

# Mitigation of harbour porpoise (*Phocoena phocoena*) by-catch in the gillnet fishery in the lower Bay of Fundy

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**Abstract:** Demersal gill nets equipped with acoustic alarms reduced harbour porpoise (*Phocoena phocoena*) by-catch rates by 77% over those without alarms in the Swallowtail area of the lower Bay of Fundy during field testing in August 1996 (68% reduction) and 1997 (85% reduction) (both years combined, three harbour porpoises in 249 alarmed nets versus 14 harbour porpoises in 267 nonalarmed nets). The alarms spaced 100 m apart along the net floatline produced a 0.3-s pulse at 10–12 kHz every 4 s at a level of 133–145 dB re 1  $\mu$ Pa at 1 m. In conditions of no rain and low wind (Sea State 0–2) the alarms were presumed to be clearly audible to harbour porpoises at ranges of 0.1–0.6 km. Catch rates of Atlantic herring (*Clupea harengus*), Atlantic cod (*Gadus morhua*), and pollock (*Pollachius virens*) were not significantly different in alarmed and nonalarmed nets (except in one season when pollock were caught in lower numbers in alarmed nets). Harbour porpoise by-catch and herring movements may be linked. During years of low herring abundance, we also observed low harbour porpoise entanglement rates.

**Résumé :** Les filets maillants de pêche démersale équipés d'avertisseurs acoustiques ont réduit le taux de prises accessoires de marsouin commun (*Phocoena phocoena*) de 77% par rapport aux filets sans avertisseurs dans la région de Swallowtail, à l'entrée de la baie de Fundy, pendant les essais sur le terrain menés en août 1996 (réduction de 68%) et en 1997 (réduction de 85%) (pour les deux années combinées, trois marsouins communs capturés dans 249 filets avec avertisseurs par rapport à 14 marsouins communs dans 267 filets sans avertisseurs). Les avertisseurs placés à intervalle de 100 m le long de la ralingue supérieure du filet émettaient une impulsion de 0,3 s à une fréquence de 10 à 12 kHz à toutes les 4 s à un niveau de 133 à 145 dB, soit 1  $\mu$ Pa à 1 m. En l'absence de pluie et par vent léger (état de la mer 0–2), les avertisseurs devaient être nettement audibles pour les marsouins communs entre 0,1 et 0,6 km. Les taux de capture du hareng atlantique (*Clupea harengus*), de la morue franche (*Gadus morhua*) et de la goberge (*Pollachius virens*) n'étaient pas significativement différents pour les filets avec et sans avertisseurs (sauf au cours d'une saison où la goberge a été capturée en plus faible quantité dans des filets avec avertisseurs). Il peut y avoir un lien entre les prises accessoires de marsouin commun et les déplacements du hareng. Pendant les années de faible abondance du hareng, nous avons également observé peu de cas où les marsouins communs se prenaient dans les filets.

[Traduit par la Rédaction]

## Introduction

Marine mammal – fishery interactions are becoming of increasing concern to those involved in the conservation of marine living resources. In the early 1990s, the annual incidental mortality of harbour porpoise (*Phocoena phocoena*) in demersal gill nets in the Bay of Fundy and Gulf of Maine was estimated to be ~3–4% of the population size (Trippel et al. 1996a; Bravington and Bisack 1996) (Table 1). This level of mortality is comparable with the estimated annual growth rate of this population (Woodley and Read 1991; Blaylock et al. 1995). In the lower Bay of Fundy, harbour

porpoise by-catch rate peaks during August such that ~75% of the annual mortalities occur during this month on two fishing grounds known as the Swallowtail and Wolves areas (Trippel et al. 1996a) (Fig. 1). Therefore, a localized short-term closure is one means of reducing harbour porpoise by-catch in the lower Bay of Fundy. However, gillnet fishers find this action undesirable, as groundfish landings during August typically comprise ~40% of annual landings (Fig. 2).

Acoustic alarms that emit high-frequency pulsed sounds seem to be a promising alternative to seasonal area closures. An experimental study demonstrated that alarms (fundamental frequency 10–12 kHz) were effective in reducing harbour

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**Table 1.** Estimates of harbour porpoise population size and by-catch for the Gulf of Maine, U.S.A., and Bay of Fundy, Canada (1990–1996).

Year	Population size	By-catch		Source
		Gulf of Maine	Bay of Fundy	
1990		2900 (1500–5500)		Bravington and Bisack 1996
1991	37 500 (26 700 – 86 400)	2000 (1000–3800)		Palka 1995a; Bravington and Bisack 1996
1992	67 500 (32 900 – 104 600)	1200 (800–1700)		Palka 1995a; Bravington and Bisack 1996
1993		1400 (1000–2000)	424 (200–648) <sup>a</sup>	Bravington and Bisack 1996; Trippel et al. 1996a
1994		2100 (1400–2900)	101 (80–122)	Bisack 1997; Trippel et al. 1996a
1995	74 000 (40 900 – 109 100)	1400 (900–2500)	87	Palka 1995a; Bisack 1997; Trippel et al. 1996b
1996		1200 (800–1400)	20–50	Anonymous 1998; DFO 1998
1997			43	DFO 1998
1998			10	DFO 1998

**Note:** Harbour porpoises in the Gulf of Maine and Bay of Fundy are considered to form a separate subpopulation (Wang et al. 1996). Ranges in parentheses are 95% confidence limits.

<sup>a</sup>Range in parentheses is  $\pm 1$  SE.

porpoise entanglements in demersal gill nets on Jeffreys Ledge, Gulf of Maine (Kraus et al. 1997). Variable success was obtained in reducing harbour porpoise by-catch rate, however, when using alarms of a different design (broad-range frequency 1–25 kHz) (Fullilove 1994; Lien et al. 1995; Gearin et al. 1998). Strong et al. (1995), Kastelein et al. (1997), and Laake et al. (1998) studied the potential for negative effects of alarms and suggested that sound levels that are too high may lead harbour porpoises to avoid commonly used habitat.

