The influence of siting and deterrence methods on seal predation at Atlantic salmon (*Salmo salar*) farms in Maine, 2001–2003

Marcy L. Nelson, James R. Gilbert, and Kevin J. Boyle

Abstract: We document the nature and frequency of seal predation at Atlantic salmon (*Salmo salar*) farms in Maine and determine whether the severity of predation is related to the proximity of farms from one another and nearby harbor seal (*Phoca vitulina concolor*) haul-outs. We surveyed farm managers annually from 2001–2003 to document management techniques, husbandry practices, and predator deterrence methods employed for comparison with the extent of seal predation. Biweekly aerial surveys were conducted between January and March of each year to document harbor seal presence. An empirical estimate from a negative binomial model showed seal predation at farms declined significantly with distance to the nearest haul-out, suggesting that seal predation may be deterred by maximizing the distance between farms and seal haul-outs. Farms located further than 4 km from harbor seal haul-outs experienced minimal losses. At farms located within 4 km of harbor seal haul-outs, seal predation decreased with increasing distance from neighboring farms, indicating that areas where farms are concentrated may be more vulnerable. The regular replacement of primary and secondary cage netting was negatively correlated with seal predation. Finally, this study documents the apparent ineffectiveness of acoustic harassment devices at deterring seal predation.

Résumé : Nous étudions la nature et la fréquence de la prédation par les phoques dans les élevages de saumons atlantiques *(Salmo salar*) au Maine et déterminons la relation entre l'importance de la prédation et la proximité des élevages les uns avec les autres et avec les échoueries de phoques communs *(Phoca vitulina concolor*) des environs. À chaque année en 2001–2003, nous avons interrogé les gestionnaires des élevages afin de connaître leurs techniques d'aménagement, leurs pratiques zootechniques et leurs méthodes de dissuasion des prédateurs et de les relier à l'importance de la prédation par les phoques. Des inventaires aériens à toutes les deux semaines de janvier à mars de chaque année ont permis de déterminer la présence des phoques communs. Une estimation empirique dérivée d'un modèle binomial négatif montre que la prédation par les phoques dans les élevages décline significativement en fonction de la distance de l'échourie la plus proche, ce qui laisse penser que la prédation par les phoques pourrait être découragée en maximisant la distance entre les élevages et les échouries de phoques. Les élevages situés à plus de 4 km des échoueries de phoques communs connaissent des pertes minimales. Dans les élevages situés à moins de 4 km des échouries de phoques communs, la prédation diminue en fonction de la distance avec les élevages voisins, ce qui indique que les aires de concentration des élevages sont plus vulnérables. Il y a une corrélation négative entre le remplacement régulier des grilles primaires et secondaires des cages et la prédation par les phoques. Enfin, notre étude confirme l'inefficacité apparente des appareils de harcèlement acoustique comme moyens de dissuasion de la prédation par les phoques.

[Traduit par la Rédaction]

Introduction

Adverse interactions between seals and marine finfish farms are of economic and regulatory concern. The emergence of an aquaculture industry in the State of Maine has coincided with substantial increases in "regional seal populations" (National Marine Fisheries Service (NMFS) 1996).

Within the past 20 years, aquaculture in Maine has developed into a thriving shellfish farming industry and the lead producer of farmed Atlantic salmon (*Salmo salar*) in the United States. The culture and husbandry of marine finfish and shellfish is second only to lobsters in economic value for fisheries in the State (Maine Department of Marine Resources 1997). The total harvest of farm-raised finfish

Received 5 August 2005. Accepted 14 March 2006. Published on the NRC Research Press Web site at http://cjfas.nrc.ca on 8 July 2006.
J18828

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 doi:10.1139/F06-067

from Maine waters has risen from an initial 0.45 million kilograms in 1988 to a peak of over 16.33 million kilograms in 2000 (Jonathan Lewis, Maine Department of Marine Resources, P.O. Box 8, West Boothbay Harbor, ME 04575, USA, unpublished data).

High densities of fish concentrated in relatively small areas, such as net pens, inevitably appeal to fish-eating wildlife. Pinnipeds, in particular, exhibit plasticity in their feeding strategies and prey consumption, and individual seals and sea lions have learned to exploit situations where salmonids are concentrated and vulnerable (NMFS 1999). Offered protection under The Marine Mammal Protection Act of 1972, the harbor seal (*Phoca vitulina concolor*) population in Maine has been steadily increasing since 1981 (Kenney 1994; Marine Mammal Commission 1995; Gilbert and Guldager 1998). The population size from the latest survey in 2001 was estimated to be 99 000 seals, making them the most commonly found pinniped along the coast of Maine (Gilbert et al. 2005). Harbor seals are opportunistic feeders that prey on available species of demersal and pelagic fish and invertebrates, including salmonids (Bowen and Harrison 1996; Tollit et al. 1997; Williams 1999). They tend to be gregarious animals that haul-out in groups ranging from a few individuals to several hundred (Wynne and Schwartz 1999).

Maine waters are centrally located within the distribution of the western Atlantic subspecies of harbor seal. As a result, harbor seals can be found in the Gulf of Maine throughout the year; however, they are most abundant during late spring and summer. By early May, the majority of individuals have arrived in the sheltered bays and inlets of Maine. The greatest concentrations of harbor seals occur in Penobscot and Machias bays and off Mt. Desert and Swans islands. The majority of harbor seals migrate south to Long Island or the southern portion of the Gulf of Maine and southern New England in the fall (Payne and Selzer 1989; Gilbert et al. 2005; G.T. Waring, J.R. Gilbert, J. Loftin, and N. Cabana, unpublished data).

