Technical Report

Massachusetts Division of Marine Fisheries
Technical Report TR-66

A Stock Assessment of Channeled Whelk (*Busycotypus canaliculatus*) in Nantucket Sound, Massachusetts

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Commonwealth of Massachusetts
Executive Office of Energy and Environmental Affairs
Department of Fish and Game
Massachusetts Division of Marine Fisheries

April 2018

Massachusetts Division of Marine Fisheries Technical Report Series

Managing Editor: Michael P. Armstrong

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Ronald Amidon, Commissioner
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David E. Pierce, Director

Summary: The channeled whelk (*Busycotypus canaliculatus*) supports a valuable commercial fishery in Massachusetts coastal waters. Recent declines in relative abundance and commercial catch rates, the absence of large whelk from the population, and reports from commercial fishermen suggest the long-term sustainability of the commercial fishery is threatened. To assess the status of channeled whelk, multiple assessment techniques were applied to available data. Results from most methods indicate that fishing mortality rates are high and female spawning stock biomass is declining. Based on biomass, abundance and F-based reference points, it is concluded that the channeled whelk population in Nantucket Sound is likely overfished and overfishing is occurring.

Introduction

The channeled whelk (*Busycotypus canaliculatus*) supports a valuable commercial fishery in Massachusetts coastal waters. In 2016 a total of 1.6 million lbs, valued at $4.85 million, were landed by 82 active fishermen. Landings are entirely from Massachusetts state waters with the majority coming from Nantucket Sound. The majority of channeled whelk are harvested through directed effort with "conch" traps, and a smaller portion are harvested as by-catch from draggers, clam dredgers, and a few hand harvesters. This fishery started in the 1980's and remained fairly stable until the early 2000's, when landings and fishing effort for channeled whelk increased dramatically as a result of increased market demand, increased price, and the decline of the SNE lobster stock.

The Massachusetts Division of Marine Fisheries (DMF) is solely responsible for the management and regulation of the channeled whelk fishery occurring within state waters. It is our goal to maintain a healthy channeled whelk resource that supports a sustainable and profitable fishery within Massachusetts coastal waters. Successful fisheries management requires a strong understanding of fishery and population trends, as well as an accurate assessment of stock status. This report summarizes historical and current data on landings, population characteristics, mortality and stock status of channeled whelk in Massachusetts. This is the first formal stock assessment conducted for channeled whelk in Massachusetts waters.

Life History

The channeled whelk is an edible marine gastropod of the family Melonogenidae and subfamily Busyconinae. It is a prosobranch, which are gastropods that breath using gills. Channeled whelk are carnivorous scavengers as well as predators of live shellfish. This species ranges from Florida to Massachusetts (generally confined to south of Cape Cod). As with most gastropods they are benthic, have a muscular foot, and a coiled shell.

Habitat

Channeled whelk are benthic organisms that typically inhabit embayments, estuaries, and nearby shallower waters. They are found subtidally in waters less than 30 meters on sandy, silt, shell hash, and muddy sediments. Channeled whelk are often found in and amongst shellfish beds seeking food such as *Mercenaria mercenaria*, *Mya arenaria*, *Spisula solidissima*, *Mytilus edulis*, or *Crepidula fornicata*. Movement is thought to be limited with only small scale seasonal migrations of less than several kilometers taking place (Sisson 1972, Edmundson 2015). Adult channeled whelk seem to exhibit thermal preferences and bury into the sediment when water temperatures become too warm or too cold (Magalhaes 1948). Channeled whelk below age 4 have not been observed in pot/trap or otter trawl gear based monitoring studies (Peemoeller and Stevens 2013, Wilcox 2013, Fisher and Rudders 2017). However, they have been observed *in situ* during studies focused on hand collection of egg strings (Harding 2011, Edmundson 2015). Lack of smaller size classes may be due to gear selectivity of standard whelk traps and otter trawls used in monitoring surveys, or it may reflect demographic differences in habitat preferences of young channeled whelk.

Age

The age of channeled whelk can be estimated using annuli produced on different hard body parts. The two structures most often used are the operculum and the statolith. Wilcox (2013) and Peemoeller and Stevens (2013) found a maximum age of 14 for female channeled whelk using the operculum. A follow-up study conducted by *MarineFisheries* in 2015 used both operculum and statolith aging. The maximum age observed in this study was 11 for female channeled whelk, however less large whelk were collected in this study. The size of age 11 whelk was similar to the data collected by Wilcox

2013. At the time of these studies landings and effort were at or near time series high levels. As a result there were fewer large whelk in the population than we observed in sea sampling data collected in 2003 and 2004. Based on the largest whelk observed in historic data, as well as growth and age estimates from Peemoeller and Stevens (2013), a maximum age of 20 years was estimated for Massachusetts.

Growth

Channeled whelk appear to have seasonal variability in growth. Wilcox (2013) found that growth rings on the operculum were formed between December and April as growth either slowed or ceased. When water temperature drops below about 8° C whelk seem to burrow into the sediment and stop feeding. Incremental growth bands on the operculum suggest there are periods of higher growth rates in the spring and fall, with some growth occurring in summer.

Early natural growth information is somewhat unknown. Newly hatched whelk burrow into the sediment and tend to be scavengers for the first few years of life. Around age 3 or 4 they first become susceptible to traditional harvest methods. The youngest whelk observed in the research studies of Wilcox (2013) and Peemoeller and Stevens (2013) was age 4. Tank based studies have been used to monitor growth in newly hatched individuals, but results have differed from estimates based on field-collected samples. Harding (2011) witnessed quick growth in the first 6 months after hatch; whelk size at hatch was 3.8 mm total length and reached an average of 48.4 mm total length in the first 171 days in ambient seawater. Growth curves produced by Peemoeller and Stevens (2013) for channeled whelk harvested in Buzzards Bay did not reach 48.4 mm until age 3.

Peemoeller and Stevens (2013) found differences in growth rates between sexes. Growth between sexes was similar until age 4-6, the age range where male whelk began to mature. At this point male growth began to slow and females grew faster and attained larger sizes. As such, Peemoeller and Stevens (2013) generated separate growth curves for each sex:

Female: $L_a = 247.15(1 - e^{-0.15(age - 1.78)})$

Male: $L_a = 177.8(1 - e^{-0.20(age - 1.63)})$

where L_a is the length at age a. Growth data used in the estimation came primarily from ages 4-14; data were lacking from t_0 through age 3 and ages 15 and greater.

Maturity

MarineFisheries collected and dissected 1,788 channeled whelk from Nantucket Sound (n=790), Buzzards Bay (n=399), Vineyard Sound (n=252), and New Bedford Harbor (n=347) between 2010 and 2015 for maturity study (Wilcox 2013, and MADMF unpublished data). Standard shell width and length were measured to the nearest millimeter and total weight was measured to the nearest gram. Next the shell was removed and another weight was taken of the internal organism. Sex was determined by presence or absence of a penis. Maturity was evaluated and gonads were removed and weighed to the nearest gram. The egg capsule gland was also removed and weighed in all females. The operculum was removed for aging and in the 2015 samples the statoliths were also aged. Operculum are aged using a dissecting microscope and counting the annuli on the back side of the structure. Statoliths are sectioned, polished, and then annuli are counted under magnification.

Maturity was determined macroscopically at the time of dissection. Male maturity was determined by observing if there was sperm present in the vas deferens. For animals that appeared immature or just maturing, a cross slice of the vas deferens revealed whether or not there was sperm stored inside. In addition to presence of sperm there was also a notable change in teste color associated at the onset of maturity.

Immature female ovaries have a transparent orange appearance and lack ova. At the onset of maturity the ovary becomes larger and darker orange with individual ova becoming visible. Based on ovary size and egg capsule gland size, it was determined at this stage that the female was developing and had not yet reproduced. As the ovary proceeded to develop through the season it would continue to change in size, color and consistency. Individual ova also became columnalar in shape as they developed. Just prior to extrusion individual ova became brown and larger, and the ovary peaked in size in comparison to other months. The egg capsule gland exponentially grew from a relatively small structure when immature to a much larger structure as the females became mature. Following the period of egg extrusion the ovaries and egg capsule gland both decreased in overall size, but remained relatively large and were easily distinguishable from those that where immature or developing for the first time.

Several samples of ovaries were also examined using standard histological techniques with Hemotoxylin and Eosin staining. The histological cross sections were used to confirm macroscopic valuations of maturity. This was done for all levels of ovary development. Due to the size of channeled whelk ova and the results from histoloigical cross sections it was determined that macroscopic evaluation was sufficient.

Logistic regression was used to create maturity ogives for both sexes in each region. The width at 50 percent maturity and the standard error associated with each estimate were compared by area and sex. Males matured at significantly smaller sizes and younger ages than females in all areas. Males from Nantucket Sound were found to mature at the largest size 70.5 mm shell width and males from Vineyard Sound were the smallest at 64.6 mm width. Regional age at 50 percent maturity did not correspond to regional size-at-maturity, as males from Buzzards Bay were found to mature at the youngest age 6.1 years and males from Vineyard Sound at the oldest 6.9 years, suggesting different regional growth rates.

Female whelk matured 2 to 3 years later than males and at 25-30 mm larger widths, and also exhibited regional differences in size and age at maturity. Females from Nantucket Sound were found to mature at the largest size 98.8 mm and females from New Bedford Harbor were found to mature at the smallest size 85.7 mm. Females from Vineyard Sound were found to mature at the oldest age 10 years and New Bedford Harbor had the youngest age at maturity 8.5 years. Within Buzzards Bay, two separate studies found similar results in terms of size at 50% maturity; 89.4 mm and 89.7 mm (Wilcox (2013) and Peemoeller and Stevens (2013) respectively). In Nantucket Sound where the majority of landings and effort occurs there are few if any female whelk mature at 89 mm (Table 1).

General fecundity traits remain unknown. No work has been conducted to examine the relationship between female size and reproductive output. As the larger size class of whelk has diminished in recent years of sea sampling, it would be useful to understand how overall reproductive output has been affected.

Reproduction

Channeled whelk copulate with direct transfer of

Table 1. Size (shell width) of mature female channeled whelk in Nantucket Sound by percent maturity increment .

Nantucket Sound Females					
% Mature	Width (mm)	SE (mm)	Width (inches)	Age	SE Age
5%	91.34	1.57	3.60	8.13	0.22
10%	93.23	1.31	3.67	8.49	0.18
15%	94.40	1.18	3.72	8.72	0.16
20%	95.28	1.11	3.75	8.89	0.15
25%	96.01	1.07	3.78	9.02	0.15
30%	96.64	1.05	3.80	9.14	0.15
35%	97.22	1.05	3.83	9.25	0.15
40%	97.76	1.06	3.85	9.36	0.16
45%	98.28	1.08	3.87	9.46	0.16
50%	98.78	1.11	3.89	9.55	0.17
55%	99.29	1.14	3.91	9.65	0.18
60%	99.81	1.19	3.93	9.75	0.19
65%	100.35	1.25	3.95	9.85	0.20
70%	100.93	1.32	3.97	9.96	0.21
75%	101.56	1.40	4.00	10.08	0.23
80%	102.29	1.50	4.03	10.22	0.24
85%	103.17	1.63	4.06	10.39	0.27
90%	104.34	1.82	4.11	10.61	0.30
95%	106.22	2.15	4.18	10.97	0.35

sperm from male to female. Females of other Busyconinae whelk were found capable of mating with multiple male whelk and storing sperm for upwards of a year (Walker et al. 2007). Female channeled whelk spawn between July and September based on field observations and gonodosomatic index (Wilcox 2013). Fertilization occurs internally and the eggs are enclosed in cases then released in a large string of multiple casings, with the string reaching around 0.5 m in length. Within the casing eggs can be fertilized by multiple paternal contributors. The process of deploying the egg casing can take females 1-2 weeks of continuous effort (Edmundson 2016). Spawning takes place in relatively shallow coastal embayments and sounds, and the strings are anchored into the sediment in depths from the low water line to about 20 meters. Whelk embyros develop within the egg casings and hatch as miniature adults directly onto the sea floor; there is no larval dipsersal. Hatching takes place about nine months after the female deposits the egg casing.

Determination of Natural Mortality

Natural mortality rate was estimated using an empirical model developed for macrobenthic invertebrates by Brey (1999). The equation is

$$\log_{10}(M) = 1.672 + 0.993 \cdot \log_{10}\left(\frac{1}{t_{\max}}\right) - 0.035 \cdot \log_{10}(BM_{\max}) - 300.447/T$$

where M is natural mortality rate, t_{max} is the maximum age, BM_{max} is the maximum body mass (kJ) and T is mean water temperature (Kelvin). The maximum age recorded by Wilcox (2013) and Peemoeller and Stevens (2013) was 14 years. Since the channeled whelk have experienced heavy commercial exploitation for many years, the maximum age is likely truncated. To estimate what the theoretical maximum age may have been, the age of the largest individual recorded during historical DMF sampling was back-calculated by using the von Bertalanffy growth equations of Peemoeller and Stevens (2013), and a shell length-age relationship and von Bertalanffy equations developed for each sex from Wilcox (2013) and 2015 data (MADMF unpublished data). The maximum size (shell-length (SL)) of channeled whelk was determined by converting the maximum shell width observed in the 2003-2004 at-sea sampling to shell length by using shell width-shell length equations developed from Wilcox (2013) and 2015 MADMF data. The maximum size was 230 mm SL and, coincidently, was identical to the maximum shell length observed for knobbed whelk (*Busycon carica*) (Harding et al., 2007). Since the sex of the maximum-size individual is unknown, the maximum age was back-calculated using both sex-specific equations.

The maximum age estimates are shown in Table 2 and range from 15 to 79 years. The value of 20 years was selected as the maximum age and was assumed female since it appeared reasonable given females grow larger than males.

To obtain BM_{max}, the shell-free body weight was determined from shell length using a relationship developed from Wilcox (2013) and 2015 MADMF data:

$$sfbw(g) = 10^{-5.674 + 3.593 \cdot \log_{10}(SL(mm)) + 0.0025}$$

where *sfbw* is shell-free body weight in grams. The estimate of shell-free body weight was 651.9 g for shell length of 230 mm.

BM_{max} was calculated by multiplying the shell-free body weight by the average Gastropoda conversion factor of 3.818 kJ/gram wet-weight (Arrighetti et al., 2011). This gave an estimate of 2489 kJ.

Using the maximum age (20), BM_{max} (2489 kJ) and mean bottom temperature in 2014 at the DMF reef (11.6^{o}C = 284.6 K), the estimate of M was 0.16/ year. In comparion, Arrighetti et al. (2011) estimated M to be 0.091/yr for the giant snail *Adelomelon beckii* (maximum shell length: 390 mm) and de Vooys and van der Meer (2010) estimated M to be 0.597 for the whelk *Buccinum*

Table 2. Estimates of maximum age from maximum shell-length. NA means the age could not be calculated because the $L_{infinity}$ parameter was less than the maximum size.

Reference	Method	Female	Male
Peemoeller and Stevens (2013)	von Bertalanffy equation	20	NA
Wilcox (2013) and 2015 data	Shell-Length vs Age	15	19
Wilcox (2013) and 2015 data	von Bertalanffy equation	79	NA

undatum (maximum shell length: 103 mm SL).

Fishery Description

In Massachusetts, channeled whelk were historically considered a nuisance shellfish predator with mandatory rules for disposing of them above the high tide line. Over time a small scale market developed, and fishermen began landing whelk as bycatch from lobster, otter trawl, dredge, and general shellfish fisheries. As the demand developed at niche markets domestically and delicacy markets in the Far East, some fishermen began targeting whelk seasonally as a directed fishery. The transition was easy for lobster fishermen that already had the appropriate boat set up, and only needed to invest in whelk-specific traps. With increased landings and other similar gastropod markets crashing worldwide, the ex-vessel value has nearly tripled since 2005 from $1.07/pound to $3.00/pound. The fleet is comprised of all day boats in the 5 - 15 meter size range. Most whelk trap fishermen also fish for other trap-caught species such as lobster, sea bass, or scup. In recent years many fishermen have shifted effort (especially in the fall) from the lobster fishery to the whelk fishery as a result of the increase in whelk price and a serious decline in the Southern New England lobster resource (ASMFC 2015).

MarineFisheries requires all permit holders to submit monthly catch reports with trip level information. The catch reports collect information on how many whelk were landed, how many traps were hauled, total traps in water, how long the traps were soaking, and which DMF statistical area the traps were hauled. A condition of permit renewal is that all catch reports from the previous year be submitted. Additionally all dealers are required to submit weekly catch purchase reports quantifying species, poundage, and price information. Data from these reports are used to monitor annual fishery landings and effort trends.

Regulations Historically the only rules in Massachusetts regarding whelk were the mandatory disposal above the high tide mark mentioned above which has since been eliminated. As the fishery began to develop in the early 1990's a state whelk trap endorsement became required to fish whelk traps, and otter trawlers were required to obtain a state coastal access permit. In 1992 a minimum legal size of 2 ¾" shell width, a maximum trap limit of 200 per permit holder, and a closed season for whelk traps from December 15-April 14 inclusive was established. The minimum legal size was set from market demands and was not biologically based. In 2009 a group of fishermen, primarily from Martha's Vineyard, petitioned *MarineFisheries* to increase the minimum legal size. The group was concerned about increased effort and fewer whelk in previously productive areas. *MarineFisheries* began a life history study to adequately address their concerns. Following the results of the study (Wilcox 2013) a standardized gauge was implemented for the first time in 2013, and minimum legal size was increased by 1/8" annually in 2014 and 2015. Additionally in 2014 a 1,000 pound (knobbed and channeled whelk combined) daily trip limit was implemented for otter trawlers. In 2016 commercial hand harvesters received a daily limit of one level-filled fish tote of channeled and knobbed whelk combined. Also in 2016 recreational harvest became limited to 15 channeled and knobbed whelk (combined) with no minimum legal size.

Landings Records of commercial whelk landings are available back to 1950 through the National Marine Fisheries Service (NMFS) website. From 1950 to the late 1970's whelk landings in MA (channeled and knobbed) were less than 250,000 lbs annually. In the 1980's whelk landings increased substantially, exceeding 1,000,000 lbs for the first time, presumably related to increased market demand. It was first possible to differentiate between channeled whelk and knobbed whelk landings in the early 1990's with improvements to the landings data reporting system. Channeled whelk is consistently the predominant species landed in Massachusetts. From the mid-2000s through 2013, total landings increased and varied between 2.5 and 3 million pounds (Figure 1). A standardized gauge was implemented for the first time in 2013, and in 2014 and 2015 minimum legal size was increased by 1/8", which may account (at least partially) for the observed decline in landings 2014-2016 (Figure 1).

