ARTICLE

Trends in cetacean abundance in the Gully submarine canyon, 1988–2011, highlight a 21% per year increase in Sowerby's beaked whales (*Mesoplodon bidens*)

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Abstract: Long time series of abundance data have advanced ecological understanding. I examined trends in incidental sightings of cetaceans in the Gully and neighbouring submarine canyons on the edge of the Scotian Shelf during summers between 1988 and 2011. There were a total of 2938 h of sighting effort in good conditions. I fit Poisson models to the sighting count data, and examined the support for models that included parameters representing monthly variations in abundance, trends over years, and different sighting rates in the different canyons. Sowerby's beaked whales (*Mesoplodon bidens* (Sowerby, 1804)) were sighted 3.5 times more often in the Shortland and Haldimand canyons, compared with the Gully. For all other species, the best-supported models did not include differential sighting rates between canyons. The sighting rates of four species decreased over the 23 years of the study, while three species increased. Some of these trends may be related to changes in overall population size or variation in food resources, but a remarkable 21%/year increase in Sowerby's beaked whale is perhaps most plausibly explained by a reduction in anthropogenic disturbance.

Key words: Cetacea, whales, dolphins, canyon, trends, the Gully, marine protected area, Sowerby's beaked whale, *Mesoplodon bidens*.

Résumé : Les longues séries chronologiques de données d'abondance ont fait avancer la compréhension des systèmes écologiques. J'ai examiné les tendances en matière d'observations fortuites de cétacés dans le Goulet et dans des canyons sous-marins voisins en bordure du Plateau néo-écossais, pour les étés de 1988 à 2011. Les données représentent un total de 2938 h d'effort d'observation dans de bonnes conditions. J'ai ajusté des modèles de Poisson aux données de dénombrement des observations et examiné la concordance aux données de modèles qui intègrent des paramètres reflétant les variations mensuelles d'abondance, les tendances sur plusieurs années et différentes fréquences d'observations dans les différents canyons. Des baleines à bec de Sowerby (*Mesoplodon bidens* (Sowerby, 1804)) ont été observées 3,5 plus souvent dans les canyons de Shortland et de Haldimand que dans le Goulet. Pour toutes les espèces, les modèles concordant le mieux avec les données n'intègrent pas de fréquences d'observations différentielles entre les canyons. Les fréquences d'observations de quatre espèces ont diminué au cours des 23 ans qu'a duré l'étude, alors que celles de trois autres espèces ont augmenté. Si certaines de ces tendances pourraient être associées à des changements de la taille globale de la population ou à la variabilité des ressources alimentaires, une augmentation notable de 21 % / année des observations de baleines à bec de Sowerby s'explique vraisemblablement mieux par une diminution des perturbations d'origine humaine. [Traduit par la Rédaction]

Mots-clés : cétacés, baleines, dauphins, canyon, tendances, le Goulet, zone marine protégée, baleine à bec de Sowerby, *Mesoplodon bidens*.

Introduction

In attempts to explain patterns of biodiversity, long time series of organism abundance can be particularly informative, and this is perhaps especially the case in the ocean (Bjørnstad and Grenfell 2001). Among other patterns, series of measures of organismal abundance can show stability, or the lack of stability, over time (e.g., McGinty et al. 2012), close correlations with abiotic changes (e.g., Fiedler and Reilly 1994; Burrows et al. 2012), the effects of anthropogenic activities (e.g., Baum et al. 2003), and regime shifts (e.g., Beamish et al. 1999). Thus, these time series have a major role in shaping our understanding of the dynamics of ocean ecosystems. Often they are the primary source of hypotheses about ocean dynamics, for instance in the case of regime shifts. But they also have a primary role in comparing competing hypotheses, for instance weighing the importance of top–down or bottom–up forcing (Baum and Worm 2009).

A second benefit of long time series of organism abundance is in monitoring the effects of management and conservation measures (Kaschner et al. 2012). In particular, they are used to assess the effectiveness of marine protected areas (MPAs) (e.g., Ronconi et al. 2012). For this goal, the series should ideally extend from substantially before the establishment of the MPA to well afterwards.