Seal predation can result in several types of serious negative impacts to the Maine finfish aquaculture industry. Seals are thought to bite and swipe at fish through the mesh netting, occasionally gaining access by creating holes in the netting. In addition to the loss of marketable product through direct injury and mortality, predation can result in stress, increased susceptibility to disease, and escapement of farm-raised fish (Pickering and Pottinger 1985; Pemberton and Shaughnessey 1993; Morris 1996). Besides the economic impacts of seal predation, potential escapements of farm-raised fish are of particular concern because of the endangered status of wild Atlantic salmon in Maine. On 17 November 2000, the Gulf of Maine distinct population segment of Atlantic salmon was listed as endangered under The Endangered Species Act of 1974 (ESA). Included in this listing were existing wild stocks from eight Maine rivers: the Dennys River, East Machias River, Machias River, Pleasant River, Narraguagus River, Cove Brook, Duck Trap River, and Sheepscot River (US Fish and Wildlife Service and National Marine Fisheries Service (USFWS & NMFS) 2002). The close proximity of salmon farms to five of the listed rivers has raised concern regarding the potential for competition, transmission of disease, and genetic mixing between escaped farmed salmon and wild stocks from the surrounding rivers (Peterson 1999; USFWS & NMFS 1999, 2002).

Currently, under state and federal discharge regulations, farms are required to develop site-specific predator deterrent plans (Maine Department of Environmental Protection, http://www.maine.gov/dep/blwq/docstand/aquaculture/MEG130000.pdf). With limited understanding of the interaction between seals and finfish aquaculture, the effectiveness of these predator deterrent plans is questionable. Investigations into the interactions between seals and finfish aquaculture sites throughout Maine will provide a better understanding of pinniped behavioral responses to the presence of this growing industry. In particular, knowledge of pinniped predation and response to deterrence methods employed is needed before effective guidelines and regulations for siting and containment can be developed.

The goal of this study was to document patterns of seal predation at marine salmon farms in Maine. The specific questions addressed include: Is seal predation at Maine marine salmon farms related to the proximity of farms from one another and nearby harbor seal haul-out sites? Are particular farm management practices related to levels of seal predation experienced at marine salmon farms in Maine?

Materials and methods

Study area

This study was conducted from 2001–2003 in Hancock and Washington counties, Maine. Data collection was restricted to the areas between Blue Hill Bay and Cobscook Bay, where all of Maine's marine salmon farms, at the time, were located (Fig. 1).

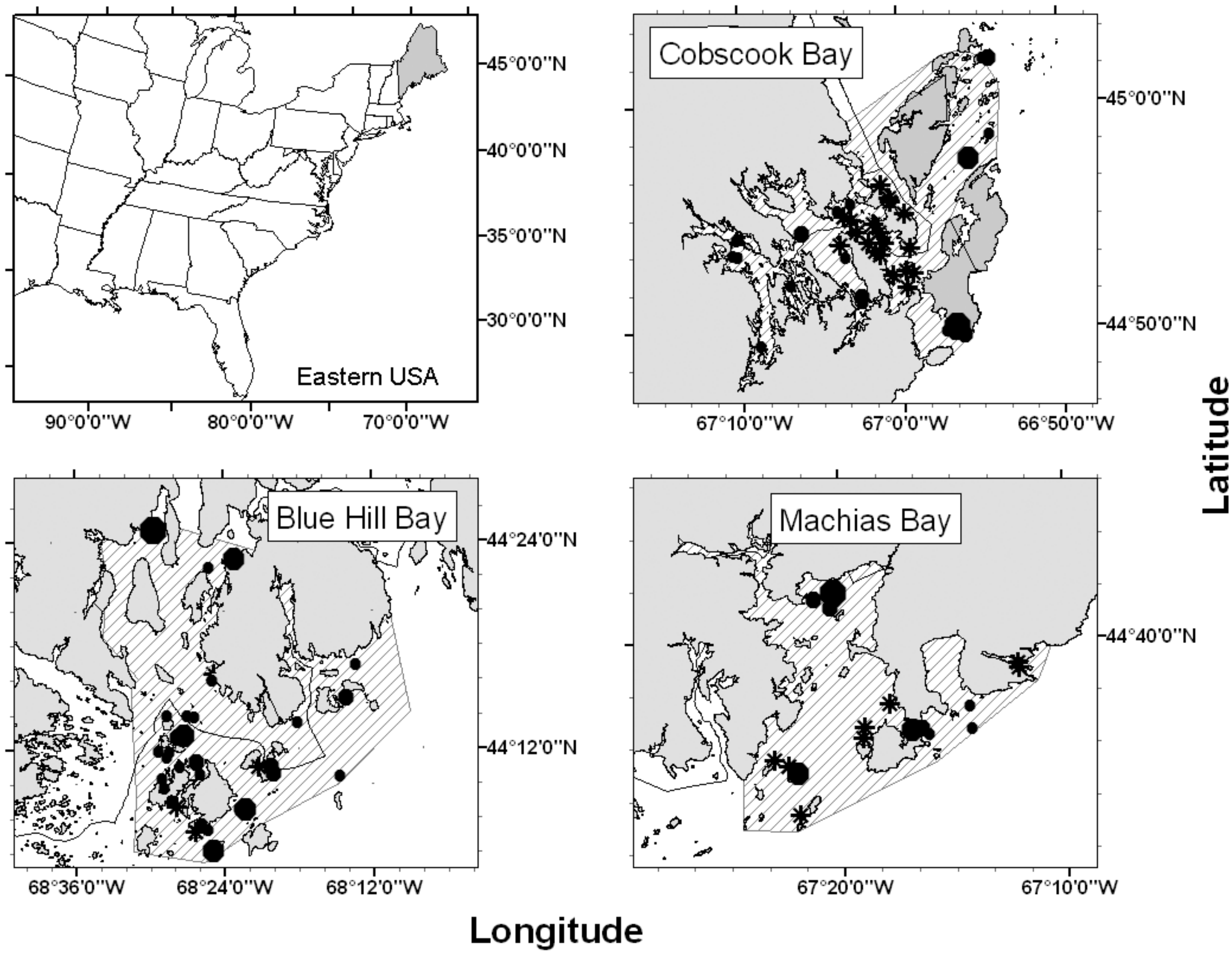
The coast in this region is generally rocky, with many bays and islands. Salmon farms are located in bays that provide protection from storms and adequate current to flush the sites of waste material. Small, half-tide ledges are abundant and are frequently used as haul-out sites by harbor seals for resting and pupping (Terhune and Almon 1983; Pauli and Terhune 1987; Kovacs et al. 1990). This means that suitable sites for aquaculture pens also provide desirable habitat for pinnipeds.

