# Fishing-gear threat to right whales (*Eubalaena glacialis*) in Canadian waters and the risk of lethal entanglement

**Angelia S.M. Vanderlaan, R. Kent Smedbol, and Christopher T. Taggart**



**Abstract:** Commercial fishing gear can potentially entangle any whale, and this is especially true for the endangered North Atlantic right whale (*Eubalaena glacialis*), for which entanglement is second only to vessel strike as being responsible for documented right whale deaths. We use right whale survey data and Canadian fishing-gear deployment data to estimate the relative threat of gear entanglement in a Scotia–Fundy study area and the relative risk of lethal entanglement in the Bay of Fundy and on Roseway Basin, Scotian Shelf, where Critical Habitat has been legislated. We focus on groundfish and pelagic hook-and-line; groundfish gillnet; and crab-, hagfish-, and inshore and offshore lobster-trap gear. Our analyses demonstrate that groundfish hook-and-line gear poses the greatest threat to right whales among the seven gear types analysed during the summer-resident period in Critical Habitat and that gear from the lobster fisheries poses the greatest threat during the spring and autumn periods when whales are migrating to and from Critical Habitat. We suggest that area-specific seasonal closures of some fisheries would reduce threat and risk to whales without unduly compromising fishing interests.

**Résumé :** Toutes les baleines peuvent potentiellement s'empêtrer dans les engins de pêche commerciale et cela est particulièrement le cas de la baleine franche du Nord (*Eubalaena glacialis*) chez qui l'enchevêtrement est la seconde cause connue de mortalité après les chocs avec les navires. Nous utilisons les données d'inventaire des baleines franches du Nord et les données canadiennes sur le déploiement des engins de pêche pour estimer la menace relative de l'enchevêtrement dans les engins de pêche dans une zone d'étude de Scotia–Fundy, ainsi que le risque relatif d'enchevêtrement létal dans la baie de Fundy et le bassin de Roseway sur la plateforme néo-écossaise où un habitat critique a été désigné par législation. Nous nous intéressons à la pêche à la ligne et à l'hameçon des poissons benthiques et pélagiques, à la pêche au filet maillant des poissons de fond et à la pêche au casier de crabes, de myxines et de homards, tant au large que près des côtes. Nos analyses démontrent que les engins de pêche à la ligne et aux hameçons des poissons de fond représentent la menace la plus importante pour les baleines franches du Nord parmi les sept types d'engins analysés durant la période de résidence d'été des baleines dans l'habitat critique; les engins de pêche aux homards posent la menace la plus grande durant les périodes de printemps et d'automne quand les baleines migrent vers l'habitat critique ou en ressortent. Nous proposons des fermetures saisonnières de certaines pêches commerciales dans des zones précises, ce que réduirait la menace et le risque pour les baleines, sans compromettre outre mesure les intérêts de la pêche commerciale.

[Traduit par la Rédaction]

## Introduction

Any cetacean can potentially become entangled in fishing gear, and entanglements are a major source of anthropogenic mortality among whales (Reeves et al. 2003). Although small whales are less likely to free themselves from an entanglement and thus drown, an entangled baleen whale is capable of dragging the gear for extended periods (Clapham et al. 1999). Gear entanglements are not necessarily lethal for large whales, and many right whales appear to shed gear or self-disentangle with no chronic effect (Johnson et al. 2007).

The frequency of reported entanglements varies among whale species and regions, and coastal species appear especially vulnerable. This is particularly true for the humpback whale (*Megaptera novaeangliae*) and the North Atlantic right whale (*Eubalaena glacialis*; Rosenbaum et al. 2000; hereafter referred to as right whale) as documented by Kraus (1990) and Lien (1994), wherein the entanglements are associated with various kinds of fishing gear that include longlines (hook-and-line), drift nets, traps or pots, and gillnets, etc. Johnson et al. (2005) report that 89% (32/36) of documented entanglements of humpback and right whales in the north-

Received 19 February 2011. Accepted 11 August 2011. Published at www.nrcresearchpress.com/cjfas on xx December 2011.
J2011-0026

Paper handled by Associate Editor C. Tara Marshall.

**A.S.M. Vanderlaan and R.K. Smedbol.** Department of Oceanography, Dalhousie University, 1355 Oxford Street, P.O. Box 15000, Halifax, NS B3H 4R2, Canada; Fisheries and Oceans Canada, St. Andrews Biological Station, 531 Brandy Cove Road, St. Andrews, NB E5B 2L9, Canada.
**C.T. Taggart.** Department of Oceanography, Dalhousie University, 1355 Oxford Street, P.O. Box 15000, Halifax, NS B3H 4R2, Canada.

**Corresponding author:** Angelia S.M. Vanderlaan (e-mail: angelia.vanderlaan@phys.ocean.dal.ca).

west Atlantic are attributable to trap (pot) and gillnet gear, when gear was identifiable. Between 80% and 90% of large cetacean entanglements in coastal Newfoundland and Labrador are attributable to cod traps and groundfish gillnets (Lien 1994).

Of all documented right whale deaths attributed to human activities, death from entanglement in fishing gear is second only to death from vessel strike. Over the period 1970 through 1999, Knowlton and Kraus (2001) report that 6.7% of documented right whale mortalities and 55% of serious injuries were due to entanglement. The percentage of right whale deaths attributable to entanglement increases to 13% when estimates are based only on those whales necropsied over the period 1970 through 2002 (Moore et al. 2004). Approximately 73% of all photographically identified right whales show scarring that is consistent with at least one entanglement (Knowlton et al. 2008), and nearly every year an entangled whale either dies or disappears from the photographic-identification record (Johnson et al. 2007). Moore et al. (2006) estimate that between 49 and 136 right whales are entangled annually, and they conclude that the number of lethal entanglements is likely underestimated. As preventing the deaths of two female right whales per year has a measureable influence on population growth rate (Fujiwara and Caswell 2001), measuring the threat of fishing-gear entanglement provides the information required to mitigate negative influences on the population. As there is virtually no information on the nature of whale and fishing gear "interaction" and exactly how a whale becomes entangled, the simplest method to reduce the risk of entanglement is to reduce the amount and extent of fishing gear in those habitats and at those times where and when the whales are expected to be present (Kraus et al. 2005).

The threat to large whales of fishing-gear entanglements from commercial fisheries is being addressed in the United States of America (USA) via the imposition of selective area closures and gear modifications (e.g., National Oceanic and Atmospheric Administration 2007*a*, 2007*b*). Gear modifications include the use of weak links at buoys and the use of sinking groundlines, where the latter are required at various times throughout the range of right whales in USA waters (National Oceanic and Atmospheric Administration 2007*b*). Such gear modifications are designed to reduce the probability of entanglement and increase the likelihood of self-disentanglement. Fishing closures and the reduction of lines in the water column most simply reduce mortality via reduced probability of a gear encounter and thus lethal entanglement. In contrast with the USA, there have been no mandatory modifications of fishing practices in Canadian waters to protect right whales where and when they migrate to and from the Bay of Fundy and Roseway Basin feeding habitats, where the whales aggregate during the July through October period.

Right whale conservation initiatives in Canadian waters have included the designation of Right Whale Conservation Area(s) (Brown et al. 1995) and Right Whale Critical Habitat (Brown et al. 2009; as illustrated in Fig. 1) and modified vessel navigation in the Bay of Fundy and Roseway Basin regions (Vanderlaan et al. 2008; Vanderlaan and Taggart 2009). Although the conservation areas served to warn mariners of the presence of right whales and were associated with recommendations for voluntary actions to minimize the probability of a vessel strike, they did not provide regulations, recommendations, or guidelines for fishing practices or sanctions to minimize the probability of an entanglement. In effect, the conservation areas no longer exist, as they have been superseded by Critical Habitat areas (Brown et al. 2009). According to the Canadian Species at Risk Act (SARA: Species at Risk Act 2002), activities within a Critical Habitat that would destroy the habitat are prohibited, though such prohibitions do not explicitly address fishing practices. Any modifications to contemporary fishing practices for the protection of right whales in Canadian waters, either through fishing closures or gear modifications, will require quantitative estimates of the threat or risk to the whales from fishing gear, as well as where and when entanglements are most likely to occur.

Here we quantify the relative threat of Canadian fishing-gear entanglement to right whales in the Scotia–Fundy region (Fig. 1). We then focus on estimating the risk of lethal entanglement in regions defined as Critical Habitat under SARA (Brown et al. 2009): the Grand Manan Basin region in the Bay of Fundy and the Roseway Basin region on the southwest Scotian Shelf (Fig. 1). We focus on six different fisheries and their associated gear: the crab-, hagfish-, and offshore lobster-trap (pot) fisheries; the groundfish gillnet and hook-and-line fisheries; and the pelagic hook-and-line fishery. We also address a seventh, the inshore lobster-trap fishery, though the data are much more limited in relation to the above six fisheries. We use the results to identify possible management methods that could be used to minimize the threat and risk of lethal entanglements in right whale habitat without unduly compromising fishing interests.

## Material and methods

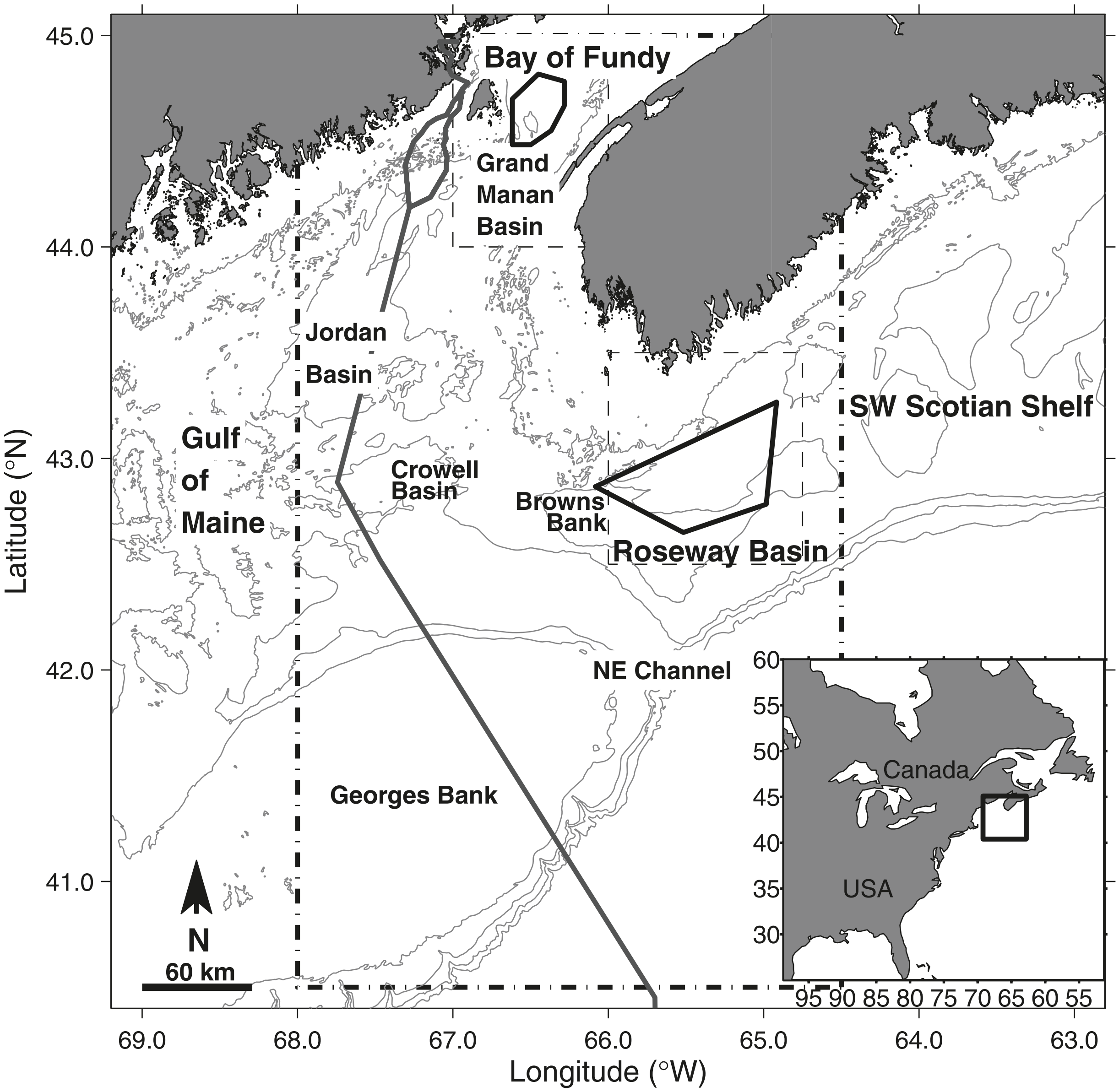
### Overview

We quantitatively addressed (*i*) the temporal coincidence of fishing gear and right whales in the Scotia–Fundy study area, (*ii*) the threat of right-whale entanglement in the Scotia–Fundy study area during the spring-immigration period, the summer-resident (feeding) period, and the autumn-emigration period, and (*iii*) the risk of lethal right-whale entanglement in the Bay of Fundy and Roseway Basin study areas (Fig. 1). The Scotia–Fundy study area was defined by 40.5°N through 45.0°N latitude and 64.5°W through 68.0°W longitude (area ≈ 194 500 km$^2$). The smaller study areas (Fundy and Roseway) were delineated by right-whale survey and whale-sighting data (sightings per unit effort, SPUE) that were used for similar purposes when addressing the risk of lethal vessel strikes (Vanderlaan et al. 2008).

### Whale and fishing gear data

Quality controlled right whale SPUE data for the period 1979 through 2007 were provided for each of the Fundy and Roseway study areas by the North Atlantic Right Whale Consortium (North Atlantic Right Whale Consortium 2008). An overview of the right-whale surveys are provided in Brown et al. (2007), and the most salient features are provided in Vanderlaan et al. (2008). The aggregate 1979–2007 SPUE data were resolved over 20 × 20 cell (Fundy; area ≈ 8643 km$^2$) and 25 × 20 cell (Roseway; area ≈ 11 319 km$^2$)

**Fig. 1.** Bathymetric (100, 200, 500, and 1000 m isobaths) chart illustrating the location (inset) of the Scotia–Fundy study area (black dot-dash rectangle), the Bay of Fundy and Roseway Basin study areas (black dash rectangles) and associated right whale Critical Habitat (black solid-line polygons), and the Canadian Exclusive Economic Zone boundary and “grey zone” polygon (grey solid line).






grids, where each grid-cell was defined by 3′N latitude and 3′W longitude (5.6 km N–S and ~3.9 km E–W for Fundy and ~4.1 km E–W for Roseway). This was the limiting resolution used for all spatial analyses below except when noted. The total Canadian open-waters area in the Scotia–Fundy study area is ≈87 800 km$^2$ and those for the Fundy and Roseway study areas are ≈8200 km$^2$ and ≈11 200 km$^2$, respectively, representing 9% and 13% of Canadian open waters in the Scotia–Fundy study area.