In this paper I present a series of abundance indices spanning 23 years for cetaceans that use the Gully submarine canyon on the edge of the Scotian Shelf. This series is unusual for its length and because it is for an offshore marine area (200 km from the mainland), and was collected over a major oceanographic feature: the Gully is the largest submarine canyon off the east coast of North America. The Gully borders the eastern Scotian Shelf, where long-term trends in marine ecosystem structure have been well described and closely analyzed (Frank et al. 2011). Additionally, the
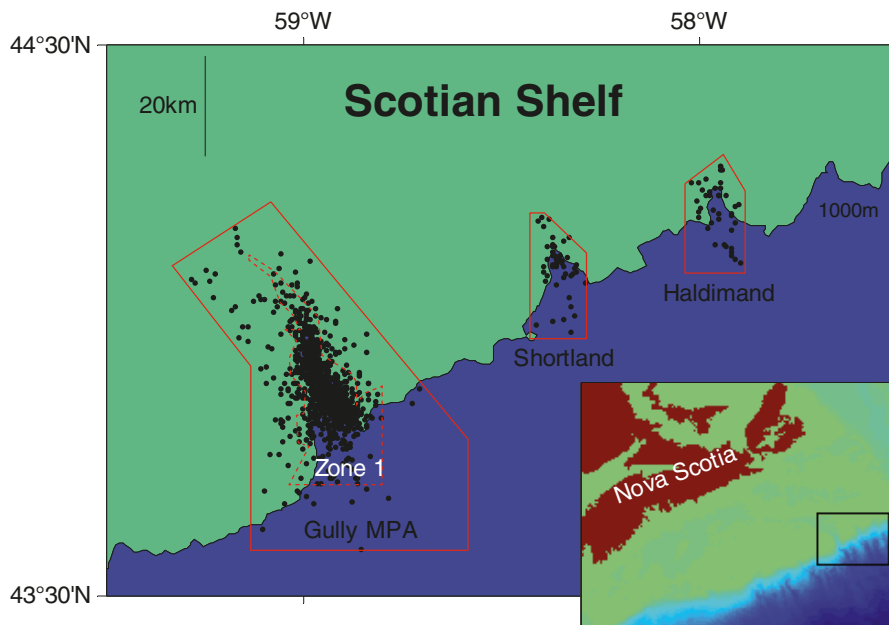
Fig. 1. Study area (Gully marine protected area (MPA), with Zone 1; Shortland Canyon; Haldimand Canyon), showing positions in which 3 h environmental data were collected in good conditions and 1000 m contour. Zones 2 and 3 of the Gully MPA are the areas of the MPA outside Zone 1 (broken line). The insert shows the position of the study area, 200 km from the land mass of Nova Scotia.

Gully was declared a pilot MPA in 1998 half way through the data series, a move that restricted oil and gas exploration in the area, and a full MPA in 2004 (Westhead et al. 2012). The MPA regulations prohibit many activities, including fishing, from the core area of the MPA.

The data used in this paper are incidental sightings of cetaceans during studies of northern bottlenose whales (*Hyperoodon ampullatus* (Forster, 1770)) and, to a lesser extent, sperm whales (*Physeter macrocephalus* L., 1758), in what is now the Gully MPA, as well as in two other canyons along the edge of the eastern Scotian Shelf, the Shortland Canyon and the Haldimand Canyon. Within an overall objective of generating hypotheses about the dynamics of cetacean populations within submarine canyons, this study addressed five primary questions. At what rates are cetaceans (other than northern bottlenose whales and sperm whales) sighted in what is now the Gully MPA? Are they sighted more frequently in Zone 1, the core that includes the deep waters of the canyon and receives fullest protection (Fig. 1), compared with the outer parts of the MPA? Are they sighted at different rates in the different summer months? Is there a trend between 1988 and 2011 in the sighting rates? Are species sighted more frequently in the Gully MPA compared with the Shortland and Haldimand canyons?

Materials and methods

Data were collected from a 10 m auxiliary sailing vessel (1988–1990), or a 13 m auxiliary sailing vessel (1993–2011). The studies were carried out in a comparable manner, and from two quite similar research vessels, over the 23-year period, during the summer months.