Maine finfish aquaculture industry questionnaires

To determine the nature and extent of seal predation, managers at marine salmon farms in Maine were sent annual questionnaires between 2001 and 2003. At the time of the study, there were a total of 43 marine salmon farms in Maine operated by four companies. Only 35 questionnaires, however, were mailed each of the three study years. Two of the 43 farms were known to have never been operational and were omitted from the study. In other instances, adjacent farms operated by the same company were often managed as a single farm and thus had to be treated as such for the purposes of this study. Farm managers within a company were often responsible for the operation of more than one farm. They were asked to fill out a separate questionnaire for each farm under their management.

Questions were modified from the approach of Ross (1988) and developed in cooperation with industry representatives (Salant and Dillman 1994). Farm managers were questioned regarding the following topics: farming practices, predation

Fig. 1. Maps depicting locations of marine salmon farms along the Maine coast (asterisks), regions where aerial surveys of winter harbor seal (*Phoca vitulina concolor*) haul-outs were flown (hatched areas), and the average abundance of seals at nearby haul-outs (graduated solid polygons) between 2001 and 2003.



and predator deterrent methods employed, and their education and work experience in aquaculture-related fields. Each year, managers were asked to provide an estimate of the number of fish lost to seal predation. In addition to direct mortalities, fish that escaped through holes in the netting or were injured as a result of seal predation were also categorized as a loss. When there were no witnesses to a predation event(s), farm operators relied on indicators, such as bite marks, to determine which predator(s) were responsible for the damage. Many farmers also cited the difficulty inherent in differentiating between pre- and post-mortality predation by seals. Seals preying on live fish and mortalities are both, however, indicative of these predators having access to net pens and thus farm stock.

Respondents were asked to limit their answers to the previous year and the specific farm in question. Midpoints of any reported ranges were used in analyses. Farms that were fallow or non-operational were excluded from subsequent analyses. Farms were considered operational if occupied by fish at some point during the previous 12 months.

Aerial surveys and spatial analysis of winter harbor seal haul-out sites

Although actual numbers of seals within the region are greatest during the months of May through August, a task force convened to evaluate the interactions between pinnipeds and aquaculture in Maine reported that insurance claims submitted by Maine finfish growers increased during the winter months (Morris 1996; NMFS 1996). In Scotland, greater than 50% of all site managers reported that seal predation was highest during the winter months (Ross 1988). Results were similar in Australia: most seal attacks occurred between autumn and spring (Pemberton and Shaughnessey 1993). To document the winter distribution of seals around Maine marine salmon farms, aerial surveys were conducted from January through March of 2001, 2002, and 2003, the time of year when seal predation is thought to be most prevalent. Aerial surveys focused on the Blue Hill Bay, Machias Bay, and Cobscook Bay regions. Because of limited funding and the large geographical extent of the area, the region between Blue Hill Bay and Machias Bay was not surveyed.

As a result, two farms (four lease sites) were omitted from aerial surveys (Fig. 1).

Aerial surveys were conducted 2 h either side of midday low tides and during favorable weather conditions to take advantage of the maximum number of harbor seals hauled out (Pitcher and McAllister 1981; Suryan and Harvey 1998; Simpkins et al. 2003). Because of poor weather conditions, surveys were conducted only three times in 2001 (3 February, 18 February, and 4 April). Surveys were flown on five dates in 2002 (22 January, 8 February, 22 February, 6 March, 26 March) and four dates in 2003 (26 January, 26 February, 11 March, 27 March). A Cessna 182 single-engine aircraft was used during all survey work. The plane surveyed at an altitude of approximately 305 m, dropping to approximately 213 m when photographing haul-outs. Haul-outs were photographed using a 35 mm camera with a 300 mm telephoto lens. Counts were made from 35 mm slides of surveyed haul-out sites. Occasional grey seals (*Halichoerus grypus*) were observed at surveyed haul-outs and were included in subsequent seal counts. The months during which aerial surveys were conducted, however, coincide with pupping and mating in grey seals. Thus, the majority of grey seals were likely at other, more suitable haul-outs (Reeves et al. 2002).

Distances between Maine marine salmon farms and documented seal haul-out sites or other marine finfish farms were calculated for each survey year using the Spatial Analyst extension in ArcMap Version 8.3 (ArcGIS, ESRI 2003). Distances were measured as a seal would be expected to travel from farm to farm or farm to haul-out, precluding measurements from being made across land (Pemberton and Shaughnessey 1993). The Maine Office of Geographic Information Systems provided maps of the Maine coastline and islands. The Maine Department of Marine Resources provided geographic locations of all marine finfish aquaculture facilities in Maine. The New Brunswick Department of Agriculture, Fisheries and Aquaculture provided the geographic locations of all finfish aquaculture sites in New Brunswick waters. Maps and farm polygons were converted to raster format with a 10 m^2 cell size. Because seals use small half-tide ledges, as well as islands, for hauling out, not all documented sites were represented in the same detail on available charts. Therefore, a 10 m^2 cell in the center of each haul-out was used for measurement purposes. Measurements were calculated from cell center to cell center. All haul-outs with a minimum of one seal on at least one occasion during a particular year were included in analyses.

Analysis procedures

To determine whether seal predation was related to the proximity of farms to harbor seal haul-out sites, a logistic regression analysis (SPSS Inc. 2000) was initially performed using a binary response variable for seal predation (0 = 100 or less fish lost to seal predation and 1 = greater than 100 fish lost to seal predation, for the year in question) and an independent continuous variable representing distance to the nearest harbor seal haul-out (km) for each farm (Agresti 1996).

Additional analyses were conducted in which a generalized linear model, using the negative binomial distribution for the random component, was used to analyze relationships between the magnitude of fish lost to or damaged by seal predation and explanatory variables representing proximity to nearby farms and harbor seal haul-out sites, farm operations, husbandry practices, predator deterrence efforts, and farm manager education and experience (Econometric Software, Inc. 2002). Because the estimated number of fish lost to seal predation was a discrete count, a generalized linear model assuming a Poisson distribution was initially used to evaluate the effect of each explanatory variable independently (Greene 2002). However, the distribution of losses had many zeros and a few large counts, which resulted in data that were overdispersed. A negative binomial distribution allowed for separate estimates of the variance and produced a better fit to the distribution of the estimated numbers of fish lost to seal predation (Liao 1994; Gabe and Hite 2003).

