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Grey (Halichoerus Grypus) And Harbor Seal (Phoca Vitulina) Bycatch And Depredation In New England Sink-Gillnet Fisheries

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GRAY (*HALICHOERUS GRYPUS*) AND HARBOR SEAL (*PHOCA VITULINA*) BYCATCH AND DEPREDATION IN NEW ENGLAND SINK-GILLNET FISHERIES

BY

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This thesis is dedicated to:

My fiancé, who moved all the way to Maine to be with me while
I pursued my graduate degree and who I know will continue
to support me in any direction life takes us

My entire family, who have always encouraged me
and supported me in all aspects of my life

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wagging tails, instantly brightening my day

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ABSTRACT

GREY (*HALICHOERUS GRYPUS*) AND HARBOR SEAL (*PHOCA VITULINA*)
BYCATCH AND DEPREDATION IN NEW ENGLAND
SINK-GILLNET FISHERIES

by

Laura N. Sirak

University of New England, July, 2015

Marine mammals interact with commercial fisheries via competition for resources, depredation (feeding on fish caught in gear), entanglement, and bycatch in fishing gear. In New England, gray seals (*Halichoerus grypus*) and harbor seals (*Phoca vitulina*) are often taken as bycatch in sink-gillnet fisheries and are believed to depredate fish in gillnets. As seal populations increase, interactions with fisheries are also likely to increase, affecting both seal stocks and the New England fishing industry. This study aims to understand seal bycatch in the New England sink-gillnet fisheries by identifying the spatial and temporal trends in bycatch as well as the characteristics of seals that are taken most frequently as bycatch. Depredation is also a concern in the commercial fishing industry, however, there is some controversy among fishermen and scientists concerning the identification of the species responsible for depredation (e.g. seal vs. spiny dogfish (*Squalus acanthias*)). Therefore, a protocol for identifying seal and spiny dogfish depredation was developed and used to identify depredation in a small-scale study of the sink-gillnet fishery targeting skate.

Data from the Northeast Fisheries Observer Program (NEFOP) from 2005 – 2013 were analyzed to assess seal bycatch in the Northeast sink-gillnet fishery. Male seals were taken significantly more frequently than females, with young of the year most commonly occurring as bycatch. Areas where seals were taken in New England shifted seasonally, generally following the annual life history of each seal species. Gray seal bycatch showed an increasing trend over the years of study, with highest bycatch occurring in the spring in areas closest to haul out sites: Muskeget and Monomoy Island, MA, USA. Harbor seal bycatch was much more variable between years, with highest bycatch occurring in the winter near major harbor seals haul out sites along the southern Maine coast and southeastern Massachusetts. This study was a crucial step to understanding the complexities of seal-fishery interactions in New England.

In order to mitigate damage from depredation, it is important to know the source of the damage. Characteristics of seal and spiny dogfish bites were identified using foam imprints from jaws and bites by captive animals in the soft tissue of fish. Measurements from bite imprints and damaged fish were used to develop a protocol for identifying damage in the field. In general, dogfish bites were clean (flesh completely removed), circular in shape, and wider than long (bite ratio (bite length/bite width) < 0.6), whereas seal bites were ragged (flesh not completely removed, but partially torn from the bite), rectangular or trapezoidal in shape, and usually longer than wide or equal in length and width (bite ratio > 0.7). This protocol was used to identify damaged catch observed on a commercial gill-net fishing vessel targeting skate in New England waters June – August 2014. In this

small-scale study, dogfish bites were identified as the damage source significantly more frequently than seal bites (Multifactor ANOVA: $F_{df=2,66} = 9.306$, $p = 0.0003$; Tukey HSD: $p < 0.0001$). This inexpensive, quick, and practical protocol can be used on a larger scale to further understand depredation by seals and dogfish throughout New England.

CHAPTER I

BYCATCH OF GRAY (*HALICHOERUS GRYPUS*) AND HARBOR SEALS (*PHOCA VITULINA*) IN SINK GILLNET FISHERIES IN THE NORTHEAST UNITED STATES

Abstract

Gray seals (*Halichoerus grypus*) and harbor seals (*Phoca vitulina*) are often taken as bycatch in sink-gillnet fisheries in New England and are believed to consume and damage fish in gillnets. As seal populations increase, interactions with fisheries are also likely to increase, affecting both seal stocks and the New England fishing industry. Data from the Northeast Fisheries Observer Program (NEFOP) from 2005 – 2013 were analyzed to assess bycatch in the Northeast sink-gillnet fishery. Male seals were taken significantly more frequently than females, with young of the year most commonly occurring as bycatch. Areas where seals were taken in New England shifted seasonally, generally following the annual life history of each seal species. Gray seal bycatch showed an increasing trend over time, with highest bycatch occurring in the spring in areas closest to haul out sites: Muskeget and Monomoy Island, MA, USA. Harbor seal bycatch was much more variable over time, with highest bycatch occurring in the winter near major harbor seal haul out sites along the southern Maine coast and southeastern Massachusetts. This study

was a crucial step to understanding the complexities of seal-fishery interactions in New England.

Introduction

Marine Mammal – Fishery Interactions

As marine mammals and fisheries target similar species of fish, they often search for these fish in the same areas and may interact directly (e.g. bycatch and depredation) or indirectly (e.g. competition for resources) (Auge et al 2012, Morissette et al 2012, Heltzel et al 2011, Varjopuro 2011, DeMaster et al 2001, Baraff and Loughlin 2000). The large quantities of fish trapped during commercial fishing activities are an easy target for marine mammals. Depredation occurs when predators forage on fish directly in nets, resulting in a portion of the fish becoming unsellable due to damage (Peterson et al 2013, Auge et al 2012, Rafferty et al 2012, Varjopuro 2011, Forney et al 2011, Read et al 2008, Baraff and Loughlin 2000, Stanley and Shaffer 1995, Wickens et al 1992). While marine mammals are foraging on fish in nets, they may become entangled and if they are able to break free often take a portion of the net with them, remaining entangled indefinitely (Adimey et al 2014, Moore 2014, Waluda and Staniland 2013, Allen et al 2012, Bogomolni et al 2010b). If they cannot break free and remain submerged for extended periods of time, they drown and are taken in the fishery as incidental bycatch (Brown et al 2015, Lewison et al 2014, Moore 2014, Auge et al 2012, Moore et al 2009, Atkinson et al 2008, Read et al 2006, Baraff and Loughlin 2000). These interactions are detrimental to both marine mammals and fishermen, often resulting in damaged gear, lost fishing time, and loss of revenue for fishermen and entanglement or death for marine mammals (Auge et al 2012, Varjopuro 2011). Therefore, there are incentives to reduce entanglement, bycatch, and depredation from both fishery and conservationist perspectives (Twiss and Reeves 1999).

Bycatch in fisheries is one of the most critical threats to marine mammal populations as most marine mammals, especially cetaceans, have slow reproductive rates and are unable to maintain their populations when bycatch is high (Reeves et al 2013, Read et al 2008, Read et al 2006). An average of 6,215 marine mammals (3,029 cetaceans and 3,187 pinnipeds) were bycaught annually from 1990 to 1999 in the United States alone, with 84% of cetacean and 98% of pinniped bycatch occurring in gillnet fisheries (Read et al 2006). These numbers represent minimum estimates as bycatch in many fisheries have not been adequately monitored and voluntary reporting by fishermen is believed to be low (Karp et al 2011, Moore et al 2009, Read et al 2006). Globally, an extrapolated 653,365 marine mammals (307,753 cetaceans and 345,611 pinnipeds) are bycaught annually (Read et al 2006). These values have been extrapolated from US values and are believed to be overestimates for pinniped bycatch as their global distributions are not homogenous, and underestimates for cetacean bycatch due to incomplete knowledge of globally active fishing vessels, especially small-scale artisanal fisheries in developing countries. Bycatch in these artisanal fisheries can have detrimental effects on marine mammal populations, as in the case of the critically endangered vaquita (*Phocoena sinus*) in the Gulf of California, Mexico (Moore et al 2009, Gerrodette et al 2011). Mitigation measures, including time-area closures and acoustic deterrent devices, have been successful in reducing marine mammal bycatch in the US but are rarely used in other areas of the world (Geijer and Read 2013, Gotz and Janik 2013, Schakner and Blumstein 2013, Bowles and Anderson 2012, Carretta and Barlow 2011, Read et al 2006). For example, acoustic pingers attached to gillnets have been successful in reducing bycatch of harbor porpoise (*Phocoena phocoena*) in the Gulf of Maine and have also helped to reduce bycatch of gray (*Halichoerus grypus*) and harbor seals (*Phoca vitulina*) to some degree (Geijer 2013, Moore et al 2009).

Bycatch in gillnets has resulted in the decline of many pinniped species (Reeves et al 2013) and is also considered a threat to many endangered species, including the Ladoga ringed seal (*Pusa hispida ladogensis*, Kovacs et al 2012), the Australian sea lion (*Neophoca cinerea*; Woodley and Lavigne 1991), the Caspian seal (*Phoca caspica*; Kovacs et al 2012), and the New Zealand sea lion (*Phocarctos hookeri*; Auge et al 2012). Within US waters, many fisheries in both the Pacific and Atlantic oceans take pinnipeds as bycatch, including the set and drift gillnet fisheries off California and sinkgillnet fisheries in the northeast (Caretta et al 2014, Waring et al 2014, Moore et al 2009). From 2000 to 2003, the California set net fishery for halibut (*Hippoglossus stenolepis*) and angel shark (*Squatina squatina*) took an annual average of 904 to 1,842 pinnipeds, including California sea lions (*Zalophus californianus*), harbor seals, and elephant seals (*Mirounga angustirostris*) (Moore et al 2009). The California/Oregon drift net fishery has been responsible for bycatch of approximately 75 to 250 pinnipeds annually in the 1990s, including Steller sea lion (*Eumetopias jubatus*), California sea lion, harbor seal, and northern elephant seal, with bycatch declining to less than 100 total takes in recent years due to large time-area closures (Caretta et al 2014, Moore et al 2009). The status of pinniped bycatch in many Alaskan fisheries is unknown due to limited observer coverage, but species commonly taken include the endangered Steller sea lions, the Northern fur seal (*Callorhinus ursinus*), and the harbor seal (Allen and Angliss 2014, Moore et al 2009, NMFS 2008). In the Atlantic Ocean, pinniped bycatch occurs primarily in the northeast and mid-Atlantic sink gillnet fisheries, with few animals taken in the trawl fishery (Waring et al 2014, Moore et al 2009). Species taken include gray seals, harbor seals, harp seals (*Pagophilus groenlandicus*), and hooded seals (*Cystophora cristata*).

The Northeast sink gillnet fishery is listed as a Category I fishery under the List of Fisheries, indicating that it is responsible for frequent incidental mortality or serious injury of marine mammals, specifically harbor porpoises, humpback whales (*Megaptera novaeangliae*), minke whales (*Balaenoptera acutorostrata*), and North Atlantic right whales (*Eubalaena glacialis*; List of Fisheries for 2015, Waring et al 2014, The Marine Mammal Protection Act of 1972 As Amended 2007). Under the Marine Mammal Protection Act, all Category I fisheries must acquire a permit authorizing the take of marine mammals during fishing activity, must take observers on board their fishing vessel when requested, and must comply with all take reduction plans in affect (The Marine Mammal Protection Act of 1972 As Amended 2007). This Northeast sink gillnet fishery must comply with the Atlantic Large

Whale Take Reduction Plan (ALWTRP) and the Harbor Porpoise Take Reduction Plan (HPTRP), each requiring time-area closures and gear requirements (Taking of Marine Mammals Incidental to Commercial Fishing Operations and Atlantic Coastal Fisheries Cooperative Management Act Provisions; American Lobster Fishery 2014, Taking of Marine Mammals Incidental to Commercial Fishing Operations; Harbor Porpoise Take Reduction Plan Regulations 2013). Under the ALWTRP, gillnets are required to be marked for identification and weak links must be used to prevent entanglement (Taking of Marine Mammals Incidental to Commercial Fishing Operations and Atlantic Coastal Fisheries Cooperative Management Act Provisions; American Lobster Fishery 2014). Under the HPTRP, pingers are required in certain areas at specified times of the year to reduce bycatch and entanglement of harbor porpoises (Taking of Marine Mammals Incidental to Commercial Fishing Operations; Harbor Porpoise Take Reduction Plan Regulations 2013). Bycatch is monitored and additional time-area closures may be enforced if bycatch thresholds are exceeded.

The northeast sink gillnet fishery targets many species of fish and skate, which are managed under a variety of management plans including: the northeast multispecies large mesh/groundfish (includes Atlantic Cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), redfish (*Sebastes marinus*), and other groundfish), northeast multispecies small mesh/whiting (includes silver hake (*Merluccius bilinearis*), red hake (*Urophycis chuss*), and offshore hake (*Merluccius albidus*)), and the northeast skate complex (includes winter (*Leucoraja ocellata*), barndoor (*Dipturus laevis*), little (*Leucoraja erinacea*), and other skate species (Family *Rajidae*)). Fishing occurs year-round peaking during May, June, and July in the Gulf of Maine, Georges Bank, and Southern New England. Gear used is mostly bottom-tending gillnet composed of monofilament nets with mesh sizes ranging from 6 to 12 inches (15.24 – 30.48 cm) depending on the target fish species. Gray and harbor seals are the most commonly bycaught pinniped in this fishery (Waring et al 2014).

Seals in New England

Gray and harbor seals inhabit much of the northwest Atlantic Ocean, including New England waters (Baraff and Loughlin 2000). In order to reduce seal populations and their assumed competition with fisheries in New England, both Maine and Massachusetts paid seal bounties from 1888-1962 (Lelli et al 2009). During this time between 72,284 and 135,498 seals were killed, resulting in local extirpation of gray seals in New England and drastically reducing the harbor seal population. Although these bounties ended in 1962, seal hunting persisted as fishermen still viewed them as a threat to fish stocks. In 1972, the Marine Mammal Protection Act was enacted, prohibiting the hunting, harassing, capturing, or killing of any marine mammal within US waters and by US citizens on the high seas (Moore et al 2009, The Marine Mammal Protection Act of 1972 As Amended 2007). Gray seals began to migrate back into US waters from Sable Island, Canada and by the late 1990s they had established a breeding colony on Muskeget Island, Massachusetts where an estimated 2,095 pups were born in 2008 (Waring et al 2014, Wood Lafond 2009). Harbor seal populations also began to grow after the passage of the MMPA.

The most recent official harbor seal population estimates in 2001 and 2012 indicated there were 99,340 and 70,141 harbor seals inhabiting New England respectively, indicating the population may currently be declining or fluctuating (Waring et al 2014). Although official population counts for gray seals in the New England area are not available, a partial count from 2001 indicated that approximately 1,731 gray seals inhabited the Maine coast in the non-breeding season and in 2011 a maximum count of 15,756 gray seals were counted in southeastern Massachusetts (Gilbert et al. 2005, Waring et al 2014, Thomas et al 2011). The gray seal population in the US is believed to be increasing rapidly as a result of reproduction and continued immigration from Canada (Waring et al 2014). As seal populations increase, interactions with fisheries are also likely to increase, detrimentally affecting both seal stocks and the New England fishing industry.

Gray seals in New England inhabit northern Maine from the Canadian border to southeastern Massachusetts and range seasonally as far south as New Jersey (Waring et al 2014). Major gray seal breeding colonies in New England include Muskeget and Monomoy Islands in Massachusetts and Green and Seal Islands off the coast of Maine, with few pups observed on Mt. Desert Rock and Matinicus Rock, Maine in recent years (Figure 1; Ampela 2009, Bogomolni et al 2010a, Waring et al 2014). Gray seals in the western Atlantic give birth from December through early February, with a peak in mid-January; during this time adult breeders fast (Breed et al 2009). Adult seals mate after the lactation period and then disperse while pups remain on shore, fast for 1 to 4 weeks and shed their lanugo (Beck et al 2007). Once weaned pups enter the ocean, Breed et al (2011, 2013) found that they spend significant time and energy learning to forage, traveling far from haul-out sites to avoid intraspecific competition with older, more experienced gray seals.

Harbor seals in New England haul out around Isle of Shoals, Monomoy Island, and Nantucket Island (Figure 1) in the winter, pup along the Maine coast during the spring and summer, peaking in May and June, and range seasonally as far south as New Jersey (Baraff and Loughlin 2000, Waring et al 2014). Their lactation period lasts approximately three to four weeks and, unlike most phocids, harbor seal mothers forage during this time because they are unable to obtain the energy stores necessary to fast during lactation due to their smaller body size (Boness et al 1994). Harbor seals appear to tailor their foraging behavior to their habitat and prey availability, foraging relatively close to their haul-out sites and showing strong fidelity for these sites (Thompson et al 1996). Pups are born capable of swimming and may follow their mothers to sea during foraging trips, but it is unlikely that pups are foraging during this time (Bowen et al 1999, Muelbert and Bowen 1993). However, by accompanying their mothers, harbor seal pups are able to learn how and where their mother is foraging and what she is foraging on (Bowen et al 1999).

