Barium sulphate modified fishing gear as a mitigative measure for cetacean incidental mortalities

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ABSTRACT

Incidental mortality from entanglements in fishing gear is threatening cetacean populations worldwide. In eastern Canadian waters, entanglement deaths of the critically endangered transboundary North Atlantic right whale (*Eubalaena glacialis*) are a key conservation concern and incidental mortalities of harbour porpoise (*Phocoena phocoena*) in gillnets are a major source of mortality. Since the 1990s, a number of mitigation techniques to reduce mortalities in both species have been tested and the use of some in the US commercial fishery have been legislated. Despite this, the North Atlantic right whale population remains in a precarious state and entanglement deaths of harbour porpoise have been increasing in recent years. Further, mitigation devices, such as acoustic alarms, carry with them concerns about habituation, noise pollution, maintenance requirements and cost. The modifying of the physical characteristics of commercial fishing gear has shown some promise at reducing entanglement mortalities in initial testing while avoiding many of the drawbacks of other mitigation methods. In this study the current state of development and effectiveness of mitigation techniques through the addition of barium sulphate to fishing gear rope and twine were investigated. The development of a neutrally buoyant groundline, through the addition of barium sulphate, was undertaken in order to reduce the probability of large whale entanglements in lobster pot gear. The resulting product maintained a much lower profile in the water column relative to traditional polypropylene groundline, however, it was found unsuitable for hard-bottom areas as it was susceptible to chaffing and breaking. In order to reduce mortalities once large whales are entangled, a weak rope was developed again with the addition of barium sulphate. The breaking strength of this product was found to be 1,065lb which meets the US legislated limits (1,100lb), as opposed to traditional polypropylene rope which had a breaking strength of over 2,400lb. To meet the challenge of harbour porpoise entanglements, a gillnet twine was developed to have an increased acoustic profile and a more stiff form through the addition of barium sulphate. In field testing trials, the barium sulphate modified gillnets reduced harbour porpoise bycatch and had minimal effects on targeted groundfishes. Although they are in an early state of development, barium sulphate modified fishing gear shows promise at reducing entanglement deaths of cetaceans.

KEYWORDS: GILLNETS; INCIDENTAL CATCHES; CONSERVATION; NORTH ATLANTIC RIGHT WHALE; HARBOUR PORPOISE; FISH; ATLANTIC OCEAN; NORTH AMERICA; SUSTAINABILITY; NORTHERN HEMISPHERE; ECHOLOCATION; FISHERIES

INTRODUCTION

Incidental mortality of cetaceans due to bycatch and entanglement in commercial fishing gear is a conservation concern worldwide (Perrin *et al.*, 1994). It is estimated that the North Atlantic right whale (*Eubalaena glacialis*), an endangered species (IUCN, 2008) with recent estimates of a population size of 350 (Kraus *et al.*, 2005), owes over 10% of its mortality and over half of its serious injuries to entanglement in lobster pot and gillnet gear lines (Knowlton and Kraus, 2001; Moore *et al.*, 2004). Further, in the North Atlantic, bycatch mortality of harbour porpoise (*Phocoena phocoena*) in gillnets has recently been identified as possibly exceeding sustainable levels in many areas, including the Gulf of Maine, Bay of Fundy and in the North, Celtic and Baltic seas (Read *et al.*, 2004; Trippel *et al.*, 1999; Vinther, 1999). Although recent management measures, such as time-area closures and the use of acoustic alarms on gillnets have been introduced to some areas in order to reduce cetacean mortality levels (NOAA, 1998), deaths from incidental capture in commercial fishing gear remains a concern and in the northeast USA, recent estimates of harbour porpoise bycatch (NMFS, 2006) show yearly increases in the last three years of observations (2002-04).

In the northwestern Atlantic, North Atlantic right whales become entangled in many major fishing gears but most often in lobster pot and gillnet gear buoy lines and buoyant groundlines that are suspended in the water column (Johnson *et al.*, 2005). Entanglement most commonly occurs at the mouth or tail and most fatally when a whale becomes entangled with multiple body parts (Knowlton and Kraus, 2001). Incidental mortalities of harbour porpoises have occurred since the development of a gillnet fishery in the Bay of Fundy in the 1960s (Gaskin, 1992) and have since occurred throughout their range (Fontaine *et al.*, 1994; Gaskin, 1984; NMFS, 2006; Perrin *et al.*, 1994; Read and Gaskin, 1988; Trippel *et al.*, 1996; Vinther, 1999). The mechanism of entanglement of porpoises includes entanglement of flukes and/or other body parts followed by an inability to surface for air from the bottom-set gear.

In US waters, attempts to mitigate whale entanglements in fishing gear have included area closures, gear modifications and requirements regarding how gear is fished (Lyman and McKiernan, 2005; McKiernan, 2002). Some of these regulations are common to lobster pot and gillnet gear, for example, no portion of buoy lines can be floating at the surface[1]. Others are more gear specific, such as the general prohibition of straight set gillnets at night in southeast USA waters[1]. However, area closures do not fully cover movements of right whales and gear modifications have not yet reduced entanglement rates (Kraus *et al.*, 2005). In the 1980s, 52% of North Atlantic right whales showed signs of previous entanglements, while more recent estimates show almost three quarters of right whales have signs of having been entangled at least once (Knowlton *et al.*, 2003).

[1] Atlantic large whale take reduction plan regulations. Code of Federal Regulations Title 50, Part 229.32.

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A number of mitigation techniques have been used in an attempt to reduce incidental mortality of small cetaceans in gillnet fisheries. Time-area closures, in which areas of high porpoise density are closed to gillnet fishing during certain times of the year, and the required use of acoustic alarms or 'pingers' are in place for a number of areas in the northeast USA[2]. During initial trials, pingers were shown to be effective in reducing harbour porpoise bycatch (Kraus *et al.*, 1997; Trippel *et al.*, 1999) and their routine use in the northeast USA sink gillnet fishery began in 1999. However, the apparent utility of pingers as a mitigation tool has not translated into reduced bycatch in the commercial gillnet fishery in which mortalities have been increasing since 2001 (NMFS, 2006). Beyond this, numerous concerns exist surrounding the use of acoustic deterrent devices, such as habituation to sounds, mechanical failure, monitoring, noise pollution and habitat displacement (Culik *et al.*, 2001; Gearin *et al.*, 2000; Kastelein *et al.*, 2000).

Newer mitigation techniques in development involve altering the physical and/or chemical makeup of either the rope used for buoy and groundlines or the twine used to construct gillnet mesh material (Larsen *et al.*, 2007; Mooney *et al.*, 2007; Mooney *et al.*, 2004; Trippel *et al.*, 2003). These include the addition of barium sulphate[3] or other material to gillnet twine to reduce small cetacean bycatch by increasing its echolocation signature. Also, attempts have been made to reduce the breaking strength and decrease the buoyancy of gear rope through the addition of barium sulphate. Here the current status of development and effectiveness of mitigation techniques through the addition of barium sulphate to fishing gear rope and net twine are reviewed. Fishing products partly made of barium sulphate, which are relatively inexpensive to manufacturer, may serve to augment or replace current management measures that are in place to reduce the incidental mortality of cetaceans.

