Elevations of lobster fishery groundlines in relation to their potential to entangle endangered North Atlantic right whales in the Bay of Fundy, Canada

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Fishing gear is known to be a threat to North Atlantic right whales (*Eubalaena glacialis*), and groundlines used in the American lobster (*Homarus americanus*) trap fishery are hypothesized to be an integral component of entanglements that may, in some incidents, lead to mortality. This research measured the elevations above the seabed of 17 regular groundlines on commercially active lobster gear in the Bay of Fundy and evaluated several factors governing rope elevation profiles. Mean elevation was 1.6 m (s.d. $= 0.9$, $n = 5968$, range $= 0.0-7.0$ m). The hypothesis that groundline elevations were ≤ 1.0 m (predicted height of taut groundlines) was rejected (Fisher's $C = 66.9$, $p < 0.01$), as was the hypothesis that elevations were >3.0 m (approximate body height of a right whale; Fisher's $C = 129.5$, $p < 0.01$). The proportion of groundline elevations ≤ 1.0 m was 0.32, and that <3.0 m was 0.92. Groundline elevations were negatively related to tidal current velocity at the time of setting ($p < 0.001$, $r^2 = 0.33$) and were closer to the seabed in deep than in shallow water ($p < 0.05$, $r^2 = 0.07$). It is suggested that groundlines in the Bay of Fundy may not constitute a large part of the risk associated with the entanglement of right whales, because most lines remained below the elevation hypothesized to be a threat (3 m). We also identified factors within the control of fishers setting trawls that minimize groundline elevations.

Keywords: depth profile, entanglement, *Eubalaena glacialis*, groundline, lobster fishery, right whale.

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Introduction

North Atlantic right whales (*Eubalaena glacialis*) range seasonally along the coast from Canada to Florida (Kraus and Rolland, 2007), an area that also carries large volumes of vessel traffic (Laist *et al.*, 2001; Knowlton and Brown, 2007) and contains extensive fishing activity (NOAA, 2008a). Consequently, North Atlantic right whales have two significant causes of mortality: strikes by vessels and entanglement in fishing gear (Kraus *et al.*, 2005; Moore *et al.*, 2007). There are other species of large whales (e.g. fin, *Balaenoptera physalus*; humpback, *Megaptera novaeangliae*; minke, *B. acutorostrata*) in the Atlantic that are also threatened by these sources of mortality, but with fewer than 400 North Atlantic right whales remaining (Kraus *et al.*, 2001; Kraus and Rolland, 2007), the species is one of the most endangered large whales in the world and the only one whose recovery has been federally mandated in both Canada and the United States. Both countries are seeking to accomplish this by reducing the incidence of entanglements (NMFS, 2005; Brown *et al.*, 2009).

It has been postulated that ropes in the water column present a risk to whales (Johnson *et al.*, 2005). Fixed-gear fisheries (i.e. those using pots, traps, or gillnets) use ropes in several parts of their operation, but most notably as buoylines (connecting gear on the bottom to a surface buoy) and groundlines (connecting traps or nets together in a series; Johnson *et al.*, 2005). Fixed-gear fisheries operate along the entire east coast of North America out to the edge of the continental shelf (NOAA, 2008b). American lobster (*Homarus americanus*) fishing has been of particular interest in this matter because it is a relatively large fishery. In the United States, there are 11 500 commercial lobster licenses using >4 million lobster traps and landing 35 000 t of lobster year-round (ASMFC, 2006). Approximately three-quarters of the fishery operate within Maine waters (Steneck, 2006). In Canadian waters of the Bay of Fundy and the western Scotian Shelf, there are >1300 licensed lobster fishers (DFO, 2006, 2007) involved in a seasonal fishery, and during the 2003/2004 season, ~500 000 traps were used to land 23 000 t of lobster (DFO, 2006, 2007).

The US National Marine Fisheries Service (NMFS) considers groundlines to be a significant threat to whales because they are normally constructed of floating rope. Therefore, NMFS requires all fixed-gear fisheries in the United States to use sinking or neutrally buoyant ropes for their groundlines (ALWTRP, 2007). Despite this, there is little information about the elevations of groundlines or the factors affecting them. In 1998, Carr (reported in McKiernan *et al.*, 2002) used a remotely operated vehicle to inspect the groundlines (18 m long) of lobster traps and reported the maximum elevation to be 3 m. McKiernan *et al.* (2002) reported the results of scuba divers measuring the elevations of floating and sinking groundlines (of unreported length) on trawls, i.e. a string of traps connected in a series, of lobster traps set by a fisher. They reported that the sinking groundlines were in contact with or within 10 cm of the seabed, but that floating groundlines ranged from 0.6 to 7.5 m above the seabed. They noted, however, that the trawl with the greatest elevation was damaged *in situ* (possibly by a dragger) and may not, therefore, have been typical of the fishery. Another study (Lyman and McKiernan, 2005) used scaled models (1:10) of groundlines in a flume tank at various (scaled) current velocities and showed that groundlines of floating rope have relatively low profiles ($<$1 m) when the perpendicular current velocity was 0.75 knots (0.38 m s^{-1}) or faster. The lengths of these scaled groundlines were 1.5$\times$ water depth. The only study to examine the elevations of rope continuously in the water column was that of Trippel *et al.* (2008), who attached depth data-loggers to various types of ropes anchored in 25 m of water and showed that, under natural conditions, sinking groundlines and lines with large specific gravities (e.g. $BaSO_4$ ropes) have significantly less elevation than typical floating groundlines. They did not, however, examine the elevations of groundlines on commercially active gear.

Cooperative research is required with fishers in Canada that aims to develop management measures that can be applied to reduce the chance of entangling whales. The need to do so is, however, crucial, particularly with respect to the North Atlantic right whale because a significant proportion of the small remaining population aggregates in the Bay of Fundy and the western Scotian Shelf each summer, and many often remain until early winter (Brown *et al.*, 2007).

Objective and hypotheses

The objective of this research was to provide information about the elevations of lobster fishery groundlines above the seabed. We tested two central hypotheses about the elevations and assessed several factors that may influence these elevations. The first hypothesis was that groundline elevations would be greater than the approximate body height of an adult right whale (3 m; Moore *et al.*, 2005). An elevation known to pose a significant risk to whales has never been established and, as a result, we chose this definition as a conservative estimate. The second hypothesis was that the elevations of groundlines would be no more than 0.6 m above a typical lobster trap (0.4 m), and hence 1.0 m above the seabed. This elevation was chosen because, in setting their trawls, fishers strive to set their traps near their maximum distance apart, suggesting that a groundline is taut and therefore of low elevation.

The elevation profiles of the groundlines were also examined. As they are made of flexible rope, fixed at each end, and have a force (buoyancy) acting upon their whole lengths, it was expected that groundlines would form inverted catenaries in the water column. Determining the shape of the groundlines was necessary because this allows the distance between each trap on a trawl to be estimated.