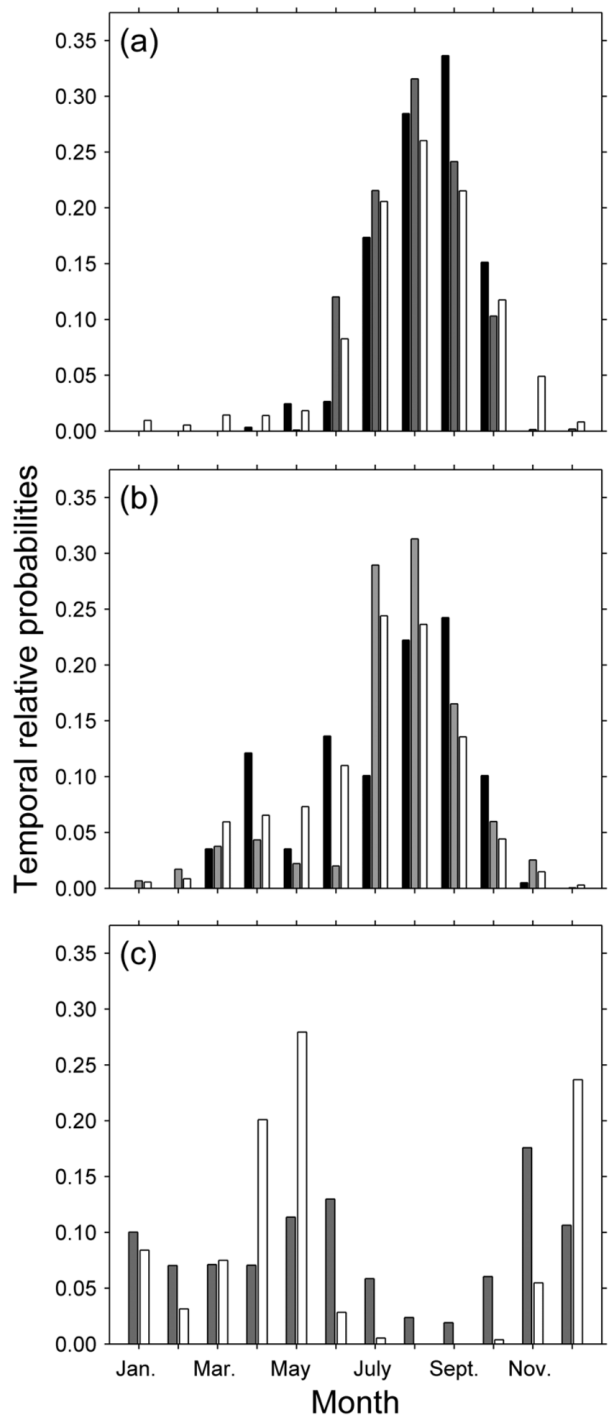
The fishing-gear deployment data for the six fisheries above were derived from two statistical databases detailing commercial-fishery landings that are maintained by Fisheries and Oceans Canada (DFO). The databases detail information for all fishing trips where a landing is reported within the DFO Maritimes region. Our aggregate gear-specific data for the period 1999 through 2007 were extracted from the Zonal Interchange File Format (ZIFF) database for 1999 through 2001 and from the Marine Fish (MARFIS) database for 2002 through 2007. Each database, along with details on gear configuration, is described in Johnston et al. (2007). The data contain a variety of information pertaining to date, trip, gear type, set location, amount of gear used in a set, and species landed, etc. All of our analyses involving fishing gear are based on date and location of each set, where each set is quantified by the amount of gear deployed, $G$, (i.e., number of hooks, nets or panels, traps or pots, deployed at a set location and time). We also use only the number of sets deployed within a fishery regardless of the amount of gear used within a set. Species-specific landings data are used for interpretive considerations in the Discussion.

The resolution of the inshore lobster-fishery data is considerably different from that associated with the six fisheries above in that the data were provided in aggregate across "logbook reporting areas", with a spatial resolution varying from 100 to 340 km$^2$. Further, the number of sets deployed is not reported for the inshore-lobster fishery, and as the only measure reported is the number of traps hauled, we assume it is equivalent to $G$. We cannot quantify risk of entanglement, as the low and varying spatial and temporal resolution prevents us from achieving the same relatively high resolution associated with the other fisheries. Thus, the inshore lobster-gear data and analyses are treated separately from the other fisheries. There are very likely reporting biases associated with the inshore logbook data that cannot be assessed. To minimize potential bias, we selected only those years (2005–2008 within the 1998–2010 series) with the most extensive and relatively constant spatial and temporal coverage. The number of logbooks reporting traps hauled in 1998 was 67, and this rose systematically to 592 in 2004. Over the period 2005–2008, the mean and standard deviation of logbooks reporting hauls was 801 and 12, respectively. There were 568 logbooks reporting hauls in 2009, and this declined to 214 in 2010. A portion (~14%) of inshore-lobster fishers reports haul data as part of the offshore-lobster fishery, and we have used those data as part of the offshore fishery.

The aggregate gear-specific data (except inshore lobster) were spatially resolved over a 90 × 70 cell grid covering the Scotia–Fundy study area that also encompasses the smaller Fundy and Roseway study areas (Fig. 1), and each cell was defined as above for the right whale data. We also examined fishing-gear threat in the Scotia–Fundy study area using aggregate data over three seasonal periods relevant to the whales: (1) May through June — spring immigration, (2) July through October — summer resident, and (3) November through December — autumn emigration. These periods were based on the seasonal migration and aggregation patterns for right whales in Canadian waters (Winn et al. 1986; Murison and Gaskin 1989; Gaskin 1991; see also Fig. 2). The relative risk of a lethal entanglement in the Fundy and Roseway study areas was estimated for the summer-resident period only.

The ZIFF and MARFIS databases include incomplete records (null observations) within and among the various fisheries. For example, the number of nets in a groundfish gillnet set (deployment) was not recorded after 2004. Some of the data were considered to be erroneous (statistical outliers) or unsubstantiated; e.g., hooks per set were sometimes >10 000 in the groundfish hook-and-line fishery and are considered incorrect (Johnston et al. 2007). Such data were initially nullified. To replace a null datum within a set, a $k$-nearest neighbour imputation (Jönsson and Wohlin 2004) was used, as the numbers of hooks, traps, etc. were spatially autocorrelated and their distributions were skewed. To complete the imputations, the data were classified into two subsets: the first where the number of hooks, traps, etc. was available and the second that contained the null observations. For each observation in the "null" subset, the Euclidean distance to each observation in the "available" subset was calculated. The median value for the number of hooks, traps, etc. of the $k$ = 25 neighbours nearest the null observation was then used to replace the null observation.

**Fig. 2.** Histograms of the monthly temporal relative probabilities of observing (*a*) right whales ($P_{rel}$(Whale), black bars) and gear ($P_{rel}$(Gear)) for each of (*a*) pelagic (grey bars) and groundfish (open bars) hook-and-line fisheries, (*b*) hagfish- (black bars) and crab- (grey bars) trap fisheries and the groundfish-gillnet fishery (open bars), and (*c*) the offshore- (grey bars) and inshore- (open bars) lobster fisheries in the Scotia–Fundy study area.




## Temporal coincidence of fishing gear and right whales

To assess the temporal coincidence between whales and the amount of gear deployed across the entire Scotia–Fundy study area, and thus the temporal variation in threat of entanglement for right whales, the temporal relative probabilities of the amount of gear being deployed and of observing right whales in the Scotia–Fundy domain were calculated for each month. Fishing-gear data for all fisheries, including inshore lobster, were aggregated by month across the years 2005 through 2008 (4 years), because of the limitations of the inshore lobster-gear data. The number of traps set in the offshore lobster fishery was only reported prior to 2002, and for this reason, and to be consistent with the other fisheries, the temporal relative probability of offshore lobster gear being deployed was estimated using the 1999 though 2001 data (3 years).

We assumed that the above temporal aggregations of fishing-gear data can be used to provide the best estimate of the relative probability (0,1) of observing a given type of fishing gear, $P_{\mathrm{rel}}$(Gear), over a given month ($t$) in the Scotia–Fundy study area by using the number ($G$) of hooks, nets, or traps, etc. deployed over the month and was calculated as

$$(1) \qquad P_{\mathrm{rel}}(\mathrm{Gear})_t = \frac{G_t}{\sum_{t=1}^{12} G_t}$$

Similarly, and as in Vanderlaan et al. (2008, 2009), we assumed that the 1979–2007 aggregate SPUE estimates can be used to provide the best estimate of the relative probability of observing a right whale, $P_{\mathrm{rel}}$(Whale), over a given month ($t$) in the Scotia–Fundy study area by using SPUE in a given month, as in eq. 1 above.

To quantify the temporal coincidence of $P_{\mathrm{rel}}$(Whale) with $P_{\mathrm{rel}}$(Gear) for each fishery in the Scotia–Fundy study area across months, we used a sum of squares (SSW) statistic defined as

$$(2) \qquad \mathrm{SSW} = \sum_{t=1}^{12} \left[P_{\mathrm{rel}}(\mathrm{Gear})_t - P_{\mathrm{rel}}(\mathrm{Whale})_t\right]^2$$

where large estimates of SSW represent large differences in the temporal coincidence of the relative probability estimates. Seasonal cross-correlations using monthly lags between $P_{\mathrm{rel}}$ $(\mathrm{Whale})_t$ and $P_{\mathrm{rel}}(\mathrm{Gear})_t$ were also used as a measure of the temporal similarity between the two $P_{\mathrm{rel}}$ estimates for each fishery in the Scotia–Fundy study area.

### Threat of fishing-gear entanglement in the Scotia–Fundy study area

We assumed that the aggregate fishing-gear data provide the best estimates of $P_{\mathrm{rel}}$(Gear) at a 3′ spatial resolution across grid-cells ($i$) for the amount of each type of fishing gear deployed, which was calculated as

$$(3) \qquad P_{\mathrm{rel}}(\mathrm{Gear})_i = \frac{G_i}{\sum_{i=1}^{n} G_i}$$

To quantify the threat of a fishing-gear entanglement, we weighted the $G_i$ estimate by depth to the seabed (local bathymetry at each grid-cell centroid), as the end-buoy lines associated with each set extend throughout the water column and present an additional threat of entanglement. For all grid-cells where depth was >200 m, a weight of 200 was used, as right whales generally tend to dive to a depth less than this (Winn et al. 1995; Nowacek et al. 2001, 2004).

The relative threat of an entanglement in fishing gear in a grid-cell, relative to all other cells in a domain of $n$ cells, was calculated as

$$(4) \qquad P_{\mathrm{rel}}(\mathrm{Threat})_i = \frac{G_i \times W_{i\forall i \leq 200}}{\sum_{i=1}^{n} G_i \times W_{i\forall i \leq 200}}$$

where $W_i$ is the depth (m) to the seabed in a grid-cell. To compare relative threat measures across different periods (immigration, summer-resident, and emigration), eq. 4 was modified to

$$(5) \qquad P_{\mathrm{rel}}(\mathrm{Threat})_i = \frac{G_i \times W_{i\forall i \leq 200}}{\sum_{i=1}^{m} G_i \times W_{i\forall i \leq 200}}$$

where $m = (n_{\mathrm{immigration}} + n_{\mathrm{resident}} + n_{\mathrm{emigration}})$ or $m = (n_{\mathrm{immigration}} + n_{\mathrm{emigration}})$ as required.

For the Scotia–Fundy study area, the relative threat of a fishing-gear entanglement (eq. 4) was estimated for the summer-resident period, and the standardized relative threat of entanglement (eq. 5) was estimated for comparative purposes between the right whale spring-immigration and autumn-emigration periods.

### Risk of fishing-gear entanglement in Bay of Fundy and Roseway Basin

We use the formal definition of risk (Kaplan and Garrick 1981) that in this context is the intersection of the probability of a whale encountering gear and the probability of a lethal injury given an encounter has occurred: $P$(Lethal | Encounter). We used an approach similar to that of Wiley et al. (2003) and Vanderlaan et al. (2008) to estimate the relative probability that fishing gear and a whale will occupy (encounter each other in) a given space (grid-cell). As in Vanderlaan et al. (2008, 2009), we assumed that the 1979–2007 aggregate SPUE estimates provide the best estimate of the relative probability, at 3′ resolution, that a whale occupies a grid-cell ($\mathrm{SPUE}_i$) relative to cells ($i$) in a domain and was calculated in a manner similar to eq. 4 above:

$$(6) \qquad P_{\mathrm{rel}}(\mathrm{Whale})_i = \frac{\mathrm{SPUE}_i}{\sum_{i=1}^{n} \mathrm{SPUE}_i}$$

Using eq. 4 and eq. 6 above, the relative probability that fishing gear and a whale will occupy a given grid-cell was then calculated as

$$(7) \qquad P_{\mathrm{rel}}(\mathrm{Encounter})_i = \frac{P_{\mathrm{rel}}(\mathrm{Whale})_i \times P_{\mathrm{rel}}(\mathrm{Threat})_i}{\sum_{i=1}^{m} P_{\mathrm{rel}}(\mathrm{Whale})_i \times P_{\mathrm{rel}}(\mathrm{Threat})_i}$$

where $P_{\mathrm{rel}}(\mathrm{Encounter})_i$ is normalized such that the sum across the grid is equal to one.

### Probability of lethal entanglement

To estimate the lethality of an entanglement, we first estimated the total, population-wide (entire range) number of gear entanglements over the period of 1986 through June 2005 using right whale population abundance (Kraus and Rolland 2007), entanglement rate (Knowlton et al. 2008), and entanglement reports (Moore et al. 2006). We then estimated $P(\mathrm{Lethal} \mid \mathrm{Encounter})$ using the total number of deaths (observed, presumed, or expected; Moore et al. 2006) resulting from an entanglement divided by the total number of entanglements. The errors associated with the probability estimates were calculated using conventional propagation of error.