Predator–prey interactions might influence the regional distribution of harbour porpoise and thus be a significant factor in the design of long-term measures to reduce by-catch across the population's range. Harbour porpoise typically enter the Bay of Fundy in early July, reach their peak abundance in August, and then diminish in abundance during September when many return to the Gulf of Maine (Gaskin and Watson 1985; Palka 1995b; Westgate and Read 1995; Trippel et al. 1996a). This northward migration in summer followed by southward movements in autumn may be related to the migration of Atlantic herring (*Clupea harengus*), their principal prey (Creaser et al. 1984; Gaskin and Watson 1985; Recchia and Read 1989; Brodie 1995; Palka 1995a). A juvenile Atlantic herring weir fishery of substantial magnitude operates on the western side of the lower Bay of Fundy (Stephenson et al. 1996) where harbour porpoise concentrations and by-catch rates are reported to be the highest in the population's range (Palka 1995a, Bravington and Bisack 1996; Trippel et al. 1996a).

The objectives of this study were to (i) field test the effectiveness of acoustic alarms in reducing harbour porpoise by-catch rate in the Swallowtail area, Grand Manan Island, New Brunswick, the principal by-catch area in the lower Bay of Fundy, (ii) record the sound levels emitted by alarms and determine whether harbour porpoise abandon an area in which alarms are used, and (iii) examine the relationship between harbour porpoise and Atlantic herring abundance, in particular their seasonal and annual fluctuations, using the Swallowtail area gillnet data.

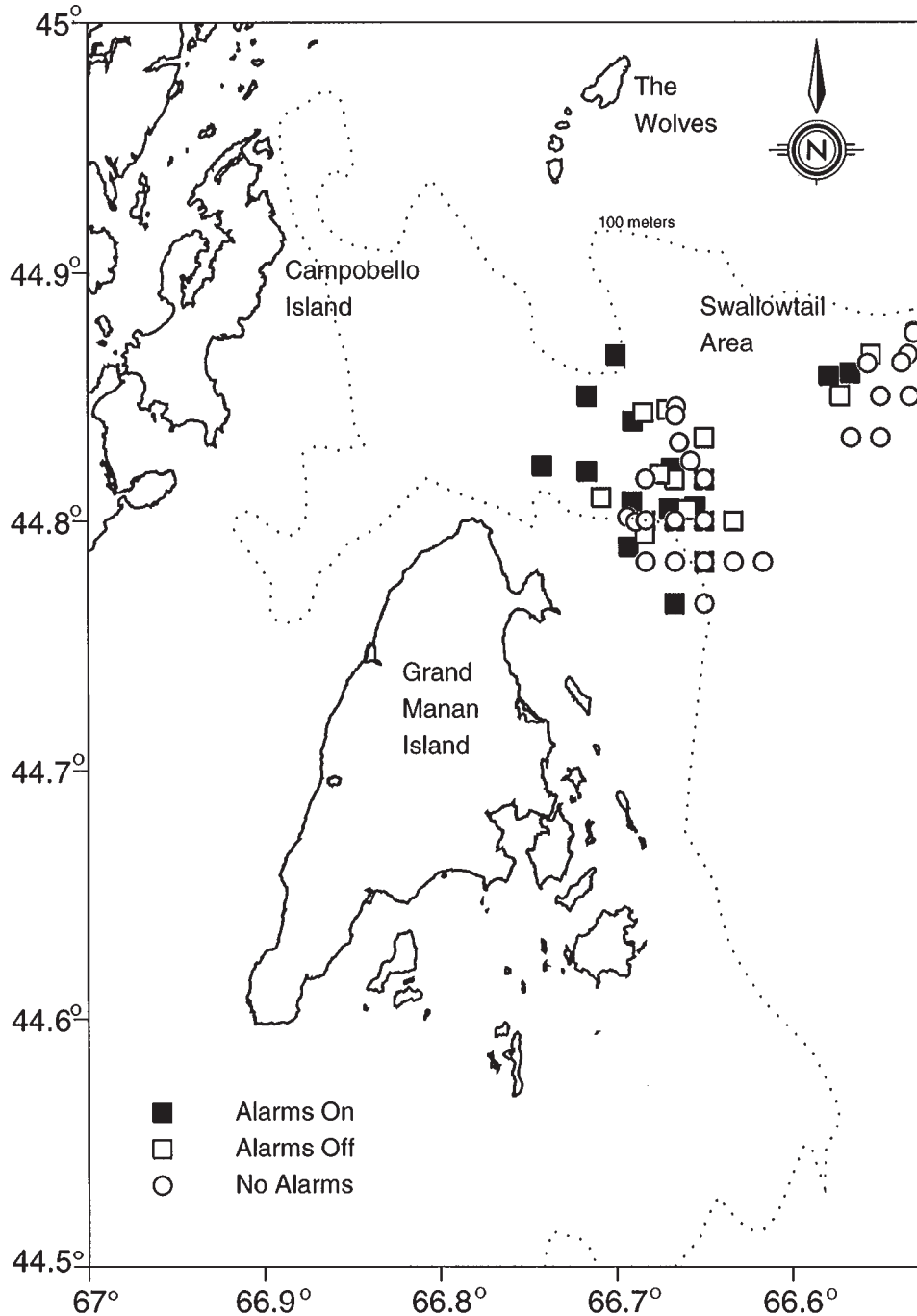
## Methods

The gillnet fishery in the Swallowtail area on the western side of the lower Bay of Fundy is directed primarily for Atlantic cod (*Gadus morhua*) and pollock (*Pollachius virens*), although white hake (*Urophycis tenuis*), haddock (*Melanogrammus aeglefinus*), spiny dogfish (*Squalus acanthias*), and other species are also taken. Six to 10 vessels fished the Swallowtail area and operated from North Head, Grand Manan Island. Typically, fishers of each vessel (11- to 14-m vessels) set five or six strings of nets, each made up of three panels (or webs) of monofilament mesh. Each web was ~100 m long and 3–4 m high with 15-mm stretched mesh. Nets were retrieved 24–48 h after being set. Some strings were four or five webs in length, although these comprised <5% of fishing effort and were excluded from analyses.

Field tests were conducted in 1996 and 1997 to evaluate the efficacy of acoustic alarms in reducing harbour porpoise entanglements in the Swallowtail area, where 65% of the annual mortality in the lower Bay of Fundy occurs (Trippel et al. 1996a). Tests were conducted during July 8–19 and August 1–15 in both 1996 and 1997. More extensive coverage was not possible because low groundfish quotas resulted in closures of the gillnet fishery during the latter parts of July and August. Observers attended ~50% of July trips and 95% of August trips made by the fishing fleet (high observer coverage occurred during periods of anticipated high by-catch; Trippel et al. 1996a). The alarms (Netmark 1000, Dukane Corporation, St. Charles, Ill.) were cylindrical (height 17 cm, diameter 5.6 cm) with an epoxy casing. Testing in 1996 was done by deploying a string of nets with (i) activated alarms, (ii) inactive alarms (i.e., batteries deactivated), or (iii) no alarms. In each trial, an alarm was attached to the floatline at each bridle between webs and at each string end, resulting in four alarms per three-web string (i.e., one every 100 m). Observers assisted with alarm use except during July 8–19, 1996, when fishers' deactivated batteries on three of the six vessels in operation.