Both gray and harbor seals forage on a variety of commercially valuable fish species. Gray seal scat and stomach analysis from 2004 through 2008 from Southeastern Massachusetts indicate that diet composition differs between young and adult seals, as well as between seals foraging close to shore versus farther away (Ampela 2009). Commercially valuable fishes found in the gray seal diet (%biomass in scat, % biomass in stomachs; Ampela 2009) included red/white hake (3%, 33%), silver hake (1%, 29%), Atlantic cod (6%, 1.7%), winter flounder (*Pseudopleuronectes americanus*; 19%, 15%), redfish (0%, 2%), windowpane flounder (*Scophthalmus aquosus*; 2%, <0.1%), and skate (6%, <0.1%; Ampela 2009). Harbor seal diet studies encompass only small portions of the seal's range in New England waters (from Northern Maine to Massachusetts; Payne and Selzer 1989, Wood 2001, Waring et al 2014). These studies indicate that harbor seal diet varies throughout their range and that they consume a variety of commercially valuable fishes (% frequency; Wood 2000), including red/white hake (16%), silver hake (45%), Atlantic cod (3%), Atlantic herring (*Clupea harengus*; 6%), redfish (8%), and winter flounder (<1%) (Wood 2000, Payne and Selzer 1989).

Most of these commercially valuable fishes are harvested in the northeast sink gillnet fishery and, as a result, this fishery is responsible for most of the pinniped bycatch in the Northeast US, with a mean annual mortality of 346 harbor seals and 1,043 gray seals (Waring et al 2014). The purpose of this study is (1) to identify areas and times of the year with high pinniped bycatch in New England waters, (2) to identify how fishing parameters affect bycatch, and (3) to identify commonalities among seals that are taken most frequently as bycatch in the northeast sink-gillnet fishery.

Materials and Methods

Study Site

Analysis of pinniped-fishery interactions focused on the waters off of the Northeastern United States, from the New Jersey coast to the Canada-Maine border, between 39^{O} and 45^{O} North and 67^{O} and 75^{O} West (Figure 1). The study area was subdivided using Northwest Atlantic Fisheries Organization (NAFO) statistical areas. Only NAFO statistical areas with Northeast Fishery Observer Program or At-Sea Monitor coverage between 2005 and 2011 were used in this analysis, including areas 513, 514, 515, 521, 526, 537, 539, 612, 613, 615, and 616.

Data source and limitations

Data for individually bycaught gray and harbor seals in the study area was provided for the years 2005 through 2013 by the Northeast Fisheries Observer Program (NEFOP). Data for this analysis was provided in terms of observed bycaught seals, not seals per fishing trip, and included information on fishing operations for all takes (type of gear, target species of net taken in, year and month of take, gillnet soak duration, NAFO statistical area, use of pingers) and specific information on individually bycaught seals for some animals (species of seal, total length, gender, blubber thickness). Data used to identify trends in area, year, and season were standardized using the number of observed trips in each area (available from 2005-2011 from http://www.nefsc.noaa.gov/fsb/stat_charts/ index.html) and represent average bycaught seals taken per 1000 fishing trips.

However, data used for other analyses could not be standardized in this way and are reported as total observed bycatch. For this reason and due to a lack of baseline data on the prevalence of various fishing practices, results regarding the use of pingers, target species of fishery taken in, and gillnet soak duration may not represent an accurate description of overall bycatch in New England. It is important for the reader to note that while these analyses provide valuable information, they may be a function of the underlying fishing effort in the region rather than the effects of each parameter on bycatch.

Analysis of gray and harbor seal bycatch data

All analyses were completed for gray and harbor seals independently to determine how each species interacts with fisheries. Total observed gray and harbor seal bycatch were assessed separately to determine the effects of a variety of fishing parameters (use of pingers, target species of fishery taken in, and gillnet soak duration) and seal characteristics (sex, age, and blubber thickness). Gillnet soak duration was defined as the length of time the net was left in the water to catch fish, and was categorized into the following 24 hour bins, with the exception of a 0-12 hour bin to account for the large number of short soak durations: 0-12, 12-24, 24-48, 48-72, 72-96, 96-120, 120-144, 144-168, 168-192, 192-216, 216-240, 240-264.

A preliminary chi-square test determined that bycatch in gillnets with and without pingers differed significantly from equal totals for both gray ($x^2_{df=1}$=33.5821, p<0.001) and harbor seals ($x^2_{df=1}$=74.1378, p<0.001); the use of pingers was therefore included in analyses of fishing parameters. Given that the data were available in terms of individual bycaught seals independent of fishing trips, a sampling unit was considered as the total number of seals bycaught in each 3-way combination of fishing parameters. Total bycatch was log transformed for further analyses to fit the assumption of normality. Two multifactor ANOVAs were used to assess the main effects and interactive effects of target species, soak duration, and pingers on seal bycatch. One model tested the effect of target species and pingers on bycatch using soak duration as a replicate, and the second model tested the effect of soak duration and pingers on bycatch using target species as a replicate. Tukey's HSD post hoc tests were used to identify significant differences between factor levels.

Bycaught seals that had additional information on length, sex, and/or blubber thickness available were used to determine which seals occur most frequently as bycatch. Age categories were defined as young of the year (YOY; 0-1 years) and juvenile/adult (>1 years). Lengths for these age categories were estimated from established growth curves (Table 1, McLaren 1993) for each species and sex (male, female). Length and gender data were not available for all seals, therefore individual chi-square tests were used to determine if observed bycatch varied by age and sex. Expected values for seal age categories were based on proportions of YOY and juvenile/adults for Canadian gray seals (Fisheries and Oceans Canada 2014) and the Western North Atlantic stock of harbor seals (Waring et al 2014). Expected values for seal gender were assumed equal, and linear regression was used to determine if blubber thickness and seal bycatch were correlated.

Additionally, bycatch data were analyzed for seasonal and annual trends. Given the nature of the data, a sampling unit was considered as the total number of seals bycaught in each combination of year, season (Winter: December – February; Spring: March – May; Summer: June – August; Fall: September – November), and NAFO statistical area. Number of observed trips for each combination were available from 2005-2011 and extracted from http://www.nefsc.noaa.gov/fsb/stat_charts/index.html. Specific information about use the of pingers, target species, and soak duration for these observed trips were not available. Data were averaged using the following equation:

$$\frac{total\ seal\ bycatch}{total\ number\ of\ observed\ fishing\ trips} \times 1000 = average\ seal\ bycatch\ per\ 1000\ fishing\ trips \qquad (1.1)$$

The effect of season and NAFO statistical area on seal bycatch was assessed using a multifactor ANOVA with multiple comparisons using years as a replicate. Similarly, the effect of year and area on seal bycatch was assessed using a multifactor ANOVA with multiple comparisons using season as a replicate. All statistical analysis was completed using R version 3.0.2.

Results

Gray Seal Bycatch

A total of 670 gray seals were reported taken as bycatch in NEFOP observed gillnet fishery trips from 2005 – 2013. Total observed gray seal bycatch in gillnets using pingers (n = 260) was significantly lower than those without pingers (n = 410; $x^2_{df=1}$=33.5821, p<0.001). Log-transformed gray seal bycatch varied significantly with target species ($F_{df=6, 62}$=8.3170, p<0.001), with highest bycatch occurring in the monkfish (*Lophius americanus*) and skate fisheries (Figure 2). Bycatch was significantly greater in the monkfish fishery than in all other fisheries except skate (Tukey's HSD: |t| > 3.338, p < 0.0199), while bycatch in the skate fishery was only significantly greater than the flounder fishery (Tukey's HSD: t=3.952, p=0.003). Log-transformed gray seal bycatch did not vary significantly with soak duration ($F_{df=13, 48}$=0.6602, p=0.7903). The use of pingers did not have a significant effect on gray seal bycatch when analyzed with target species ($F_{df=1, 62}$=0.7096, p=0.4028) or soak duration ($F_{df=1, 48}$=0.6543, p=0.4226) in individual multi-factor ANOVAs.

The gender of 264 bycaught grey seals was known; males (n = 180) were bycaught significantly more than females (n = 84; Figure 3 a., $x^2_{df=1}$=4608, p<0.001). Length data for 362 bycaught gray seals was converted to age, and total observed gray seal bycatch differed significantly by age from expected proportions, with young of the year occurring more frequently than expected (expected = 51 YOY; Figure 3 b.; n = 276; $x^2_{df=1}$= 919.6, p<0.001). Blubber thickness data was available for 291 bycaught grey seals, with an average blubber thickness of 2.16 cm (0.5 – 12 cm). Blubber thickness and log-transformed total observed gray seal bycatch were not significantly correlated ($F_{df=1, 32}$=2.209, p=0.147, r^2=0.0646).

Gray seal bycatch per 1000 fishing trips varied significantly by season ($F_{df=3, 224}$=8.9834, p<0.001) with greatest bycatch occurring during March-May and lowest bycatch in September-November (Figure 4 a.). Gray seal bycatch also varied significantly with year (Figure 4 b.; $F_{df=6, 185}$=2.2588, p=0.0397), with highest bycatch in 2010 and an increasing trend over time. Gray seal bycatch varied significantly by NAFO statistical area in both multifactor regressions (Figure 4 c.; bycatch = area + season + area x season: $F_{df=10, 224}$=7.8470, p<0.001; bycatch = area + year + area x year: $F_{df=10, 185}$=10.9044, p<0.001) with greatest bycatch occurring in areas 537 south of Cape Cod and 526 and 521 east of Cape Cod (Figure 5). Both the interaction between season and area ($F_{df=30, 224}$=2.2552, p<0.001) and year and area ($F_{df=54, 185}$=2.0627, p<0.001) had a significant effect on gray seal bycatch (Figure 6). From June-February, bycatch was highest in NAFO statistical areas 521 and 537. From March-May, when bycatch was highest overall, the highest bycatch occurred in statistical areas 526, 537, and 616 south of Cape Cod, followed by area 521 east of Cape Cod and 515 north of Cape Cod.

Harbor Seal Bycatch

A total of 341 harbor seals were taken as bycatch in NEFOP observed gillnet fishery trips from 2005 – 2013. Significantly fewer harbor seals were bycaught in gillnets with pingers (n = 91) than without (n = 250; $x^2_{df=1}$=74.1378, p<0.001). The highest bycatch occurred in fisheries targeting monkfish and Atlantic cod (Figure 7;

$F_{df=6, 48}$=4.7937, $p<0.001$). Bycatch was significantly greater in the monkfish fishery than in the flounder, groundfish, and skate fisheries (Tukey HSD: $|t| > 3.072$, $p < 0.047$), while bycatch in the Atlantic cod fishery was not significantly greater than any other fishery (Tukey HSD: $|t| < 2.297$, $p > 0.256$). Log-transformed harbor seal bycatch did not vary significantly with soak duration ($F_{df=12, 39}$=0.6718, p=0.7671). The use of pingers did not have a significant effect on harbor seal bycatch when analyzed with target species ($F_{df=1, 48}$=2.4941, p=0.1208) or soak duration ($F_{df=1, 39}$=1.0735, p=0.3065) in individual multi-factor ANOVAs.

The gender of 128 bycaught harbor seal was known; males (n = 86) were bycaught significantly more than females (n = 42; Figure 8 a.; $x^2_{df=1}$=968, $p<0.001$). Length data for 177 seals was converted to age, and total observed harbor seal bycatch differed significantly from expected proportions, with young of the year occurring more frequently than expected (expected = 40 YOY; Figure 8 b.; n = 128; $x^2_{df=1}$=160.1, $p<0.001$). Blubber thickness data was available for 139 animals, with an average (range) blubber thickness of 2.12 cm (0.6 – 12 cm). Log-transformed blubber thickness and log-transformed total observed harbor seal bycatch were not significantly correlated ($F_{df=1, 28}$=3.903, p=0.05813, r^2=0.1223).

Harbor seal bycatch per 1000 fishing trips varied significantly by season ($F_{df=3, 224}$=6.0584, $p<0.001$) with significantly greater bycatch occurring from December-May (Figure 9 a.). Harbor seal bycatch also varied significantly by year (Figure 9 b; $F_{df=6, 192}$=2.4365, p=0.0271), with higher bycatch occurring in 2005, 2009, and 2010. Harbor seal bycatch did not vary significantly by NAFO statistical area in either multifactor ANOVA (Figure 9 c.; bycatch = area + season + area x season: $F_{df=10, 224}$=0.9084, p=0.5262; bycatch = area + year + area x year: $F_{df=10, 192}$=0.8004, p=0.6284), but the largest average annual bycatch was found in NAFO statistical area 537 south of Cape Cod, followed by NAFO statistical area 539 off the coast of Rhode Island and 513 off the coast of southern Maine (Figure 10). While the interaction between season and area was not statistically significant, seasonal trends were evident in the NAFO statistical areas (Figure 11); in September-November, bycatch was highest in areas 513 and 539, whereas in December-February bycatch was highest overall, especially in areas 521, 537, and 612. From March-May, bycatch was highest in areas 515 and 616, and from June-August bycatch was highest in area 513.

Discussion

Finding trends in bycatch of gray and harbor seals in New England is an important topic of study from both a conservationist and an economical perspective. The seals in New England are protected species and their populations are currently rebounding to historical levels, resulting in more bycatch and interactions with fisheries (Waring et al 2014, Lelli et al 2009, The Marine Mammal Protection Act of 1972 As Amended 2007). The New England fishing industry is a major source of revenue for the Northeast US and interactions with seals cost fishermen time and money. By understanding these interactions, we can work to reduce them by changing fishing techniques or using mitigation measures, which will benefit the fishing industry while allowing the seal populations to thrive.

Most gray seal bycatch in the Northeast sink gillnet fishery occurs in areas closest to their major haul-out and pupping sites of Muskeget and Monomoy Island (Figure 5; Ampela 2009, Bogomolni et al 2010a, Waring et al 2014). Most (84%) of gray seals taken were young of the year, which is similar to gray seals taken in the Baltic Sea (Vanhatalo et al 2014). The seasonal trends in bycatch of gray seals generally followed the life history of pups during their first year of development. Pups are born from December through early February, with a peak in mid-January (Breed et al 2009); during this time bycatch is low, occurring almost exclusively off the breeding sites of Muskeget and Monomoy Islands. During the pupping and breeding season, adult gray seals fast on land and once they re-enter the ocean, they spend most of their time foraging to recover from their fast (Breed et al 2009). Pups remain on land and fast for an additional 1 to 4 weeks after the lactation period, entering the ocean for the first time in late winter/early spring when gillnet fishing efforts in New England begin to increase (Waring et al 2014, Beck et al 2007). At this point, pups begin foraging for the first time and are extremely vulnerable to bycatch in gillnets (Breed et al 2011, Bjørge et al 2002), which is evident in the high levels of spring bycatch seen in this study. Pups are also traveling farther from shore to forage (Breed et al 2011) and correspondingly higher bycatch occurred in offshore regions in the spring than during the rest of the year. In the summer, young of the year seals are still developing their foraging skills while adult and juvenile gray seals return to land to molt (Breed et al 2011). Bycatch at this time is again concentrated in areas near the gray seal haul out sites of Muskeget and Monomoy Island. During the fall, bycatch is relatively low and occurs almost exclusively in NAFO areas 521 and 537 near Muskeget and Monomoy Islands. At this time pups from the previous season have become more efficient foragers and are likely not as vulnerable to bycatch in gillnets (Breed et al 2011, Bjørge et al 2002).

Harbor seals were taken less often than gray seals during the study period. Most harbor seal bycatch in the Northeast sink gillnet fishery occurred in areas closest to their major haul-out sites of Isle of Shoals, Monomoy Island, and Nantucket Island as well as pupping sites along the coast of Maine (Figure 10; Waring et al 2014, Baraff and Loughlin 2000). Most (81%) of harbor seals taken are young of the year, which is similar to a previous study where young of the year and juvenile seals constituted 93% of harbor seals taken in the Northeast sink gillnet fishery from 1991 to 1997 (Williams 1999). Harbor seal bycatch varied significantly by season and the seasonal patterns generally follow their life history. In the spring/summer, when harbor seals are pupping, molting, and foraging close to shore in Maine (Baraff and Loughlin 2000, Waring et al 2014), bycatch occurred almost exclusively along the Maine coast. In the late summer and early fall, harbor seals spend a lot of time foraging at sea as adults recover from the reproductive and molting periods and pups develop diving and foraging skills (Reeves et al 2002, Jorgensen et al 2001, Bekkby and Bjorge 2000). During this time, bycatch was lower but still evident and concentrated along the Maine coast. Harbor seals migrate southward toward their winter haul out sites in Southern New England during early winter (Reeves et al 2002), and bycatch was highest, occurring all along the New England coastline during this time. Harbor seals spend more time in the water during the winter to avoid extreme wind chill temperatures on haul out sites and pups at this time are continuing to develop their foraging skills, making them more susceptible to fishing operations (Boulva and McLaren 1979). In the spring, harbor seals migrate back towards their pupping grounds along the Maine coast (Reeves et al 2002) and bycatch levels are again relatively high throughout New England, with more bycatch occurring offshore.

Most gray and harbor seals taken as bycatch in the sink gillnet fishery had blubber layers between 1 and 3 cm, which is similar to young of the year harbor seals in the Southern Alaska (females averaging (± s.e.) 2.23 (±0.146) and males averaging 2.03 (±0.130); Pitcher 1986) and young gray seals taken as bycatch in the Gulf of Bothnia (females averaging (± s.d.) 3.7 (±7) cm and males averaging 2.5 (±4) cm and 3.1 (±6) cm in the spring and autumn respectively; Backlin et al 2011). The blubber layer acts as an insulator and energy reserve for marine mammals and can vary in thickness depending on an animal's health and diet (Strandberg et al 2008, Koopman et al 2002, Ryg et al 1988). Gray seals taken as bycatch in the Gulf of Bothnia were thinner than those taken in hunts, indicating starvation could drive seals to forage in fishing gear (Backlin et al 2011). However, blubber thicknesses in young seals is known to vary throughout the first year of life, increasing rapidly during nursing, decreasing after weaning, and remaining variable for the remainder of the first year (Pitcher 1986, Boulva and McLaren 1979). Further research is necessary to understand the development of blubber with age before we can understand the implications of blubber thicknesses in bycaught seals.