The relative risk (RR) of a lethal entanglement in the Bay of Fundy and Roseway Basin study areas during the right whale summer-feeding period was estimated using the relative probability of an encounter and the probability that the encounter is lethal

$$(8) \qquad \mathrm{RR}_i = P_{\mathrm{rel}}(\mathrm{Encounter})_i \times P(\mathrm{Lethal}|\mathrm{Encounter})_i$$

## Results

### Estimating the lethality of an entanglement

The Knowlton et al. (2008) scarring-study data, based only on "adequately photographed" whales in consecutive years, allowed us to estimate an average annual entanglement rate of 0.28 ± 0.11 over a 23-year period (1982 through 2004). This estimate corresponds to annual estimate of $e_1 = 97 \pm 39$ individual entanglements sufficient to cause scarring, but not death, based on a whale population size of 350 individuals (Kraus and Rolland 2007). Moore et al. (2006) reports $e_2 = 23$ lethal entanglements (observed, presumed, or expected) over a period $t = 19.5$ years (1986 through June 2005). The above estimates allowed us to estimate the probability of a lethal entanglement given an encounter as

$$(9) \qquad P(\mathrm{Lethal}|\mathrm{Encounter}) = \frac{e_2}{e_1 \times t + e_2} = 0.012 \pm 0.0047$$

i.e., approximately a 1% chance of a right whale dying as the result of a fishing-gear entanglement.

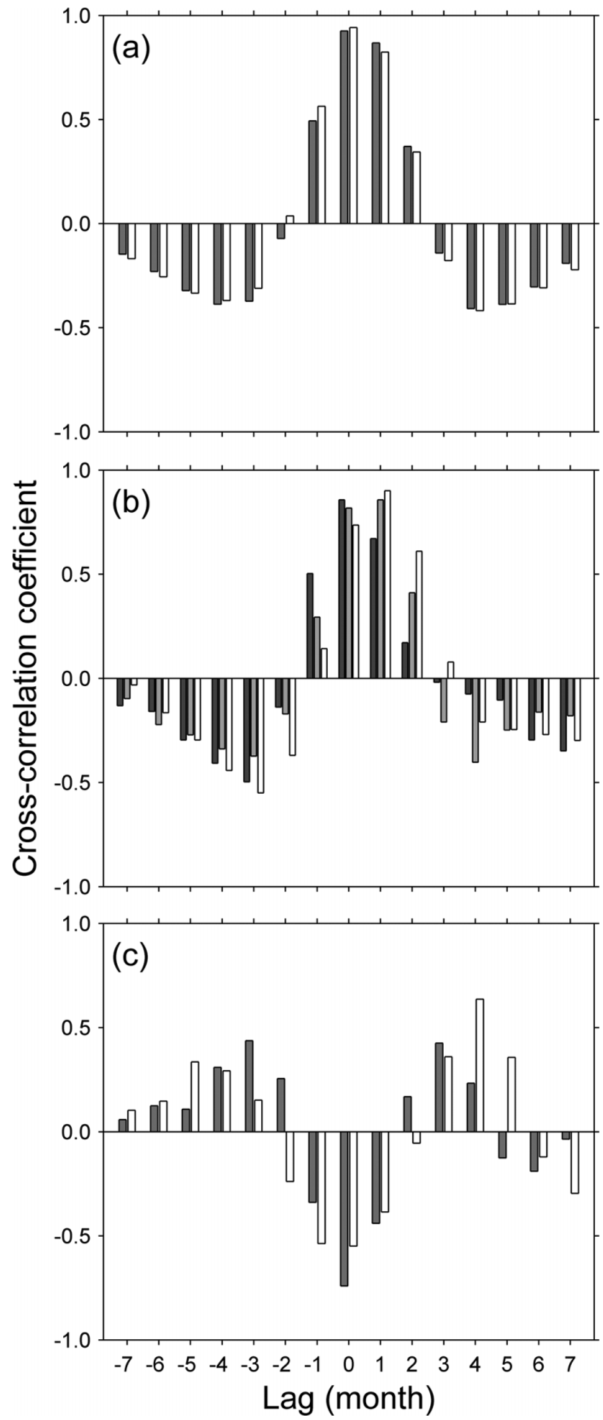
The paucity of data concerning gear-specific entanglements among right whales (Johnson et al. 2005) forces us to assume that all fishing gear is equally likely to be lethal if encountered by a right whale. The consequences of this assumption are addressed in detail in the Discussion.

### Temporal coincidence of fishing gear and right whales

The greatest (>0.15) temporal relative probabilities of observing a right whale in the Scotia–Fundy study area occur in July through September, a period that corresponds to the greatest relative probabilities of pelagic and groundfish hook-and-line gear being deployed (Fig. 2*a*), and similarly for hagfish-trap and crab-trap and groundfish-gillnet gear (Fig. 2*b*). Conversely, while whale probabilities are greatest during the July–September period, the probabilities of inshore and offshore lobster gear being deployed over the same period are at their lowest and zero for inshore gear during August and September when the fishery is closed (Fig. 2*c*).

The fishery with the lowest SSW statistic, and thus the greatest temporal coincidence with the presence of right whales over the entire Scotia–Fundy study area, is the pelagic hook-and-line fishery (SSW = $2.34 \times 10^{-2}$), closely followed by the groundfish hook-and-line fishery (SSW = $2.35 \times 10^{-2}$). These two fisheries also have the highest temporal cross-correlation near one at zero lag, each decreasing to negative cross-correlations at –4 and +4 month lags (Fig. 3*a*). Thus, the

**Fig. 3.** Temporal cross-correlation estimates at 1-month lags between aggregate (1979 through 2007) right whale SPUE estimates and aggregate (2004 through 2007 except offshore lobster; 1999 through 2001) amounts of fishing gear deployed ($G_t$) for each of the (*a*) pelagic (grey bars) and groundfish hook-and-line (open bars) fisheries; (*b*) hagfish-trap (black bars), crab-trap (grey bars), and groundfish-gillnet (open bars) fisheries; and (*c*) offshore (grey bars) and inshore (open bars) lobster-trap fisheries, in the Scotia–Fundy study area.



groundfish and pelagic hook-and-line fisheries are temporally coincident and near-perfectly in phase with the right whales in the Scotia–Fundy area. The crab- and hagfish-trap and groundfish-gillnet fisheries have greater SSW statistics of $5.59 \times 10^{-2}$, $4.79 \times 10^{-2}$, and $7.62 \times 10^{-2}$, respectively, though their temporal cross-correlations with right whales at zero lag are relatively high, with lags decreasing to negative at $\leq -3$ and $\geq +4$ months (Fig. 3*b*), indicating moderate temporal coincidence with right whales. Relative to the other fisheries above, the lobster fisheries have the highest SSW statistics of $4.20 \times 10^{-1}$ for the inshore and $2.76 \times 10^{-1}$ for the offshore. In contrast with the other fisheries, the lobster fisheries are negatively cross-correlated with the whales at zero lag and increase toward positive values at lags of $\leq -3$ to $\geq +3$ months, indicating that these fisheries are out of phase with the presence of right whales in the Scotia–Fundy study area (Fig. 3*c*). The relatively large SSW statistics and cross-correlation analyses indicate temporal separation between the deployment and hauling of lobster gear and the presence of right whales. The SSW statistic for the inshore-lobster fishery is not only the highest among all fisheries, it is fivefold greater than any other fishery with the exception of the offshore-lobster fishery. The SSW statistics for the inshore and offshore fisheries are, respectively, also 12- and 18-fold greater than each of the hook-and-line fisheries, indicating temporal separation between the lobster gear, both inshore and offshore, and the presence of right whales, relative to all of the other fisheries and their associated gear.

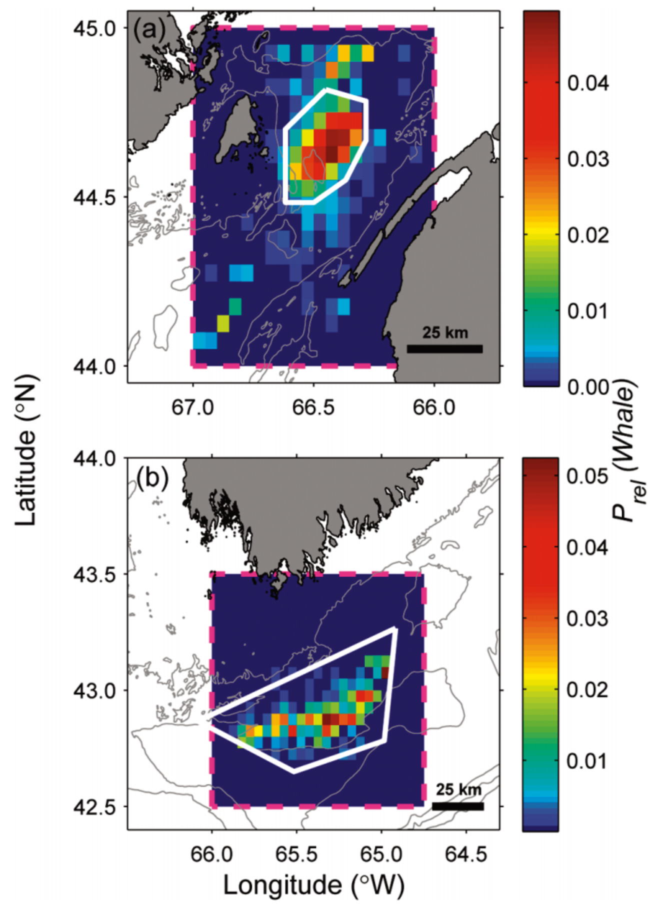
Although there is low temporal coincidence between the lobster fisheries and the right whales, mostly attributable to the lobster fishing seasons being out of phase with the presence of the whales, we have included both the offshore and inshore fisheries in the remaining analyses. The data limitations described above for the inshore-lobster fishery (lower spatial and temporal resolution and nonreporting of the number of sets fished) prevent direct comparisons between the inshore lobster fishery and any of the other fisheries we address.

## Relative probability of observing a right whale

During summer in the Bay of Fundy study area, right whales are most concentrated in the Grand Manan Basin (Fig. 4*a*), and overall the chance of observing a right whale within the Critical Habitat is 68% (see also Vanderlaan et al. 2008). This corresponds to a 23-fold greater chance, on average, of observing a right whale inside the Critical Habitat than outside. There are slightly elevated relative probabilities north of the Critical Habitat that is bounded by the 100 m isobath and a relatively small probability of observing a right whale to the south, a region of ingress and egress of right whales to and from the Bay of Fundy.

In the Roseway Basin study area, the whales are most concentrated within the Critical Habitat (Fig. 4*b*) during summer, and there is an overall 99% chance of observing a right whale within the Critical Habitat, corresponding to a 73-fold greater chance of observing a right whale within the Habitat than elsewhere in the study area.

**Fig. 4.** Bathymetric (100, 200, 500, and 1000 m isobaths) charts illustrating the relative probability of observing a right whale, $P_{\mathrm{rel}}$(Whale), within each of the (*a*) Bay of Fundy and (*b*) Roseway Basin study areas (pink dashed-line rectangles) and their associated right whale Critical Habitat (white solid-line polygons).




## Gear threat and risk during the summer-resident period

### *Pelagic hook-and-line*

Pelagic hook-and-line gear is deployed in a concentrated manner along the shelf break of the Scotian Shelf and Georges Bank (Supplemental Fig. S1*a*[1] ). The relative threat from the amount of gear associated with this fishery is very small in the both the Fundy and Roseway Basin study areas, contributing 0.014% and 0.51%, respectively, to the overall Scotia–Fundy relative threat.

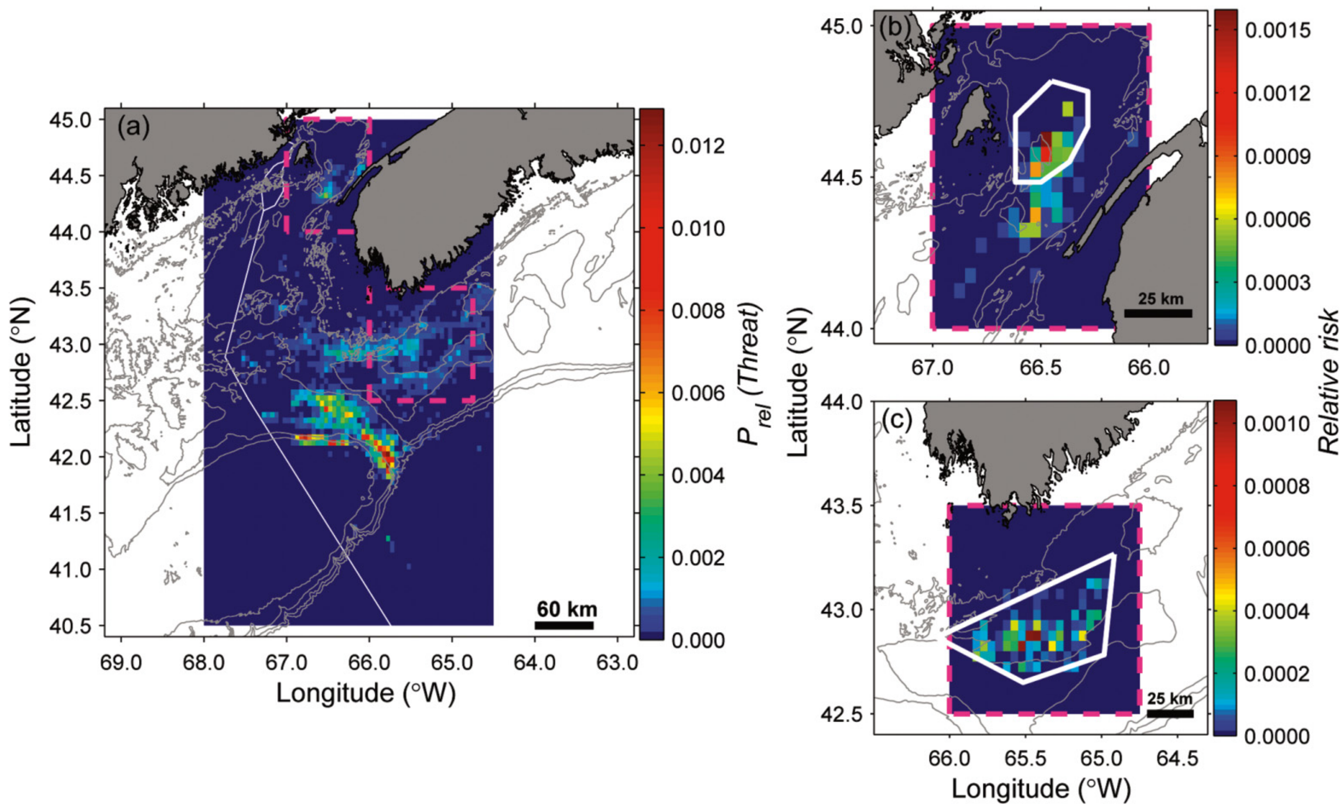
The fishery is not prosecuted in the Fundy area, and thus there is virtually no risk of lethal entanglement to right whales (Supplemental Fig. S1*b*[1]). In the Roseway area, there is one grid-cell (~23 km$^2$) that is associated with high relative risk from pelagic hook-and-line gear, and it is contained within the Critical Habitat (Supplemental Fig. S1*c*[1]).

