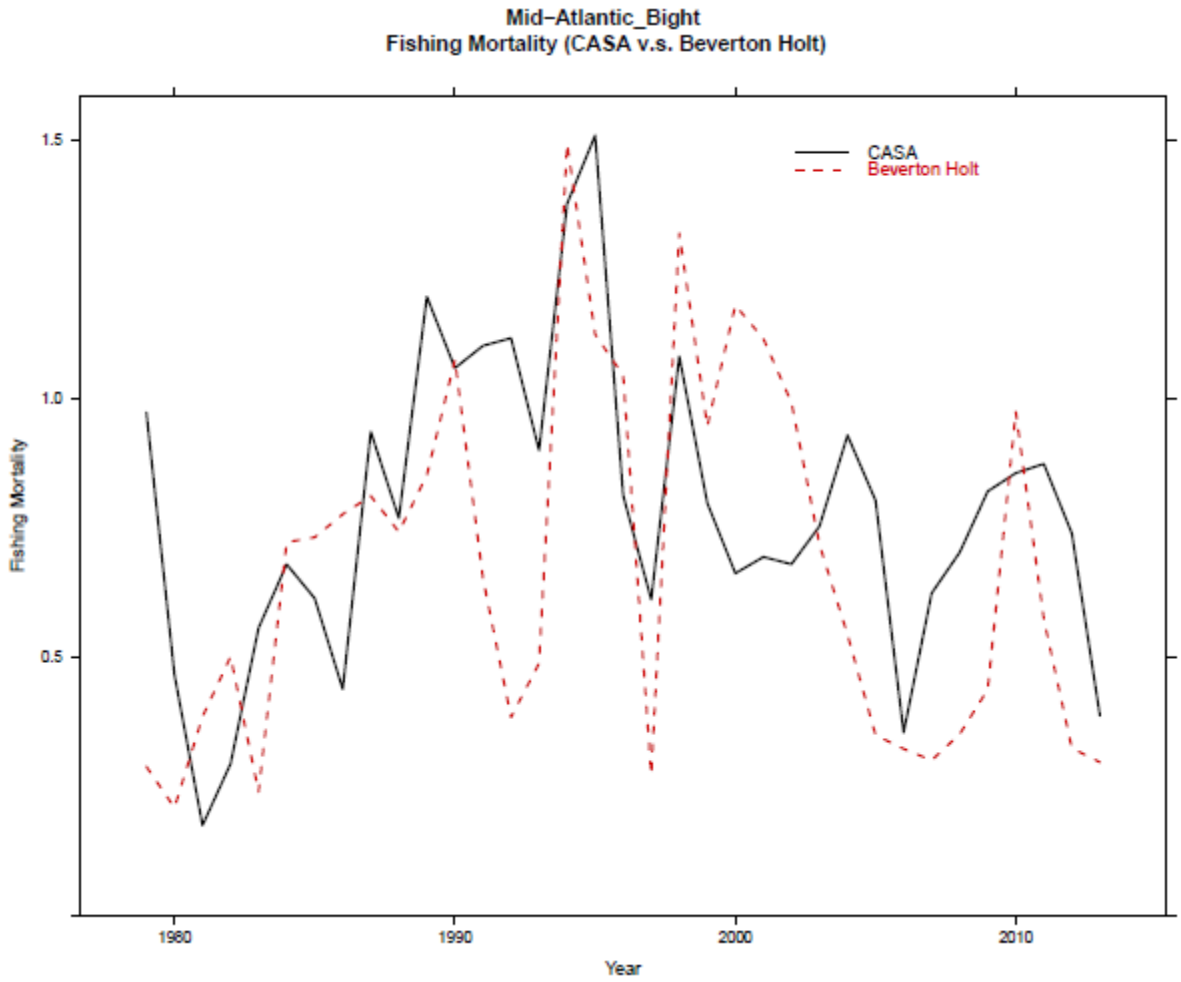


Figure B6.43. Comparison of fully recruited CASA fishing mortality with those calculated from the Beverton-Holt equilibrium estimator for the Mid-Atlantic Bight.

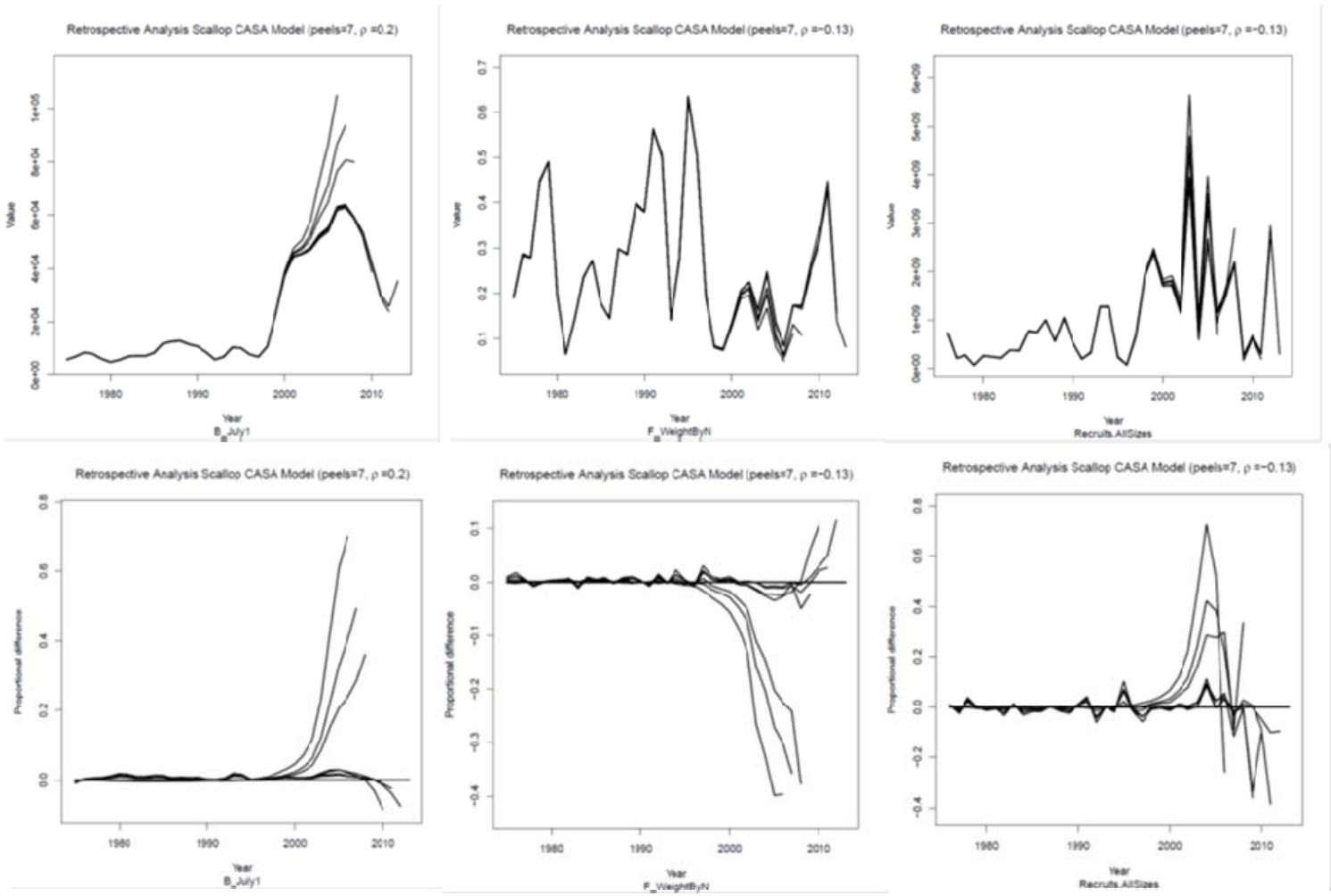


Figure B6.44. Retrospective plots for biomass, fishing mortality and recruitment for the Mid-Atlantic Bight. Retrospective patterns are shown on both absolute and relative scales.

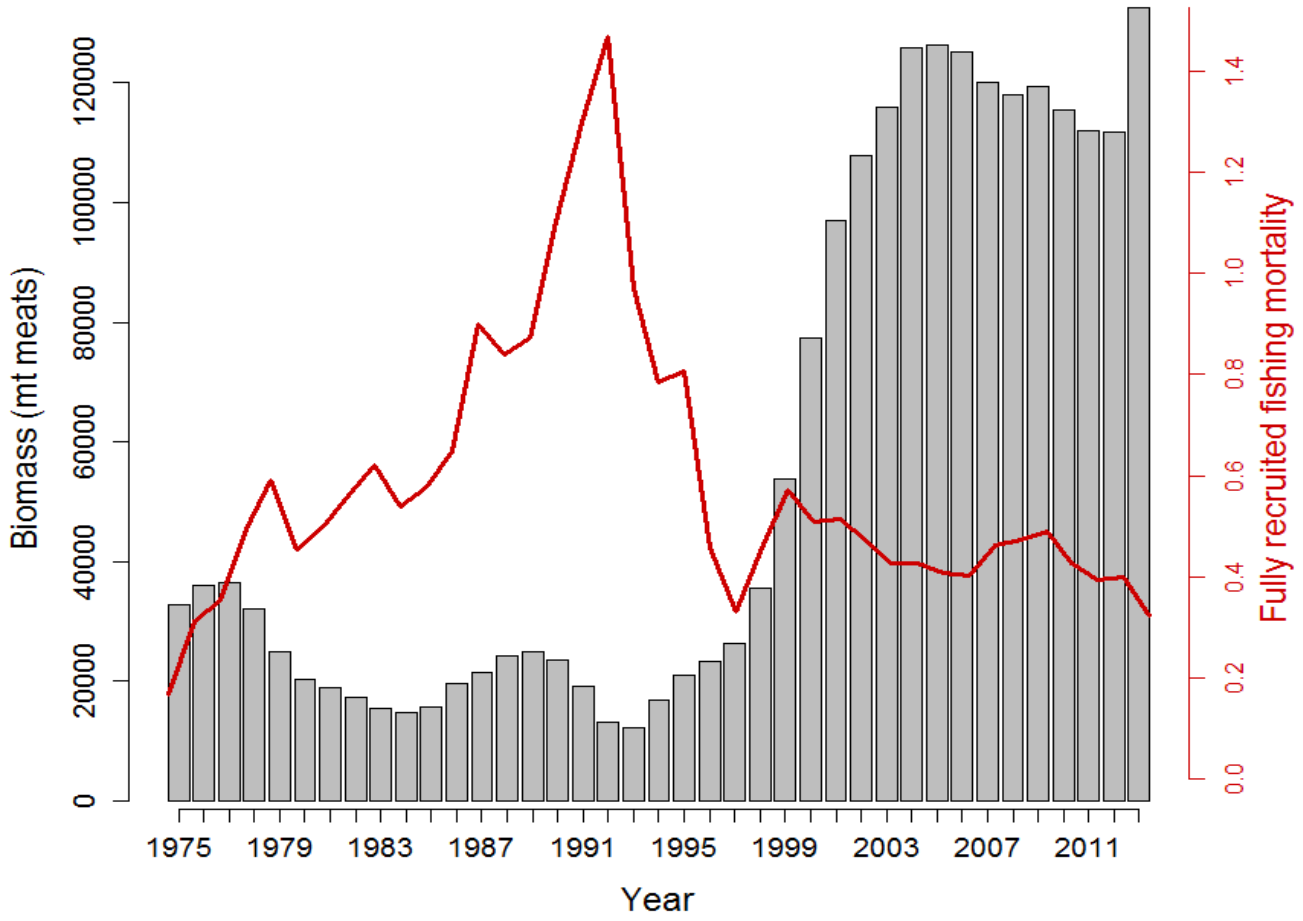


Figure B6.45. Total estimated biomass and fully recruited fishing mortality for Georges Bank and Mid-Atlantic combined.

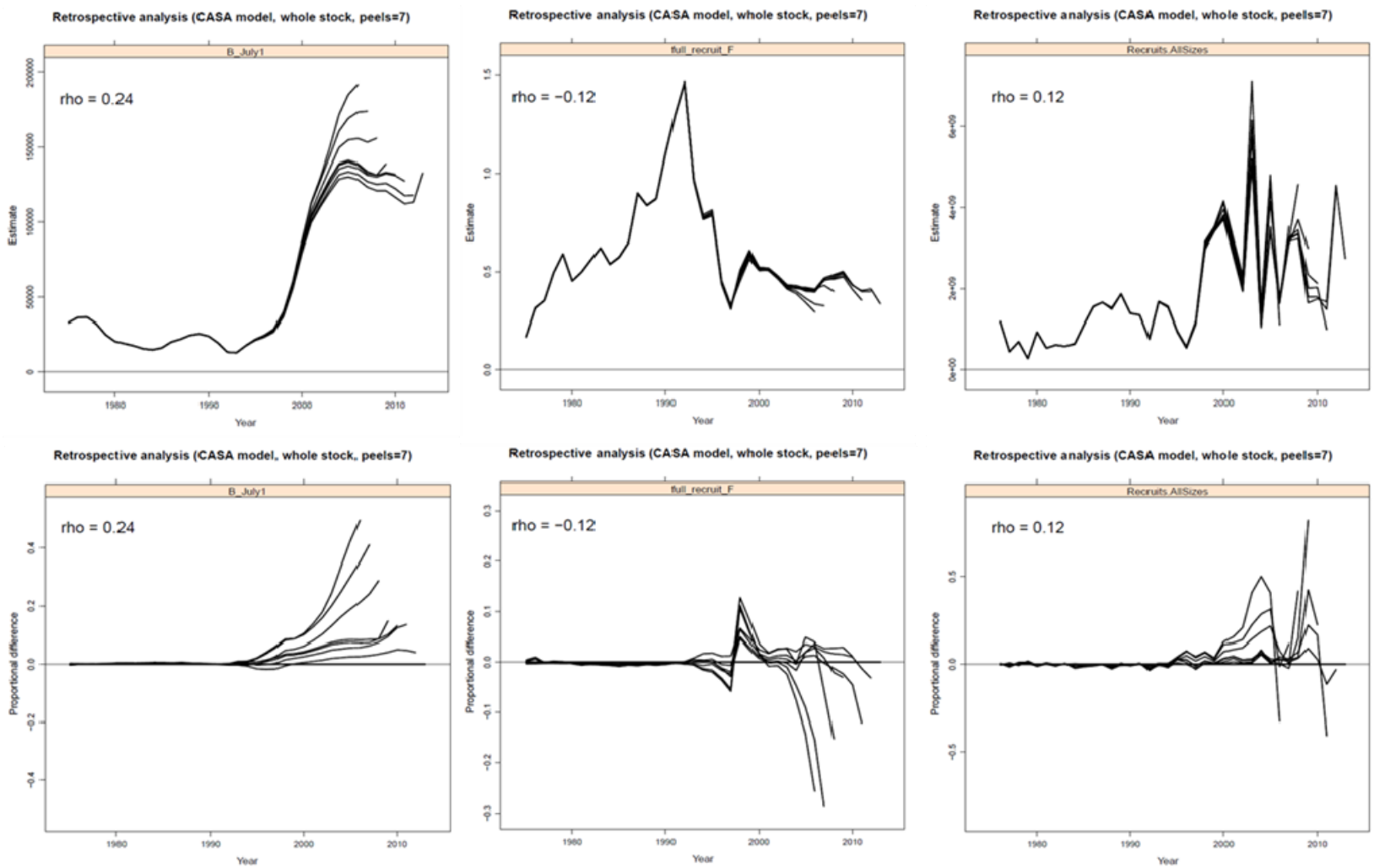


Figure B6.45b. Retrospective plots for the entire sea scallop stock.