MATERIALS AND METHODS

Neutrally buoyant groundline

In October-November 2005 and March 2006, a field study was conducted to evaluate the behaviour of a barium sulphate modified lobster pot groundline. Standard polypropylene groundline is positively buoyant and presumably remains high in the water column causing increased risk of entanglement to large whales such as the North Atlantic right whale. The barium sulphate groundline of the same diameter was designed by Atlantic Gillnet Supply Ltd. (now Better Gear Inc.), to be neutrally or slightly negatively buoyant (density=1.04-1.06kg/m^3) after a call by the US government for industry to develop both neutrally buoyant and sinking groundlines. The relatively dense barium sulphate particles caused increased weight in the groundline and it was expected it would lead to it remaining lower in the water column, and in theory, lead to decreased risk of entanglement to large whales.

The behaviour of three types of 0.5" groundline rope were evaluated in natural conditions: (1) standard polypropylene rope that is positively buoyant and tends to float; (2) weighted, negatively buoyant rope; and (3) barium sulphate modified rope that was designed to be neutrally buoyant (20% barium sulphate by weight). The behaviour of each rope in the water column was monitored using depth sensors, DST milli, manufactured by Star-Oddi, Reykjavík, Iceland, which record depth (pressure) and temperature every five minutes. The dimensions of each cylindrical sensor were: length 4cm, diameter 1.2cm, weight 9g and with plastic housing each totalled 20g.

In 2005, a 150ft line was used composed of all three types of rope. Depth sensors were placed at the ends of each rope and on each rope at three stations evenly spaced between the anchors (Fig. 1a). The line was set approximately 500m from the wharf of the Biological Station in St. Andrews, New Brunswick in an area 20-25m deep on 5 October 2005 and left for 44 days, before being retrieved on 18 November 2005. In 2006, a 360ft line was used that was composed of two types of rope: standard polypropylene; and barium sulphate modified. The line was anchored at each end and at two other locations, at 120ft and 240ft (Fig. 1b). Between each set of anchors, three depth sensors were placed on each rope every 30ft (each rope within a line was of equal length). The line was set near the St. Andrews Biological Station in an area approximately 25m deep on 2 March 2006 and left for 7 days, being retrieved on 10 March 2006. To examine the potential effect of depth sensors on rope buoyancy, a 5m segment of 0.5" diameter floating polypropylene rope was placed in a tank at the Biological Station with a depth sensor and observed no effect on rope buoyancy at the point of sensor attachment.

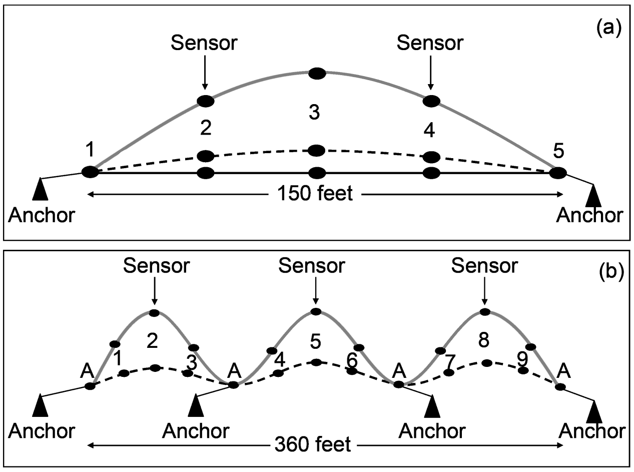

Fig. 1. Diagram of test gear configuration from the 2005 (a) and 2006 (b) study of mitigative groundline: weighted groundline – black, neutrally buoyant barium sulphate modified groundline – dotted, standard nylon groundline – grey. Numbers indicate stations (sites) at which depth sensors (black ovals) were secured. Stations 1 and 5 indicate anchor sensor stations in 2005 and 'A' indicates anchor sensor stations in the 2006 study.

Samples of the barium sulphate modified rope were also given to three fishermen for use in their lobster fishing gear configuration. One of these fishes from Metaghan, Nova Scotia in an area of rough bottom referred to as the McDormond Patch and used the sample provided in the winter of 2005/06. Two others, who fish from Grand Manan, New Brunswick, were given the barium sulphate modified rope in the summer of 2005. One of the Grand Manan fishermen used the sample provided on his gillnet gear for the rope segment from the anchor to one end of the net, whereas the other used it in lobster gear. All three participants fish in an area of extremely high tides (Bay of Fundy, Canada), which may affect net configuration and

[2] Harbor Porpoise Take Reduction Plan Implementing Regulations. Code of Federal Regulations Title 50, Parts 229.32 and 229.33.

[3] Barium sulphate is a white crystalline solid that has a very low solubility in water. It is used extensively as a radiocontrast agent in medical applications, as a white pigment for paint and as a high temperature oxidiser in pyrotechnics.

rope profiles. Samples of the rope being used by fishermen were collected and sent to Seaside Inc. in Warren, Maine for testing of breaking strength.

Weak rope

For over 20 years polypropylene rope, which is easy and inexpensive to produce, has been used in gillnets as 'head rope' or 'float line' i.e. the rope across the top of the net. However, observations of whale entanglements in gillnets have noted that it is this headrope that represents a danger to whales; in short, an entangled whale could break the netting and the sink rope at the bottom of the net but not the headrope. Based on these observations, the National Marine Fisheries Service (NMFS) called for a headrope that would break at 1,100lb in order to reduce the risk of fatal whale entanglements in US waters[4]. While there has been no call for specific gear changes in Canadian waters, entanglements in fixed fishing gear have been identified as a major threat to the population (COSEWIC, 2003) and a reduction of the impacts of encounters with fishing gear is a key aspect of the recovery strategy of the North Atlantic right whale in Atlantic Canadian waters (Brown *et al*., 2009).

There was no precedent for making a weaker head rope and several companies had previously tried to solve the problem through changing the draw ratio of the polypropylene (draw ratio is a measure of the degree of stretching during the orientation of a fibre or filament, expressed as the ratio of the cross-sectional area of the undrawn material to that of the drawn material). Normally the draw ratio is around seven, but by dropping it to two, a weaker product can be made. However this type of product has elasticity too great to be of use as a rope for gillnets. The approach applied in this study was to maintain the higher draw ratio to keep the elasticity low and to fill the fibres with 'foreign' materials that would not contribute to their strength[5]. Several means of doing this were tested. Starch was added, but this caused clogging of the extrusion die and the resulting rope fibres were inappropriate for use. A very fine grade of sodium chloride was evaluated but unless it was very dry there was clogging of the filtering screens (bridging), which shut down the extruder. Both of these, had they been successful, would have dissolved/biodegraded out of the fibres to leave a product with the density of polypropylene. Barium sulphate was investigated finally because it has a very low tendency to bridge in an extruder and gave a reproducible product that had good handling qualities.

Approximately 9.5km of 3/8" diameter barium sulphate modified head rope was made at Seaside Inc., Warren, Maine. This weak rope was considerably negative in buoyancy (50% barium sulphate by weight) and was dyed light purple in colour to distinguish it from other ropes. The weak rope was distributed for use among three fishermen in the lower Bay of Fundy, Canada (Fig. 2) in autumn 2003 and spring of 2004. Initially it was intended solely for the float lines of gillnets but was also used for gillnet end lines (end lines equal the height of a gillnet, 3-4m, and connect the bottom and float lines at the end of each gillnet mesh panel which typically measure around 100m in Canada) and as connecting lines in single and paired lobster pots which enabled a broader test of its possible application. A questionnaire was developed with both general and detailed questions to learn first-hand about how the rope was used and its appraisal by fishermen. Lengths of used weak rope

[4] Atlantic large whale take reduction plan regulations. Code of Federal Regulations Title 50, Part 229.32.

[5] United States Patent Application 20050155271.

