The seasonal distribution and abundance of barndoor skate on Georges Bank based on scallop dredge surveys

Jasper S. Leavitt[a,b], Carl J. Huntsberger[a,c], Ronald J. Smolowitz[a], Liese A. Siemann[a,*]

[a]*Coonamessett Farm Foundation, Inc., East Falmouth, MA, USA*
[b]*Department of Biology, Trent University, Peterborough, ON, Canada*
[c]*Darling Marine Center, University of Maine, Walpole, ME, USA*

* Corresponding author at: Coonamessett Farm Foundation, Inc., East Falmouth, MA, USA
E-mail address: lsiemann@cfarm.org

Abstract

Barndoor skate (*Dipturus laevis*) are one of the largest skate species in the Northwest Atlantic, and seasonal trawl surveys have identified Georges Bank as critical barndoor skate habitat. We examined fine-scale changes in the seasonal distribution and relative abundance of barndoor skate in the scallop access areas in Closed Area I (CAI) and Closed Area II (CAII) on Georges Bank using catch data from a three-year seasonal scallop dredge survey. Throughout the survey, 2,664 barndoor skates were caught and measured, and over 92% of the skates were juveniles. Seasonal changes in skate abundance were documented in both Closed Areas, with catches peaking in August and September. During the summer and fall, skates were caught across all surveyed depths, while catch was limited to deeper waters in the winter and spring. Barndoor skate relative abundance in each Closed Area was modeled using generalized additive mixed models with Tweedie distributions, and the final models, with month, depth, and bottom temperature as fixed effects, effectively explained the spatiotemporal distribution patterns observed in each area. Barndoor skate abundance estimates are based on data collected during the Northeast Fisheries Science Center (NEFSC) spring and fall bottom trawl surveys, and the Essential Fish Habitat (EFH) designations for barndoor skate are currently being reassessed as part of the Omnibus Habitat Amendment 2. Our study strongly supports the recommendation to expand barndoor skate EFH since we observed high numbers of barndoor skate on Georges Bank in the late summer, a season with limited numbers of NEFSC surveys.

Keywords:
dredge survey, Essential Fish Habitat, Tweedie model, scallop access areas, spatiotemporal distribution

1. Introduction

Barndoor skate (*Dipturus laevis*) is one of the largest skate species in the Northwest Atlantic skate complex, reaching lengths greater than 145 cm and weights of up to 20 kg (Bigelow et al. 2002, Simon et al. 2002). It was historically thought that the species ranged from Cape Hatteras to southern Nova Scotia in depths from shallow water to 400 m (McEachran and Musick 1975). However, recent survey data has shown that the geographical range of barndoor skate is in more northern waters, from Hudson Canyon to the Labrador Shelf (Kulka et al. 2002, Packer et al. 2003, Simon et al. 2002). Furthermore, the depth range for the species was previously underestimated. Recent surveys suggest that barndoor skate are found in waters as deep as 1600 m, with significantly higher catch rates below 450 m (Kulka et al. 2002, Simon et al. 2002).

Barndoor skate are often caught as bycatch in sea scallop dredges and groundfish trawls, but until the late 1990s, this bycatch was largely ignored (Gedamke et al. 2005). Like most elasmobranchs, barndoor skate populations are especially vulnerable to the impacts of fishing mortality due to their slow growth, late maturity, and low fecundity (Gedamke et al. 2005). The threat to this species from bycatch was brought to the forefront when Casey and Myers (1998) published a report asserting that the species was in danger of becoming extinct due to overfishing and was already extirpated throughout much of its northern range. The Northeast Fisheries Science Center (NEFSC) seasonal trawl surveys on Georges Bank and in the Gulf of Maine caught only 116 individuals between 1970 and 2000 (Gedamke et al. 2008). However, since the late 1990s, increases in catch rates during these seasonal surveys indicate the population seems to be recovering (Gedamke et al. 2008). Updated population growth estimates using seasonal trawl survey data indicate that barndoor skate are not at risk of extinction (Gedamke et al. 2009). Although it has been listed as “endangered” by the International Union for Conservation of Nature (IUCN) (Dulvy 2003), repeated petitions to list it as a federally endangered species in the United States have failed (NMFS 2002, NMFS 2011).