Landings over the time series increased concomitantly with a dramatic increase in total catch and effort observed in Nantucket Sound (SRA 10; Figures 1 and 2A). Landings and total trap hauls (fishing effort) more than doubled in Nantucket Sound between 2006 and 2012. Since 2013, landings and to a lesser extent trap hauls have begun to decline in Nantucket Sound. Landings and

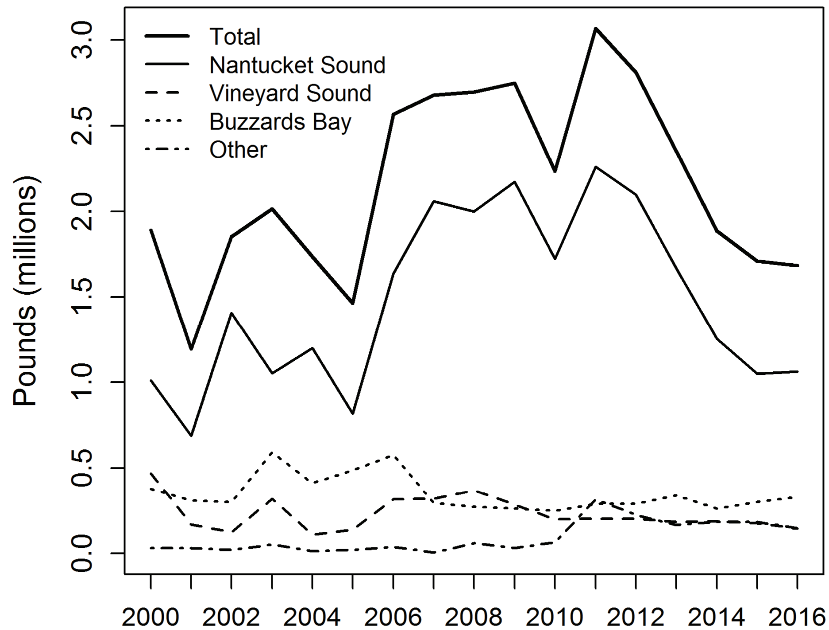


Figure 1. Massachusetts channeled whelk total landings (all gear combined 2000-2016) and landings by region. Source: Massachusetts Division of Marine Fisheries catch reports.

effort have remained relatively stable in Buzzards Bay (SRA 14) and Vineyard Sound (SRA 13; the other two major channeled whelk producing areas in MA) over the last decade, and landings in these areas seem less affected by the implementation of the standardized gauge and 1/8" minimum size increases (Figure 1 and 2A).

Total catch per trap haul (CPUE) has declined over time in Nantucket Sound, Vineyard Sound, and Buzzards Bay (Figure 2B). CPUE has varied without trend in the group of other SRAs where there are reported landings (Figure 2B). The decline in CPUE began while overall landings were still increasing. This was the result of an increase in

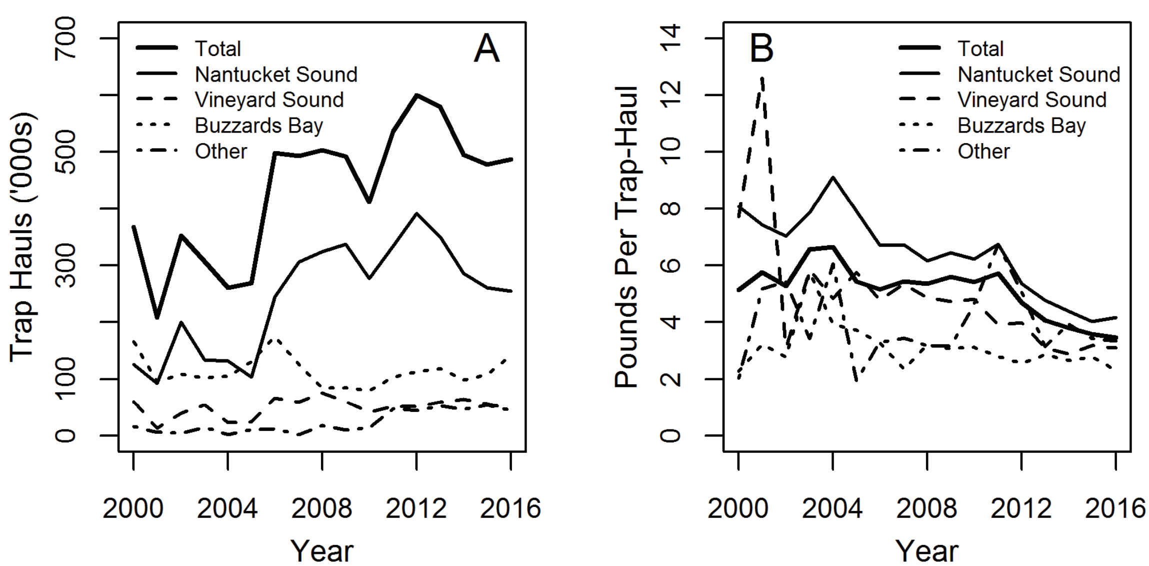


Figure 2. Total and region-specific trap hauls and catch-per-unit effort (pounds per trap-haul) for channeled whelk

Table 3. Whelk trap endorsements and reporting status 2000-2016 . Source: MADMF commercial catch reports and National Marine Fisheries Service VTRs.

Year	Issued	Fished	Did Not Fish	Did Not Report
2000	164	84	67	13
2001	161	83*	71	90
2002	165	97	62	6
2003	166	87	75	4
2004	166	88	73	5
2005	159	79	76	4
2006	155	96	56	3
2007	155	96	57	2
2008	155	88	63	4
2009	153	90	57	6
2010	151	78	69	4
2011	147	84	57	6
2012	145	87	54	4
2013	144	90	53	1
2014	143	83	58	2
2015	141	83	56	2
2016	139	82	54	3

*83 permit holders reported fishing, however data entry problems prohibited entry of 17 reports, thus effort and landings statistics below only include 66 permits

the number of traps being hauled within each region. Activation of latent effort in the form of unfished traps or unfished permits could further exacerbate this trend.

Active participation in the channeled whelk trap fishery has remained stable since 2000. While the number of permits issued gradually declined from a high of 166 in 2004 to a low of 139 in 2016 (Table 3), the number of permits actively fished varied without trend. It is noteworthy that the large increase in catch and effort in the channeled whelk fishery since 2005 occurred during a time when the number of actively fished permits declined slightly. The observed increase in effort from 2005 to present is the result of increased fishing effort from active fishermen, rather than latent permits becoming active. There is also substantial risk of additional increases in effort due to the number of latent permits; in 2016 only 50% of the permitted traps were actively fished. With the ex-vessel price of whelk nearly tripling over the last decade (Table 4), there is a substantial financial incentive for latent permit holders to start fishing.

Table 4. Annual landings and values of channeled whelk 2005-2016. Source: SAFIS dealer reports.

Year	Live Pounds	Est. Value	Price/lb.
2005	1,354,821	$1,454,295	$1.07
2006	2,420,481	$3,104,430	$1.28
2007	2,496,497	$2,466,229	$0.99
2008	2,701,409	$3,212,108	$1.19
2009	2,847,042	$3,720,139	$1.31
2010	2,505,855	$3,961,252	$1.58
2011	3,042,868	$6,117,755	$2.01
2012	3,649,270	$6,274,224	$1.72
2013	2,305,408	$5,699,013	$2.47
2014	1,921,067	$4,866,462	$2.53
2015	1,971,478	$4,814,498	$2.44
2016	1,971,153	$4,876,260	$2.47

Description of Fishery-Dependent and - Independent Sampling

Fishery-Dependent Sampling MADMF conducts at-sea sampling aboard cooperative commercial whelk vessels. The objective of this sampling is to characterize the size distribution of legal and sublegal trap catch in the state waters whelk fishery. This is the only data source for accurate information about discard rates of sublegal whelk. In recent years a target of six whelk trap sampling trips has been set for the state. Of those six an attempt is made to sample two trips in Nantucket Sound in both the spring and fall season. Trips were conducted opportunistically based on both staff and vessel availability. At the beginning of each trawl or string of single traps, location was taken in most years using a hand-held GPS. All whelks in each trap were measured for shell-width (and shell-length in some years) to the nearest millimeter using a specialized slide-style measuring board. While the complete whelk contents of all sampled traps were measured, not all traps were sampled due to high number of whelks in each trap. At-sea samplers collected data from 15 trips in 2003, 7 trips in 2004, 10 trips in 2011, 2 trips in 2013, 1 trip in 2015 and 3 trips in 2016. The locations of sampled trawls/traps are shown in Figure 3.

Size distributions of measured channeled whelks are shown in Figure 4. Annual sample size ranged from 1,961 to 15,699 whelks. Mean shell-width was 79.9 (standard deviation=13.84), 77.5 (14.54), 70.8 (12.43), 69.4 (13.43), 71.1 (9.79) and 70.6 (11.93) in 2003, 2004, 2011, 2013, 2015 and 2016, respectively.

Fisheries-Independent Survey Since 1978, annual spring and autumn bottom trawl surveys of Massachusetts territorial waters have been conducted by the Resource Assessment Project of MADMF. The objective of this survey is to obtain fishery-independent data on the distribution, relative abundance and size composition of finfish and select invertebrates. The study utilizes a stratified random sampling design. The survey area is stratified based on five bio-geographic regions and six depth zones. Trawl sites are allocated in proportion to stratum area and randomly chosen in advance within each sampling stratum. Randomly chosen stations in locations known to be untowable due to hard bottom are reassigned. Sampling intensity is approximately 1 station per 19 nm^2. A minimum of two stations are assigned to each stratum.

A standard tow of 20-minute duration at 2.5 knots is attempted at each station during daylight hours with

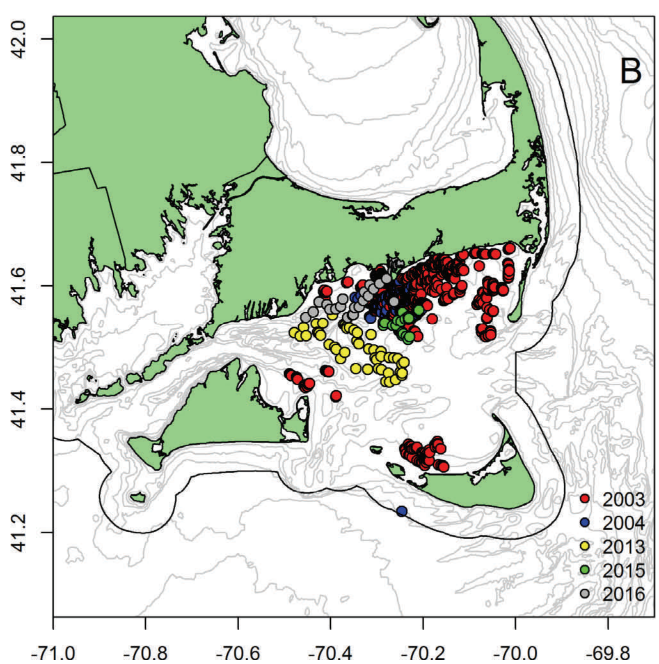


Figure 3. At-sea whelk sampling locations for years with latitude and longitude coordinates. The solid black line represents the Massachusetts management boundary. Gray lines are depth contours.

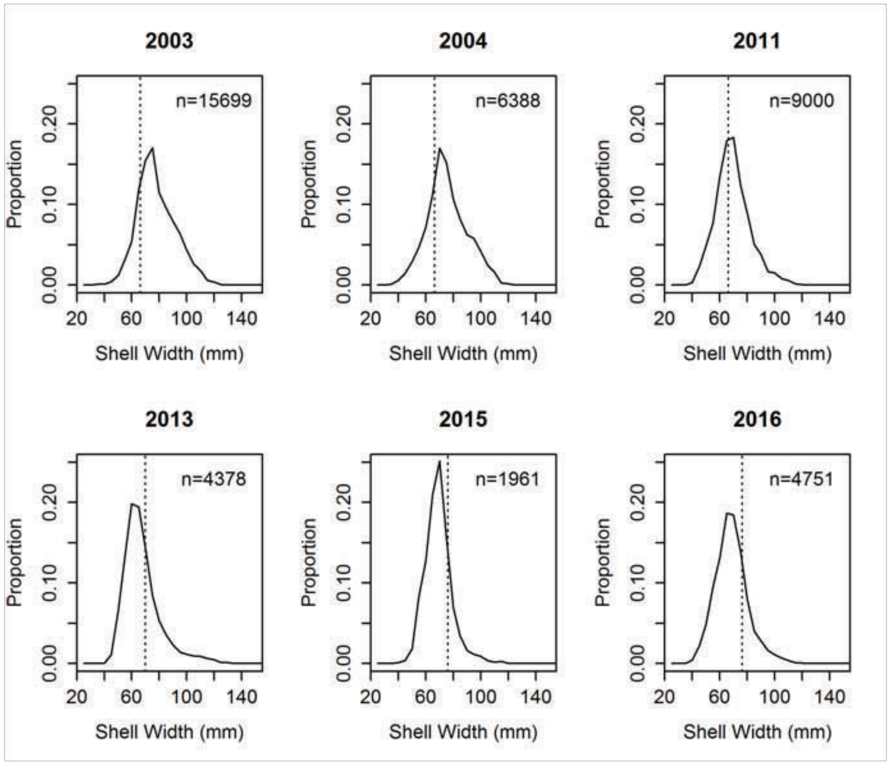


Figure 4. Size distribution of commercial catch observed in sea sample trips in Nantucket Sound . Vertical lines represent the legal minimum size limit.

a 3/4 size North Atlantic type two seam otter trawl (11.9 m headrope/15.5 m footrope) rigged with a 7.6 cm rubber disc sweep; 19.2 m, 9.5 mm chain bottom legs; 18.3 m, 9.5 mm wire top legs; and 1.8 x 1.0 m, 147 kg wooden trawl doors. The codend contains a 6.4 mm knotless liner to retain small fish. Abbreviated tows no shorter than 13 minute duration are accepted as valid and expanded to the 20 minute standard. The F/V *Frances Elizabeth* conducted all surveys through fall 1981. The NOAA ship R/V *Gloria Michelle* has been the survey platform for every survey since spring 1982. Standard bottom trawl survey techniques are used when processing the catch. The total weight and length-frequency of each species including channeled whelk are recorded directly into Fisheries Scientific Computer System (FSCS) data tables.

Channeled whelk are caught during the spring and fall bottom trawl surveys and the data provide an index of relative abundance for the population. Relative abundance indices for this assessment were computed as the stratified mean number and weight per standardized tow but catch data were transformed using ln(x+1) prior to calculation to stabilize the variance and reduce the influence of sampling variability between tows. In addition, the time series method of Pennington (1986) for estimating relative abundance was applied to smooth the time series by using function *surveyfit* in R package *fishmethods*. The stratified mean number and weight per tow values for fall were not used in this assessment because estimates were less precise than the values from spring.

Relative biomass (weight) and abundance (numbers) of channeled whelk in Nantucket Sound appears to have declined from 1979 through the mid -2000s (Figure 6). The fitted values from the Pennington model suggest that relative biomass and abundance have declined by about 72% and 61%, respectively, between 1980-1982 and 2014-2016.

Fisheries-Independent Biological Sampling DMF initiated a life history study in 2010 to collected data on size, sex, maturity and age (as described in Wilcox 2013) by using trap sampling. Standard commercial traps were used and baited with a combination of horseshoe crab, (*Limulus polyphemus*), spider crab, (*Libinia emarginata*), and quahog, (*Mercenaria mercenaria*). Traps were set with a single buoy and vertical line complying with all fishery-related regulatory standards associated with protected species. Ten traps were set haphazardly in a line along a compass heading to run the same direction

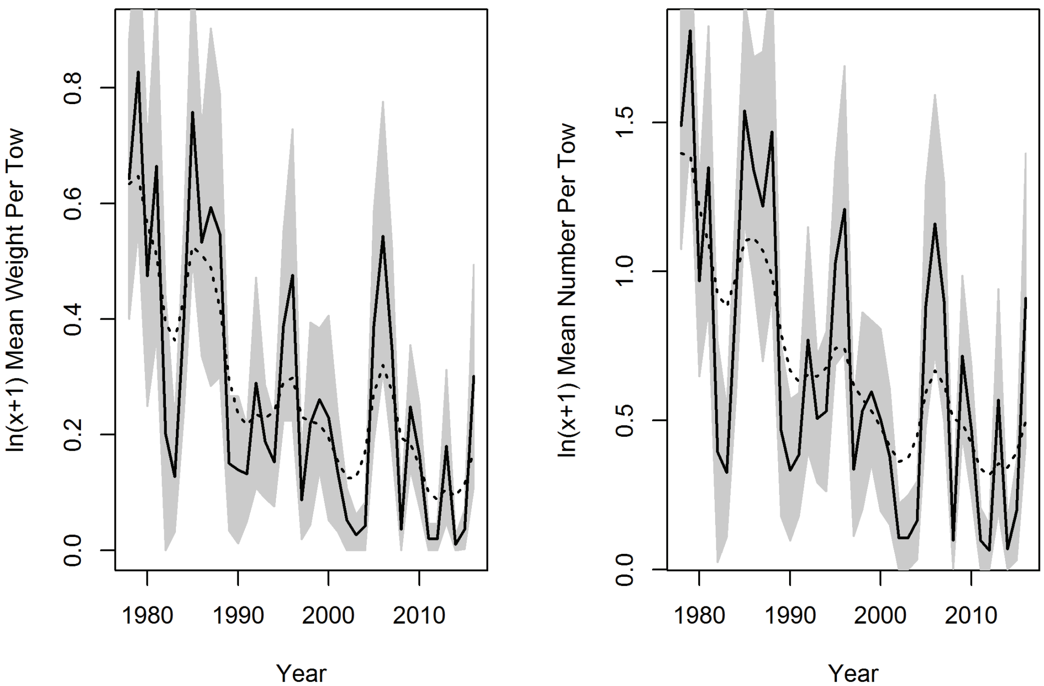


Figure 5. DMF spring trawl survey indices (mean wgt and number per tow (ln(x+1)-transformed)) for channeled whelk in Nantucket Sound. The indices are shown as black solid lines, the area between the 95% confidence intervals are shown as gray shading , and the Pennington (1986) fits are shown as dotted lines.

as commercial traps in the area or to follow a depth contour, and waypoints were taken at either end of the string. Distance between the two end pots ranged between 0.5 and 0.65 km for all sets. When commercial gear was present, traps were set a fair distance away to avoid infringing on their fishing practice. Trap haul-back frequency followed commercial fishing practices (sampled at one to three day intervals depending on weather conditions). Once traps were retrieved, all whelk were placed in a cooler and returned to the laboratory for processing.

An attempt was made to collect reproductive-size females monthly between April and December when whelk are actively feeding and therefore catchable, and not during the winter dormancy. For the seasonal sampling effort larger whelk were targeted. Preliminary efforts showed the onset of maturity starting in females >90 mm. For this portion of the study anything <80 mm was released to maximize the chance of collecting reproductive females and to decrease the numbers of male and immature females collected.

In 2015, sampling occurred using twenty five whelk traps set in Nantucket Sound following procedures of Wilcox (2013) and hauled on 4 separate trips. All individuals from the first trip were returned to the lab and processed. A target of 5 whelks per millimeter size bin per sex was desired for ageing, but since sex cannot be determined until the shell is removed, the target for each sex was often not achieved in a given size bin. To fill in specific size bins, samples were collected during the remaining trips.

Processing of samples for sex, maturity, age, size (shell-width and shell-length in millimeters) and total and shell-free body weight (in grams) in 2010, 2011 and 2015 followed methods described in Wilcox (2013). Maturity staging, maturity ogive development and ageing of operculum followed procedures of Wilcox (2013).

Assessment Methods

Data for assessing channeled whelk in Massachusetts are limited. Therefore, multiple assessment techniques with increasing data needs and different model assumptions were applied to available data. This strategy allows results and conclusion from each model to be compared for consistency.