### *Groundfish hook-and-line*

Groundfish hook-and-line gear is deployed throughout the larger Scotia–Fundy study domain, and the greatest relative threat is located along the northeast slope of Georges Bank and in the Northeast Channel (Fig. 5*a*). There is elevated

[1]Supplementary data are available with the article through the journal Web site at http://www.nrcresearchpress.com/doi/suppl/10.1139/f2011-124.

**Fig. 5.** Bathymetric (100, 200, 500, and 1000 m isobaths) charts illustrating (*a*) the Scotia–Fundy study area, the Canadian Exclusive Economic Zone boundary and "grey zone" polygon (white solid line), the Bay of Fundy and Roseway Basin study areas (pink dashed-line rectangles), and the relative threat of entanglement in groundfish hook-and-line gear over the July through October period and the relative risk of lethal entanglement in each of the (*b*) Bay of Fundy and (*c*) Roseway Basin study areas (pink dashed-line rectangles) and their associated right whale Critical Habitat (white solid-line polygons).






threat in the lower Bay of Fundy and in the southwest Scotian Shelf region including Browns Bank and Roseway Basin. For the entire Scotia–Fundy area, 4.4% of the relative threat is located in the Fundy study area and 17% in the Roseway study area.

The highest relative risk of lethal groundfish hook-and-line entanglement in the Fundy area occurs within the Grand Manan Basin (Fig. 5*b*), and the average relative risk inside the Critical Habitat is 17-fold greater than outside. The Critical Habitat in the Fundy area does not encompass the majority of the risk, as it extends well to the south. In the Roseway Basin study area, the Critical Habitat encompasses virtually all of the risk, where on average it is two orders of magnitude greater than outside the Habitat; i.e., risk of lethal entanglement inside the Critical Habitat is 90-fold greater than outside (Fig. 5*c*).

### *Hagfish traps*

The hagfish-trap fishery is a very small fishery relative to the other fisheries we examined. The total number of sets for any given month over the 9-year study period is smaller, by one to three orders of magnitude, relative to the other fisheries. The majority of hagfish traps are deployed in June through September when they coincide with the presence of right whales (see Fig. 2). Sixty-three percent of the threat from this fishery is located within the Roseway study area, and an additional 11% is located in the Fundy area northwest of the Critical Habitat (Supplemental Fig. S2*a*[1]).

In the Fundy study area, 2% of the grid-cells (~173 km$^2$) have relative risk values greater than zero, and there is zero relative risk of lethal entanglement with hagfish-trap gear in the Critical Habitat (Supplemental Fig. S2*b*[1]). The few grid cells associated with risk are west and northwest of the Critical Habitat and are located where the probability of observing a right whale is low. In the Roseway study area, the risk is greatest in the northeast sector of the Critical Habitat (Supplemental Fig. S2*c*[1]). Although the average relative risk within the Critical Habitat is 23-fold higher than outside, it is derived from very few sets, amounting to 116 over 9 years during the summer-resident period.

### *Crab traps*

The majority of the threat posed by crab-trap gear to right whales in the Scotia–Fundy study area during July through October is outside the Fundy and Roseway study areas. Most threat is located southwest of Grand Manan Island and along the margins of the Jordan and Crowell basins and along the shelf break of Georges Bank and the Scotian Shelf (Supplemental Fig. S3*a*[1]). The relatively large amount of the gear deployed just south of Grand Manan Island extends well into the "grey zone" (Cook 2005). However, owing to the very low relative probability of observing a right whale in this area, there is minimal risk of crab-gear entanglement (but see below). Overall, for the Scotia–Fundy study area, 9.5% of crab-gear threat is within the Fundy study area and 0.39% is within the Roseway study area.

The relative risk to right whales of lethal entanglement in crab-trap gear is partially contained within the Critical Habitat of the Fundy study area, where it is generally elevated just south of the Critical Habitat (Supplemental Fig. S3*b*[1]), a region of whale ingress and egress to and from the Grand Manan Basin. Because of the aggregated nature of the whales, the average relative risk inside the Critical Habitat is approximately fourfold greater than outside. Risk is entirely contained within the Roseway Critical Habitat (Supplemental Fig. S3*c*[1]), where it is limited to seven grid-cells (~158 $km^2$). There is virtually no risk to right whales of entanglement in crab-trap gear outside the Roseway Critical Habitat in the study area.

### *Groundfish gillnets*

Groundfish-gillnet gear is deployed throughout the larger Scotia–Fundy study domain (Supplemental Fig. S4*a*[1]). Outside the Fundy and Roseway study areas, the majority of the relative threat is located east of Jordan Basin and north of Crowell Basin. There is some threat of entanglement within the two smaller study areas, with the Fundy and Roseway study areas contributing 12% and 8.2%, respectively, to the overall entanglement threat in the Scotia–Fundy study area.

The majority of the relative risk in the Fundy study area is contained within the Critical Habitat (Supplemental Fig. S4*b*[1]). On average, inside the Critical Habitat, the relative risk is 7.5-fold greater than outside. In the Roseway study area, few grid cells (~4% = 475 $km^2$) are associated with a measurable risk of lethal entanglement (Supplemental Fig. S4*c*[1]); the average relative risk inside the Critical Habitat is threefold greater than outside.

### *Offshore lobster traps*

There are four major concentrations of offshore lobster fishing activities in the Scotia–Fundy study area: along the northeast margins of the “grey zone” southwest of Grand Manan Island, the northeast margins of Crowell Basin, the southeast margin of Georges Bank, and the southwest shelf break of the Scotia Shelf (Supplemental Fig. S5*a*[1]). Some fishers who report as part of the offshore fishery also deploy lobster gear in the Bay of Fundy and Roseway Basin study areas; i.e., the deployments are actually associated with the inshore fishery (below). For the entire Scotia–Fundy study area, 5.0% of the relative threat is located in the Fundy study area and 1.4% in the Roseway study area.

On average, the risk of lethal entanglement is three orders of magnitude greater in the Bay of Fundy Critical Habitat than outside, and this corresponds to offshore fishers reporting gear deployments in three grid cells in the Grand Manan Basin (Supplemental Fig. S5*b*[1]). These reported locations are most likely erroneous, as the offshore fishery is prohibited from fishing in this area, and the removal of these cells from the risk analyses reveals that there is no risk of a lethal entanglement in offshore lobster gear in the Bay of Fundy Critical Habitat. There is no measurable risk of entanglement from offshore lobster gear in the Roseway Basin study area (Supplemental Fig. S5*c*[1]).

### *Inshore lobster traps*

During the resident period for right whales (July through October), the inshore lobster fishery reports gear deployment along the northwest coast of Nova Scotia in the Bay of Fundy, and then only in the last 2 weeks of October; consistent with licensing regulations (Fig. 6). There are no other areas in the Scotia–Fundy study area where the inshore lobster fleet reports the hauling of lobster traps during July through October.

When the above gear-threat estimates for the entire Scotia–Fundy study area are standardized and proportionally partitioned within gear type among the migration and resident periods, all but the inshore and offshore lobster gear present the greatest threat (≥70%) during the summer-resident period (Table 1). Conversely (and consistent with Figs. 2*c* and 3*c*), lobster gear presents the least amount of threat (≤26%) during the summer-resident period, and for inshore lobster the threat during spring (85%) is comparable to that of all the non-lobster fisheries during summer (Table 1). These latter estimates highlight the degree of threat presented by most gear types during the spring-immigration period relative to the autumn-emigration period.

## Gear threat in the Scotia–Fundy study area during seasonal migrations

The standardized gear-threat estimates (eq. 6 above) and comparisons below are based on the relative threat presented by each gear type deployed in the Scotia–Fundy study area but only for the spring-immigration (May and June) and autumn-emigration (November and December) periods that bracket the summer-resident period (July though October).

### *Pelagic hook-and-line*

Virtually all (96%) of the threat from the pelagic hook-and-line fishery is present during the spring-immigration period (Supplemental Fig. S6[1]), and the majority of the threat is concentrated in a rectangular area (40.5°N to 42.5°N and 64.5°W to 66°W) south of the shelf break on Georges Bank and the southwest Scotian Shelf (Supplemental Fig. S6[1]). Though rarely surveyed, <0.1% of all right whale sightings (survey and opportunistic over the period 1978 though 2008) occur in this area.

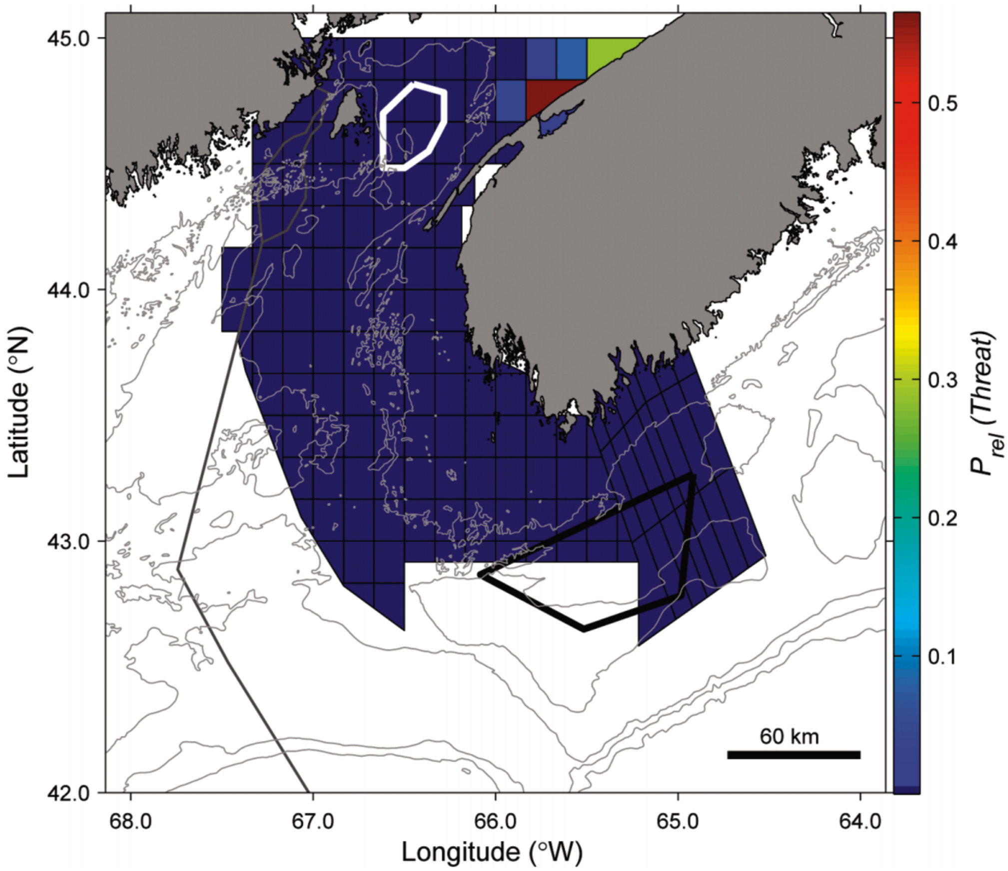
### *Groundfish hook-and-line*

Although the amount of gear deployed by the groundfish hook-and-line fishery poses a broadly distributed threat during the summer (Fig. 5), it is even more broadly distributed during the spring-immigration period (Fig. 7*a*), when it accounts for 61% of the threat compared with 39% of the threat during the autumn-emigration period (Table 1). During the spring period, the majority of the threat is located in the Northeast Channel where it extends to the Roseway Basin and Browns Bank region and through to the lower Bay of Fundy and Grand Manan Basin. Gear threat during the autumn period is located primarily in the Northeast Channel, along the northeast margin of Georges Bank and in the Roseway Basin region (Fig. 7*b*). From a gear-set perspective, there are 2.5-fold more 3′ grid cells containing sets during the immigration period than during the emigration period.

### *Hagfish traps*

The amount of hagfish-trap gear also poses the greatest threat (95%) during the spring period (Table 1; Supplemental Fig. S7*a*[1]) and the remaining 5% during the autumn period

**Fig. 6.** Bathymetric (100, 200, 500, and 1000 m isobaths) chart illustrating the Canadian Exclusive Economic Zone boundary and "grey zone" polygon (grey solid line), right whale Critical Habitat (white and black solid-line polygons), and the relative threat of entanglement in inshore lobster gear (based on trap hauls) over the July through October period. Note the lower resolution and irregular grid structure (black solid line) relative to all other fisheries.






(Supplemental Fig. S7*b*[1]). The majority of the threat in both periods is located within the Roseway Basin study area.

### *Crab traps*

For the migration periods, 79% of the threat associated with the amount of crab-trap gear in the Scotia–Fundy study area is present during the spring-immigration period (Table 1), although distributed well outside the smaller Fundy and Roseway study areas (Supplemental Fig. S8[1]). The threat is concentrated within and around Crowell Basin where it extends across possible whale-migration routes, as well as along the southwest margin of the Scotian Shelf and in spring along the southeast margin of Georges Bank.

### *Groundfish gillnets*

As with the amount of crab-trap gear, groundfish gillnet gear-threat is greatest during the spring-immigration period (88%) relative to the autumn period (12%; Table 1), and though the threat is again distributed well outside the Fundy and Roseway study areas, it extends across possible whale-migration routes (Supplemental Fig. S9[1]).

### *Offshore lobster traps*

Threat from the amount of offshore-lobster fishing gear during the spring-immigration (64%) and autumn-emigration periods (36%) is also located well outside of the Fundy and Roseway study areas (Table 1). The threat is most concentrated along the northeast margin of Georges Bank and the southwest margin of the Scotian Shelf in the spring and southeast of Crowell Basin in autumn where it extends across possible whale-migration routes (Supplemental Fig. S10[1]).