Past estimates of barndoor skate abundance used long-term data from the NEFSC surveys collected every fall (since 1963) and spring (since 1968) (Packer et al. 2003). Limited presence/absence data was also collected during NEFSC winter and summer surveys that are now discontinued (Packer et al. 2003). Low numbers of adult skates were found on Georges Bank year-round, with a few found as far south as Mid-Atlantic waters and north into the Gulf of Maine in the winter and the Bay of Fundy in the fall (Packer et al. 2003). Juvenile skate were found primarily on the southern half of Georges Bank throughout the year, with the highest catches occurring in the fall (Packer et al. 2003). Based on these trawl surveys, Essential Fish Habitat (EFH) for barndoor skate has been identified (NEFMC 2016) (**Figure 1**). The EFH for adult barndoor skate includes areas across Georges Bank and in the northern Gulf of Maine (NEFMC 2016). Except for a few scattered locations, the EFH for juvenile barndoor skate is limited to the southern edge of Georges Bank (NEFMC 2016). New EFH designations have been proposed, which would expand the area to include more of Georges Bank (NEFMC 2016).

The NEFSC seasonal trawl surveys have been instrumental for tracking long-term population fluctuations and identifying Georges Bank as critical barndoor skate habitat. Yet they do not provide sufficient data at a fine enough spatiotemporal scale for examining seasonal changes in barndoor skate distributions on Georges Bank. Analysis of the seasonal distributions of flatfish on Georges Bank have shown that peak abundances may occur in summer or winter, seasons not covered by the NEFSC trawl survey (Winton et al. 2017). As such, the trawl survey may underestimate the importance of Georges Bank for species that utilize the area during summer or winter months. Because Georges Bank is a highly productive area for the scallop industry, Coonamessett Farm Foundation (CFF) has conducted a three-year seasonal scallop dredge survey in the scallop access areas of Closed Area I (CAI) and Closed Area II (CAII). This study uses the catch data from this survey to examine fine-scale changes in the seasonal distribution of this species in two areas of Georges Bank.

2. Materials and Methods

2.1. Seasonal bycatch survey

We conducted twenty-seven survey trips aboard sixteen commercial sea scallop fishing vessels between May 2011 and March 2014. Surveys were performed monthly from May 2011 through November 2011, and then every six weeks from January 2012 until March 2014. The sampling locations were in the scallop access areas of CAI and CAII on Georges Bank (**Figure 1**), with additional stations south of CAII. The survey used a fixed grid design, with 22 stations in CAI sampled at least 26 times, separated by 5.4 km east to west and 7.2 km north to south, and 29 stations in CAII sampled at least 26 times, separated by 8.6 km east to west and 11.1 km north to south.

During each survey, two dredges were towed from the vessel: a standardized 4.6m-wide turtle-deflector dredge (TDD) and a New Bedford-style dredge (NBD) supplied by the vessel or by CFF. Each tow passed through the center of the pre-determined grid cell from a start point decided by the vessel captain. Under ideal conditions, the tows were 30 minutes long at 4.8 knots (8.89 km/h). If a tow lasted less than twenty minutes or had gear complications (e.g. flipped dredge), it was declared invalid and the station was towed a second time. Start and end coordinates, depth, and bottom temperature were recorded for each tow. Beginning in May 2011, depth and bottom temperature were recorded every 30 seconds by two loggers (Vemco Minilog temperature logger and Star-Oddi DST milli-TD temperature-depth logger) attached to the dredges.

After each tow, scallops and commercially important bycatch species were sorted, counted, and measured. Barndoor skate were sorted from all other skate in the catch and released after total length was measured to the nearest centimeter. Using this measurement, the skate were separated into two age classes: juveniles (length < 102 cm) and adults (length > 102 cm) (NEFMC 2014). This distinction was based on the length at which 50% of the population is sexually mature (Frisk et al. 2001).

2.2. Mapping seasonal changes in barndoor skate abundance

Because the NBD was not rigged the same for all trips, analysis of barndoor skate relative abundance included only catch from the TDD. Skate catch per station was plotted over time to examine seasonal changes in relative abundance over the three years included in the study. To examine how barndoor skate abundance was distributed relative to sampled depths and bottom temperatures, the unweighted and abundance-weighted cumulative frequency distributions of each variable were plotted by season. Using the start coordinates recorded at sea to specify survey locations, barndoor skate catch in the TDD was plotted by month using ARCGIS. The locations of the current adult and juvenile barndoor skate EFH were downloaded from the NOAA Habitat Conservation website (http://www.habitat.noaa.gov/protection/efh/newInv/index.html) and included in all maps to allow comparisons between barndoor skate catch and EFH that overlapped with our survey sites (two-sample t-tests).