In 1996, the fishing fleet operated in a series of successive periods with alarms activated for 3 days and then deactivated for 3 days. Data were pooled for each test condition for each July and August period. Each 3-day on and off pattern exposed both control and treatment groups to similar fishing conditions. As harbour porpoise abundance and by-catch rate typically vary during summer (Gaskin and Watson 1985; Trippel et al. 1996a), results might have been influenced significantly if longer trial periods had been used.

**Fig. 1.** Distribution of demersal gillnet strings having different alarm conditions in the Swallowtail area, Grand Manan Island, New Brunswick, on August 7–8, 1996 (marked isobath = 100 m).



In 1997, another experimental design was used in which nets were deployed with either activated alarms or no alarms. A chi-square test was used to determine whether harbour porpoise by-catch was lower in nets with alarms versus no alarms (Sheskin 1997, p. 220; one-tailed directional alternative hypothesis).

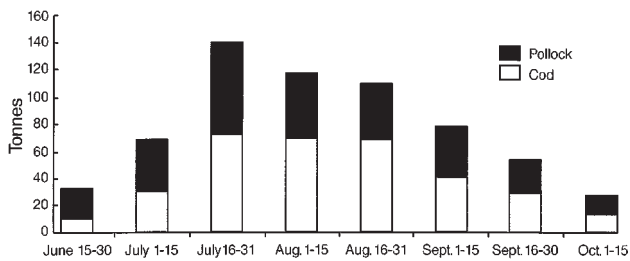
Areas suitable for setting groundfish nets are limited in the lower Bay of Fundy, resulting in high concentrations of gill nets in small areas (Fig. 1). Consequently, blind tests were not needed for the Swallowtail fishery (30–50 strings in use simultaneously). Kraus et al. (1997) found that blind tests were required when vessel operators setting nets with activated alarms could select areas known to be low or high in harbour porpoise by-catch.

Staggering the activation of alarms in 1996 permitted us to test whether harbour porpoises abandoned the Swallowtail area with

alarm use. Although the low observer height (wheelhouse windows ~2.5 m above sea level) precluded the ability to make a quantitative assessment of harbour porpoise abundance (Palka 1995a), observer sighting data were still useful for assessing whether harbour porpoises were present or absent in the study area. The harbour porpoises were counted by observers when traveling between gillnet sites under Beaufort Sea conditions of <2 and good visibility (i.e., no fog or rain). Observation transects between gillnet sites were 5–35 min (mean = 13 min) at speeds of 11–15 km/h. Comparison was made of the mean number of harbour porpoise sightings under active and inactive alarm conditions, with sighting rate standardized to 10-min durations.

Sounds of three Netmark 1000 acoustic alarms were evaluated and calibrated at depths of 2–4 m. The signals were recorded using

**Fig. 2.** Mean biweekly gillnet landings of Atlantic cod and pollock from 1990 to 1994 in southwestern New Brunswick.



a Bruel and Kjaer 8100 hydrophone and 2635 charge preamplifier connected to a Sony TCD-D3 DAT recorder. Recordings were made with the hydrophone and alarms at a similar depth and at 45° intervals around the long axis of the alarms. Received sound pressure levels were calibrated using a Bruel and Kjaer 4220 pistonphone fitted with an adapter for the 8100 hydrophone. The recorded sounds were analyzed using a Loughborough Speech Workstation FFT analyzer. The analyzing bandwidth was set at 31 Hz for the frequency measurements and 100 Hz for the duration measurements. The sound pressure levels that would be expected at various distances from the alarms were calculated by assuming spherical spreading (a 6-dB loss per doubling of distance from the source). Expected values were used to estimate the distance that harbour porpoises would be able to detect this sound, based on detection levels of a captive harbour porpoise (Andersen 1970).

In the laboratory, operable battery life was tested by fitting new batteries (four 1.5-V AA) to each of three alarms and the open-circuit voltage (no load) measured daily for 40 days and every 2–3 days thereafter until attainment of 95 days of continuous use (alarms kept at an air temperature of 5–7°C). The relationship between battery pack voltage and alarm frequency was assessed independently for the three alarms. The open-circuit voltage and frequencies were measured at voltages ranging from 6.48 to 3.34 V. The output frequency was measured in air using a Realistic sound level meter (as a microphone) and a Loughborough Speech Workstation FFT analyzer. The analyzing bandwidth was 31 Hz.

The Department of Fisheries and Oceans also provided observer coverage from late July to early September in 1993 and 1994 (Trippel et al. 1996a). Estimates of the mean daily by-catch per string of harbour porpoise and Atlantic herring in gill nets without alarms were made for the Swallowtail area for each of these years. During August 1–15, 1996 and 1997, the effects of alarm sound on Atlantic herring, Atlantic cod, and pollock were examined by testing for significant differences in catch rates of these fish species in alarmed compared with nonalarmed strings. Single classification of analysis of variance (ANOVA) was used to test for significant differences in catch rates among active, inactive, and nonalarmed nets (e.g., in 1996) whereas in other cases, Student's *t* test was used to test between control and treatment (e.g., no alarms and active alarms in 1997) (SPSS 1990). The Spearman rank correlation coefficient was used to test for a significant correlation between August 1–15 mean harbour porpoise and Atlantic herring catch rates in 1993, 1994, 1996, and 1997 (Siegel 1956, p. 202). Limitation in length of time series ( $n = 4$  years) necessitated the use of a nonparametric test, and correlation results should therefore be treated with caution.