**Table 1.** Percent total relative threat to right whales of fishing-gear entanglement based on the amount of gear deployed in the Scotia–Fundy study region and partitioned within gear type among the spring-immigration (May through June), summer-resident (July through October), and autumn-emigration (November through December) periods (data in parentheses indicates partitioned between the spring and autumn periods only).

| Gear type | Spring immigration | Summer resident | Autumn emigration |
|---|---|---|---|
| Pelagic hook-and-line | 17 (96) | 82 | 0.72 (4.1) |
| Groundfish hook-and-line | 9.7 (61) | 84 | 6.2 (39) |
| Hagfish trap | 28 (95) | 70 | 1.4 (4.8) |
| Crab trap | 18 (79) | 77 | 4.8 (21) |
| Groundfish gillnet | 24 (88) | 73 | 3.1 (11) |
| Offshore lobster trap | 47 (64) | 26 | 27 (36) |
| Inshore lobster trap | 85 (89) | 3.6 | 11 (11) |

### *Inshore lobster traps*

Because of the seasonal timing of the inshore-lobster fishery, threat from inshore lobster fishing gear (trap hauls) during the spring-immigration period is much greater (88%) than

**Fig. 7.** Bathymetric (100, 200, 500, and 1000 m isobaths) charts illustrating the Scotia–Fundy study area, the Canadian Exclusive Economic Zone boundary and "grey zone" polygon (white solid line), the Bay of Fundy and Roseway Basin study areas (pink dashed-line rectangles), and the relative threat of entanglement in groundfish hook-and-line gear during periods of right whale (*a*) spring immigration (May through June) and (*b*) autumn emigration (November through December) to and from the study areas.

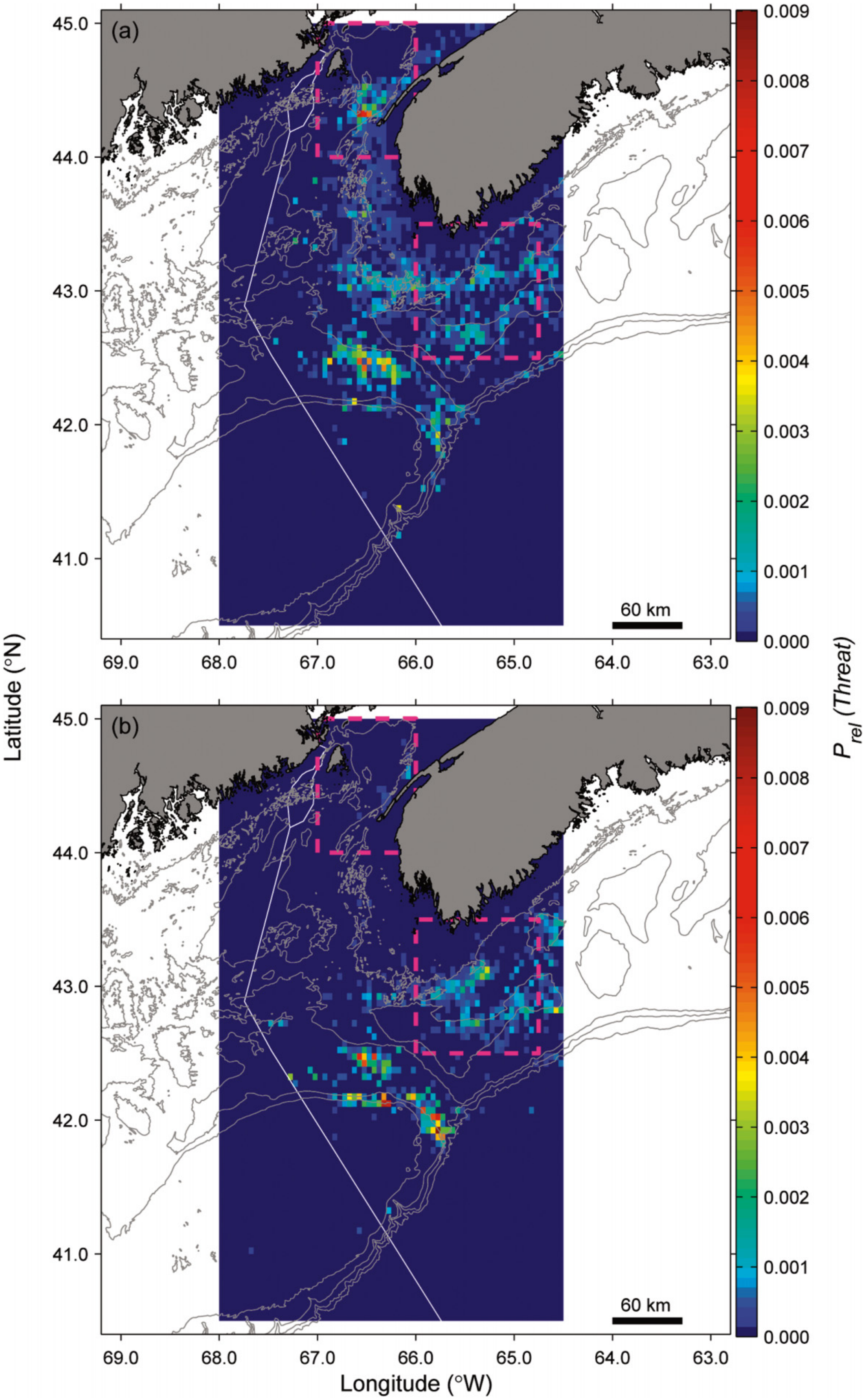
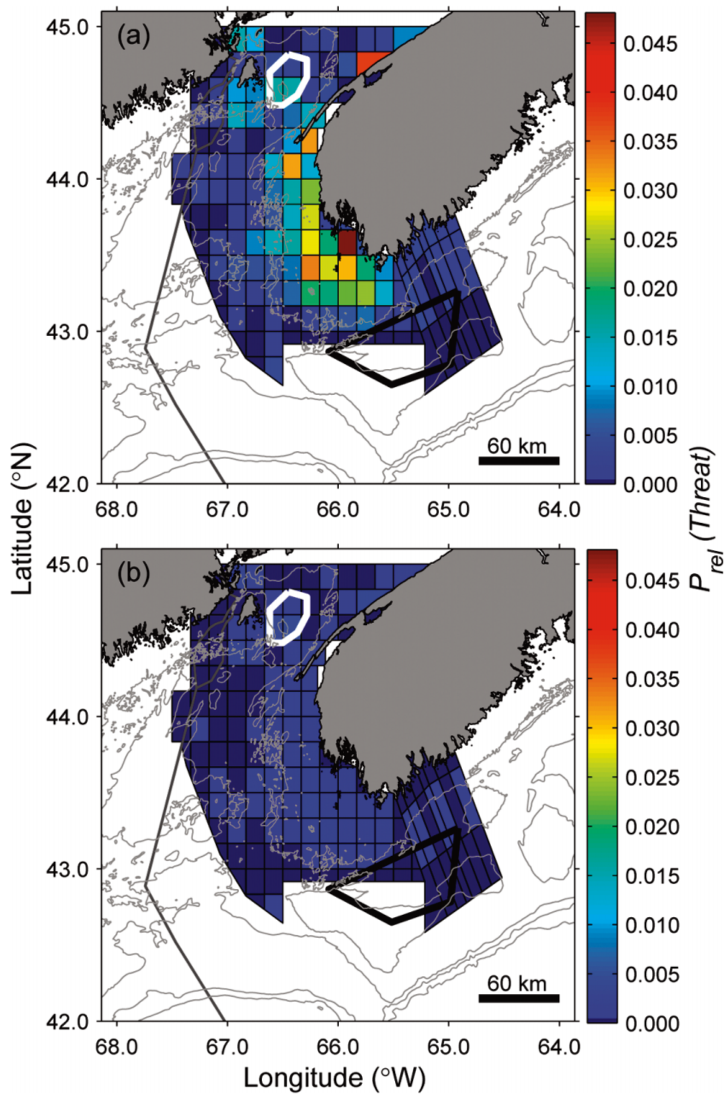


**Fig. 8.** Bathymetric (100, 200, 500, and 1000 m isobaths) charts illustrating the Canadian Exclusive Economic Zone boundary and "grey zone" polygon (grey solid line), right whale Critical Habitat (white and black solid-line polygons), and the relative threat of entanglement in inshore lobster gear (based on trap hauls) during periods of right whale (*a*) spring immigration (May through June) and (*b*) autumn emigration (November through December) to and from the critical habitats. Note the lower resolution and irregular grid structure (black solid line) relative to all other fisheries.






during the autumn period (12%; Table 1) and is broadly distributed in the lower Bay of Fundy and extends southward to the margins of the Roseway Basin Critical Habitat (Fig. 8). The threat extends across potential routes for whales immigrating to the Fundy and Roseway critical habitats as well as whales moving between the two habitats. Gear threat during the autumn-emigration period is also broadly distributed, though it is ~8-fold lower than during the spring period.

In summary, for the gear threat assessed among the seven fisheries, and based on the amount of gear deployed and partitioned between the spring and autumn migration periods, the spring-immigration period is associated with the greatest overall threat in all cases (Table 1). The threat averaged over all gear types in spring is 82% ± 13% (median = 88%) relative to 18% ± 14% during the autumn. These estimates reflect the fact that during the autumn period, 23% of the grid-cells in Canadian waters of the Scotia–Fundy study area are associated with fishing-gear sets (excluding inshore lobster; no set data, low resolution), while during the spring-immigration period 56% of all grid-cells are associated with gear sets. These estimates are lower than that for the summer-resident period when 84% of all grid-cells are associated with fishing-gear sets. When we partition the percent contributions to the total threat among gear types based on gear sets at 3′ resolution (excluding inshore lobster gear) for each of the seasonal migration periods, it is offshore lobster-gear sets that contribute the most: 38% of the threat during the immigration period and 70% of the threat during the emigration period (Table 2). Secondarily, the groundfish hook-and-line sets represent 21% and 16% of the threat in spring and autumn, respectively.

## Discussion

### Gear threat and risk during the summer-resident period

The above results demonstrate that among the gear types analysed it is the amount of groundfish hook-and-line gear

**Table 2.** Percent total relative threat to right whales of fishing-gear entanglement based on the number of sets deployed in the Scotia–Fundy study region and partitioned among gear type sets within each of the spring-immigration (May through June), summer-resident (July through October), and autumn-emigration (November through December) periods and the percent of the total threat across all gear-type sets partitioned into each of the Bay of Fundy and Roseway Basin study areas.

| Gear type | Spring immigration | Summer resident | Autumn emigration |
|---|---|---|---|
| Pelagic hook-and-line | 5.7 | 9.7 | 0.36 |
| Groundfish hook-and-line | 21 | 42 | 16 |
| Hagfish trap | 0.95 | 0.69 | 0.080 |
| Crab trap | 16 | 19 | 9.6 |
| Groundfish gillnet | 17 | 18 | 3.5 |
| Offshore lobster trap | 38 | 9.6 | 70 |
| Inshore lobster trap | — | — | — |
| Bay of Fundy | 5.5 | 11 | 1.0 |
| Roseway Basin | 5.7 | 9.1 | 5.1 |

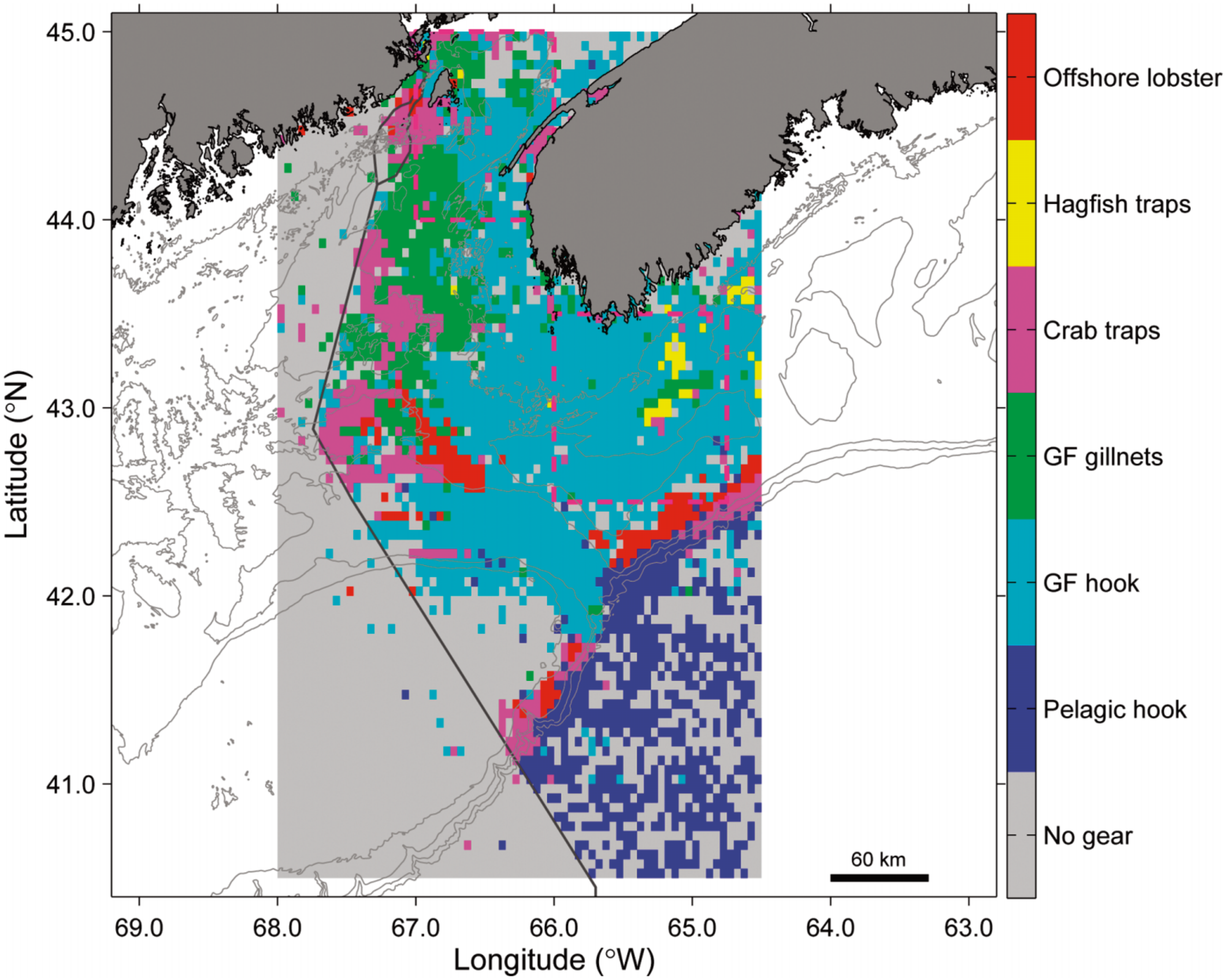
that poses the greatest overall relative threat (42%) to right whales during the July through October period in the Scotia–Fundy study area. This period is associated with the greatest probability of right whales being in the region. This fishery represents the majority of gear sets in the Scotia–Fundy study area, and the sets are widely distributed. This fishery has the second lowest SSW statistic that represents a high degree of temporal coincidence with right whales, consistent with the high and in-phase seasonal cross-correlation between right whales and gear deployment in the area. Compared with the other fisheries, the gear deployed for this fishery presents considerable and extensive risk of lethal entanglement in each of the Fundy and Roseway study areas where right whales are most aggregated during summer and autumn. The design and deployment of the gear provides the potential for entanglement, given the lengths of hook-laden line that typically measures $10^3$ m or more for one or more strings that are anchored near bottom and are associated with buoyed end-lines that remain unattended in the water column for 24 h or more (Johnston et al. 2007). In many respects, the deployment configuration of the gear is similar to that of a lobster-trap trawl; i.e., comprising buoyed end-lines and an off-bottom profile.