2.3. Comparison of barndoor skate length-frequency distributions from the CFF dredge and the NEFSC bottom trawl

We compared the length-frequency distributions of barndoor skates caught during our dredge survey to those caught on Georges Bank in the NEFSC seasonal survey from 2009-2015 (NEFSC Trawl Survey Data unpublished). The NEFSC has conducted seasonal bottom trawl surveys along the northeastern coast of the United States since 1963 using standardized trawls with small-mesh cod-end liners to retain small fish (NEFSC 2014). To assess differences in the barndoor skate size selectivity of the two surveys, length-frequency data was plotted for each season (winter: December-February, spring: March-May, summer: June-August, fall: September-November) and for all seasons combined.

2.4. Modelling seasonal changes in barndoor skate distributions

Because CAI and CAII are not contiguous, each area was modeled separately. The number of barndoor skate per tow in each Closed Area was modeled using a Tweedie distribution found within the R package “mgcv” (generalized additive model function “gam” with family = “Tweedie”, link = “log”, and cubic smoothing splines) (R Core Team 2015, Wood 2011). We used a model with a Tweedie distribution because the count data was overdispersed with a high proportion of zero values (Shono 2008, Tweedie 1984). Fixed effects available for modeling the barndoor skate numbers included location (“easting” and “northing” with latitude and longitude coordinates projected into UTM space using the R package “rgdal”), bottom depth (in meters), bottom temperature (rounded to the nearest °C), and month (Bivand et al. 2015). Prior to running the mixed models, we looked for evidence of high collinearity between the fixed effect variables using variance inflation factors (VIFs) and examined the data for evidence of spatial auto-correlation using the spline correlogram function “spline.correlog” available in the R package “ncf” (Bjornstad 2013, Zuur et al. 2009).

Random effects for survey trip and station were added to the initial model (random effect smooth) to account for differences in barndoor skate catch numbers due to changes in survey vessels or survey protocol and any consistent differences between survey stations. The final model was selected based on generalized cross validation (GCV) scores after eliminating variables and interaction terms (Wood 2011).

3. Results

3.1. Overall abundance and length-frequency of barndoor skate catch

Throughout the survey, 2,664 barndoor skates were caught in the TDD, and they were present in 49.0% of the 1,940 tows conducted during the study. There were 816 skates caught in CAI with an average of 0.991 skate per station (**Table 1**) and 1,848 skates caught in CAII with an average of 1.654 skates per station (**Table 2**). In CAI, 92.4% of skates caught were juveniles and 7.6% were adults (**Table 1**). In CAII, 93.6% of skate caught were juveniles and 6.4% were adults (**Table 2**). In CAI, the number of skate caught per tow decreased each year from 2011 to 2013 (**Table 1**). The opposite trend was recorded in CAII, with the number of skate caught per tow increasing from 2011 to 2013 (**Table 2**).

Most skate caught in the TDD were between 41 cm and 65 cm long (average length = 56.5 cm). The largest skate was 128 cm long and the smallest skate was 12 cm long (**Figure 2a**). Larger skates on average were caught in the TDD in summer and fall (**Figure 2**). These lengths are comparable to those observed during the 2009-2015 NMFS trawl survey (**Figure 2a**). The trawl survey caught mostly skates between 44 cm and 76 cm long (average length = 61.2 cm). The largest skate caught in the trawl surveys was 138 cm long and the smallest was 17 cm long (**Figure 2a**). The average length of skates caught in the trawl were similar for both the fall and spring surveys (**Figures 2c and 2e**).

3.2. Seasonal changes in distribution

Over the course of the three-year survey, stations were sampled a total of three times in January, March, June, and September; two times in April, May, July, August, October, November, and December; and once in February. Overall, skate catch was relatively high in CAI from July through October (**Table 1, Figure 3**). Barndoor skate relative abundance peaked in August when 157 skate were caught during 58 tows, for an average of 2.71 skate caught per tow, and they were present in 79.3% of the tows (46 out of 58) (**Table 1**). Skate relative abundance in CAI was lowest in the late winter and early spring (**Table 1, Figure 3**). Only one skate was caught in February (1 tow out of 33) and March (1 tow out of 94) (**Table 1**).