Catch MSY Martell and Froese (2012) developed a method to estimate MSY using only catch data, given information on resilience and simple assumptions about relative stock sizes at the first and final year of the catch data time series. The base model is a Schaefer biomass dynamics model :

$$B_{t+1} = B_t + r \cdot B_t \cdot \left(1 - \frac{B_t}{K}\right) - C_t$$

where B_t and B_{t+1} are biomass in time t and $t+1$, r is the intrinsic growth rate, K is carrying capacity and C_t is catch (harvest in pounds) in time t. Prior distributions of r and K are sampled and values are used to calculate a biomass time series subtracting catch. The main idea is to find all plausible values of r and K. To do this, an estimate of biomass in the last year is compared with the specified relative biomass in the last year (B_t/K) and, if the biomass values are within the range specified, the r and K values are said to be likely and are stored. If the end year biomass does not fall within the relative range, the r and K values are not likely. Very large numbers of random draws are required to determine the distribution of the parameter estimates. The values of K and r are considered precautionary estimates because they tend to produce higher biomass thresholds and lower fishing mortality thresholds than data-rich stock assessments.

The starting biomass is calculated from the specified relative biomass in the first year (B_1/K) and the assumed K parameter:

$$B_1 = K \cdot B_1 / K$$

From the plausible values of r and K, management parameters are generated:

$$MSY = \frac{rK}{4} \quad B_{MSY} = \frac{K}{2} \quad F_{MSY} = \frac{r}{2}$$

where MSY is the maximum sustainable yield, B_{MSY} is the biomass as MSY, and F_{MSY} is the fishing mortality to achieve MSY.

The relative biomass in 2000 was determined by calculating the change in the average of the smoothed values of the DMF trawl spring weight index during 1980-1982 (0.49) and the average of smoothed values for 1999, 2000, and 2001 (0.19). The relative biomass in 2000 was 0.39 of the assumed biomass at K. The range in relative biomass in year 2000 explored was +30% of 0.39 (0.27-0.51).

Similarly, the relative biomass in year 2016 was determined by calculating the change in the average of smoothed values from the DMF trawl spring weight index during 1980-1983 (0.49) and the average of smoothed values for 2014, 2015, and 2016 (0.13). The relative biomass in 2016 was 0.26 and the range explored was 0.05-0.26 .

As recommended by Martell and Froese (2012), the range of K was initially specified as the maximum observed catch (2,258,616.2 pounds) to 100 times the maximum observed catch (2,258,616,200 pounds). However, preliminary analysis showed that the specified maximum K was well outside any possible combinations given the data, so maximum K was reduced to 50 times the maximum observed catch.

Since channeled whelk are a relatively slow growing, long-lived species, the low resilience range (0.05-0.5) listed in Martell and Froese (2012) was used for r.

All parameters were sampled assuming a uniform distribution and 50,000 random draws were made. Management quantities were calculated as described above using M of 0.16.

Results

Of the 50,000 random draws, only 2,108 produced acceptable trajectories (Figure 6). There was a general trend of declining biomass over the time series (Figure 6). The plots of acceptable r and K parameters along with the MSY, F_{MSY} and B_{MSY} management quantities are shown in Figure 7. The distributions of r, K , F_{MSY} were highly skewed, while those for MSY and B_{MSY} were less so. The median value for r and K was 0.102 and 42.96 million pounds, respectively (Table 5). The derived median values of MSY, B_{MSY} and F_{MSY} were 1.18 million pounds, 21.48 million pounds and 0.051, respectively. Comparison of the median MSY value to catch indicated that whelk landings during 2006-2013 were well above MSY (Figure 8).

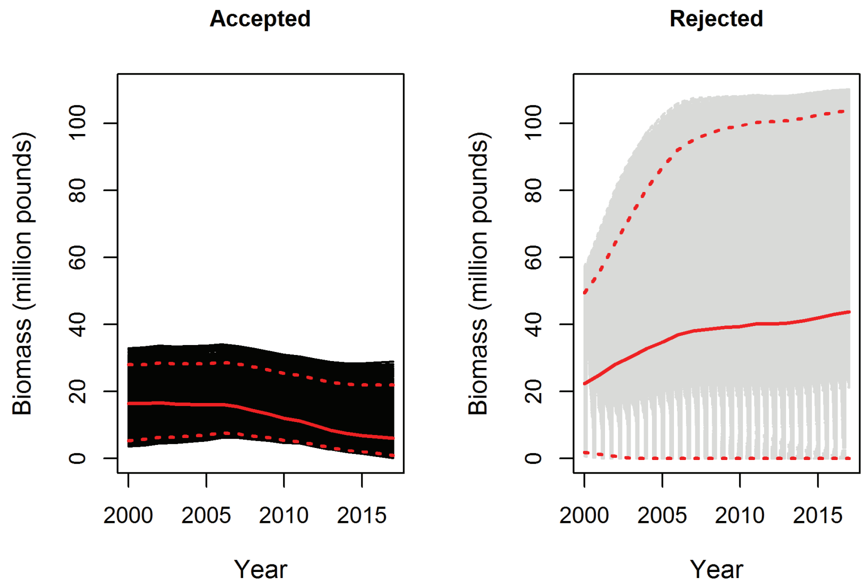


Figure 6. Estimates of biomass from the Catch MSY model for acceptable and rejected trajectories.

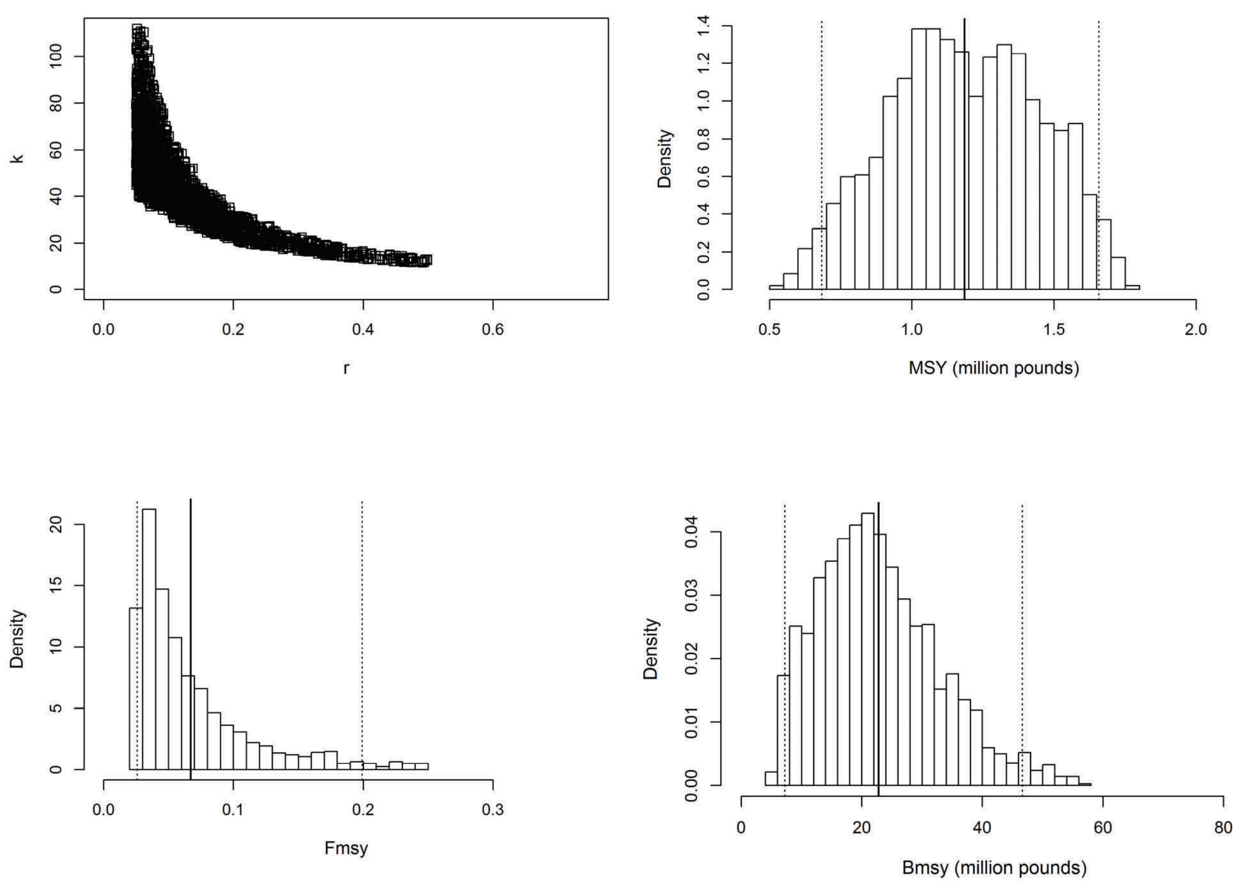


Figure 7 . Plots of r and K joint distributions and management quantities (MSY, F_{MSY} and B_{MSY}) for accepted trajectories. Solid vertical is the mean and dotted vertical lines are the 2.5th and 97.5th percentiles.

Table 5. Parameter estimates and derived management quantities from Catch MSY model .

Parameter Estimates	Mean	Median	2.5%	97.5%
K (million pounds)	45.57	42.96	14.49	93.20
r	0.134	0.102	0.052	0.398

Management Quantities	Mean	Median	2.5%	97.5%
MSY (million pounds)	1.18	1.18	0.68	1.66
Bmsy (million pounds)	22.78	21.48	7.25	46.60
Fmsy	0.067	0.051	0.026	0.199

Depletion-Based Stock Reduction Analysis

Depletion-Based Stock Reduction Analysis (DBSRA) (Dick and MacCall 2011) was used to derive an estimate of *MSY*. DBSRA estimates the carrying capacity (*K*) necessary to have sustained an observed time series of catch resulting in recent stock biomass levels. The method requires user-specified values of natural mortality (*M*), the ratio of F_{MSY} and natural mortality (F_{MSY}/M), B_{MSY} relative to carrying capacity (B_{MSY}/K), and biomass in a recent year relative to carrying capacity (B_r/K).

DBSRA uses a delay-difference reparameterization of the Pella-Tomlinson production model to describe the changes in biomass and production. The process model is:

$$B_t = B_{t-1} + P(B_{t-a}) - C_{t-1}$$

where B_t is biomass at time t, B_{t-1} is biomass at $t-1$, P is the production of B_{t-a}, a is the median age of entry into the exploitable biomass, and C_{t-1} is the catch (harvest in weight) at time $t-1$. $P(B_{t-a})$ is

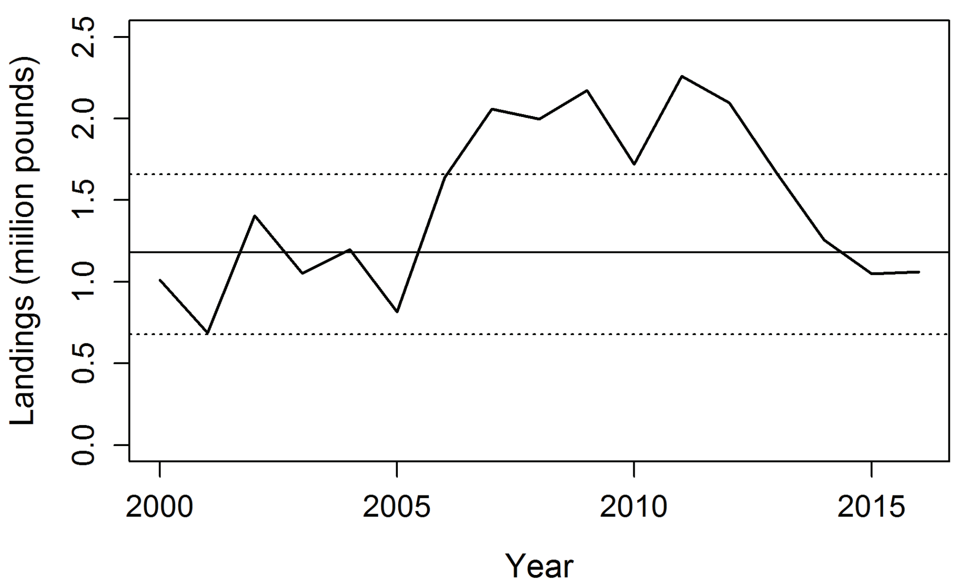


Figure 8. Comparison of landings and the median MSY estimate (solid horizontal line with 2.5th and 97.5th percentiles (dotted lines)) from the catch-MSY model.

calculated as

$$P = g \cdot MSY \cdot \left(\frac{B_{t-a}}{K}\right) - g \cdot MSY \cdot \left(\frac{B_{t-a}}{K}\right)^{n}$$

The parameter controlling the shape of the production curve (n) is related to the leading parameter B_{MSY}/K and is solved iteratively conditional on the B_{MSY}/K parameter. The parameter g is related to n and is derived after solving for n (see Dick and MacCall 2011 for details). MSY is calculated when K is solved.

Dick and MacCall (2011) hybridized the Pella-Tomlinson production model with a Schaefer production function to address excessive production estimates at low biomasses of highly skewed Pella-Tomlinson production curves. The hybridized production function estimates production with a Pella-Tomlinson production function at biomasses above a specified biomass (B_{join}) and a Schaefer production function at biomasses below B_{join}. The optimal B_{join} is dependent on the shape of the production curve (i.e., B_{MSY}/K) and recommendations by Dick and McCall (2011) were used for specifying B_{join}.

A modification to the DBSRA model was made to incorporate uncertainty that the stock in the first year was not in an unfished condition. Similar to Catch MSY, biomass in year 1 was assumed related to K by $K*B_1/K$ where B_1/K is the biomass in year 1 relative to K. An initial K parameter is specified and stock biomass is projected forward in each subsequent year with the production model and the catch time series. K is then solved iteratively conditional on the assumed B_r/K and specified bounds around K. If the absolute difference between the estimated B_r/K and assumed B_r/K is not within a tolerance range, the model is considered implausible and is rejected. In addition, the possible range of the shape parameter (n) for the production function was limited to values$\leq$4 because there is little evidence in fisheries literature that n can be greater. If the model is accepted, the parameters are used to derive MSY reference points. M, F_{MSY}/M, B_{MSY}/K, and Bt/K are sampled from specified distributions.

Management quantities are derived using specified parameters and estimates of K. F_{MSY} is derived from the product of F_{MSY}/M and M and exploitation corresponding to MSY (U_{MSY}) is derived by:

$$U_{MSY} = \left(\frac{F_{MSY}}{M + F_{MSY}}\right)(1 - e^{-M - F_{MSY}})$$

Biomass at MSY is calculated as:

$$B_{MSY} = K\left(\frac{B_{MSY}}{K}\right)$$

and MSY as:

$$MSY = B_{MSY} \cdot U_{MSY}$$

For channeled whelk, age 6 was selected as the median age of entry to exploitable stock using the selectivity curve derived above . The search range for K was the same as that used in the Catch MSY model presented above. M was set to 0.16. B_1/K was set to 0.39. Bt/K was generated from a uniform distribution with range 0.05 to 0.26, where the upper bound was taken from the upper bound of Catch MSY relative biomass in the last year. F_{MSY}/M values were generated from a uniform distribution with range 0.3-0.9 which encompassed an initial F_{MSY}/M (0.58) derived for whelk using the F_{MSY} proxy (=0.093) from the SPR analysis (see below). B_{MSY}/M values were generated from a uniform distribution with range 0.3-0.9 which encompasses the value of 0.5 typically found for a Schaefer production model. Fifty thousand random draws were made from each distribution and management quantities were calculated as described above using $M = 0.16$.

Results

Of 50,000 random draws, 24,083 produced acceptable trajectories (Figure 9). There was a general trend of declining biomass over the time series. The distributions of acceptable K, B_{MSY} and MSY values showed slight skewness (Figure 10). The median values for K, B_{MSY} and MSY were 44.2 million pounds, 19.9 million pounds, and 1.6 million pounds, respectively (Table 6). Comparison of the median MSY value to catch indicated that whelk landings during 2007-2013 were above MSY (Figure 11).

Non-equilibrium Biomass Dynamics Model

A non-equilibrium Schaefer biomass dynamics model (Hilborn and Walters, 1992) was applied to channeled whelk catch (pounds) and effort (trap-hauls) to estimate MSY, annual biomass-based F, F at MSY (F_{MSY}) and biomass at MSY (B_{MSY}). The

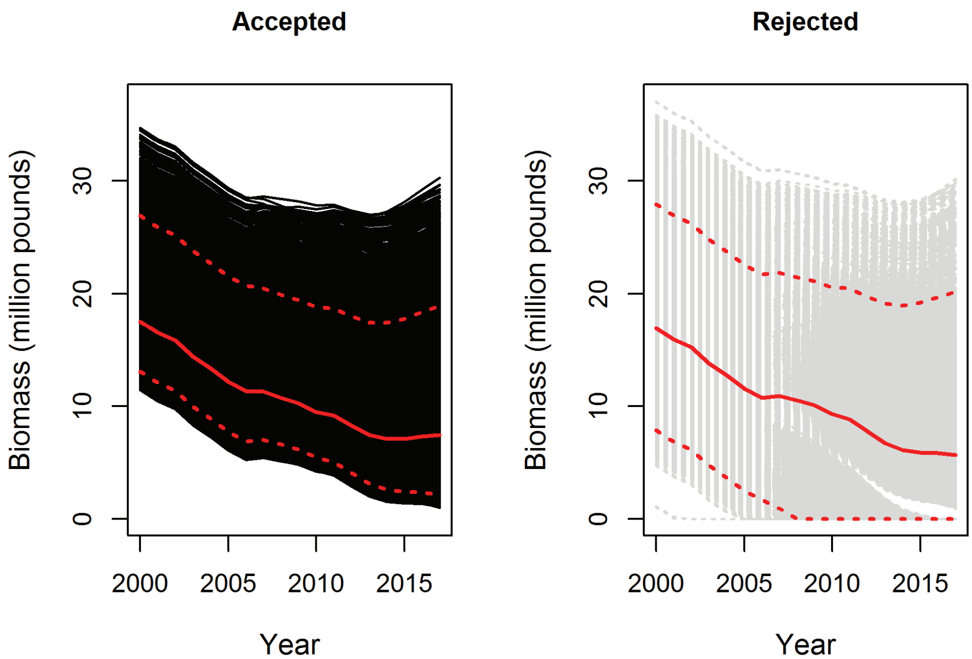


Figure 9. Estimates of biomass from the DBSRA model for acceptable and rejected trajectories.