Total metric tons of fish landed in all Northeast gillnet fisheries, from 2005 – 2011 increased from 15,390 to 19,279 (Waring et al 2014). While this data includes fishery landings both in the Northeast anchored float and drift gillnet fisheries and not just the Northeast sink gillnet fishery, it is clear that fishing effort has increased, especially in recent years. While fishery landings may not directly reflect fishing effort or time at sea, it is the only parameter publically available for this fishery as most of the fishery is managed by daily or seasonal catch limits. Gray seal bycatch varied significantly by year, with an increasing trend in recent years, but was not significantly correlated with fishery landings during the study period ($F_{df=1,5}$=1.27, p=0.3109, r^2=0.203). Harbor seal bycatch also varied significantly by year, but there was no annual trend in harbor seal bycatch. In addition to an increase in fishing activity, there was also an increase in observer coverage over the study period, where estimated percent observer coverage from 2005 – 2011 was 7, 4, 7, 5, 4, 17 and 19 respectively (Waring et al 2014). Since bycatch data was averaged using the number of observed trips in each statistical area, the increasing trend is not likely due to increased observer coverage and is most likely the result of increased fishery effort.

Both gray and harbor seal bycatch varied significantly by target species of the fishery, with highest bycatch of gray seals occurring in the monkfish and skate fisheries and highest bycatch of harbor seals occurring in the monkfish and Atlantic cod fisheries. The high bycatch in these fisheries could be due to seal diets, as skate and Atlantic cod are important components of gray and harbor seal diets respectively (Ampela 2009, Wood 2001, Payne and Selzer 1989). Neither seal species is known to forage on monkfish, although it is possible that they are foraging on monkfish without detection in diet studies due to loss or degradation of otoliths (Ampela 2009, Wood 2001, Payne and Selzer 1989). These seals may also be foraging around the monkfish nets and feeding on other, smaller species that are either not captured by the net or are discarded as bycatch. While gillnet fishing effort occurs year round, it peaks in May – July (Waring et al 2014) and coincides with the higher bycatch of gray seals observed in this study. Therefore, fishing effort and observer coverage may be responsible for the trends observed in target species.

Significantly fewer gray and harbor seals were taken as bycatch when pingers were in use than when pingers were not in use. In the Northeast sink gillnet fishery, pingers are in use in certain areas for parts of the year in accordance with the Harbor Porpoise Take Reduction Plan (Taking of Marine Mammals Incidental to Commercial Fishing Operations; Harbor Porpoise Take Reduction Plan Regulations 2013) and appear to indirectly deter pinniped bycatch as well. However, since total bycatch was used in this analysis, it is possible that observer coverage was not equal in times when pingers were required or not required by the HPTRP. While acoustic deterrent devices have been used to deter cetacean bycatch and depredation with relatively high levels of success (Maccarrone et al 2014, Waring et al 2014, Waples et al 2013, McPherson 2011, Barlow and Cameron 2003), they are generally not as effective at deterring pinnipeds (Gotz and Janik 2013, Bowles and Anderson 2012, Caretta and Barlow 2011, Barlow and Cameron 2003). Studies have shown that both harbor and gray seals are prone to habituation and even attraction to pingers after relatively short periods of exposure, especially when motivated by food (Bowles and Anderson 2012, Gotz and Janik 2011). In fact, there is evidence that pingers may act as “dinner bells” for pinnipeds, and gray seals can even use sounds from acoustic tags to locate fish (Stansbury et al 2015, Bowles and Anderson 2012, Caretta and Barlow 2011).

The Northeast sink gillnet fishery is listed as a Category I fishery, indicating that frequent incidental mortality of marine mammals occurs, where “frequent” is defined as takes totaling more than 50% of an individual marine mammal species’ Potential Biological Removal (PBR; List of Fisheries for 2015 2014). PBR is defined by the MMPA as “the maximum number of animals, not including natural mortalities, that may be removed from a marine mammal stock while allowing that stock to reach or maintain its optimum sustainable population” (The Marine Mammal Protection Act of 1972 As Amended 2007). A PBR value is calculated for each marine mammal stock as the minimum population size times half the maximum net productivity rate times a recovery factor between 0.1 and 1. The classification of the Northeast sink gillnet fishery is due to the fisheries interactions with harbor porpoises, humpback whales, minke whales, and North Atlantic right whales (Waring et al 2014, List of Fisheries for 2015). According to the 2013 stock assessment, harbor seals in the northwest Atlantic have a PBR of 1,662 individuals with an average of 347 seals being taken annually from 2007-2011 in the Northeast sink gillnet fishery (Waring et al 2014). The annual average take in this fishery is approximately 21% of the PBR for harbor seals, which would classify it as a Category II fishery according to the MMPA (The Marine Mammal Protection Act of 1972 As Amended 2007). Like Category I fisheries, Category II fisheries must acquire a permit to take marine mammals during fishing operations, must take observers on board when requested, and must comply with all take reduction plans.

Since there is currently no valid population estimate for gray seals, a PBR has not been calculated and it is unclear whether the bycatch of this species should be considered frequent or not. A hypothetical PBR value for gray seal populations in US waters calculated using the most recent population estimates from the 2014 stock assessment (minimum population estimate = 1,731 (gray seals along Maine coast in 2001) + 15,756 (gray seals in southeastern Massachusetts coastal waters in 2011; Waring et al 2014), the default net productivity rate for all pinnipeds of 12%, and a recovery factor of 1.0 for stocks of unknown status that are believed to be increasing, indicates 1,049 gray seals can be taken annually without affecting the optimum sustainable population. An average of 1,043 seals were taken annually from 2007-2011 in the Northeast sink gillnet fishery (Waring et al 2014). The annual average take in this fishery is nearly 100% of this hypothetical PBR for gray seals, which would classify it as a Category I fishery according to the MMPA (The Marine Mammal Protection Act of 1972 As Amended 2007). While the Northeast sink gillnet fishery may not be having a major impact on harbor seal populations, it has the potential to seriously impact gray seal population through bycatch.

The seal population history and interactions with fisheries in New England is very similar to that in the Baltic Sea and we may be able to learn from their actions (Varjopuro 2011, Simila 2006). Gray seals were hunted extensively in the Baltic Sea during the 20th century in order to reduce competition with fisheries, but the population has recently rebounded, resulting in elevated levels of bycatch, with an estimated 2,180 – 2,380 seals taken as bycatch annually (Vanhatalo et al 2014, Harding et al 1999). Gray seal depredation in the Baltic Sea has resulted in loss of revenue for fishermen and a growing disdain for the seals (Varjopuro 2011). While numerous mitigation efforts have been taken to reduce these interactions, few have proven successful and the seals are still considered a threat to the fishing industry (Varjopuro 2011). Fishermen have tried to reduce depredation and net damage by reducing net soak duration, which increases operational costs for the fishermen, but provides better catches with less seal damage (Varjopuro 2011). However, the current study found that soak duration does not seem to affect depredation in New England (see Chapter 2) and also indicated that soak duration did not significantly affect bycatch, indicating that the fishing location may be a more important factor.

In addition, small-scale seal culling has occurred annually since 1998 in the Baltic Sea resulting in stabilized population growth, but has not scared seals away from fishing activities as originally hoped (Varjopuro 2011). Other studies have also found that culling of marine mammals does not necessarily increase the fish biomass available to fisheries (Morisette et al 2012) and would not likely help the current situation in New England. New fishing technologies have also been developed to mitigate seal-fishery interactions in the Baltic Sea with limited success, including a seal-proof trap-net that keeps seals away from catches (Lehtonen and Suuronen 2010, Hemmingsson Fjalling et al 2008, Varjopuro and Salmi 2006). Further research and development of these seal-mitigating technologies could help reduce seal-fishery interactions around the world.

While gray and harbor seals are known to interact with the Northeast sink gillnet fishery through depredation and bycatch, few attempts have been made to directly mitigate these interactions. Before successful mitigation is possible, it is imperative to understand the interactions as they occur, which requires data collection on both the marine mammals and the fisheries involved. Better, more complete knowledge of the movements and behaviors of gray and harbor seals throughout the year, especially young seals, can provide insight on where and when interactions may occur. In addition, we need to have more reliable population estimates for the seal species in New England, especially gray seals, before we can truly understand the impact of bycatch on seal populations. Further analysis of fishing effort data, including more precise fishing locations, bycatch per fishing trip, and soak durations, can help indicate areas of high fishing effort that may overlap pinniped range. By identifying these areas of high interaction, fishermen may be able to adjust their fishing efforts to reduce damage to their catch by seals and seal bycatch, saving them both time and money. As seal populations and fishing effort increase, interactions with fisheries are also likely to increase, affecting both seal stocks and the New England fishing industry. It is imperative to fully understand these interactions as they currently exist so we can predict and follow their evolution through time.

Table 1: Age-length categories for male and female **a.** gray seals, and **b.** harbor seals. These age-length relationships were estimated from established growth curves for each species (McLaren 1993) and were used to define age classes for bycaught seals.

a. Gray seal age-length categories

Sex	Age Class	Age	Length (cm)
Male	Young of the Year	<1 year	≤147
	Juvenile/Adult	>1 year	>147
Female	Young of the Year	<1 year	≤130
	Juvenile/Adult	>1 year	>130

b. Harbor seal age-length categories

Sex	Age Class	Age	Length (cm)
Male	Young of the Year	<1 year	≤112
	Juvenile/Adult	>1 year	>112
Female	Young of the Year	<1 year	≤112
	Juvenile/Adult	>1 year	>112

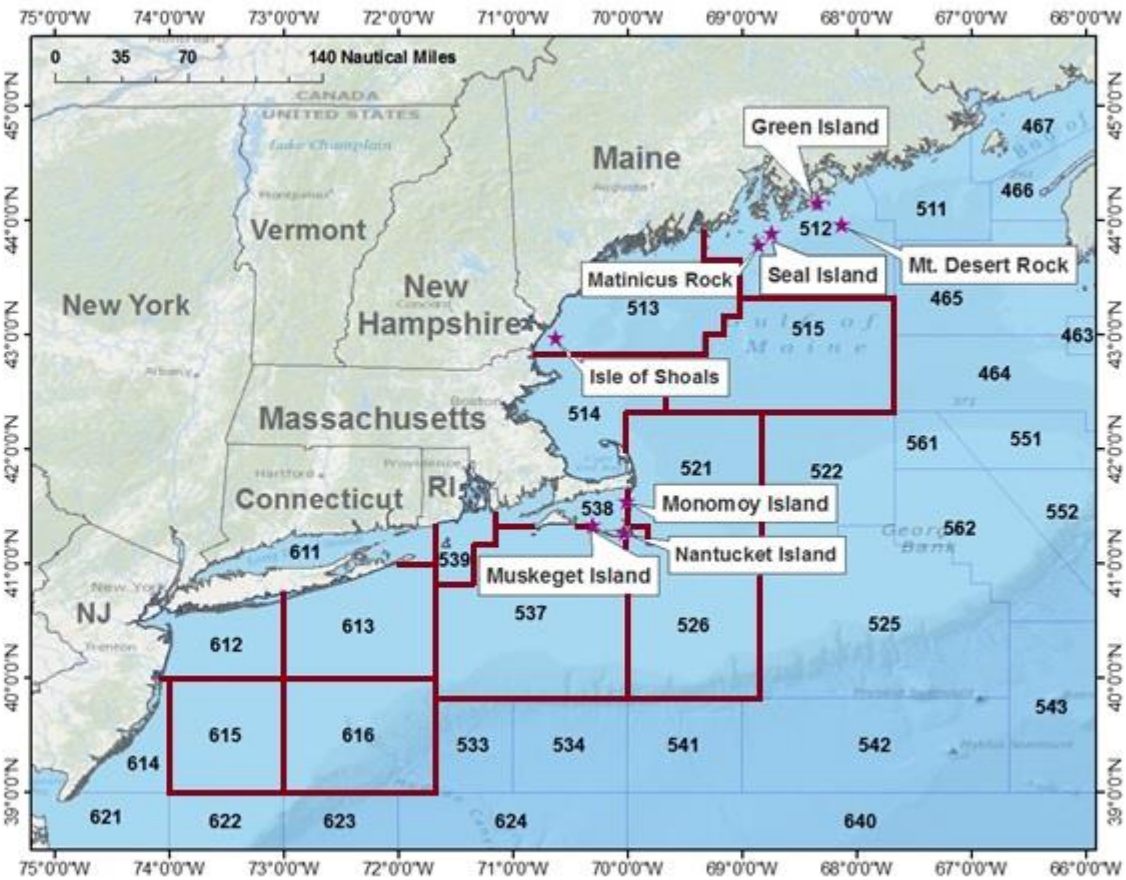


Figure 1: Map of seal haul out and breeding sites in New England. Areas with Northeast Fisheries Observer Program (NEFOP) coverage for study period (2005 – 2011) are outlined in red. Map created using ERSI® ArcMap™ 10.0.

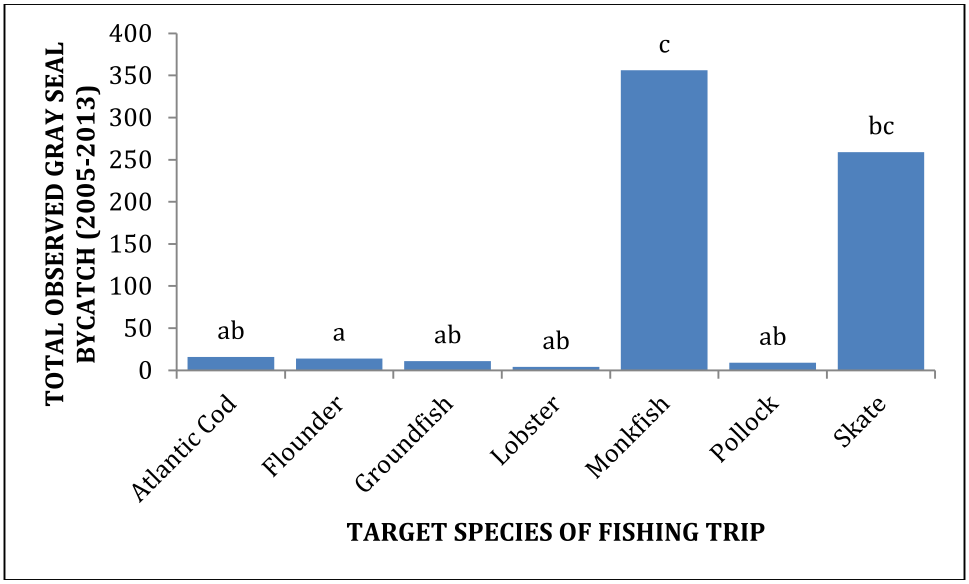


Figure 2: Total observed gray seal bycatch by target species. The letters above the data points denote the results of Tukey's HSD post hoc comparisons.

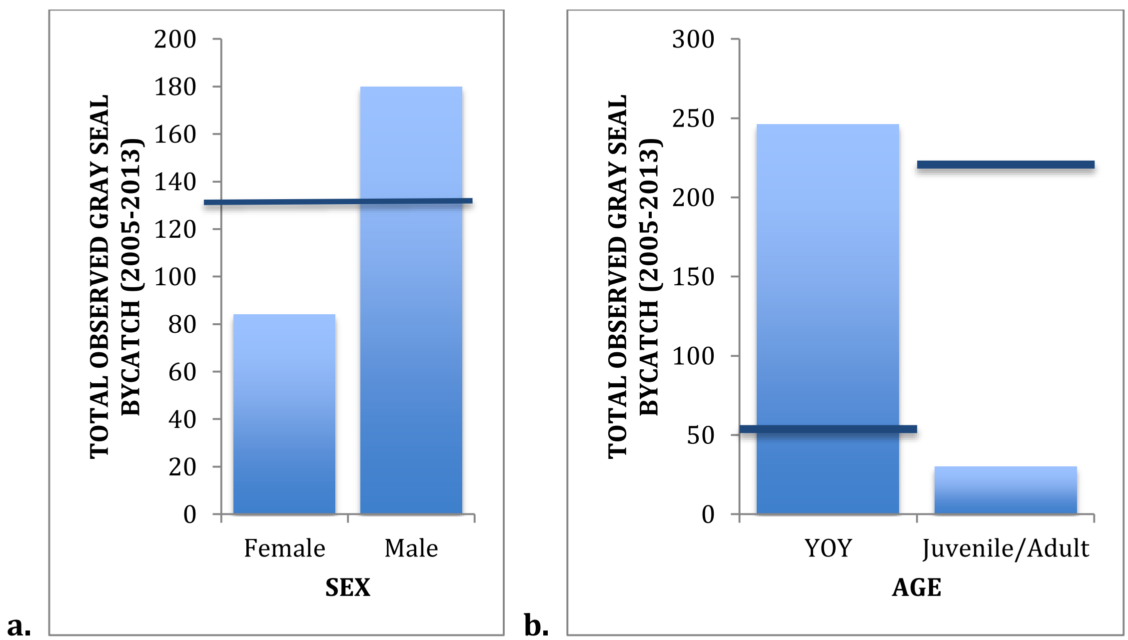


Figure 3: Total observed gray seal bycatch by: **a.** sex and **b.** age. Dark blue bars indicate the expected proportions for each factor. (YOY indicates Young of the Year)