Four factors were identified that may influence groundline elevation. The first was the order of the groundlines on a trawl. As a trawl is set, each trap is postulated to sink to the seabed more quickly than the previous one because of the increasing weight of the trawl in the water as more traps are released. If this were true, the maximum elevations of the groundlines between the first traps set on a trawl will be lower than those between the last traps. The second factor was the depth where the trawl was set. Trawls set in deep water will have more time to spread out than trawls set in shallow water. Therefore, we predicted that the elevations of groundlines on trawls set in deep water would be lower than those in shallow water. The third and fourth factors were related to tidal current velocities. Trawls are typically set parallel to and in the same direction as the tidal currents because this is thought to maximize the distance between traps. If so, the elevations of groundlines on trawls are expected to be higher when they are set during slow than during fast tidal currents. Once trawls are set, however, strong tidal currents apparently push the groundlines to the seabed (Lyman and McKiernan, 2005). This was tested by examining the relationship between the groundline elevation and the forces of the tidal current velocities parallel and perpendicular to the orientation of the groundline.

Material and methods

Normal fishing practice

In the outer Bay of Fundy, Canadian lobster fishers typically attach 10–50 traps together in series with an anchor and a buoyline at each end. The weight of individual traps and end anchors ranges from 15 to 40 kg (30–80 lb), depending on local hydrographic conditions. Groundlines (Figure 1) are typically made from synthetic rope (the most popular brands are a blend of polypropylene and polyethylene) that is positively buoyant (floating rope). Traps are attached to the groundline usually at intervals of 22–37 m by gangions connected to the bridles on the ends of the traps. Gangions are typically 1.2–1.5 m long. Floating rope is preferred for groundlines in many areas because lines that lie on the seabed can chafe (depending on substratum type and the strength of local tidal currents) and wear out more quickly. This is important to the fishing operation because the groundlines are used to haul up the traps one after another and must, therefore, be able to bear a considerable weight (the tensile breaking strength of new ropes ranges from 2000 to 4000 kg).

There are some variations in how trawls are deployed, but the fishing vessel is generally driven in the same direction as the running tide, and an anchor from one end of a trawl is dropped off the stern and the traps allowed to pull themselves off the back, one after another as their groundlines are played out, until the last anchor is pulled off. Most lobster boats in the Bay of Fundy have open sterns to assist this means of setting, which is believed to maximize the distance between the traps on the seabed because the combined velocity of the boat and the tidal currents maximize the forward momentum of each trap as it settles. Lobster fishers strive to set their traps as far apart as allowed by the length of the groundline because that reduces the overlap of fishing effort between traps and ensures that the groundline is relatively taut and not floating freely in the water column, where it can snag or cause other difficulties.

Measuring groundline elevations

The research was carried out with assistance from fishers on commercially active lobster gear being fished in two locations in the Bay of Fundy (Figure 2): (i) at the mouth of St Mary's Bay, NS (March and May 2008), and (ii) off the west coast of Grand Manan, NB (July 2008). Data-logger sensors (Star-Oddi DST milli) were attached to some of the groundlines on trawls of lobster traps. The buoyant weight of the sensors and their housings was ~0.009 kg (negatively buoyant), but this was considered negligible considering the buoyant mass of the floating groundlines between each trap (22 or 37 m; −0.170 to −0.320 kg). The sensors recorded pressure (in bar) for the duration that the gear was set (at least 2 d).

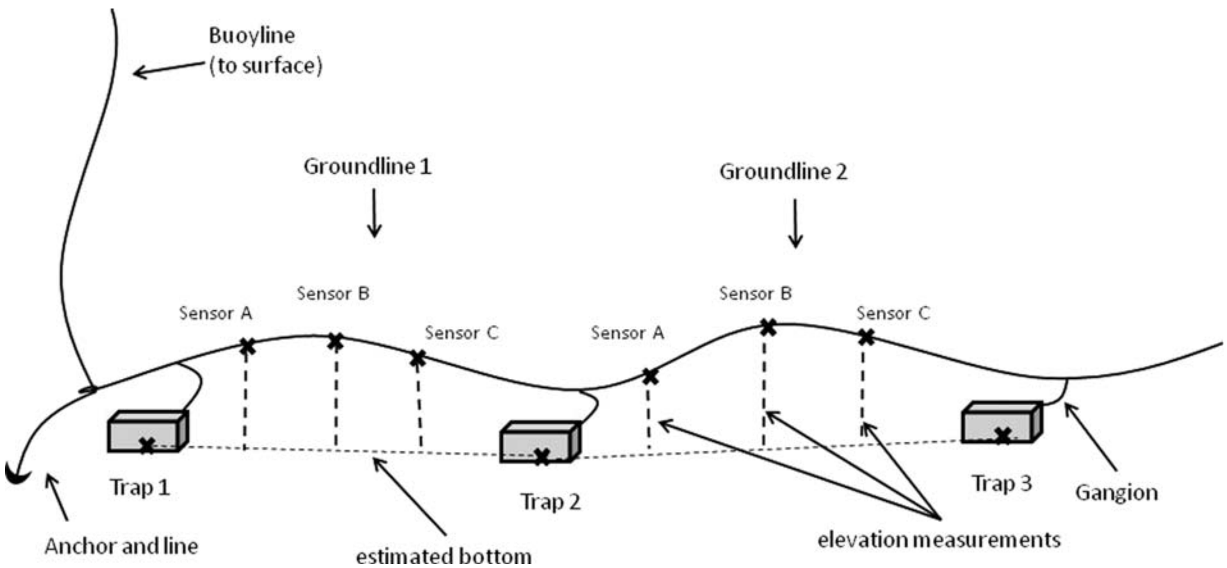

Figure 1. Unscaled representation of the front part of a lobster trawl indicating locations of sensors (crosses) on the groundlines and traps. The sensor arrangement shown here was used for the trawls evaluated in March. For those in May and July, Sensors A and C were not used.

In March, three sensors were attached to each of the last two groundlines on three different 14-trap trawls. The sensors were attached at equal distance along the length of the groundlines between two traps (~22 m; sensors were placed every 5.5 m; Figure 1) and recorded the pressure every 5 min. One sensor was also attached to the bottom of each trap connected to each end of the groundlines. These latter sensors provided a measure of the depth of the seabed (Figure 1). In May, only one sensor was placed on each groundline at the centre of its length (11 m from each adjacent trap), and pressure was recorded every 15 min. Sensors were placed on the first two and last two groundlines on each of two 14-trap trawls. On a third trawl (12 traps), only the last two groundlines were measured, one of which was made of sinking rope (lead core). For each groundline, a sensor was also attached to the base of each adjacent trap. In July, the elevations of three groundlines on one trawl were measured. A sensor was placed in the centre of the first, tenth, and last (19th) groundlines of a 20-trap trawl, as well as at the base of each trap next to these groundlines, and pressure was recorded at 15-min intervals. The distance between traps on this trawl was ~37 m. The details of all the trawls and lines measured in this research are summarized in Table 1. The pressure data (bar) from the sensors were converted to depth (m), and the elevations (m) of each groundline sensor were calculated by subtracting the depth of the seabed immediately below each sensor (based on the weighted mean of the depths of the two adjacent traps) from the depths recorded by that sensor (Figure 1). As the elevations were based on comparing depths among sensors, the precision of the sensors was measured by holding the sensors at a fixed depth for a period before the field experiment. The mean range of differences among the sensors was 0.13 m, and the maximum difference recorded among any of the sensors for the duration of the calibration period was 0.58 m.