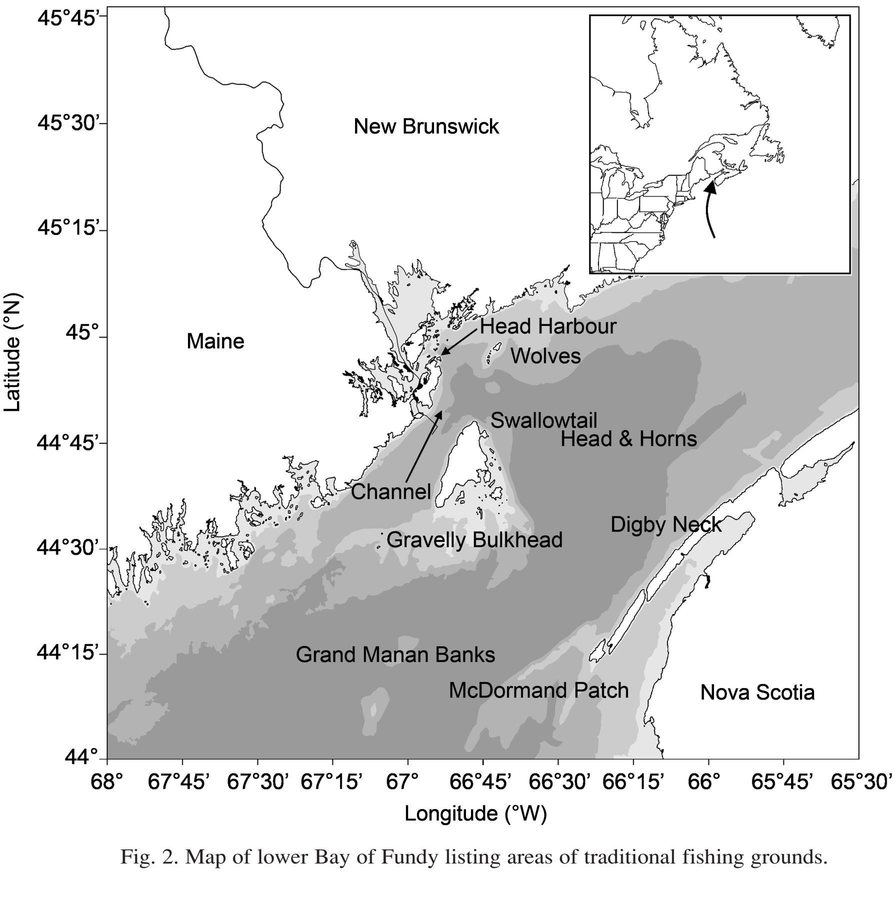

Fig. 2. Map of lower Bay of Fundy listing areas of traditional fishing grounds.

were sent to Seaside Inc. and in association with a local company undertook breaking strength tests of various segments of rope (16ft sample lengths) on a US government certified machine.

To gather more objective information on the weak rope's performance in field conditions, an outdoor experiment was set up at the St. Andrews Biological Station. The barium sulphate modified rope was exposed to sunlight and seawater over a four month period. The rope was suspended above the high tide level, below the high tide level but above the low tide level (intertidal) and below the low tide level. Standard polypropylene rope was also suspended above the high tide level. Breaking strength was measured at the start of the study and once a month, for four months. In order to determine longer-term performance, breaking strengths of ropes held above the high tide level and intertidal samples were measured after 24 months. It is extremely difficult to conduct a control-impact type study with weak rope. This is due to the relative rarity of right whale entanglements that would occur in an experimental setting over for example a two-year study period coupled with the limited amount of rope made available to fishermen. This is in contrast to harbour porpoise bycatch gillnet experiments in which entanglements are frequent enough to evaluate mitigative gear in a short period.

Acoustically reflective gillnets

From 1998 until 2001, Fisheries and Oceans Canada and others were part of an effort to develop and test the effectiveness of a barium sulphate modified gillnet mesh in reducing harbour porpoise bycatch (Trippel *et al.*, 2003). Two types of nylon monofilament mesh gillnets (strand diameter 0.57-0.60mm) were used, one in which the strands contained fine barium sulphate particles (3% by volume; 10% by weight) and another in which the strands were made of 100% nylon (used regularly worldwide). As barium is a heavy metal, it was assumed its presence would make gillnet mesh more reflective to echolocation signals produced by small cetaceans. The barium sulphate modified net was dyed pale blue to mask the white opaque colour of barium sulphate, whereas the standard nylon net was colourless and far more transparent. Gillnet strings used were 300m long (three 100m panels (mean was 3.02 panels ± 0.003 SE), 4m deep, had a stretched mesh size of 15cm, and were set at a depth of approximately 60m (mean depth was 59.1m ± 0.11 SE). Whenever possible, the strings were fished for 24 hours and retrieved daily (mean soak time was 26.2hr ± 0.29 SE).

As a part of this study, observers were placed onboard gillnet fishery vessels in the lower Bay of Fundy, Canada, in order to quantify porpoise and groundfish catches in both standard nylon mesh nets and barium sulphate mesh nets. Observer coverage in 1998 was augmented by fishing vessels that operated without an observer but who participated in a voluntary reporting programme on the effectiveness of the two types of gillnet mesh. In 1999, a number of fishing trips used mixed strings comprised of both standard nylon mesh panels and barium sulphate modified gillnet panels. Field coordination of the observer programme was provided by the Grand Manan Fishermen's Association (in 1998, 2000 and 2001) and Javitech Ltd (in 1999). Fishing took place from July-September and participation in the observer programme included six vessels in 1998 and three vessels in 2000 and 2001. Trained observers were used in each year except 1998. Observers were trained by Fisheries and Oceans Canada on detection and description of porpoise entanglement, identification of fish species, and recording of details of the characteristics of gillnet set location and duration. In 1998, voluntary reporting of this information was made by fishermen. As voluntary reports were only made in 1998 its inclusion as a model variable over all years would not be appropriate. However, the mean porpoise catch in voluntary reports (0.009 porpoise string^{-1}) was similar to that of observers (0.007 porpoise string^{-1}).

Typically, count data (e.g. the number of animals captured) are most appropriately modelled using discrete probability distributions such as the Poisson distribution when equi-dispersed (variance equals the mean), or the negative binomial distribution when over-dispersed (variance is greater than the mean). In the case of very rare count data, neither of these distributions adequately account for an excessive amount of zero observations. One way to approach the problem of zero-inflation is to use models that are a mixture of both the distribution of observed counts and an excess number of zero observations. A zero-inflated Poisson model (ZIP) was introduced by Lambert (1992) to account for an excess of zeros in counts of defects introduced during manufacturing processes. Since then, zero-inflated models have been slowly gaining popularity in ecology and have been used in applications such as species survey counts (Potts and Elith, 2006) and bycatch of rare species (Minami *et al.*, 2007).

For a ZIP model, given set of observed species counts $y_t = 1,...n$ and

$y_i = 0$, with a probability $1 - \pi(x)$

$y_i \sim Poisson[\lambda(z)]$, with a probability $\pi(x)$ such that

$P(Y=0 \mid x,z) = 1 - \pi(x) + \pi(x)e^{-\lambda(z)}$ and

$$P(Y=r \mid x,z) = \frac{\pi(x)e^{-\lambda(z)}\lambda(z)^r}{r!},\ r = 1, 2,\ldots$$

where $\pi(x)$ is the probability of the number of animals at a sample location that has a Poisson distribution and $\lambda(z)$ is the mean number of animals at the location. Both π and λ may depend on the same or a different group of covariates x and z, respectively (Cunningham and Lindermayer, 2005). In simple terms, species counts are modelled using a mixture of a logistic regression (when the counts equals zero) and a Poisson regression (when the counts are greater than zero).