During daylight in the study areas, there was a constant watch for cetaceans. Every 3 h at sea the crew recorded a suite of environmental data, including latitude and longitude (Loran-C between 1988 and 1990; and GPS thereafter), sea surface temperature (SST; °C), wind speed (Beaufort scale), and estimated visibility (m). All groups of cetaceans sighted were recorded, together with time of sighting, species (where ascertainable), and position. As definitions of group size changed over the course of the study, sightings of individuals are not independent invalidating the Poisson-distribution analytical models used, and estimates of group size

are very inaccurate and biased by factors such as the behaviour of the animals and the weather, I only use group sighting data, rather than numbers of individuals.

Positions were annotated as to whether they were within Zone 1 of what is now the Gully MPA, other areas of the Gully MPA, Shortland Canyon, or Haldimand Canyon (Fig. 1). Zone 1 includes the axis of the Gully canyon and surrounding waters with depths greater than 500 m. Zones 2 and 3 include shallower waters along the edge of the canyon, as well as deep oceanic waters to the south of the canyon, although there was little effort in these deep waters (Fig. 1). The boundaries of the Gully MPA and Zone 1 are from http://gazette.gc.ca/archives/p2/2004/2004-05-19/html/sor-dors112-eng.html. Boundaries of Shortland and Haldimand canyons were defined by critical habitat of northern bottlenose whale in the Recovery Strategy for the Northern Bottlenose Whale (http://publications.gc.ca/collections/collection_2009/mpo-dfo/En3-4-66-2009E.pdf; Fig. 1).

I used the number of daytime environmental records (those at the hours of 0600, 0900, 1200, 1500, 1800, 2100; Atlantic daylight time, Z-3) as an index of survey effort. Sightings were made for about 15 h a day (0600–2100) throughout the summer field seasons from early June until early September. Hence the sighting effort in hours was the number of environmental records in good conditions multiplied by 2.5 (15 h/day divided by 6 records/day). Sighting rates fell with visibilities less than 1000 m and with wind speeds greater than Beaufort force 4 (>28 km/h), so both environmental records and sightings in such conditions were omitted from further analysis.

As they were targets of the research, and effort on these species varied with specific research objectives in different field seasons, sightings of northern bottlenose whales and sperm whales were omitted from this analysis. A trend analysis for northern bottlenose whales has been conducted separately using mark–recapture analyses of photoidentifications. No trend was detected (K. O'Brien and H. Whitehead, unpublished data). Sperm and bottlenose whales are deeper divers than any other cetacean species using the area, and their distributions were not obviously correlated with those of the other species, so the changes in biases in effort for northern bottlenose and sperm whales should not affect the

sighting rates of the other species. Otherwise I used all sightings identified to the species level. However, records of "*Mesoplodon* spp." were assigned to Sowerby's beaked whale (*Mesoplodon bidens* (Sowerby, 1804)) as, later in the study, it was clear that all mesoplodonts that could be assigned to species (approximately 30 sightings) were Sowerby's beaked whale. The very early parts of this data set have been used to describe the general abundances of the different species using the Gully, as well as their seasonal and spatial distributions (Gowans and Whitehead 1995; Hooker et al. 1999).

I investigated variations in sighting rate with season and year by fitting the following general Poisson model to the number of sightings in any month of a particular year:

[1]   Expected (no. of sightings) $= x \cdot \alpha(m) \cdot e^{\beta \cdot y}$

In this model, x, an offset variable, is effort—the number of environmental records during that month and year in good conditions. m is a categorical variable with three values: 6 (June), 7 (July), and 8 (August–September). There were very few September data points, all early in the month, so they were lumped with August. y is a continuous variable giving the year of study (1988–2011). α allows for seasonal effects and β estimates the rate of increase or decrease in sighting rates over time. I also fit three more restricted models:

[2]   Expected (no. of sightings)
$$= x \cdot \alpha \cdot e^{\beta \cdot y}, \text{ i.e., no seasonal variation}$$

[3]   Expected (no. of sightings)
$$= x \cdot \alpha(m), \text{ i.e., no trend with time}$$

[4]   Expected (no. of sightings)
$$= x \cdot \alpha, \text{ i.e., constant sighting rate through the study}$$

For each species with at least 20 sightings in the Gully MPA and each of the four models, I found the parameters giving the maximum log-likelihood and calculated the QAIC (Akaike's information criterion adjusted for overdispersion of count data) for each model. The variance inflation factor used to calculate QAIC, $\hat{c}$, was the Pearson χ^2 statistic calculated from the fit of the fullest model. The model with the lowest QAIC was selected as being best supported by the data (Burnham and Anderson 2002). Standard errors (SE) for trend estimates in models 1 and 2 were estimated using the jackknife method in which each year with data was omitted in turn to calculate "pseudovalues", whose dispersion indicated the precision of the trend estimate (Efron and Stein 1981).