Each of the two central hypotheses was tested separately by examining the frequency distribution of the elevations for each groundline and rejecting them at $p < 0.05$. Because each groundline was used as an independent test of each hypothesis, a meta-analysis (Fisher's combinatorial test; Fisher, 1948) was used to integrate these results and to test the hypotheses. The influence of the position of the groundlines on the trawls on their elevations and the comparison between the elevations of groundlines made from floating rope, with one made from sinking rope, were each tested using ANOVA. The influence of water depth on groundline elevations was tested by linear regression. The elevations for these analyses were expressed as a standard length of groundline (22 m) because the groundlines were of different lengths (Table 1). Instantaneous tidal current velocities were calculated for each location and time using the latest version of the Fisheries and Oceans Canada Tidal Prediction Model (DFO, 2009). For each elevation recorded on the groundlines, the tidal current at the time was decomposed into parallel and perpendicular components relative to the orientation of the groundline. Multiple linear regressions were used to test whether these two components influenced the elevations of the groundlines (R v2.6.2).

The data collected in March (when three sensors were placed on each groundline) were used to evaluate the shapes (i.e. depth profiles) of the groundlines. If the groundlines formed an inverted catenary with sensor B at the vertex (Figure 1), the elevations of sensors A and C can be predicted from the equation for the inverted catenary:

$$\text{Elevation} = -a\ \cosh\left(\frac{x}{a}\right) + a + B, \qquad (1)$$

where x is the horizontal distance between the endpoint and the vertex, B the elevation of the vertex, and a a curvature constant. If this does not accurately predict the elevations of sensors A and C, the lines are not forming inverted catenaries.

The curvature constant a differed for each observation and was estimated in the following way. The equation for the length of an arc(s) of an inverted catenary from the endpoint to x is

$$s = a \sinh\left(\frac{x}{a}\right). \qquad (2)$$

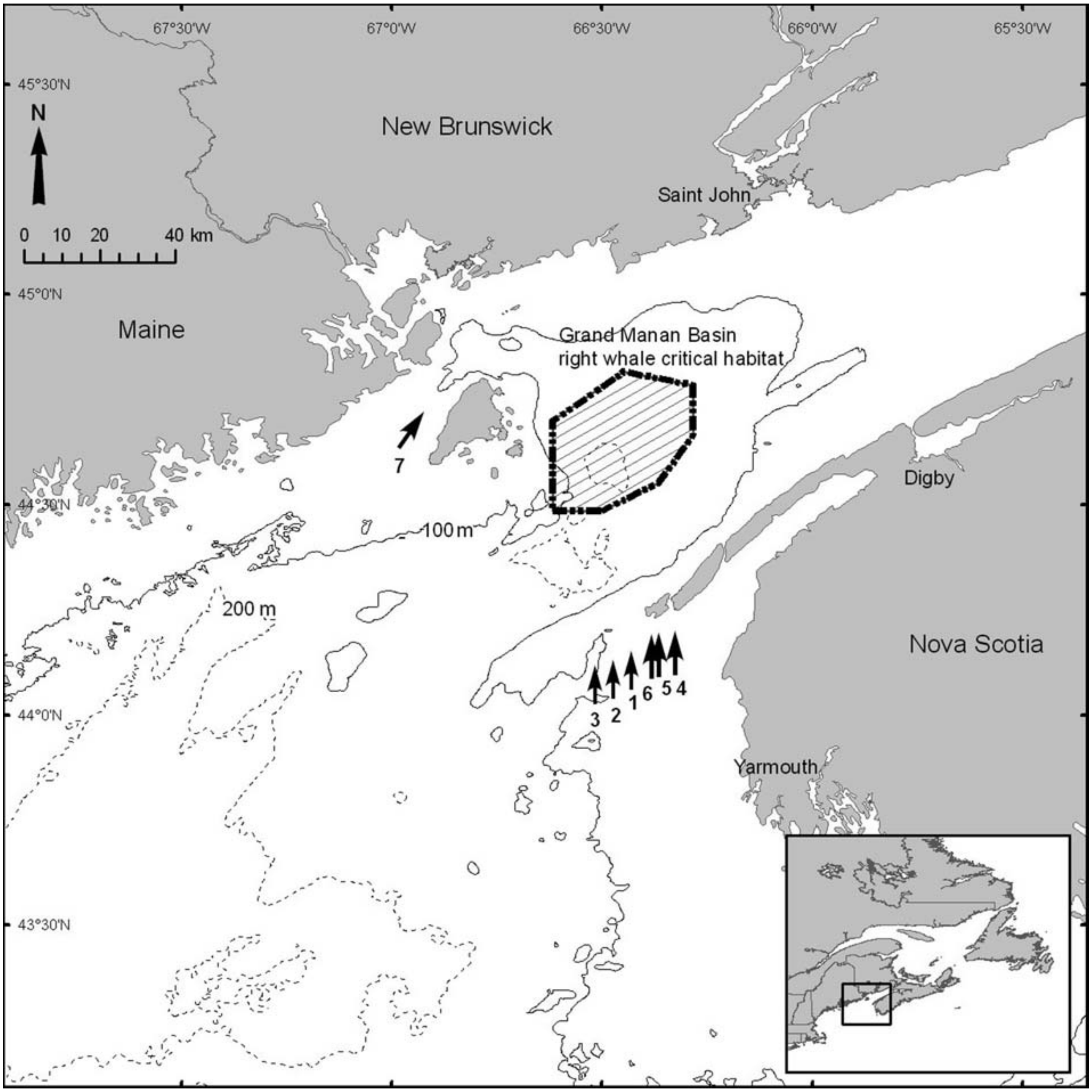

Figure 2. Map of the mouth of Bay of Fundy and the southwest coast of Nova Scotia indicating the locations of the trawls evaluated in this study in relation to the Grand Manan Basin North Atlantic right whale critical habitat designated by the Canadian Species at Risk Act (SARA; Brown *et al.*, 2009).