Using a ZIP model in a generalised linear modelling framework, the effect of gillnet mesh type (standard nylon and barium sulphate modified), month and year on bycatch rate of harbour porpoise and fish were examined. In a generalised model framework, the zero mass is modelled using logistic regression while the observed catches are modelled using a Poisson error structure with a log link. All analyses were conducted in R v2.4.1, an open source statistical package (*http://www.r-project.org*). The analysis was limited to the Swallowtail area (Fig. 2) since other areas were not observed in all years and bycatch at Swallowtail comprised 92% of the total. The appropriateness of a Poisson model and a zero-inflated negative binomial model were also investigated however parameter estimates were very similar to those from the ZIP model and the latter was more parsimonious than the Poisson or zero-inflated negative binomial models as measured by Akaike's information criterion.

The effect of gillnet mesh type, month and year on fish catch rates were also investigated. Fish are relatively common in the gillnet catches and their distributions lacked an excessive probability mass at zero, thus zero-inflated models were not used. Instead a generalised linear model with a negative binomial model error structure and a log link was used, which is often appropriate for over-dispersed count data. The data were again limited to the Swallowtail area. The year 1999 was excluded from the statistical analysis due to the use of mixed mesh type strings. This is the first time the Bay of Fundy barium sulphate gillnet trial data have been published collectively and undergone external peer review. Previous analyses focused on using non-parametric methods to examine differences between catch rates in different mesh types for a limited data set (Trippel *et al*., 2003; Trippel and Shepherd, 2004). This analysis uses more advanced techniques to more accurately model the data and error distribution, and simultaneously examines multiple factors such as year and month. This allows the effect of each factor on catch rate to be resolved rather than just examining a single factor.

RESULTS

Neutrally buoyant groundline

The weighted and barium sulphate modified ropes showed smooth, cyclic changes in depth during the first 40 hours of being set which corresponded to changes in water height due to daily tidal cycles (Figs 3 and 4). The depth of the standard polypropylene rope showed a similar cycle as well as the addition of short-cycle variations, likely due to water turbulence from currents and waves (Figs 3 and 4). The barium sulphate modified rope was consistently higher in the water column than the weighted rope, while the standard polypropylene rope was consistently the highest in the water column and showed a higher variation in depth, again likely due to the short-cycle variation from water turbulence (Table 1). Exhibiting 40 hours of recording of the rope profiles over approximately three tidal cycles permitted examination of the depth variation that could occur during a typical single set of a lobster trawl. At times, polypropylene rope had floated quite high in the water column such that it was 15m higher than barium sulphate modified and weighted ropes (Figs 3 and 4), though the mean difference commonly ranged from 3 to 6m (Table 1). Over the 7 days of the 2006 study, there was no discernible pattern in mean depth change compared to the first 40 hours for either the polypropylene rope or the barium sulphate modified rope (Table 1).

Comments on the barium sulphate modified rope were available from the fishermen from Metaghan, Nova Scotia and Grand Manan, New Brunswick. The general impression of a fisherman from Nova Scotia was that the composition of the barium sulphate modified rope could not withstand the wear and tear in the rough area he fishes, the McDormond Patch, off Southwest Nova Scotia. He reported excessive fraying and chaffing in the rope, which broke twice while gear was being hauled. After two weeks of use, he abandoned the barium sulphate modified rope completely out of fear of losing his fishing gear. Normally, he uses 0.5" Polysteel® groundline that lasts 3-4 years in the rough area he fishes and has a breaking strength of 5,100lb. The lobster fisherman from Grand Manan expressed similar concerns. After three weeks of fishing over rough grounds, chaffing had occurred to the rope and he had lost some gear.

Weak rope

The breaking strength of unused barium sulphate modified rope was 1,065lb (SE=13.7) compared to 2,471lb (SE=42.0) for polypropylene rope (Table 2). In the controlled study of rope strength changes over the first four months there was little indication of weakening and no apparent effect of exposure location (Table 2). Breaking strengths of

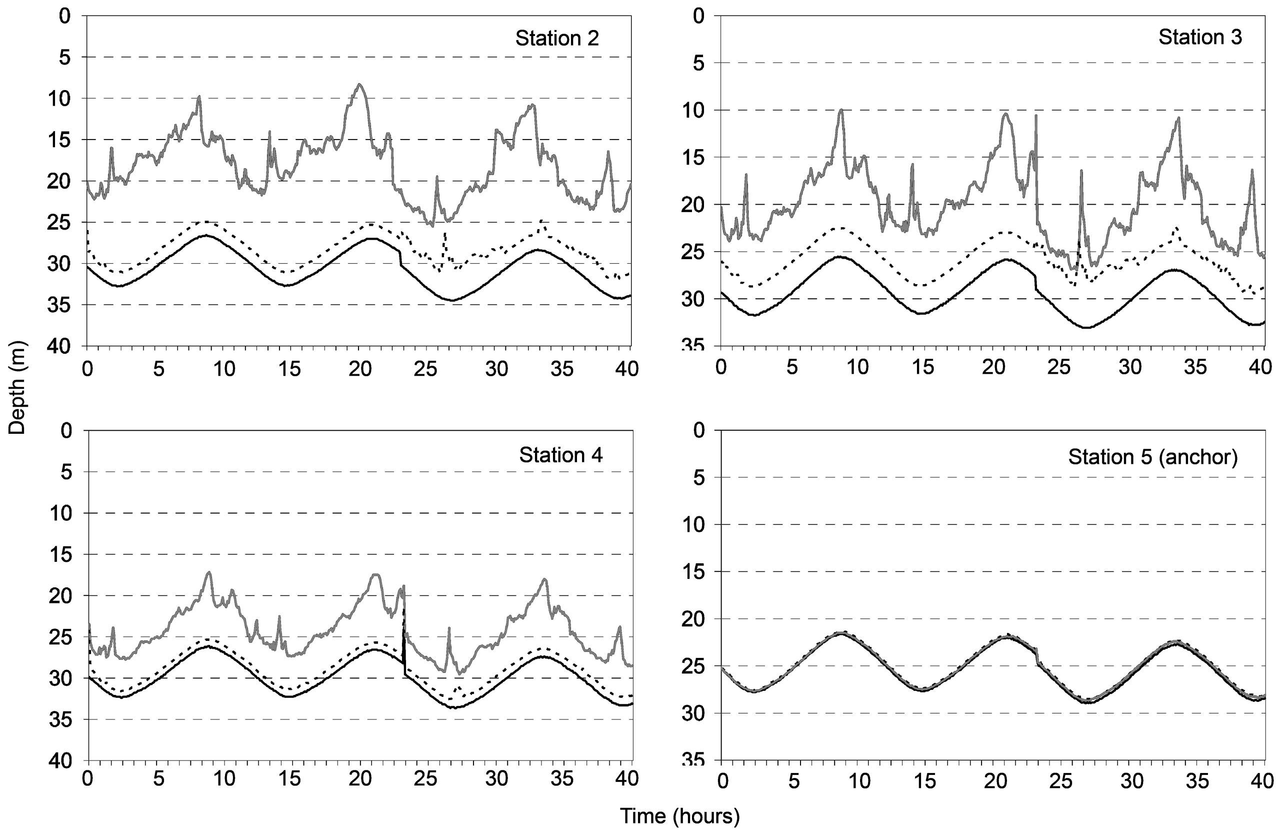

Fig. 3. Time series of depth over the first 40 hours of the 2005 neutrally buoyant groundline study: weighted rope – black, barium sulphate modified rope – dotted, standard polypropylene rope – grey. The sensor on station 1 (anchor) failed during deployment.