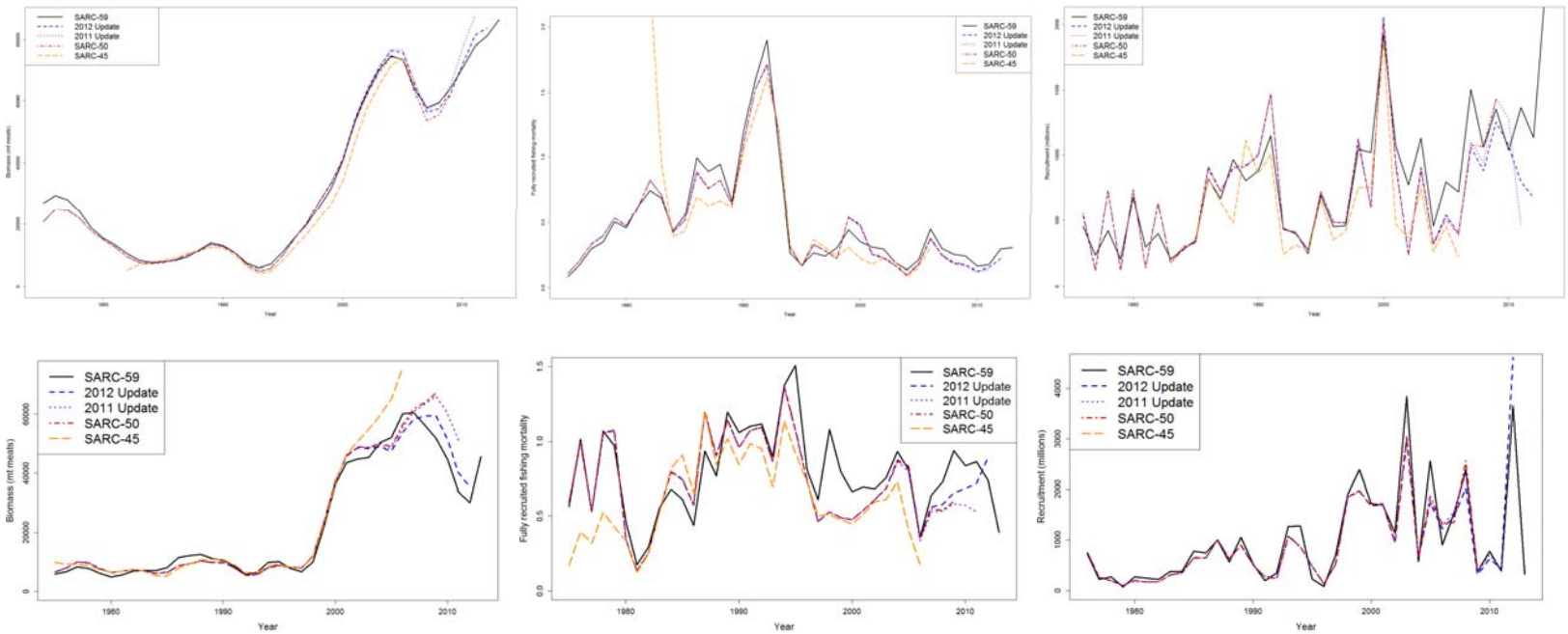


Figure B6.46. Comparison of current CASA model estimates of biomass (left), fishing mortality (middle), and recruitment (right) to previous CASA model estimates for Georges Bank (top) and the Mid-Atlantic (bottom) sea scallops.

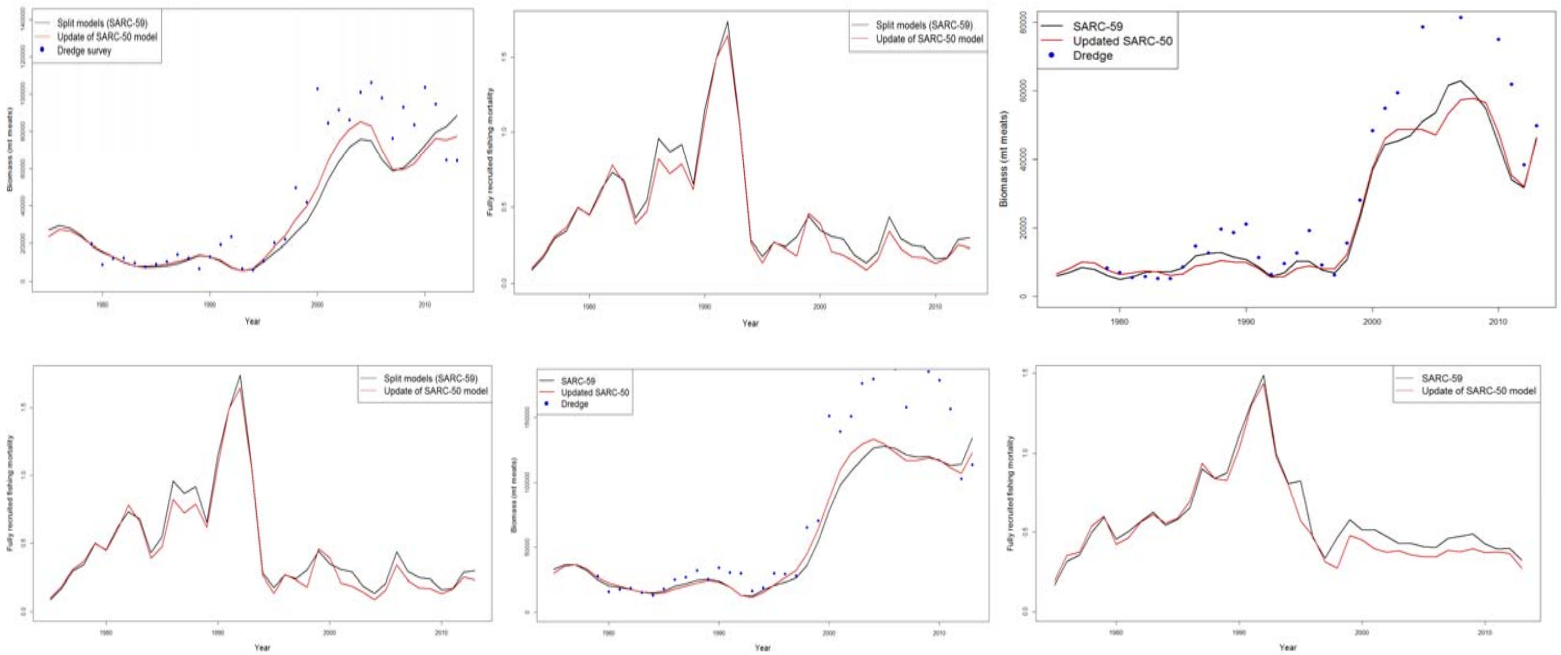


Figure B6.47. Comparisons of biomass and F estimates for the current configurations of the CASA model with the SARC-50 configurations, updated through 2013, for Georges Bank (top left and middle), Mid-Atlantic (top right and bottom left) and total (bottom middle and right). Expanded dredge survey estimates are also given for the biomass plots.

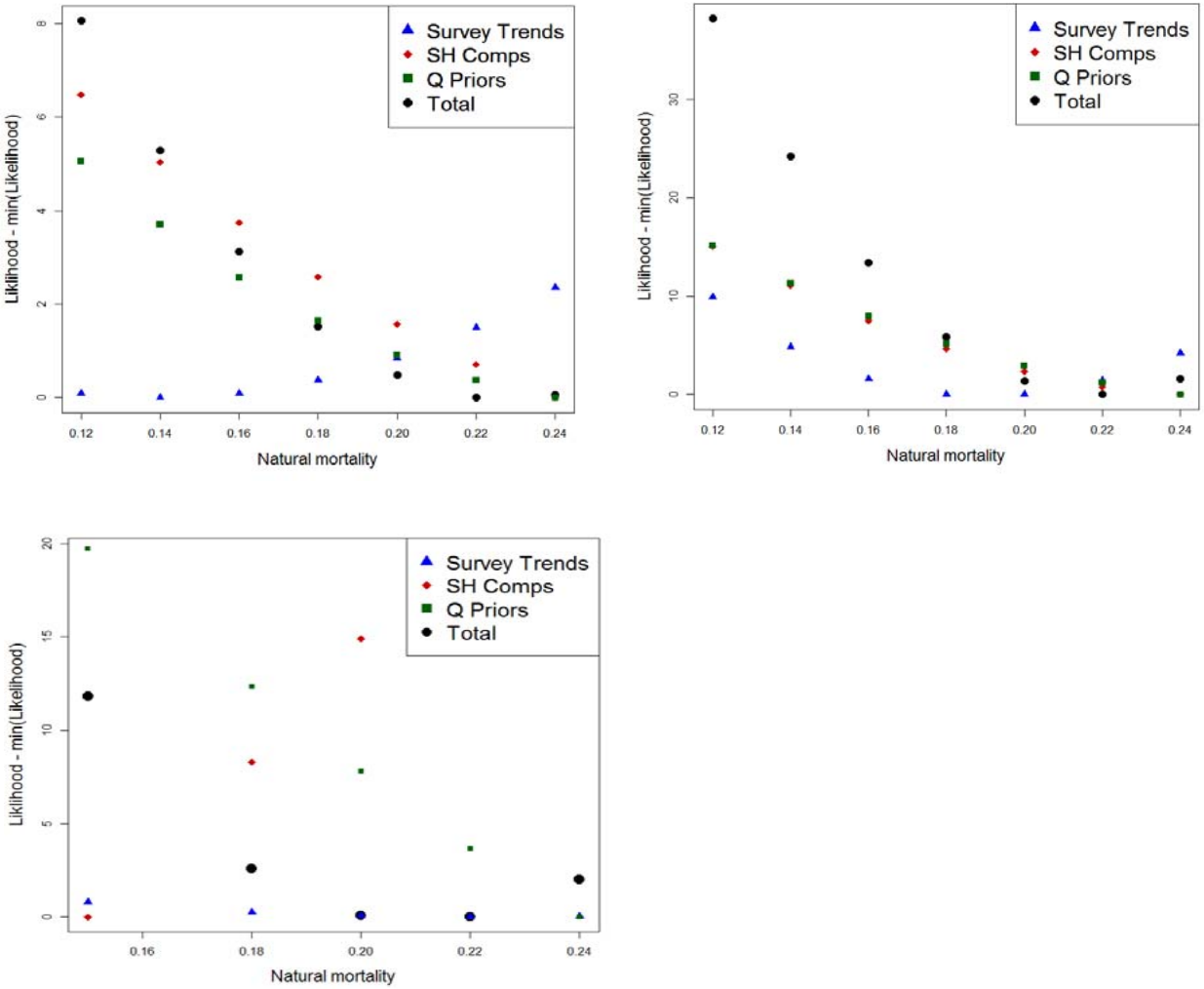


Figure B6.48. Likelihood profiles over the assumed natural mortality for all but the largest size bin (plus group mortality is 1.5x smaller sizes) for (top left) Georges Bank Open, (top right) Georges Bank Closed, (bottom) Mid-Atlantic sea scallops.

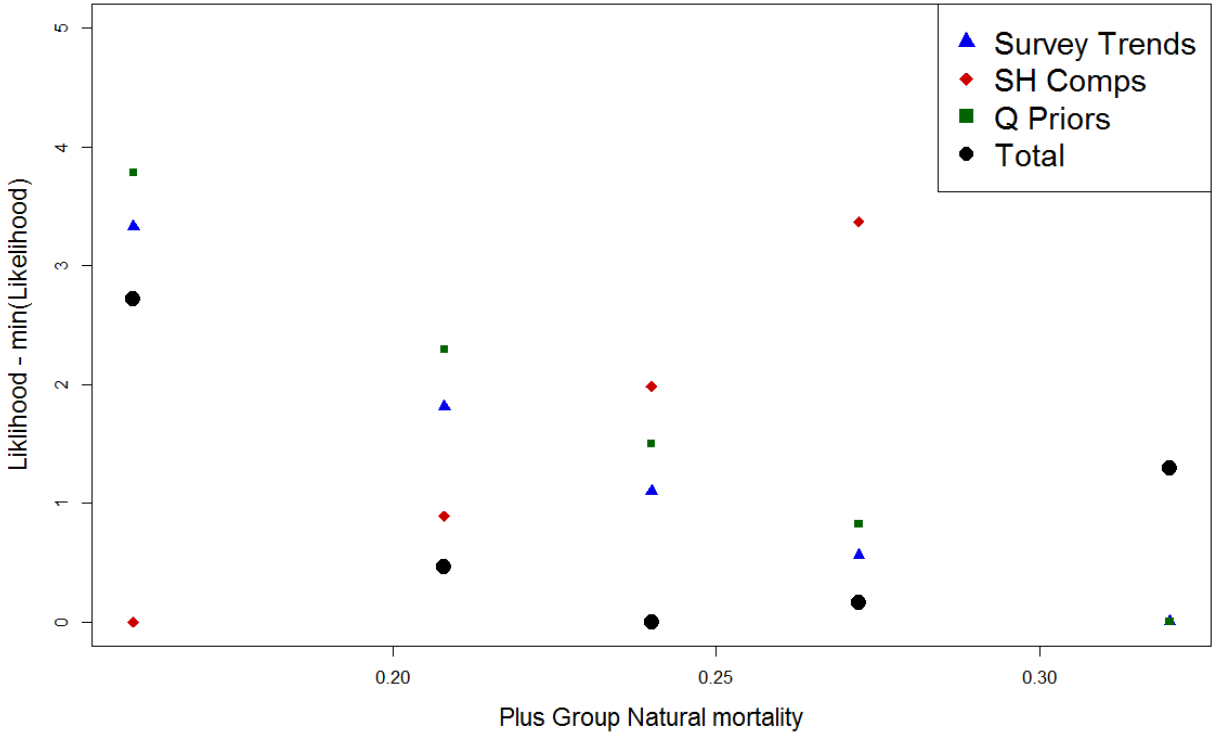


Figure B6.49. Likelihood profile analysis for the assumed plus-group natural mortality in the CASA model for sea scallops in Georges Bank closed areas. Natural mortality on the smaller size classes was fixed at 0.16.

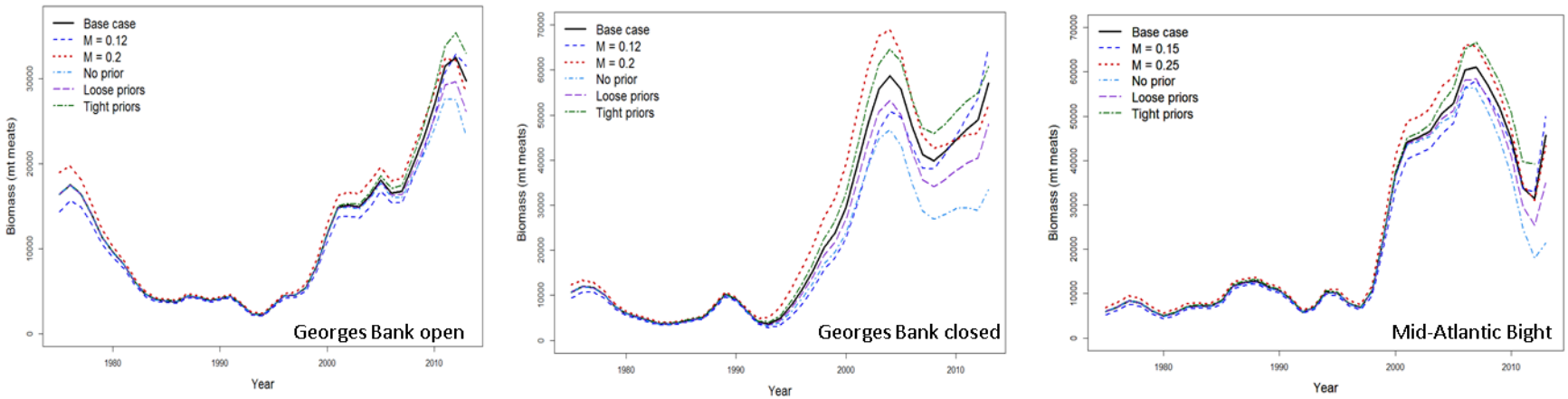


Figure B6.50. Sensitivity of estimated biomass to assumptions about natural mortality and survey efficiency priors in CASA models for Georges Bank open (left), Georges Bank closed (middle), and the Mid-Atlantic Bight (right).