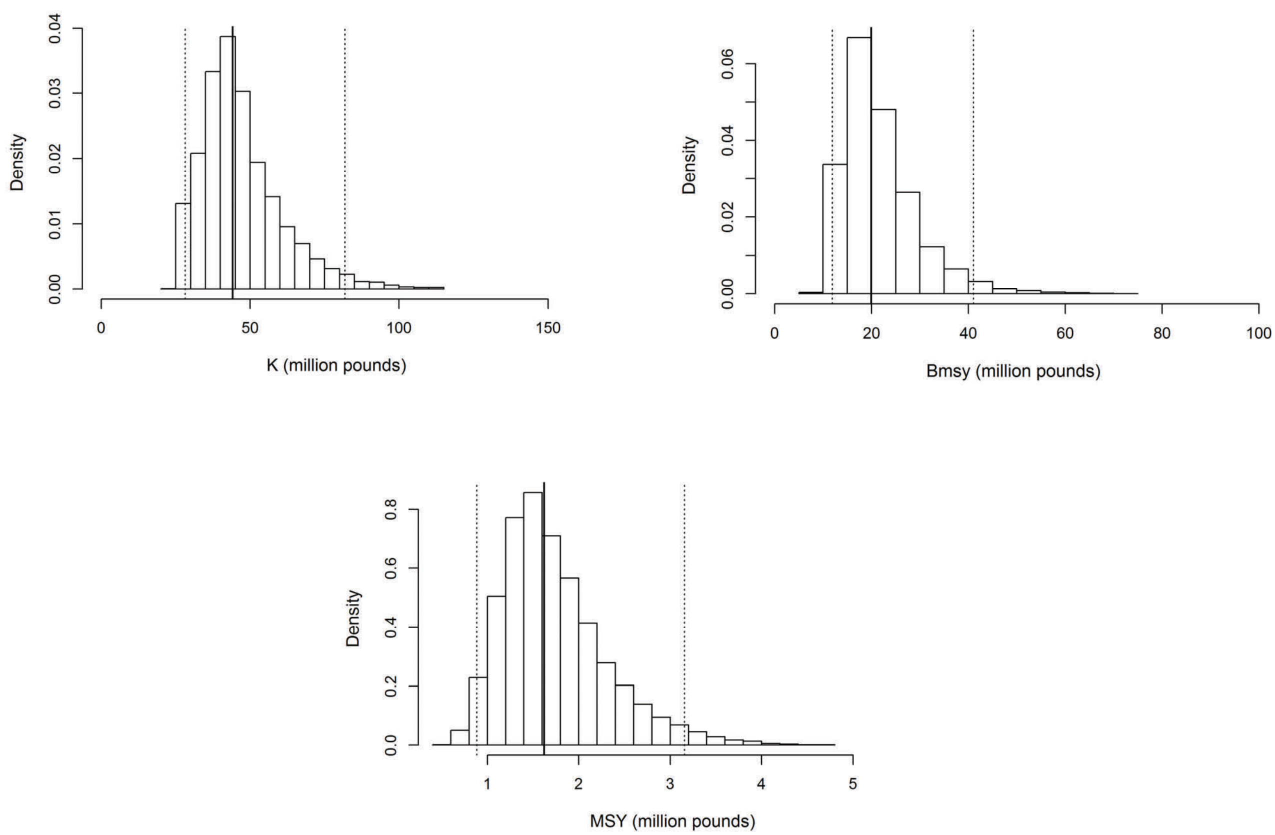


Figure 10. Distributions of K and management quantities MSYand Bmsy for accepted trajectories. Solid vertical is the mean and dotted vertical lines are the 2.5th and 97.5th percentiles.

Table 6. Parameter estimates and derived management quantities from DBSRA model .

Parameter Estimates	Mean	Median	2.5%	97.5%
Fmsy/M	0.59	0.59	0.31	0.88
Bt/K	0.17	0.17	0.06	0.26
Bmsy/K	0.46	0.46	0.31	0.62
M	0.16	0.16		

Management Quantities	Mean	Median	2.5%	97.5%
MSY (million pounds)	1.73	1.62	0.88	3.15
Bmsy (million pounds)	21.59	19.93	11.91	41.05
Fmsy	0.095	0.095	0.050	0.141
K (million pounds)	46.91	44.17	28.15	81.78
B2016 (million pounds)	8.08	7.33	2.37	18.39

process model is

$$B_t = B_{t-1} + rB_{t-1}\left(1 - \frac{B_{t-1}}{K}\right) - C_{t-1} + \varepsilon$$

where B is biomass at time t and t-1, r is the intrinsic rate of increase from the logistic growth function, K is the unfished stock size (carrying capacity in the logistic curve) , C_{t-1} is the catch (in weight) at time t-1, and ε is error. The observation model used to relate catch and effort to biomass is:

$$C_t = B_t q E_t$$

where B_t and C_t are as defined previously, E_t is the nominal effort expended, and q is the catchability coefficient.

Initially, two different values for q, one corresponding to the time frame from 2000-2011

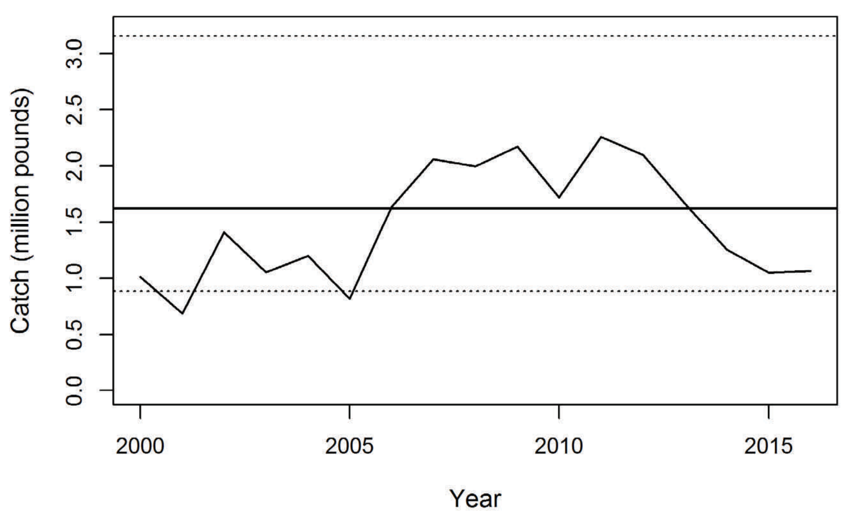


Figure 11. Comparison of catch and the median MSY estimate (solid horizontal line with 2.5th and 97.5th percentiles (dotted lines)) from the DBSRA model.

and one for post-2011, were used in an attempt to account for changes in size regulations, but the fit was no better than the fit using only one q for the entire time-series. Estimation of r, q and K was done by minimizing the sum of squared deviations between observed C_t and predicted C_t . It should be noted that the effort (trap-haul) time series may be biased because soak-time was not accounted for in the standardization. Biomass in the first year was calculated by using the relative biomass in 2000 of 0.39 from the DMF trawl survey as described in the Catch MSY section above, and the parameter K (B_1=0.39*K) during optimization.

Fishing mortality in year t was calculated as:

$$F_t = qE_t$$

From estimates of r and K, MSY was calculated as $rK/4$, B_{MSY} was derived by $K/2$ and F_{MSY} was estimated from $r/2$ (Hilborn and Walters, 1992). Errors in biomass and fishing mortality estimates were determined through bootstrap resampling of the residuals (Hilborn and Walters 1990).

Results

The model fit the data fairly well as indicated by comparison of observed and predicted catch values (Figure 12) . Estimates of model parameters and derived management quantities are listed in Table 7. Based on the coefficients of variation (SE/parameter), precision of parameters was moderate to low (all CVs>0.3). The model results were sensitive to starting values indicating that the sum of squares space did not have a well-defined global minimum. Given the current parameter estimates, the model suggests that biomass has been declining since 2007 and F had increased from 0.049/year in 2005 to its peak at 0.14/year in 2012 (Table 8; Figure 12. F has declined in recent years to an average of 0.100/ year, but remains above F_{MSY} (Table 8; Figure 12).

Delury Model A Delury depletion model (Hilborn and Walters, 1992) was used to estimate fishing mortality for channeled whelk. The Delury model treats a population as a homogenous assemblage of individuals that are equally exposed to fishing and natural mortality events. With the

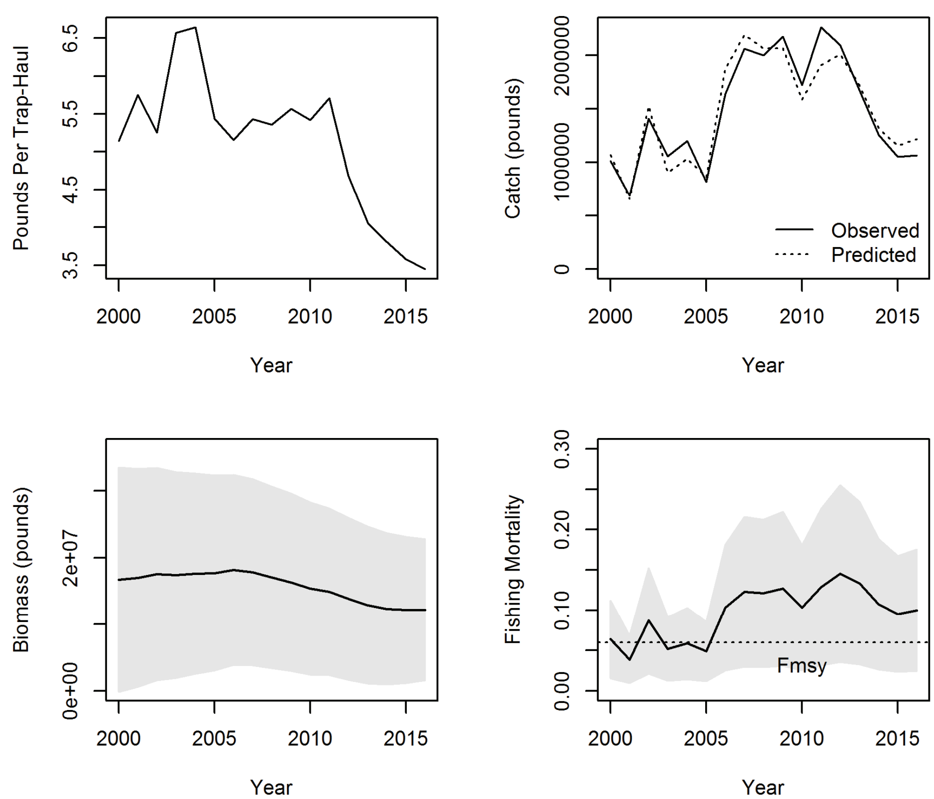


Figure 12. Pounds per trap-haul, observed and predicted catches, and estimated biomass and fishing mortality from the Biomass Dynamics model. Shaded areas are the area between 95% confidence intervals. Estimated F_{MSY} is shown as the vertical dashed line.

Table 7 Parameter estimates and derived management quantities from the biomass dynamics model .

Parameter Estimates	Mean	Median	CV
K (million pounds)	42.82	2.33E+07	0.544
r	0.123	0.063	0.513
q	3.25E-07	1.07E-07	0.329

Management Quantities	Estimate
MSY (million pounds)	1.32
Bmsy (million pounds)	21.41
Fmsy	0.062

Delury model, the objective is to estimate the recruitment and population sizes that must have occurred to produce the observed pattern in catch. The process model for abundance is :

$$N_t = (R_{t-1} + N_{t-1})e^{-M} - C_{t-1}e^{-M/2}$$

where N_t and N_{t-1} is the abundance (in numbers) at the beginning of time periods t and $t-1$, R_{t-1} is the number of individuals recruited into the population at time $t-1$, C_{t-1} is the catch (harvest in numbers) during time $t-1$, and M is the instantaneous natural mortality rate. The recruitment values do not necessarily reflect the input of "new" individuals into the population through reproduction or growth, but rather

Table 8. Observed catch (pounds), effort (trap-hauls), predicted catch, estimated biomass and fishing mortality (F) with standard errors (SE) from the biomass dynamics model

Year	Catch (pounds)	Effort (trap-hauls)	Pred Catch	Biomass (pounds)	SE	F	SE
2000	1,012,122	196,857	1,067,445	16,700,331	9,086,107	0.064	0.021
2001	687,337	119,520	657,579	16,944,774	8,837,079	0.039	0.013
2002	1,406,192	267,726	1,523,025	17,520,463	8,557,234	0.087	0.029
2003	1,053,325	160,344	905,420	17,391,154	8,334,935	0.052	0.017
2004	1,199,401	180,581	1,032,632	17,611,766	8,008,137	0.059	0.019
2005	816,914	150,122	862,333	17,691,270	7,705,169	0.049	0.016
2006	1,637,730	317,528	1,871,751	18,154,983	7,515,195	0.103	0.034
2007	2,058,197	378,837	2,190,372	17,807,196	7,445,030	0.123	0.040
2008	1,997,776	372,796	2,061,624	17,032,072	7,330,813	0.121	0.040
2009	2,171,424	390,086	2,064,458	16,299,545	7,174,320	0.127	0.042
2010	1,721,108	317,366	1,584,162	15,373,347	6,944,424	0.103	0.034
2011	2,258,616	395,498	1,909,233	14,867,722	6,658,949	0.128	0.042
2012	2,095,842	447,311	2,005,192	13,806,267	6,294,070	0.145	0.048
2013	1,666,628	410,911	1,716,346	12,864,329	6,042,269	0.133	0.044
2014	1,255,008	329,886	1,318,301	12,307,784	5,837,600	0.107	0.035
2015	1,049,638	293,442	1,156,156	12,134,565	5,643,858	0.095	0.031
2016	1,062,101	307,855	1,215,242	12,157,546	5,470,378	0.100	0.033

individuals from multiple age classes that had to enter the exploitable portion of the population at the beginning of the year to produce the observed pattern in catch.

Predicted catch is estimated from the relationship between catch and effort

$$\hat{C}_t = q\overline{N}_t E_t$$

where $\hat{C}_t$ is the predicted catch during time t, q is the average catchability coefficient, E_t is the standardized effort expended during time t , and N_t is the estimated average population size during time t. The average population size is approximated from the population size (N_t+R_t) at the beginning of time t using the equation,

$$\overline{N}_t = (N_t + R_t)e^{-M/2} - C_t / 2$$

Given estimates of average population size and observed catch, fishing mortality (F) at time t is then estimated by

$$F_t = \frac{C_t}{\overline{N}_t}$$

Estimation of parameters (i.e., N_t at the start of the time series (2000) and R_t in the subsequent periods are estimated) was done by minimizing the sum of squares between the observed catch and predicted catch at time t ($(C_t$-$\hat{C}_t)^2$) estimated in the model. Standard errors for R, N and F were determined through bootstrap resampling of the residuals (Hilborn and Walters 1990).

To use the Delury model, the number of whelks harvested are required. These data are not available and, therefore, had to be estimated by using data from biological sampling. First, total weights (TW) were assigned to individual whelk by applying a combined-sex shell-width-weight equation (no difference between sexes was indicated by analysis of covariance) developed from Wilcox (2013) and 2015 data (n=877). The resulting equation was

$$TW = 10^{-2.991\,(0.033)+2.779\,(0.018)\cdot\log 10(SW)+0.0002\;/2}$$

where TW is total weight of an individual in grams, SW is shell-width in millimeters. Parameter standard errors are shown in parentheses. Commercial shell-width samples were available only for years 2003, 2004, 2011, 2013, 2015, and 2016. The average weight was then calculated for exploitable individuals (based on the minimum legal size corresponding to each year). The average weight of a legal individual for those years with biological samples was:

Year	Weight (g)
2003	244.76
2004	238.23
2011	202.99
2013	226.43
2015	237.25
2016	247.33

Values were converted from grams to pounds, then the annual catch (pounds) was divided by the average weight of an individual to produce the number of individuals landed. The 2003 average individual weight was used for years prior to 2003, based on the assumption of a similar size structure to the catch, and prior years had the same minimum legal size as 2003. Average individual weights for years 2005-2010 were imputed from a regression (without intercept) of average weights between years 2004 and 2011. For 2012 and 2014, average weight from 2013 was used. The estimates of catch in numbers is shown in Figure 13. An alternate imputation by using the average of 2004 and 2011 for 2005 – 2010 was tried but the resulting estimates were not much different from those generated by using linear regression (Figure 13).

Results

Comparison of observed and predicted catch (Figure 14) indicated the model fit well. Estimates of recruits, abundance and fishing mortality and corresponding standard errors are listed in Table 9 The catchability coefficient (q) was estimated to be 1.988149E-6 (SE= 6.005E-08). Precision of the estimates was fairly high (coefficients of variation generally <0.2). Results showed that abundance and recruitment declined steadily after 2012 and 2011, respectively (Figure 14) . Fishing mortality was relatively stable at an average 0.35 through 2005, but then increased abruptly in 2006 to 0.62/year. Fishing mortality then remained relatively stable through 2010 around an average of 0.73, but increased thereafter to its peak at 0.90 in 2012. Fishing mortality then declined through 2015 and has remained around 0.59/ year (Table 9).

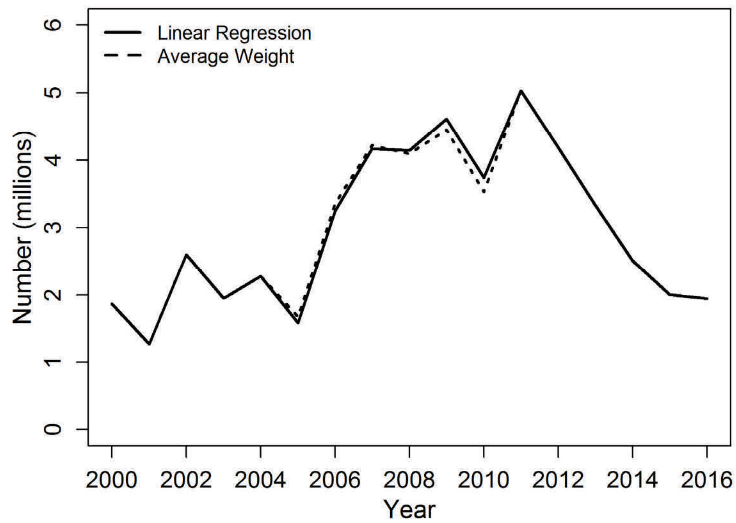


Figure 13 Estimates of channeled whelk harvest numbers by imputation method.

Catch Curve Analysis Catch curve analysis was conducted to estimate total instantaneous mortality (*Z*) from which fishing mortality (*F*) can be determined by subtraction of natural mortality (*F*=*Z* -*M*). Age data were available for only 2011 and 2015 for this analysis. The 2011 and 2015 age frequencies were generated by applying annual age-width keys to the size (shell width) frequency data collected during 2011 and 2015 DMF at-sea sampling.

Because sample sizes were small, Z was estimated for sexes combined. A generalized linear model with Poisson error structure and log-link function was used to estimate the slope of the number-age frequencies (Millar 2015). Only ages above the age at peak recruitment (highest number-at age) were used in the calculation (Smith et al., 2012).

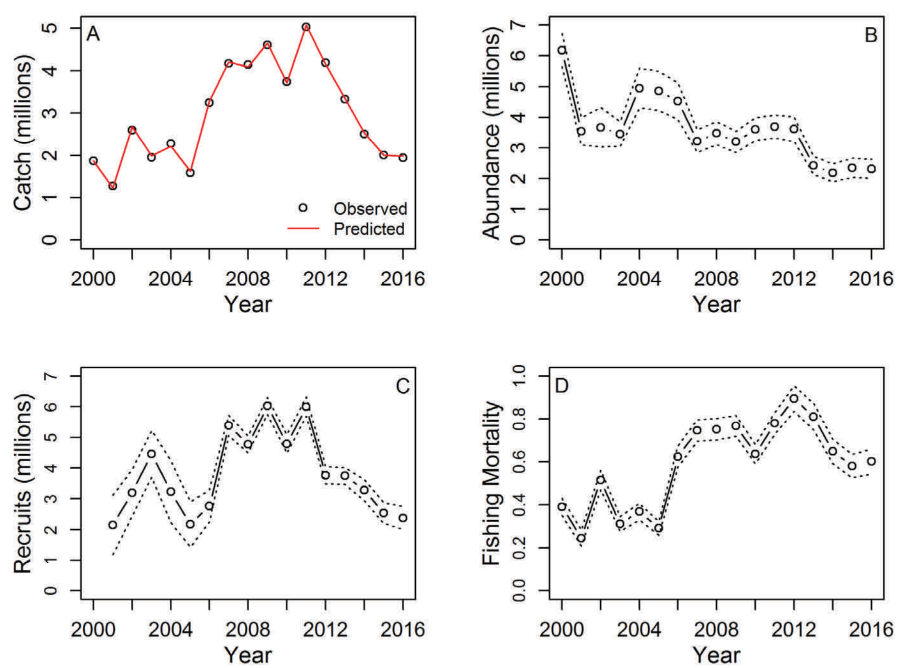


Figure 14. Results from the Delury model. A) Observed versus predicted catch, B) estimates of exploitable population size, C) estimates of recruits and D) estimates of fishing mortality. 95% confidence intervals are indicated by the dotted black lines.