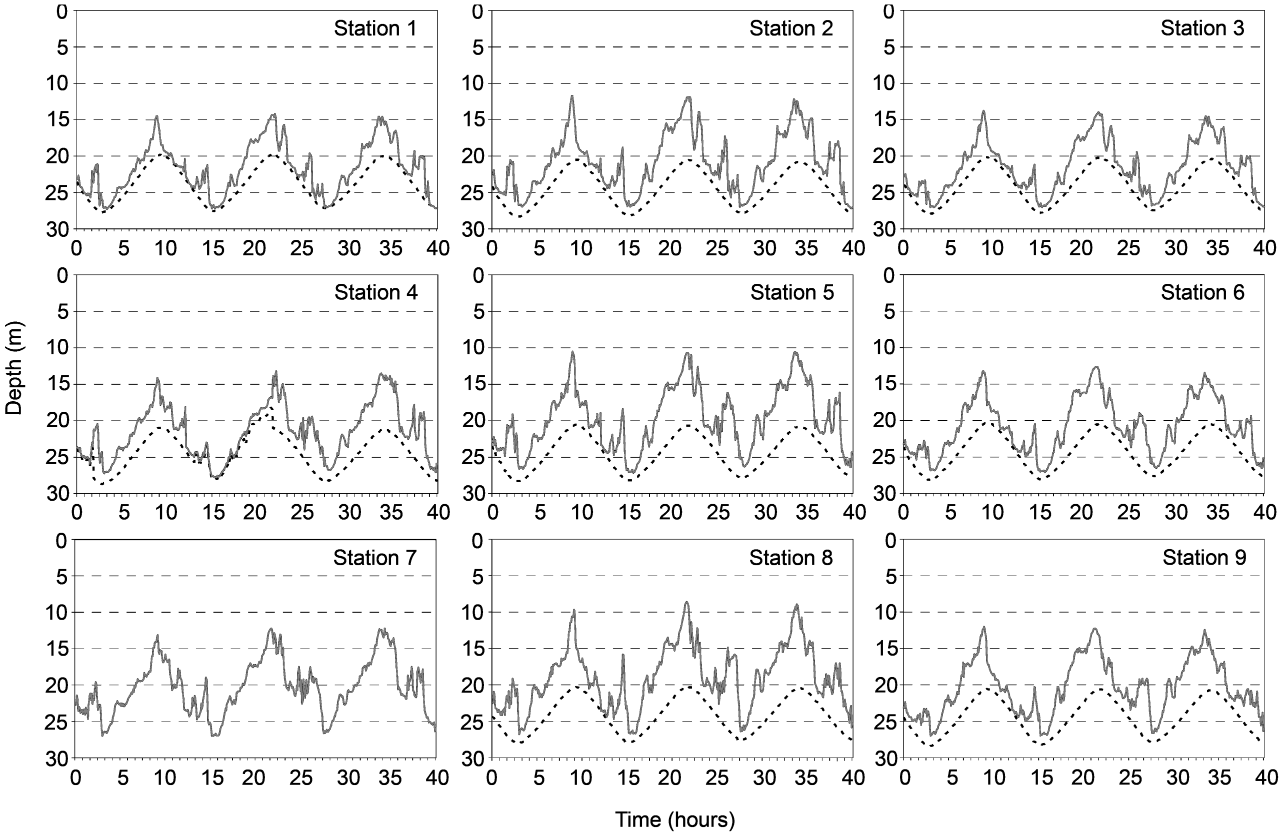

Fig. 4. Time series of depth over the first 40 hours of the 2006 neutrally buoyant groundline study: barium sulphate modified rope – dotted, standard polypropylene rope – grey. The station 7, barium sulphate modified rope sensor failed during deployment.

Table 1

Mean depth (standard error in parentheses) of each 0.5" rope type, over the first 40h and 7 days for the 2005 and 2006 neutrally buoyant groundline study. Stations designated with an 'A' are anchor sites and $BaSO_4$ represents barium sulphate modified rope.

2005			2006			
		40 hours			40 hours	7 days
Station	Rope	Depth (m)	Station	Rope	Depth (m)	Depth (m)
2	Weighted	26.1 (0.02)	A1	N/A	23.7 (0.11)	23.7 (0.05)
	$BaSO_4$	24.3 (0.02)	A2	N/A	24.8 (0.11)	24.8 (0.05)
	Polypropylene	16.2 (0.03)	A3	N/A	24.7 (0.11)	24.6 (0.05)
3	Weighted	24.9 (0.02)	A4	N/A	24.6 (0.11)	24.4 (0.05)
	$BaSO_4$	21.9 (0.02)	1	$BaSO_4$	23.9 (0.12)	23.9 (0.05)
	Polypropylene	18.3 (0.03)		Polypropylene	21.7 (0.16)	20.9 (0.07)
4	Weighted	25.3 (0.02)	2	$BaSO_4$	24.5 (0.11)	24.4 (0.05)
	$BaSO_4$	24.5 (0.02)		Polypropylene	20.8 (0.18)	19.6 (0.08)
	Polypropylene	21.0 (0.02)	3	$BaSO_4$	24.1 (0.11)	24.1 (0.05)
5	Weighted	20.8 (0.02)		Polypropylene	21.5 (0.16)	20.6 (0.08)
	$BaSO_4$	20.5 (0.02)	4	$BaSO_4$	24.5 (0.12)	24.8 (0.05)
	Polypropylene	19.8 (0.04)		Polypropylene	21.5 (0.17)	20.5 (0.08)
			5	$BaSO_4$	24.5 (0.11)	24.4 (0.05)
				Polypropylene	19.8 (0.20)	18.7 (0.09)
			6	$BaSO_4$	24.3 (0.11)	24.2 (0.05)
				Polypropylene	20.8 (0.17)	20.1 (0.07)
			7	$BaSO_4$	N/A	N/A
				Polypropylene	20.3 (0.17)	19.4 (0.08)
			8	$BaSO_4$	24.2 (0.11)	24.0 (0.05)
				Polypropylene	18.9 (0.19)	17.7 (0.09)
			9	$BaSO_4$	24.5 (0.11)	24.3 (0.05)
				Polypropylene	20.4 (0.18)	19.6 (0.07)

commercially deployed barium sulphate modified rope used by one fisherman showed similar breaking strengths (1,043lb and 1,039lb) to the barium sulphate rope in the controlled study (Table 2). The standard polypropylene rope used by this fisherman had a breaking strength of 2,851lb. A second fisherman used the barium sulphate modified rope in lobster pot lines over a period of three months. The rope was hauled approximately 75 times over hard rock bottom during that time period. After three months of use and three months of outdoor storage, the breaking strength of the barium sulphate rope had dropped to 932lb (SE=22.4; Table 2). Samples of standard rope used by the second fisherman varied from a maximum of 3,196 to 1,960lb. Both the barium sulphate modified rope and the standard polypropylene rope exposed to ambient, non-submerged conditions for 24 months lost a significant amount of their strength (Table 2). The intertidal barium sulphate modified rope retained most of its strength over the same 24 months.

In their questionnaires, the fishermen were generally positive about the performance of the weak rope, giving it an average of 8.3/10 on a subjective ranking scale (full questionnaire results available from authors upon request). One fisherman liked the smaller diameter of the weak rope, which he believed caused it to be less affected by currents. The second fisherman reported the weak rope broke once when it was caught on the bottom but otherwise reported no problems and was interested in using it again. The third fisherman was positive but did not complete the questionnaire.