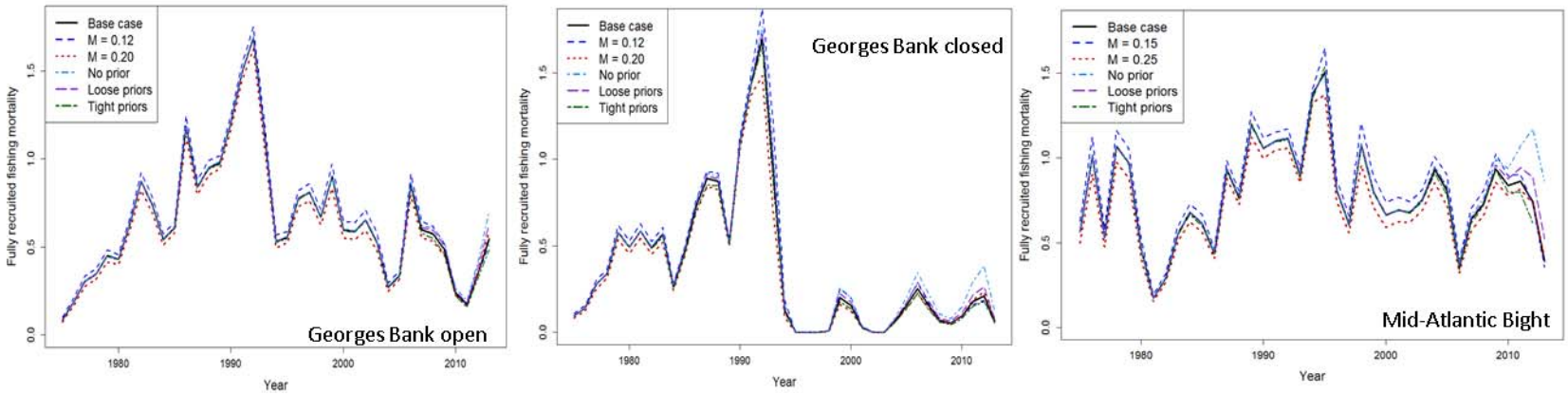


Figure B6.51. Sensitivity of estimated fishing mortality to assumptions regarding natural mortality and survey efficiency priors in CASA models for Georges Bank open (left), Georges Bank closed (middle), and the Mid-Atlantic Bight (right).

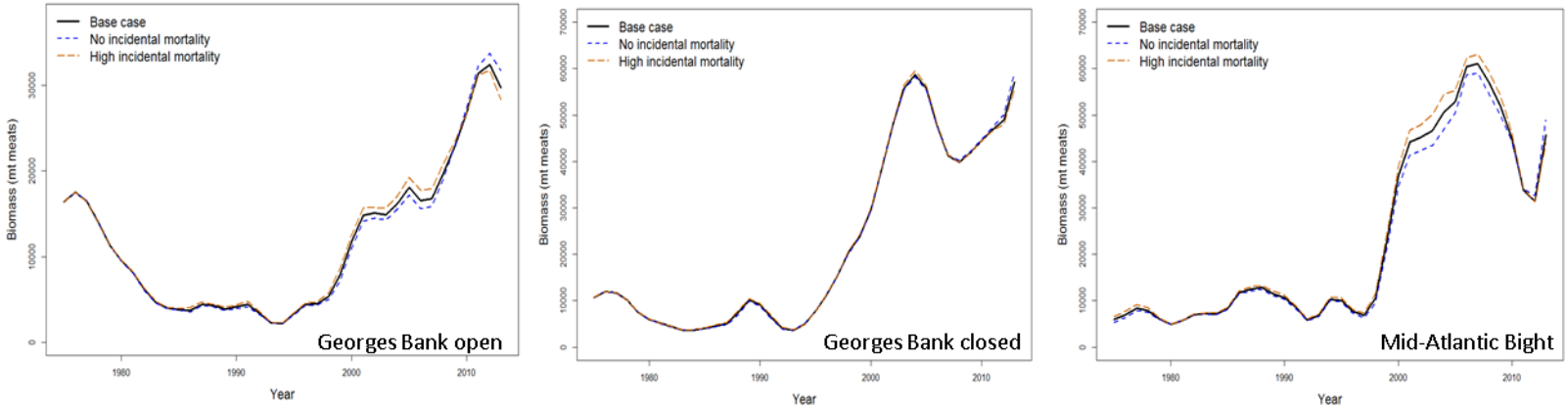
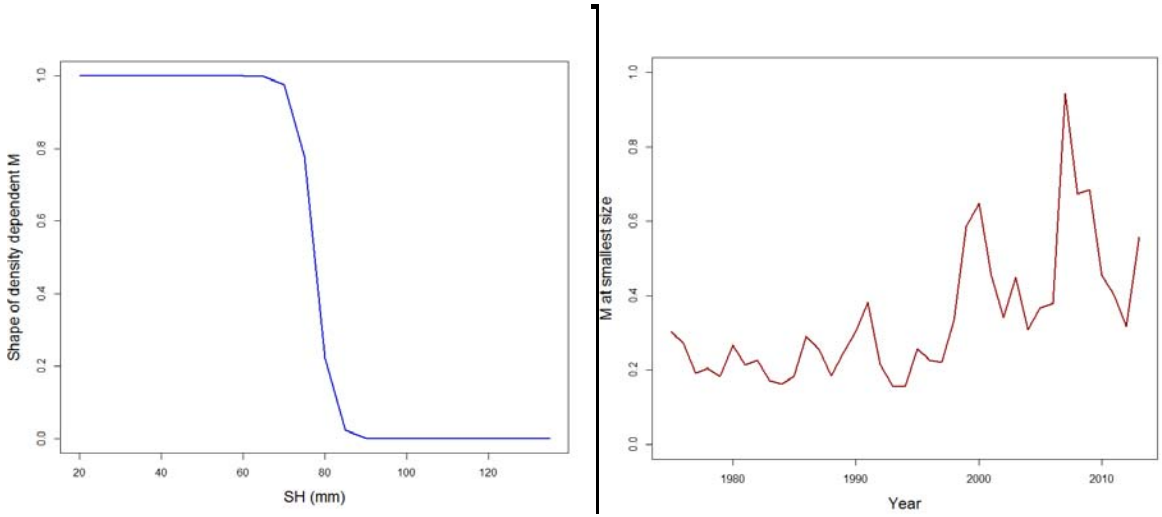


Figure B6.52. Sensitivity of estimated biomass to assumptions regarding incidental fishing mortality in CASA models for Georges Bank open (left), Georges Bank closed (middle), and the Mid-Atlantic Bight (right).



B6.53. (continued). Form of logistic curve used to define juveniles in an experimental model for density-dependent natural mortality in the Georges Bank open area.

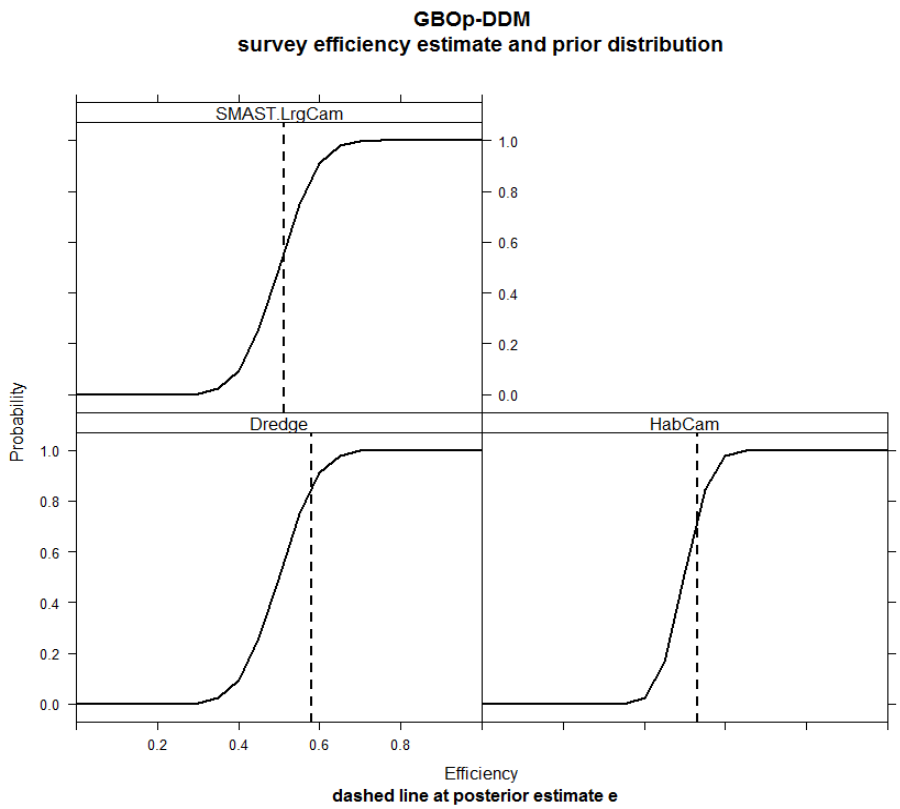


Figure B6.53. Output from experimental density-dependent natural mortality model for Georges Bank open. *Above*: Efficiency priors for three main surveys in an experimental model for density-dependent natural mortality in the Georges Bank open area.

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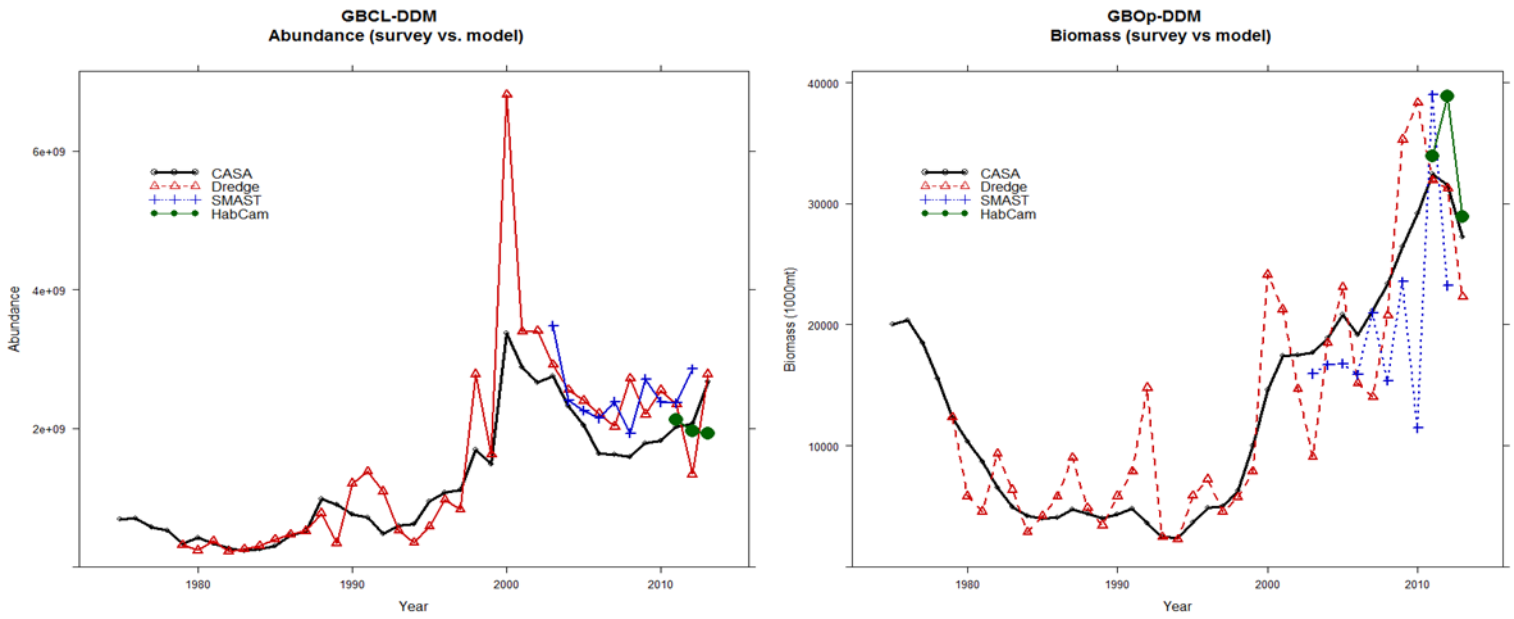


Figure B6.53. (continued). Model estimates of abundance (above) and biomass (below), together with survey stock size estimates from the dredge, SMAST and HabCam surveys in an experimental model for density-dependent natural mortality in the Georges Bank open area.

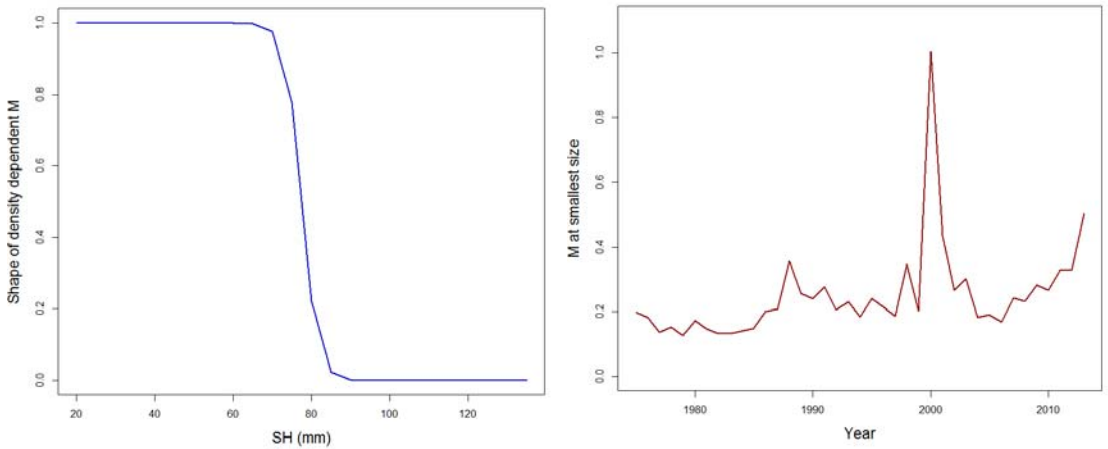


Figure B6.54. Output from experimental density-dependent natural mortality model for Georges Bank open. *Above:* Form of logistic curve used to define juveniles, and estimated natural mortality in the smallest size bin in an experimental model for density-dependent natural mortality in the Georges Bank closed area.