Table 9. Observed catch (numbers), predicted catch, effort, and estimates of recruits, abundance and fishing mortality (F) with bootstrapped standard errors (SE) from the Delury model.

Year	Catch	Pred Catch	Effort (trap-hauls)	Recruits	SE	N	SE	F	SE
2000	1,871,074	1,868,911	196,857	0	0	6,186,346	305,470	0.39	0.023
2001	1,270,654	1,225,230	119,520	2,729,408	723,596	3,544,438	258,085	0.25	0.027
2002	2,599,576	2,681,068	267,726	2,691,252	390,615	4,173,256	537,390	0.52	0.029
2003	1,947,243	1,988,288	160,344	4,361,383	666,001	3,449,838	257,540	0.31	0.025
2004	2,278,132	2,213,257	180,581	3,053,304	512,747	4,858,751	477,837	0.37	0.026
2005	1,585,131	1,621,371	150,122	2,104,148	455,667	4,639,227	402,163	0.29	0.020
2006	3,247,940	3,283,636	317,528	3,110,822	430,095	4,283,065	343,775	0.62	0.030
2007	4,173,890	4,208,653	378,837	5,011,545	184,607	3,302,427	230,217	0.75	0.034
2008	4,144,864	4,090,497	372,796	4,991,919	168,077	3,231,714	232,132	0.75	0.033
2009	4,611,571	4,653,980	390,086	5,816,984	163,470	3,181,526	224,694	0.77	0.032
2010	3,743,652	3,714,770	317,366	4,994,441	192,543	3,411,008	230,785	0.64	0.030
2011	5,034,628	5,076,133	395,498	6,013,471	174,736	3,706,825	256,824	0.78	0.033
2012	4,188,271	4,158,462	447,311	3,698,457	164,963	3,635,543	251,129	0.90	0.038
2013	3,330,541	3,350,724	410,911	3,863,704	158,985	2,383,362	187,086	0.81	0.034
2014	2,507,973	2,536,458	329,886	3,298,968	192,287	2,248,921	155,509	0.65	0.032
2015	2,001,894	2,010,510	293,442	2,405,045	166,117	2,412,448	178,180	0.58	0.027
2016	1,943,051	1,974,798	307,855	2,290,414	179,095	2,257,216	146,389	0.60	0.035

Results

Estimates of Z for 2011 and 2015 were 0.94 and 0.74, respectively (Table 10). Subtracting M (=0.16) from Z resulted in F estimates of 0.78 and 0.58 for 2011 and 2015, respectively.

Statistical Catch-At-Age Model (SCA) The model structure of the single sex population model is age-based and projects the population numbers-at -age forward through time given model estimates of recruitment and age-specific total mortality. The model allows missing values. The population numbers-at-age matrix has dimensions Y x A, where Y is the number of years and A is the oldest age group. The time horizon is 2000-2016. The number of year classes in the model was 12, representing ages 4 through 15+.

Population numbers-at-age ($a<A$) are calculated through time by using the exponential cohort survival model

$$\hat{N}_{y,a} = \hat{N}_{y-1,a-1} e^{-\hat{F}_{y-1,a-1} - M}$$

where $N_{y,a}$ is abundance of age a in year y, $N_{y-1,a-1}$ is abundance of age $a-1$ in year $y-1$, $F_{y-1,a-1}$ is the instantaneous fishing mortality rate for age $a-1$ in year $y-1$, and M is the instantaneous natural mortality (assumed constant across years and ages). For the plus group (A), numbers-at-age are the sum of survivors of $A-1$ in year $y-1$ and survivors from the plus group in year $y-1$:

$$\hat{N}_{y,A} = \hat{N}_{y-1,A-1} e^{-F_{y-1,A-1} - M} + \hat{N}_{y-1,A} e^{-F_{y-1,A} - M}$$

Table 10. Catch curve estimates of instantaneous total mortality and fishing mortality for the channeled whelk (sexes combined) by year. *nlength* is the number of length samples

Year	n_{length}	Z	SE	M	F
2011	5,602	0.94	0.11	0.16	0.78
2015	430	0.74	0.13	0.16	0.58

Recruitment (numbers of age-4 whelk) in year y ($N_{y,1}$) is estimated as a log-normal deviation from average recruitment:

$$\hat{N}_{y,4} = \breve{N}_4 \cdot \exp^{\hat{e}_y}$$

where $N_{y,4}$ is the number of age 4 whelk in year y, $\breve{N}_4$ is the average recruitment parameter, e_y are independent and identically distributed normal random variables with zero mean and constant variance and are constrained to sum to zero over all years.

The initial population abundance-at-age for ages 4-15+ in 2000 was calculated by using the estimate of N_4 in 2000:

$$\hat{N}_{2000,a} = \hat{N}_{2000,a-1} e^{-\hat{F}_{2000,a-1} - M}$$

An attempt was made to estimate N of ages 4-10 as separate parameters but the estimates were very uncertain.

Estimation of fishing mortality-at-age is accomplished by assuming that fishing mortality can be decomposed into yearly and age-specific components (separability assumption):

$$\hat{F}_{y,a} = \hat{F}_y \cdot \hat{s}_a$$

where F_y is the fully-recruited fishing mortality in year y and s_a is the average selectivity value of fish of age a. The dimensions of the F-at-age matrix are Y x A. Similar to recruitment, F_y is modeled as a log-normal deviation from average fishing mortality:

$$\hat{F}_y = \dot{F} \cdot \exp^{d_y}$$

where F_y is the fishing mortality in year y, $\dot{F}$ is the average recruitment parameter, and d_y are independent and identically distributed normal random variables with zero mean and constant variance and are constrained to sum to zero over all years. A fishing mortality penalty is imposed to ensure that extremely small Fs are not produced during the early phases of the estimation process:

$$P_F = \left\{ \begin{array}{l} phase < 3, 10 \cdot \sum_y (F_y - 0.40)^2 \\ phase \geq 3, 0.000001 \cdot \sum_y (F_y - 0.40)^2 \end{array} \right\}$$

Selectivity is modeled by using the logistic equation where α and β are parameters estimated in the model.

$$s_a = \frac{1}{1 + e^{\alpha - \beta \cdot a}}$$

To ensure at least one age had a maximum selectivity of 1, s_a is divided by max(s_a). Two regulatory periods (2000-2013, 2014-2016) were assumed for which selectivity was estimated.

For ease of computation, total mortality-at-age (Z) is calculated as

$$Z_{y,a} = F_{y,a} + M$$

and fills a matrix of dimension Y x A.

Catch (harvest in numbers), age composition (proportions-at-age) and length compositions are the primary data from which fishing mortalities, selectivity, numbers of ages 4-10 in 2000 and recruitment numbers are estimated. Given estimates of F, M, and population numbers, predicted catch-at-age is computed from Baranov's catch equation (Ricker, 1975):

$$\hat{C}_{y,a} = \frac{\hat{F}_{y,a}}{\hat{F}_{y,a} + M} (1 - e^{-\hat{F}_{y,a} - M}) \hat{N}_{y,a}$$

where $\hat{C}_{y,a}$ is the predicted catch of age a during year y and other variables are as defined above. All predictions are stored in a matrix of dimension Y x A. Predicted catch-at-age data are then compared to the observed total catch and proportions of catch-at-age through the equations:

Predicted Total Catch

$$\hat{C}_y = \sum_a \hat{C}_{y,a}$$

Predicted Proportions of Catch-At-Age

$$P'_{y,a} = \frac{\hat{C}_{y,a}}{\sum_a \hat{C}_{y,a}}$$

where $\hat{C}_{y,a}$ is the predicted catch in year y and $\acute{P}_{y,a}$ is the predicted proportions of age a in the catch during year y. Total catch CVs were assumed equal to 0.01 since there is no indication that error is present in the reported landings. This decision effectively causes the model to be influenced mostly by catch numbers.

Length Composition Data

Length data from 2003, 2004, 2010, 2011, 2013, 2015 and 2016 were available from DMF commercial trap sampling. In the sampling, all individuals regardless of size are measured. To generate length frequencies that would reflect individuals harvested, individuals below each year's minimum legal size were removed.

Length data were incorporated into the model by first creating an age-width key from inputted mean shell width-at-age estimates and a coefficient of variation (ALK CV) estimated in the model. These values are used in a cumulative normal distribution to calculate probabilities for a given width and age which, when multiplied by the predicted age composition, produce predicted proportions-at-width. For whelk, width bins ranged from 10 mm to 150 mm shell width by 5-mm increments. The mean widths-at-age for ages 4-14 were calculated from Wilcox (2013) and 2015 data for sexes combined. The mean size of age 14 was assigned to age 15+. The mean width-at-age values used were:

Age	Mean Width (mm)
1	26.4
2	34.7
3	50.4
4	57.0
5	66.2
6	72.9
7	78.4
8	82.5

Age	Mean Width (mm)
9	91.0
10	99.9
11	106.1
12	115.0
13	120.0
14	127.3
15+	127.3

The DMF spring survey index (ln(x+1)-transformed number per tow) for whelk was assumed an aggregate index of ages 4-6 (based on size distribution analysis) and was incorporated into the model by linking them to aggregate age abundances and the time of year:

$$\hat{I}_{y,\sum a} = \hat{q} \cdot \sum_{a} \hat{N}_{y,a} \cdot e^{-pZ_{y,a}}$$

where $\hat{I}_y$ is the predicted index in year y, q is the catchability coefficient, $N_{y,a}$ is the abundance of age a in year y, p is the fraction of total mortality that occurs prior to the survey, and $Z_{y,a}$ is the total instantaneous mortality rate. The value of p was set to 0.333 to reflect the timing of the trawl survey which takes place in May. The annual CVs were calculated by dividing model estimates of standard errors by the index.

Female spawning stock biomass (SSB; pounds) in each year was derived from abundance at age ($N_{y,a}$), estimates of proportion of females-at-age (sr_a), proportion female mature-at-age (m_a), and weights-at-age (sw_a):

$$SSB_y = \sum_{a=1}^{A} N_{y,a} \exp^{-pF \cdot F_{y,a} - pM \cdot M_{y,a}} \cdot sr_a \cdot m_a \cdot sw_a / 1000 \cdot 2.21$$

where pF (=0.26) and pM (=0.50) are the proportions of fishing and natural mortality that occur prior to spawning. Values for sr_a, m_a and sw_a were calculated from Wilcox (2013) and 2015 data. The calculated values used in the model are:

Age	Prop. Female	Prop. Mature	Weight (g)
1	0.50	0.000	8.9
2	0.50	0.000	19.0
3	0.53	0.000	53.4
4	0.50	0.000	74.9
5	0.50	0.000	113.3
6	0.50	0.001	148.2
7	0.58	0.005	180.9
8	0.51	0.038	208.8
9	0.64	0.241	274.1
10	0.79	0.717	354.2
11	0.86	0.953	419.5
12	1.00	0.994	523.8
13	1.00	0.999	589.4
14	1.00	1.000	694.7
15+	1.00	1.000	694.7

For catch and the DMF spring survey index, lognormal errors were assumed throughout and the concentrated likelihood, weighted for variation in each observation, was calculated. The generalized concentrated negative log-likelihood ($-L_l$)(Parma 2002; Deriso et al. 2007) is

$$-L_l = 0.5 \cdot \sum_i n_i \cdot \ln\left(\frac{\sum_i RSS_i}{\sum_i n_i}\right)$$

where n_i is the total number of observations and RSS_i is the weighted residual sum-of-squares from dataset i. The weighted lognormal residual sum-of-squares (RSS_c) for catch is calculated as

$$RSS_c = \lambda_c \sum_y \left(\frac{\ln(C_y + 1e^{-5}) - \ln(\hat{C}_y + 1e^{-5})}{CV_y} \right)^2$$

where C_y is the observed catch in year y, $_y$ is the predicted catch in year y, CV_y is the coefficient of variation for observed catch in year y, and λ_c is the relative weight (Parma 2002; Deriso et al. 2007). The weighted residual sum of squares for the DMF survey is given by:

$$RSS_I = \lambda_I \sum_y \left(\frac{\ln(I_y + 1e^{-5}) - \ln(\hat{I}_y + 1e^{-5})}{CV_y} \right)^2$$

where I_y is the observed index in year y, $\hat{I}_y$ is the predicted index in year y and CV_y is the coefficient of variation for the observed index in year y.

For the catch (C) age and shell-width (L) compositions, multinomial error distributions were assumed throughout and the negative log-likelihoods were calculated using the general equation,

$$-L_c = \lambda_c \sum_y - n_{c,y} \sum_a P^c_{y,a} \cdot \ln(\hat{P}^c_{y,a} + 1e^{-7})$$

$$-L_L = \lambda_L \sum_y - n_{L,y} \sum_l P^L_{y,l} \cdot \ln(\hat{P}^L_{y,l} + 1e^{-7})$$

where n_y is the effective sample size (ESS) of fish aged or measured for length in year y and $P_{y,a}$ are the observed proportions of catch-at-age or catch–at -length, and λ_c and λ_L are the relative weights. The multinomial probability assumes that the number of fish aged or measured used to apportion the catch into age or length classes are sampled randomly and independently of each other. This is truly not the case because gear and fishing practices collect fish in groups or clusters; thus, the effective sample size is much smaller than the actual number of fish aged or measured. The ESS for the catch age and length composition data were derived using the equation 1.8 method of Francis (2011). The derived multiplier was applied to the input ESS (50 for age composition and 100 for length composition) and then input ESSs are replaced with the new computed values.

The total negative log-likelihood of the model is

$$f = -L_I - L_c - L_L + P_F$$

The total log-likelihood is used by the auto-differentiation routine in AD Model Builder to search for the "best" selectivity parameters, average recruitment, recruitment deviations, average F, fishing mortality deviations, abundance-at-age in 2000, catchability coefficient and length coefficient of variation that minimize the total log-likelihood. AD Model Builder allows the minimization process to occur in phases. During each phase, a subset of parameters is held fixed and minimization is done over another subset of parameters until eventually all parameters have been included. In this model, average recruitment, average fishing mortality and selectivity parameters were solved during phase 1, while recruitment and fishing mortality deviations, the catchability coefficient and coefficient of variation for length composition were solved during phase 2.

The estimation proceeds by first calculating $F_{a,y}$ using initial starting values for F_y and s_a (initial parameters estimates are used for the selectivity equations) and, with M (which is fixed at 0.16) and initial values of average recruitment by year, the abundance matrix is filled. All predicted values were calculated using the equations described above.

Initial starting values for all parameters were selected based on trial-and-error. They were:

Parameter	Value
Average Recruitment	8,886,110
Average Fishing Mortality	0.36
Selectivity Logistic α	9.78
Selectivity Logistic β	1.73
Length CV	0.1
Catchability Coefficient	5.00E-04

All parameters except those for selectivity and length CV were estimated on the $\log_e$-scale. Based on preliminary analyses, a relative weight of 5 was used for the age and length compositions and relative weight for the DMF index was set to 1.

Catch in numbers was available for years 2000-2016, age data were available for years 2011 and 2015, shell-width data were available for years 2003, 2004, 2010, 2011, 2013, 2015 and 2016, and DMF spring index for years 2000-2016. The average size (width) composition for 2003-2004 was used to represent the size composition in 2000 and the age compositions for 2003 and 2004 were

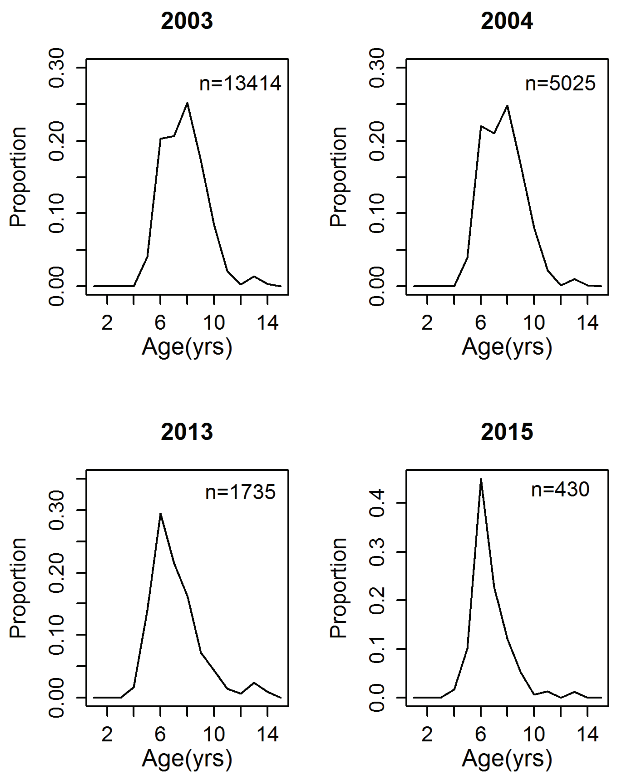


Figure 15. Age frequencies of harvested whelk estimated for 2003, 2004, 2011, 2013 and 2015 .

derived from an age-width key using 2011 data (Figure 15). For 2013, the age composition was estimated using a combined age-width key of 2011 and 2015 data (Figure 15).

Model fit for all components is checked by using standardized residuals plots. Standardized residuals (r) for log-normal errors were calculated as:

$$r_y = \frac{\ln I_y - \ln \hat{I}_y}{\sqrt{\ln(CV_y^2 + 1)}}$$

For age and length composition (multinomial) data, standardized residuals were calculated as:

$$r_{y,a} = \frac{P_{y,a} - \hat{P}_{y,a}}{\sqrt{\frac{P_{y,a}(1 - \hat{P}_{y,a})}{\hat{\bar{n}}_y}}}$$

where n_y is the average effective sample size.

Results

Resulting contributions to converged total likelihood (5372.8) were 2.8, 177.3, 5171.9 and 109.8 for catch, age composition, size composition and DMF index, respectively. Estimates of fully-recruited fishing mortality, recruitment, parameters of the selectivity, catchability coefficient and length composition CV are given in Table 11 and, for recruitment and fishing mortality, are shown graphically in Figure 16. The estimated average effective sample sizes for the age and size composition data were 2.7 and 32, respectively. Graphs depicting the observed and predicted values and residuals for catch and DMF index, catch age composition and size age composition are given in Appendix Figures 1-4. The model fit the observed total catches well (Appendix Figure 1) but the observed DMF index poorly (Appendix Figure 2). Catch age compositions were fitted fairly well in 2003, 2004 and 2013 but were poorly fitted in the remaining years (Appendix Figure 3). Observed size composition data were fitted very well (Appendix Figure 4).

The estimates of age-4 numbers (R) for 2000-2012 were low to moderately precise ($CV \leq 0.20$), but the precision declined near the terminal year (Table 11). This was due to the limited amount of information available on young age classes in years approaching 2016. Age-4 numbers showed declining recruitment after 2009.

The estimates of fully-recruited fishing mortality were low to moderately precise (CV<0.2) except in 2016 (Table 11). Fishing mortality increased from an average of 0.37/year during 2000-2005 to its peak of 0.65/year in 2014 and then it declined to 0.32 in 2016 (Figure 16) .