Acoustically reflective gillnets

Over the entire four year period, 52 porpoise captures were observed in three areas: Swallowtail, the Wolves and Gravelly Bulkhead (Table 3; Fig. 5), although minimal observer coverage occurred elsewhere. All but four porpoise captured were observed at Swallowtail and two of the porpoise catches at the Wolves were in standard nylon mesh panels within strings using a combination of standard nylon

Table 2

Mean breaking strengths (standard error in parentheses) of 3/8" barium sulphate ($BaSO_4$) modified 'weak' rope and standard polypropylene ropes from both a controlled exposure study and after commercial applications.

Controlled study					Commercial application					
Rope	Depth	Time (months)	Ropes tested	Breaking strength (lb)	Rope	Source	Age	Ropes tested	Breaking strength (lb)	Description
$BaSO_4$	N/A	0	6	1,065 (13.7)	$BaSO_4$	1	16d	2	1,043 (7.0)	Head line
	0	1	3	1,048 (12.8)				3	1,039 (18.9)	End line
		2	3	1,072 (15.6)	Polypropylene	1	6-10y	3	2,851 (6.5)	Head and end lines
		3	3	1,041 (9.9)	$BaSO_4$	2	3mo	3	932 (22.4)	Lobster gear
		4	3	1,036 (12.1)	Polypropylene	2	8y	3	1,960 (49.4)	3/8in prickly twisted
		24†	4	385 (6.2)			5y	3	3,196 (29.5)	3/8in twisted
	Intertidal	1	6	1,059 (21.0)			9y	3	2,025 (34.4)	5/16in hard lay
		2	3	1,028 (13.5)			8y	3	2,062 (261.8)	Twisted
		24	3	961 (11.6)						
	Submerged	1	6	1,084 (9.4)						
		2	3	1,032 (22.2)						
Polypropylene	N/A	0	2	2,471 (42.0)						
	0	1	2	2,415 (130.0)						
		2	2	2,165 (18.0)						
		3	2	2,058 (2.5)						
		4	2	2,426 (16.0)						
		24†	4	587 (37.1)						

†24 month samples of zero depth ropes were continuously exposed to ambient, non-submerged conditions by being placed on a roof of a nearby building.

Table 3

Summary of vessel participation, fishing effort and harbour porpoise catches in a barium sulphate ($BaSO_4$) modified gillnet study near Swallowtail, Grand Manan, New Brunswick.

		Nylon mesh nets				$BaSO_4$ mesh nets			
Season	Vessels observed	Strings fished	Porpoise captured	Porpoise per string when captured	Probability of not capturing at least one porpoise	Strings fished	Porpoise captured	Porpoise per string when captured	Probability of not capturing at least one porpoise
1998									
Jul. 01-15	6	136	3	3.00	0.9926	25	0	-	1.000
Jul. 16-31	4	42	0	-	1.0000	23	0	-	1.000
Aug. 01-15	3	20	1	1.00	0.9500	5	0	-	1.000
Aug. 16-31	1	7	0	-	1.0000	2	0	-	1.000
Sep. 01-15	0	0	0	-	1.0000	0	0	-	1.000
2000									
Jul. 01-15	0	0	0	-	1.0000	0	0	-	1.000
Jul. 16-31	3	58	2	1.00	0.9655	33	0	-	1.000
Aug. 01-15	3	90	3	1.00	0.9667	51	0	-	1.000
Aug. 16-31	3	80	0	-	1.0000	50	0	-	1.000
Sep. 01-15	0	0	0	-	1.0000	0	0	-	1.000
2001									
Jul. 01-15	3	63	7	1.17	0.9048	64	3	1.00	0.9531
Jul. 16-31	3	110	9	1.13	0.9273	104	6	1.00	0.9423
Aug. 01-15	3	68	1	1.00	0.9853	82	2	1.00	0.9756
Aug. 16-31	3	86	3	1.00	0.9651	92	1	1.00	0.9891
Sep. 01-15	3	55	3	1.00	0.9455	59	4	1.00	0.9322

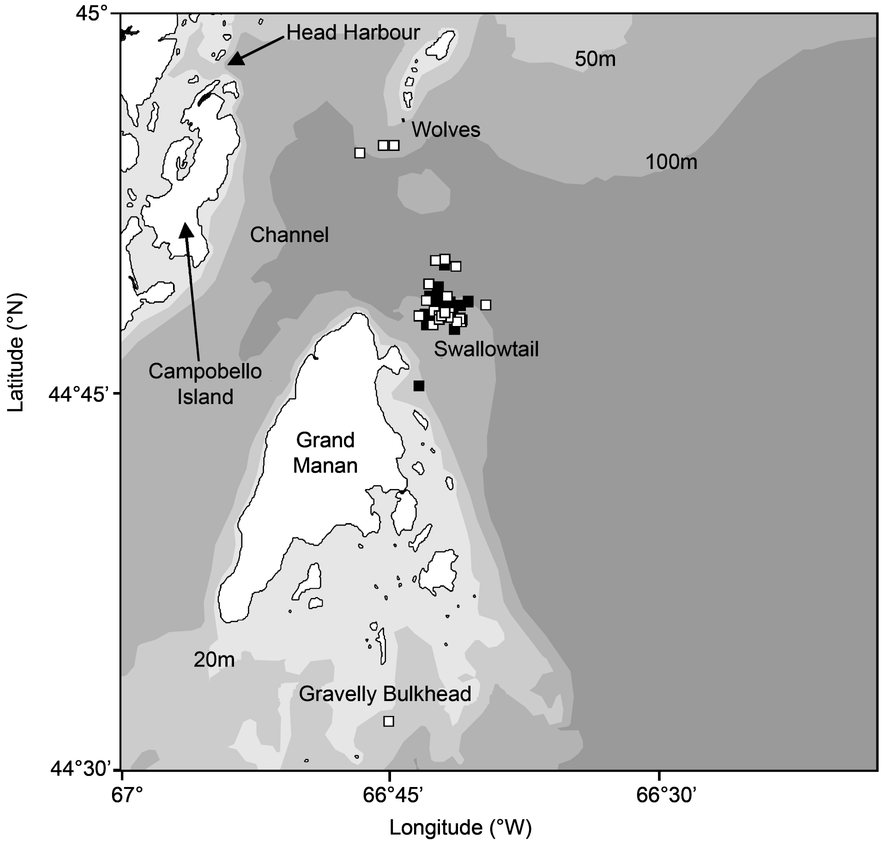

Fig. 5. Map of all observed porpoise mortalities in the lower Bay of Fundy demersal gillnet fishery from 1998-2001 (n=52). White squares represent mortalities in 100% nylon-mesh nets while solid squares represent mortalities in barium sulphate nets.

and barium sulphate modified panels. For the Swallowtail region, porpoise were not captured in the barium sulphate modified gillnets while four and five were caught in the standard nylon nets in 1998 and 2000, respectively (Table 3). In 2001, 16 porpoise were captured in barium sulphate modified nets (401 strings fished) while 23 were captured in standard nylon nets (382 strings fished).