## Results

### Calibration of acoustic alarms

The fundamental frequencies of the three Netmark 1000 alarms examined ranged from 10.5 to 12.6 kHz. Sound pressure levels measured perpendicular to the long axis of the

alarms ranged from 139 to 145 dB re 1  $\mu$ Pa at 1 m. Sound levels were typically  $\leq 6$  dB lower when measures were made with the long axis pointing toward the hydrophone. The pulse durations were 0.30 s with a 3.8- to 4.0-s pulse interval. All harmonics below the fundamental frequency of the alarm were at least 54 dB below the amplitude of the alarm pulse. Within each pulse, however, two to four transient clicks 1–8  $\mu$ s in duration did generate low-frequency sound energy. These sounds were 42 and 44 dB below the amplitude of the pulse at 8 and 4 kHz, respectively. Short underwater recording sessions were made near the surface on two days in July 1996 in the area where the net alarms were deployed. Neither seal acoustic deterrent devices (frequency centered at 10 kHz, Strong et al. 1995) nor net alarms were detected (closest aquaculture site was located 10–20 km away between Grand Manan and Long islands). Transient sounds above 8 kHz were attributable to vessel operations or waves and were typically below 80 dB re 1  $\mu$ Pa.

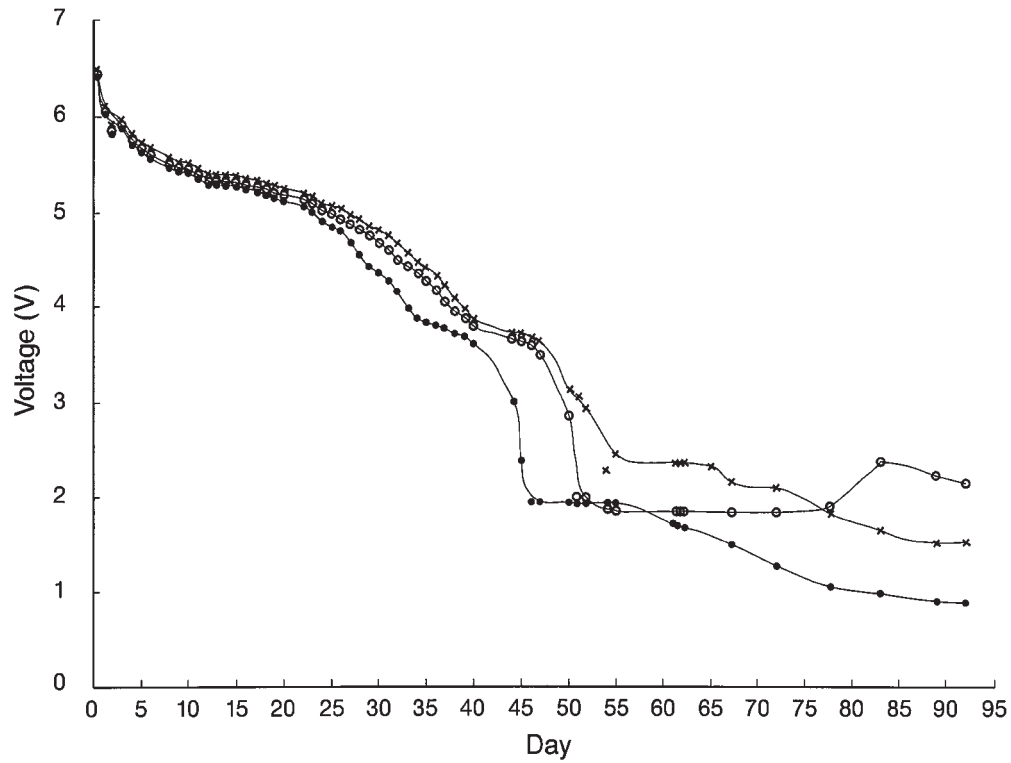
The rates of decline in battery voltage with continuous use of three alarms over 95 days are shown in Fig. 3. New batteries declined in voltage from 6.5 to 3.5 V in 42–47 days and declined rapidly thereafter, reaching 2.0–2.5 V after another 10 days of use before leveling off or undergoing further declines (one alarm increased slightly). Below 2.5 V, the alarms sometimes generated faint sounds with erratic duration (e.g., 9 s in duration every 4 s or 0.3 s in duration every 10 s) and below 1.8 V were not audible. Fundamental frequencies declined modestly with battery use (Fig. 4). The alarm frequencies dropped from 11.3–11.4 kHz at a voltage of 6.4 V (the equivalent of fully charged batteries) to 10.0–10.4 kHz at 3.3 V (the equivalent of almost depleted batteries).

### Field test of acoustic alarms

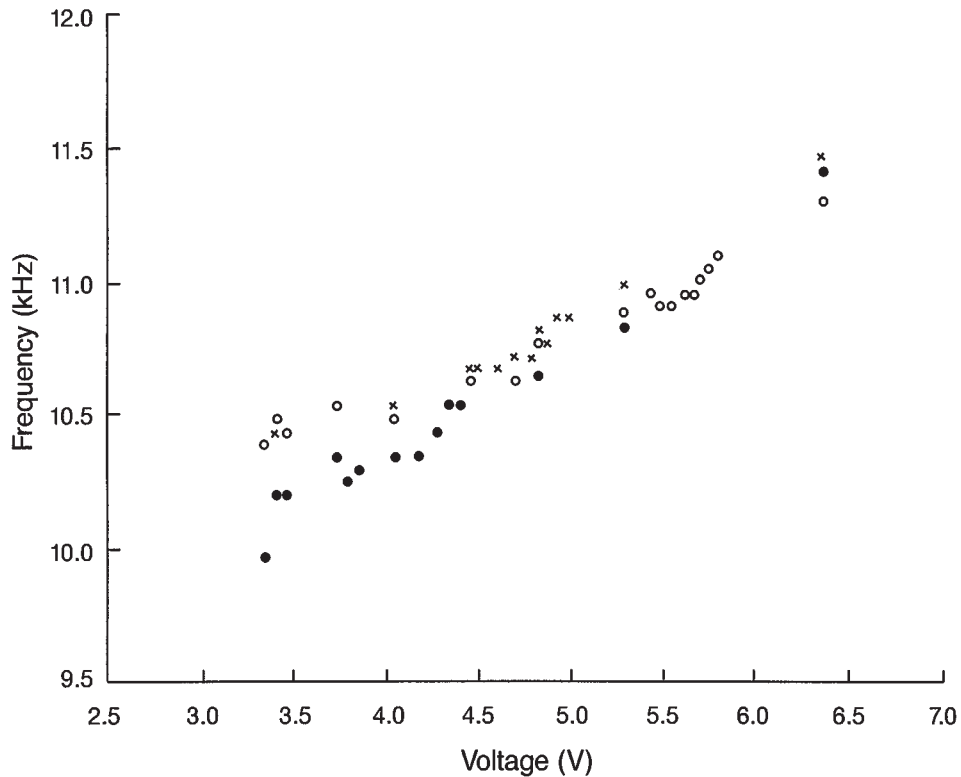
From August 1–15, 1996, mean harbour porpoise by-catch rates in nets with active alarms, with inactive alarms, and without alarms were 0.0083, 0.0351, and 0.0231 per string, respectively (Table 2). Pooling data of the latter two groups gives a by-catch of 0.0261 harbour porpoise per string for silent gear (*t* test,  $p = 0.63$ ). Harbour porpoise by-catch rate was 68% lower in nets with active alarms compared with silent gear, yet was not significantly different ( $\chi^2 = 1.28$ ,  $df = 1$ ,  $p < 0.15$ ; one harbour porpoise mortality in 121 strings with active alarms and six harbour porpoises in 230 silent strings). No harbour porpoise by-catch was observed from July 8 to 19, 1996. From August 1 to 15, 1996, Atlantic herring, Atlantic cod, and pollock catch rates did not differ among nets with active alarms, with inactive alarms, and without alarms (ANOVA,  $p = 0.14$ , 0.59, and 0.77, respectively) (Table 2). During this period, 481 Atlantic herring were captured in 132 strings with active alarms and 880 Atlantic herring in 246 silent strings, 2101 Atlantic cod in 132 strings with active alarms and 4130 Atlantic cod in 246 silent strings, and 89 pollock in 132 strings with active alarms and 150 pollock in 246 silent strings.