This was rearranged to solve for x:

$$x = a \sinh^{-1}\left(\frac{s}{a}\right), \tag{3}$$

and inserted into Equation (1) to solve a for the arc from an elevation of 0 to B:

$$a = \frac{(s_{\max}^2 - B^2)/B}{2}, \tag{4}$$

where $s_{\max}$ is the length of the groundline. For the groundlines to rise above the seabed, there must be slack in the line. Given that the length of the groundline is fixed, this slack must result from the shortened distance between the fixed ends (i.e. the traps). Therefore, if the groundlines form inverted catenaries [based on Equation (1)], then Equation (3) can be used to estimate the maximum distances between traps ($=2x$). The actual distance between the traps may be less than this estimated maximum distance because the groundline may never have been elevated to its maximum possible elevation. This estimated distance between the traps was used as a direct surrogate for the amount of slack in the intervening groundline, and this was compared with the perpendicular and parallel components of the tidal currents as well as the orientation of the trawl relative to the tidal ellipse to determine how tidal currents influenced the groundlines.

Table 1. Fishing gear in the Bay of Fundy to which depth sensors were attached in 2008.

Date (set–retrieved)	Trawl	Groundline number within trawl	Depth (m)	Number of traps	Groundline rope (specific gravity)	Tidal current Velocity ($m s^{-1}$)	Tidal current Bearing (0°N)
27–29 March	1	12	96.7	14	9/16-in Movdan (0.93)	0.60	175
		13	94.3				
	2	12	87.4	14	9/16-in Movline (0.93)	0.48	176
		13	86.6				
	3	12	113.7	14	9/16-in Polysteel (0.95)	0.36	179
		13	114.6				
29–31 May	4	1	77.6	14	9/16-in Movdan (0.93)	0.08	253
		2	77.6				
		12	74.8				
		13	75.8				
	5	1	65.0	14	9/16-in Movdan (0.93)	0.12	216
		2	64.0				
		12	62.8				
		13	62.3				
	6	10	58.5	12	1/2-in sink rope (>1.10)	0.11	307
		11	59.1		9/16-in Movdan (0.93)		
22–26 July	7	1	97.4	20	1/2-in Movdan (0.93)	0.64	205
		10	92.2				
		19	99.1				

The groundline number within a trawl refers to the order that the groundlines entered the water when each trawl was set. Groundlines used in March and May were ~22 m (12 fm) long, and those in July were 37 m (20 fm) long. The brands of ropes used in this research (Movdan, Movline, and Polysteel) are synthetic ropes made of a blend of polypropylene and polyethylene. The depth of the seabed at the middle of each groundline and the number of traps on each trawl are listed, as are the velocity and bearing of the tidal current at the time each trawl was set.

Results

The elevations of 19 groundlines were recorded in the Bay of Fundy for at least 2 d each, at either 5- or 15-min intervals. The groundlines were on seven different trawls set by two fishers at three times of the year (Table 1). Trawls were numbered chronologically, and throughout this research, the groundlines are referred to by numbers (e.g. Line 10, Line 13) indicating their order on the trawl according to when they were set; e.g. Line 1 was the first groundline in the water as a trawl was being set.

Of the 19 groundlines, 17 were made from floating rope and appeared to be set normally and, hereafter, are referred to as "regular" groundlines. Each of the two remaining groundlines was not considered regular for different reasons. One (Trawl 17, Line 10) appeared to have been set irregularly because its elevation was very high (mean = 7.2 m), but stable (variance = 0.04), and it did not have the periodicity typical of other groundlines. We believe this groundline was set across a ledge with the adjacent traps set on each side of the ledge, so we excluded it from the analyses. The other non-regular groundline (Trawl 6, Line 10) was made of sinking line (i.e. specific gravity >1.1); therefore, its elevations were not included in the data analyses except where noted as a comparison for the regular buoyant groundlines.

Elevations and elevation profiles

The mean elevation of all regular groundlines was 1.6 m (s.d. = 0.9, $n = 5968$). One groundline (Trawl 1, Line 12) never rose higher than 1.0 m, and five groundlines never rose higher than 3.0 m (Table 2). Data from four of the regular groundlines each clearly rejected ($p < 0.05$) the hypothesis that the elevations of groundlines were ≤1.0 m, and this hypothesis was rejected overall when the data from each of the groundlines were combined (as 17 independent tests using Fisher's combinatorial test; Fisher, 1948). Similarly, elevations of nine of the regular groundlines each rejected the hypothesis that groundline elevations were >3.0 m, so this hypothesis was also rejected overall (Table 2). The mean distribution of the elevations for all regular groundlines (Figure 3) shows that 0.32 of the recorded elevations were ≤1.0 m and that 0.92 were <3.0 m. The maximum recorded elevation was 7.0 m. The elevations of all regular groundlines were significantly greater than the elevation of the groundline made of sinking rope (ANOVA, $F = 49.6$, 1, d.f. = 22, $p < 0.001$). The maximum elevation of the sinking groundline was 0.4 m (mean = 0.2 m).

All elevations of the regular groundlines were autocorrelated with a period approximately corresponding to the tidal period (mean period = 12.4 h). Many (12) of the regular groundlines also had a weaker period (i.e. smaller autocorrelation function) in their data, approximately corresponding to each half tide (6.5–7 h).

The equation for an inverted catenary accurately predicted the observed elevations of sensors A and C on five of the six groundlines measured in March (i.e. Trawls 1–3). The sixth groundline (Line 12 of Trawl 3) could not be tested because the sensor at the centre of the line failed. For that groundline, the distance between traps was calculated using the elevations of sensors A and C and assuming straight lines (Pythagorean theorem). Most traps were estimated to be between 92 and 100% of their maximum distance apart (22 or 37 m; Table 1), but the elevations of the sixth groundline suggest that the traps were only 72% (15.7 m) of their maximum distance apart (Table 3). Differences in the elevation between adjacent traps were generally small (mean = 1.5 m); only three pairs of traps had elevation differences exceeding 3 m (Trawl 1, Line 2 = 3.3 m; Trawl 3, Line 2 = 3.5 m; and Trawl 7, Line 19 = 5.8 m).

Table 2. Mean, minimum (Min), and maximum (Max) elevations of each groundline monitored in the Bay of Fundy, the number of elevations recorded (*n*), and the probability of each groundline being ≤1.0 or >3.0 m based on the distribution of observations. Fisher's combinatorial test (Fisher, 1948): *p* (groundline elevations ≤ 1.0 m) < 0.01 (*C* = 66.9); *p* (groundline elevations > 3 m) < 0.01 (*C* = 129.5).