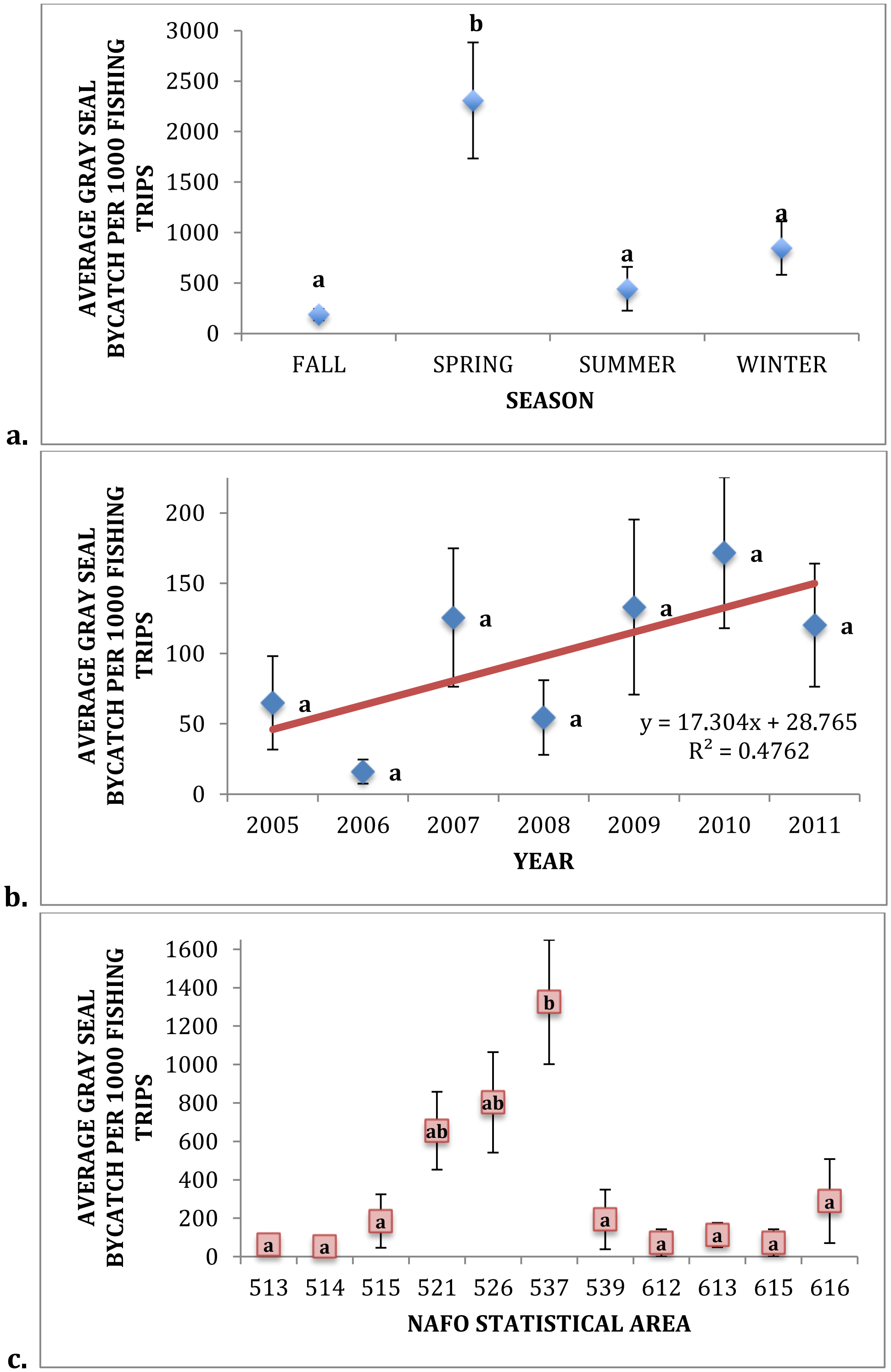


Figure 4: Average (± s.e.) gray seal bycatch per 1000 fishing trips by: **a.** season, **b.** year, and **c.** NAFO statistical area. The letters associated with each data point denote the results of Tukey's HSD post hoc comparisons.

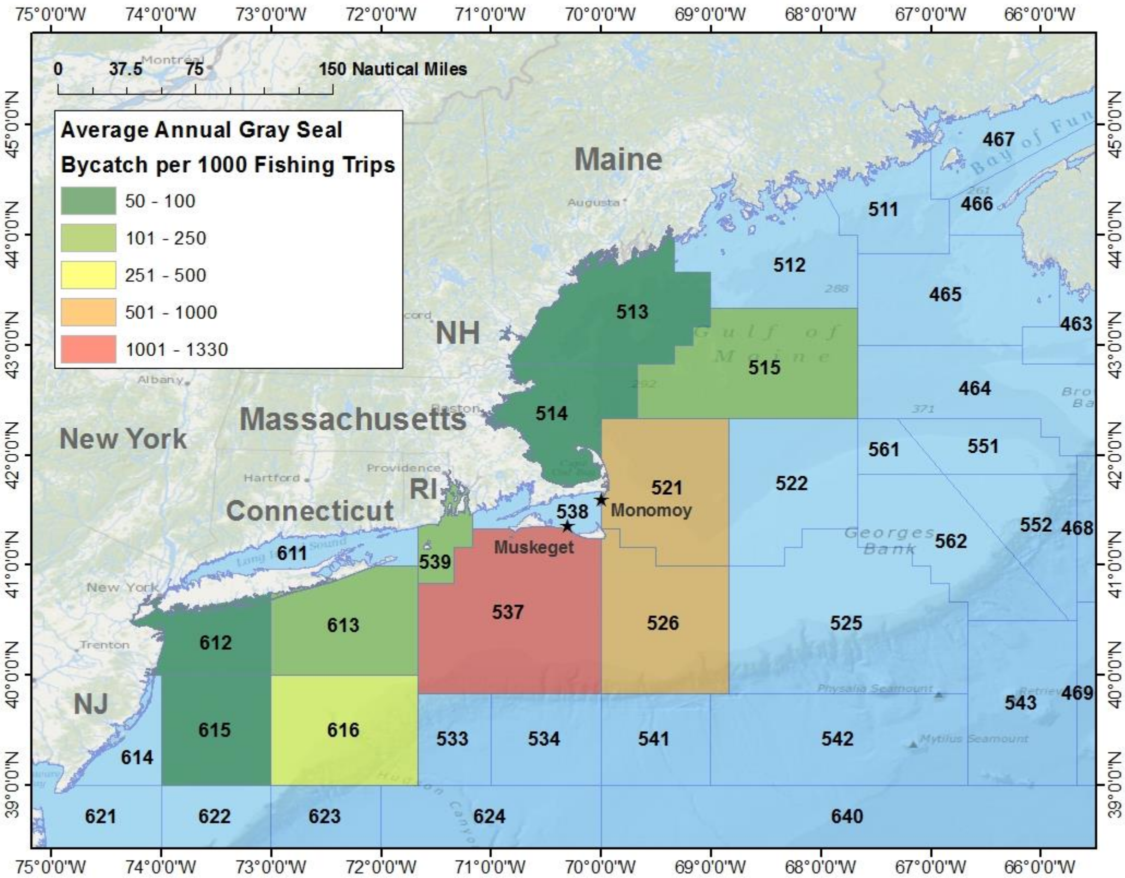


Figure 5: Average annual gray seal bycatch per 1000 fishing trips by NAFO statistical area from 2005 – 2011 NEFOP data. Map created using ERSI® ArcMap™ 10.0.

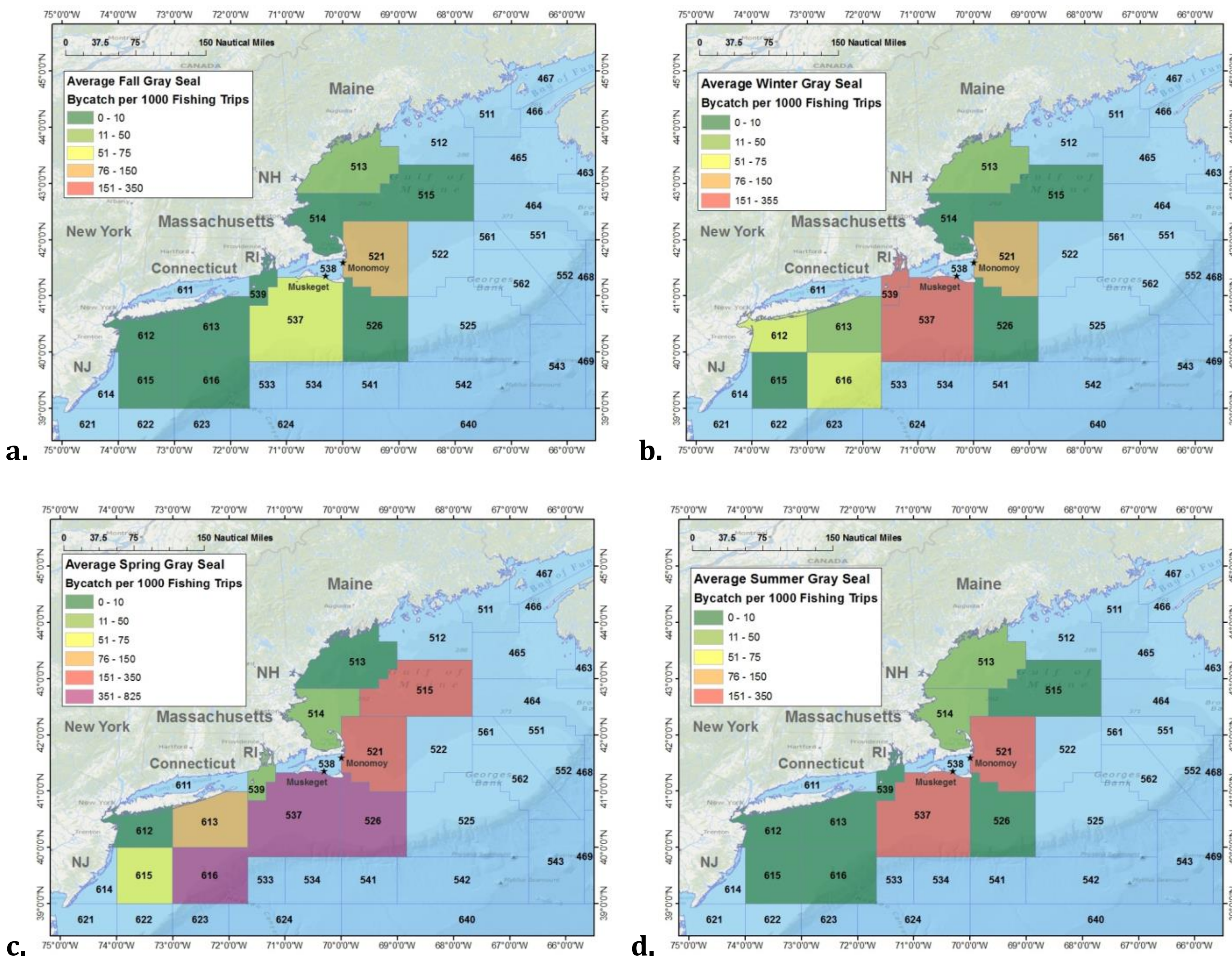


Figure 6: Average seasonal gray seal bycatch per 1000 fishing trips by NAFO statistical area from 2005 – 2011 NEFOP data: **a.** average fall (September – November) bycatch; **b.** average winter (December – February) bycatch; **c.** average spring (March – May) bycatch; **d.** average summer (June – August) bycatch. Maps created using ERSI® ArcMap™ 10.0

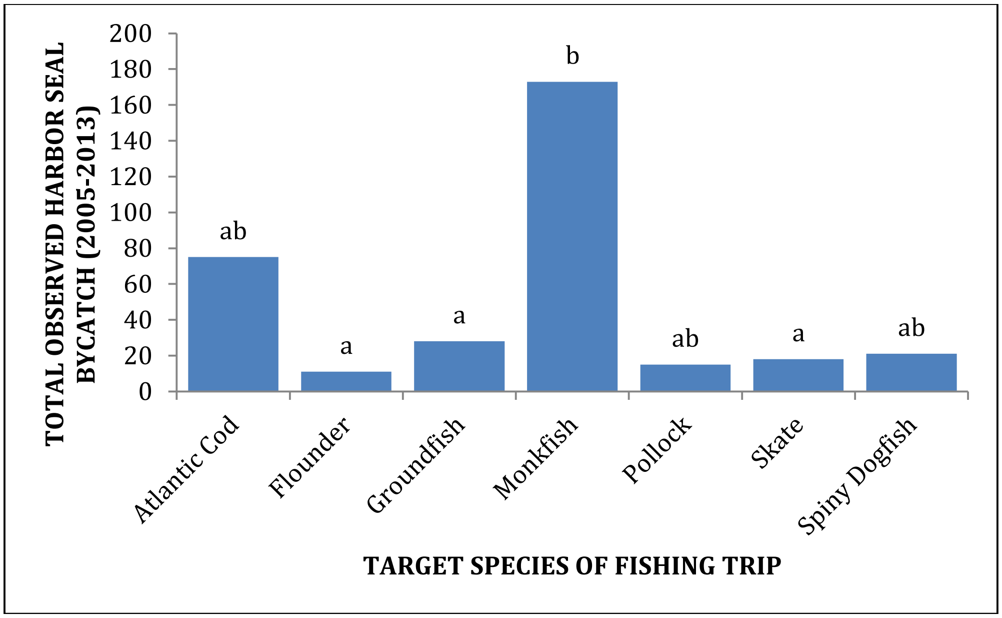


Figure 7: Total observed harbor seal bycatch by target species. The letters above the data points denote the results of Tukey's HSD post hoc comparisons.

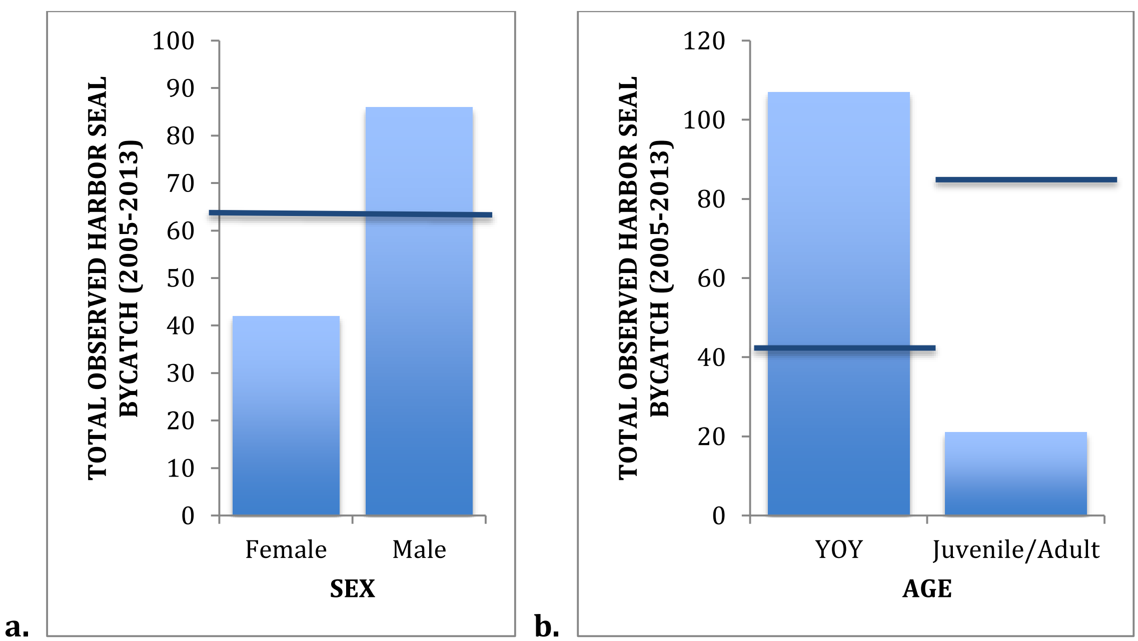
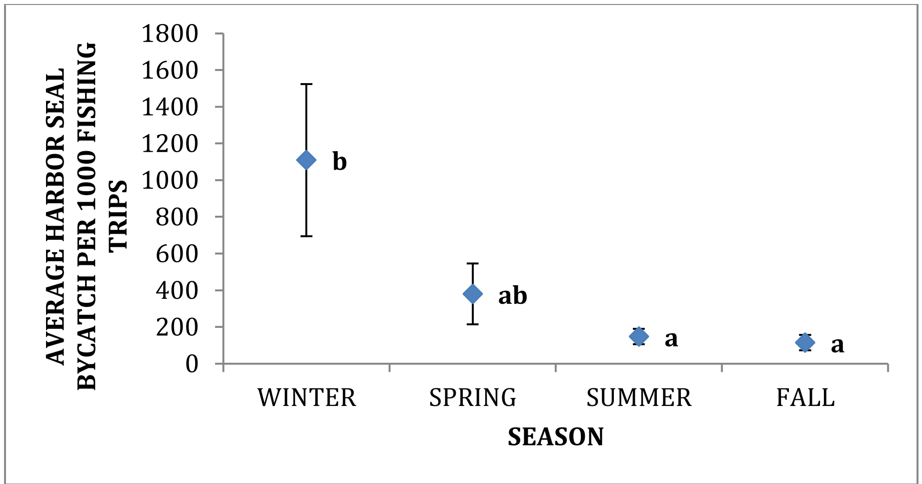
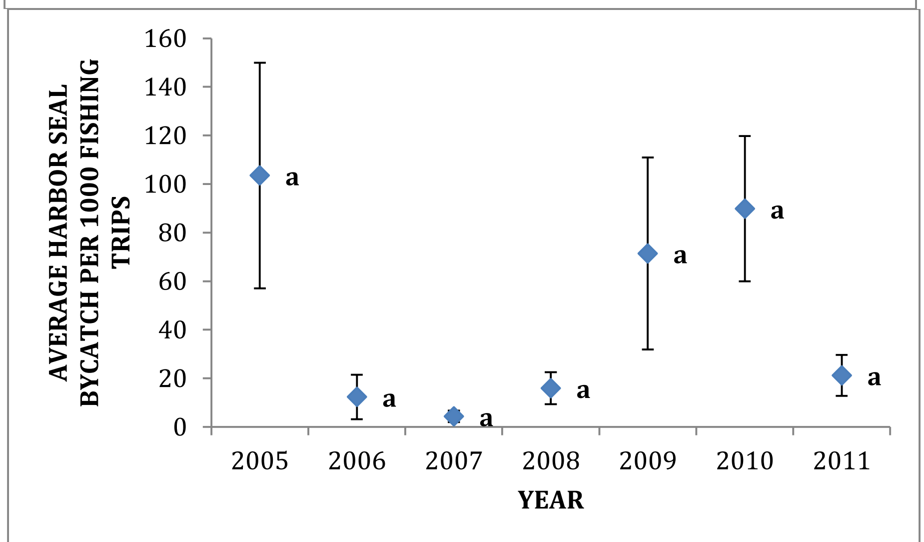


Figure 8: Total observed harbor seal bycatch by: **a.** sex and **b.** age. Dark blue bars indicate the expected proportions for each factor. (YOY indicates Young of the Year)



a.