While a number of gear modifications might reduce risk of lethal entanglement within the Bay of Fundy and Roseway Basin critical habitats (e.g., weak links, sinking groundlines), the simplest, most direct, and practical means of reducing groundfish hook-and-line risk to the whales may be to curtail sets within Critical Habitat over the July through October period (i.e., area-specific seasonal closure). The effects of such a closure are explored below as an illustration of the potential mitigation strategy. Area-specific closures, if implemented in the Roseway Basin and Bay of Fundy critical habitats, would result in the average annual displacement of 5.6% ± 1.0% and 0.30% ± 0.18%, respectively, of all sets deployed throughout the Scotia–Fundy study area. If the entire Bay of Fundy study area was considered for seasonal closure, it would remove virtually all risk of lethal entanglement in the gear during the summer-resident period. Such a closure would result in an average annual loss of 8.5% ± 3.5% of the total sets in Scotia–Fundy study area and for the most prevalent fish species a loss of 1.4% ± 1.1% of cod (*Gadus morhua*), 0.33% ± 0.18% of haddock (*Melanogrammus aeglefinus*), and 0.27% ± 0.44% of cusk (*Brosme brosme*) landings. If the above seasonal closure was implemented, catches for this fishery in the closed areas would represent small proportions of the Scotia–Fundy landings, and thus the economic impact may be marginal. The displacement of the small proportions of sets out of high-risk Critical Habitat would be to regions of considerably lower risk; i.e., the risk reduction in Critical Habitat would likely be far greater than the risk increase elsewhere.

Based on the number of sets, the crab-trap fishery represents 21% of the total number of sets and 19% of the relative threat in the Scotia–Fundy study area (Fig. 9). This fishery has been declining in the Scotia–Fundy study area, with the number of sets per year declining by an average of 60% over the 2005 through 2007 period. However, with the overall decline in the fishery, crab-trap deployments have increased in the Bay of Fundy, but not in the Critical Habitat. If a seasonal closure of an area slightly larger than the Critical Habitat (e.g., increase the boundaries of the Critical Habitat by 3′ to the south, west, and north) was considered for implementation, the majority of the risk would be removed. There have been seven crab-trap sets within the Fundy Critical Habitat over the 9-year study period, and relative to the 9825 sets in the Scotia–Fundy study area, a seasonal closure of this nature would have a minimal affect (0.07% of total sets) with an associated maximum affect on risk reduction. A similar seasonal closure of the Roseway Basin Critical Habitat would virtually eliminate the risk of crab-trap gear entanglement and would have a measurable but small impact on 0.17% of the total sets in the Scotia–Fundy study area during the summer-resident period. The impact on individual fishing licenses would likely have to be considered. As with groundfish hook-and-line gear, the risk reduction in Critical Habitat through displacement would be far greater than the risk increase elsewhere.

The groundfish-gillnet fishery appears to pose considerable gear-related threat (18% of total threat; Table 2) to right whales, as the majority of gear deployments in the Scotia–Fundy study area occur during the months of July though October, and sets are widely distributed throughout the study area, including the Bay of Fundy and Roseway Basin study areas (Fig. 9). To reduce the risk of lethal entanglement, a seasonal closure of the Fundy Critical Habitat could be considered because, on average, 0.35% ± 0.40% of annual Scotia–Fundy sets occur in the Habitat during the summer-resident period. Such a closure would reduce the risk that is, on average, 12.5-fold greater inside the Habitat than outside, with a presumedly small consequence to the fishery. A seasonal closure of the Roseway Critical Habitat would also reduce the risk of entanglement to near zero and would represent a loss of 3.9% of the total number of sets in the Scotia–Fundy study area during the July through October period. Such a closure would also represent an annual average loss of 1.9% ± 0.94% of pollock (*Pollachius virens*), 6.9% ± 4.8% of cod, and 1.2% ± 0.65% of white hake (*Urophycis tenuis*) landings in the Scotia–Fundy study area. Such a closure would likely have a marked effect on the groundfish gill-

**Fig. 9.** Bathymetric (100, 200, 500, and 1000 m isobaths) chart illustrating the Scotia–Fundy study area, the Canadian Exclusive Economic Zone boundary and "grey zone" polygon (grey solid line), the Bay of Fundy and Roseway Basin study areas (pink dashed-line polygons), and the type of fishery with the greatest number of set deployments within each of the 3′ grid cells over the period July through October when pelagic (Pelagic hook) and groundfish (GF hook) hook-and-line, groundfish gillnet (GF gillnets), crab (Crab traps) and hagfish (Hagfish traps) traps, and offshore lobster (Offshore lobster) gear is set.




net fishery, though it would decrease the risk of lethal entanglement to near zero.

The pelagic hook-and-line fishery represents 9.7% of the total gear-threat in the Scotia–Fundy study area during the summer-resident period, and the majority of the gear is deployed along and beyond the Continental Shelf margin (Fig. 9). Less than 0.11% of sets (i.e., four sets over 9 years) for this fishery were deployed in the Bay of Fundy study area. Similarly, in the Roseway Basin study area 11 sets were deployed over the 9-year period. The three most prevalent species landed by the fishery were swordfish (*Xiphias gladius*) and bigeye (*Thunnus obesus*) and yellowfin (*Thunnus albacares*) tuna, and they are typically fished along and off the shelf break. A permanent closure of the pelagic hook-and-line fishery in each Critical Habitat would reduce risk to near zero with what appears to be negligible impact on the fishery.

The hagfish-trap fishery represents 0.1% of the total number of sets deployed in the Scotia–Fundy study area over the 9-year period (Fig. 9). The gear may represent one of the least threatening gear types, as there is only one trap and one buoy line for each set, and there were only 116 sets deployed over the study period. However, 63% of the threat from this fishery occurs within the Roseway study area, and the majority of the gear sets (61%) are deployed when the whales are aggregated in the area. A closure in the Critical Habitat would remove the risk of lethal entanglement but may have serious ramifications for the hagfish-trap fishery, as most of the effort is concentrated there. Relative to the other fisheries, seemingly few licenses would be affected, and displacement elsewhere would have near zero impact.

The offshore lobster fishery, during the summer-resident period, represents 9.6% of the total gear threat based on sets in the Scotian–Fundy study area. The majority of threat is distributed well outside the two critical habitats, as they are not enveloped by the offshore lobster management areas. Nevertheless, four sets in the Fundy and one set in the Roseway Critical Habitat areas were reported over the 9-year period. We assume that these sets are erroneously reported. On this assumption, the offshore lobster fishery represents no threat to right whales inside Critical Habitat during the summer-resident period.

Based on the admittedly limiting nature of the inshore lobster logbook reporting data, our analyses show that there is not a measureable threat to right whales during the summer period in any part of the Scotia–Fundy study area, including Critical Habitat except within seven of the 10′ reporting-grids located east of 66°W in the Bay of Fundy. Over a 30-year period (1978 through 2008), and based on all right whale sighting data (survey and opportunistic; North Atlantic Right Whale Consortium 2008), there have been two right whales sighted east of 66°W in the Bay of Fundy. Barring unknown distributions of right whales in the Bay of Fundy, it is reasonable to conclude that the inshore lobster fishery constitutes no measureable threat to right whales during the summer period.

## Gear threat during the spring- and autumn-migration periods

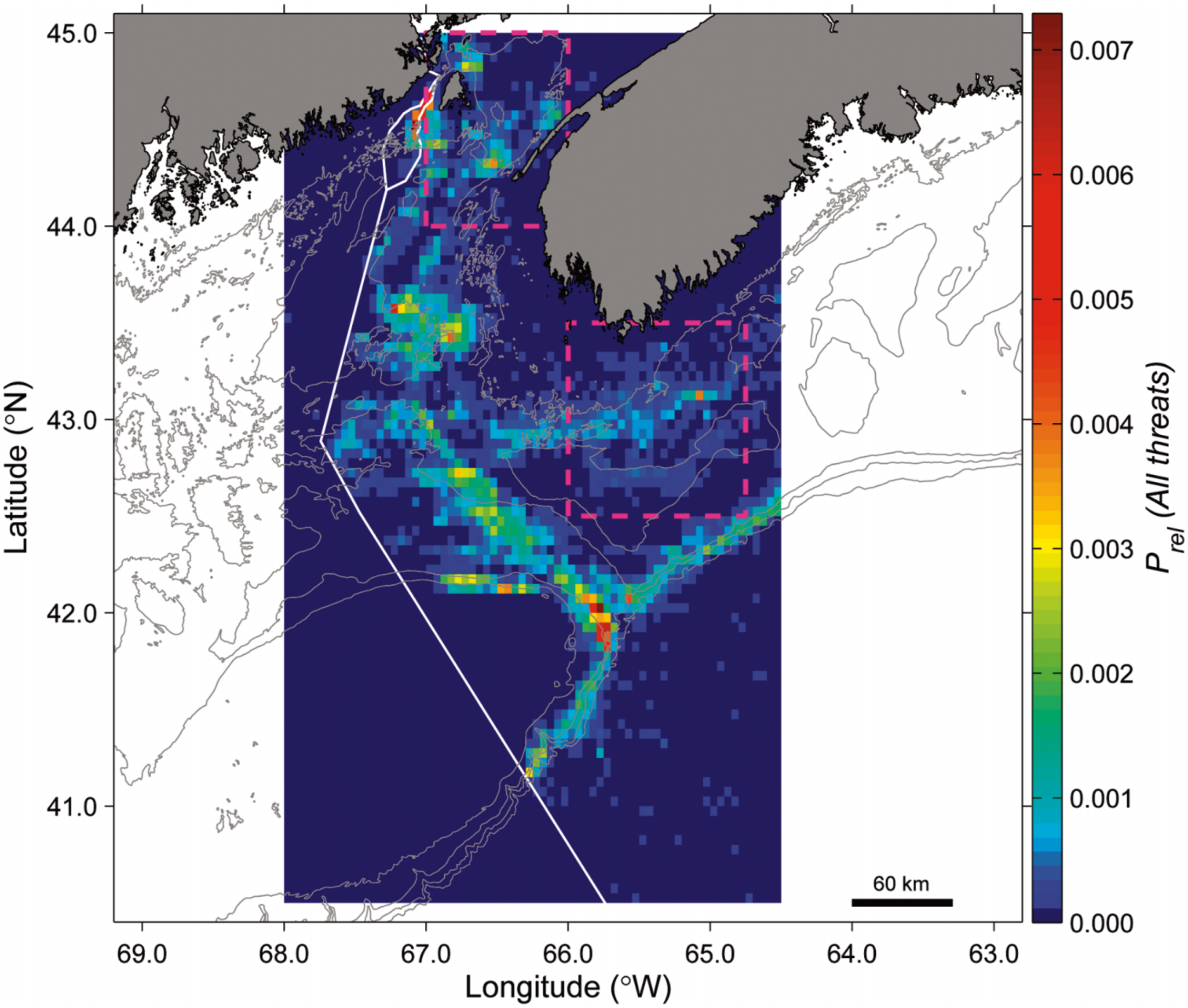
From a temporal perspective, and in light of the spatially related interpretations above that focus on the summer-resident period, it is clear that of the seven fisheries considered, all but the two lobster fisheries are strongly and positively cross-correlated and mostly in phase with the presence of right whales in the Scotia–Fundy study area. This led to suggestions that gear-specific seasonal or permanent closures for the other five fisheries in Critical Habitat could be considered to minimize measureable risk to the whales and with measurable consequences to each fishery. It is equally clear that the two lobster fisheries are strongly and negatively cross-correlated and out of phase with the presence of right whales during the summer-resident period when these two fisheries present negligible risk.

A comprehensive comparison of Figs. 2, 3, 7, 8 and Supplemental Figs. S6 through S10[1], along with Tables 1 and 2, leads to the conclusion that some of the most threatening gear to whales when migrating toward and away from the Fundy and Roseway regions, but not in Critical Habitat when whales are present, is that associated with inshore and offshore lobster traps. The threat is most prevalent during the spring-immigration period for each lobster fishery and less so but substantial during autumn emigration for the offshore fishery. In terms of total fishing-gear threat, the offshore lobster-trap fishery represents the greatest threat (70%) in the autumn period, when it is nearly double that relative to all gear types (except inshore lobster that is not quantifiable) in the spring. Further, four gear types (where measureable) are responsible for 92% of the threat during spring (38% offshore lobster, 21% groundfish hook-and-line, 17% groundfish gillnet, and 16% crab trap), but only two are responsible for 86% during the autumn period (70% offshore lobster and 16% groundfish hook-and-line). Outside the Fundy and Roseway study areas, we cannot estimate risk of lethal entanglement for any gear type, particularly during the immigration and emigration periods, as the right whale SPUE data are much too sparse in the Scotia–Fundy study area during these periods.