To compare sighting rates in the Gully MPA with those in the Haldimand and Shortland canyons, I added data for the months and years in which there was effort in either Shortland or Haldimand canyon and introduced a new term into the model:

[1a]   Expected (no. of sightings) $= x \cdot \alpha(m) \cdot e^{\beta \cdot y + \gamma \cdot C}$

Here, $C = 0$ for data from the Gully canyon and $C = 1$ for data from the Shortland and Haldimand canyons. e^{γ} is an estimate of the ratio of the sighting rate in Shortland and Haldimand compared with that in the Gully in similar conditions. Similarly, I added the canyon factor, γ, to models 2–4, giving models 2a, 3a, and 4a. In these analyses, I used the entire Gully MPA data set (not just Zone 1), as the Shortland and Haldimand study areas (as designated by the critical habitat of the northern bottlenose whale) are in terms of water depth more comparable with the entire Gully MPA than to Zone 1 (Fig. 1). I also combined data from Haldimand and Shortland, as their sighting rates looked very similar on inspection, and the data were rather few for each canyon

Table 1. Numbers of sightings of the different species, as well as effort, in good conditions in the different study areas (W., whale; D., dolphin; P., porpoise).

	Gully MPA Zones		Shortland Canyon	Haldimand Canyon
	1	2 and 3		
Blue W.	30	3	9	5
Fin W.	46	9	4	3
Sei W.	6	0	0	2
Minke W.	3	11	0	1
Humpback W.	41	5	0	0
Sowerby's beaked W.	72	1	12	30
Cuvier's beaked W.	0	0	0	1
Pilot W.	175	23	26	15
Risso's D.	0	0	1	0
White-sided D.	225	19	12	4
Common D.	181	32	10	9
Striped D.	46	2	6	6
Bottlenose D.	16	2	1	0
Harbour P.	1	0	0	0
Effort hours	2375	328	133	103

Note: Refer to the text for the binomen of the species mentioned above. MPA, marine protected area.

separately (Tables 1 and 2). So, in this analysis, QAIC was calculated for models 1, 2, 3, 4, 1a, 2a, 3a, 4a and the best supported model chosen by that with lowest QAIC.

Except for the between-canyon comparisons, I will generally present results for just Zone 1 of the Gully where there are most data, but will note how well these agree with results using data for the entire MPA.

Results

Effort

Between 1988 and 2012, there were a total of 2938 h of sighting effort in good conditions in the Gully MPA and the Shortland and Haldimand canyons, 81% in Zone 1 of the Gully MPA (Table 1). There were 263 h in June, 1100 in July, 1553 in August, and 12 in September. Effort varied substantially between years, with no effort in some years (1991, 1992, 2000, 2004, 2008, 2009) but 507 h in 1997. Effort was also haphazard (neither uniform nor random) temporally and spatially (within and between study areas) within field seasons. However the spatial pattern of effort within the Gully MPA and the Shortland and Haldimand canyons was similar in different field seasons.

Sighting rates

Three delphinid species were abundant, with over 200 sightings each, and overall sighting rates of greater than 0.05/h: long-finned pilot whale (*Globicephala melas* (Traill, 1809)), short-beaked common dolphin (*Delphinus delphis* L., 1758)), and Atlantic white-sided dolphin (*Lagenorhynchus acutus* (Gray, 1828)) (Table 1). Three baleen whale species, the blue whale (*Balaenoptera musculus* (L., 1758)), fin whale (*Balaenoptera physalus* (L., 1758)), and humpback whale (*Megaptera novaeangliae* (Borowski, 1781)), as well as Sowerby's beaked whale and the striped dolphin (*Stenella coeruleoalba* (Meyen, 1833)), were sighted fairly frequently, with 45–115 sightings during the studies. There were occasional (8–15) sightings of minke whale (*Balaenoptera acutorostrata* Lacépède, 1804), sei whale (*Balaenoptera borealis* Lesson, 1828), and bottlenose dolphin (*Tursiops truncatus* (Montagu, 1821)), and just one sighting each of Cuvier's beaked whale (*Ziphius cavirostris* G. Cuvier, 1823), Risso's dolphin (*Grampus griseus* (G. Cuvier, 1812)), and the harbour porpoise (*Phocoena phocoena* (L., 1758)).