During summer months, skate catch distributions were similar to sampled depths and temperatures, while the abundance-weighted cumulative frequency curves for depth were shifted toward deeper waters beginning in the fall (**Figure 4**). During winter and spring months, this shift toward deeper waters was pronounced, with a low percentage of skate caught in depths below 70 meters (**Figure 4**). During most of the year, skate catch distributions were similar to sampled bottom temperatures, although skate catch distributions shifted slightly toward warmer waters in the winter and spring and cooler waters in the fall **(Figure 4**).

There appeared to be a yearly cycle in barndoor skate relative abundance in CAI, with the highest catch in the late summer and early fall and lowest catch in late winter and early spring (**Table 1 and Figure 3**). Skates appeared in the northwestern portion of CAI in May, and then moved across the area into the southern portion throughout the summer and fall (**Figure 5**). After October, skate catch dropped and most were caught in the deeper waters in CAI (**Figure 5**).

Barndoor skate catch in CAII exhibited similar trends, with the largest catches occurring from June through November (**Table 2, Figure 3**). Barndoor skate relative abundance was highest in September when a total of 405 individuals were caught during 125 tows, for an average of 3.24 skate per tow, and they were present in 76.8% of the tows (96 out of 125) (**Table 2**). February had the lowest skate catch, with an average of 0.256 skate per tow, and they were present in 17.9% of the tows (7 out of 39) (**Table 2**).

Seasonal changes in barndoor skate relative abundance in CAII were similar to those observed in CAI, with high catch totals in late summer and early fall and low catch totals in late winter and early spring (**Figure 3**). Skate were caught in deeper waters south of the scallop access area in March and April, then moved across the surveyed area through May and June (**Figure 6**). They remained in the shallower waters on the bank through September before moving back into deeper waters along the southern edge through January (**Figure 6**).

3.2. Barndoor skate catch and current EFH designation

EFH is defined and mapped using 10-minute by 10-minute squares (NEFMC 2014). Only one 10-minute square of adult barndoor skate EFH overlapped the surveyed area of CAI, while none of the current juvenile barndoor skate EFH is close to this region (**Figure 5**). Yet even though there is no juvenile EFH in CAI, 105 out of the 112 individuals caught in the adult EFH were juveniles (93.8%), and 92.4% of the barndoor skate caught in CAI overall were juveniles (**Table 1**). There was no significant difference between adult skate catch per tow inside (mean = 0.07) and outside (mean = 0.03) of the EFH (two-sample t-test, $t = 0.91$, $p = 0.37$).

There were four juvenile and three adult EFH squares located in our CAII survey area, and one of these 10-minute squares was included for both age groups (**Figure 6**). The majority of the skates caught in the juvenile EFH in the survey area were juveniles (98.7%, 747 out of 757 individuals). However, most skates caught in the adult EFH were also juveniles (97.5%, 268 out of 275). There was a significant difference between juvenile skate catch per tow inside (mean = 2.68) and outside (mean = 1.26) of the juvenile EFH (two-sample t-test, $t = 6.49$, $p < 0.001$), while adult skate catch per tow was not significantly different inside (mean = 0.05) and outside (mean = 0.04) of the adult EFH (two-sample t-test, $t = 0.49$, $p = 0.62$).

3.3. Modelling seasonal changes

Location was not used in the model because longitude was correlated with depth in both Closed Areas and with latitude in CAII. Because there was no strong spatial autocorrelation between sampling stations based on the skate count data or residuals from a simple linear model incorporating all of the fixed effect variables (spatial correlation < 0.1 between neighboring stations, lower for more distant stations), we did not include a spatial autocorrelation term in the model. Examination of scatter plots of depth and bottom temperature versus barndoor skate catch numbers in each area indicated there was a non-linear relationship between skate catch and these variables, so catch number was modeled using a generalized additive mixed model. Since a seasonal trend was evident in the data and there was a range of observed depths and temperatures during each month, both variables were included in the model by month. The initial models included random effect terms for trip and station. The full model and the models with each effect dropped for each area are shown in **Table 3**.

Based on the generalized cross-validation (GCV) statistics, the final models for predicting barndoor skate in both Closed Areas included all of the fixed and random effects. The models accounted for most of the observed variation in CAI (deviance explained = 67.6%) and more than half of the observed variation in CAII (deviance explained = 59.0%). Eighty-six percent of the predicted catch values for CAI and 78% of the predicted catch values for CAII differed from observed values by ≤ 1 skate (**Figure 7**).