Dummy variables were created for all categorical explanatory variables. In this manner, the intercept stood in for the level of the excluded category and the significance tests of the remaining coefficients were comparisons to the missing category. For example, an independent variable with three categories was represented, in the model, by dummy variables for two of the three categories:

$$Y = \alpha + \beta_1 D_1 + \beta_2 D_2 \qquad (1)$$

Testing the significance of β_1 and β_2 asked whether the categories identified by D_1 and D_2 were different from the omitted category (Neter et al. 1996).

Because of small sample sizes and collinearity between the explanatory variables, the equation was estimated using one explanatory variable at a time. A critical value of p = 0.10 was used in all statistical analyses because of limited power resulting from small sample sizes.

Results

Ninety-two percent of questionnaires were returned completed; responses were received from all but eight farms for a total of 97 returned questionnaires. A total of 40 farms were non-operational at some point during the 3-year study, primarily because of a disease outbreak in Cobscook Bay during 2001 (Jonathan Lewis, Maine Department of Marine Resources, P.O. Box 8, West Boothbay Harbor, ME 04575, USA, unpublished data). Additionally, three managers at active farms did not provide estimates of fish lost to seal predation. These limitations reduced the useable sample for analysis to 54 observations or farm-years. Each year that a farm was active represented one observation. Data were pooled across years because activities at a single farm often differ between years. For example, the number of fish stocked, the number and types of pens utilized, etc., can change from year to year.

Impacts of seal predation

Losses attributed to seal predation ranged from 0 to 27 629 salmon per farm per year, with 46% of farms reporting no losses. Seal predation on farm-raised salmon was slightly greater in 2001 than in 2002 (n = 54, p = 0.104). There was, however, no detected difference in seal predation levels between 2001 and 2003 (n = 54, p = 0.189) and 2002 and 2003 (n = 54, p = 0.920), further supporting the pooling of data across years (Table 1).

Table 1. Estimates of the relationships between survey year and the number of fish lost to seal predation at Atlantic salmon (*Salmo salar*) farms in Maine.

Model[a]	Coefficient[b,c]	Marginal effect[d]	Frequency
Survey year vs 2003			
2001	1.589 (1.210)	4205	23
2002	–0.127 (1.253)	–335	19
Constant	6.919 (1.001)		
Survey year vs 2001			
2002	–1.715* (1.053)	–4540	19
2003	–1.589 (1.210)	–4205	12
Constant	8.507 (0.736)		

[a]All variables are binary and coded 1 if “yes”, 0 if “no”.
[b]Asterisks denote significance: ***, 1% level; **, 5% level; *, 10% level.
[c]Standard errors are listed in parentheses.
[d]The predicted change in the number of fish lost to seal predation following a one-unit increase in the explanatory variable *X*, above the mean. For dummy variables, a one-unit increase in the explanatory variable is from a value of 0 (no) to 1 (yes).

Of all salmon losses to predation between 2001 and 2003, 84% were attributed to seals. Respondents at 48% of farms were of the opinion that seals were responsible for the greatest amount of predator-induced damage to farm stock, 33% considered birds to be the greatest problem, and 19% did not specify one group over another. The majority (74.3%) of respondents considered seal predation to be most prevalent during the months of January and February. Furthermore, market-size fish (3–5 kg) were reported, by 58% of respondents, to be the most affected by seal predation. Between 2001 and 2003, 40% of site managers felt seal predation had decreased from previous years, 8% felt predation was worse than in previous years, and 52% felt there was no difference.

Proximity to winter harbor seal haul-out sites

The probability of a salmon farm in Maine experiencing the loss of more than 100 fish to seal predation decreases significantly with increasing distance to the nearest harbor seal haul-out (Fig. 2) ($n = 46$, $p < 0.001$). Logistic regression analysis provided the following model:

$$(2) \qquad P(>100 \text{ fish lost}) = \frac{\exp(1.23 - 0.60\text{MinDist})}{[1 + \exp(1.23 - 0.60\text{MinDist})]}$$

where MinDist represents the distance (km) to the nearest harbor seal haul-out, $\alpha = 1.23$ and $\hat{\beta}_1 = -0.60$. For example, the probability of a farm experiencing seal predation if located 1 km from the nearest seal haul-out is 0.65, whereas the probability is only 0.24 if the farm is located 4 km from the nearest haul-out. The negative relationship between distance to the nearest harbor seal haul-out and the occurrence of seal predation at marine salmon farms was further supported by the likelihood ratio test ($-2(L_0 - L_1) = 15.60$, df = 1, $p < 0.001$). The Pearson chi-square goodness of fit test supported the null hypothesis of model fit (statistic = 37.04, $p = 0.76$, df = 44) (Agresti 1996).

Actual numbers of fish lost to seal predation also decreased with increasing distance to the nearest harbor seal haul-out site ($n = 46$, $p < 0.001$). According to the marginal effects resulting from negative binomial regression analysis, the predicted number of fish lost to seal predation decreases by 4053 fish for every 1 km increase above the average distance between a farm and the nearest harbor seal haul-out (Table 2). Maine salmon farms were located an average of 3.5 km from harbor seal haul-outs. The range of distances between active salmon farms and the nearest haul-out was 0.2–8.6 km. An examination of the raw data suggests that farms located further than 4 km from the nearest harbor seal haul-out site are likely to experience minimal losses of fish to seal predation. All farms located further than 4 km from the nearest harbor seal haul-out reported losses of less than 400 fish to seal predation. In fact, all but one of the 19 farms with no seal haul-outs within 4 km lost ≤100 fish to seal predation. Of those 19 farms, 15 reported no losses of fish to seal predation (Fig. 3).

Results from the previous analyses showed minimal losses of farm-raised fish to seal predation at farms located further than 4 km from the nearest haul-out. To determine what factors, other than proximity to seal haul-outs, were related to seal predation at Maine salmon farms, subsequent analyses were performed excluding observations at farms located further than 4 km from the nearest harbor seal haul-out (n = 27).