Table 2. Sighting rates (numbers/h) in good conditions in the different study areas.

	Zone 1	Zones 2 and 3	Entire MPA	Shortland Canyon	Haldimand Canyon	Shortland and Haldimand canyons
Blue W.	0.0126	0.0092	0.0122	0.0679	0.0488	0.0596
Fin W.	0.0194	0.0275	0.0204	0.0302	0.0293	0.0298
Minke W.	0.0013	0.0336	0.0052	0.0000	0.0098	0.0043
Humpback W.	0.0173	0.0153	0.0170	0.0000	0.0000	0.0000
Sowerby's beaked W.	0.0303	0.0031	0.0270	0.0906	0.2927	0.1787
Pilot W.	0.0737	0.0702	0.0733	0.1962	0.1463	0.1745
White-sided D.	0.0947	0.0580	0.0903	0.0906	0.0390	0.0681
Common D.	0.0762	0.0977	0.0788	0.0755	0.0878	0.0809
Striped D.	0.0194	0.0061	0.0178	0.0453	0.0585	0.0511
Bottlenose D.	0.0067	0.0061	0.0067	0.0075	0.0000	0.0043

Note: Refer to the text for the binomen of the species mentioned above. MPA, marine protected area.

Sightings in the Gully MPA

Effort within the Gully MPA but outside Zone 1 was limited, so I have combined Zones 2 and 3. Although effort was much less in Zones 2 and 3, the temporal distribution of effort was similar (by month and year) in the different zones, so it is reasonable to compare sighting rates in the different parts of the MPA (Table 2). Using paired two-sided t tests on years of observation with at least three sightings in the Gully MPA, for those species with at least three such years, only one species showed a significantly different sighting rate in Zone 1 versus Zones 2 and 3. Minke whales ($P = 0.045$) were much more common in Zones 2 and 3 and so may be considered shallow-water animals in this area (Table 2). Sowerby's beaked whales ($P = 0.110$) were largely within Zone 1 of the Gully and striped dolphins ($P = 0.089$) were more frequent in Zone 1. Other species had t tests far from significance, and were sighted at similar rates in the deep (Zone 1) and mainly shallow (Zones 2 and 3) waters.

Sightings by month in the Gully MPA

In Fig. 2, I show the monthly rates of sighting the different species within Zone 1 of the MPA, indicating (with an asterisk) those species for which a monthly component was part of the best-supported model (as indicated by the minimum QAIC for model 1 or model 3; Table 3). The models supported monthly variation in sighting rates for four species. White-sided dolphins were more commonly sighted early in the summer (June), common dolphins in mid-summer (July), and pilot whales and striped dolphins peaked in late summer (August–September). Results were similar when data for the entire Gully MPA, rather than just Zone 1, were used, except that now the monthly variation in sighting rates for striped dolphins was not included in the best-supported model.

Trends in abundance

The sighting rates of the species sighted more than 20 times in Zone 1 of the Gully MPA are plotted against year in Fig. 3. The plots show trend lines for those species for which the best-supported model (indicated by minimum QAIC) included a temporal trend (model 1 or 2). Table 3 tabulates these trends for Zone 1, along with their SE. The sighting rates of four species decreased over the 23 years of the study: fin whales at 7%/year (SE 2%), humpback whales at 15%/year (SE 7%), white-sided dolphins at 4%/year (SE 2%), and striped dolphins at 6%/year (SE 10%). The sightings of three species increased: blue whales at 11%/year (SE 8%), pilot whales at 9%/year (SE 14%), and, most dramatically, Sowerby's beaked whales at 21%/year (SE 6%). Sowerby's beaked whales were not sighted before 1994, there were 8 sightings between 1995 and 2000, 20 between 2001 and 2006, and 87 in 2011 and 2012. Results were similar when data for the entire Gully MPA, rather than just Zone 1, were used, except that now the declining trend in sighting rates for striped dolphins was not included in the best supported model.