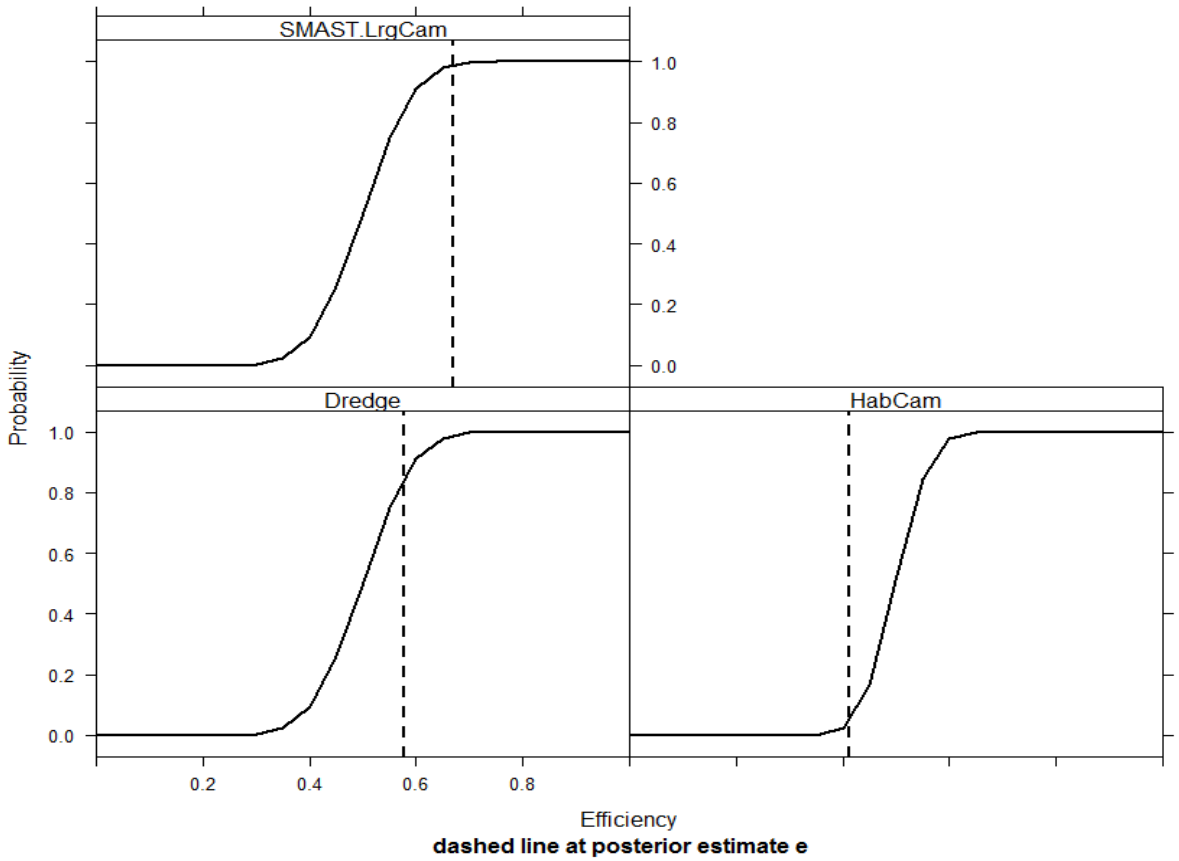


Figure B6.54. (continued). Efficiency priors for three main surveys in an experimental model for density-dependent natural mortality in the Georges Bank open area.

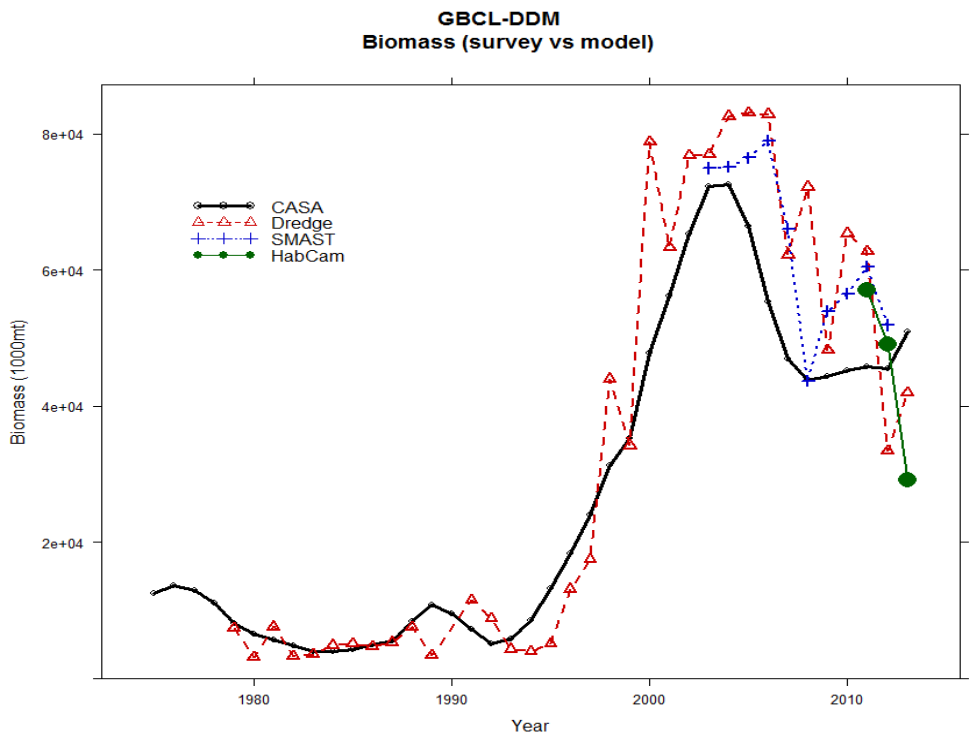


Figure B6.54. (continued). Model estimates of biomass, together with survey stock size estimates from the dredge, SMAST and HabCam surveys in an experimental model for density-dependent natural mortality in the Georges Bank open area.

B7. REFERENCE POINTS (TOR 5)

Per recruit reference points F_{MAX} and B_{MAX} were used as proxies for F_{MSY} and B_{MSY} in assessments prior to 2010 (SARC-50). F_{MAX} is the fishing mortality rate for fully recruited scallops that generates maximum yield-per-recruit. B_{MAX} was defined as the product of BPR_{MAX} (biomass per recruit at $F = F_{MAX}$ from yield-per-recruit analysis) and median numbers of recruits. As selectivity has shifted to larger scallops, yield per recruit curves have become increasingly flat, particularly in the Mid-Atlantic, making per-recruit reference points unstable. Additionally, recruitment has been stronger during the recent period when biomass has been high, suggesting that spawner-recruit relationships should be included. Finally, risk-based reference points are needed to calculate Acceptable Catch Levels/Allowable Biological Catch (ACLs/ABCs) and target fishing mortalities.

To address these issues, the SARC-50 assessment introduced a stochastic model (SYM – Stochastic Yield Model; Hart 2013) for calculating reference points and their uncertainty. It uses Monte-Carlo simulations to propagate the uncertainty in per recruit and stock-recruit calculations while calculating yield curves. B_{MSY} and F_{MSY} reference points are estimated at points where the (trimmed mean) yield curve peaks.

<u>Stochastic yield model</u>

The SYM model combines per-recruit calculations with stock-recruit relationships in order to estimate yield curves, as discussed in Beverton and Holt (1957) and Shepherd (1982). However, the SYM approach treats both the per-recruit and the stock-recruit relationships as being uncertain, and takes this uncertainty into account.

Although the SYM model is separate from CASA, efforts were made to make the two models as compatible as possible. Recruits are initially spread out over 10 size bins (20-70 mm). Growth was modelled using the same stochastic growth matrices used in the CASA model for the most recent period.

Per recruit calculations depend on a number of parameters that each carry a level of uncertainty:

1) Shell height/meat weight parameters a and b
2) Natural mortality rate M
3) Fishery selectivity parameters α and β
4) The cull size of the catch and the fraction of discards that survive
5) The level of incidental fishing mortality, i.e., non-catch mortality caused by fishing.

Details for each of these parameters are given below.

Shell height/meat weight relationships - Meat weight W at shell height H is calculated using:

$$W = \exp(a + b\ln(H))$$

The means, variances and covariance of parameters a and b were taken from Appendix B3. Similar to the growth parameters, the estimates of a and b have a strong negative correlation. This means that the predicted meat weight at a given shell height carries less uncertainty than it would appear from the variances of the individual parameters. Meat weights vary seasonally, with the greatest meat weights during the late spring and early summer (Appendix B3; Hennen and Hart 2012). However, Haynes (1966) constructed a number of monthly shell height/meat weight relationships, and did not find any significant trend in the slopes indicating that seasonality should not affect the F_{MAX} or F_{MSY} reference point. For this reason, seasonal variability was not considered a source of uncertainty for this analysis.

Natural mortality M - Natural mortality for sea scallops was estimated by Merrill and Posgay (1964) as

$$M = \frac{1}{S}\frac{C}{L} \qquad (1)$$

where L is the number of live scallops, S is the mean clapper separation time and C is the number of clappers. Probably the greatest uncertainty in this calculation is the mean separation time S. For example, Dickie (1955) estimated S to be 100 days (14.3 weeks), less than half that estimated by Merrill and Posgay (33 weeks). Reflecting this uncertainty, it was assumed S was distributed as a gamma random variable, with mean set to match the assumed mean natural mortality for each region (S=20.625 weeks on Georges Bank and 16.5 weeks in the Mid-Atlantic) and standard deviation 12 weeks. The resulting distribution of M has the desirable characteristic of being skewed to the right. The skew is reasonable because, for example, a natural mortality of $M = 0.3$ is possible, but an $M = 0$, or even close to zero, is not. Note that because S appears in the denominator of the formula above, the expected value of M is not equal to applying equation (1) with the mean value of S.

Fishery selectivity - Fishery selectivity s was estimated using an ascending logistic curve of the form:

$$s = \frac{1}{1+\exp(\alpha - \beta H)}$$

where H is shell height. The means and covariances of the α and β parameters were taken as estimated by the CASA stock assessment model during the most recent selectivity period. For Georges Bank, we used the open area selectivity in the most recent period, since reference points are calculated under the assumption that all areas are fished. Note that fishery selectivity reflects targeting and discarding as well as gear selectivity.

Cull size and discard mortality - Sea scallops that are caught but are less than 90 mm are assumed to be discarded, based on observer data. Sea scallops likely tolerate discarding fairly well, provided they are returned to the water relatively promptly and they are not damaged by the capture process or their time on deck. Here, discard mortality was simulated as a gamma distribution, with a mean of 0.2 and a standard deviation of 0.15, reflecting the high uncertainty in this parameter. This feature is also included in the SAMS projection model but not in the CASA model.

Incidental fishing mortality - Incidental fishing mortality occurs when scallops are killed but not captured by the gear. Consistent with the assumptions of the CASA model, incidental mortality F_I was estimated as 0.2 on Georges Bank and 0.1 in the Mid-Atlantic for the smallest size group. Because of the considerable uncertainty in these numbers, incidental mortality was simulated here with a gamma distribution with these means and coefficients of variation of 0.75.

Stock-recruit relationships - Beverton-Holt stock-recruit curves were fitted to spawning stock and recruitment estimates from basecase CASA model runs:

$$R = \frac{sB}{\gamma + B},$$

assuming square-root-normal errors (Figure B7.1). Here R is recruitment, B is spawning stock biomass (or egg production), and s and γ are parameters, representing the asymptotic recruitment when B is large, and the spawning stock biomass where the expected recruitment is half its asymptotic value, respectively. Standard errors of the stock-recruit parameters and their correlation were estimated using the delta method.

<u>Calculation of equilibrium yield per recruit and yield</u>

At each iteration of the simulation model, parameter values were drawn from their corresponding distribution and per recruit and yield curves were calculated. This was repeated $n = 100{,}000$ times and the results of each iteration were stored. The stock-recruit parameters were simulated as correlated square-root normals (chi-squared with 1 df).

For each run, equilibrium recruitment at fishing mortality F is given by

$$R = s - \gamma/b(F)$$

where b is biomass per recruit. Total yield is therefore

$$Y(F) = y(F)R = y(F)[(s - \gamma)/b(F)]$$

where y is yield per recruit.

Although simulation results in this assessment were stable, mean yield curves calculated by this method can be disproportionately influenced by outliers (Hart 2013). For this reason, a 10% trimmed mean was used to obtain the central tendency of per recruit and yield curves as a function of fishing mortality. The probabilistic F_{MSY} (and F_{MAX}) were taken as the fishing mortality that maximizes the trimmed mean yield curve (yield per recruit curve). The probabilistic MSY and B_{MSY} are the trimmed mean yield and biomass at F_{MSY} over all runs.

Results

Stock-recruit curves were better defined on Georges Bank than in the Mid-Atlantic (Figure B7.1). While Y_{MAX} and B_{MAX} values were generally well defined, F_{MAX} was highly uncertain in both regions, and hit the $F = 1$ bound in a majority of the simulations in the Mid-Atlantic (Figures B7.2 to B7.4). MSY based reference points were better defined, as potential stock-recruit relationships tend to reduce F_{MSY} to well below F_{MAX} (Figures B7.5 and B7.7).

MSY estimates for the combined Georges Bank and Mid-Atlantic areas range from 10,000 mt to 40,000 mt meats, and B_{MSY} between about 40,000 to 150,000 mt (Figures B7.8 to B7.10). F_{MSY} values for the combined stock are highly uncertain.

Trimmed mean yield curves have a maximum at $F_{MSY} = 0.3$ on Georges Bank, and $F_{MSY} = 0.74$ in the Mid-Atlantic, with corresponding MSY values of 9,148 and 15,737 mt meats, respectively (Table B7.1, Figure B7.11). Trimmed mean estimates for the combined stock are F = 0.48, MSY =23,798 mt, and B_{MSY} = 96,480 mt. The entire distribution of yield for the combined stock is shown in Figure B7-12).

Special considerations for sedentary resources under area management

The above reference point calculations are based on the assumption that fishing mortality risk does not vary among individuals. For sedentary organisms such as sea scallops, these assumptions are never even approximately true. With closed and rotational area management, the assumption of uniform fishing mortality is strongly violated (Hart 2001, 2003; Smith and Rago 2004). In such situations, mean yield-per-recruit, averaged over all recruits, may be different than yield-per-recruit obtained by a conventional per-recruit calculation performed on a recruit that suffers the mean fishing mortality risk (Hart 2001). In these types of situations, estimates of fishing mortality may be biased low, because individuals with low mortality risk are overrepresented in the population (Hart 2001, 2003).

Reference point	**SARC-50**	**SARC-59**
F_{MSY}	0.38	0.48
B_{TARGET}=B_{MSY} (mt, meats)	125,358	96,480
$B_{THRESHOLD}$=1/2 B_{MSY} (mt, meats)	62,679	48,240
MSY (mt, meats)	24,975	23,798

Table B7-1. Previous (SARC-50) and revised (SARC-59) reference points for sea scallops.