From August 1 to 15, 1997, mean harbour porpoise by-catch rates in nets with active alarms and without alarms were 0.0156 and 0.1064 per string, respectively (Table 2). Harbour porpoise by-catch rate was 85% lower in nets with active alarms versus no alarms and was significantly different ( $\chi^2 = 6.08$ ,  $df = 1$ ,  $p < 0.001$ ; two harbour porpoises in 128 strings with active alarms and 10 harbour porpoises in

**Fig. 3.** Relationship between alarm battery pack voltage and days of continuous use for three Netmark 1000 alarms at 5–7°C (each alarm represented by a unique symbol).



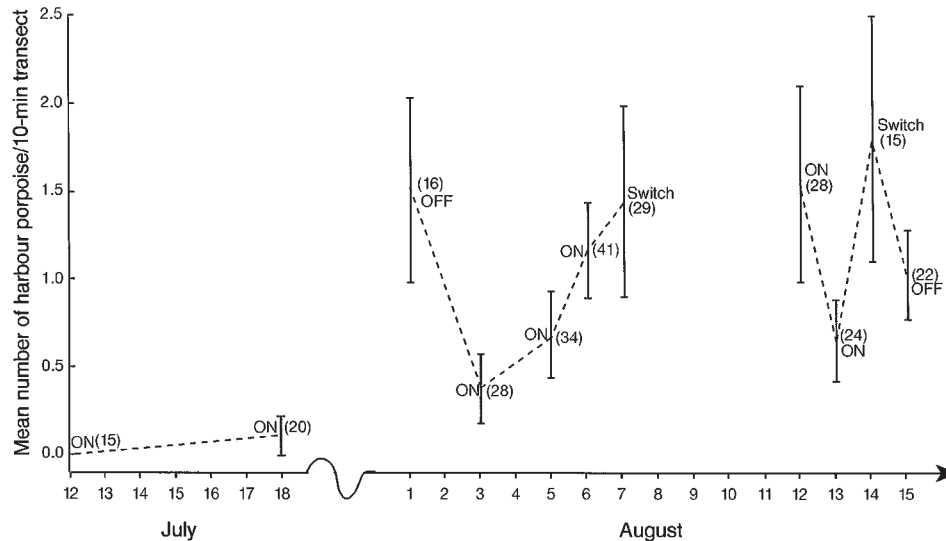
**Fig. 4.** Relationship between fundamental frequency and battery pack voltage for three Netmark 1000 alarms (each alarm represented by a unique symbol).



**Table 2.** Catch per unit effort of harbour porpoise, Atlantic herring, Atlantic cod, and pollock in gillnet strings under different alarm conditions in the Swallowtail area, Grand Manan Island, New Brunswick, for August 1–15, 1996 and 1997, and for both years combined and the mean duration and depth of gillnet sets for each alarm condition.

Alarms	Catch per gillnet string (mean ± SE)					Gillnet set		No. of gillnet strings
	Harbour porpoises	No. of observed harbour porpoise mortalities	Atlantic herring	Atlantic cod	Pollock	Duration (h)	Depth (m)	
<b>1996</b>								
Active	0.0083±0.0083	1	3.98±1.25	15.07±1.28	0.71±0.10	30.7±1.1	102.4±1.3	121
Inactive	0.0351±0.0246	2	6.81±1.75	14.67±1.42	0.70±0.12	29.1±1.7	101.3±2.2	57
No alarms	0.0231±0.0115	4	2.84±0.95	16.44±1.14	0.62±0.08	27.4±0.7	103.3±1.1	173
Silent (inactive and no alarms combined)	0.0261±0.0105	6	3.83±0.84	16.00±0.92	0.64±0.07	27.8±0.7	102.8±1.1	230
<b>1997</b>								
Active	0.0156±0.0110	2	6.38±1.56	13.11±1.15	3.57±0.49	25.3±0.7	92.0±1.3	128
No alarms	0.1064±0.0380	10	4.66±0.96	15.80±1.60	6.32±0.83	27.4±0.9	89.5±1.3	94
<b>1996 and 1997 combined</b>								
Active	0.0120±0.0069	3	5.21±1.01	14.06±0.86	2.18±0.27	27.9±0.7	97.2±0.9	249
No alarms	0.0524±0.0156	14	3.48±0.70	16.22±0.92	2.63±0.34	27.4±0.6	98.3±0.9	267
Silent (inactive and no alarms combined)	0.0494±0.0136	16	4.07±0.66	15.94±0.80	2.29±0.28	27.7±0.6	98.8±0.9	324