The Gully, Shortland, and Haldimand canyons

As explained in the Materials and methods, I reran the models adding sightings for Shortland and Haldimand canyons and a term to each model contrasting the Gully MPA to the other two canyons. The analysis supported a differential sighting rate for the Gully MPA compared with the Shortland and Haldimand canyons for only one species, Sowerby's beaked whale (for trend model with canyon variation (model 2a), QAIC = –42.87; for trend model without differences between canyons (model 2), QAIC = –37.35). The estimate of e^γ in the analysis suggested that Sowerby's beaked whales were sighted 3.5 times more often in the Shortland and Haldimand canyons, compared with the same year in the Gully. When only Zone 1 was used for the Gully data, the results were qualitatively identical (only Sowerby's beaked whale showing differences between the canyons) and quantitatively similar (sighting rate for Sowerby's beaked whale 3.1 times greater in the Shortland and Haldimand canyons).

Discussion

Spatial and seasonal distributions

The list of species sighted, their overall relative rates of sighting, and their seasonal and depth dependence are all much as would be expected from general overviews of the cetacean fauna of these latitudes of the western North Atlantic (Katona et al. 1993), as well as analyses of the earlier parts of this data set (Gowans and Whitehead 1995; Hooker et al. 1999). However, a remarkable exception is the prominent appearance of Sowerby's beaked whale in the full data set, which is only mentioned in passing by Hooker et al. (1999) as being "documented . . . outside the study period". Later, I discuss the appearance of Sowerby's beaked whale in the canyons towards the end of the study period.

Also unexpected were the results of the comparisons between the Gully and the Shortland and Haldimand canyons. Moors' (2012) review of the associations of cetaceans with submarine canyons indicates that whales and dolphins are more attracted to larger canyons, and this is expected as large canyons enhance the oceanographic processes that promote production (Hickey 1995). However, rates of sighting cetaceans in the large and prominent Gully were similar to those in the much smaller and less dramatic Shortland and Haldimand canyons. In the case of the surprise species of these analyses, Sowerby's beaked whale, the expected pattern was reversed. It would be most interesting to compare sighting rates in the canyons to those over similar depths along the more linear segments of the continental slope. Unfortunately, there are insufficient data to do this with any power at this time. In the cases of the northern bottlenose whale and sperm whale, Moors (2012) has analyzed extensive "PopUp" hydrophone recordings from the Gully, the Shortland and Haldimand canyons, and from similar water depths along the neighbouring shelf edge. Both the sperm and northern bottlenose whale were heard at somewhat similar rates in the Gully and the smaller canyons, and

Fig. 2. Sighting rates (numbers/h) of different species during the summer months in Zone 1 of the Gully marine protected area. An asterisk indicates that monthly differences in sighting rates were included in the best-supported model. Order of bar groups (colour on Web) from top to bottom: Aug.–Sept., July, June.
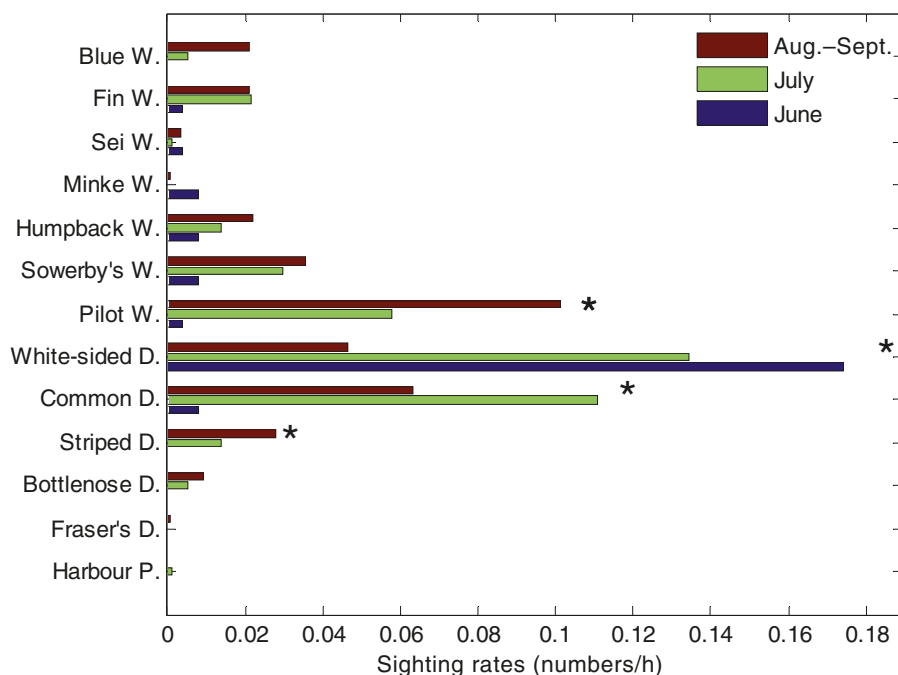
Table 3. Support for models of sighting rates in Zone 1 of Gully MPA (marine protected area).