Whelk abundance (4+) increased steadily from 2000 through 2009 when it peaked around 30 million snails (Table 12; Figure 17). Total abundance declined thereafter to 24.6 million snails in 2016 (Table 12; Figure 17).

Based on the precision of estimates, two period selectivity functions were justified to account for changes to size regulations (Table 11; Figure 17).

Female spawning stock biomass declined from 0.97 million pounds in 2002 to 0.56 million pounds in 2008. SSB increased through 2011 but then declined through 2015 (Table 13; Figure 18).

Based on a four-year peel, no well-defined retrospective pattern in estimates of recruits was present. In contrast, fully-recruited F was mostly under-estimated near the terminal year and female SSB tended to be over-estimated near the terminal year (Figure 19).

Reference Points

Fishing Mortality Threshold Yield per recruit and spawning biomass per recruit analysis (YPR and SPR; Gabriel et al. 1989) were used to estimate fishing mortality reference points (YPR: $F_{0.10}$ and F_{max}; SPR: F at % maximum spawning biomass per recruit) to which estimated fishing mortality rates could be compared to determine overfishing status. Estimates of selectivity-at-age from the SCA model and natural mortality described above were used in YPR. Additionally, the proportions of females mature-at-age were used in SPR. Both methods require average weight for each age and these were developed from Wilcox (2013) and 2015 data. The selectivity estimates from the SCA model for the period 2014-2016 (Figure 17) were used in the computation.

Since whelk spawn in summer, correct calculation of SPR requires estimates of the proportion of natural (*pM*) and fishing mortality (*pF*) that occurs prior to spawning. *pF* was estimated by using the monthly landings of channeled whelks reported by the National Marine Fisheries Service (http://www.st.nmfs.noaa.gov/commercial-fisheries/index)

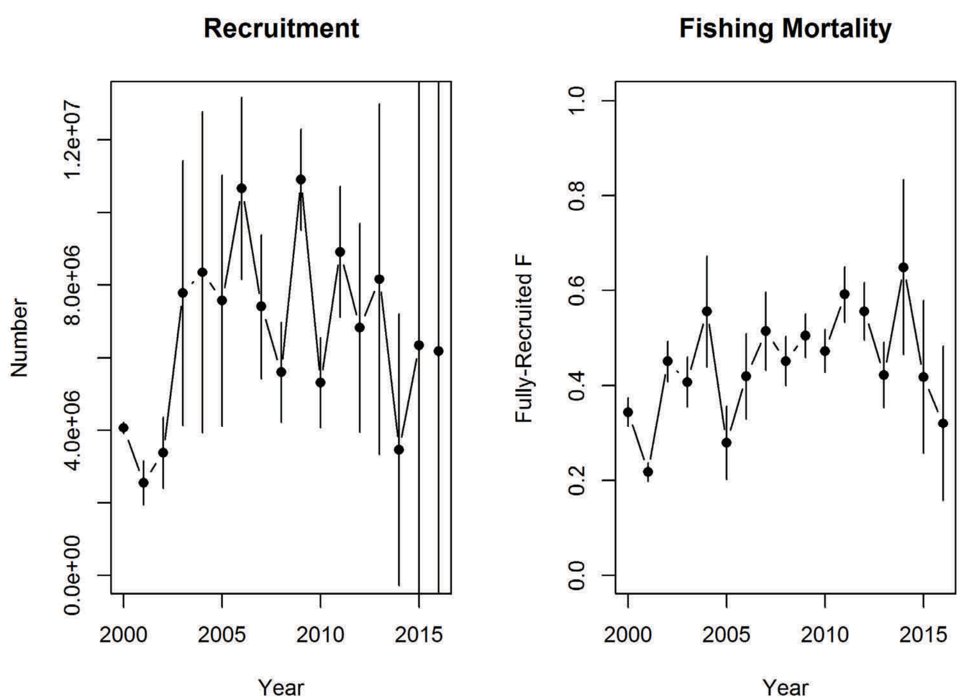


Figure 16. Recruits (age-4 numbers) and fishing mortality and associated 95% confidence intervals.

Table 11. Estimates of parameters, associated standard errors and coefficients of variation from the whelk statistical catch-at-age model. R is recruitment abundance, F is fully-recruited fishing mortality and SSB is female spawning stock biomass.

Parameter	Estimates	SE	CV
R_{2000}	4,065,800	80,032	0.020
R_{2001}	2,550,700	310,900	0.122
R_{2002}	3,377,400	500,610	0.148
R_{2003}	7,778,700	1,859,200	0.239
R_{2004}	8,349,100	2,257,700	0.270
R_{2005}	7,570,900	1,767,400	0.233
R_{2006}	10,659,000	1,283,800	0.120
R_{2007}	7,405,900	1,013,400	0.137
R_{2008}	5,604,400	700,740	0.125
R_{2009}	10,900,000	709,030	0.065
R_{2010}	5,315,400	636,910	0.120
R_{2011}	8,918,800	920,650	0.103
R_{2012}	6,820,700	1,469,600	0.215
R_{2013}	8,162,600	2,468,500	0.302
R_{2014}	3,457,100	1,910,200	0.553
R_{2015}	6,337,200	4,460,700	0.704
R_{2016}	6,183,100	4,529,100	0.732
F_{2000}	0.344	0.015	0.045
F_{2001}	0.217	0.010	0.046
F_{2002}	0.451	0.022	0.048
F_{2003}	0.408	0.027	0.066
F_{2004}	0.556	0.060	0.107
F_{2005}	0.279	0.040	0.142
F_{2006}	0.420	0.046	0.109
F_{2007}	0.514	0.042	0.081
F_{2008}	0.452	0.026	0.058
F_{2009}	0.505	0.023	0.046
F_{2010}	0.473	0.023	0.049
F_{2011}	0.592	0.030	0.051
F_{2012}	0.556	0.031	0.055
F_{2013}	0.422	0.035	0.083
F_{2014}	0.649	0.094	0.145
F_{2015}	0.418	0.082	0.196
F_{2016}	0.320	0.083	0.259

Parameter	Estimates	SE	CV
SSB_{2000}	880,380	86,259	0.098
SSB_{2001}	909,990	87,628	0.096
SSB_{2002}	972,500	89,970	0.093
SSB_{2003}	883,520	86,530	0.098
SSB_{2004}	794,830	91,577	0.115
SSB_{2005}	680,670	100,630	0.148
SSB_{2006}	678,000	107,250	0.158
SSB_{2007}	591,870	101,750	0.172
SSB_{2008}	558,050	98,569	0.177
SSB_{2009}	639,050	109,370	0.171
SSB_{2010}	699,540	99,493	0.142
SSB_{2011}	745,310	83,894	0.113
SSB_{2012}	723,440	72,157	0.100
SSB_{2013}	684,890	71,847	0.105
SSB_{2014}	674,350	86,191	0.128
SSB_{2015}	640,810	124,210	0.194
SSB_{2016}	740,820	193,940	0.262
q	1.39E-07	2.08E-08	0.150
ALK CV	0.03318	0.00114	0.034
Selectivity 2000-2013			
a	18.269	1.627	0.089
b	6.2014	0.557	0.090
Selectivity 2014-2016			
a	14.885	1.464	0.098
b	3.6146	0.400	0.111

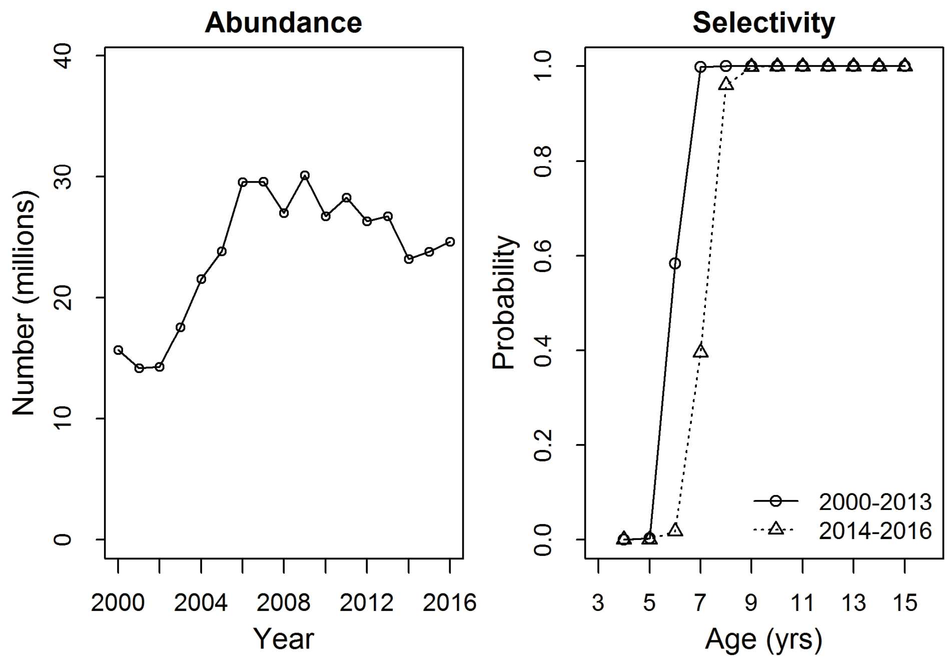


Figure 17. Plots of total abundance (left) and estimated period age-specific selectivities (right).

and calculating the proportion of annual landings that occurred prior to July (mean of years 2006-2015 = 0.26). *pM* was calculated assuming equal M across months (*pM* = 0.50). R function *ypr* and *sbpr* in package *fishmethods* was used for YPR and SPR analysis. *M* (=0.16) was assumed constant across ages.

The fishing mortality to achieve maximum sustainable yield (F_{MSY}) is often used as an overfishing limit in many teleost stocks (Gabriel and Mace 1999). The proxy for F_{MSY} is $F_{40\%}$ from a spawning biomass per recruit analysis (Gabriel and Mace 1999).

Female Spawning Stock Biomass Threshold
Female SSB_{MSY} was developed as an SSB threshold using a stochastic projection drawing recruitment from empirical estimates, a distribution of starting population abundance at age and the F_{MSY} proxy

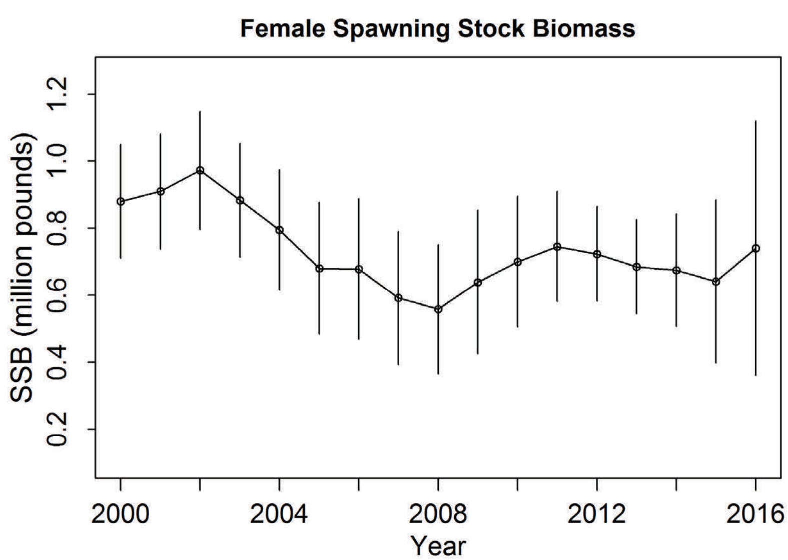


Figure 18. female spawning stock biomass (pounds) with 95% confidence intervals.

Table 12. Estimates of age-specific whelk abundance (numbers) for ages 4-15+.

Abundance	Age											
Year	4	5	6	7	8	9	10	11	12	13	14	15+	Total
2000	4,065,840	3,464,680	2,949,530	2,056,120	1,242,240	750,150	452,991	273,546	165,185	99,750	60,236	91,823	15,672,091
2001	2,550,750	3,464,680	2,949,530	2,056,120	1,242,240	750,150	452,991	273,546	165,185	99,750	60,236	91,823	14,157,001
2002	3,377,390	2,173,600	2,950,590	2,214,460	1,410,520	851,926	514,450	310,659	187,597	113,283	68,408	104,282	14,277,165
2003	7,778,660	2,878,020	1,849,860	1,932,910	1,202,820	765,650	462,435	279,250	168,630	101,830	61,492	93,738	17,575,295
2004	8,349,130	6,628,520	2,449,660	1,242,730	1,096,150	681,716	433,943	262,092	158,269	95,573	57,713	87,979	21,543,475
2005	7,570,920	7,114,640	5,639,580	1,509,230	607,670	535,565	333,077	212,019	128,054	77,328	46,696	71,183	23,845,962
2006	10,659,100	6,451,510	6,057,910	4,083,630	973,138	391,662	345,188	214,678	136,652	82,535	49,840	75,977	29,521,820
2007	7,405,910	9,083,090	5,491,090	4,041,400	2,288,330	544,983	219,341	193,314	120,226	76,529	46,222	70,461	29,580,895
2008	5,604,400	6,310,880	7,728,850	3,466,490	2,060,360	1,165,750	277,633	111,740	98,481	61,247	38,987	59,442	26,984,260
2009	10,900,300	4,775,740	5,370,920	5,061,290	1,881,720	1,117,700	632,393	150,609	60,616	53,424	33,225	53,395	30,091,332
2010	5,315,380	9,288,580	4,063,810	3,409,710	2,605,230	967,882	574,899	325,278	77,467	31,179	27,479	44,554	26,731,448
2011	8,918,820	4,529,460	7,904,630	2,628,730	1,812,370	1,383,820	514,109	305,369	172,778	41,148	16,561	38,262	28,266,057
2012	6,820,670	7,600,090	3,853,300	4,769,060	1,240,090	854,248	652,252	242,321	143,933	81,437	19,395	25,840	26,302,636
2013	8,162,580	5,812,170	6,466,200	2,374,350	2,332,540	606,040	417,475	318,759	118,424	70,341	39,799	22,107	26,740,784
2014	3,457,090	6,955,670	4,946,900	4,307,460	1,327,170	1,303,000	338,546	233,210	178,065	66,154	39,294	34,582	23,187,140
2015	6,337,220	2,945,920	5,925,410	4,168,440	2,840,170	606,231	580,503	150,721	103,823	79,273	29,451	32,889	23,800,051
2016	6,183,070	5,400,190	2,509,850	5,012,980	3,011,640	1,620,270	340,328	325,738	84,573	58,258	44,482	34,980	24,626,359

Table 13. Estimates of age-specific whelk female spawning stock biomass (pounds) for ages 4-15+.

Female Spawning Stock Biomass (pounds)						Age							
Year	4	5	6	7	8	9	10	11	12	13	14	15	Total
2000	0	0	0	0	9,870	58,902	170,243	174,878	159,787	109,665	78,054	118,985	880,384
2001	0	0	0	0	10,202	60,883	175,969	180,759	165,161	113,353	80,679	122,987	909,993
2002	0	0	0	0	10,901	65,065	188,056	193,176	176,506	121,140	86,221	131,435	972,500
2003	0	0	0	0	9,401	59,136	170,951	175,605	160,451	110,121	78,378	119,480	883,523
2004	0	0	0	0	8,243	50,660	154,345	158,576	144,892	99,442	70,778	107,894	794,830
2005	0	0	0	0	4,911	42,771	127,316	137,859	125,986	86,467	61,542	93,815	680,668
2006	0	0	0	0	7,582	30,157	127,211	134,580	129,621	88,978	63,330	96,540	677,998
2007	0	0	0	0	17,396	40,941	78,868	118,240	111,266	80,497	57,304	87,354	591,865
2008	0	0	0	0	15,921	89,019	101,472	69,471	92,644	65,484	49,130	74,908	558,048
2009	0	0	0	0	14,340	84,176	227,957	92,351	56,240	56,334	41,294	66,363	639,055
2010	0	0	0	0	20,021	73,505	208,972	201,129	72,478	33,153	34,439	55,839	699,537
2011	0	0	0	0	13,502	101,879	181,158	183,042	156,704	42,416	20,121	46,486	745,308
2012	0	0	0	0	9,326	63,485	232,008	146,623	131,776	84,740	23,787	31,692	723,436
2013	0	0	0	0	18,162	46,632	153,751	199,697	112,257	75,782	50,538	28,072	684,891
2014	0	0	0	0	9,807	94,533	117,538	137,730	159,120	67,187	47,037	41,396	674,348
2015	0	0	0	0	22,235	46,707	214,041	94,534	98,531	85,505	37,441	41,812	640,806
2016	0	0	0	0	24,158	128,033	128,704	209,548	82,321	64,449	58,001	45,611	740,826

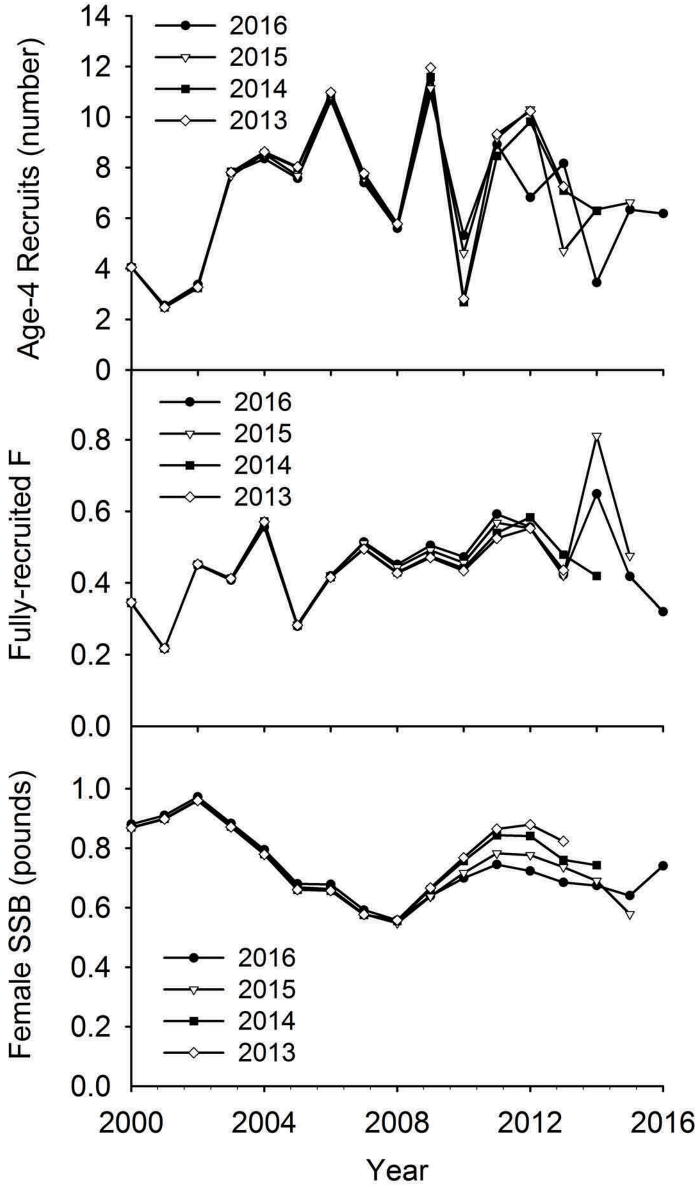


Figure 19. Retrospective analyses for recruits, fully-recruited fishing mortality and female spawning stock biomass..