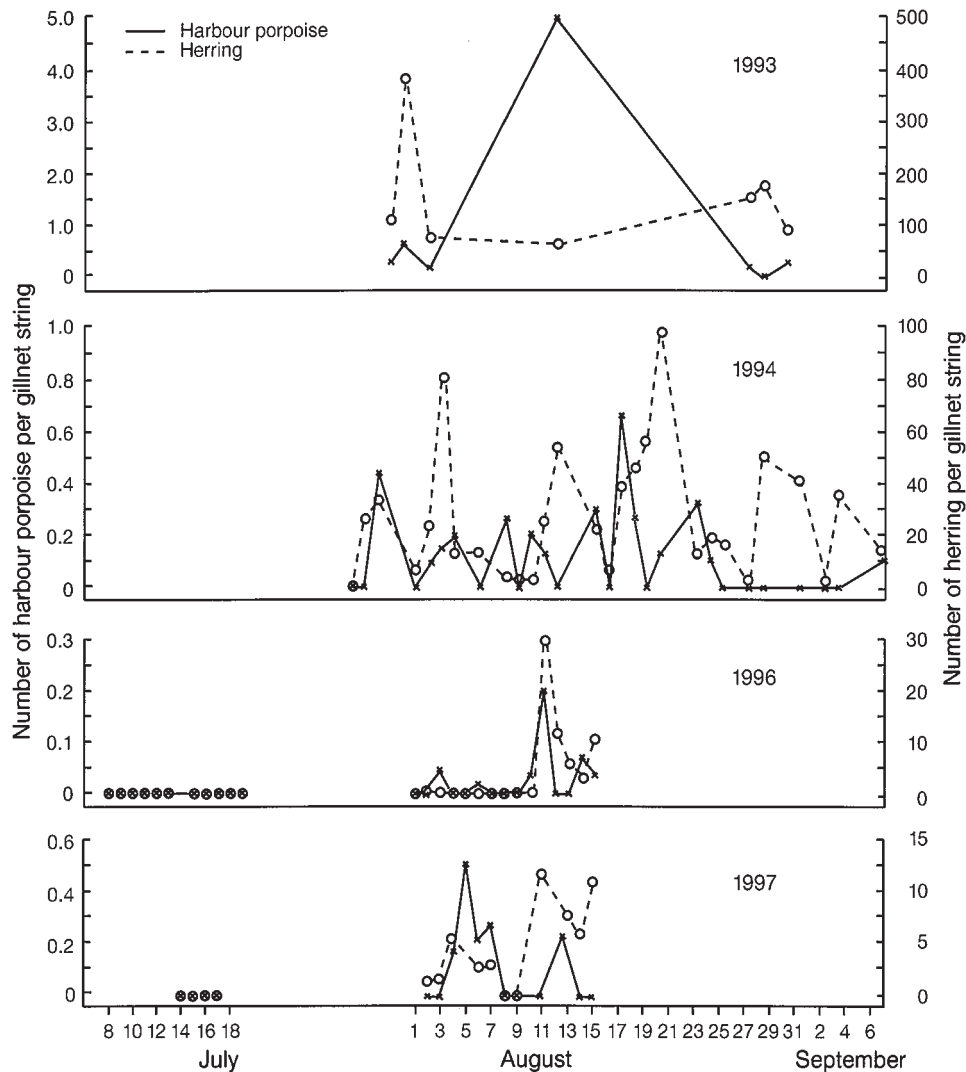
**Fig. 5.** Sightings of harbour porpoise (number per 10 min transect) from the wheelhouse of fishing vessels during July–August 1996 under Beaufort Sea conditions <2 and good visibility (i.e., no fog or rain). Days represented fishing activity with alarms active, alarms inactive, or alarms in the process of having their batteries switched off or on. On the days that batteries were deactivated or activated, the alarm sounds produced in the gillnet area would likely be somewhere between off and on days (these are referred to as switch days). Number of transects per date in parentheses.



94 nonalarmed strings). In two control strings, two harbour porpoises were caught in the same string; in all other cases, only a single harbour porpoise was taken. When combining 1996 and 1997 data, mean harbour porpoise by-catch rates in nets with active alarms and without alarms were 0.0120 and 0.0524 per string, respectively, such that by-catch rate was 77% lower in alarmed gear (three harbour porpoise mortalities in 249 strings with active alarms and 14 harbour porpoises in 267 strings with no alarms) ( $\chi^2 = 4.94$ ,  $df = 1$ ,  $p < 0.005$ ). From August 1 to 15, 1997, Atlantic herring and Atlantic cod catch rates did not differ significantly among nets with active alarms and no alarms ( $t$  test,  $p = 0.39$  and

0.16, respectively). However, pollock catch rate was significantly lower (by about half) in alarmed nets ( $t$  test,  $p = 0.002$ ) (Table 2). During this period, 816 Atlantic herring were captured in 128 strings with active alarms and 438 Atlantic herring in 94 nonalarmed strings, 1678 Atlantic cod in 128 strings with active alarms and 1485 Atlantic cod in 94 nonalarmed strings, and 457 pollock in 128 strings with active alarms and 594 pollock in 94 nonalarmed strings. Combining 1996 and 1997 data, Atlantic herring, Atlantic cod, and pollock catch rates did not differ significantly among nets with active alarms and no alarms ( $t$  test,  $p = 0.16$ , 0.09, and 0.30, respectively) (Table 2).

**Fig. 6.** Mean daily estimates of harbour porpoise and Atlantic herring by-catch rates in nonalarmed gill nets in the Swallowtail area during 1993, 1994, 1996, and 1997. Fishers hypothesize that the 15- to 25-cm Atlantic herring become captured in the 15-mm mesh size by swimming into nets with their mouths open, thereby becoming caught on a gillnet filament and subsequently wrapping themselves around adjoining meshes.



Harbour porpoises were present in the Swallowtail area on days when alarms were activated (Fig. 5). The harbour porpoise sighting rate was lower between July 8 and 19 than between August 1 and 15, 1996 (Fig. 5). Only one harbour porpoise was sighted during 4 h and 46 min of observations during days when alarms were activated from July 8 to 19. Sightings increased in August (156 harbour porpoises over 32 h and 24 min of observations), with harbour porpoises sighted on days when alarms were active and inactive (Fig. 5).

**Relationship between harbour porpoise and Atlantic herring abundance**

Declines in mean harbour porpoise and Atlantic herring catch rates occurred in nonalarmed strings between 1993, 1994, and 1996 and then increased in 1997 (Fig. 6). Mean by-catch rates of harbour porpoise in gill nets from August 1 to 15 for 1993, 1994, 1996, and 1997 were 1.57, 0.126, 0.0231, and 0.1064 per string, respectively. Mean by-catch rates of Atlantic herring during these periods were 72.9, 24.4, 2.8, and 4.7 per string, respectively. We observed for

the four years a Spearman rank correlation between harbour porpoise and Atlantic herring catch rates of  $r = 1.00$  ( $p < 0.05$ ). By-catch studies conducted further offshore in 1993 and 1994 (Grand Manan Basin, Northeast Bank, and McDormand Patch) did not observe captures of either harbour porpoise or Atlantic herring (Trippel et al. 1996a; E.A. Trippel, unpublished data). In 1996, no harbour porpoises and few if any Atlantic herring (mean = 0.2 per string) were observed in Swallowtail gill nets from July 8 to August 10, after which both Atlantic herring and harbour porpoise by-catch rates increased (Fig. 6). No harbour porpoises or Atlantic herring were captured in Swallowtail gill nets from July 14 to 17, 1997.