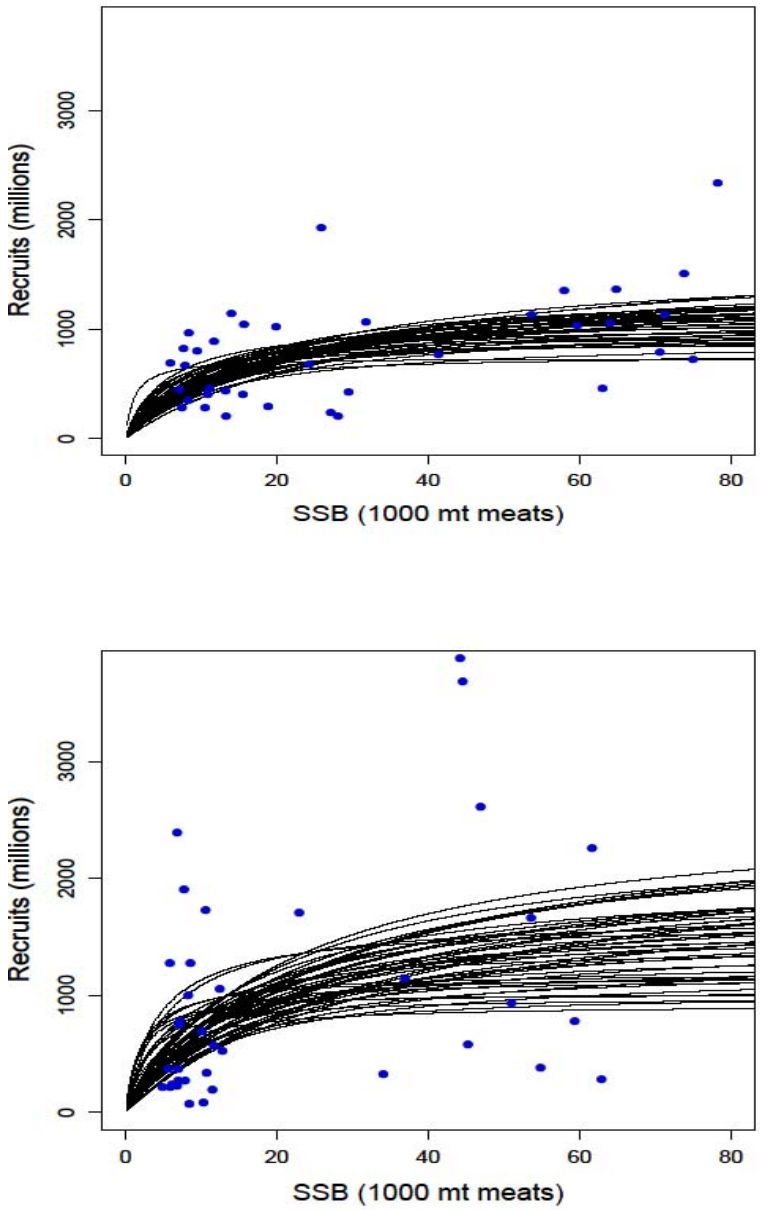


Figure B7.1 Stock-recruit relationships for Georges Bank (top) and the Mid-Atlantic (bottom) showing spawner-recruit estimates from the CASA model (blue dots) and 50 example fitted Beverton-Holt curves.

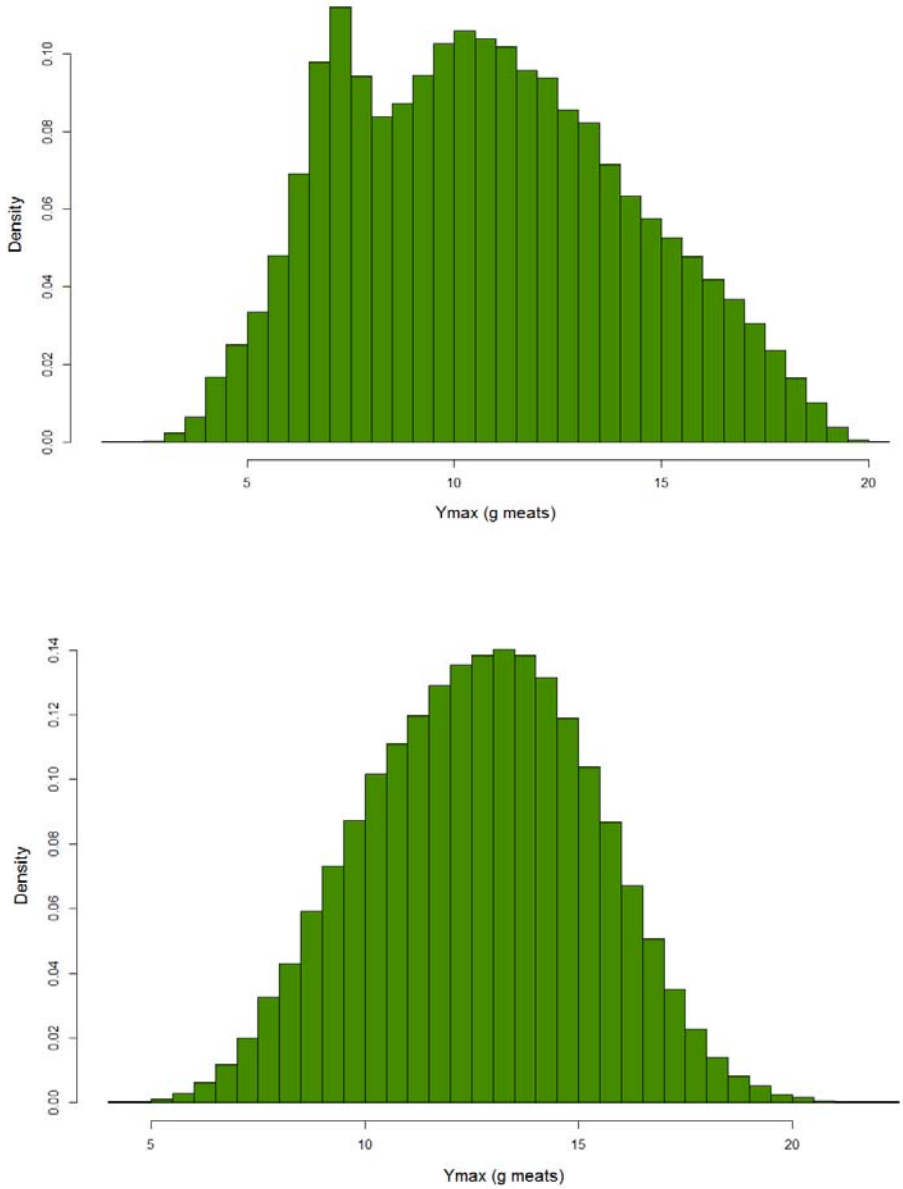


Figure B7.2. Probability distributions for maximum yield per recruit Y_{max} in the Georges Bank (top) and Mid-Atlantic (bottom) regions.

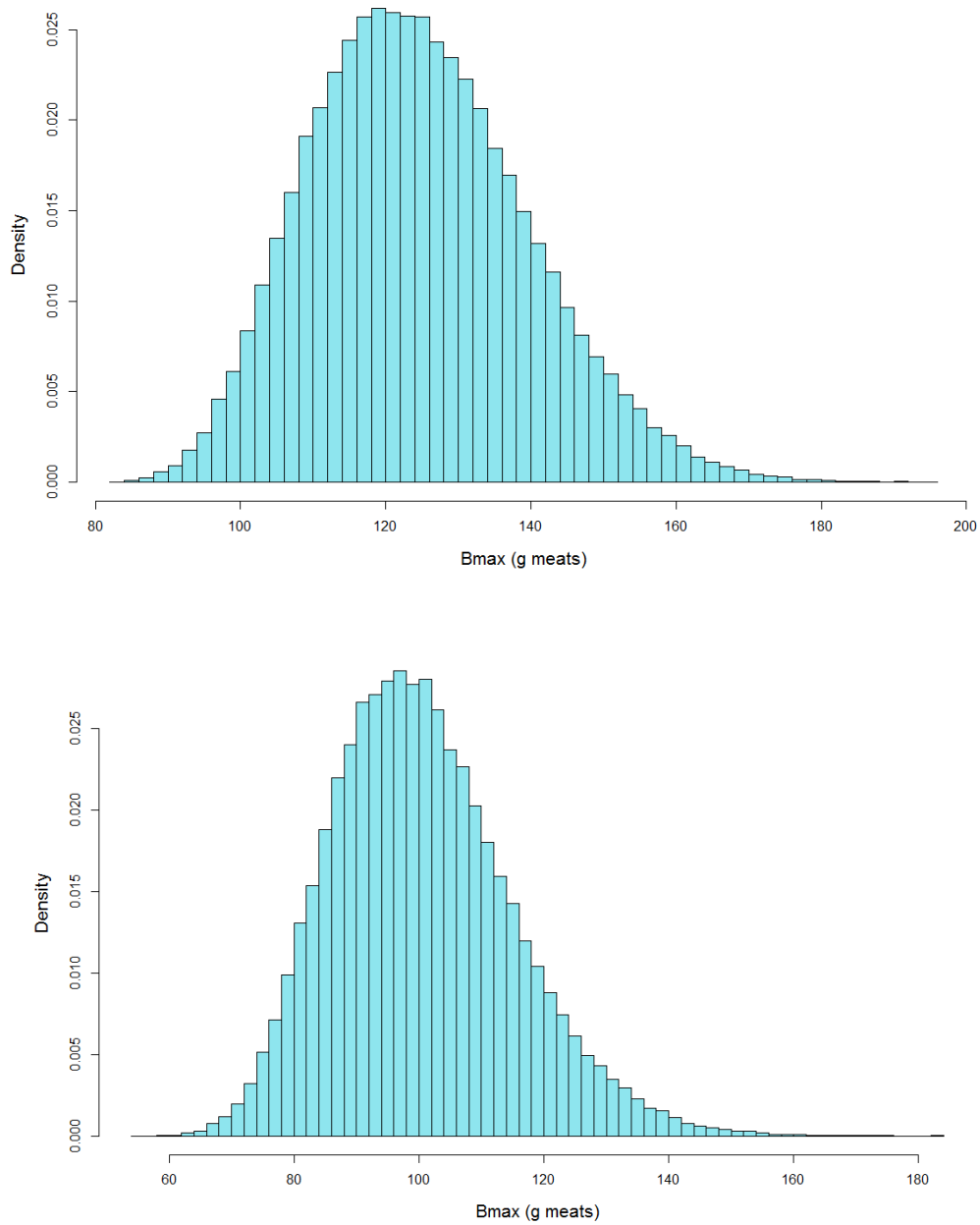


Figure B7.3. Probability distributions for biomass per recruit at B_{max} in the Georges Bank (top) and the Mid-Atlantic (bottom) regions.

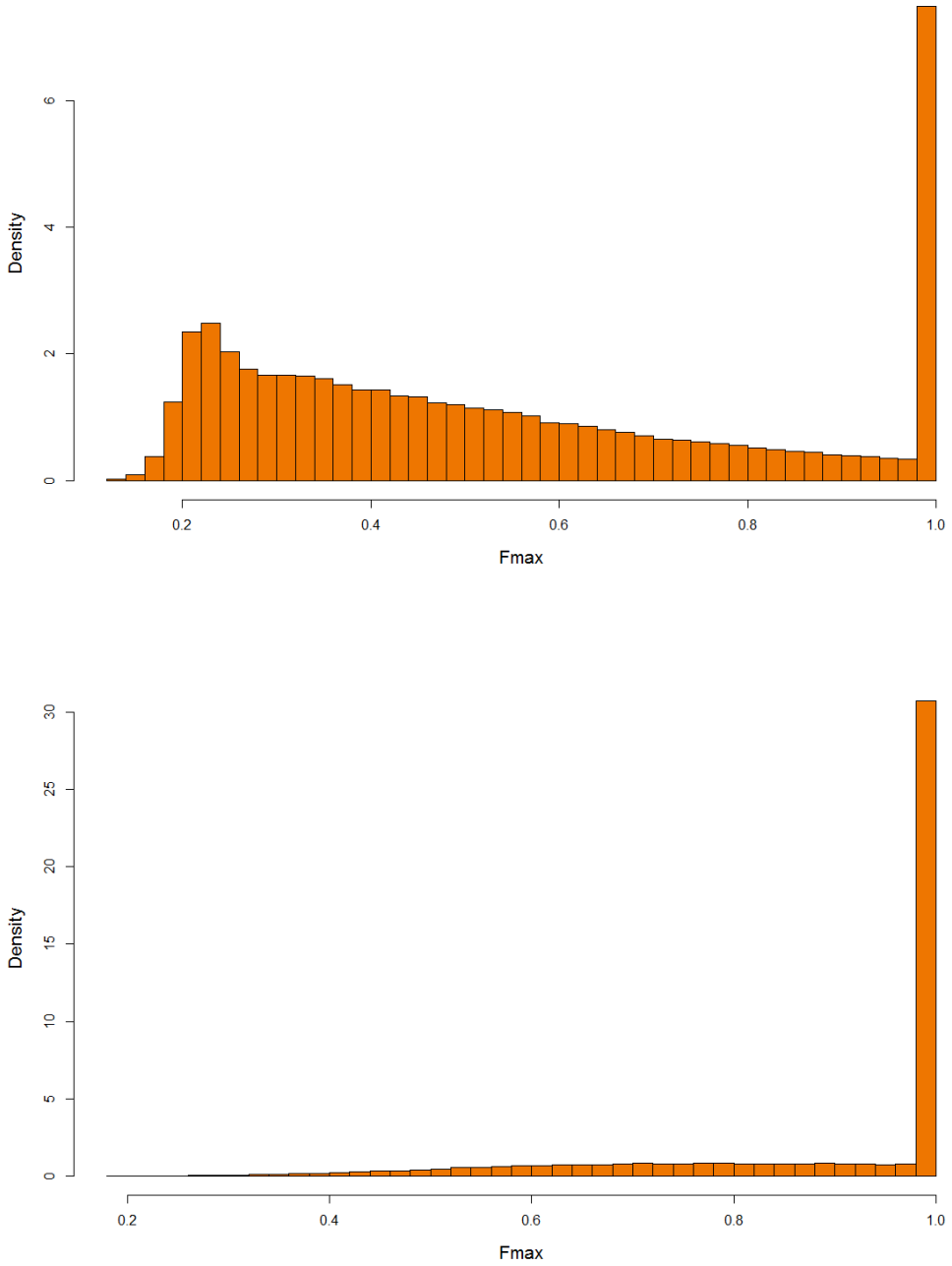
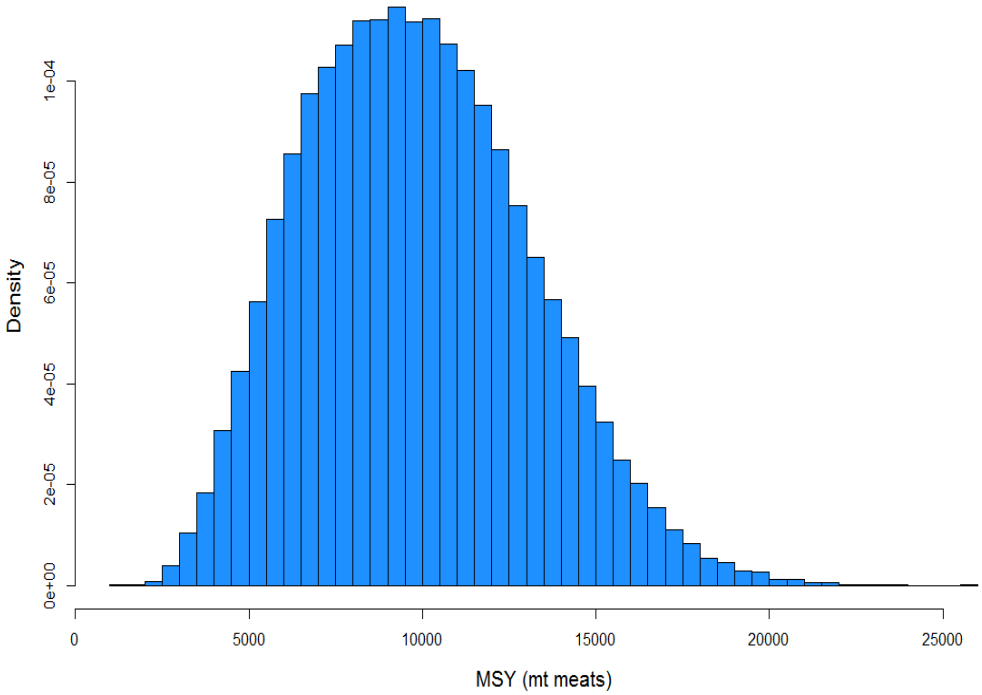


Figure B7.4. Probability distributions for the fishing mortality that gives maximum yield per recruit (F_{max}) in the Georges Bank (top) and Mid-Atlantic Bight (bottom) regions.