Abundance of seals at nearby winter haul-outs

The average minimum number of seals at nearby winter harbor seal haul-out sites was not related to levels of seal predation at marine salmon farms in Maine. Using negative binomial regression analysis, we determined that there was no relationship between the number of fish lost to seal predation and the total number of seals, averaged over the three survey years, at haul-outs within 4 km of a farm ($n = 49$, $p = 0.400$). For farms located within 4 km of a seal haul-out, we further determined that the average abundance of seals documented at the nearest haul-out site for each of the three survey years ($n = 27$, $p = 0.887$) and the weighted abundance of seals at the nearest haul-out (average abundance × (distance from farm)$^{-1}$) were not related to the magnitude of fish lost to seal predation ($n = 27$, $p = 0.873$) (Table 2).

Proximity to neighboring finfish aquaculture sites

The average distance between marine salmon farms was 2.1 km, with a range of 0.3 to 9.8 km. The results of this study suggest that farms located within 4 km of a harbor seal haul-out are likely to experience greater levels of seal predation with decreasing distance to the nearest neighboring salmon farm ($n = 27$, $p = 0.005$) (Table 2; Fig. 4). In other words, farms with harbor seal haul-outs nearby are more susceptible to seal predation if they also have another salmon farm(s) nearby.

Farm management

The results of models describing the relationships between farm management and the estimated number of fish lost to seal predation are presented (Table 3). The size of Maine farms, represented by the maximum number of fish on site at any one time during the year in question ($n = 27$, $p = 0.906$), and whether or not they were active (had fish on site) for the entire year in question ($n = 27$, $p = 0.370$) do not appear to

Fig. 2. The predicted probability of seal predation (solid line) as a function of distance to the nearest winter harbor seal (*Phoca vitulina concolor*) haul-out. Observed losses (greater than 100 fish lost = 1) are denoted by diamonds.

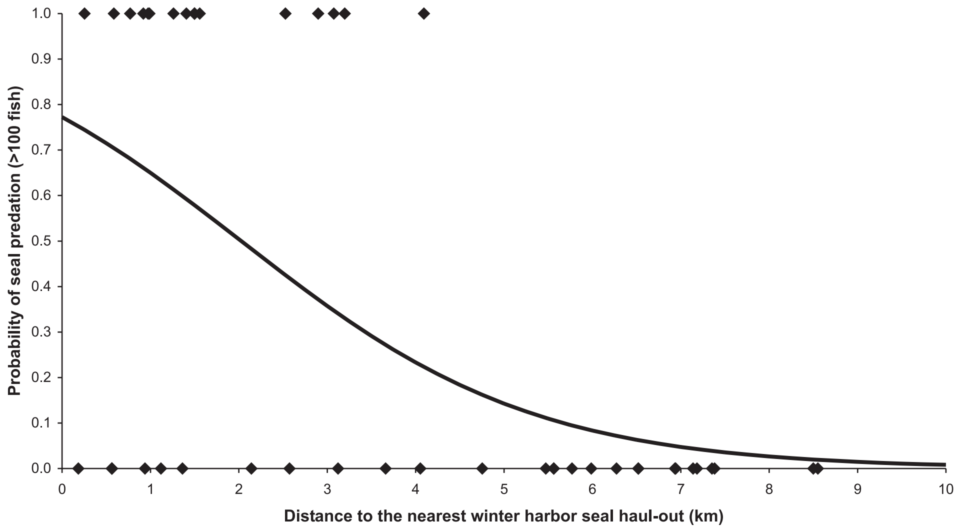


Table 2. Estimates of the relationships between proximity to other marine finfish farms or winter harbor seal (*Phoca vitulina concolor*) haul-out sites and the number of fish lost to seal predation at Atlantic salmon (*Salmo salar*) farms in Maine.

Model[a]	Coefficient[b,c]	Marginal effect[d]	Mean	Range
Distance to the nearest winter harbor seal haul-out (km)				
Distance	–1.032*** (0.208)	–4053	3.5	8.4
Constant	10.003 (0.903)			
Total number of seals within 4 km				
Sum of average number of seals at haul-outs within 4 km (2001–2003)	0.024 (0.028)	60	13.1	76
Constant	7.369 (0.683)			
Average abundance of seals at the nearest haul-out				
Average number of seals at nearest haul-out	–0.003 (0.020)	–11	15.1	110.3
Constant	8.297 (0.635)			
Weighted abundance of seals at the nearest haul-out				
Average number of seals at nearest haul-out × distance^{-1}	–0.007 (0.043)	–26	8.7	36.4
Constant	8.314 (0.673)			
Distance to the nearest neighboring farm (km)				
Nearest farm	–0.698*** (0.251)	–2860	2.1	9.5
Constant	9.139 (0.749)			

[a]Dummy variables are indicated with question marks and coded 1 if "yes", 0 if "no".
[b]Asterisks denote significance: ***, 1% level; **, 5% level; *, 10% level.
[c]Standard errors are listed in parentheses.
[d]The predicted change in the number of fish lost to seal predation following a one-unit increase in the explanatory variable *X*, above the mean. For dummy variables, a one-unit increase in the explanatory variable is from a value of 0 (no) to 1 (yes).

be related to the estimated number of fish lost to seal predation. Between 2001 and 2003, Maine salmon farms stocked an average of 340 637 Atlantic salmon in net pens. Fifty-two percent of these farms had fish on site during the entire year in question, whereas the other 48% were devoid of fish at some point during the year.

The majority of site managers considered seal predation most prevalent during winter months. Of the farms located within 4 km of a haul-out site that did not have fish on site year-round, however, only five respondents included the months of the year that fish were on site. Thus, evaluation of a possible relationship between active months and seal predation was not possible.

Maine farmers reported using two types of pens for the culture of Atlantic salmon: steel cages and polar circles. Steel cages are comprised of square steel frames from which nets are suspended. They are usually arranged in systems of multiple pens separated by ~1.5 m walkways. Individual pens can be of varying sizes — Maine farmers reported using 12, 15, or 24 m^2 pens. Polar circles are constructed of high-density plastic frames from which nets are suspended. The Maine industry reported using polar circles with circumferences of 50, 70, and 100 m. Generally, polar circles are deployed individually within a grid system. Farms that used only one type of pen, either polar circles or steel cages, reported similar losses to seal predation (n = 27, p = 0.889).