4. Discussion

Our study confirmed that there are clear seasonal changes in the distribution and abundance of barndoor skate in the scallop access areas on Georges Bank. Barndoor skates were most prevalent and widely distributed in late summer and early fall in both Closed Areas. They were least prevalent in the winter and early spring and were concentrated in the deepest surveyed waters on the southern edge of Georges Bank.

Overall, the NEFSC seasonal trawl surveys have caught few barndoor skate in the areas surveyed by CFF, but the reported trends are consistent with CFF data (Packer et al. 2003). It is known that barndoor skates can be found in deeper waters beyond the NEFSC trawl survey boundaries (Kulka et al. 2002). In the 2007 trawl survey, 277 of the 325 barndoor skates caught were in one tow on the southeastern edge of Georges Bank, and 110 of these skate were adults (Frisk et al. 2008, Frisk et al. 2014). The trawl surveys caught few skate in the winter and spring, with most taken in 200-meter water along the edge of Georges Bank (Packer et al. 2003). In the fall, barndoor skate were caught in shallower waters on the bank (Packer et al. 2003). Summer trawl surveys were conducted for a limited number of years, and a few skate were caught, mostly on Georges Bank (Packer et al. 2003). Our survey caught the largest number of barndoor skate on Georges Bank in the late summer, and it is likely that the limited number of NEFSC summer surveys explains this difference.

The best models for predicting the spatiotemporal distribution patterns of barndoor skate incorporated month, depth, and bottom temperature. These variables are recognized as important determinants of fish distributions (Mountain and Murawski, 1992; Murawski and Finn, 1988; Perry and Smith, 1994; Perry et al., 1994; Scott, 1982; Stefánsson, 1996; Swartzman et al., 1992). Although barndoor skate are found across a wide range of temperatures, previous studies reported that they are most abundant where bottom temperatures range from 4-12°C in the spring and 5-16°C in the fall (Packer et al. 2003). Barndoor skate EFH documents describe juvenile skate abundance as highest from 4-12°C, and adult skate abundance as highest from 3-16°C (NEFMC 2016). Our study had similar results, with the majority of barndoor skate caught when bottom temperatures ranged from 5-10°C in the spring and 10-15°C in the fall. Skate relative abundance was shifted toward warmer waters in the winter and spring when average temperatures were cold and cooler waters in the fall when average temperatures were warm, suggesting the skate might prefer temperatures that are not at the extremes of those we sampled. Barndoor skate are also found across a wide range of depths, but previous research has noted a preference for waters ranging from 70-120 meters, with adults also preferring waters deeper than 200 meters (Packer et al. 2003). We consistently caught more barndoor skates at stations with depths greater than 70 meters, with over 90% of the catch at stations with depths greater than 70 meters for all months but October when 85% of the catch was in the deeper surveyed waters. The shift toward higher catches in deeper waters was most noticeable in winter and spring when catches were low and when barndoor skate may move into deeper waters beyond the range of our survey.

Seasonal migrations of varying distances have been described in five of the seven skate species that make up the northeast skate complex, specifically clearnose skate (*Raja eglanteria*), little skate (*Leucoraja erinacea*), thorny skate (*Amblyraja radiata*), smooth skate (*Malacoraja senta*), and winter skate (*Leucoraja ocellata*) (Frisk 2010). Clearnose, little, and winter skates all migrate to the south and offshore in the winter, come inshore in the spring, and then migrate north in the late summer or early fall (Frisk 2010). This migration pattern is consistent with our findings for barndoor skate. Frisk (2010) suggested that the migrations correlate to reproductive seasons in the three long-distance migrating species (clearnose, little, and winter skate). Not much is known about the seasonality of barndoor skate reproduction, but the presence of fully formed egg capsules in females caught in December and January has indicated they could reproduce in the winter (Bigelow et al. 2002). In captivity, barndoor skates laid the most eggs per month in the fall and the fewest in the spring, with females laying all through the winter months (Parent et al. 2008). Our survey data indicates that there may be a seasonal migration offshore through the southeastern edge of the sampling area, further supporting a hypothesis that barndoor skate spend time in deeper, unsampled areas off Georges Bank.