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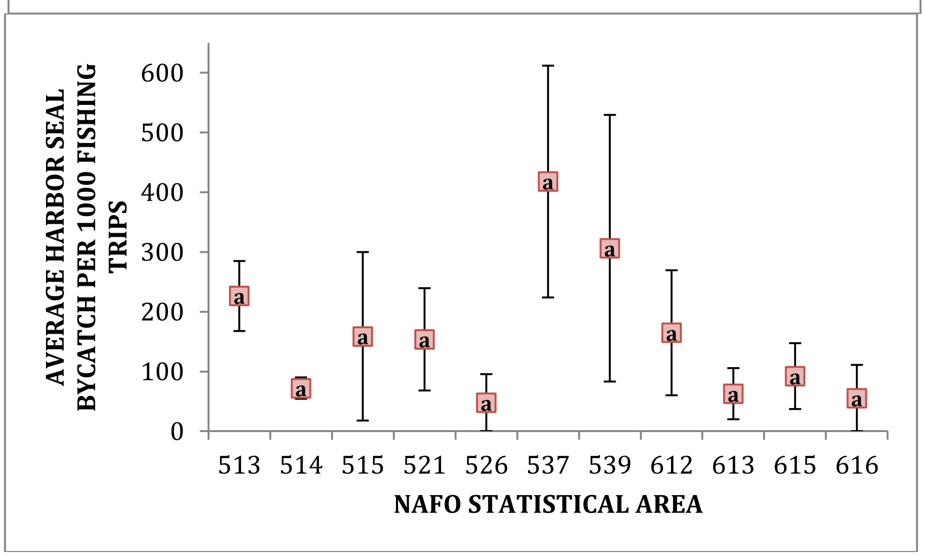

c.

Figure 9: Average (± s.e.) harbor seal bycatch per 1000 fishing trips by: **a.** season, **b.** year, **c.** NAFO statistical area. The letters associated with each data point denote the results of Tukey's HSD post hoc comparisons.

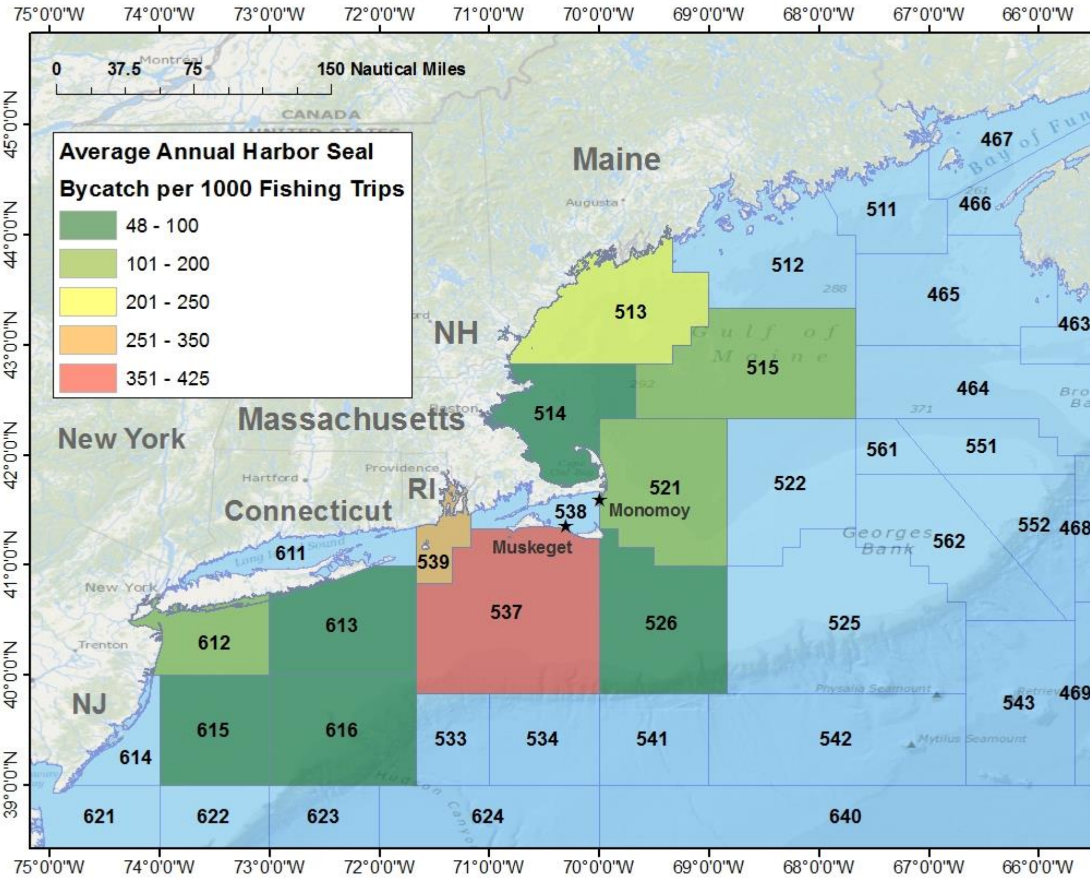

Figure 10: Average annual harbor seal bycatch per 1000 fishing trips by NAFO statistical area from 2005 – 2011 NEFOP data. Map created using ERSI® ArcMap™ 10.0.

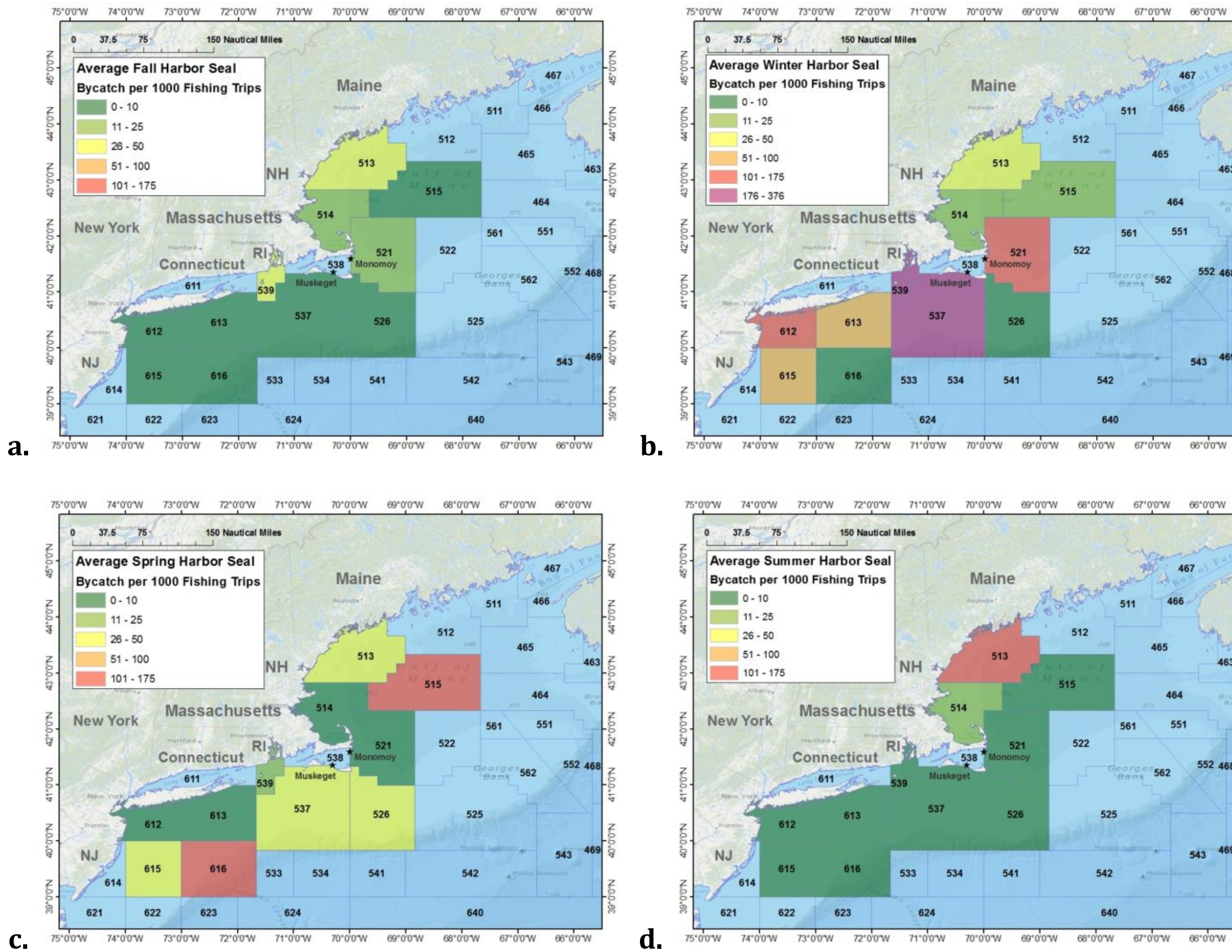

Figure 11: Average seasonal harbor seal bycatch per 1000 fishing trips by NAFO statistical area from 2005 – 2011 NEFOP data: **a.** average fall (September – November) bycatch; **b.** average winter (December – February) bycatch; **c.** average spring (March – May) bycatch; **d.** average summer (June – August) bycatch. Maps created using ERSI® ArcMap™ 10.0.

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CHAPTER II

CHARACTERIZING BITE MARKS FOR THE IDENTIFICATION OF DEPREDATION SOURCES

Abstract

Gray seals (*Halichoerus grypus*) and harbor seals (*Phoca vitulina*) are often taken as bycatch in sink-gillnet fisheries in New England and are believed to consume and damage fish in gillnets. As seal populations increase, interactions with fisheries are also likely to increase, affecting both seal stocks and the New England fishing industry. There is some uncertainty among fishermen and scientists concerning the identification of sources of depredation (e.g. seal vs. spiny dogfish (*Squalus acanthias*)). Characteristics of seal and spiny dogfish bites were identified using foam imprints of jaws and bites by captive animals in the soft tissue of fish. Measurements from bite imprints and damaged fish were used to develop a protocol for identifying the source of damage in the field. In general, dogfish bites were clean (flesh completely removed), circular in shape, with a bite ratio (bite length/bite width) less than 0.6, whereas seal bites were ragged (flesh not completely removed, but partially torn from the bite), rectangular or trapezoidal in shape, with a bite ratio greater than 1. This protocol was tested by three independent observers, who identified the correct source of damage 95.2% of the time (n=49), with overall 87.8% agreement in identification. The application of this protocol was then used to

identify damaged catch observed on a commercial gillnet fishing vessel targeting skate in New England waters June – August 2014. In this small-scale study, dogfish bites were identified as the damage source significantly more frequently than seal bites. This inexpensive, quick, and practical protocol can be used on a larger scale to further understand depredation by seals and dogfish throughout New England. Once sources of depredation are identified, mitigation methods can be developed to more effectively exclude certain predators.

Introduction

Depredation, or damage of commercial goods by an animal, is a major economic issue worldwide, both in terrestrial and marine environments, and can result in loss of livestock and fish harvests (Magrini 2014, Nichols et al 2014, Maccarone et al 2014, Holmern and Roskaft 2013, Auge et al 2012, Read et al 2008, Baraff and Loughlin 2000). Depredation has been well studied in terrestrial environments, where large canids and felids damage livestock and smaller carnivores target poultry stocks (Magrini 2014, Lyngdoh et al 2014, Holmern and Roskaft 2013). While it is more difficult to study in the marine environment, many marine animals are known to forage in nets during fishing operations, but are not always observed in the act, making the depredation source difficult to identify (Nichols et al 2014, Peterson et al 2013, Robbins et al 2013, Raffery et al 2012, Varjopuro 2011, MacNeil et al 2009, Mandelman et al 2008). Mitigation measures, including acoustic deterrent devices, have been employed in both marine and terrestrial environments with varying levels of effectiveness (Johnson et al 2014, Dalmasso et al 2012, Marucco and Boitani 2012, Reinhardt et al 2012, Salvatori and Mertens 2012, VerCauteren et al 2005).

Many predators are responsible for depredation in marine environments, most notably sharks and marine mammals (Peterson et al 2013, Robbins et al 2013, MacNeil et al 2009, Gilman et al 2007, Baraff and Loughlin 2000). Depredation by these predators can cause over 20% catch loss and result in the loss of thousands of dollars in revenue per fishing trip (Gilman et al 2007, Gilman et al 2008). Additional damage by sea lice (Family *Caligidae*), hagfish (Family *Myxinidae*), and invertebrates can result in further loss of catch, especially when the catch has already been damaged by other predators (NFSC 2013, pers. obs.). Sharks (Subclass *Elasmobranchii*), in particular, often depredate a variety of tuna (*Thunnus* spp.) and billfish (Family *Istiophoridae* and *Xiphiidae*) species in pelagic longline fisheries around the world (MacNeil et al 2009, Gilman et al 2007). Fishermen attempt to avoid shark depredation, at additional operational costs, by changing their fishing location when shark interactions are high or by changing their fishing practices by setting lines deeper, for shorter periods of time, and/or by using different bait (MacNeil et al 2009, Gilman et al 2008, Gilman et al 2007).

Resident killer whales (*Orcinus orca*) and sperm whales (*Physeter macrocephalus*) in the Bering Sea, Aleutian Islands, and Gulf of Alaska feed on a variety of commercially valuable fishes and have been observed depredating halibut (*Hippoglossus stenolepis*), sablefish (*Anoplopoma fimbria*), arrowtooth flounder

(*Atheresthes stomias*), Greenland turbot (*Reinhardtius hippoglossoides*) and Pacific cod (*Gadus macrocephalus*) in the longline fishery (Fearnbach et al 2014, Peterson et al 2013, Lunsford and Rutecki 2010, Matkin et al 2007). Resident killer whales in particular were responsible for a 35.1-69.3% reduction in catch per unit effort, which can cost from $289 to $522 for additional fuel to avoid whales and additional days at sea to compensate for damages (Peterson et al 2014, Peterson and Carothers 2013). Dolphins and porpoises are also responsible for depredation to a lesser extent in some areas of the world, including Australia, the Mediterranean Sea, and the United States coastlines (Maccarone et al 2014, Waples et al 2013, Powell and Wells 2011, Zollett and Read 2006, Read et al 2003, Chilvers and Corkeron 2001, Reeves et al 2001).

Pinnipeds are known to interact with fisheries worldwide and can have serious impacts on fishery catch via depredation, most notably in the Baltic Sea (Cronin et al 2014, Varjopuro 2011, Konigson et al 2007, Kauppinen et al 2005). Rebounding populations of gray seals in the Baltic Sea damage an average of 45% of catch in some regions and small-scale seal culling has been in place since 1998 in an attempt to reduce depredation (Varjopuro 2011, Simila 2006). While seal populations in this region appear to have stabilized, the effect of hunting on this population and its effect on depredation are unknown (Varjopuro 2011, Ministry of Agriculture and Forestry 2007). The herring (*Clupea harengus*) gillnet fishery is particularly vulnerable as this fishery uses fixed gear that remains stationary in the water for extended periods of time and targets the major food source for gray seals in the Baltic Sea (Konigson et al 2007, Lundstrom et al 2005). The Finnish Game and Fisheries Research Institute has attempted to develop new fishing technologies to mitigate seal-fishery interactions, including a pontoon trap with double mesh walls that traps fish between the walls to prevent seal depredation (Lehtonen and Suuronen 2010, Hemmingsson et al 2008, Suuronen et al 2006, Varjopuro and Salmi 2006). This net has been shown to reduce depredation by up to 80% (Varjopuro 2011, Hemmingsson et al 2008).