The above analyses indicate lobster gear poses a considerable threat to migrating right whales during the immigration and emigration periods, but less so for the summer-resident period. Therefore, a potential exists for substantial change in risk in the future if ongoing climate change induces spatial or temporal changes in right whale food production in and around Critical Habitat and (or) changes in the timing of immigration, emigration, and the length of the summer-residency period of right whales in Canadian waters. For example, a delay of just a few weeks in autumn emigration would likely result in a much larger coincidence between the whales and lobster gear associated with the autumn inshore lobster fishery that opens in early November and thus a greatly increased risk of lethal entanglement. Observations on the timing of migration for the eastern Pacific grey whale (*Eschrichtius robustus*) indicate such changes can occur. Rugh et al. (2001) used a data series over the period 1967 through 1999 to estimate a 1-week delay (6.8 ± 2.0 days, mean ± confidence interval) in the southbound migration of the whales subsequent to 1980. The change in timing was concurrent with the North Pacific “regime shift” of the late 1970s that is related to the influence of the Pacific Decadal Oscillation (Francis et al. 1998).

Although risk cannot be quantified when right whales are outside the Bay of Fundy or Roseway Basin study areas, or when migrating to, from, and among these and other regions, we can provide some insights into the spatial–temporal distribution of fishing-gear threat that the whales must navigate. When the whales are moving among the two feeding habitats and other regions during summer, and there is evidence of this from tagging data (Mate et al. 1997) and transition-matrix studies based on individually identified whales (Vanderlaan 2010), they are likely navigating and encountering widely distributed “fences” of fishing gear associated primarily with the groundfish hook-and-line and gillnet fisheries as well as the crab and offshore lobster fisheries (Fig. 9). When relative threat, based only on the number of sets, imposed by all fishing gear above (except inshore lobster) during summer is examined, the threat is extensive and generally parallels the isobaths (Fig. 10). Threat is greatest throughout the Northeast Channel and along the margins of the continental shelf, east of Jordan Basin, in Crowell Basin, and extending into the Bay of Fundy and Roseway Basin regions, each representing areas that right whales very likely transit when moving among summer-feeding habitats and other locations. During the summer-feeding period, the average annual number of sets in the Scotia–Fundy study area for all six fisheries is 5270 ± 480. Each set has at least one or two buoy lines, tens to hundreds of metres of float and (or) groundlines connecting tens to hundreds of traps and multiple net-panels, and hundreds to thousands of metres of hook-laden line. These gear deployments correspond to a daily average number of sets in July, August, September, and October of 52, 53, 40, and 26, respectively, in the Scotia–Fundy study area. On average, on any given day in August, a right whale swimming in the Scotia–Fundy study area could encounter 53 fishing-gear sets, each associated with multiple lines, and nets or traps. Approximately 84% of all grid-cells in Canadian waters in the Scotia–Fundy study area are associated with some type of gear over the 9-year study period (Fig. 9). There is a 3.7-fold increase in the number of grid-cells associated with fishing gear during the summer-feeding period (July through October) over that of the autumn-emigration

**Fig. 10.** Bathymetric (100, 200, 500, and 1000 m isobaths) chart illustrating the Scotia–Fundy study area, the Canadian Exclusive Economic Zone boundary and "grey zone" polygon (white line), the Bay of Fundy and Roseway Basin study areas (pink dashed-line polygons), and the relative threat of entanglement in any fishing gear, except inshore lobster, based on the number of sets deployed over the July through October period.






period (November, December) and a 1.5-fold increase over that of the spring-immigration period (May, June).

In comparing the migration periods of the right whale, there is almost a 2.5-fold increase in the number of grid-cells that are fished in the spring-immigration period relative to the autumn-emigration period, and this excludes the thousands of inshore lobster trap deployments. Accordingly, as the whales migrate from Cape Cod Bay and the Great South Channel (Winn et al. 1986) and move through the Scotia–Fundy study area during the spring-immigration period, they are about three times more likely to encounter fishing gear than in the autumn when they emigrate. Until better information is available on the probabilistic movements of the animals when they migrate through the Scotia–Fundy region, it is not possible to ascertain the nature of protective measures that would be most effective in reducing the risk of a fishing-gear entanglement outside the critical habitats during the migration periods. Efforts are underway to determine the time and space probabilistic distributions of right whales throughout the Gulf of Maine and Scotia–Fundy region over the entire year (S. Brillant, Canadian Wildlife Federation, 350 Michael Cowpland Drive, Kanata, ON K2M 2W1, Canada, unpublished data), and when completed, fishing gear risk analyses in Canadian waters in regions external to critical habitat will be afforded. Until completed, gear threat offers the only quantitative measure of potential risk.

## Estimating the lethality of an entanglement

We estimated that a right whale has ~1% chance of a lethal injury resulting from a fishing-gear entanglement and that 97 $\pm$ 39 entanglements may occur annually (eq. 9 above). This estimate is consistent with Moore et al. (2006), who estimate that between 49 and 136 right whales are entangled annually based on 1986–2005 reports. The estimate can be calculated differently following Knowlton et al. (2008) by considering only the most recent period of 1993 through 2004, when ≥50 right whales were "adequately photographed" each year. Using this shorter time series, we estimated an average annual entanglement rate of 0.25 ± 0.081 (again based on a population of 350 individuals) corresponding to annual estimate of 87 ± 29 entanglements sufficient to cause scarring, as opposed to 0.28 ± 0.11 and 97 ± 39, respectively. Therefore, a second estimate of the probability of a lethal entanglement (death occurred, was presumed, or was expected) using eq. 9 can be estimated as 23/1720 = 0.013 ± 0.0044: again, approximately a 1% chance of a lethal entanglement, consistent with our first estimate of lethality. Though these two estimates are marginally different for lethality in our risk estimations, we used 0.012 for three reasons. First, it is based on the longer data series (greater *N* and the resultant advantages offered by central tendency) that covers a greater period of variation in gear type, gear amount, and distribution pattern, as well as whale abundance and distribution pattern. Second, our analyses showed that the coefficient of variation, based on the annually incrementing mean and variance, stabilized at 0.4 in 1995 and remained virtually constant (stationary) thereafter; i.e., entanglement probability based on scarring reports has remained near constant at 0.28 over the data period. The third reason is that if we base the estimate on the more recent period (shorter series as in Knowlton et al. 2008) and incorporate an increase in whale population abundance to at least 400 (Pettis 2009), the estimate remains at 0.012.

Our *P*(Lethal | Encounter) estimate is lower than that estimated by Kraus (1990) at 4.3% annually, and it is assumed that such estimates are underestimates (Knowlton and Kraus 2001; Moore et al. 2004, 2006) given that for the entire species it is estimated that only 17% of all mortalities are known (Kraus et al. 2005). We can adjust the number of whales that have died due to entanglements by using a method similar to that of Vanderlaan et al. (2009) to account for the 17% mortality detection. If we remove the $\psi$ term from eq. 4 in the above-cited paper (i.e., no dead whales where death may be attributed to entanglement; Moore et al. 2004), then we estimate the total number of lethal entanglements to be 66 over a 32-year period. This corresponds to *P*(Lethal | Encounter) = 0.021 using the above number of annual entanglements or 0.022 using the median number of annual entanglements from Moore et al. (2006). One other estimate is possible by using the qualitative statistic from Johnson et al. (2007), who state that nearly every year a right whale either dies from a fishing-gear entanglement or disappears when still entangled. This "statistic" and the median value of the estimated number of entanglements (Moore et al. 2006) approximate a *P*(Lethal | Encounter), assuming a "disappeared" whale is dead, of 0.011, equivalent to our initial estimate above. The latter estimate decreases slightly to 0.010 if we use the estimated number of entanglements (97 ± 39), though it remains within the limits of uncertainty. Finally, if we adjust, varyingly, for unknown, undetected, presumed, and expected deaths, we estimate there is a 1%–2% chance of an entangled right whale dying. Given all of the above, we can reasonably conclude that the probability that an entanglement proves lethal is between 1% and 2% and perhaps as high as 4% (Kraus 1990), and note from our analyses of the scarring reports above that it has remained relatively constant over at least a decade.

We have taken a precautionary approach to estimating risk of a lethal fishing-gear entanglement by assuming lethality is constant across all gear types, primarily because the data available among gear types is far too sparse to validate the assumption in a statistically robust manner. We argue that the assumption is reasonable, until statistically shown otherwise, for seven reasons. (1) All parts of fixed fishing-gear types have been recovered from right whales and humpback whales (Johnson et al. 2007). (2) Of the gear types we examined here, each has been associated with a known large-whale fishing-gear entanglement (Baird et al. 2002; Johnson et al. 2005; Neilson et al. 2009). (3) There is a statistically small number of right whale entanglements reported in the literature where gear type is identified (14/31 = 45%; Johnson et al. 2005). (4) There is a very large number of right whales that exhibit scarring events consistent with fishing-gear entanglements, and each results from one or more unknown gear type (Knowlton et al. 2008). (5) Of 30 necropsied right whales, death was attributed to entanglement in four cases, of which two were associated with a particular gear type (Moore et al. 2004). (6) There is a suite of problems associated with identifying fishing gear involved in a given entanglement, and there is no known means by which to standardize entanglement rate across fishing-gear effort (Johnson et al. 2005, 2007). (7) Although Johnson et al. (2005) provide an analysis of the gear associated with entangled right and humpback whales that could provide insights into risk across gear types, we concur with their conclusion that the threat posed by a specific gear type cannot be estimated without adjusting reported entanglements by fishing effort that is currently not available over the entire range of right whales.

## Relative risk estimates

We emphasise that the relative risk estimates we provide, based on constant lethality across gear type (eq. 8), can be easily converted to a gear-specific lethality when such estimates are resolved. Accordingly, all spatial representations of relative risk can be reinterpreted simply by modifying the estimates within gear type by using the "new" gear-specific lethality. The encounter probabilities we provide and use to estimate risk need not be re-estimated. Until there is more information on the mechanics of a fishing-gear entanglement, the likelihood of each gear type entangling a right whale, the likelihood of self-disentanglement by gear type, and the standardization of entanglement rates by fishing effort across the right whale range, it is not possible to estimate in any robust manner the lethality of an entanglement among the various gear types. New research is underway using advanced modeling techniques to determine the mechanics of right whale entanglements among gear types (L.E. Howle, Belle-Quant Engineering, PLLC, 7813 Dairy Ridge Road, Mebane, NC 27302, USA, personal communication, 2010) that may offer insights regarding gear-specific lethality.

We have estimated the risk of lethal fishing-gear entanglements in defined right whale aggregation areas and the seasonal threat of fishing gear throughout the Scotia–Fundy study area. In each case, the threat estimates are underestimates for right whales throughout their known range, as we have examined only Canadian fishing-gear threat and risk in the Scotia–Fundy study area, and we have not included fishing gear deployed in USA waters and elsewhere in Canadian waters. West of the Exclusive Economic Zone boundary

(Hague Line), there is an unknown amount of threat and risk from USA fisheries that may be larger than we estimate from Canadian fisheries in the Scotia–Fundy study area. For example, the lobster fishery in Maine is active year-round and uses 8- to 9-fold more traps at any given time than those used in Lobster Fishing Area 34 (south and west of Nova Scotia and western Bay of Fundy; inshore lobster) in Canadian waters (Myers et al. 2007). Entanglement mitigation through gear modifications for the lobster fishery in the USA have been adopted (National Oceanic and Atmospheric Administration 2007*b*; Maine Department of Marine Resources 2008).

We suggested that fishery closures offer a simple and direct method of reducing the risk of gear entanglements in right whale summer-feeding habitats in Canadian waters. Various regulatory modifications to fishery operations (e.g., seasons and boundaries) and their associated gear (e.g., number of buoys, sinking and neutrally buoyant lines, and weak links) have been adopted in a number of fisheries in the USA, including gillnet and trap or pot fisheries, to protect whales in general and right whales in particular (National Oceanic and Atmospheric Administration 2007*a*, 2007*b*; Knowlton et al. 2008). Such regulations are considered in some cases to be operationally ineffective and inadequate for reducing risk to right whales (Levesque 2009*a*) and in other cases provide various conservation benefits (Levesque 2009*b*). Most gear modifications are based on the assumption that they will reduce the entangling nature of gear. As we know little of the mechanics of a fishing-gear entanglement — how it occurs or how a whale frees itself once entangled — it is difficult to predict how and which gear modifications are most likely to measurably reduce the risk of a lethal entanglement. The process of developing gear modifications is generally slow, is rarely scientifically tested for effectiveness (but see Brillant and Trippel 2010), is often frequented by failure (Johnson et al. 2007), and can take years to implement (Kraus et al. 2005; Levesque 2009*a*). Given the many unknowns concerning the effectiveness of gear modifications, area-specific seasonal closures may be the most effective means for reducing the risk of entanglements to right whales, at least in the short term.

Canada has yet to mandate any changes among the Scotia–Fundy fisheries to reduce the risk of entanglements to right whales. Gear modifications may reduce some portions of the gear in the water column and (or) make it easier for an entangled whale to shed the gear, though the effectiveness of gear modifications has yet to be demonstrated (but see Brillant and Trippel 2010). As a result, we have no information on the functional form of lethality in relation to gear modification within or among gear types. Unless gear lethality can be reduced to near zero, fishery closures may represent the most effective means of reducing the risk, as they remove the entirety of the risk in the closed area. We have suggested where fishery- and area-specific seasonal closure might prove most effective and suggest that in many cases they may have limited effect on the fishery in terms of the most prevalent landings. Seasonal closures may also prove beneficial by providing an opportunity for the biomass of the targeted standing stock to build (e.g., lobsters; Myers et al. 2007).

In many respects, when it comes to options for reducing human-induced right whale mortality, gear modifications vs. fishery closures are analogous to vessel-speed limits vs. vessel rerouting. In each case, the first option is designed to minimize the lethality of the event (entanglement or vessel strike), though it can still occur, whereas the second option is designed to minimize the probability of the event occurring, in which case lethality becomes secondary. Given that vessel rerouting has proven to be highly successful in being adopted by the shipping industry (Vanderlaan et al. 2008; Vanderlaan and Taggart 2009), it is possible that fishery closures, as opposed to gear modifications, will be adopted by the fishing industry, though we have no evidence. Canada should not delay in implementing changes to current fishing practices if reducing the risk of right whale entanglement is considered a desirable goal. Doing so may also help avoid the same predicament facing Mexico, where fishing "buy-outs" are being used (Morell 2008) in an attempt to reduced the gillnet fishery and preserve the critically endangered vaquita (*Phocoena sinus*).