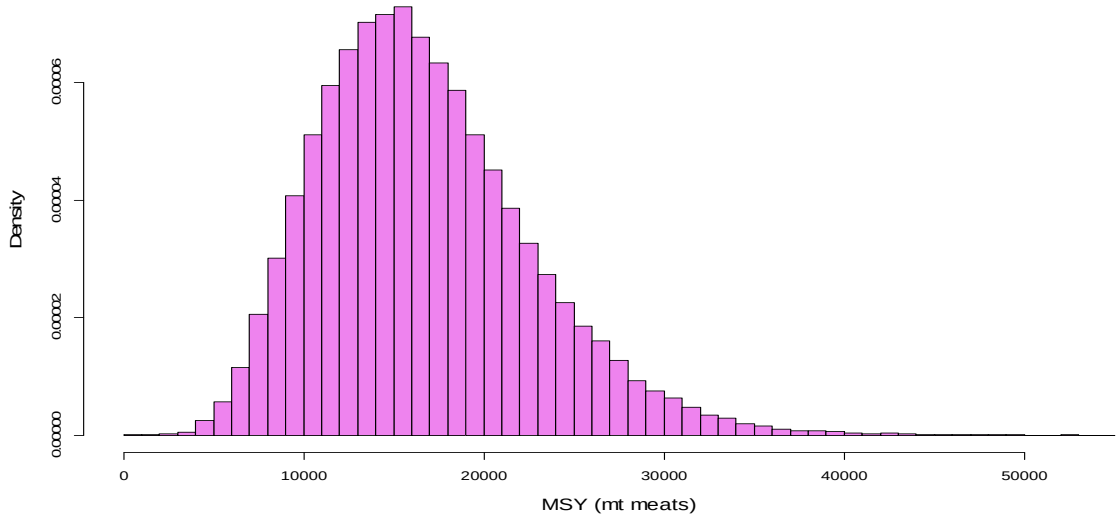
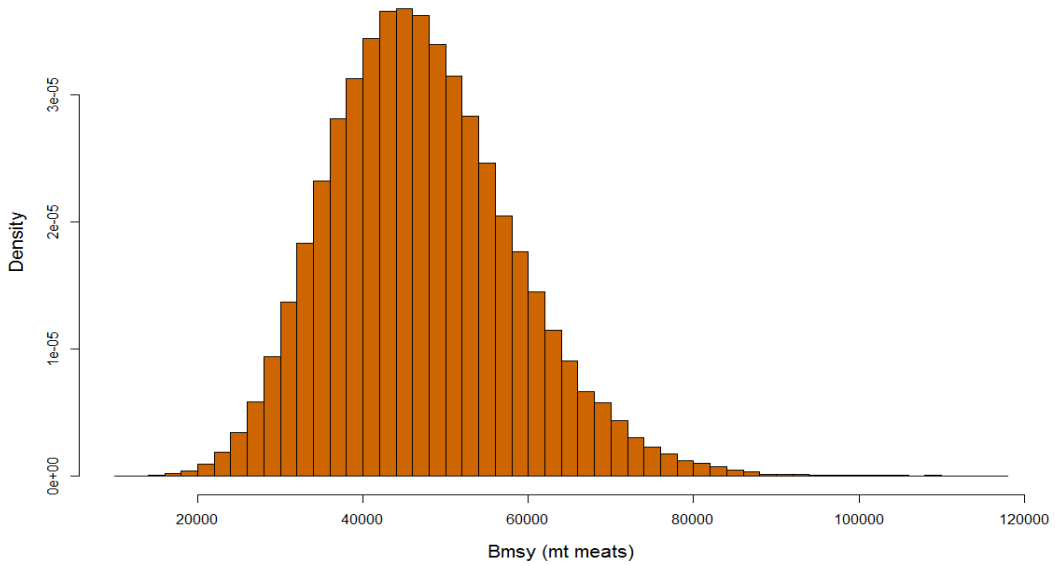


Figure B7.5. Probability distributions for MSY in the Georges Bank (top) and Mid-Atlantic (bottom) regions.



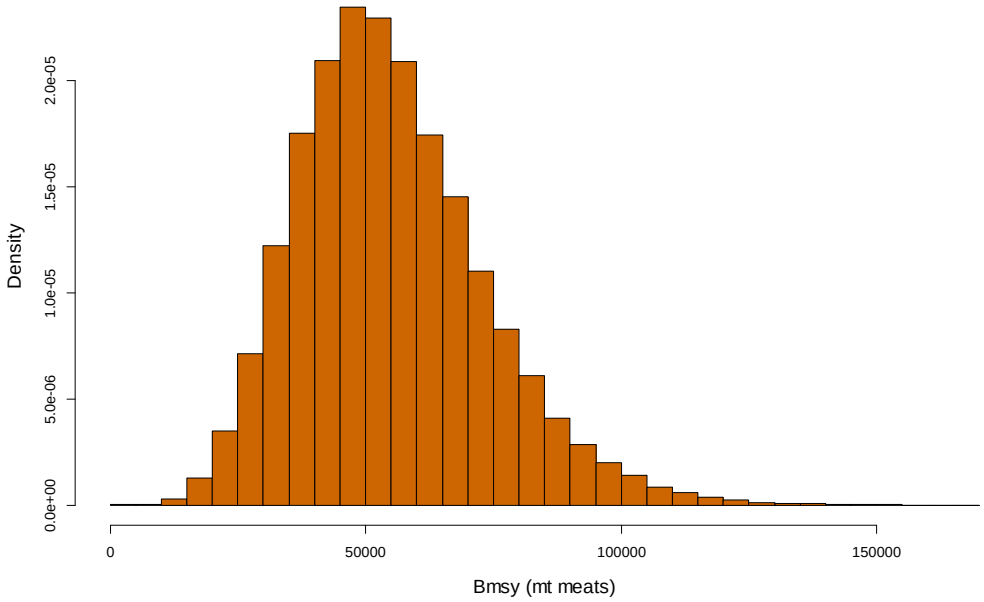


Figure B7.6. Probability distributions for B_{MSY} in the Georges Bank (top) and Mid-Atlantic (bottom) regions.

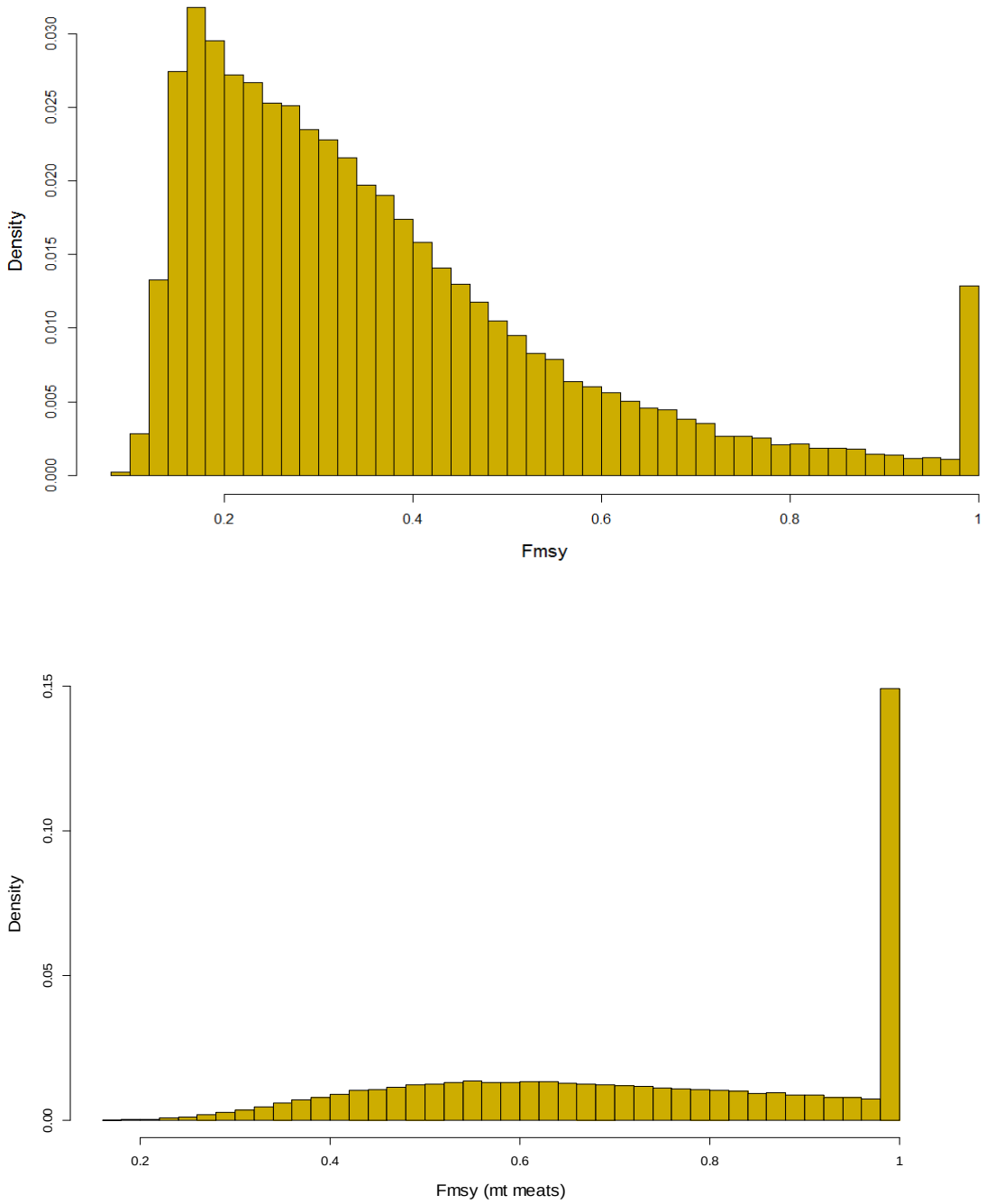


Figure B7.7 Probability distributions for F_{msy} in the Georges Bank (top) and Mid-Atlantic (bottom) regions.

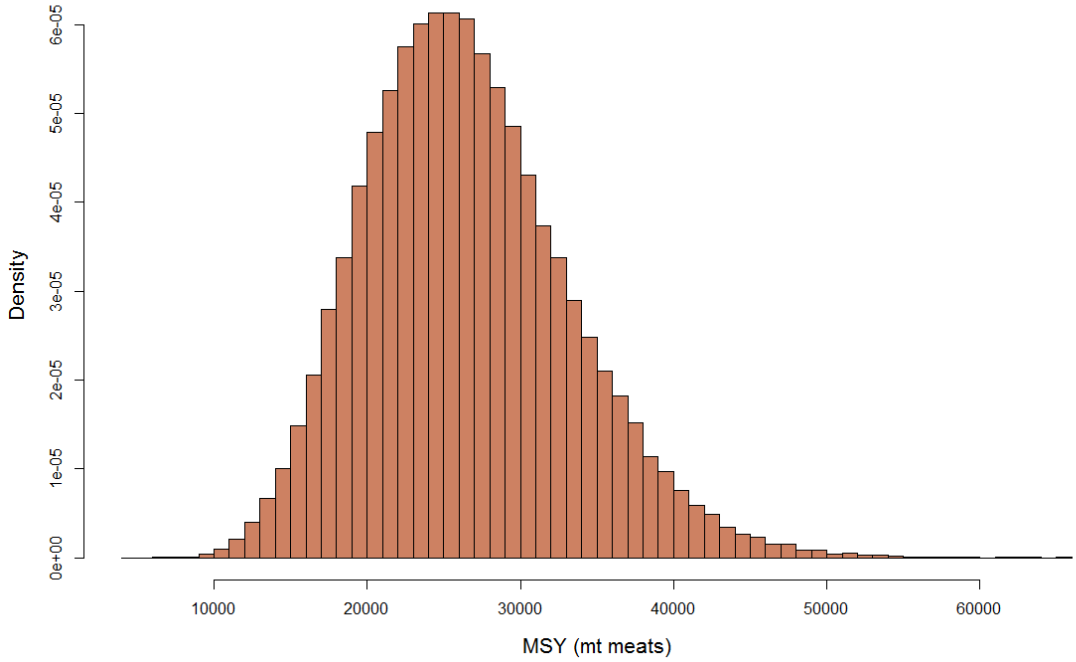


Figure B7.8. Probability distribution for MSY in the combined Georges Bank and Mid-Atlantic region.

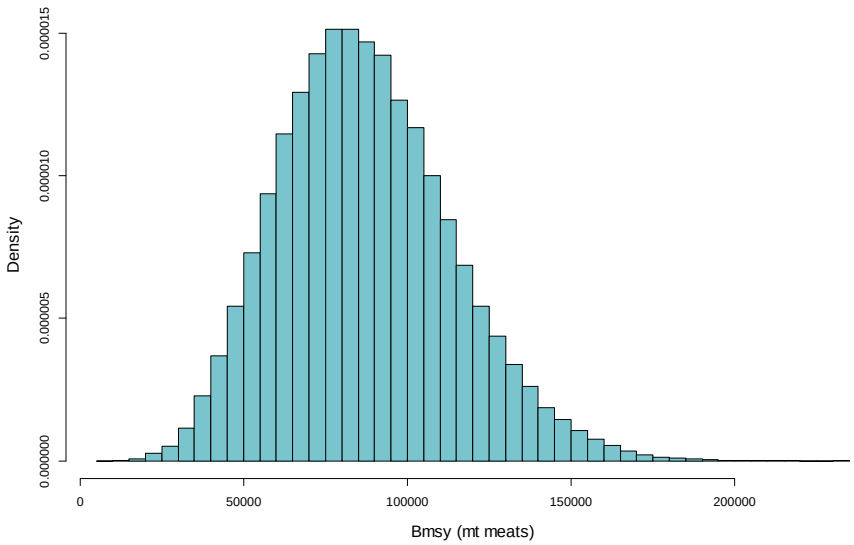


Figure B7.9. Probability distribution for B_{MSY} in the combined Georges Bank and the Mid-Atlantic region.

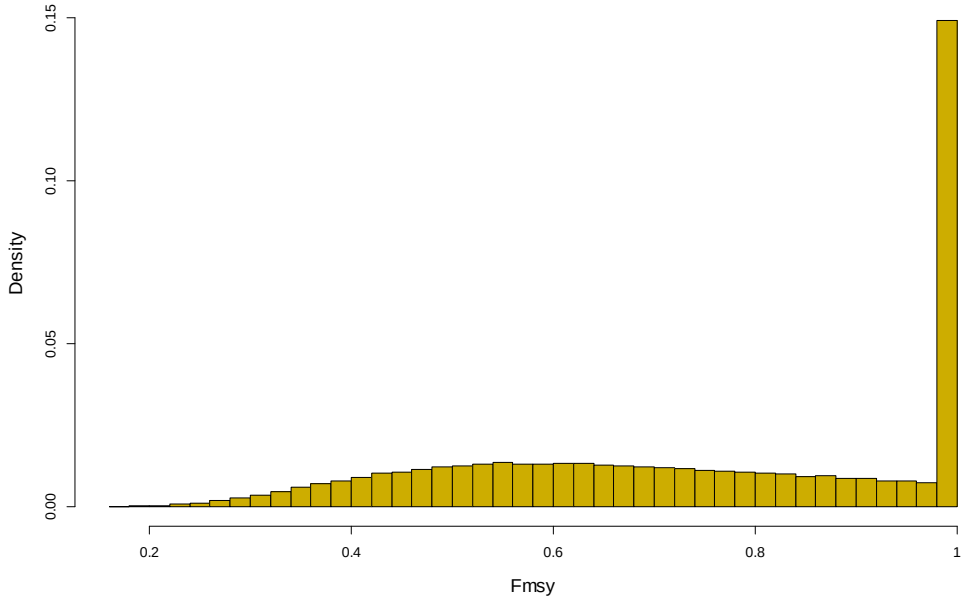


Figure B7.10. Probability distribution for F_{MSY} in the combined Georges Bank and the Mid-Atlantic region.