Less than 10% of the barndoor skate caught in the scallop dredge were adults, which could be due to two reasons: low catchability in the dredge or a small adult population size in the study area. Other studies using scallop dredges also caught very few adult barndoor skate (Gedamke et al. 2005, Gedamke et al. 2008). The TDD was developed to reduce sea turtle bycatch, but gear studies indicate it also reduces flatfish bycatch (Smolowitz et al. 2012). Because this dredge has the cutting bar moved forward, the designers hypothesize that flounder could escape over the top of the dredge to avoid capture (Smolowitz et al. 2012). Furthermore, the TDD has a turtle mat with a square grid of chains rather than a chain sweep between the headbale and the dredge bag, making the gaps that allow scallops to enter the bag smaller than many large fish. Taken together, these properties of the TDD could result in low bycatch of large barndoor skate. However, the NEFSC trawl survey also caught few adult barndoor skate (Packer et al. 2003), which could mean that there are not many adult skate in the survey area.

The EFH designations for barndoor skate are currently being reassessed as part of the Omnibus Habitat Amendment 2 (NEFMC 2016). These discussions have included new definitions for what is considered essential habitat based on NEFSC survey data. The current barndoor skate EFHs are 100% of the range where juveniles and adults were caught in the NEFSC trawl surveys between 1964 and 1999 (NEFMC 2003). The new proposed EFH would encompass areas with depth and temperature profiles that correspond to high catches of juveniles and adults in the

1963-2003 NEFSC bottom trawl surveys and with the average juvenile catch rates at the 90th percentile for the 1968-2005 NEFSC bottom trawl surveys (NEFMC 2016). This new habitat designation would expand the EFH for barndoor skate on Georges Bank to include most of the southern edge of Georges Bank (NEFMC 2016). The results of our survey strongly support this change because we caught a large number of barndoor skate in the proposed EFH expansion area and our modeling results indicate that both bottom temperature and depth are important environmental parameters for predicting barndoor skate presence and abundance.

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Table 1. Monthly barndoor skate catch data for Closed Area I.

	Counts						Percentage		
Month/ Year	Number of Tows	Tows with Skate	Skate Catch	Juvenile Skate	Adult Skate	Skate per Tow	Presence	Juvenile	Adult
January	94	17	24	24	0	0.255	18.1%	100.0%	0.0%
February	33	1	1	1	0	0.303	3.0%	100.0%	0.0%
March	94	1	1	1	0	0.106	1.1%	100.0%	0.0%
April	60	3	3	3	0	0.050	5.0%	100.0%	0.0%
May	59	12	15	15	0	0.254	20.3%	100.0%	0.0%
June	93	44	67	63	4	0.720	47.3%	94.0%	6.0%
July	66	45	157	138	19	2.379	68.2%	87.9%	12.1%
August	58	46	157	151	6	2.707	79.3%	96.2%	3.8%
September	86	49	146	140	6	1.698	57.0%	95.9%	4.1%
October	58	51	135	112	23	2.328	87.9%	83.0%	17.0%
November	62	33	77	73	4	1.242	53.2%	94.8%	5.2%
December	60	19	33	33	0	0.550	31.7%	100.0%	0.0%
2011[a]	200	120	336	308	28	1.680	60.0%	91.7%	8.3%
2012	319	116	282	272	10	0.884	36.4%	96.5%	3.5%
2013	242	78	189	165	24	0.781	32.2%	87.3%	12.7%
2014[b]	62	7	9	9	0	0.145	11.3%	100.0%	0.0%
Total	823	321	816	754	62	0.991	39.0%	92.4%	7.6%

[a] Only months May through November

[b] Only months January and March

Table 2. Monthly barndoor skate catch data for Closed Area II.