		QAIC of model				
	$\hat{c}$	1 (month + trend)	2 (month)	3 (trend)	4 (constant)	Trend (SE)/year
Blue W.	5.3	13.43	14.09	**11.81**	13.33	0.11 (0.08)
Fin W.	3.9	14.33	14.64	**11.85**	11.90	−0.07 (0.02)
Humpback W.	5.4	13.48	16.82	**10.68**	13.50	−0.15 (0.07)
Sowerby's beaked W.	4.5	−17.58	7.59	**−21.58**	5.14	0.21 (0.06)
Pilot W.	3.3	**−118.73**	−97.12	−115.02	−87.83	0.09 (0.14)
White-sided D.	2.6	**−222.26**	−218.75	−205.34	−198.07	−0.04 (0.02)
Common D.	3.9	−89.02	**−89.78**	−82.39	−83.24	
Striped D.	3.8	**14.90**	15.02	15.57	15.04	−0.06 (0.10)

Note: Refer to the text for the binomen of the species mentioned above. The best supported model for each species, indicated by the lowest quasi-Akaike's information criterion adjusted for overdispersion of count data (QAIC; calculated using the variance inflation factor ($\hat{c}$)), is shown in boldface type. The estimated trend parameter is shown where a trend with year was included in the best supported model. Estimated SEs are from the jackknife procedure.

rather less frequently in the noncanyon locations. The Shortland and Haldimand canyons have no legal protection, so the implication is that protection provided by the Gully MPA has not yet made a large difference to the abundances of the species considered in this paper, although the time span since designation may be too short for the effectiveness of the MPA to fully emerge. Additionally, and unlike the Banks Peninsula Marine Mammal Sanctuary, New Zealand, for which the first evidence for the positive effect of a MPA on a marine mammal population has recently been published (Gormley et al. 2012), the Gully MPA was not designed specifically for marine mammal protection, nor to remove a specific identified threat.

Trends

The fitted models supported trends in abundance over the study period for all but one of the species with sufficient data. Three species had increasing sighting rates with time, for four they decreased, but the data did not support a trend for the common dolphin. I will consider four potential causes for these trends: change in overall population size, change in the relative habitat

suitability of the study area compared with other potential areas, competition, and changes in the level of anthropogenic disturbance. In Table 4, I assess the likelihood that these factors might have played a role in the observed trends of the seven species for which the sighting data supported a trend.

Change in overall population size

None of the species considered in this analysis have populations confined to the Gully MPA, or even nearby waters. Some, like humpback whales, make seasonal migrations, and all are, to some extent, nomadic. Thus, their numbers in the Gully will be strongly affected by how they use the canyon relative to how they use other waters. Nevertheless, changes in overall population size will, all else being equal, be reflected by trends in the Gully. For changes in overall population size to be major drivers of the Gully trend, the Gully trend should have the same direction as the known or expected trend of the overall population, and, if an increase, be not much greater than the maximum potential rate of increase for the species. As the overall humpback whale population in the North Atlantic has been increasing over much of the study period at