Groundlines		Mean (m)	Min (m)	Max (m)	*n*	*p*-value (≤1.0 m)	*p*-value (>3.0 m)
Regular							
Trawl 1	Line 12	0.7	0.3	1.0	577	1.00	<0.01**
	Line 13	1.0	0.7	1.3	577	0.48	<0.01**
Trawl 2	Line 12	1.6	0.8	2.6	577	0.08	<0.01**
	Line 13	1.2	0.5	2.1	577	0.31	<0.01**
Trawl 3	Line 12	2.6	0.8	4.3	577	<0.01**	0.26
	Line 13	2.3	0.1	5.0	577	0.04*	0.22
Trawl 4	Line 1	1.9	0.3	3.7	193	0.13	0.09
	Line 2	1.7	0.1	4.1	193	0.18	0.05*
	Line 12	1.0	0.0	3.4	193	0.51	<0.01*
	Line 13	0.9	0.0	2.7	193	0.50	<0.01**
Trawl 5	Line 1	2.3	0.6	5.5	193	0.04*	0.25
	Line 2	1.9	0.6	4.4	193	0.12	0.11
	Line 12	2.3	0.5	5.3	193	0.06	0.16
	Line 13	1.7	0.0	4.3	193	0.23	0.03**
Trawl 6	Line 11	2.3	0.6	4.3	185	0.03*	0.10
Trawl 7	Line 1	1.1	0.2	7.0	388	0.69	0.06
	Line 19	1.3	0.1	4.4	388	0.41	0.03**
Non-regular							
Trawl 6	Line 10 (sinking)	0.2	0.0	0.4	185	1.00	<0.01
Trawl 7	Line 10 (irregular)	7.2	6.6	8.0	388	<0.01	1.00

*$p < 0.05$.
**$p < 0.01$.

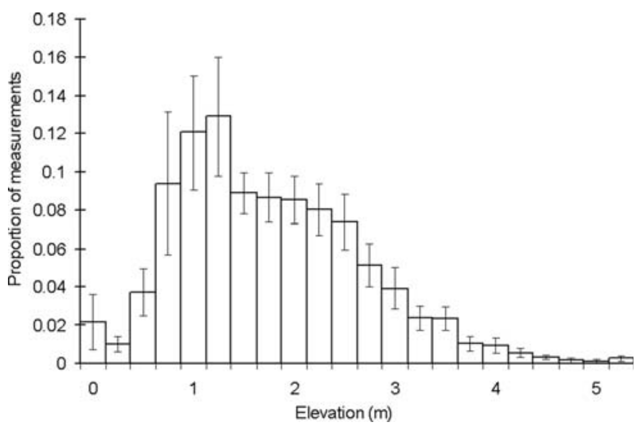

Figure 3. Frequency distribution of all groundline elevations measured at the vertex of each in 5- or 15-min intervals for at least 2 d (see text). Bars indicate the mean (±s.e.) proportion of observations for all groundlines ($n = 17$). The maximum elevation was 7.0 m. The proportion of observations ≤1.0 m was 0.32 and that <3.0 m was 0.92.

Table 3. The percentage of the maximum distance between the endpoints (i.e. traps) of each groundline based on the maximum recorded elevations of each at the vertex.

Groundline		Maximum elevation (m)	% of maximum distance
Trawl 1	12	1.3	99
	13	1.0	100
Trawl 2	12	2.1	98
	13	2.6	97
Trawl 3	12	5.5	72
	13	5.0	92
Trawl 4	1	3.7	95
	2	4.1	94
	12	3.4	95
	13	2.7	97
Trawl 5	1	5.5	92
	2	4.4	93
	12	5.3	92
	13	4.3	94
Trawl 6	10	0.4	100
	11	4.4	93
Trawl 7	1	7.0	94
	19	4.4	97

The maximum elevation reported for Line 12 of Trawl 3 is not from the vertex of the groundline (see text). The groundlines of Trawls 1–6 were 22 m long, and the groundlines of Trawl 7 were 37 m long.

Factors affecting groundline elevation

The order of the groundlines on a trawl did not influence their elevations. There were no significant differences between the maximum elevations of the first two and the last two groundlines during each tidal period on each of Trawls 4–6 (Table 4). Water depth (Table 1) had a statistically significant ($p < 0.05$), but small, effect ($r^2 = 0.07$) on the elevation of the groundlines (Figure 4). The effect was, however, in the manner predicted by the hypothesis; i.e. groundline elevation was lower in deep water than in shallow.

The velocity of the tides influenced groundline elevation in two ways. During each tidal cycle, the maximum elevation of each groundline (relative to its length) was negatively related to the velocity of the tide at the time they were set ($p < 0.001$, $r^2 = 0.34$; Figure 5). This was in agreement with our hypothesis that tidal velocity at setting had an influence on groundline elevation.

Tidal current velocity also influenced the elevations once the trawls were set on the seabed, but not in the manner predicted. The parallel and perpendicular components of the tidal currents significantly influenced the elevations of 17 and 15 of the

Table 4. Results of the ANOVA examining the effect of order of setting (i.e. the first two and last two groundlines) on elevation of groundlines in Trawls 3 and 4.

Source	d.f.	MS	*F*	*p*-value
Trawl	1	3.89	2.54	n.s.
Order (trawl)	2	1.53	3.25	n.s.
Groundline (order × trawl)	4	0.47	0.43	n.s.
Residual	16	1.09		

n.s. indicates $p > 0.05$.

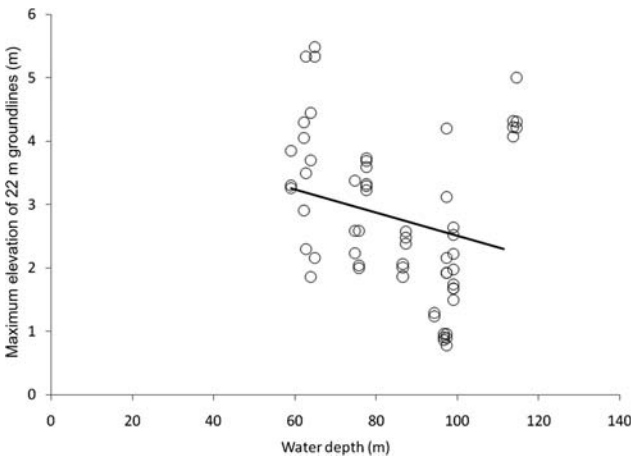

Figure 4. Water depth at trawl locations and the maximum elevations of each groundline during each tidal period (linear regression indicated by the solid line: $F = 4.3$, $r^2 = 0.07$, $p < 0.05$). Maximum elevations are expressed as if all groundlines were the same length (22 m; see text).