($F_{40\%}$). Empirical estimates of recruitment, selectivity, female proportions-at-age and proportions mature-at-age, and the starting population came from the SCA model results. The selectivity estimates for the two periods (Figure 17) were used for corresponding years and the estimates for second period (2014-2016) were used in the projection beyond 2016. Because of large uncertainty in recruitment estimates near the terminal year, the projection began at year 2012. However, the fishing mortality estimates from 2012 -2016 were used to project the population through 2016 given that the estimates were fairly precise. Beyond 2016, the F_{MSY} proxy of 0.093 was used. Recruitment for years 2013 and later were randomly drawn from values for years 2000-2012. The female SSB_{MSY} was determined as the median female SSB in the last projection year of 1,000 simulations when the population was projected forward 200 years.

Results

The yield-per-recruit curve, female SPR and the % maximum SPR curves are shown in Figures 20 and 21. The estimate of $F_{0.10}$ was 0.138 with corresponding YPR = 0.130 pounds and F_{MAX} was 0.226 with corresponding YPR = 0.138 pounds

(Figure 20). For SPR analysis, F levels at 40, 30, 20, 10, 5, 2.5 and 1.0% of maximum SPR are listed in Table 14.

Based on the stochastic projections using the F_{MSY} proxy of 0.093, SSB_{MSY} was estimated to be 9.5 million pounds (Figure 22).

Determination of Stock Status

A summary of all management values and reference points generated by the assessment methods used is shown in Table 15.

Biomass Models Comparison of *MSY* estimates from the Catch MSY (1.2 million pounds), DBSRA (1.6 million pounds) and Biomass Dynamics (1.3 million pounds) models to historical landings showed that whelk landings in Nantucket Sound exceeded *MSY* during 2006-2013, but recently have been below *MSY* (Figure 23A). Annual fishing mortality estimates from the Biomass Dynamics model have been above the F_{MSY} estimates from Catch MSY (0.067), DBSRA (0.092) and Biomass Dynamics (0.062) models since 2006 (Figure 23B) and biomass estimates have been below B_{MSY} since 2000 (Figure 23C). Using F_{MSY} and B_{MSY} as overfishing and overfished thresholds, these results imply that overfishing is occurring and the Nantucket Sound whelk population is overfished.

Abundance Models Comparison of *F* point estimates generated by Catch Curve Analysis, the Delury model and the SCA model to the F_{MAX}, $F_{0.10}$ and F_{MSY} proxy ($F_{40\%}$) showed that fishing mortality greatly exceeded most reference points, indicating overfishing has been occurring since 2001 (Figure 24). The entire time series of female spawning stock biomass estimates from the SCA model has been well below the female SSB_{MSY} threshold (9.4 million pounds), indicating the Nantucket Sound whelk population is overfished as well (Figure 24).

Conclusions

The life history characteristics of channeled whelk, specifically the slow maturation, slow growth rate and lack of a broad scale dispersal mode for larvae, make them especially prone to depletion. This type of life history strategy is common in many marine snails, and the pattern of fishery booms followed by stock depletion has been consistent globally among fisheries for whelk and conch (Fahey et al. 2000, Fahey 2001, Leiva and Castilla 2002, Power et al.

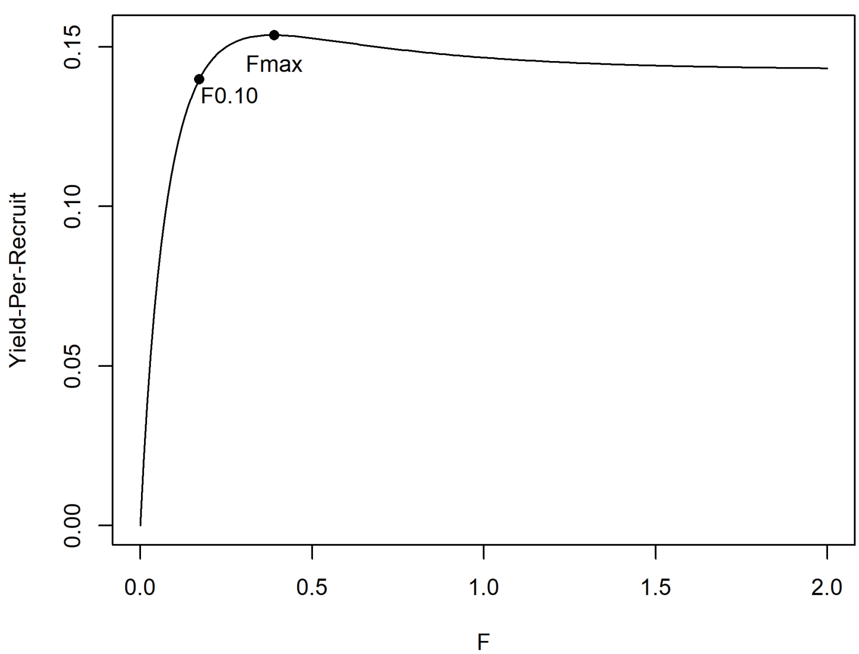


Figure 20. Yield-per-recruit (pounds) versus fishing mortality for channeled whelk. F0.10 and Fmax reference points are shown.

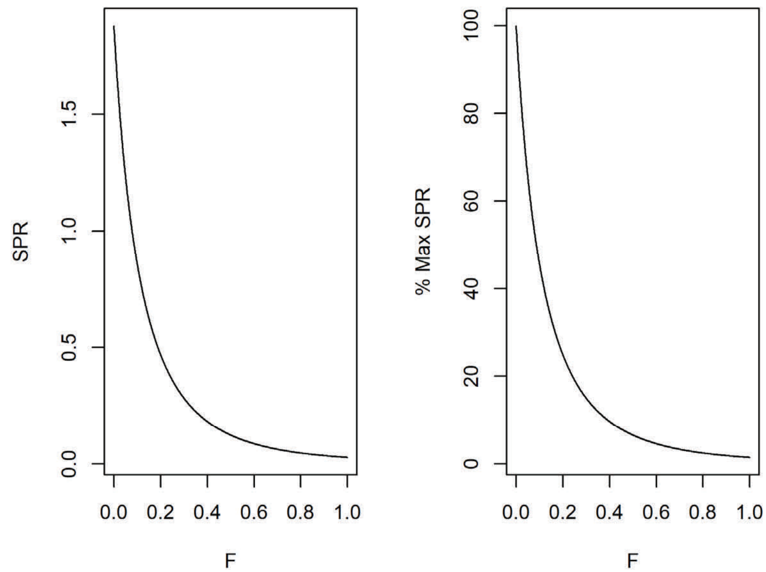


Figure 21. Female spawning stock biomass per recruit (SPR in pounds; left) and percent maximum SPR (right) versus fishing mortality for channeled whelk.

2009). This pattern has been observed for common whelk (*Buccinum undatum*) in Canada (Gendron 1992), the Netherlands (de Voys and van der Meer 2009) and Ireland (Fahey et al. 2005, 2008), neptune whelk (*Neptunea arthritica*) in Japan (Miranda et al. 2008), knobbed whelk in Georgia (Power et al 2009) and South Carolina (Eversole et al 2008), black murex snail (*Hexaplex nigritus*) in Mexico (Bueno 2001), fine snails (*Zidona dufresnei*) and loco (*Concholepus concholepus*) in South America (Gimenez et al. 2005, Cleodon et al. 2005), topshell whelk (*Cittarium pica*) in Costa Rica and the US Virgin Islands (Schmidt et al. 2002, Toller and Gordon 2005), abalone (*Haliotis rufescens*) in California (Karpov et al. 2000), and queen conch (*Strombus gigas*) in Panama (Cipriani et al 2008) among others.

There is no evidence to suggest that the fate of channeled whelk in Massachusetts will be any different if the high harvest rates continue. This is supported by the dramatically declining trend of channeled whelk relative abundance in the MADMF trawl survey (Figure 6), as well as anecdotal reports from commercial fishermen who report that portions of Buzzards Bay and Nantucket

Table 14. Percent maximum female spawning biomass per recruit, associated fishing mortality and female spawning stock biomass per recruit (pounds).

% Maximum SPR	F	SPR
40.0	0.12	0.752
30.0	0.167	0.563
20.0	0.241	0.375
10.0	0.391	0.187
5.0	0.573	0.094
2.5	0.796	0.047
1.0	1.145	0.018

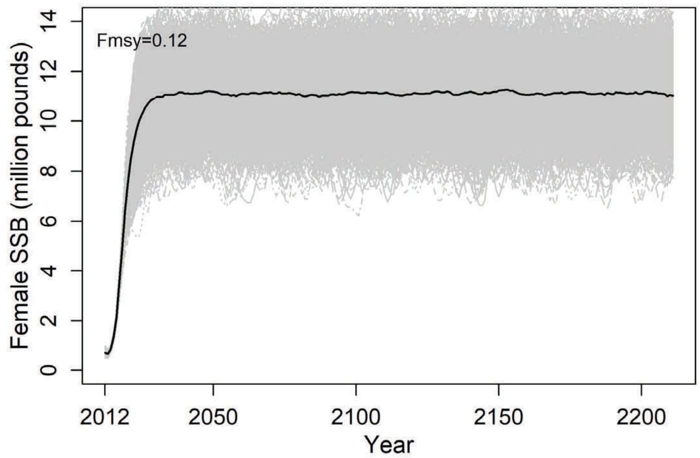


Figure 22. Stochastic projections (gray lines) of female spawning stock biomass using the F_{MSY} proxy = 0.12 for channeled whelk. Black line is the median of all stochastic projections.

Sound are already devoid of whelk. Additionally, there is strong evidence of severe truncation in the population size structure over the last 15 years. Large sexually mature female whelk were evident in the fishery size structure in 2003 and 2004 (Figure 5). These larger whelk are now mostly absent from the population which is a classic sign of growth overfishing.

All available information suggests that the channeled whelk stock in Massachusetts coastal waters is in poor condition. Fishing mortality rates

Table 15. Summary of management values estimated from assessment methods applied to channeled whelk data.

Method	Value	Estimate	
Biomass-Based Management Quantities and Reference Points			
Catch MSY	MSY	1.2	million pounds
	B_{MSY}	21.9	million pounds
	F_{MSY}	0.07	
DBSRA	MSY	1.6	million pounds
	B_{MSY}	20.8	million pounds
	F_{MSY}	0.09	
Biomass Dynamics	MSY	1.3	million pounds
	B_{MSY}	21.4	million pounds
	F_{MSY}	0.06	
	F_{2016}	0.1	
Number-Based Management Quantities and Reference Points			
Catch Curve	F_{2011}, F_{2015}	0.78, 0.58	
Delury	F_{2016}	0.6	
SCA	F_{2016}	0.32	
	SSB_{2016}	740,820	pounds
YPR	F_{max}	0.39	
	$F_{0.10}$	0.17	
SPR	$F_{40\%}$ (F_{MSY} proxy)	0.12	
Stochastic Projections	SSB_{MSY}	11	millon pounds

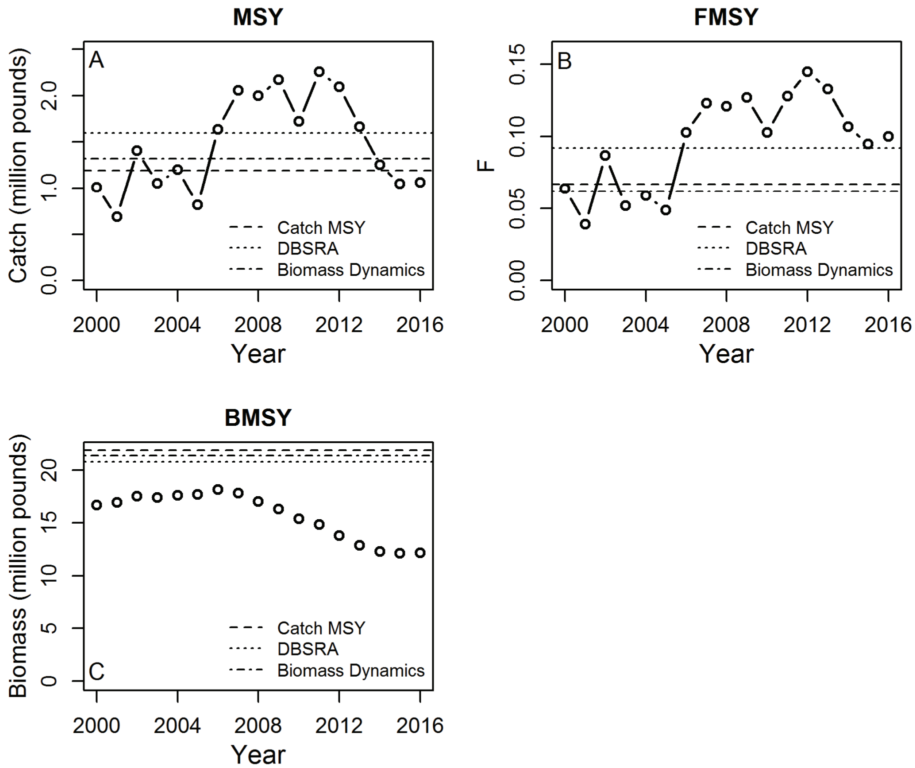


Table 23. Comparisons of biomass-based reference points (MSY, FMSY and BMSY) to A) landings, B) fishing mortality estimates from the Biomass Dynamics model, and C) biomass estimates from the biomass dynamics model estimates of B_{MSY} .

are high and when compared to a whole suite of different potential F-based reference points it is clear that overfishing is occurring. Stock abundance and total biomass are very low and when compared to a whole suite of different biomass-based or abundance-based reference points typically used in fisheries management, it is clear that the stock is likely overfished. Continued high harvest of primarily immature whelk continues to be the primary threat to the long term sustainability of the channeled whelk fishery in Massachusetts.

Literature Cited

Atlantic States Marine Fisheries Commission. 2015.American lobster benchmark stock assessment and peer-review report. Alexandria, VA. August 2015. 493 p.

Arrighetti, F., T. Brey, A. Mackensen and P. E. Penchaszadeh. 2011. Age, growth and mortality in the giant snail *Adelomelon beckii* (Broderip 1983) on the Argentinean shelf. Journal of Sea Research 65: 219-223.

Brey, T. 1999. Growth performance and mortality in aquatic macrobenthic invertebrates. Advances in Marine Biology 35: 155-223.

Bueno, R.C. 2001. Co-management of the hookah diving fisheries. CEDO News Vol. 2 No. 9.

de Vooys, C.G.N. and J.van der Meer, 2010. The whelk (*Buccinum undatum* L.) in the western Dutch Wadden Sea in the period 1946–1970: Assessment of population characteristics and fishery impact. Journal of Sea Research 63: 11–16.

Cipriani, R., H.M. Guzman, A.J. Vega, and M. Lopez. 2008. Population assessment of the conch *Strombus galeatus* (Gastropoda, Strombidae) in Pacific Panama. J. Shellfish Res. 27: 889-896

Clark, W. G. 1991. Groundfish exploitation rates based on life history parameters. Canadian. Journal of Fisheries and Aquatic Sciences

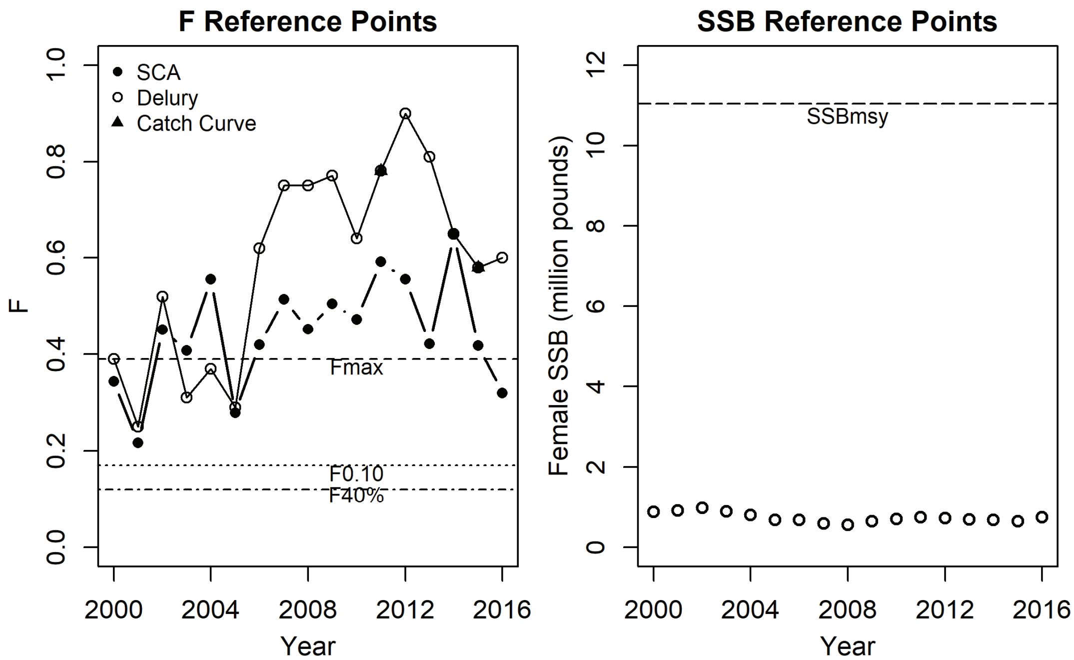


Table 24. Comparisons of number-based reference points (F_{max}, $F_{0.1}$,$F_{40\%}$ and SSB_{MSY}) to fishing mortality estimates from the Delury, Catch Curve and SCA models (left) and female spawning stock biomass from the SCA model (right).

48: 734- 750.

Deriso RB, Maunder MN, Skalski JR. 2007. Variance estimation in integrated assessment models and its importance for hypothesis test. Canadian Journal of Fisheries and Aquatic Sciences 64: 187-197.

Dick, E. J. and A. D. MacCall. 2011. Depletion based stock reduction analysis: a catch-based method for determining sustainable yields for data-poor fish stocks. Fisheries Research 110: 331-341.

Edmundson, S. E. 2016. Channeled Whelk (*Busycotypus Canaliculatus*) Ecology in Relation to the Fishery in Vineyard and Nantucket Sounds, Massachusetts. Doctoral Dissertation. University of New Hampshire. 178p.

Fahey, E., E. Masterson, D. Swords, and N. Forrest. 2000. A second assessment of the whelk fishery *Buccinum undatum* in the southwest Irish Sea with particular reference to its history of management by size limit. Marine Fisheries Service Division, Marine Institute, Dublin.

Fahey, E. 2001. Conflict between two inshore fisheries: for whelk (*Buccinum undatum*) and brown crab (*Cancer pagurus*), in the southwest Irish Sea. Hydrobiologia 465: 73 -83.

Fahey, E., J. Carroll, M. O'Toole, C. Barry, and L. Hother-Parkes. 2005. Fishery associated changes in the whelk *Buccinum undatum* stock in the southwest Irish Sea 1995-2003. Irish Fisheries Investigations No. 15. 26 p.

Fisher, R. A. and D. B. Rudders. 2017. Population and Reproductive Biology of the Channeled Whelk, *Busycotypus Canaliculatus* in the US Mid-Atlantic. Journal of Shellfish Research 36(2): 427-444.

Gabriel, W. L., M. P. Sissenwine, and W. J. Overholtz. 1989. Analysis of spawning stock biomass per recruit: an example for Georges Bank haddock. North American Journal of Fisheries Management 9: 383-

391.