			Counts				Percentage		
Month/ Year	Number of Tows	Tows with Skate	Skate Catch	Juvenile Skate	Adult Skate	Skate per Tow	Presence	Juvenile	Adult
January	130	57	156	151	5	1.208	43.8%	96.8%	3.2%
February	39	7	10	10	0	0.256	17.9%	100.0%	0.0%
March	128	24	64	64	0	0.492	18.8%	100.0%	0.0%
April	86	48	160	159	1	1.860	55.8%	99.4%	0.6%
May	74	43	88	80	8	1.189	58.1%	90.9%	9.1%
June	122	87	240	207	33	1.967	71.3%	86.3%	13.8%
July	81	57	183	175	8	2.259	70.4%	95.6%	4.4%
August	80	55	143	137	6	1.788	68.8%	95.8%	4.2%
September	125	96	405	387	18	3.240	76.8%	95.6%	4.4%
October	79	51	122	103	19	1.544	64.6%	84.4%	15.6%
November	87	61	154	137	17	1.770	70.1%	89.0%	11.0%
December	86	43	123	119	4	1.430	50.0%	96.7%	3.3%
2011[a]	260	170	352	287	65	1.354	65.4%	81.5%	18.5%
2012	423	242	667	637	30	1.577	57.2%	95.5%	4.5%
2013	348	189	710	688	22	2.040	54.3%	96.9%	3.1%
2014[b]	86	28	119	117	2	1.384	32.6%	98.3%	1.7%
Total	1117	629	1848	1729	119	1.654	56.3%	93.6%	6.4%

[a] Only months May through November

[b] Only months January and March

Table 3. Summary of the Tweedie model analysis for each Closed Area. The full model and the models with each effect dropped from the full model are shown. Trip and station were included as random effects. (BT = bottom temperature, D = bottom depth, M = month, Edf = estimated degrees of freedom, GCV = generalized cross-validation statistic)

Barndoor skate count CAI (Tweedie parameter =1.01)			
Full model: Barndoor Skate ~ Month + ƒ(BT by Month) + ƒ(Depth by Month) + ƒ(Trip) + ƒ(Station)			
Models	Edf	GCV	Deviance explained (%)
Full model	105.39	1.024	67.6
M + ƒ(BT by M) + ƒ(D by M) + ƒ(Station)	106.17	1.070	66.3
M + ƒ(BT by M) + ƒ(D) + ƒ(Trip) + ƒ(Station)	84.35	1.081	63.7
M + ƒ(BT) + ƒ(D by M) + ƒ(Trip) + ƒ(Station)	94.59	1.087	64.5
M + ƒ(BT by M) + ƒ(Trip) + ƒ(Station)	88.13	1.090	63.8
M + ƒ(D by M) + ƒ(Trip) + ƒ(Station)	87.74	1.111	63.1
M + ƒ(BT by M) + ƒ(D by M) + ƒ(Trip)	89.09	1.124	62.8
ƒ(BT) + ƒ(D) + ƒ(Trip) + ƒ(Station)	67.83	1.180	58.6
Barndoor skate count CAII (Tweedie parameter =1.01)			
Full model: Barndoor Skate ~ Month + ƒ(BT by Month) + ƒ(Depth by Month) + ƒ(Trip) + ƒ(Station)			
Models	Edf	GCV	Deviance explained (%)
Full model	124.77	1.569	59.0
M + ƒ(BT by M) + ƒ(D by M) + ƒ(Station)	118.10	1.628	56.8
M + ƒ(BT) + ƒ(D by M) + ƒ(Trip) + ƒ(Station)	94.59	1.638	55.4
M + ƒ(D by M) + ƒ(Trip) + ƒ(Station)	101.52	1.649	54.8
M + ƒ(BT by M) + ƒ(D) + ƒ(Trip) + ƒ(Station)	90.07	1.753	50.9
M + ƒ(BT by M) + ƒ(Trip) + ƒ(Station)	89.79	1.774	50.3
M + ƒ(BT by M) + ƒ(D by M) + ƒ(Trip)	88.14	1.863	47.6
ƒ(BT) + ƒ(D) + ƒ(Trip) + ƒ(Station)	71.49	1.868	45.8

Figure 1. Location of bycatch survey project in scallop access areas in Closed Area I and Closed Area II (inset). The designated boundaries of current Essential Fish Habitats for juvenile and adult barndoor skate are also shown (GIS shapefiles from http://www.nmfs.noaa.gov/sfa/hms/documents/fmp/am1/shapefiles.html)

Figure 2. (a) Length-frequency histograms for all barndoor skate caught per size class and separated by season into (b) summer, (c) fall, (d) winter, and (e) spring. The gray area plots show skate caught during the bycatch survey from May 2011-March 2014, while the black lines show skate caught during the spring and fall NEFSC bottom trawl surveys from spring 2009-fall 2014.