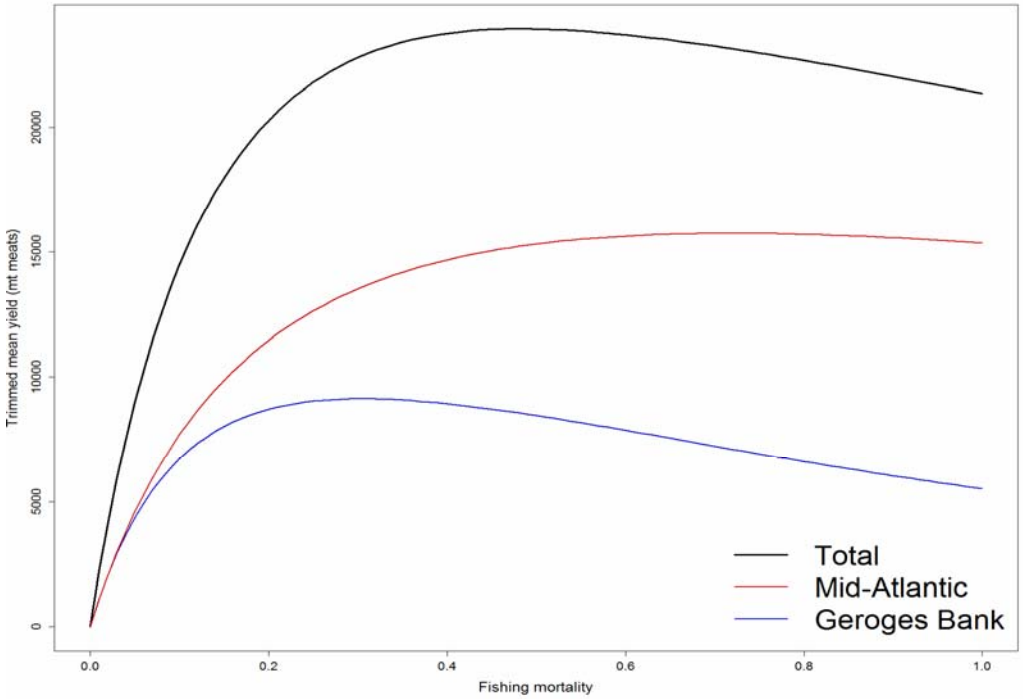


Figure B7.11. Trimmed mean yield as a function of fishing mortality for Georges Bank, the Mid-Atlantic, and combined areas.

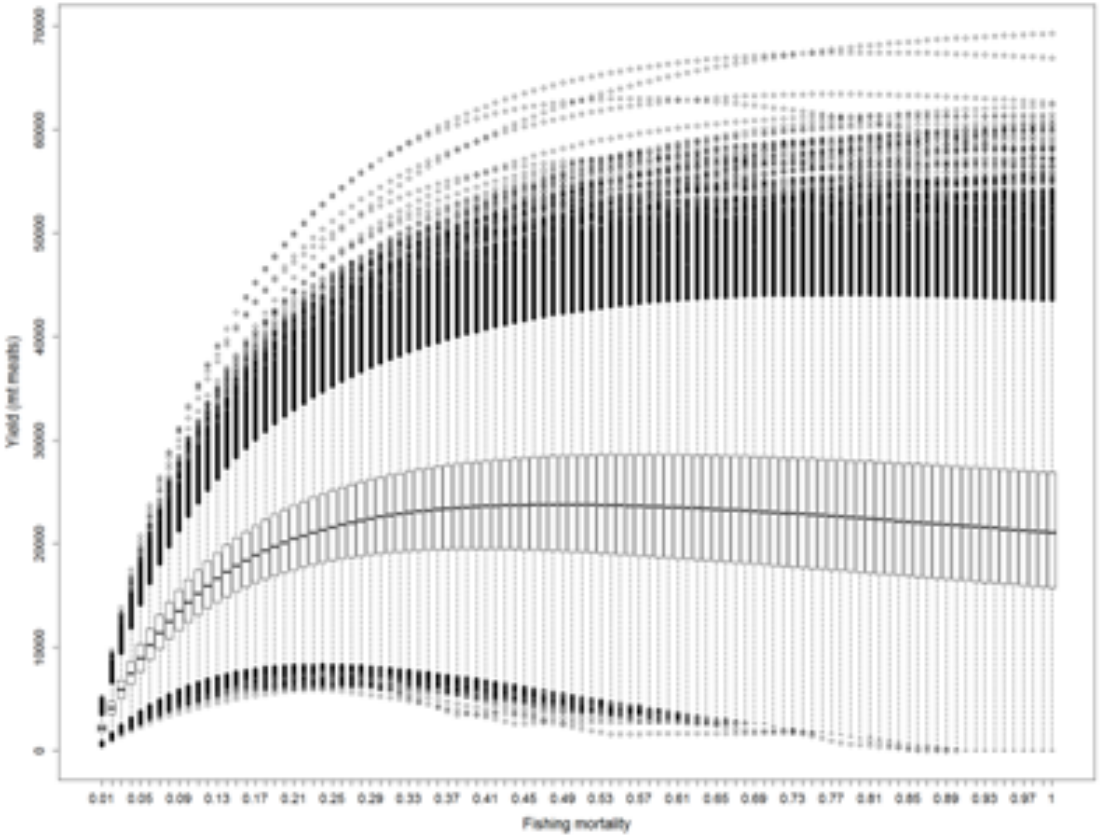


Figure B7.12. Boxplots for yield in the combined Georges Bank and Mid-Atlantic region as a function of fishing mortality.

B8 - Status Determination (TOR 6)

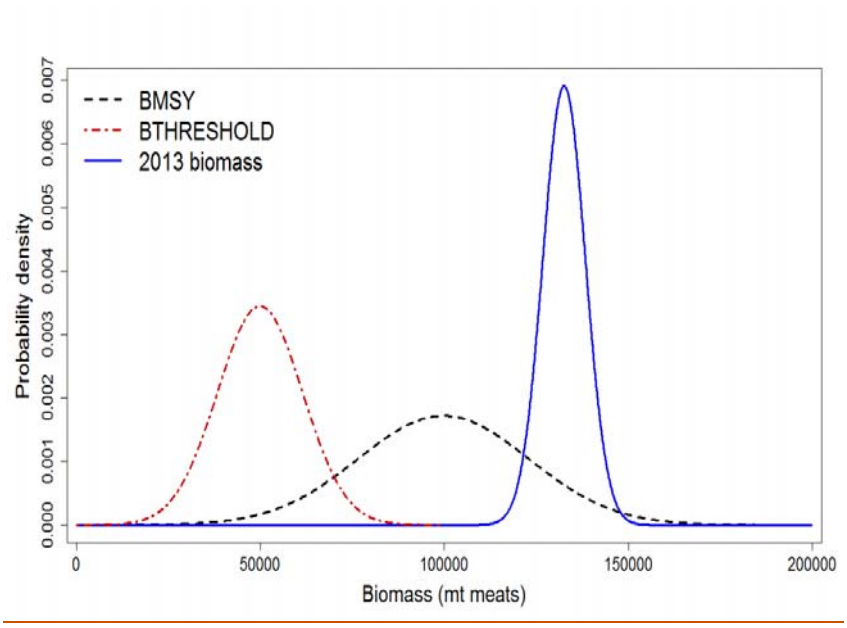
According to the Amendment 10 overfishing definition (NEFMC 2003), sea scallops are overfished when the survey biomass index for the whole stock falls below 1/2 B_{TARGET}, with B_{TARGET} set equal to B_{MSY} or its proxy (see table below). The current $B_{THRESHOLD}$ is 62,679 mt (NEFSC 2010) and the recommended value in this assessment is 48,240 mt. The estimated combined stock biomass in 2013 was 132,561 mt, which is above both $B_{THRESHOLD}$ reference point values. Thus, the stock is not overfished based on either criterion.

None of the 100,000 simulations done for the SYM model estimated a B_{MSY} that was greater than twice the CASA estimated 2013 biomass. The standard error in the 2013 CASA biomass was estimated at 5772 mt, which is likely underestimates the uncertainty. However, given that both surveys estimated biomasses over 110,000 mt in 2013, it is highly likely that the actual biomass in 2013 was above 100,000 mt. Because less than 1% of the SYM runs estimated a B_{MSY} greater than 200,000 mt, it can be concluded that the chances that the stock is overfished is very small, probably less than 1% (Figure B8.1).

The current F_{MSY} = 0.38 (NEFSC 2010) and the recommended F_{MSY} in this assessment is 0.48. The estimated fishing mortality for the whole stock in 2013 was 0.32, which is below both F_{MSY} reference points. Therefore, overfishing was not occurring in 2013 based on either criterion.

Based on SYM model results, there is about a 12% chance that F_{MSY} is below 0.32. The standard error for fishing mortality in 2013 was 0.03 from the CASA model. Combining these results indicate that the probability of overfishing in 2013 was about 13% (Figure B8.1). This probability of overfishing is likely understated because CASA is probably underestimating uncertainty.

Type	2013 stock estimate	Reference point	NEFSC (2010)		Recommended this assessment	
			BRP	Overfished, overfishing?	BRP	Overfished, overfishing?
Biomass (mt)	132,561	$B_{target}=B_{MSY}$ $B_{Threshold}=B_{Target}/2$	125,358 62,679	No	96,480 48,240	No
Fishing mortality	0.32	F_{MSY}	0.38	No	0.48	No



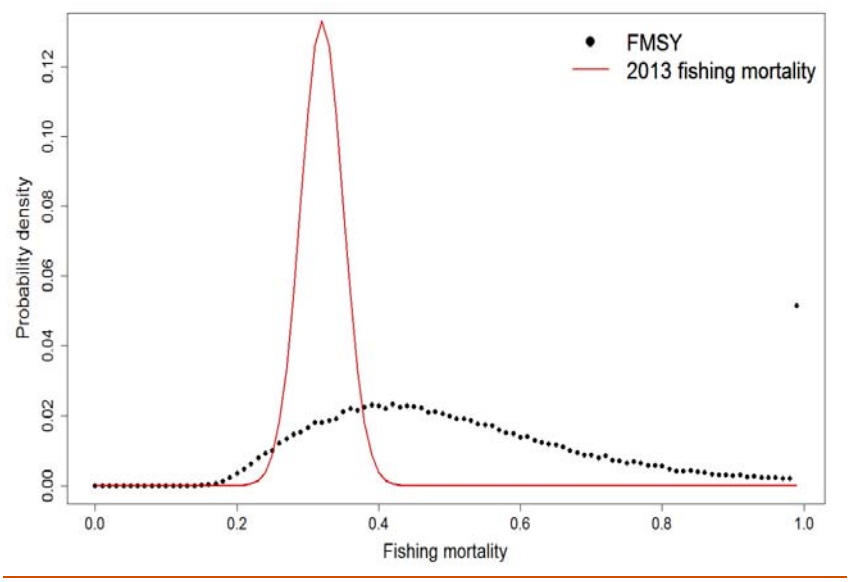


Figure B8.1. *Top*: Probability distributions for B_{MSY}, $B_{THRSHOLD}$ and 2013 biomass. *Bottom*: Probability distributions of F_{MSY} and 2013 fishing mortality.

B9 STOCK PROJECTIONS (TOR 7)

Because of the sedentary nature of sea scallops, fishing mortality can vary considerably in space even in the absence of area specific management (Hart 2001). Rotational management and long-term closures exacerbate this heterogeneity. Projections that ignore spatial variation can be unrealistic and misleading. For example, suppose 80% of the stock biomass is in areas closed to fishing (as occurred in some years in Georges Bank). A stock projection that ignored the closure and assumed an overall *F* of 0.2 would forecast landings nearly equal to the entire stock biomass in the areas open to fishing. Thus, using a non-spatial forecasting model could lead to unsustainable harvest levels under area management. For these reasons, a spatial forecasting model (the Scallop Area Management Simulator, SAMS) was developed for use in sea scallop management (Appendix B10). Various versions of SAMS have been used since 1999.

Growth is modeled in SAMS and CASA in a similar manner, except that each subarea of Georges Bank and the Mid-Atlantic in SAMS has its own stochastic growth transition matrix derived from the shell increments collected in that area. Mortality and recruitment are also area-specific. Fishing mortality can either be explicitly specified in each area, or calculated using a simple fleet dynamics model that assumes fishing effort is proportional to estimated LPUE.

Projected recruitment is modeled stochastically with the log-transformed mean and covariance for recruitment in each area matching that observed in NEFSC dredge survey time series. In the example projection shown here, initial conditions are based on regional shell height data from the 2013 dredge surveys, with mean regional biomass (Georges Bank open and closed, and Mid-Atlantic) set to match CASA estimates for 2013. Initial values in each subarea are varied according to specified uncertainties. Natural mortality for each run is selected from the same distributions used in the SYM reference point model. Further details regarding the SAMS model are given in Appendix B10.

One set of example runs are used in this assessment to demonstrate of the utility of the SAMS model. Projections used to manage the fishery are carried out by the Scallop Plan Development Team while evaluating potential management measures. For example, SAMS runs for management in 2015-2016 will be updated with 2014 survey data in the fall of 2014 after this assessment is complete.

Example SAMS runs

For the example simulations, the stock area was split into 16 subareas (Figure B3-1), seven in the Mid-Atlantic (Virginia Beach, Delmarva, Elephant Trunk, Hudson Canyon South, New York Bight, Long Island, and New York Bight inshore) and ten on Georges Bank (Closed Area I, II and Nantucket Lightship EFH closures, Closed Area I, II and Nantucket Lightship access areas, Great South Channel proposed closure and the remainder of the Great South Channel, Northern Edge and Peak, and Southeast Part).

The EFH (Essential Fish Habitat) closures on Georges Bank were assumed to be closed for the duration of the simulations. The Georges Bank access areas were assumed to be fished on a rotating basis corresponding to actual management in 2013-2014, and probable management in

2015 (Closed Area I is fished in 2013, 2016, 2017, Closed Area II in 2013, 2014, 2016 and 2017, Nantucket Lightship in 2013, 2014, 2016, and 2017). The Hudson Canyon South rotational closure area was assumed to be fished in 2013, closed in 2014-2015, and fished 2016-2017. The Elephant Trunk rotational area was assumed closed in 2013-2014, and fished in 2015-2017. Delmarva was closed in 2013 and fished in 2014-2017. All other areas (Virginia Beach, New York Bight, Long Island, South Channel, Northern Edge and Peak, Southeast Part) were part of the open areas, where scallop fishermen may chose where to fish, subject to a day at sea limit. These days at sea limits were set at 33 days in 2013, 31 days in 2014, and the number of days that will result in an open area $F=F_{MSY}$ = 0.48 in 2015-2017. The effort distribution in the open areas was assumed proportional to projected catch rates.

A total of n=1000 projection runs were performed in this example with stochastic initial conditions, recruitment, and natural mortality. Example result indicate that projected mean biomass in both regions would increase modestly from 2013-2016 (Figure B9.1). Fishing mortality is projected to increase in the Mid-Atlantic, primarily due to reopening of the Elephant Trunk and Hudson Canyon South rotational areas. Fishing mortality is expected to be fairly steady and low on Georges Bank. Landings are expected to rise from about 17,000 mt in 2014 to 23,000 mt in 2017, due to reopening rotational areas. While there is some uncertainty in projected biomass, fishing mortality and landings (Figure B9.2), the example projections indicate almost no chance of either overfishing or the stock becoming overfished in the near future under the assumed management conditions. Results from the SAMS model include projected biomass for each management area as well as for the Georges Bank and Mid-Atlantic and combined areas (Figure B9.3).