Gabriel, W. L., and Mace, P. M. 1999. A review of biological reference points in the context of the precautionary approach. In Proceedings of the Fifth National NMFS Stock Assessment Workshop: Providing Scientific Advice to Implement the Precautionary Approach under the Magnuson-Stevens Fishery Conservation and Management Act, pp. 34 – 45. Ed. by V. R. Restrepo. NOAA Technical Memorandum NMFS-F/SPO-40. National Marine Fisheries Service, USA.

Gendron, L. 1992. Determination of the size at sexual maturity of the waved whelk *Buccinum undatum* Linnaeus, 1758 in the Gulf of St Lawrence, as a basis for the establishment of a minimum catchable size. J. Shellfish Res. 11: 1-7.

Gimenez, J., M. Lasta, G. Biggatti, and P.E. Penchaszadeh. 2005. Exploitation of the volute snail *Zidona dufresnei* in Argentine waters, southwestern Atlantic Ocean. J. Shellfish Res. 24: 1135-1140.

Harding, J. M. 2011. Observations on the Early Life History and Growth Rates of Juvenile Channel Whelks *Busycotypus canaliculatus* (Linneaus, 1758). Journal of Shellfish Research 30(3): 901-903.

Harding, J. M., R. Mann, C. W. Kilduff. 2007. The effects of female size on fecundity in a large marine gastropod *Rapana venosa* (Muricidae). Journal of Shellfish Research 26: 33-42.

Hilborn, R. and C. J. Walters. 1992. Quantitative Fisheries Stock Assessment: Choice, Dynamics and Uncertainty. Chapman and Hall, Inc. New York, New York. 570 p.

Karpov, K.A., P.L. Haaker, I.K. Taniguchi, and L. Rogers-Bennet. 2000. Serial depletion and the collapse of the California abalone (*Haliotis sp.)* fishery. Can. J. Fish. Aquat. Sci. Spec. Publ. 130: 11-24.

Leiva, G.E. and J.C. Castilla. 2002. A review of the world gastropod fishery: evolution of catches, management and the Chilean experience. Rev. Fish Biol. Fish. 11: 283-300.

Magalhaes, H. 1948. An ecological study of snails of the genus Busycon at Beaufort, North Carolina. Ecological Monographs 18: 377-409.

Miranda, R.M., K. Fujinaga, and S. Nakao. 2008. Age and growth of *Neptunea arthritica* estimated from growth marks in the operculum. Mar. Biol. Res. 4: 224-235.

Martell, S. and R. Froese. 2012. A simple method for estimating MSY from catch and resilience. Fish and Fisheries 14: 504-514.

Millar, R. B. 2015. A better estimator of mortality rate from age-frequency data. Canadian Journal of Fisheries and Aquatic Sciences 72: 364-375.

Parma A. 2002. Bayesian approaches to the analysis of uncertainty in the stock assessment of Pacific halibut. American Fisheries Society Symposium 27: 113-136.

Peemoeller, B. and B. G. Stevens. 2013. Age, size, and sexual maturity of channeled whelk (*Busycotypus canaliculatus*) in Buzzards Bay, Massachusetts. Fishery Bulletin 111: 265-278.

Power, A.J., C.J. Sellers, and R.L. Walker. 2009. Growth and Sexual Maturity of the knobbed whelk, *Busycon carica* (Gmelin 1791), from a commercially harvested population in coastal Georgia. 2009. Occasional Papers of the University of Georgia Marine Extension Service Vol. 4.

Schmidt, S., M. Wolff, and J.A. Vargas. 2002. Population ecology and fishery of *Cittarium pica* (Gastropoda: Trochidae) on the Caribbean coast of Costa Rica. Rev. Biol. Trop. 50: 1079-1090.

Sisson, R. T. 1972. Biological and commercial fisheries related research on the channeled whelk Busycon canaliculatum (Linne) in Narragansett Bay, Rhode Island. Master Thesis. University of Rhode Island. 68p.

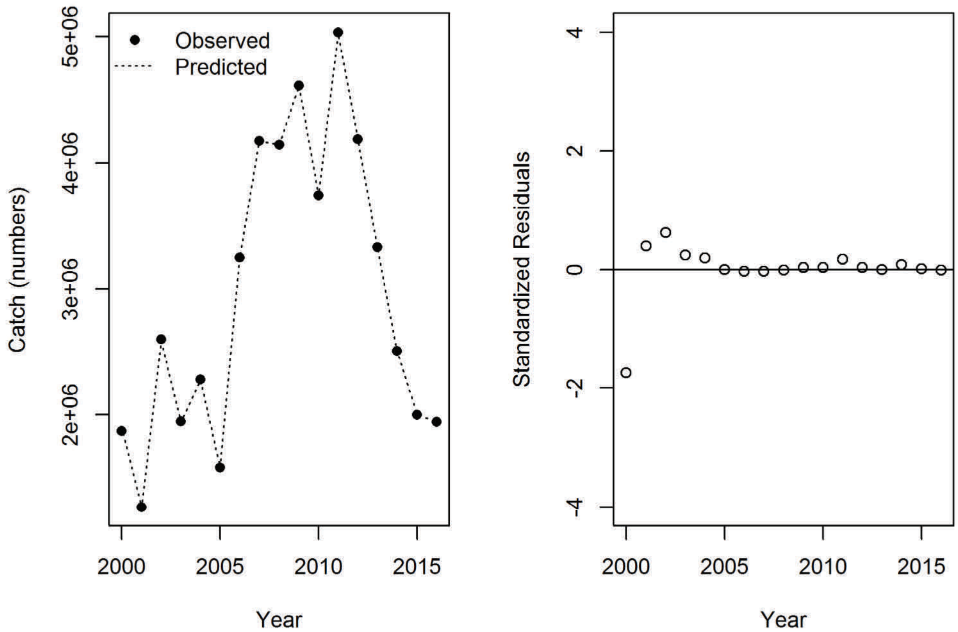
Smith, M. W., A. Y. Then, C. Word, G. Ralph, K. H. Pollock and J. M. Hoenig. 2012.

Recommendations for catch-curve analysis. North American Journal of Fisheries Management 32: 956-967.

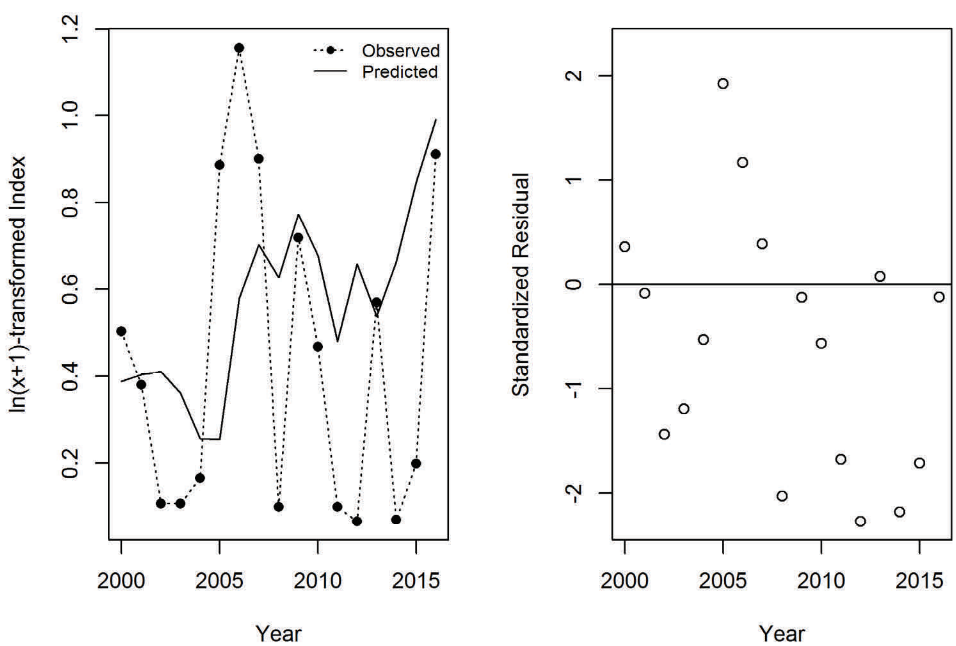
Toller, W., and S. Gordon. 2005. A population survey of the West Indian topshell or whelk (*Cittarium pica*) in the U.S. Virgin Islands. SEAMAP-C: USVI Whelk survey final report. Division of Fish and Wildlife, US Virgin Islands.

Wilcox, S. H. 2013. Size and age at maturation of the Channeled Whelk (*Buscotypus canaliculatus*) in Southern Massachusetts. Masters Thesis, University of Massachusetts, Dartmouth. 229 p.

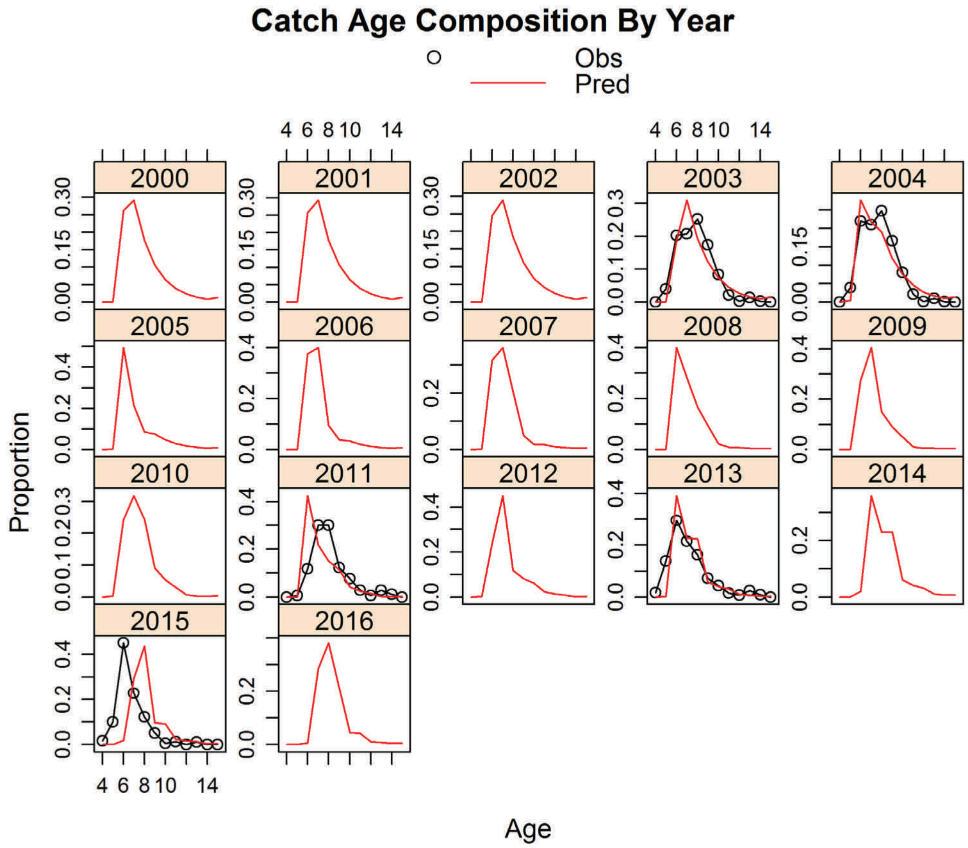
Appendix Figures

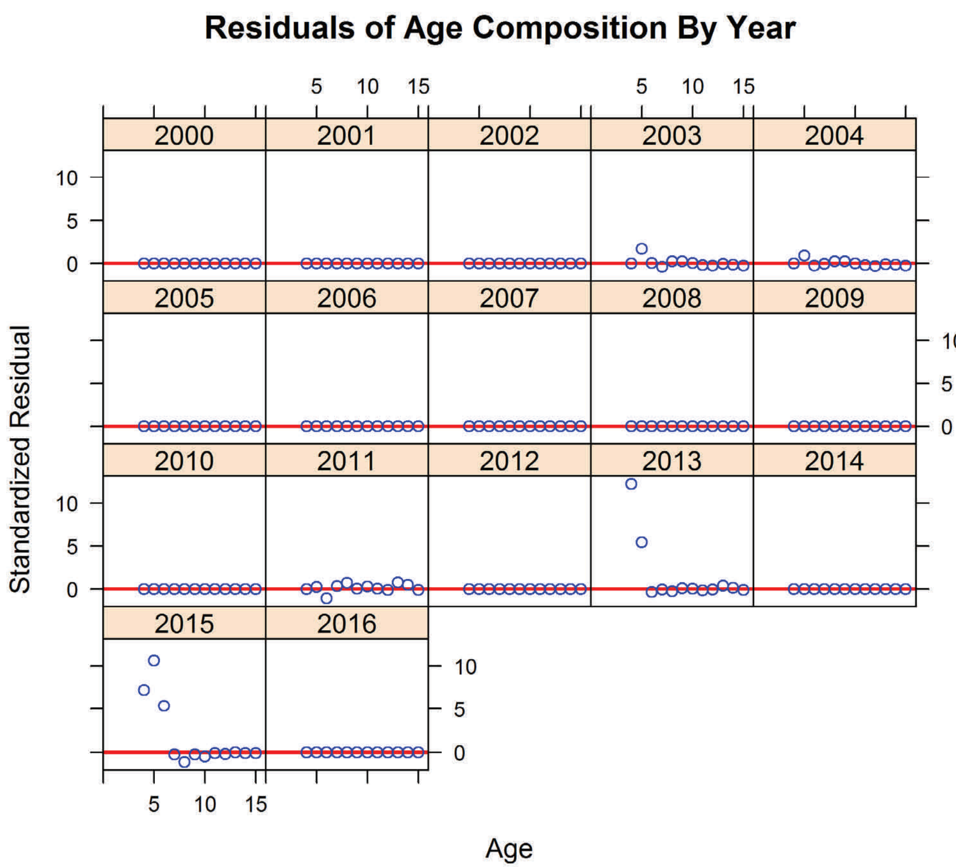


Appendix Figure 1. Plots of observed versus predicted values of catch numbers and standardized residuals.

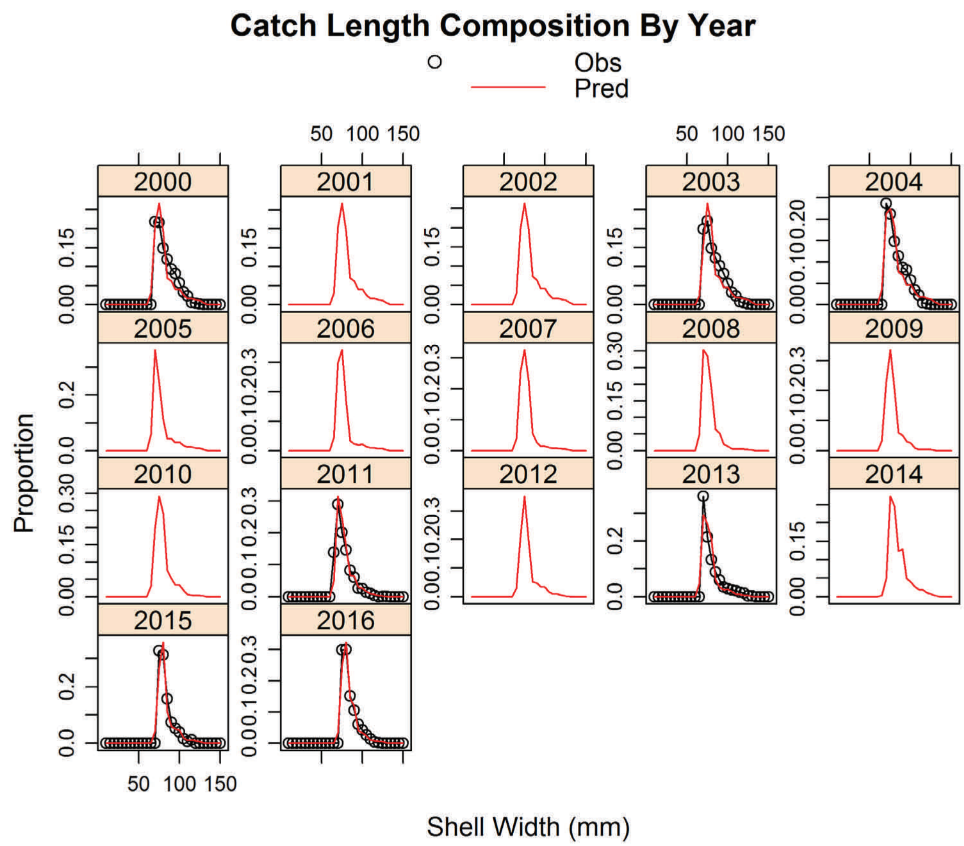


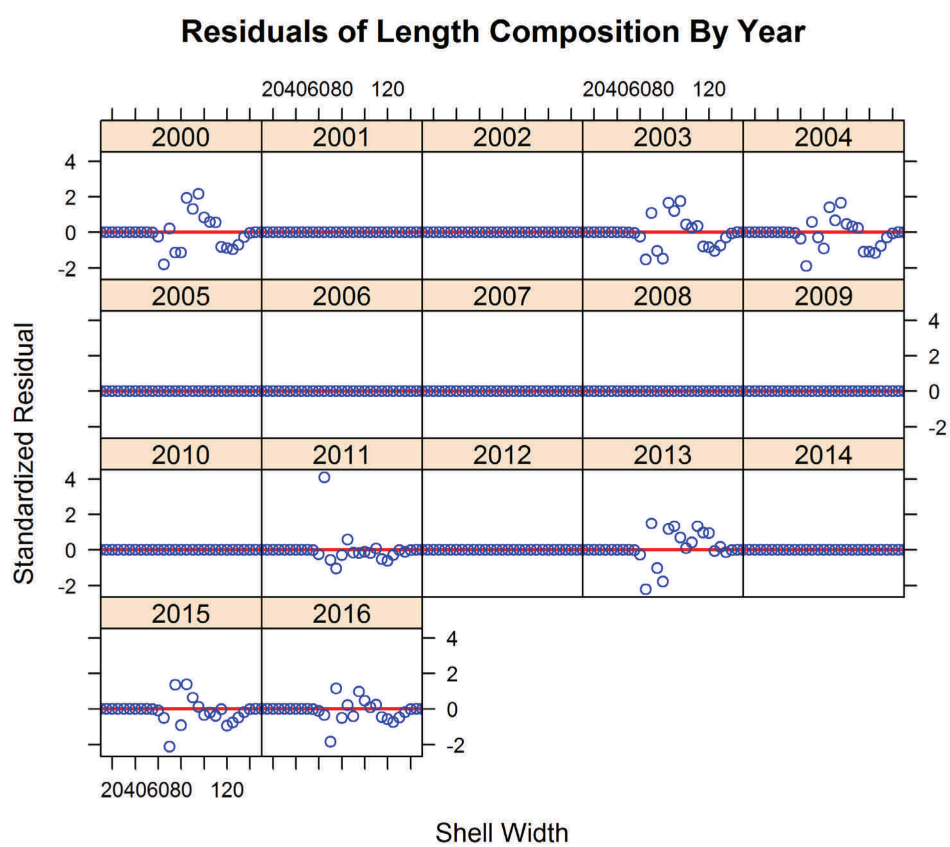
Appendix Figure 2 Plots of observed versus predicted index values and standardized residuals





Appendix Figure 3. Observed versus predicted age composition (proportions-at-age) (top) and standardized residuals (bottom).





Appendix Figure 3. Observed versus predicted size composition (proportions-at-size) (top) and standardized residuals (bottom).