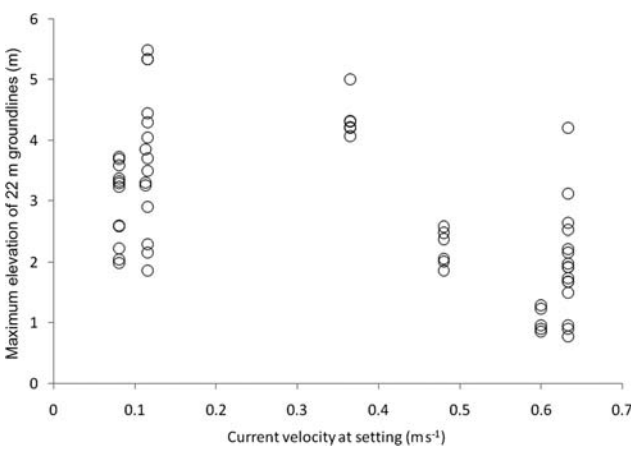

Figure 5. Maximum elevations of groundlines in relation to tidal current velocity at the time a trawl was set (linear regression: $F = 29.2$, $r^2 = 0.33$, $p < 0.001$). Maximum elevations are expressed as if all groundlines were the same length (22 m; see text).

groundlines, respectively. The nature of this relationship changed, however, relative to the amount of slack in the line. Groundlines with less slack showed a linear relationship between their elevation and the parallel and perpendicular components of the tidal currents, but this relationship became less linear for groundlines

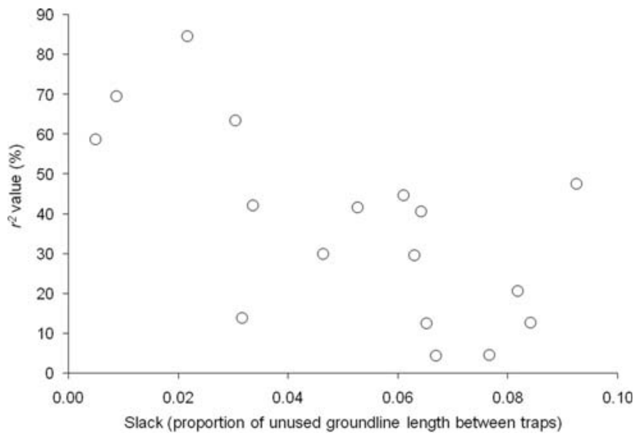

Figure 6. Relationship between r^2 values (%) of multiple linear regressions for each groundline (of the groundline elevation with parallel and perpendicular components of the tidal current velocities) and the amount of slack in each groundline, expressed as the proportion of groundline length between each trap that was unused (linear regression: $F = 18.6$, $r^2 = 0.42$, $p < 0.01$).

with more slack (Figure 6). Examination of these regressions suggests that the effect of tidal currents on the elevations of groundlines with less slack was directional and linear, but that for groundlines with more slack, faster currents produced higher elevations than slower currents regardless of the direction of the current.

For example, for Groundline 12 of Trawl 1, estimated to be one of the most taut groundlines (Table 3), fast currents running parallel to it increased its elevation when currents ran in one direction, but lowered the elevations when they ran in the opposite (but still parallel) direction (Figure 7a). Slower currents produced intermediate elevations. On the other hand, for groundlines with greater slack, such as Groundline 12 of Trawl 5, elevations were generally highest when current velocities were fastest, and lowest when currents were slowest (Figure 7b).

The angle of the trawl relative to the predominant tidal currents (i.e. the long axis of the tidal ellipse) was not related to the amount of slack in the groundlines ($F = 0.51$, $p > 0.05$) nor to the maximum elevation ($F = 0.02$, $p > 0.05$).

Discussion

The central goal of this research was to evaluate the elevations of groundlines on trawls of commercial lobster traps in the Bay of Fundy. This was done by testing two main hypotheses: (i) groundline elevations were high enough to be a significant risk to right whales (>3 m), and (ii) groundline elevations were low (≤1 m) because traps are set near to their maximum distance apart. The results indicate that the elevations of groundlines were not as low as predicted if the groundlines were taut, but that most were below the (conservative) elevation hypothesized to be an entangling threat to whales in the water column.

Predicting the risk that groundlines pose to North Atlantic right whales (or other whale species) requires knowledge of the spatio-temporal distribution of both the fishing gear and the whales, and knowledge of location in the water column of both groundlines and whales. We have documented groundline depth profiles, but knowledge of the vertical distribution of right whales in the water column is currently poor. Several studies

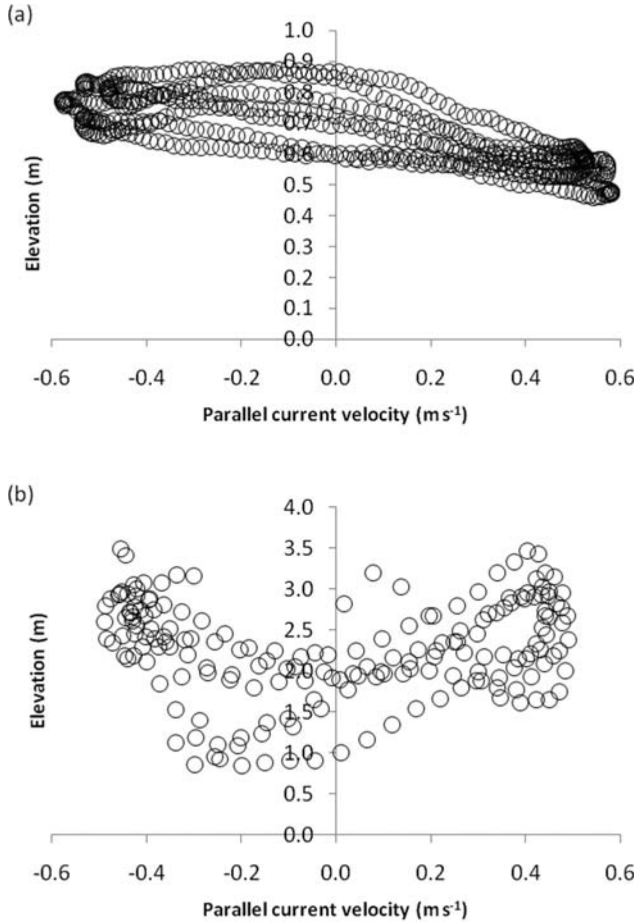

Figure 7. Relationship between elevation of (a) Groundline 12 of Trawl 1 and (b) Groundline 12 of Trawl 5 with the parallel forces of tidal currents relative to each groundline. For each groundline, elevations were averaged at 1.5-h intervals. The amount of slack in each groundline, expressed as the proportion of unused groundline length between traps, was (a) 0.01, and (b) 0.08. Results of multiple linear regressions for parallel tidal components shown here were (a) $F = 540$, $r^2 = 69.7$, $p < 0.001$, and (b) $F = 42.8$, $r^2 = 20.8$, $p < 0.001$.

have investigated different aspects of the diving behaviour of right whales (Goodyear, 1993; Nowacek *et al.*, 2001), but most do not report the proximity of the whales to the seabed. Winn *et al.* (1995) studied dive profiles of right whales in the Great South Channel (50–100 m deep) and showed that just 1% of the dives ($n = 935$) were to depths >30 m. Baumgartner and Mate (2003) attached depth data-loggers to right whales in the Bay of Fundy and Roseway Basin and recorded 149 dives from 53 right whales. Five of the dives went to the seabed (~200 m deep), but most of the deepest dives were to the top of the bottom mixed layer, 30–50 m above the seabed, and the whales showed great fidelity to that depth.