The ZIP model for porpoise bycatch showed significant effects of year and mesh type on harbour porpoise bycatch (Table 4). On a monthly basis, harbour porpoise catch rates in the barium sulphate gillnets were consistently lower than in nylon mesh gillnets with the exception of September 2001 (Fig. 6). For the Poisson portion of the model, which evaluates catch rates when at

Table 4

Results of models testing the effect of gillnet mesh type on catch rates of harbour porpoise, cod, pollock, haddock and spiny dogfish. For the zero-inflated Poisson model, the Poisson regression part models the positive catches only (catch rate when at least one porpoise was captured) while the logistic regression part models the probability of catching no porpoise. Statistical significance levels for model estimates are * ≤0.05, **≤0.01, ***≤0.001, otherwise non-significant. SE=standard error.

Harbour porpoise zero-inflated Poisson model

Poisson regression part			Logistic regression part		
Factor	Coefficient	SE	Factor	Coefficient	SE
Nylon	1.83*	0.769	Nylon	1.95	1.316
Year 2000	-4.06***	0.806	Year 2000	-17.03	579.58
Year 2001	-1.23	0.797	Year 2001	-3.06**	0.956
August	-0.94	0.645	August	0.23	0.970
September	-0.31	0.8774	September	-0.30	1.163
Intercept	-1.08	1.097	Intercept	2.92*	1.402

Finfish negative binomial models

Factor	Cod	SE	Haddock	SE	Pollock	SE	Dogfish	SE
Nylon	0.02	0.059	0.42*	0.162	0.190	0.118	0.03	0.099
Year 2000	0.88***	0.099	1.72***	0.240	0.666**	0.252	0.38*	0.162
Year 2001	1.22***	0.086	-0.32	0.247	1.489***	0.216	0.31*	0.140
August	-0.43***	0.064	-0.16	0.171	-0.364**	0.129	0.30**	0.110
September	-0.98***	0.115	-1.51*	0.686	-0.139	0.196	0.44*	0.188
Intercept	1.49***	0.085	-0.83***	0.233	-1.508***	0.219	3.28**	0.138

least one porpoise is captured, the year 2000 was significantly lower than 1998 (Table 4). The logistic portion of the model, which evaluates the probability of not capturing at least one porpoise, indicated that the probability of not capturing any porpoises was significantly lower in 2001 than in 1998 (Table 4). The model results are supported by the observed data wherein catch rates of porpoise, when at least one was captured, was 1.0 porpoise per string in 2000, while the probability of not capturing at least one porpoise was less than one for all cases in 2001 (Table 3).

This resulted in a significant effect of mesh type where catch rates of harbour porpoise in nylon mesh gillnets were significantly higher than in barium sulphate mesh gillnets (p=0.017). Only haddock (*Melanogrammus aeglefinus*) catch rates were affected by mesh type (p=0.010; Table 4) where standard nylon nets were 1.5 times (95%CI=1.1-2.1 times) more efficient than barium sulphate modified nets. On a monthly basis, catch rates of haddock were lower in barium sulphate modified nets except August 2001 (Fig. 6). Mesh type did not have a significant effect on catch rates of Atlantic cod (*Gadus morhua*) (p=0.726), pollock (*Pollachius virens*) (p=0.109) or spiny dogfish (*Squalus acanthias*) (p= 0.727; Table 4).

DISCUSSION

Given the precarious population status of many marine mammals worldwide, effective protective measures must be put into place to mitigate external sources of mortality. Barium sulphate modified fishing gear shows considerable promise as a mitigation tool to reduce bycatch in Northwest Atlantic gillnet and lobster pot fisheries. The addition of barium sulphate to rope can result in both a lower profile in the water column and a lower breaking strength. The advantages of this are two fold. First, the probability of large whales becoming entangled in negatively buoyant lines should be reduced over lines that maintain a high profile and remain suspended in the water column. If by chance, a large whale did become entangled in barium sulphate modified rope such as in the headrope of a gillnet, it would be able to break free much easier as its breaking strength was found to

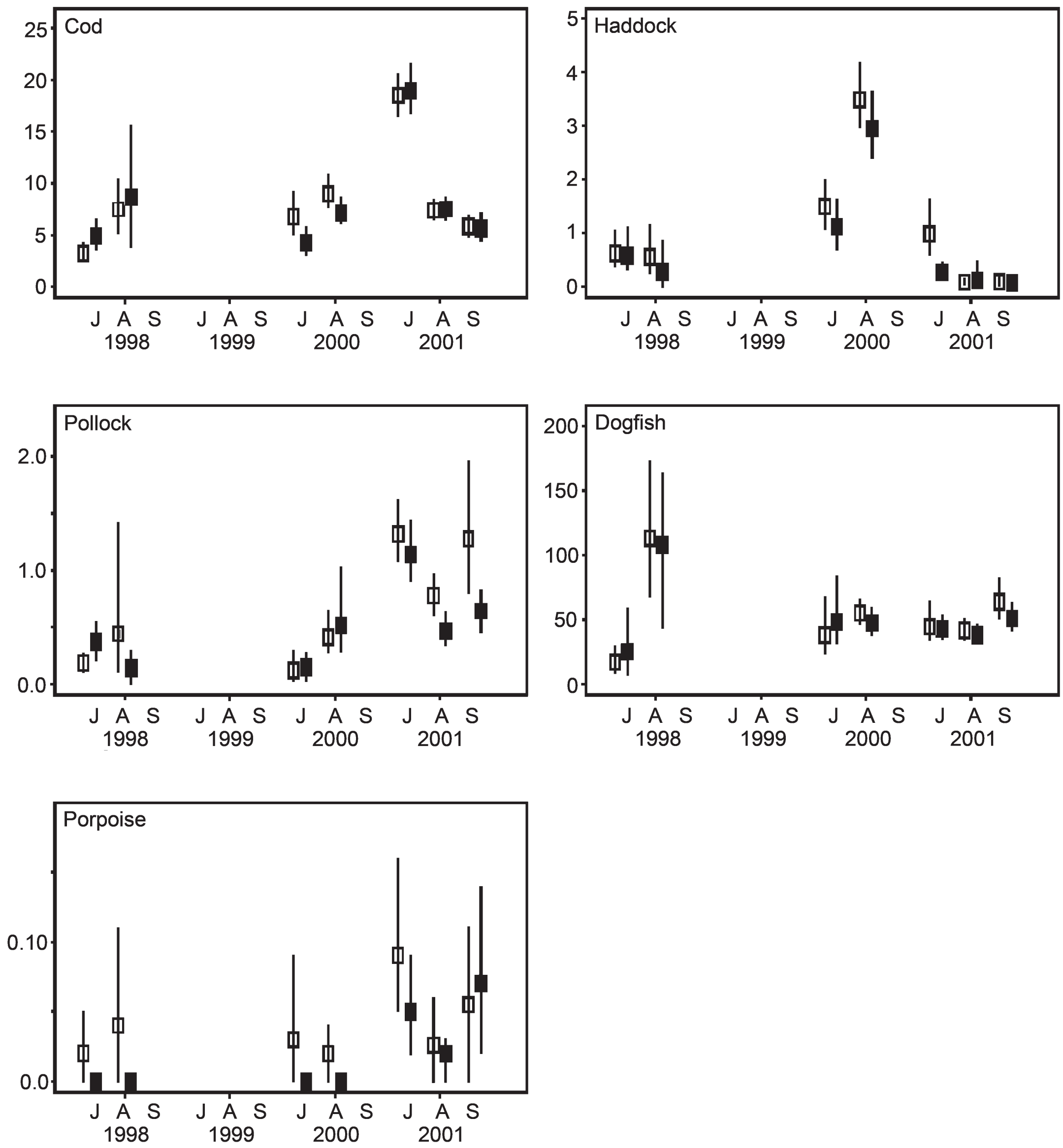

Fig. 6. Observed harbour porpoise and groundfish catch rates in gillnets (white: nylon mesh, black: barium sulphate mesh) in the Swallowtail area of Grand Manan, New Brunswick from 1998 to 2001 during the months of July (J), August (A) and September (S). 1999 results are not shown as mixed-mesh panel gillnets were used in this year. Vertical bars represent 95% confidence intervals.

be less than half of that of traditional polypropylene rope (Table 2). Additionally, in all cases when the breaking strength of barium sulphate modified rope was measured, it was below legislated limits required for fishing gear in many US waters.