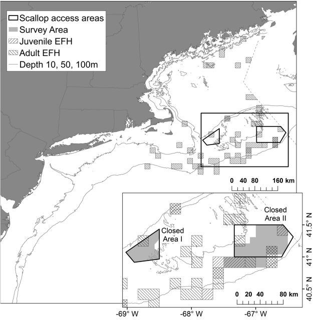
Figure 3. The average number of barndoor skate caught per trip by month from May 2011 to March 2014 in Closed Area I (top) and Closed Area II (bottom). Months with an asterisk were not sampled.

Figure 4. Unweighted (gray) and abundance weighted (black) cumulative frequency distributions of sampling station bottom depths and temperatures for each season.

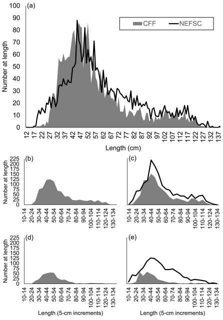
Figure 5. Maps showing the number of barndoor skate caught per station during each month in Closed Area I.

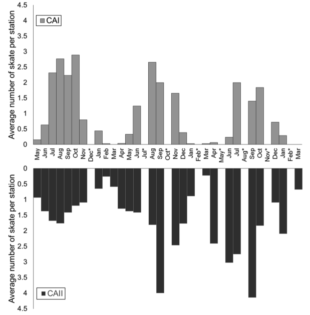
Figure 6. Maps showing the number of barndoor skate caught per station during each month in Closed Area II.

Figure 7. Frequency histograms of the differences between observed and predicted skate catches.

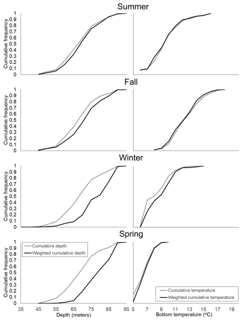


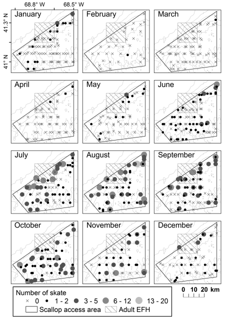
Scallop access areas
Survey Area
Juvenile EFH
Adult EFH
Depth 10, 50, 100m
0 40 80 160 km
Closed Area II
Closed Area I
41.5° N
41° N
40.5° N
0 20 40 80 km
-69° W
-68° W
-67° W


(a)
CFF
NEFSC
Number at length
Length (cm)
(b)
(c)
(d)
(e)
Number at length
Length (5-cm increments)
Length (5-cm increments)

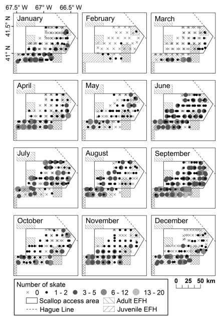


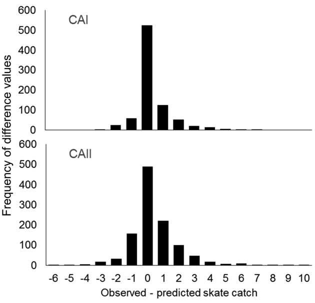
CAI
CAII
Average number of skate per station
May Jun Jul Aug Sep Oct Nov Dec* Jan Feb Mar Apr May Jun Jul* Aug Sep Oct* Nov Dec Jan Feb* Mar Apr May* Jun Jul Aug* Sep Oct Nov* Dec Jan Feb* Mar


Summer
Fall
Winter
Spring
Cumulative frequency
Depth (meters)
Bottom temperature (ºC)
Cumulative depth
Weighted cumulative depth
Cumulative temperature
Weighted cumulative temperature
35
40
45
50
55
60
65
70
75
80
85
90
95
5
7
9
11
13
15
17
19



68.8° W
68.5° W
41.3° N
41° N
January
February
March
April
May
June
July
August
September
October
November
December
Number of skate
× 0
1 - 2
3 - 5
6 - 12
13 - 20
Scallop access area
Adult EFH
0 10 20 km


67.5° W
67° W
66.5° W
41.5° N
41° N
January
February
March
April
May
June
July
August
September
October
November
December
Number of skate
× 0
• 1 - 2
3 - 5
6 - 12
13 - 20
Scallop access area
Adult EFH
Hague Line
Juvenile EFH
0 25 50 km



CAI
CAII
600
500
400
300
200
100
0
Frequency of difference values
-6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10
Observed - predicted skate catch