The results of these studies suggest that North Atlantic right whales in their two known northern feeding grounds rarely approach the seabed. This is further supported by the inference that whales at those depths are likely feeding on large concentrations of diapausing calanoids (mainly stage 5 *Calanus finmarchicus*; Michaud and Taggart, 2007), which are known to concentrate above the mixed layer, which generally extends 10–50 m above the seabed (Baumgartner *et al.*, 2003a, b).

It is worth noting that right whales have been observed surfacing with mud on their heads (Mate *et al.*, 1997), indisputably showing that they came into contact with the seabed, but it is difficult to evaluate the frequency of this behaviour. It is, however, a relatively rare observation within the records of the North Atlantic Right Whale Consortium database (1207 records of muddy whales of 35 000 observations; Right Whale Consortium, 2008), and most of the records are from the Bay of Fundy (1185). The seabed geology of the Bay of Fundy is not dramatically different from other areas where right whales are known (Wildish and Fader, 1998; Methratta and Link, 2006), suggesting that this pattern is not attributable to regional differences in seabed type. The frequency of this observation in the Bay of Fundy (1185 of 18 105 Bay of Fundy observations = 0.06; Right Whale Consortium, 2008) is, however, in the same order of magnitude that Baumgartner and Mate (2003) reported whales diving to the seabed (5 of 149 = 0.03) during their study.

The results suggest that the methods used by the fishers in this research to set their trawls were relatively effective at maximizing the distance between their traps. Most traps were set at 92% or more of their potential maximum distance apart, leaving relatively little room for improvement. What can be improved is having fishers avoid poorly set trawls, such as Line 12 of Trawl 3, for which the traps were estimated to be just 72% of their maximum distance apart.

Factors influencing groundline elevation

Of the four factors evaluated as potential influences on groundline elevation (order on the trawl, water depth, tidal current velocity while trawls were being set, and current velocities while the trawls were on the seabed), only the order of the groundlines on a trawl had no effect. The other three factors showed some influence on elevations, but this was not always strong nor in the manner predicted by the hypotheses. Trawls set in deeper water had lower groundline elevations, but this effect was relatively small. Trawls that were set while tidal currents were fast had significantly lower groundline elevations than those set near slack tide. Each of these results corroborated the hypotheses tested in the research. Contrary to the hypotheses, however, stronger currents did not generally reduce groundline elevations. Although this was true in some situations, this was determined to be more a function of the amount of slack in the groundline than current velocity. The effect of instantaneous current velocity on groundline elevation was linear and directional when groundlines had little slack, but this relationship changed and became less predictable for groundlines that were less taut.

Based on previous studies (Lyman and McKiernan, 2005) and observations from fishers, this relationship between groundline elevations and instantaneous current velocity was unexpected. In their flume-tank study, Lyman and McKiernan (2005) reported a reduction in elevation with increased current velocity, but their groundlines were arranged perpendicular to the current. Long trawls of lobster traps set by Canadian fishers are set parallel to tidal currents. This is an example of the importance of conducting this type of research on commercially active gear. Our results have shown clearly that groundlines are influenced by the tide, but also that the nature of this influence is affected by other factors, one being the amount of slack in the groundlines.

Although the effect of tidal currents on groundlines after a trawl has been set is beyond the control of fishers, the state of the tide when a trawl is being set is not. This is significant because how well a trawl is set establishes the amount of slack in the line and, thus, maximum possible elevation. This is further supported by the finding that the orientation of a trawl relative to the tidal ellipse has no influence on groundline elevation, suggesting that the effect of tidal currents on a trawl once set is less important than the state of the tide when the trawl is being set.

There are other aspects of fishing operations that may pose greater entangling risks to whales than groundlines, most notably buoylines. In the Bay of Fundy, two buoylines are used on each trawl, and these are typically made of floating line or a combination of floating and sinking line. This is a considerable length of line in the water that has not been investigated in terms of its risk to right whales, particularly considering that buoylines remain in the water column continuously, but that groundlines only rise into the water column relatively rarely. Although Johnson *et al*. (2005) concluded that a small number of observations ($n = 11$) prevented them from determining whether buoylines posed a greater risk to right whales than groundlines, buoylines were identified on more of the entangled right whales investigated. Evaluating the potential risk of buoylines is an important area of future research as well as a potential modification in the fishery in terms of reducing the risk to right whales.

Conclusions

Our work has shown that lobster fishers in the outer Bay of Fundy are capable of setting their trawls with low-elevation groundlines (e.g. Line 12, Trawl 1) and that there are several factors within their control that influence these elevations. Within their constraints of time and cost, fishers strive for low-elevation groundlines because this increases their fishing effort. Efforts to encourage trawls to be set in this way would be favourable for fishers as well as for reducing the probability of entangling large whales, including the North Atlantic right whales.

For the population of North Atlantic right whales to recover would require a reduction in anthropogenic mortality, and because the population is so threatened, even small reductions in risk may be important (Fujiwara and Caswell, 2001). Fishing does pose a significant risk to right whales, and actions are, therefore, necessary to mitigate the risk. To date, however, there has been little progress in determining the source of this risk from fishing gear, although management efforts in the United States have focused on groundlines. Will reducing the elevation of groundlines reduce the risk to right whales in the Bay of Fundy? It is quite likely that it would, for the simple reason that this will result in less line in the water column. Given, however, that most (92%) of the elevations measured in this study were within one body-height of a right whale from the seabed (i.e. 3 m), and given the apparent infrequency (as suggested from present information) that right whales come within this distance of the seabed, the absolute reduction in risk may be small. A more accurate evaluation of this reduction in risk requires knowing how close and how often right whales approach the seabed. This is a crucial area of research that is required if sound management decisions are to be made that will effectively protect right whales from entanglement. In the meantime, there are many other elements of fishing operations that need to be evaluated as a means of reducing the risk of entanglement of right whales.

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References

ALWTRP (Atlantic Large Whale Take Reduction Plan). 2007. Final environmental impact statement: broad-based gear modifications. National Marine Fisheries Service, National Oceanic and Atmospheric Administration, US Department of Commerce, Washington, DC.

ASFMC (Atlantic States Marine Fisheries Commission). 2006. American lobster stock assessment for peer review. Stock Assessment Report 06-03 (Supplement). National Oceanic and Atmospheric Administration, Silver Spring, MD. 352 pp.

Baumgartner, M. F., Cole, T. V. N., Campbell, R. G., Teegarden, G. J., and Durbin, E. G. 2003b. Associations between North Atlantic right whales and their prey, *Calanus finmarchicus*, over diel and tidal time scales. Marine Ecology Progress Series, 264: 155–166.

Baumgartner, M. F., Cole, T. V. N., Clapham, P. J., and Mate, B. R. 2003a. North Atlantic right whale habitat in the lower Bay of Fundy and on the SW Scotian Shelf during 1999–2001. Marine Ecology Progress Series, 264: 137–154.