Fig. 3. The estimated number of fish lost to seal predation as a function of distance to the nearest winter harbor seal (*Phoca vitulina concolor*) haul-out.

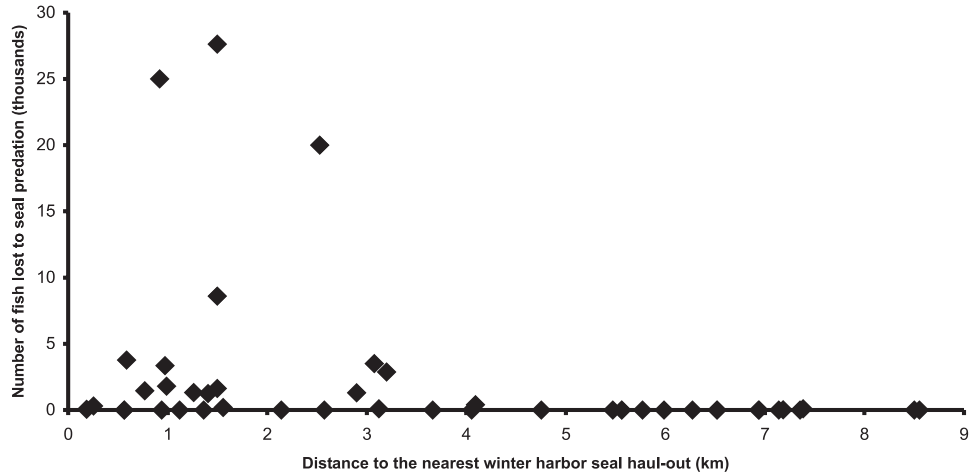
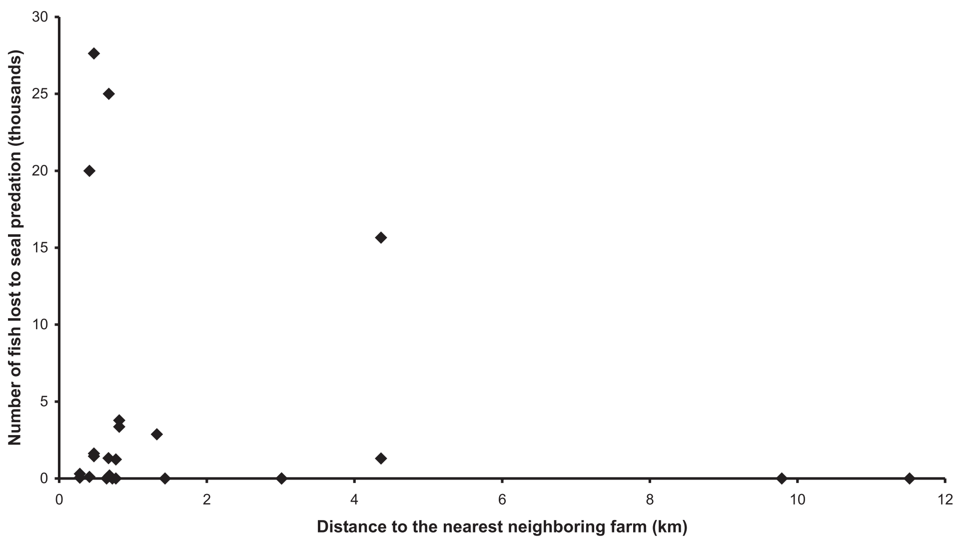


Fig. 4. The estimated number of fish lost to seal predation as a function of distance to the nearest other marine finfish farm (for farms located within 4 km of a winter harbor seal (*Phoca vitulina concolor*) haul-out site).



Farms that employed combinations of polar circles and steel cages, however, reported substantially greater losses of fish to seal predation than farms that used just polar circles (n = 27, p = 0.063) or steel cages (n = 27, p = 0.060) (Table 3).

The frequency with which fish mortalities were removed from net pens (n = 27, p = 0.340) was not found to be related to reported levels of seal predation. Managers reported the removal of fish mortalities from net pens once per week or more. Limited variability in mortality removal practices may have precluded the detection of a relationship between seal predation levels and this husbandry practice (Table 3).

The frequency with which the primary containment nets were replaced was one husbandry practice related to levels of seal predation experienced. Managers at farms where containment nets were replaced more than once per year reported fewer losses to seal predation than managers at farms where nets were replaced once per year or less (n = 27, p = 0.055) (Table 3).

Predator deterrent methods

The results of models describing relationships between predator deterrent methods and estimated losses of fish to seal predation are presented (Table 4). The deployment of acoustic harassment devices (AHDs) as a seal deterrent method at marine salmon farms appears to be ineffective. The estimated numbers of fish lost to or damaged by seal predation was greater at farms that employed AHDs than at farms where AHDs were not in use (n = 27, p = 0.100). The frequency of AHD use, however, was not related to seal predation. Reported losses of fish to seal predation were not statistically different between farms that used AHDs year-round and farms that employed them only seasonally (n = 18, p = 0.835). Nor was a relationship found between the number of hours per day that AHDs were in operation and reported numbers of fish lost to seal predation (n = 18, p = 0.185). Acoustic harassment devices were operated between 8 and 24 h per day (mean of 17.8 $h \cdot day^{-1}$). Overall, only

Table 3. Estimates of the relationships between variables describing farm operations and the number of fish lost to seal predation at Atlantic salmon (*Salmo salar*) farms in Maine.