Barium sulphate modified gillnets were also found to be effective in reducing harbour porpoise bycatch. The premise under which this gillnet material was designed was that the addition of a heavy metal salt to the nylon monofilaments would increase the echolocation signature or target strength of the nets. While this at first seems intuitive, others have found that harbour porpoise echolocation behaviour did not change in the presence of barium sulphate modified gillnets and have suggested reductions in bycatch were instead associated with the increased stiffness of the nets (Cox and Read, 2004). In a later study, Koschinski *et al.* (2006) found the distribution of harbour porpoise click intervals shifted to longer intervals when approaching a barium sulphate modified gillnet. They were able to estimate that harbour porpoise could detect the barium sulphate nets 4.4m in advance of regular nylon monofilament gillnets. However, they also found only 30% of individuals were actively echolocating when near the net and recommended the use of 2.5kHz warning tones to cause increased echolocation activity and thus an increased probability of a porpoise detecting the net. No gillnet field trials to date have been conducted that integrated barium sulphate nets with warning sounds.

The acoustic properties of barium sulphate modified gillnets have been evaluated in a number of studies (Koschinski *et al.*, 2006; Larsen *et al.*, 2007; Mooney *et al.*, 2007; Mooney *et al.*, 2004; Trippel *et al.*, 2003). Using 200kHz multibeam sonar, Trippel *et al.* (2003) found that barium sulphate gillnets were approximately three times (2.6-3.3) more acoustically reflective than standard, nylon mesh gillnets. While most of the energy of the harbour porpoise echolocation click is between 140-160kHz (Au *et al.*, 1999), they argued that these frequencies the acoustic reflectivity will be only slightly less than at 200kHz. In addition, sonar tests in the frequency range of 110-190kHz showed that the target strength of barium sulphate modified gillnets was 7.2dB higher than the target strength of standard nylon mesh nets at 150kHz (Koschinski *et al.*, 2006). In another study, Mooney *et al.* (2004) evaluated the acoustic reflectivity of barium sulphate modified gillnets using signals of 80μs in duration, with a peak frequency of 120kHz and a 3dB bandwidth of 35kHz. After measuring reflectivity at a number of incident angles, they found target strength, and thus acoustic reflectivity, was higher for barium sulphate gillnets as compared to standard nylon mesh gillnets (Mooney *et al.*, 2007; Mooney *et al.*, 2004). However, they argued that given the relatively small increase in detection distances achieved by the barium sulphate gillnets and the swimming speed of small cetaceans, it is not clear if they could detect the modified gillnets in time to avoid entanglement.

The reduction in harbour porpoise bycatch found for barium sulphate modified gillnets may also be partially due to increased stiffness. Beyond their increased acoustic reflectivity, these nets have been shown to have an increased stiffness over regular nylon mesh gillnets (Mooney *et al.*, 2007). Increased stiffness would be expected to reduce catches of both the echolocating porpoise and fish. In this study, reduced catches of haddock were found in barium sulphate modified gillnets, which perhaps could be explained through increased stiffness. This hypothesis has been previously suggested as the reason for reduced porpoise entanglements in chemically modified gillnets (Cox and Read, 2004). Given the modified behaviour of porpoise in the vicinity of barium sulphate modified gillnets (Koschinski *et al.*, 2006) and the increased acoustic target strength of these nets (Mooney *et al.*, 2007; Mooney *et al.*, 2004), it is likely reduced bycatch results from both the increased acoustic reflectivity and stiffness. The original intention of using barium sulphate was to simply increase target strength, though the increase in stiffness was an additional benefit that was unexpected.

Barium sulphate is inexpensive and commercially available and was therefore considered a good candidate substance to be used to explore modifications that aim to reduce cetacean bycatch; other products that may have a similar effect include lead and stainless steel, though these would be confined to use as added strands within rope to achieve negative buoyancy. The barium sulphate is purchased as 'blanc fixe', a white solid with a particle size under 1μm. Barium sulphate has the chemical code of CAS No. 7727-43-7; the Material Safety Data Sheet reveals that while the pure powder should not be ingested, the skin contact is listed as 'no adverse effects expected'. No adverse effects are expected when barium sulphate is encased in nylon. Due to the low solubility of barium sulphate in seawater, the concentration of barium in solution in seawater cannot rise high enough to represent a toxic risk to marine organisms (Neff, 2002).

Barium sulphate modified fishing gears are not without their drawbacks. Most notably, the 20% barium sulphate 0.5" rope when used with lobster gear appears to be susceptible to chaffing and subsequent failure when used over rough fishing grounds. This was a concern of more than one fisherman. In many applications, the gear would be fished over sandy bottoms so this would not be a major concern, however within the Bay of Fundy, fishing over rocky bottoms is common. Field testing over rocky bottoms of other types of neutrally buoyant rope for groundlines of lobster trawl is required and is underway.

In controlled field trials, acoustic alarms have been shown to be more effective than barium sulphate modified gillnets in reducing porpoise entanglements (Kraus *et al.*, 1997; Trippel *et al.*, 1999). However, the relatively high catch rates in the barium sulphate modified gillnets in 2001 may be related to an unusually high abundance of harbour porpoise in the area that year as measured from herring (*Clupea harengus*) weir entrapments (Trippel and Shepherd, 2004). Despite the possibility of being less efficient than acoustic alarms in controlled tests, barium sulphate gillnets are silent, do not require an external power source and are otherwise operationally identical to standard nylon gillnets. As such, they avoid many of the disadvantages associated with the long-term deployment of pingers (non-compliance, loss or breakage, low battery power or non-replacement of batteries, and the need to maintain an additional piece of gear). Further, compared to regular nylon mesh gillnets, the cost of barium sulphate modified nets should be comparable and they are expected to have a 10-15% longer lifespan due to the presence of barium sulphate and the manufacturing process (this is based upon the properties of nylon in other manufacturing operations where adding a solid makes the nylon more durable). Thus, barium sulphate modified nets may be more readily adopted by fishermen than pingers and hold considerable promise in not only reducing harbour porpoise entanglements but are also worth exploring for other small cetacean bycatch problems.

Cetaceans in the Northwest Atlantic are facing continued and increasing human-induced mortalities despite considerable restrictions on fishing activity (Kraus *et al*., 2005; NMFS, 2006). Suggested measures to reduce entanglement mortalities include reductions in pot gear fishing effort (Kraus *et al*., 2005; Myers *et al*., 2007). Other mitigative solutions have suggested the use of alternative rope types to reduce entanglement deaths (Kraus *et al*., 2005). Barium sulphate modified rope, which is negatively buoyant and at the same time, weaker than standard rope, provides such an alternative. Barium sulphate modified nets appear to be a possible method to reduce harbour porpoise bycatch in the gillnet fishery, which has seen increasing mortalities in the US Northwest Atlantic since 2001 (NMFS, 2006). We believe the use of mitigative solutions, such as barium sulphate modified fishing gear, will be able to play an important role in future management measures aimed at reducing cetacean mortalities.

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