**Discussion**

**Acoustic alarms and their detection**

Acoustic alarms significantly reduced harbour porpoise by-catch in demersal gill nets in the lower Bay of Fundy. The ability of harbour porpoise to detect net alarm signals in

the Bay of Fundy is proposed as follows. Where necessary, data from other species are used with respect to sound detection by the harbour porpoises. Sound transmission through water is assumed to be optimal. In practice, degradation of the signal will occur because of poorer transmission of the sound due to currents and differences in temperature and salinity in the water column (Albers 1965). The detection range of the sounds will be reduced with increasing ambient noise levels associated with wind, rain, and vessel noises (Albers 1965). In a quiet experimental pool, the auditory threshold (50% correct detection) of a harbour porpoise at 10–12 kHz would be about 50 dB re 1  $\mu$ Pa at 1 m (Andersen 1970). Assuming that the effects of background noise masking on harbour porpoise hearing are similar to those in a bottlenose dolphin (*Tursiops truncatus*) (Johnson 1968) and that sea state is between 0 and 2 (Albers 1965), the background noise would increase detection thresholds to about 60–70 dB re 1  $\mu$ Pa. Furthermore, sound levels likely have to be about 20 dB above threshold in order to be recognizable (data from human studies, Hirsch 1952). Thus the acoustic alarms would likely be recognizable by harbour porpoise when the signal levels are about 80–90 dB re 1  $\mu$ Pa at 1 m. In a calm sea the Netmark 1000 devices would be clearly audible at ranges of 0.1–0.6 km. This range reflects differences in the output levels and orientations of the acoustic alarms and variations in the ambient sound levels.

The sound pressure levels that the harbour porpoises would be exposed to at 1 m from the alarms would be equivalent to the lower levels of the whistles of bottlenose dolphins (range 125–173 dB re 1  $\mu$ Pa, Richardson et al. 1995). Thus the alarms are likely to serve to alert harbour porpoises to the presence of an object but are not as loud as some naturally occurring sounds at close range.

The detection of the Netmark 1000 alarms by marine fish is unlikely. Atlantic cod and Atlantic salmon (*Salmo salar*) underwater hearing becomes insensitive at 0.5 kHz where the sound level thresholds increase to 110 and 140 dB re 1  $\mu$ Pa, respectively (Hawkins and Johnstone 1978). Similarly, the upper frequency hearing limits of haddock and pollock and all other marine fishes reported in a summary by Fay (1988) are close to, or below, 1 kHz. Enger (1967) recorded nerve action potentials from the acoustic region of the medulla oblongata of Atlantic herring. Sound pressure levels of 150–160 dB re 1  $\mu$ Pa were required to initiate a response at 6–8 kHz. Studies on other clupeids have also shown a sensitivity of sounds up to 1–8 kHz (Nestler et al. 1992). More recently, Mann et al. (1997) reported two regions of sensitivity for American shad (*Alosa sapidissima*), one at low frequency, as is commonly found among fishes, and one at high frequencies (25–180 kHz), at which most fish have not previously been tested. The ear structures of American shad and Atlantic herring are very similar, and thus, Atlantic herring may also be able to detect these very high frequencies. It is possible that the 10- to 12-kHz pitches of the Netmark 1000 alarms may have fallen in an insensitive area of Atlantic herring hearing (i.e., between 6 and 25 kHz). Moreover, the short duration and low amplitude of the low-frequency transient clicks of the alarms suggest that these sounds would not likely be detected by Atlantic herring or other fish species. In contrast with the

present study, Kraus et al. (1997) noted an 85% reduction in Atlantic herring catch rates in gill nets with and without alarms in the Gulf of Maine (0.29 versus 1.89 per string). It is not clear why their results differed from those of our study with regard to Atlantic herring. Kraus et al. (1997) used an alarm design similar to the present study which was also manufactured by Dukane Corporation (broad-band signal centered at 10 kHz with a source level of 132 dB re 1  $\mu$ Pa at 1 m), although in their study, alarms were deployed for a longer period (October 15 – December 15, 1994). Perhaps the extended use in 1994 reduced the effectiveness of the batteries, which lowered the frequencies to levels audible to Atlantic herring. Continuous alarm use in our study ranged from 3 days in 1996 to 15 days in 1997. Deployed alarms were audible at the end of each of the 1996 and 1997 periods. Given the slight decline in voltage expected over this short period (Fig. 3), the fundamental frequencies of the alarms were likely maintained in the 10- to 12-kHz range (battery pack voltage >5.25 V). Lien et al. (1995) used acoustic alarms with a broad-band signal ranging from 1 to 25 kHz of ~115 dB re 1  $\mu$ Pa at 1 m. Their effect on Atlantic herring catch rates was not evaluated, however.

Kraus et al. (1997) did not observe an effect of alarms on Atlantic cod and pollock gillnet catch rates. Alarms in our study did not influence Atlantic cod catch rates, although pollock catch rates were ~50% those of nonalarmed gear in 1997 (no significant difference occurred in 1996 or when data for the two years were pooled). The possible cause of these differences in pollock catches is unknown. Our study suggests that alarm avoidance by harbour porpoise could not be attributed to a possible avoidance reaction of the nets by Atlantic herring, their dominant prey. This finding furthers our knowledge of why harbour porpoises are not captured in alarmed gill nets (Reeves et al. 1996) and rejects the prey effect hypothesis (i.e., Atlantic herring alarm avoidance affects harbour porpoise movements and distribution patterns). If frequencies of sounds decreased as batteries drained, harbour porpoise would still likely be able to detect the alarm, as the harbour porpoise hearing range exhibits peak sensitivity from 4 to 40 kHz (Andersen 1970).