Model[a]	Coefficient[b,c]	Marginal effect[d]	Frequency	Range
Farm size				
Maximum number of fish (active farms only)	0.000 (0.000)	0	NA	1 070 313
Constant	8.141 (1.120)			
Farm activity				
Were fish stocked at this farm all year?	0.899 (1.003)	3465		NA
Yes			13	
No			14	
Constant	7.695 (0.761)			
Pen type(s) used vs combinations				NA
Polar circles?	–2.256* (1.214)	–8700	12	
Steel cages?	–2.406* (1.280)	–9279	9	
Constant	9.465 (1.020)			
Pen type(s) used vs steel cages				NA
Polar circles?	0.150 (1.071)	579	12	
Combination of polar cirlces and steel cages?	2.406* (1.280)	9279	6	
Constant	7.059 (0.844)			
Frequency of mortality removal				NA
More than once a week?	–1.092 (1.143)	–4212		
Yes			7	
No			20	
Constant	8.447 (0.630)			
Frequency of containment net replacement				NA
More than once a year?	–2.048* (1.067)	–7899		
Yes			8	
No			19	
Constant	8.556 (0.628)			

[a]Dummy variables are indicated with question marks and coded 1 if "yes", 0 if "no".
[b]Asterisks denote significance: ***, 1% level; **, 5% level; *, 10% level.
[c]Standard errors are listed in parentheses.
[d]The predicted change in the number of fish lost to seal predation following a one-unit increase in the explanatory variable *X*, above the mean. For dummy variables, a one-unit increase in the explanatory variable is from a value of 0 (no) to 1 (yes).

50% of farm managers felt that AHDs were fairly effective, whereas 44% believed they were ineffective, and only 6% believed they were completely effective (n = 18).

The deployment of secondary or predator nets around pens was also a commonly used form of predator deterrence. These nets are usually made of large-mesh, heavy nylon or polypropylene twine. There are several designs implemented by individual operations: single panels hung on the most vulnerable side of the pen; curtain nets that encircle the pen, yet have no bottom; and box nets that completely enclose the underwater portions of the fish pen. The types of nets used and methods of deployment were relatively standardized within the Maine industry. Because nearly all of the farms (26 of 27) used predator nets between 2001 and 2003, it was not possible to examine the relationship between predator net use and the estimated number of fish lost to seal predation. Also, because of limited variability in responses, statistical analyses could not be performed on the effects of predator net type, method of deployment, or frequency of use (year-round versus seasonally). Twenty-three of the 26 active farms within 4 km of a harbor seal haul-out site and employing predator nets between 2001 and 2003 (88%) reported using box-style nets. Additionally, 22 of 26 farms (85%) deployed predator nets around each individual pen versus around groups of pens or systems. Finally, 100% of managers reported using predator nets year-round rather than on a seasonal basis (Table 4).

Farms primarily differed in the achieved levels of separation between containment and predator nets and the frequency of predator net maintenance. The average level of separation between predator and containment nets was 1.6 m. Distances ranged from 0.6 to 2.4 m. The separation between predator and containment nets (n = 26, p = 0.289) was not related to levels of seal predation. There was, however, insufficient variability in net separation between farms and therefore limited ability to detect potential trends. The frequency with which predator nets were replaced was negatively correlated with levels of seal predation experienced (n = 26, p = 0.001). Farm managers who replaced predator nets more than once per year reported substantially fewer losses of fish to seal predation than managers who replaced the predator nets at their farms only once a year or less. Fifty-eight percent of managers at Maine salmon farms were of the opinion that predator nets were fairly effective, whereas 42% felt that they were completely effective (n = 24). None of the managers that interviewed felt that predator nets were ineffective at reducing seal predation (Table 4).

Table 4. Estimates of the relationships between predator deterrent methods and the number of fish lost to seal predation at Atlantic salmon (*Salmo salar*) farms in Maine.

Model[a]	Coefficient[b,c]	Marginal effect[d]	Frequency	Range
Acoustic harrassment device (AHD) use				
Are AHDs used?	1.714* (1.041)	6 611		NA
Yes			18	
No			9	
Constant	6.862 (0.883)			
Frequency of AHD use yearly				
Are AHDs used year-round?	–0.168 (0.808)	–892		NA
Yes			12	
No			6	
Constant	8.686 (0.688)			
Frequency of AHD use				
Frequency of AHD use (h·day^{-1})	–0.079 (0.060)	–430	NA	16
Constant	9.849 (1.135)			
Separation between containment and predator nets (m)				
Net separation	1.929 (1.818)	9 732	NA	1.83
Constant	5.059 (2.957)			
Frequency of predator net replacement				
More than once a year?	–4.547*** (1.352)	–18 194		NA
Yes			4	
No			22	
Constant	8.459 (0.585)			

[a]Dummy variables are indicated with question marks and coded 1 if "yes", 0 if "no".
[b]Asterisks denote significance: ***, 1% level; **, 5% level; *, 10% level.
[c]Standard errors are listed in parentheses
[d]The predicted change in the number of fish lost to seal predation following a one-unit increase in the explanatory variable *X*, above the mean. For dummy variables, a one-unit increase in the explanatory variable is from a value of 0 (no) to 1 (yes).

Discussion

Salmon farms attract a diverse array of predators (Ross 1988; Quick et al. 2004). Of the many predators that frequent marine finfish farms, pinnipeds are considered the most troublesome in other parts of the world, e.g., the western United States, Canada, Australia, and Scotland (Pemberton and Shaughnessey 1993; Nash et al. 2000; Quick et al. 2004). The results of this study have established the existence of a similar pattern in Maine. Between 2001 and 2003, there was a large variation in the estimated numbers of Maine farm-raised Atlantic salmon predated by seals. The majority of farm managers, however, considered seals to be the greatest predatory threat to farm stock.

The results of this study demonstrate that although seals may not specifically focus their foraging activities in areas where marine salmon farms are concentrated, they may take advantage of the available food source if it is located in close proximity to their haul-out sites. The probability of experiencing seal predation and the severity of that predation were negatively correlated with proximity to the nearest harbor seal haul-out. Farms with no harbor seal haul-outs within 4 km experienced minimal losses of fish attributed to seal predation. There were, however, farms with seal haul-out sites located less than 4 km away that also did not experience any seal predation. These results suggest that although distance to the nearest harbor seal haul-out site is not the only factor influencing seal predation at marine salmon farms, seal predation is substantially reduced at farms located further than 4 km from the nearest haul-out. Pemberton and Shaughnessey (1993) concluded that the severity of predation on farm-raised fish by Australian fur seals (*Arctocephalus pusillus*) is influenced by proximity to the nearest haul-out. A review by Nash et al. (2000) suggested that farms move offshore from haul-out sites and rookeries to mitigate predation impacts. Sepulveda and Oliva (2005) found no relationship between the magnitudes of fish losses at Chilean farms and distance to the nearest sea lion (*Otaria flavescens*) colony. Harbor seals, however, have significantly smaller foraging ranges than South American sea lions (Boulva and McLaren 1979; Campagna et al. as cited in Sepulveda and Oliva 2005) and may be more apt to take advantage of available food sources nearby, especially given the lack of wild stocks of fish available near shore during winter months. The results of our study suggest, however, that it does not matter how many seals are found at haul-outs within 4 km, providing evidence that a few individuals may repeatedly visit the pen sites.