Baumgartner, M. F., and Mate, B. R. 2003. Summertime foraging ecology of North Atlantic right whales. Marine Ecology Progress Series, 264: 123–135.

Brown, M. W., Fenton, D., Smedbol, K., Merriman, C., Robichaud-Leblanc, K., and Conway, J. D. 2009. Recovery strategy for the North Atlantic right whale (*Eubalaena glacialis*) in Atlantic Canadian waters [Final]. Species at Risk Act Recovery Strategy Series. Fisheries and Oceans Canada. 66 pp.

Brown, M. W., Kraus, S. D., Slay, C. K., and Garrison, L. P. 2007. Surveying for discovery, science and management. *In* The Urban Whale: North Atlantic Right Whales at the Crossroads, pp. 105–137. Ed. by S. D. Kraus, and R. M. Rolland. Harvard University Press, Cambridge, MA. 543 pp.

DFO. 2006. Framework assessment for lobster (*Homarus americanus*) in Lobster Fishing Area (LFA) 34. Department of Fisheries and Oceans Canadian Science Advisory Secretariat Science Advisory Report, 2006/024. 17 pp.

DFO. 2007. Framework and assessment indicators for lobster (*Homarus americanus*) in the Bay of Fundy, Lobster Fishing Areas (LFAs) 35, 36, and 38. Department of Fisheries and Oceans Canadian Science Advisory Secretariat Science Advisory Report, 2007/037. 12 pp.

DFO. 2009. Webtide; Tidal Prediction Model. Fisheries and Oceans Canada. http://www.mar.dfo-mpo.gc.ca/science/ocean/coastal_hydrodynamics/WebTide/webtide.html.

Fisher, R. A. 1948. Combining independent tests of significance. American Statistician, 2: 30.

Fujiwara, M., and Caswell, H. 2001. Demography of the endangered North Atlantic right whale. Nature, 414: 537–541.

Goodyear, J. D. 1993. A sonic radio tag for monitoring dive depths and underwater movements of whales. Journal of Wildlife Management, 57: 503–513.

Johnson, A., Salvador, G., Kenney, J., Robbins, J., Landry, S., and Clapham, P. 2005. Fishing gear involved in entanglements of right and humpback whales. Marine Mammal Science, 21: 635–645.

Knowlton, A. R., and Brown, M. W. 2007. Running the gauntlet: right whales and vessel strikes. *In* The Urban Whale: North Atlantic Right Whales at the Crossroads, pp. 409–435. Ed. by S. D.

Kraus, and R. M. Rolland. Harvard University Press, Cambridge, MA. 543 pp.

Kraus, S. D., Brown, M. W., Caswell, H., Clark, C. W., Fujiwara, M., Hamilton, P. K., Kenney, R. D., *et al.* 2005. North Atlantic right whales in crisis. Science, 309: 561–562.

Kraus, S. D., Hamilton, P. K., Kenney, R. D., Knowlton, A. R., and Slay, C. K. 2001. Reproductive parameters of the North Atlantic right whale. Journal of Cetacean Research and Management, 23: 1–236.

Kraus, S. D., and Rolland, R. M. 2007. Right whales in the urban ocean. *In* The Urban Whale: North Atlantic Right Whales at the Crossroads, pp. 1–38. Ed. by S. D. Kraus, and R. M. Rolland. Harvard University Press, Cambridge, MA. 543 pp.

Laist, D. W., Knowlton, A. R., Mead, J. G., Collet, A. S., and Podesta, M. 2001. Collisions between ships and whales. Marine Mammal Science, 17: 35–75.

Lyman, E. G., and McKiernan, D. J. 2005. Scale modeling of fixed-fishing gear to compare and quantify differently configured buoy-line and groundline profiles: an investigation of entanglement threat. Massachusetts Division of Marine Fisheries Technical Report, TR-22: 46.

Mate, B. R., Nieukirk, S. L., and Kraus, S. D. 1997. Satellite-monitored movements of the northern right whale. Journal of Wildlife Management, 61: 1393–1405.

McKiernan, D., Pol, M., and Malkowski, V. 2002. A study of the underwater profiles of lobster trawl ground lines. Massachusetts Division of Marine Fisheries Contract, 50EANF-1-00048. 18 pp.

Methratta, E. T., and Link, J. S. 2006. Associations between surficial sediments and groundfish distributions in the Gulf of Maine—Georges Bank region. North American Journal of Fisheries Management, 26: 473–489.

Michaud, J., and Taggart, C. T. 2007. Lipid and gross energy content of North Atlantic right whale food, *Calanus finmarchicus*, in the Bay of Fundy. Endangered Species Research, 3: 77–94.

Moore, M. J., Knowlton, A. R., Kraus, S. D., McLellan, W. A., and Bonde, R. K. 2005. Morphometry, gross morphology and available histopathology in North Atlantic right whale (*Eubalaena glacialis*) mortalities (1970–2002). Journal of Cetacean Research and Management, 6: 199–214.

Moore, M. J., McLellan, W. A., Daoust, P-Y., Bonde, R. K., and Knowlton, A. R. 2007. Right whale mortality: a message from the dead to the living. *In* The Urban Whale: North Atlantic Right Whales at the Crossroads, pp. 358–379. Ed. by S. D. Kraus, and R. M. Rolland. Harvard University Press, Cambridge, MA. 543 pp.

NMFS (National Marine Fisheries Service). 2005. Recovery plan for the North Atlantic right whale (*Eubalaena glacialis*). National Marine Fisheries Service, Silver Spring, MD. 137 pp.

NOAA. 2008a. Taking of marine mammals incidental to commercial fishing operations. Atlantic Large Whale Take Reduction Plan Regulations, 73FR 51228. 15 pp.

NOAA. 2008b. Fisheries of the United States 2007. Current Fishery Statistics 2007. National Oceanic and Atmospheric Administration, Silver Spring, MD. 103 pp.

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. Proceedings of the Royal Society of London, Series B: Biological Sciences, 268: 1811–1816.

Right Whale Consortium. 2008. North Atlantic Right Whale Consortium Identification Database, 22 July 2008. New England Aquarium, Boston, MA.

Steneck, R. S. 2006. Is the American lobster, *Homarus americanus*, overfished? A review of overfishing with an ecologically based perspective. Bulletin of Marine Science, 78: 607–632.

Trippel, E. A., Holy, N. L., and Shepherd, T. D. 2008. Barium sulphate modified fishing gear as a mitigative measure for cetacean incidental mortalities. Journal of Cetacean Research and Management, 10: 235–246.

Wildish, D. J., and Fader, G. B. J. 1998. Pelagic-benthic coupling in the Bay of Fundy. Hydrobiologia, 376: 369–380.

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. Continental Shelf Research, 15: 593–611.

doi:10.1093/icesjms/fsp231