Pinniped depredation is also recognized as a concern in US waters (Baraff and Laughlin 2000). While pinnipeds are known to interact with fisheries in New England, limited research has been conducted concerning these interactions, especially in regards to depredation (Nichols et al 2014, Rafferty et al 2012, Nichols et al 2012). In 2014, Nichols et al documented gray seal predation in a longfin inshore squid (*Dorytheuthis pealeii*) fishery and suggested that seals were associating the weir as a food source and utilizing it as such on a regular basis. Rafferty et al (2012) found that overall depredation is relatively low in a Georges Bank gillnet fishery and that the majority of depredation was attributable to spiny dogfish (*Squalus acanthias*), not seals as most fishermen believe. There is some controversy among fishermen and scientists concerning the identification of damage as seal induced or from other sources (e.g. spiny dogfish; Raffferty et al 2012, pers. comm. Owen Nichols). Previous depredation studies have not provided detailed quantitative analysis of the differences between sources of depredation (e.g. Rafferty et al 2012). The purpose of this study was to (1) develop a specific protocol to identify different types of depredation, and (2) apply this protocol to actual damage observed in a sink-gillnet fishery to determine the extent of damage inflicted by different predators.

Materials and Methods

Pinniped jaw measurements

In order to determine the general shape and size of gray and harbor seal bites, measurements and bite imprints were taken from seal skulls at the University of New England (UNE Biddeford, ME), the Marine Mammal Stranding Center (Brigantine, NJ), and Harvard University's Museum of Comparative Zoology (Cambridge, MA). In total, 11 gray seal skulls and 25 harbor seal skulls were measured (species of seal was confirmed using dental formulas and tooth structure according to Jefferson et al 1993). Digital calipers were used to measure: (1) width of the mouth at the canines (WC) and (2) canine to rear molar length (CRML) on both the upper and lower jaw (Figure 1; adapted from Murmann 2006). In addition to these measurements, age of seal was obtained from the facility or estimated based on the size of the skull in comparison to specimens with known ages for each species. Imprints of the teeth in the upper and lower jaw for each skull were created using thin polystyrene sheets (0.15 cm thick; Michaels ® item #10597609). For each bite imprint, the length and width were measured and the presence/absence of canines were identified. Canines were identified as present in cases where teeth punctured through the foam, creating a more prominent indentation than other teeth. The bite shape was identified from the general outline made by the teeth as one of the following: rectangle (a bite outline with four straight sides and four right angles, opposing sides are approximately equal in length), trapezoid (a bite outline with four straight sides, two acute angles, and two obtuse angles, where two opposing sides are approximately equal in length and the other two are different in length), or circle (a bite outline that is rounded on at least one end).

Dogfish jaw measurements

Mouth measurements and bite imprints were taken from 58 previously frozen dogfish specimens at UNE to determine the general size and shape of dogfish mouths and bites. Calipers were used to measure: (1) rearmost jaw width (RJW), and (2) jaw length (JL) on both the upper and lower jaw (Figure 2). In addition to these measurements, imprints of the teeth from the upper and lower jaw for each skull were created using thin polystyrene sheets. The length and width were measured and the presence/absence of canines and the bite shape were identified.

Pinniped bite study

In order to identify characteristic seal bite marks in the soft tissue of fish, large fish (herring, mackerel (*Scomber scombrus*), whiting (*Merlangius merlangus*), and blue runners (*Caranx crysos*)) were frozen into ice blocks so that the heads were secured but the bodies were accessible. The exposed fish was thawed and presented to two young of the year gray seals undergoing rehabilitation through the

Marine Animal Rehabilitation and Conservation Program at UNE during the months of April, May, and June of 2014. The ice blocks kept the fish near the surface so they were easy to retrieve and simulated a fish trapped in a gillnet while not posing a threat to the seals. These "fish-sicles" were offered one or two at a time so seals had time to investigate the fish and attempt to consume them. After the seals bit or ripped the fish, the fish-sicles were recovered, thawed, and the fish were photographed along with a scale for later analysis. Although the seals used in this study were in rehabilitation, their bites should not differ from other animals in the wild.

Dogfish bite study

In order to identify characteristic dogfish bite marks in the soft tissue of fish, medium and large fish (herring, mackerel, and blue runners) were offered to captive dogfish at UNE either by hand, dropped to the bottom of the tank, or attached to a string. Dogfish were given time to investigate the fish and attempt to consume them. After the dogfish had bitten the fish, they were removed and photographed along with a scale for later analysis. Additional dogfish bite data were collected in the field during hauls targeting dogfish using brief (<30 minute) soak times. Gillnets were baited with skate and after the net was retrieved, damaged skate were removed and photographed along with a scale for later analysis. No other predators were observed at the surface during soak times or in the net during the haul, indicating dogfish were most likely responsible for damage.

Bite analysis in Image J

After completion of each bite study, photographs were analyzed to determine specific characteristics of each predator's bites. Photographs in which bite outlines could be identified or estimated were analyzed in Image J (Wayne Rasband, Version 1.48). Fish that had been torn in half or where a clear bite mark could not be distinguished were excluded from further analysis. A total of 27 dogfish bites (13 from field observations and 14 from lab trials) and 27 gray seal bites (all from laboratory trials) were analyzed in this study. Images were imported into Image J and individual bites were outlined using the "draw polygon" tool. In instances where additional flesh was removed from the fish after the bite, the outline of the bite was estimated. For each bite, the appropriate scale was established using the photographed ruler and the length and width were measured using the Image J "measure" tool. In addition, the presence/absence of canines and the bite shape were identified. Bite cleanness was also identified and characterized as clean (flesh completely removed, making bite outline very clear) or ragged (flesh not completely removed, but partially torn from bite).

Analysis of bite morphometrics

Paired t-tests were used to test for differences between the bite ratios of each jaw and its corresponding bite imprint for both the upper and lower jaws. Bite ratios were calculated using the following formula:

$$Bite\ ratio = \frac{Bite\ length}{Bite\ width} \qquad (2.1)$$

Bite ratios of seal and dogfish imprints did not overlap, obviating the need for statistical comparison. Chi-square contingency tests were used to determine if the imprint shape and presence/absence of canines is contingent upon the imprint source (seal vs. dogfish). A two sample t-test was used to compare the differences in bite ratios between the bite imprints and bites in soft tissue of fish for seals and dogfish independently. Seal imprint bite ratios were multiplied by a factor of 0.75 to provide a more realistic bite length of a live seal that has skin and cheek tissue blocking access to rear molars. This factor was estimated by superimposing a photo of a similarly sized gray seal skull on top of the jaw of a bycaught grey seal (Figure 3). Bite ratios were analyzed using a logistic regression to determine the probability of a bite being from a seal versus a dogfish based on its ratio. In addition, x^2 contingency tests were used to determine if bite shapes, presence/absence of canines, and cleanness of bites in the soft tissue of fish was contingent upon source. Due to the difference in foraging behaviors between seals and dogfish, with dogfish often using their entire jaw to bite prey and seals often using only part of their jaw length, a single regression could not be used to predict source from bite ratios.

Developing and testing bite identification protocol

Using the data obtained through the bite morphometric and bite studies with live seals and dogfish, a protocol for identifying the source of damage was developed for use during observations of commercial fishing operations (Figure 4). This protocol utilized the presence/absence of canines, the bite shape, the bite cleanness, and the bite ratio to determine the bite source. To test the effectiveness of this protocol, three naïve independent observers were introduced to and used the protocol to identify the source of damage for 49 photographed damaged fish. While the three observers did not have prior knowledge of the source of damage, the photographs used were from the pinniped (25 photographs) and dogfish (24 photographs) bite studies and each bite had a known bite source.

Field test of bite identification protocol

After the protocol was tested, it was then applied to depredated fish in a commercial gill-net fishing vessel targeting skate, where the source of the damage was unknown. Thirty-six gillnet hauls targeting skate were observed from June through August, 2014 in Northwest Atlantic Fisheries Organization (NAFO) statistical area 521 off of Cape Cod, MA (inset map in Figure 5 a.). During each haul, the catch, damaged catch, and bycatch of seals and dogfish were quantified and the majority of damaged catch was photographed. Additional data on the location of fishing efforts and net soak durations during field observations were also collected for statistical analysis. Using the bite identification protocol, 51 photographed bite marks from the field with unknown sources of damage were evaluated using Image J and identified as seal damage, dogfish damage, or unknown damage. For each haul, proportions of the total damaged catch attributable to each damage source were calculated and arcsine transformed for statistical analysis. In instances where all damaged catch was not photographed, proportions of each damage type were used to determine total damage from seal or dogfish depredation. To determine how source and fishing parameters may affect depredation, a multifactor ANOVA was used to determine the effect of source (seals, dogfish, or unknown), soak duration (categorized as days), and relative location (inshore (21.9 – 27.4 km from shore) vs. offshore (33.0 – 36.1 km from shore)) on the proportions of damaged catch. Linear regressions were used to determine if there was a relationship between the proportion of catch damaged by dogfish and the number of dogfish taken in the net, and the proportion of catch damaged by seals and the number of seals taken in the net. In addition, a multiple linear regression was used to determine if there was a relationship between the proportion of catch damaged by unknown source and the number of both seals and dogfish taken in the net.

Results

Analysis of bite morphometrics

Seal jaws (n=36) were longer than they were wide, with upper jaws averaging (± SD) 6.47 (± 1.21) cm long and 4.05 (± 1.08) cm wide and lower jaws averaging 5.613 (± 0.89) cm long and 3.23 (± 0.81) cm wide. Dogfish jaws (n=58) were wider than they were long, with upper jaws averaging 1.39 (± 0.13) cm long and 4.07 (± 0.24) cm wide and lower jaws averaging 1.57 (± 0.17) cm long and 4.33 (± 0.29) cm wide. The bite ratio of dogfish jaws and their corresponding imprint bite ratios were not significantly different (paired t-test: n=116, $t_{115} = -0.3481$, p=0.7284). The bite ratio of seal jaws and their corresponding imprint bite ratios were significantly different (paired t-test: n=56, $t_{55} = 10.4655$, p<0.0001) but correlated ($F_{df=1, 54} = 46.82$, p<0.0001, $r^2 = 0.4644$), with imprint bite ratios being slightly smaller than jaw bite ratios. The average (± SD) seal bite ratio from imprints was 1.519 (± 0.163) and the average dogfish bite ratio from imprints was 0.352 (± 0.041). Imprint bite ratios for seals (>1.2383) and dogfish (<0.4909) did not overlap, obviating the need for statistical comparison. Imprint shapes were contingent upon the bite source (x^2 contingency test; upper jaw: $x^2_{df=2} = 92$, $p<0.0001$; lower jaw: $x^2_{df=2} = 88$, $p<0.0001$), with all dogfish bites being circle shaped and all seal bites being rectangle or trapezoid shaped. The presence/absence of canines in imprints was also contingent upon the bite source (x^2 contingency test; $x^2_{df=1} = 77.03$, $p<0.0001$), with canines absent in all dogfish imprints and canines present in 88% of all seal imprints.

Of the 27 analyzed gray seal bites in the soft tissue of fish from captive seal bite trials, 63.0% of bites being rectangular and 37.0% being trapezoidal, canines were present on 59.3% of bites, and 100% of bites were ragged. The average seal bite ratio in the soft tissue of fish was 1.18 (± 0.52), and the length and width of seal bites were similar, averaging 3.62 (± 1.73) cm and 3.30 (± 1.53) cm respectively**.** Of the 27 dogfish bites in the soft tissue of fish analyzed, 100% of the bites were circle in shape, canines were absent in 100% of bites, and 51.9% of bites were clean. The average dogfish bite ratio in the soft tissue of fish was 0.41 (± 0.11), and the length and width of dogfish bites were different, averaging 2.34 (± 1.32) cm and 5.44 (± 1.96) cm respectively. The presence/absence of canines (x^2 contingency test: $x^2_{df=1}=22.737$, p<0.0001), cleanness of the bite (x^2 contingency test: $x^2_{df=1}=18.9$, p<0.0001), and shape of the bite (x^2 contingency test: $x^2_{df=2}=54$, p<0.0001) were all contingent upon bite source in these trials with captive animals. The ¾ imprint bite ratios and bite ratios of seal bites in soft tissue of fish were not significantly different (two sample t-test: $t_{87} = 0.5915$, $p=0.5558$). Imprint bite ratios and bite ratios in soft tissue of fish were significantly different for dogfish (two sample t-test: $t_{141} = 4.8756$, $p<0.0001$), with imprint bite ratios being significantly smaller than bite ratios in the soft tissue of fish. From the bite study in soft tissue data, the proportion of variance in bite source explained by bite ratio was 0.745 (logistic regression; Figure 6).

<u>Developing and testing bite identification protocol</u>

Using results from both static and live, captive bite studies, a protocol was developed to identify seal and dogfish depredation (Figure 4). In this protocol, the presence/absence of canines, bite shape, bite cleanness, and bite ratio are used to identify damage. Clean bites where canines are absent that are circular in shape and are wider than they are long (bite ratio <0.6) are identified as dogfish bites, whereas ragged bites where canines are present that are rectangular or trapezoidal in shape and are longer than they are wide or equal in length and width (bite ratio >0.7) are identified as seal bites. Bites do not have to contain all parameters to be identified as one source or the other, but the observer should use as many factors as possible to determine bite source. During the blind test of this protocol, testers identified the correct bite source on average 95.2% of the time (n=49), with overall 87.8% agreement in identification.

Field test of bite identification protocol

Overall damage of catch was low for each haul, totaling less than 5% of total catch (Figure 5). Of the 51 photographed damaged fish used to test the application of this protocol, 35 (68.6%) were identified as dogfish bites (Figure 7 a.), 2 (3.9%) were identified as seal bites (Figure 7 b.), and 14 (27.5%) were unidentifiable. Of the 14 unidentifiable bites, 9 (17.6%) were unidentifiable due to degradation and/or extensive scavenger damage. Only 5 (9.8%) showed evidence of both dogfish and seal bites and were categorized as unidentifiable for statistical analysis. For the observed hauls, damage source had a significant effect on the proportion damaged (Figure 8; Multifactor ANOVA: $F_{df=2,66} = 9.306$, $p = 0.0003$), with dogfish (average± SD: 0.0633±0.0572) causing a significantly higher average proportion of damage than seals (0.0135±0.0268; Tukey HSD: $p < 0.0001$) and unknown (0.0334±0.0496; Tukey HSD: $p = 0.0383$). The location of the net (Multifactor ANOVA: $F_{df=1,66} = 1.4773$, $p = 0.2285$) and the net soak time (Multifactor ANOVA: $F_{df=3,66} = 1.6856$, $p = 0.1786$) did not have a significant effect on the total proportion of the catch damaged. There was no relationship between the number of predators bycaught in the net (seals: 0 – 7; dogfish: 1 – 205) and the resulting proportion of catch damaged by that predator for seals (linear regression: $F_{df=1, 28} = 0.0232$, $p = 0.8800$) or dogfish (linear regression: $F_{df=1, 28} = 0.0187$, $p = 0.8924$). Similarly, the number of seals and dogfish bycaught in the net did not affect the proportion of unknown damage (linear regression: $F_{df=3, 36} = 2.18$, $p = 0.1144$).

Discussion

Despite past efforts to quantify sources of marine depredation (Peterson et al 2014, Rafferty et al 2012, Varjopuro 2011) this is the first study to assess the characteristics of damage in relation to the jaw structure of possible depredators. Bite imprints from wild and domestic animal skulls have been used to help with the identification of bites on humans, and it has been suggested that this data could be used to identify sources of damage when an animal has been scavenged (Murmann et al 2006), as is done in the present study. When using bite imprints, one would expect imprints to be consistent with the jaw in size as the jaw structure is responsible for bite characteristics. While this was the case when comparing dogfish imprint and jaw bite ratios, seal imprint bite ratios were significantly smaller than their corresponding jaw bite ratios, but were correlated. Further analysis of bite length and bite width from seal jaw and imprint measurements indicated that the difference in bite ratios lies in bite length (paired t-test: $t_{df=64} = 12.103$, $p<0.0001$), not bite width (paired t-test: $t_{df=57} = 0.049$, $p=0.9610$). The difference in bite length is likely a result of tooth width, as jaw measurements were taken from the outside of the teeth whereas only the tips of teeth were visible for measurements of bite imprints. Canines generally pierced through the foam, providing an imprint bite width measurement that was more consistent with the jaw bite width. Despite this difference, the correlation between seal jaw bite ratios and imprint bite ratios indicate the jaw structure is responsible for bite characteristics.

When bite imprints were analyzed, dogfish bites were all circular in shape with a bite ratio less than 0.5 and canines absent, whereas seal imprints were rectangular or trapezoidal with a bite ratio greater than 0.9 and canines present on 88.2% of imprints. This clear difference in bite shape and canine presence/absence is due to the differences in jaw structures between the two animals. Bites in the soft tissue of fish by live animals produced similar results to the static model, indicating that these trends in static bite imprints can be differentiated in soft tissue. However, natural bites by live animals are more violent than imprints and may be more difficult to analyze (Murmann et al 2006). For example, while seal imprint bite ratios and bite ratios from the soft tissue of fish were not significantly different, seal bites during live trials were much more variable than imprints. The seals in this study did not always use their entire mouth to bite a fish and tended to rip fish with their claws prior to consumption (pers. obs.). These foraging behaviors were likely responsible for the variation, as the depth at which a seal bites into a fish influences the bite ratio. This could result in misidentification of bite sources based solely on bite ratios. However, seal bites were consistently rectangular or trapezoidal in shape for both imprints and live bite trials. Cleanness of the bite and presence/absence of canines were also important indicators of bite source, and utilizing multiple factors is important for accurate identification.

Dogfish imprint bite ratios were significantly smaller than dogfish bites in soft tissue of fish, with bites being slightly larger than imprints. It is possible that the bite mechanics of a dogfish resulted in this difference, as dogfish have many rows of sharp teeth that concentrate their bite force (Huber and Motta 2004).