At farms located near harbor seal haul-outs, seal predation was also linked to the separation between neighboring farms: areas where farms were concentrated (i.e., Cobscook Bay, Maine) appeared to be more vulnerable to seal predation.

The types of net pen(s) used on Maine salmon farms may influence levels of seal predation experienced. Those farms employing combinations of polar circles and steel cages reported significantly higher levels of seal predation than farms employing only a single pen type. The reasons for such a relationship are not entirely clear. This study found no difference in seal predation levels between farms using polar circles and farms using steel cages. It appears that no single pen type is better at protecting farm-raised salmon from seal predation. Further analysis of the influence of pen size and type on seal predation is warranted. This particular study examined pen type only and did not investigate such potential factors as stocking densities (number of fish·m^{-3}), numbers of pens on site, and pen layout. High stocking densities could likely increase predation losses because fish are more tightly packed and thus more exposed to the net sides and predating seals. Jamieson and Olesiuk (2001) found that seal predation levels at farms in British Columbia decreased when larger pens were installed.

Heavily fouled predator and containment nets are likely under greater stress and more vulnerable to tearing, allowing fish to escape or predators to enter the pens. Fouled nets also reduce water flow, likely having a negative effect on the health of the farm stock (Ross 1988; NMFS 1996). This study suggests that replacement of containment and predator nets more than once a year may result in decreased levels of seal predation. This is further supported by Sepulveda and Oliva (2005), in which Chilean farmers reported that predator nets were effective if well maintained, including cleaned every 6 months. Our conclusions are, however, limited by the fact that the replacement of nets once a year appears to be a relatively standard practice within the Maine industry.

This study strongly suggests the ineffectiveness of AHDs at deterring seal predation. Past studies suggest that AHDs function as a temporary means of predator deterrence only, citing habituation by seals (Jamieson and Olesiuk 2001; Quick et al. 2004; Sepulveda and Oliva 2005). Jamieson and Olesiuk (2001) reported that some of the largest losses of farm-raised fish to seal predation occurred while AHDs were in operation and that seal attacks did not decline until AHDs were phased out and larger pens were installed.

There is much controversy concerning the effects of AHDs on both target and non-target species. It has been suggested that AHDs lose their effectiveness because of potential hearing damage in seals (NMFS 1996; Johnston and Woodley 1998). This potential for hearing loss or damage in seals exposed to AHDs and uncertainty surrounding their effect on non-target species, such as harbor porpoise (*Phocoena phocoena*), other marine mammals, and particular species of fish, has prompted the prohibition of AHDs at marine finfish farms in British Columbia (Jamieson and Olesiuk 2001). Olesiuk et al. (2002) and Johnston (2002) suggest that harbor porpoises are deterred from passing through or inhabiting areas where AHDs are present. The use of AHDs on the west coast of Canada was also found to have a negative effect on occurrences and distributions of pacific white-sided dolphins (*Lagenorhyncus obliquidens*) (Morton 2000) and killer whales (*Orcinus orca*) (Morton and Symonds 2002). Additionally, herring and other clupeids may detect AHD signals, yet the resultant effects are not known at this time (NMFS 1996).

No relationship was found between the numbers of fish lost to seal predation and the reported separation between containment and predator nets. The range of net separations at Maine farms was, however, limited. Previous research suggests that insufficient separation between predator and containment nets leaves fish more accessible to seal predation (Pemberton and Shaughnessey 1993; NMFS 1996; Jamieson and Olesiuk 2001). Other studies have suggested the tensioning or weighting of nets to make them less pliable for predating pinnipeds (Quick et al. 2004; Sepulveda and Oliva 2005). Some Maine salmon farmers also cited the benefits of tensioning and (or) weighting nets to maintain their rigidity and prevent seals from pushing in on them and accessing the fish. Further study into the importance of proper net weighting and (or) tensioning within the Maine industry is warranted.

In conclusion, this study has highlighted some options for mitigating the potential impacts of seal predation at marine salmon farms in Maine, including establishing a minimum distance between farms and seal haul-outs and limiting concentrations of farms close to seal haul-outs. Additionally, results of this study suggest the importance of regular net cleaning and replacement. Further research into the relationship between frequency of fish mortality removal, pen size and type, and stocking densities is warranted. Finally, this study has demonstrated the ineffectiveness of using acoustic devices as methods of deterrence and the need for further investigations into the effects of AHDs on target and non-target species.

Acknowledgements

We thank the Maine finfish farmers for their support and cooperation with all facets of this project. The crews at Trumpet Island Salmon Farm and Maine Coast Nordic provided logistic support. Jon Lewis, John Moring, and Fred Servello provided valuable advice regarding data collection and analysis and manuscript preparation. We also thank all field personnel involved with this project: Lynda Doughty, Peter Duley, Keith Dunton, Kohl Kanwit, Slade Moore, Rick Nelson, Steve Renner, and Asheley Simpson. The pilots and others at Telford Aviation, Owlshead, Maine, provided expert flying on surveys conducted during winter months and often under adverse weather conditions. We particularly thank Asheley Simpson for dedicating so much of her time to sorting through slides and counting seals. We also thank William Halteman for his statistical advice and Seth Barker and Kathleen Bell for their expertise with ArcGIS. We are grateful to two anonymous reviewers for their comments and suggestions regarding the manuscript. This research was funded by National Marine Fisheries Service contracts 40EMNF-0-01058 (to DMR), 40EMNF-0-01057, 43EANF-1-30134, and EA133F-02-0211, Maine Sea Grant contract R-10-02, The Maine Agricultural and Forest Experiment Station Project 38660, and The Maine Department of Marine Resources. All research was performed under Marine Mammal Protection Act Permit No. 482-1653-00.

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