## Acknowledgements

We thank J. McMillan, T. Johnston, L. Harris, N. Helcl, A. Serdynska, R. Kenney, and C. Denton for near endless help with data extraction, manipulation, and analyses. We thank S. Brillant, T. Wimmer, and M. Brown for discussion and insights regarding the vagaries of right whale entanglements and A. Johnson and an anonymous referee for providing critiques and insights contributing to considerable improvement in the scope of the manuscript. The research was supported by the Environment Canada Habitat Stewardship Programme, Fisheries and Oceans Canada, World Wildlife Fund Canada, and generous support from S. Haney and the Canadian Whale Institute.

## References

Baird, R.W., Stacey, P.J., Duffus, D.A., and Langelier, K.M. 2002. An evaluation of gray whale (*Eschrishtius robustus*) mortality incidental to fishing operations in British Columbia, Canada. J. Cetacean Res. Manage. **4**(3): 289–296.

Brillant, S.W., and Trippel, E.A. 2010. Elevations of lobster fishery groundlines in relation to their potential to entangle endangered North Atlantic right whales in the Bay of Fundy, Canada. ICES J. Mar. Sci. **67**(2): 355–364. doi:10.1093/icesjms/fsp231.

Brown, M.W., Allen, J.M., and Kraus, S.D. 1995. The designation of seasonal right whale conservation areas in the waters of Atlantic Canada. *In* Marine protected areas and sustainable fisheries. *Edited by* N.L. Shackell and J.H.M. Willison. Science and Management of Marine Protected Areas Association, Wolfville, N.S. pp. 90–98.

Brown, M.W., Kraus, S.D., Slay, C.K., and Garrison, L.P. 2007. Survey for discovery, science, and management. *In* The urban whale: North Atlantic right whales at the crossroads. *Edited by* S.D. Kraus and R. Rolland. Harvard University Press, Cambridge, Mass. pp. 105–137.

Brown, M.W., Fenton, D., Smedbol, R.K., and Merriman, C. Robichaud-Leblanc, K., and Conway, J.D. 2009. Recovery strategy for the North Atlantic right whale (*Eubalaena glacialis*) in Atlantic Canadian waters [online]. Species at Risk Act Recovery Series. Fisheries and Oceans Canada, Ottawa, Ont. Available from http://www.sararegistry.gc.ca/virtual_sara/files/plans/rs_north_atl_right_whale_0609_e.pdf.

Clapham, P.J., Young, S.B., and Brownell, R.L. 1999. Baleen whales: conservation issues and the status of the most endangered populations. Mammal Rev. **29**(1): 37–62. doi:10.1046/j.1365-2907.1999.00035.x.

Cook, B. 2005. Lobster boat diplomacy: The Canada–US grey zone. Mar. Policy, **29**(5): 385–390. doi:10.1016/j.marpol.2004.05.010.

Francis, R.C., Hare, S.R., Hollowed, A.B., and Wooster, W.S. 1998. Effects of interdecadal climate variability on the oceanic ecosystems of the NE Pacific. Fish. Oceanogr. **7**(1): 1–21. doi:10.1046/j.1365-2419.1998.00052.x.

Fujiwara, M., and Caswell, H. 2001. Demography of the endangered North Atlantic right whale. Nature, **414**(6863): 537–541. doi:10.1038/35107054. PMID:11734852.

Gaskin, D.E. 1991. An update on the status of the right whale, *Eubalaena glacialis*. Can. Field Nat. **105**: 198–205.

Johnson, A., Salvador, G., Kenney, J., Robbins, J., Kraus, S., Landry, S., and Clapham, P. 2005. Fishing gear involved in entanglements of right and humpback whales. Mar. Mamm. Sci. **21**(4): 635–645. doi:10.1111/j.1748-7692.2005.tb01256.x.

Johnson, A.J., Kraus, S.D., Kenney, J.F., and Mayo, C.A. 2007. The entangled lives of right whales and fisherman: Can they coexist? *In* The urban whale: North Atlantic right whales at the crossroads. *Edited by* S.D. Kraus and R. Rolland. Harvard University Press, Cambridge, Mass. pp. 380–408.

Johnston, T.L., Smedbol, R.K., Serdynska, A., Vanderlaan, A., Helcl, N., Harris, L., and Taggart, C.T. 2007. Patterns of fishing gear in areas of the Bay of Fundy and southwest Scotian Shelf frequented by North Atlantic right whales. Can. Tech. Rep. Fish. Aquat. Sci. 2745.

Jönsson, P., and Wohlin, C. 2004. An evaluation of *k*-nearest neighbour imputation using likert data. Proceedings of the 10th IEEE International Software Metrics Symposium, IEEE Computer Society, Los Alamitos, Calif., USA. pp. 108–118.

Kaplan, S., and Garrick, B.J. 1981. On the quantitative definition of risk. Risk Anal. **1**(1): 11–27. doi:10.1111/j.1539-6924.1981.tb01350.x. PMID:11798118.

Knowlton, A.R., and Kraus, S.D. 2001. Mortality and serious injury of northern right whales (*Eubalaena glacialis*) in the western North Atlantic Ocean. J. Cetacean Res. Manag. **2**: 193–208. [Special Issue.]

Knowlton, A.R., Cooper, H.A., Hamilton, P.K., Marx, M.K., Pettis, M., and Kraus, S.D. 2008. Analysis of scarring on North Atlantic right whales (*Eubalaena glacialis*): monitoring rates of entanglement interaction: 1980–2004. Final report to the Northeast Fisheries Science Center, NMFS, Contract No. EA133F-03-SE-0323. New England Aquarium, Boston, Mass.

Kraus, S.D. 1990. Rates and potential causes of mortality in North Atlantic right whales (*Eubalaena glacialis*). Mar. Mamm. Sci. **6**(4): 278–291. doi:10.1111/j.1748-7692.1990.tb00358.x.

Kraus, S.D., and Rolland, R.M. (*Editors*). 2007. Right whales in the urban ocean. *In* The urban whale: North Atlantic right whales at the crossroads. Harvard University Press, Cambridge, Mass. pp. 1–38.

Kraus, S.D., Brown, M.W., Caswell, H., Clark, C.W., Fujiwara, M., Hamilton, P.K., Kenney, R.D., Knowlton, A.R., Landry, S., Mayo, C.A., McLellan, W.A., Moore, M.J., Nowacek, D.P., Pabst, D.A., Read, A.J., and Rolland, R.M. 2005. North Atlantic right whales in crisis. Science, **309**(5734): 561–562. doi:10.1126/science.1111200. PMID:16040692.

Levesque, J.C. 2009*a*. Establishment and closure of the directed Florida whiting (M*enticirrhus americanus*) fishery and implications for North Atlantic right whale (*Eubalaena glacialis*) conservation and management. Mar. Policy, **33**(2): 233–247. doi:10.1016/j.marpol.2008.07.003.

Levesque, J.C. 2009*b*. Characterization of the southeastern US black seabass (*Centropristis striata*) pot commercial fishery and implications for western North Atlantic right whale (*Eubalaena glacialis*) management and policy. Mar. Policy, **33**(1): 40–48. doi:10.1016/j.marpol.2008.04.007.

Lien, J. 1994. Entrapments of large cetaceans in passive inshore fishing gear in Newfoundland and Labrador (1979–1990). Rep. Int. Whaling Comm. **15**(Special issue): 149–157.

Mate, B.R., Nieukirk, S.L., and Kraus, S.D. 1997. Satellite-monitored movements of the northern right whale. J. Wildl. Manage. **61**(4): 1393–1405. doi:10.2307/3802143.

Maine Department of Marine Resources. 2008. Chapter 75 — Protected Resources, 22 July 2008, amended: 16 February 2009 – Section 02(A), October 26, 2010 – Section 03(A)(1)(*d*). Department of Marine Resources, Augusta, Maine, USA.

Moore, M.J., Knowlton, A.R., Kraus, S.D., McLellan, W.A., and Bonde, R.K. 2004. Morphometry, gross morphology and available histopathology in North Atlantic right whale (*Eubalaena glacialis*) mortalities (1970–2002). J. Cetacean Res. Manage. **6**(3): 199–214.

Moore, M.J., Bogomolni, A., Bowman, R., Hamilton, P.K., Harry, C.T., Knowlton, A.R., Landry, S., Rotstein, D.S., and Touhey, K. 2006. Fatally entangled right whales can die extremely slowly. Oceans'06 MTS/IEEE, Boston, Mass., 18–21 September 2006. ISBN: 1-4244-0115-1. IEEE, Piscataway, N.J., USA.

Morell, V. 2008. Conservation biology: Can the vaquita be saved? Science, **321**(5890): 767. doi:10.1126/science.321.5890.767. PMID:18687936.

Murison, L.D., and Gaskin, D.E. 1989. The distribution of right whales and zooplankton in the Bay of Fundy, Canada. Can. J. Zool. **67**(6): 1411–1420. doi:10.1139/z89-200.

Myers, R.A., Boudreau, S.A., Kenney, R.D., Moore, M.J., Rosenberg, A.A., Sherrill-Mix, S.A., and Worm, B. 2007. Saving endangered whales at no cost. Curr. Biol. **17**(1): R10–R11. doi:10.1016/j.cub.2006.11.045. PMID:17208167.

North Atlantic Right Whale Consortium. 2008. North Atlantic Right Whale Consortium sightings database, 22 July 2008. New England Aquarium, Boston, Mass.

Neilson, J.L., Straley, J.M., Gabriele, C.M., and Hills, S. 2009. Non-lethal entanglement of humpback whales (*Megaptera novaeangliae*) in fishing gear in northern Southeast Alaska. J. Biogeogr. **36**(3): 452–464. doi:10.1111/j.1365-2699.2007.01820.x.

National Oceanic and Atmospheric Administration. 2007*a*. Taking of marine mammals incidental to commercial fishing operations; Atlantic Large Whale Take Reduction Plan. 25 June 2007. Federal Register (USA), **72**(121): 34632–34642.

National Oceanic and Atmospheric Administration. 2007*b*. Taking of marine mammals incidental to commercial fishing operations; Atlantic Large Whale Take Reduction Plan Regulations; Final Rule. 5 October 2007. Federal Register (USA), **72**(193): 57104–57194.

Nowacek, D.P., Johnson, M.P., Tyack, P.L., Shorter, K.A., McLellan, W.A., and Pabst, D.A. 2001. Buoyant balaenids: the ups and downs of buoyancy in right whales. Proc. Biol. Sci. **268**(1478): 1811–1816. doi:10.1098/rspb.2001.1730. PMID:11522200.

Nowacek, D.P., Johnson, M.P., and Tyack, P.L. 2004. North Atlantic right whales (*Eubalaena glacialis*) ignore ships but respond to alerting stimuli. Proc. Biol. Sci. **271**(1536): 227–231. doi:10.1098/rspb.2003.2570. PMID:15058431.

Pettis, H. 2009. North Atlantic Right Whale Consortium annual report card (1 November 2007 – 30 April 2009). International Whaling Commission Scientific Committee Meeting, 22–25 June, Madeira, Portugal, 2009. SC/61/BRG11, International Whaling Commission, Cambridge, England.

Reeves, R.R., Smith, B.D., Crespo, E.A., and Notarbartolo di Sciara, G. (*Compilers*). 2003. Dolphins, whales and porpoises: 2002–2010 conservation action plan for the world's cetaceans. IUCN/

SSC Cetacean Specialist Group, IUCN, Gland, Switzerland, and Cambridge, UK.

Rosenbaum, H.C., Brownell, R.L., Jr, Brown, M.W., Schaeff, C., Portway, V., White, B.N., Malik, S., Pastene, L.A., Patenaude, N.J., Baker, C.S., Goto, M., Best, P.B., Clapham, P.J., Hamilton, P., Moore, M., Payne, R., Rowntree, V., Tynan, C.T., Bannister, J.L., and DeSalle, R. 2000. World-wide genetic differentiation of eubalaena: questioning the number of right whale species. Mol. Ecol. **9**(11): 1793–1802. doi:10.1046/j.1365-294x.2000.01066.x. PMID:11091315.

Rugh, D.J., Shelden, K.E.W., and Schulman-Janiger, A. 2001. Timing of the gray whale southbound migration. J. Cetacean Res. Manage. **3**: 31–39.

Species at Risk Act. 2002. Canada. Parliament. House of Commons. S.C. 2002, c. 29. An Act respecting the protection of wildlife species at risk in Canada. Last amended 27 October 2011. Public Works and Government Services Canada, Ottawa. Ont.

Vanderlaan, A.S.M. 2010. Estimating risk to the North Atlantic right whale (*Eubalaena glacialis*) from ocean-going vessels and fishing gear. Ph.D. thesis, Department of Oceanography, Dalhousie University, Halifax, N.S., Canada.

Vanderlaan, A.S.M., and Taggart, C.T. 2009. Efficacy of a voluntary area to be avoided to reduce risk of lethal vessel strikes to endangered whales. Conserv. Biol. **23**(6): 1467–1474. doi:10.1111/j.1523-1739.2009.01329.x. PMID:19775275.

Vanderlaan, A.S.M., Taggart, C.T., Serdynska, A.R., Kenney, R.D., and Brown, M.W. 2008. Reducing the risk of lethal encounters: vessels and right whales in the Bay of Fundy and on the Scotian Shelf. Endanger. Species Res. **4**: 283–297. doi:10.3354/esr00083.

Vanderlaan, A.S.M., Corbett, J.J., Green, S.L., Callahan, J.A., Wang, C., Kenney, R.D., Taggart, C.T., and Firestone, J. 2009. Probability and mitigation of vessel encounters with North Atlantic right whales. Endanger. Species Res. **6**: 273–285. doi:10.3354/esr00176.

Wiley, D.N., Moller, J.C., and Zillnskas, K.A. 2003. The distribution and density of commercial fisheries and baleen whales within the Stellwagen Bank national marine sanctuary: July 2001 – June 2002. Mar. Technol. Soc. J. **37**(1): 35–53. doi:10.4031/002533203787537384.

Winn, H., Price, C., and Sorensen, P. 1986. The distributional biology of the right whale (*Eubalaena glacialis*) in the western North Atlantic. Rep. Int. Whaling Comm. **12**(Special issue): 129–138.

Winn, H.E., Goodyear, J.D., Kenney, R.D., and Petricig, R.O. 1995. Dive patterns of tagged right whales in the great south channel. Cont. Shelf Res. **15**(4–5): 593–611. doi:10.1016/0278-4343(94)00061-Q.