Dogfish also shake their head back and forth while biting to help with cutting of prey and extend their jaw to bite objects larger than their mouth (Huber and Motta 2004, Wilga and Motta 1998, Wilga et al 2001, pers. obs.). Both of these foraging behaviors could result in the larger bite ratios seen in the soft tissue of fish versus static imprint bites. However, these behaviors also create a very distinctive bite that is clean by completely removing flesh, making the dogfish bite outline very clear and distinguishable from a seal bite.

The jaw structure of seals and dogfish clearly influences the shape and length-to-width ratio of the bite mark in bite imprints. These imprints are comparable to bite marks from live animals in the soft tissue of fish. This relationship between animals' jaw structures and the bites they produce was used to create a field protocol for identifying depredation sources. In this protocol (Figure 4), bites where canines are present are considered seal bites. Bites that are rectangular or trapezoidal in shape are classified as seal bites, and bites that are circular in shape are classified as dogfish bites. Bites that are clean are classified as dogfish bites, whereas ragged bites are classified as seal bites. Bites that are wider than they are long (bite ratios <0.6) are mostly produced by dogfish, while bites that are longer than they are wide or equal in length and width (bite ratios >0.7) are generally produced by seals. Bite ratios may be affected by individual predator or prey species, where some predators take smaller bites using only a portion of their mouth. This would cause the seal bite ratios to be closer to 1 as the bite length and width are more equal, while dogfish bite ratios generally remain consistent. Despite this potential variation in bite ratio, the bite shape and presence/absence of canines during both static and live trials remained relatively consistent and, therefore, are reliable source indicator.

Results from field application of the protocol indicate that dogfish are responsible for more damage than seals on a small-scale basis in gillnets targeting skate, which agrees with previous studies on Georges Banks in gillnets targeting Atlantic cod, monkfish, and skate (Rafferty et al 2012). Longer soak times, location of fishing, and the number of predators occurring as bycatch did not have a significant effect on the proportions of damaged catch. On many occasions there were undamaged skate caught in a net around a bycaught seal or dogfish, indicating the seal/dogfish may have been foraging on something near the net as opposed to in it prior to death. There were also occasions where skate discards from previous hauls (either small dead skates or dressed skate discards) were caught in the net, which were not considered damaged catch but likely attracted scavengers to the area, making other damage difficult to assess. On some occasions (7 of 30 hauls observed), extensive scavenger presence made identification of damage source difficult or impossible due to mutilation of initial bite marks.

Multiple sources of damage on the same fish is a limitation in the application of this protocol. Of the 51 damaged fish observed in this small-scale study, 5 damaged fish showed potential evidence of being damaged by both a seal and a dogfish. While it is possible that both a seal and a dogfish could have fed on the same fish, it is also possible that one bite was misidentified using the protocol or that another predator was responsible for damage (e.g. bluefish (*Pomatomus* *saltatrix*)). However, extensive scavenger damage that resulted in a lack of distinguishable bite outlines was responsible for most of the unidentifiable damage. Overall, this small-scale study shows that it is possible to identify damage using the protocol outlined here and obtain valuable information on damage sources that can help fishermen avoid areas of high depredation when applied on a larger scale.

While not indicated as a significant influence on damage in this study, it is important to consider the length of time the net has been soaking when attempting to identify damage source. Longer soak times allow more time for scavengers or other predators to further damage catch, making identification of the depredator more difficult. This is comparable to free ranging livestock in the terrestrial environment where identification is difficult when animals are exposed to additional scavengers and predators if not examined soon after a depredation event (Vantassel 2012, ICWDM 2008). In general, the size, shape, and location of the wound provide useful information about the predator in the terrestrial environment, but damage by scavengers after the animal's death can make proper identification unclear (ICWDM 2008). When an animal has been further damaged by scavengers, the location of hemorrhaging can help identify which wound was responsible for the animal's death. These terrestrial techniques may be useful in the marine environment when identifying sources of damage in addition to other bite characteristics, including bite shape and location. For example, sources of identification are sometimes distinguishable in long line fisheries where sharks take large chunks out of fish, whereas Cetaceans remove the entire body, leaving only the head of the fish on the line (Gilman et al 2007, Gilman et al 2006). Identification of damage sources is crucial before mitigation measures can be effective.

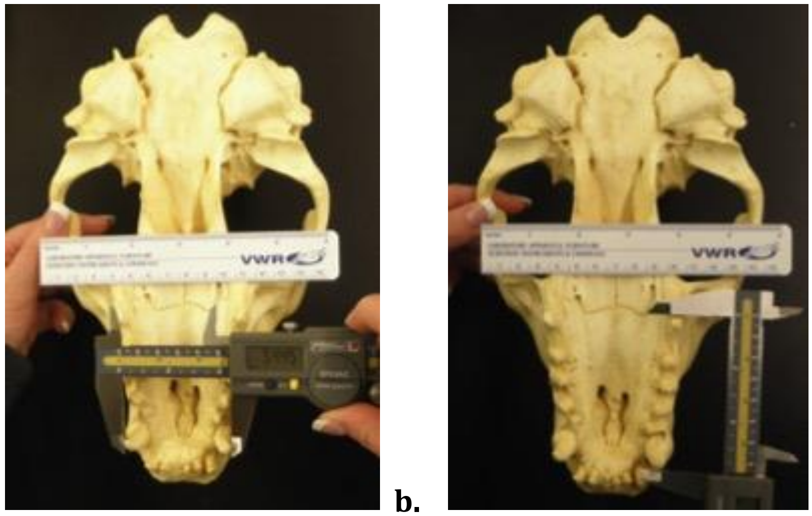
In New England, seals and dogfish are often assumed to be the source of damage to fish based on their recently increased populations (Waring et al 2014, Rafferty et al 2012, MAFMC and NEFMC 1999). Seal populations in New England have been rebounding since local extirpation in the early 20th century, with more than 17,500 gray seals and 70,000 harbor seals currently inhabiting New England waters (Waring et al 2014). Both gray and harbor seals can range from the New Jersey coast into Maine and their distribution varies depending on the time of year (Waring et al 2014, Baraff and Loughlin 2000). Harp (*Pagophilus groenlandicus*) and hooded seals (*Cystophora cristata*) may also inhabit New England waters seasonally and may be responsible for some depredation (Waring et al 2014). It has been suggested that feeding from fishing operations in marine mammals may be learned through social mechanisms, both within and between groups or individuals (Fearnbach 2014, Allen et al 2013, Whitehead and Rendell 2004). It is also believed that individual seals may associate fishing gear as a source of food and exploit it on a regular basis (Nichols et al 2014). Better understanding of migratory patterns and behaviors in these species is crucial to understanding their overlap with and impact on fisheries.

Dogfish populations increased in the Gulf of Maine during the 1980s during the decline in commercially valuable species (e.g. Atlantic cod (*Gadus morhua*) haddock (*Melanogrammus aeglefinus*), silver hake (*Merluccius bilinearis*); Frisk et al

2008, Fogarty and Murawski 1998), followed by a population decline during the 1990s resulting in the need for stock rebuilding (MAFMC and NEFMC 1999). Dogfish populations rebounded quickly and were considered rebuilt as of 2008 (Rago and Sosebee 2010). While stock estimates are unknown given the highly variable estimates of spawning stock biomass, dogfish catch limits have been increasing over the last decade and currently allow for 28,245.2 metric tons to be taken in 2015 (MAFMC 2014). Spiny dogfish are believed to be a highly migratory species, migrating south to North Carolina in the autumn and north to the Gulf of Maine in the spring (Burgess 2002, ASMFC 2002), although a more recent study suggests their migrations may be more localized (Carlson et al 2014). Understanding these migratory patterns may help scientists and fishermen understand trends in depredation in New England.

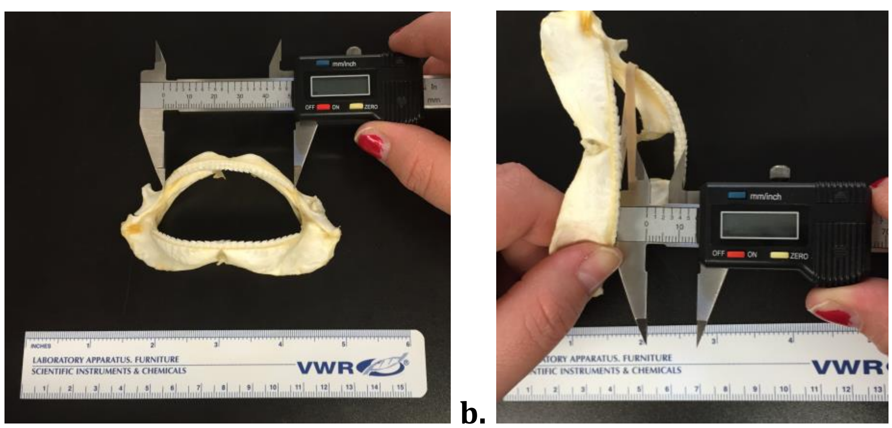
Many mitigation methods are utilized in the marine environment to reduce both depredation and bycatch of marine mammal species, some of which may be useful in the Northeast sink gillnet fishery. Pingers are currently used to deter bycatch of the threatened harbor porpoise in response to the Harbor Porpoise Take Reduction Plan (Taking of Marine Mammals Incidental to Commercial Fishing Operations; Harbor Porpoise Take Reduction Plan Regulations 2013). It is possible that these pingers may also reduce seal bycatch and depredation, but studies have indicated that pingers may also act as dinner bells, effectively attracting pinnipeds to the nets (Stansbury et al 2015, Bowles and Anderson 2012, Caretta and Barlow 2011). Some fishermen have tried reducing soak time to reduce depredation (Varjopuro 2011); although the present small scale study indicates that this may not have a significant effect on depredation, a larger sample is warranted. Depredation is influenced mainly by the distribution of possible depredators in relation to fishing times and locations. By completing a larger scale study of depredation, we will be able to determine where and when depredation is most common so that fishermen can adjust their fishing practices to avoid and reduce damage.

This study has provided an inexpensive, quick, and practical way of identifying sources of depredation in sink gillnet fisheries that can be used to study depredation by seals and dogfish throughout New England. It is possible to identify depredation sources using other methods, such as direct observation and genetics, but these are not as practical when working on fishing vessels. With advances in technology, it may become possible to use underwater cameras to capture evidence of depredation without affecting the natural environment surrounding a gillnet. However, since gillnets are often long and a camera's capture range is relatively short, this strategy might not provide the most reliable evidence. The source of damage might also be established using salivary DNA in bite wounds of damaged fish as has been used to identify gray seals as a major predator of harbor porpoises (Leopold et al 2015, Imazato et al 2012, Williams et al 2003). This salivary DNA will degrade and/or be flushed out of wounds quickly when specimens are submerged in water and is only practical when damaged animals are found freshly dead (Sweet and Shutler 1999). While genetic techniques could be used to validate the protocol established here as has been done in other studies (Leopold et al 2015), it is not a practical way to identify damage quickly in the field. It is also important to consider other potential sources of depredation including other chondrichthyes, cetaceans, or large teleosts. While this and other studies (e.g. Rafferty et al 2012) indicate that dogfish are responsible for most damage to fish in gillnets, a larger scale study is crucial to understanding if this trend is consistent throughout New England. This may be achieved through data collection on depredation source by observers and at-sea monitors using the protocol outlined in this study.



a. b.

Figure 1: Seal skull measurements: **a.** width of the mouth at the canines (WC), **b.** canine to rear molar length (CRML; adapted from Murmann 2006).



a. b.

Figure 2: Dogfish jaw measurements taken to the end of the teeth: **a.** rearmost jaw width (RJW), **b.** jaw length (JL).

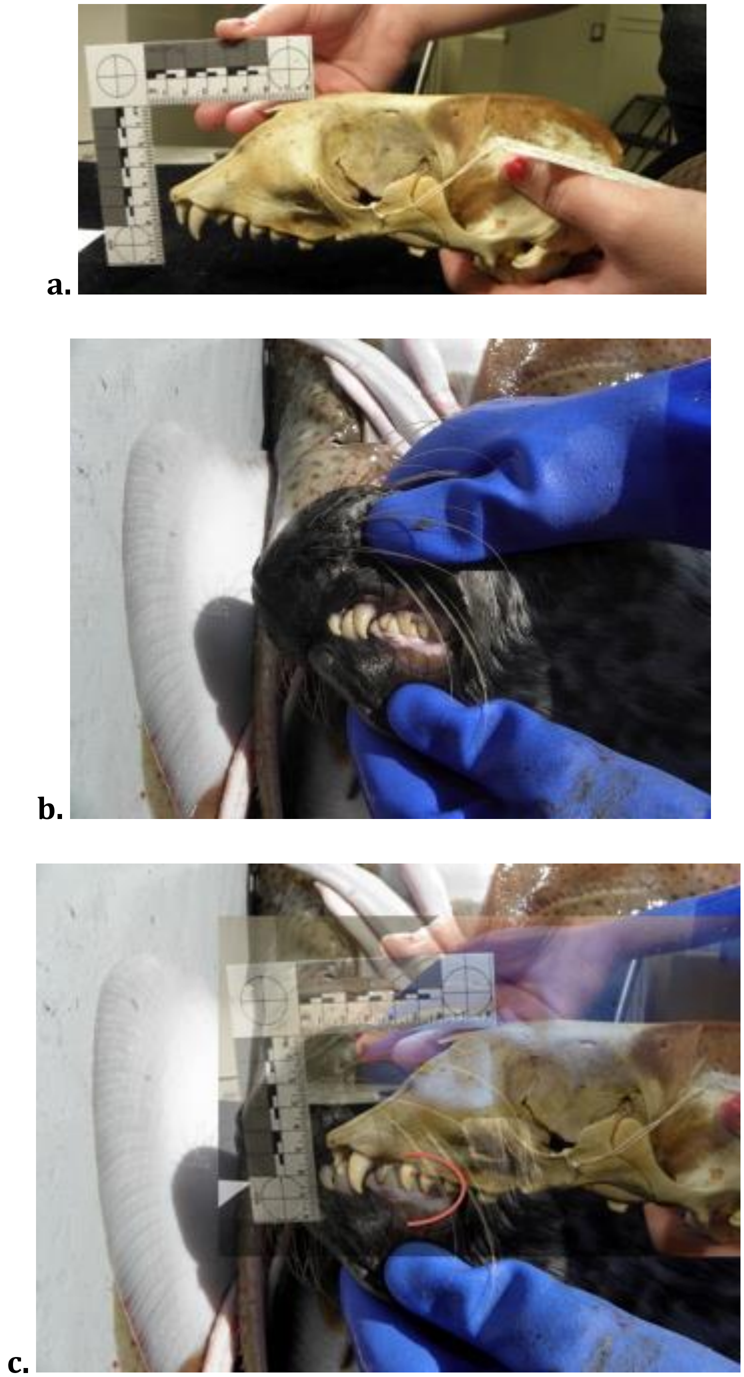


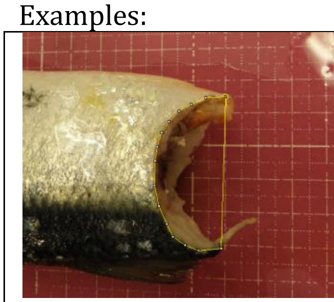
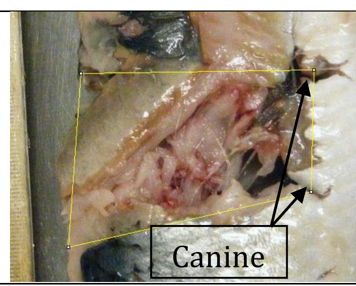
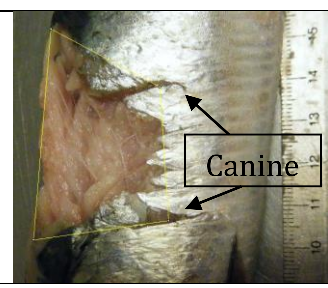
Figure 3: Process of estimating the actual seal jaw length available for biting prey when compared to a seal skull. Photos show **a.** a seal skull superimposed on **b.** a bycaught seal jaw, which is pictured in **c.** The red semi-circle in **c.** indicates the location of cheek tissue that blocks the back ¼ of the jaw, leaving approximately ¾ of the jaw is available for biting prey.