Our study did not evaluate whether alarms deterred harbour porpoises from exhibiting their normal feeding behaviour in the Swallowtail area, which might include diving and moving just above the ocean bottom to depths of 80–100 m where the majority of gill nets are set. Observations made by Westgate et al. (1995) in the lower Bay of Fundy using time–depth recorders attached to seven harbour porpoises indicated that <5% of the 8161 dives reached 80–100 m and likely formed part of feeding forays. Their research was conducted in 1991–1992 at a time when gillnet alarms were not being field tested. The distance at which diving harbour porpoises begin to avoid Netmark 1000 alarms is not known, and thus the impact that an esonified fleet of nets would have on reducing available harbour porpoise feeding space or area residence time cannot, as yet, be quantified. Further research to address this issue would require using hydroacoustics and time–depth recorders to examine the movements of harbour porpoises during suspected feeding activities in relation to use of gillnet alarms. Alternatively, shore-based observations of a set gill net could be used to

examine the possible adverse effects of alarms. For example, when Lien-type alarms (Fullilove 1994) were attached to a gill net (each alarm 17 m apart), harbour porpoises were displaced by an acoustic buffer with a radius of at least 125 m around the net (water depths did not exceed 20 m within the study area at mean tide) (Laake et al. 1998). Harbour porpoises maintained a buffer zone of 640 m from sounds swept within a band between 20 and 160 kHz at 152 dB re 1  $\mu$ Pa at 1 m (Goodson et al. 1997). The sound pressure levels at 640 m were estimated to be in the order of 90–100 dB re 1  $\mu$ Pa. From August 1 to 15, 1997, harbour porpoises were captured in nonalarmed gear within 100–200 m of nets having active alarms, further supporting our observations that harbour porpoises occur in the Swallowtail area during alarm use, although their specific avoidance distance remains to be determined.

Alarms in the present study proved to be effective in reducing harbour porpoise by-catch, although they were not as effective as those used in the Kraus et al. (1997) study. In their study, harbour porpoise by-catch rates in alarmed and nonalarmed nets were 0.0591 and 0.00475 per approximately 1090-m string, respectively (two harbour porpoises were captured in 421 active strings and 25 harbour porpoises in 423 control strings). The greater deterrence in the Kraus et al. (1997) study may in part be due to their narrower alarm separation during deployment (92 m versus our 100 m). Narrower spacing (one every 17 m) of the Lien et al. (1995) alarms resulted in an 11- to 18-fold reduction of harbour porpoise entanglements in a chinook salmon (*Oncorhynchus tshawytscha*) and sturgeon (*Acipenser* sp.) gillnet fishery (Gearin et al. 1998). Lien et al. (1995) spaced them one every 92 m and did not report statistically significant differences ( $p = 0.169$ ).

### Relationship between harbour porpoise and Atlantic herring abundance

Harbour porpoise and Atlantic herring appear to exhibit some synchrony in their movements into the Swallowtail area. Atlantic herring is a principal prey of harbour porpoise, comprising 80% of their total caloric intake (Recchia and Read 1989). The reduced Atlantic herring abundance in the Swallowtail area in 1996 may in part be responsible for the lower local harbour porpoise abundance and by-catch rate observed during that year and supports earlier suppositions of this predator–prey linkage (Brodie 1995). Palka (1995b) conducted census transects in 1991 and 1992 in the Grand Manan Island area and in the Gulf of Maine and showed that interannual changes in harbour porpoise densities were related in part to the presence of preferred water temperatures of 10–13.5°C and densities of small schooling fish, i.e., Atlantic herring, alewife (*Alosa pseudoharengus*), blueback herring (*Alosa aestivalis*), and silver hake (*Merluccius bilinearis*). The Department of Fisheries and Oceans monitored water temperature near the Swallowtail area and found temperatures in early August 1993, 1994, 1996, and 1997 to be 9.4, 11.6, 9.2, and 10.3°C, respectively. Each of these reported temperatures was based on 46–95 measurements made through the water column on a single day with SE = 0.1°C and range = 2.2–2.7°C (F. Page, St. Andrews Biological Station, unpublished data). Water temperatures in July

were 1–2°C lower than in August. Hence, annual water temperature variation was slight and unlikely accounted for the observed annual variation in harbour porpoise by-catch.

The spatial–temporal relationship of predator and prey that presumably occurs for harbour porpoise and Atlantic herring in the Gulf of Maine and Bay of Fundy is well known among other marine vertebrates. In Witless Bay, Newfoundland, during a series of surveys, the majority (96%) of baleen whales were observed when mean daily capelin (*Mallotus villosus*) densities exceeded five schools per linear kilometre traveled (Piatt and Methven 1992). Predator–prey relationships also were associated with the co-occurrence of alcids and capelin off Newfoundland (Piatt 1990). Hence, if Atlantic herring repopulate offshore areas, it might lessen the incidental mortality of harbour porpoise in coastal gillnet fisheries. A recent resurgence of Atlantic herring offshore on Georges Bank has occurred (Melvin et al. 1996) that might lead to harbour porpoises moving to this area. This could also have implications for harbour porpoise by-catch monitoring programs in the future, which may have to increase their focus on offshore gillnet sites that previously exhibited zero by-catch (Trippel et al. 1996a).

A U.S. Take Reduction Team was formed in 1996 to develop regulations that would reduce harbour porpoise by-catch in demersal gill nets in the Gulf of Maine from 1500 in 1995 to <483 animals in 1997 and eventually to levels near zero by 2001 (Blaylock et al. 1995; Anonymous 1998; Caswell et al. 1998). In the Gulf of Maine, gill nets without alarms have been shown to capture 4.4–12.4 times more harbour porpoises than gill nets with alarms (Lien et al. 1995; Kraus et al. 1997). Seasonal area closures and enforced use of alarms in specific regions have recently been implemented in the Gulf of Maine (Anonymous 1998). In Canada, a conservation strategy has set a maximum take of 110 harbour porpoises per year for the Bay of Fundy, a mortality believed to have a negligible effect on the growth potential of this transboundary population estimated to be between 40 000 and 70 000 animals (Department of Fisheries and Oceans 1995; Palka 1995b).

In summary, results of our field tests support earlier studies which found that acoustic alarms might be effective tools for reducing the rate of harbour porpoise entanglement in the lower Bay of Fundy gillnet fishery. Alarms did not cause a reduction in catch rate of the important commercial fish species Atlantic cod (although in one season, pollock catches were negatively affected). It is possible that if alarms are used for long periods or over several seasons, harbour porpoises might habituate to their sounds, thus reducing the effectiveness of this method. Continued research on alarms is therefore needed to evaluate their long-term mitigative value, although at present, they are a promising alternative to seasonal area gillnet closures.

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