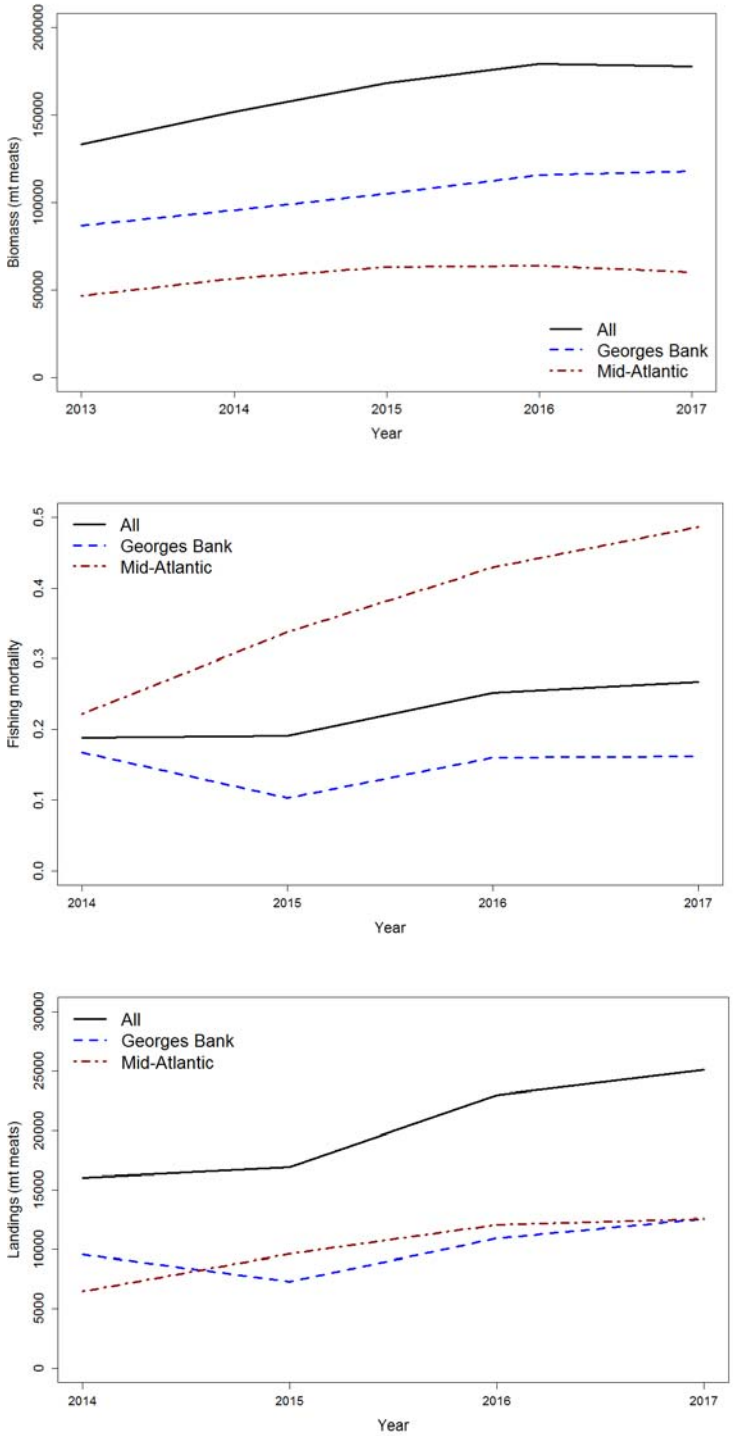


Figure B9.1. Mean projected biomass (top), fishing mortality (middle), and landings (bottom) for sea scallops in the Georges Bank, Mid-Atlantic and combined regions based on an example projection analysis with the SAMS model.

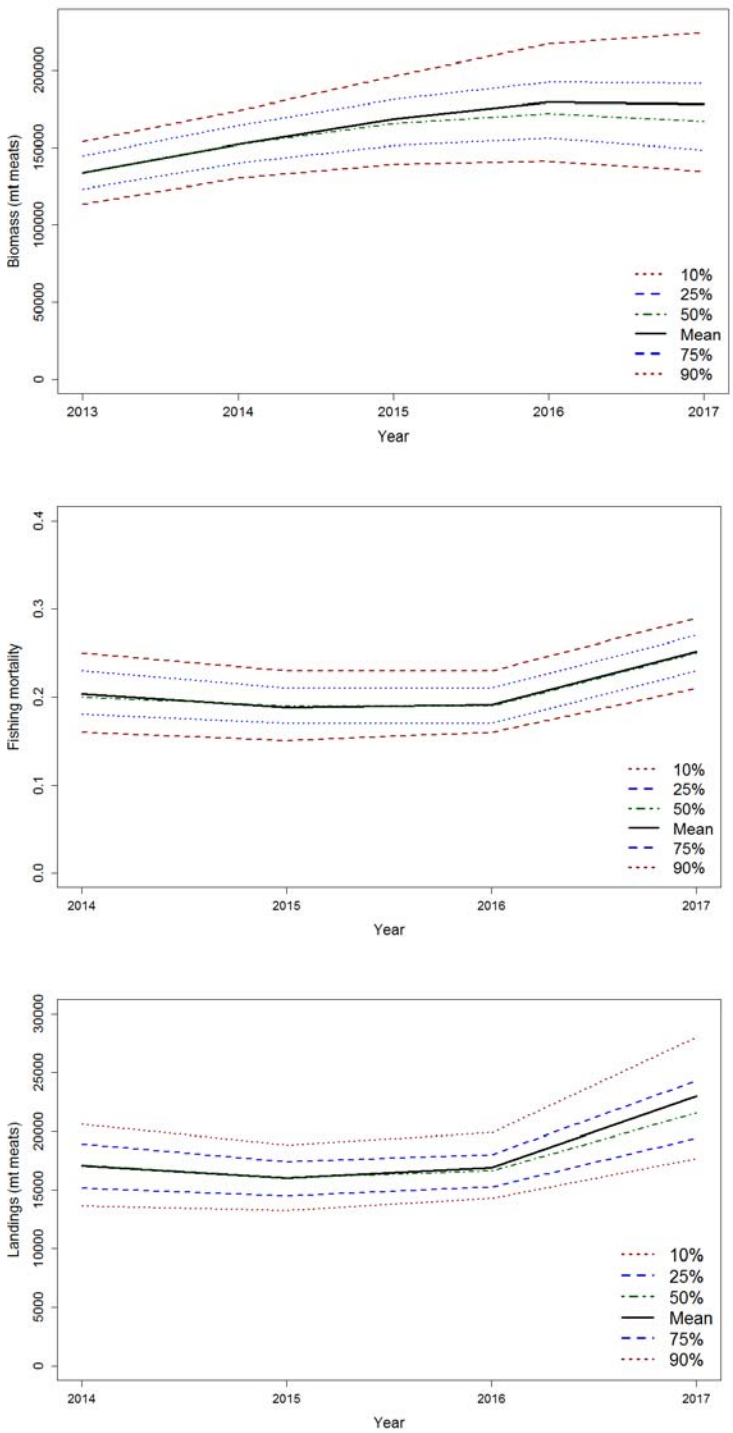


Figure B9.2. Mean and 10th, 25th, 50th, 75th, and 90th percentiles of projected total biomass (top), fishing mortality (middle) and landings (bottom).

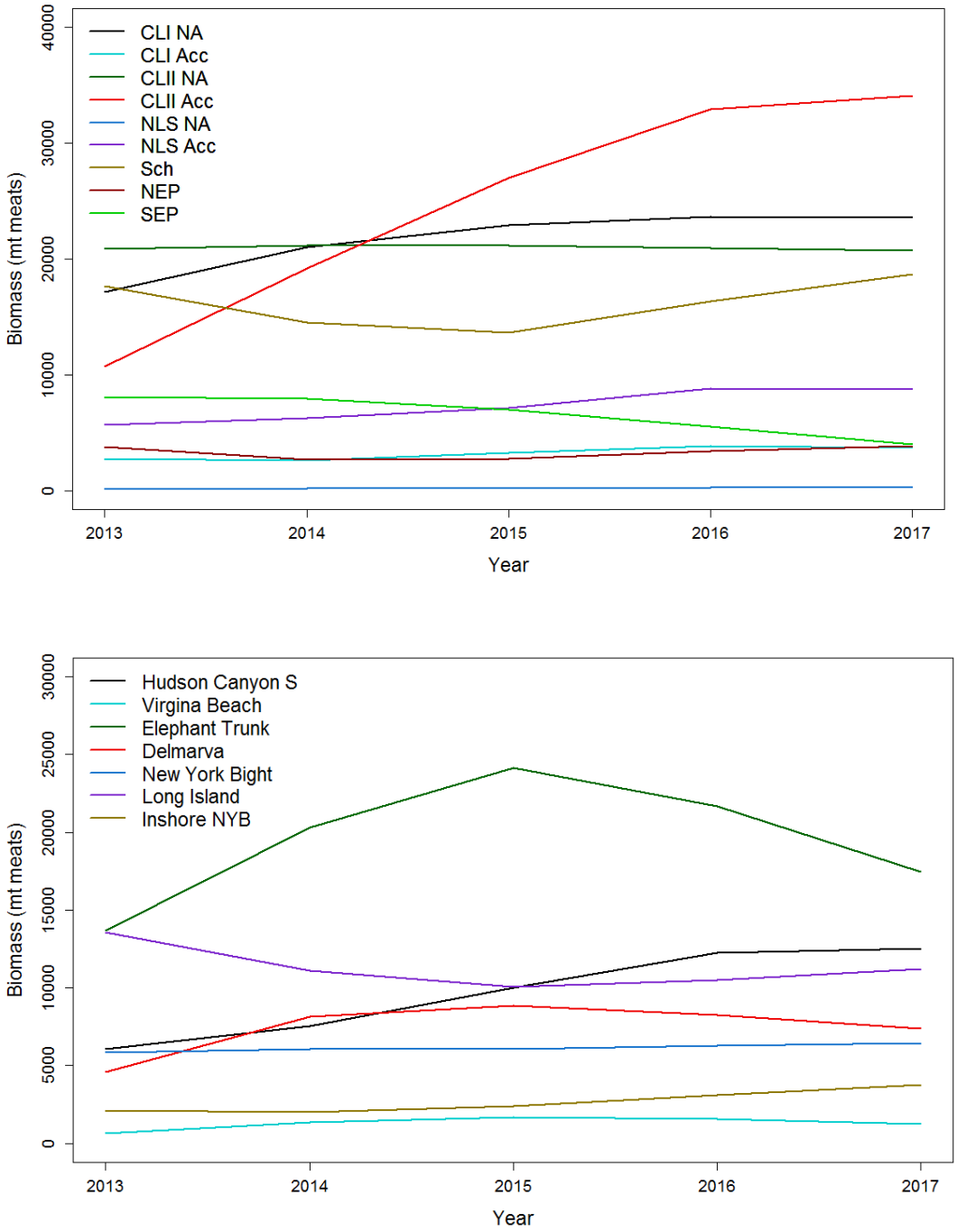


Figure B9.3 Mean projected biomass by subarea in the Georges Bank (top) and Mid-Atlantic (bottom) regions.

B10 – ENVIRONMENTAL EFFECTS ON RECRUITMENT (TOR 3)

Two potential environmental drivers of recruitment were explored: food supply (phytoplankton), and the abundance of a major predator of small scallops, the sea star *Astropecten americanus*. A tentative relationship was found between chlorophyll and scallop recruitment in the Mid-Atlantic Bight. Negative relationships were found between the spatio-temporal abundance of *A. americanus* and scallop recruitment. Both these topics are discussed in Appendix B8.

B11 - RESEARCH RECOMMENDATIONS (TOR 8)

Progress on recommendations from SARC-50 (NEFSC 2010)

1. Look into a way to fit discarded scallops, which have a different length frequency from the rest of the population, into the model. *No progress.*
2. Evaluate the effect of the four-inch rings on incidental mortality. Now that a larger fraction of small scallops are traveling through the mesh, has incidental mortality increased or are the scallops relatively unscathed? *Incidental mortality calculations were improved for this assessment to account for fishery selectivity. Several field projects were funded in 2014 to investigate the extent of incidental mortality from the currently configured fishing gear.*
3. Consider finding a better way to express the variation in the HabCam abundance data (the data were kriged for this assessment, and the variance was calculated by summing the variance of each of the kriged grids). *Two-stage GAM/Kriging models and stratified mean methods were introduced in this assessment, and several methods for calculating variance were investigated and compared in this assessment by simulation and analysis of actual data.*
4. Look at the historical patterns of the "whole stock"; how the spatial patterns of scallops and the fishery have changed over time. *These topics are handled in the description of survey and fishery data to the extent they are relevant.*
5. Estimate incidental mortality by running HabCam or an AUV along dredge tracks. *Several projects were funded this year to do work along these lines.*
6. Effort should be made to make sure the survey dredge is fitted with a camera at some point during the survey to record the movements of the dredge. This will help answer some questions about when the dredge starts and stops fishing, and the determination of tow times. *Five survey dredge tows were conducted with a camera mounted to the dredge that allowed improved interpretation of dredge sensor data.*
7. Seasonal patterns in scallop shell growth need to be analyzed and this data incorporated into the model. *No progress; the assessment team did not feel this is a high priority.*
8. Stock-recruit relationships should be calculated for various sub-sections of the stock, smaller areas than just MAB and GBK to look for possible patterns or relationships.
Appendix B8 examined the relationship between recruitment in the southern Mid-Atlantic and biomass in the entire stock.
9. Further refine the estimate of the extent of scallop habitat relative to that of the survey. *New VIMS dredge and HabCam and SMAST optical surveys were used to identify stock boundaries and improve understanding of the relationship between the dredge survey and stock areas.*
10. Age archived scallop shells from the 1980s and 1990s. *Archived shells from 1988 and 1993 were used to estimate growth matrices to represent growth when fishing mortality was high in the CASA models. However, additional years should be analyzed as described in a new research recommendation.*
11. Continue to look at patterns of seasonality in weight of the meats and gonads, and timing of spawning. *Annual meat weight anomalies used to adjust mean body weight of individual scallops in the fishery and to compute catch numbers were substantially improved. Shell height-meat weight relationships based on survey data were updated.*

New recommendations

The Invertebrate Subcommittee identified the following research topics while preparing this assessment. The topics listed below are all considered worthwhile and are not listed in order of priority.

1. Investigate methods for better survey coordination between the various survey programs.
2. Evaluate effects of uncertainty in identifying dead scallops in optical surveys and improve procedures for identifying dead scallops.
3. Collect data to refine estimates of incidental mortality. Analytical procedures were improved this assessment but further progress awaits collection of more data.
4. Improve training of annotators used in optical surveys to identify and count specimens. For example, develop and consistently apply criteria for identifying inexact shell height measurements. Formalize QA/QC procedures including revaluation of annotator accuracy. Develop and maintain reference images for training and testing.
5. Continue work to improve and simplify survey design and analytical procedures for HabCam. Ideally, procedures might be automated to the extent possible and integrated into routine survey operations.
6. Quantify and improve accuracy of SAMS projection models used to specify harvest levels. Recent projections appear to overestimate stock size to some extent.
7. Reduce uncertainty about stock size estimates from surveys and the CASA model. In particular, continue work on density dependent natural mortality for small scallops in stock assessment, reference point and projection models.
8. Collect additional biological data on a regional basis including growth increments from shells collected during historical dredge surveys, seasonality of spawning based on observer data, natural mortality on large scallops due to disease and senescence, and size-specific reproductive output.
9. Refine models that predict scallop recruitment based on chlorophyll and predator data in order to improve estimates from stock assessment and projection models. Investigate statistical approaches to estimating year class strength directly from survey data.
10. Investigate and quantify the utility of multiple scallop surveys.