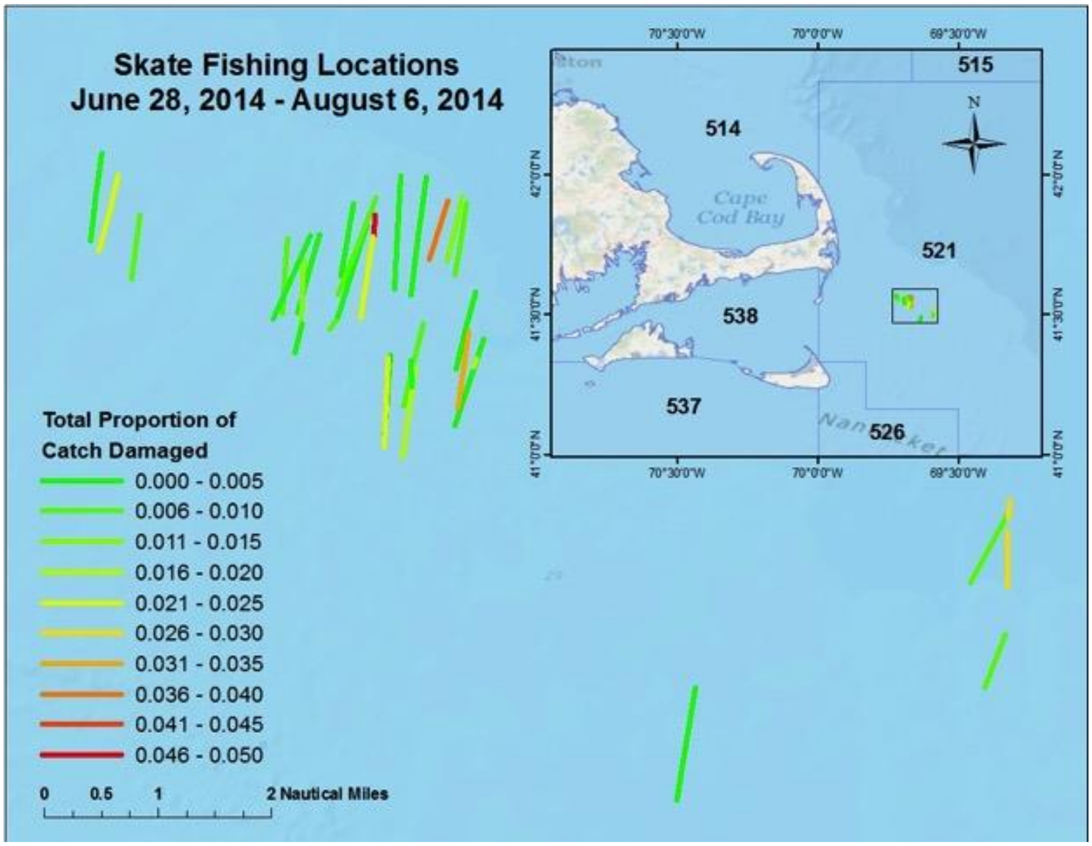
Figure 4: Bite identification protocol: Use the following protocol to identify bites as seal bites or dogfish bites.

Step 1: Look for evidence of canines in bite. If canines are present, there will be sharp, triangular, tooth-like marks at the deepest part of the bite.
Step 2: Identify shape of the bite as a rectangle (a bite outline with four straight sides and four right angles, opposing sides are approximately equal in length), trapezoid (a bite outline with four straight sides, two acute angles, and two obtuse angles, where two opposing sides are approximately equal in length and the other two are different in length), or circle (a bite outline that is rounded on at least one end). Keep in mind that additional flesh is sometimes removed during live bite trials, and you may have to visually estimate where this shape begins or ends.
Step 3: Identify if the bite is clean bite (flesh completely removed, making bite outline very clear) or ragged bite (flesh not completely removed, but partially torn from bite).
Step 4: Identify if the outline of this bite is longer than it is wide, wider than it is long, or equal in length and width. The length of the bite is how far it extends into the fishes flesh, whereas the width is how wide the bite is on the fish. For circular shape bites, compare the width at the back of the bite (the straight portion) to the length in the middle of the bite. For rectangle and trapezoid bites, compare lengths and widths taken at respective cross sections. Bite ratios (bite length/bite width) can also be calculated if estimation is unclear.
Step 5: Using the table below, identify each bite as seal or dogfish. Parameters are listed in order of importance, with canines being the best indicator of bite source.

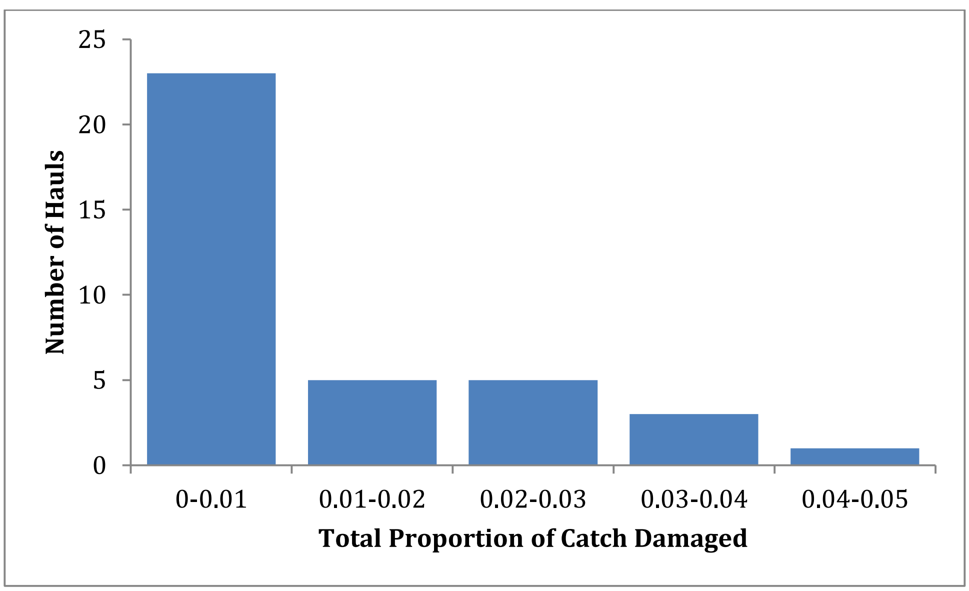
	Dogfish bite	Seal bite
Step 1: Canines	Canines absent? Not seal	Canines present? Seal (NOTE: Canines are not always present on seal bites)
Step 2: Shape	Circle shaped Dogfish	Rectangle shaped OR Trapezoid shaped Seal
Step 3 : Clean/Ragged	Clean bite Dogfish	Ragged bite Seal
Step 4: Width/Length	Wider than long (Bite Ratio <0.6) Dogfish	Longer than wide OR Equal in length and width (Bite Ratio >0.7) Seal
Step 5: ID	Dogfish	Seal

Examples:

		
1. No canines	1. Canines present	1. Canines present
2. Circle	2. Rectangle	2. Trapezoid
3. Clean bite	3. Ragged bite	3. Ragged bite
4. Wider than long	4. Longer than wide	4. Equal in length and width
5. Dogfish bite	5. Seal bite	5. Seal bite



a.



b.

Figure 5: a. Location and proportion of damaged catch recovered on a commercial sink-gillnet fishing vessel targeting winter skate in NAFO statistical area 521 from June – August 2014. **b.** Number of hauls within each proportion category.

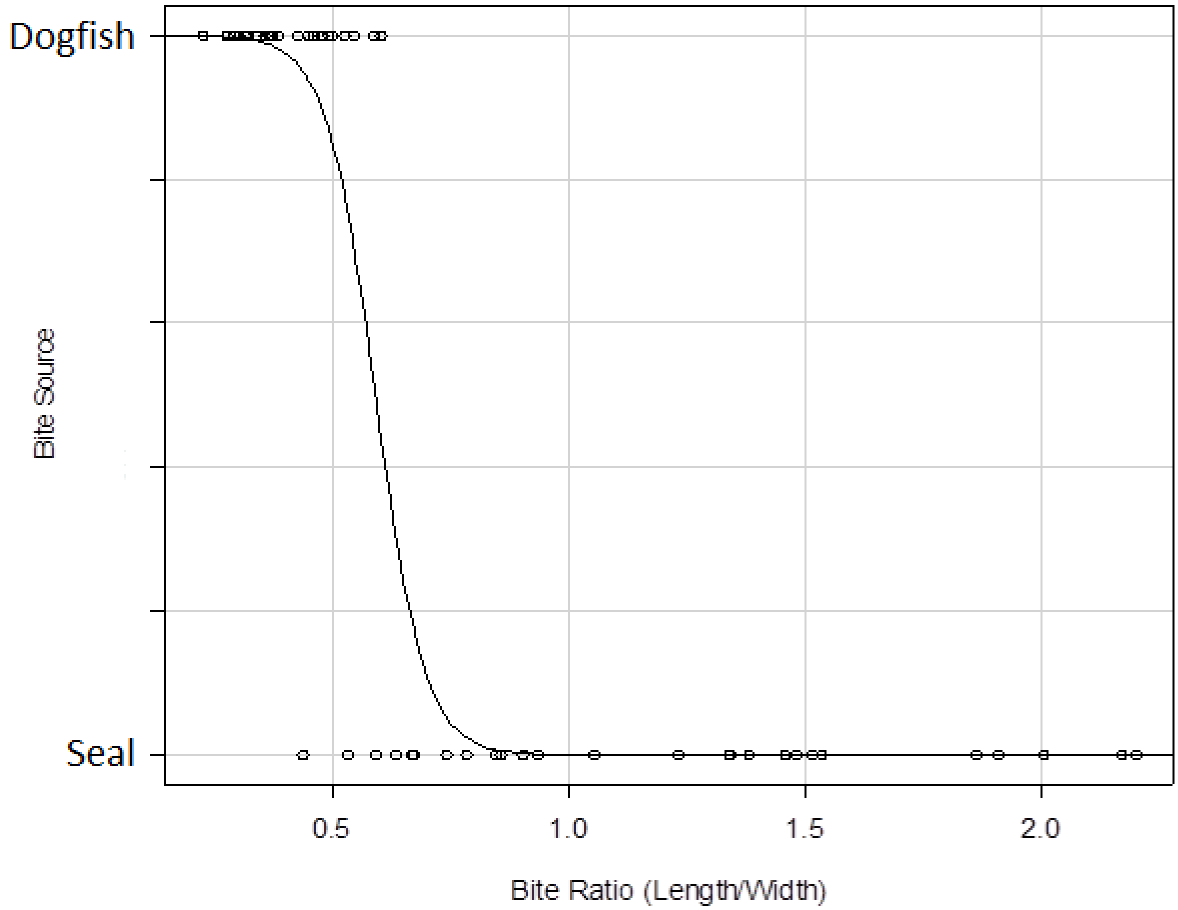


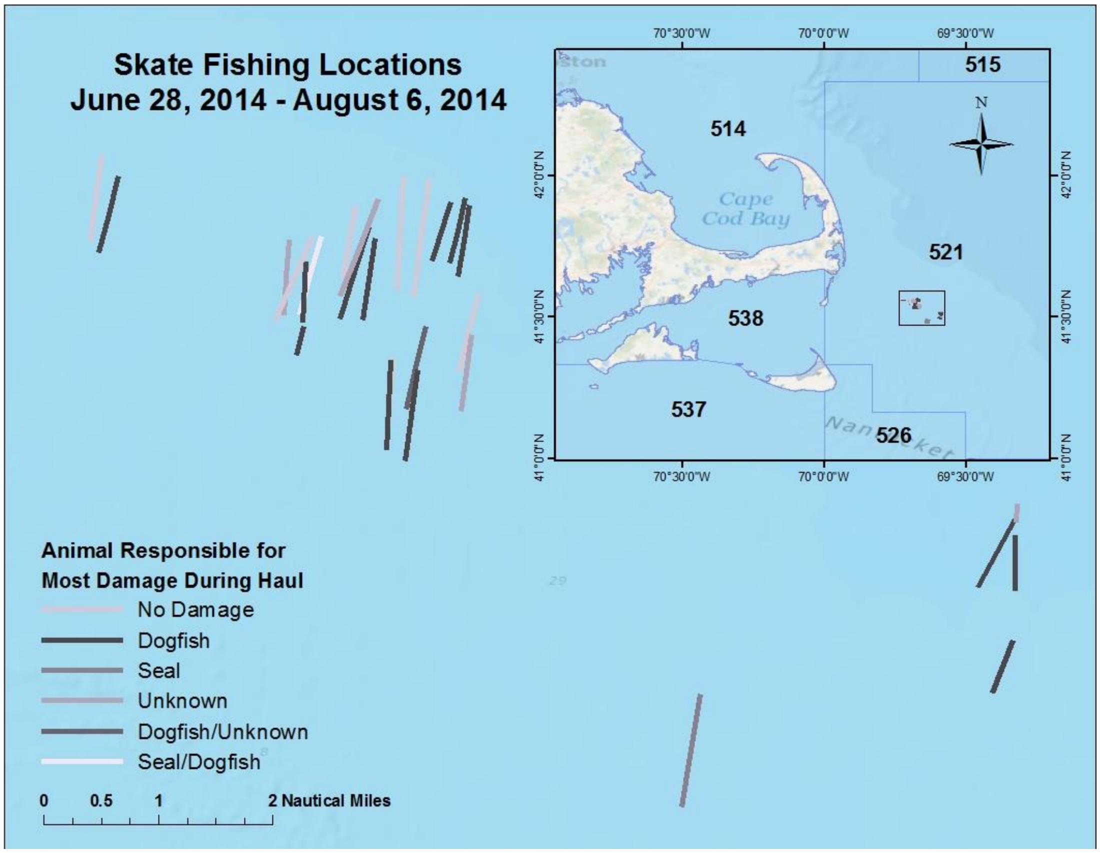
Figure 6: Logistic regression of depredator type on bite ratios in soft tissue of fish.

a.

b.

Figure 7: Examples of damaged skate identified as **a.** dogfish damage and **b.** seal damage.

a.



b.

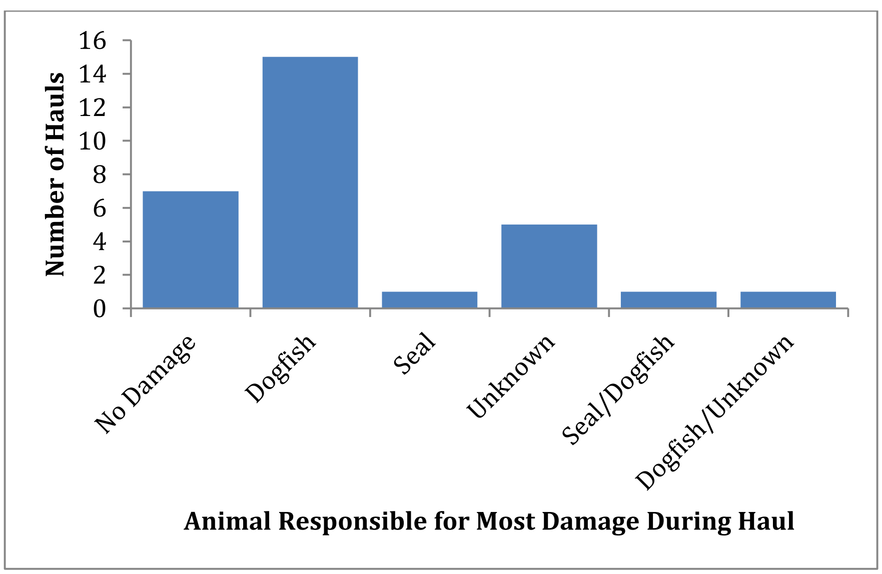


Figure 8: Animal responsible for the greatest proportion of damage during haul **a.** by location/haul and **b.** by animal. Dogfish/unknown and seal/dogfish categories indicate hauls where both sources were responsible for equal amounts of damage.

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APPENDIX A: IACUC APPROVAL LETTER

UNE UNIVERSITY OF NEW ENGLAND

Institutional Animal Care
and Use Committee

James Sulikowski, Chair

Biddeford Campus
11 Hills Beach Road
Biddeford, ME 04005
(207)602-2244 T
(207)602-5905 F

Portland Campus
716 Stevens Avenue
Portland, ME 04103

IACUC Protocol Number: UNE-20140328SIRAL

TO: Laura Sirak

FROM: James Sulikowski, Ph.D.

DATE: April 22, 2014

RE: Protocol Approval

Notice of IACUC Review - APPROVAL

Your March 28, 2014 protocol entitled "Gray and Harbor Seal Bycatch and Depredation in New England Sink-Gillnet Fisheries" as well as revisions and clarifications you submitted have all been reviewed by the UNE Institutional Animal Care and Use Committee (IACUC). Your project has been approved with the following conditions:

1. You are approved to conduct this research only during the period of approval cited below.
2. You will conduct the research according to the plan and protocol you submitted.
3. You will immediately inform the IACUC of any injuries or near injuries to researchers or animal handlers that occur in the course of your animal care or use.
4. You will immediately inform the IACUC of any adverse events that arise in the course of your research including but not limited to animal illness or unexpected animal death.
5. You will immediately request approval from the IACUC for any proposed changes in your research. You will not initiate any changes until they have been reviewed and approved by the IACUC.
6. If your research is anticipated to continue after **April 21, 2015**, you must submit a continuing review form at least 30 days prior to this date. A complete *de novo* review is required on a triennial basis. In this case, this review is due prior to the expiration date of **April 21, 2017**.

7. You are reminded that the IACUC requires animals that would otherwise experience severe or chronic pain or distress that cannot be relieved will be painlessly killed at the end of the procedure or, if appropriate, during the procedure.
8. You will follow all IACUC approved euthanasia procedures.
9. You will follow all IACUC approved procedures for the disposal of carcasses.
10. You will notify the IACUC if you terminate the study before completing it, or upon concluding it.

General Safety Requirements:

1. Accidents, injuries or illness resulting from the use of toxic, biological, or radioactive substances must be reported to the IACUC and the UNE Environmental Health and Safety department immediately.
2. Any injuries or near injuries to researchers or animal handlers that occur in the course of your animal care or use must also be immediately reported to the IACUC.
3. Appropriate protective equipment and procedures for use and handling of toxic, biological, or radioactive substances must be maintained at all times.
4. Appropriate ABSL's and/or BSL's will be maintained at all times, including the use of appropriate biosafety cabinets.

The University appreciates your efforts to conduct research in compliance with the federal and state regulations that have been established to ensure the protection of animal subjects in research, teaching and testing.

The IACUC wishes you well with your research. Please feel to contact William Harrison, Director of Research Integrity, if you have any questions about the IACUC process or continuing review procedures at 602-2244, or by email at wharrison@une.edu.

Approval Period: 4/22/14-4/21/17
Continuing Review required before: 4/21/2015
Complete *de novo* Review required before: 4/21/2017

Sincerely,

James Sulikowski, Ph.D.
IACUC Chair