Fig. 3. Sighting rates (numbers/h) of the most commonly sighted species in Zone 1 of the Gully marine protected area by year (SE error bars from Poisson-distribution approximation). A broken trend line is shown when a trend was included in the best-supported model.
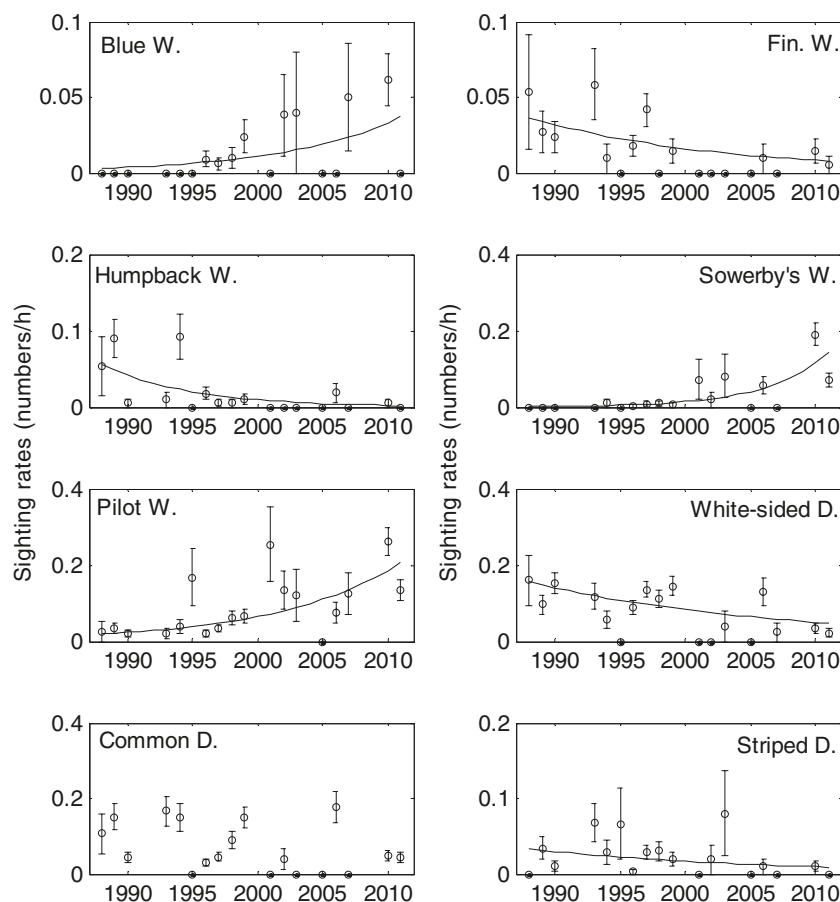
Table 4. Tentative assessment of possible drivers of trends in sighting rates for seven species in which the data supported a trend: XX, potential cause with some empirical support; X, possible cause; O, unlikely cause; ?, unknown.

	Trend/year	Diet*	Overall population change	Habitat suitability	Competition	Noise
Blue W.	0.11	LZ	X	XX	O	?
Fin W.	−0.07	SP, LZ, SS	X	XX	O	O
Humpback W.	−0.15	SP, LZ, SS	O	XX	O	O
Sowerby's W.	0.21	MF, MS?	O	?	O	X
Pilot W.	0.09	SS, SP, MS, MF	X	?	?	X
White-sided D.	−0.04	SS, SP	X	X	?	O
Striped D.	−0.06	SP, SS	X	X	?	O

Note: Refer to the text for the binomen of the species mentioned above.

*The probable diet of the species in the Gully area is indicated in decreasing order of probable importance (based upon Whitehead et al. 1998): LZ, large zooplankton; SP, small pelagic fish; SS, small pelagic squid; MS, mesopelagic squid; MF, mesopelagic fish.

about 3%/year (Stevick et al. 2003), it cannot explain the decrease of about 15%/year for this species in the Gully. Also, the 21% per annum increase of Sowerby's beaked whale in the Gully is well above the estimated maximum potential rate of increase of a cetacean population, with 4% being used as a default value for assessments under the US Marine Mammal Protection Act (Wade 1998). For the other five species listed in Table 4, the Gully trend could be explained, at least partially, by changes in overall populations. For instance, the increases in blue and pilot whales would fit with recovery from overexploitation in the western North Atlantic (Mitchell 1974; Clapham et al. 1999), although there is no independent evidence of such recoveries.

Change in habitat suitability

The physical variables most thought to affect cetacean distribution and abundance are bathymetry and SST (Kaschner et al. 2006). Bathymetry does not change and so cannot explain the temporal trends in abundance. SST varies through the summer and is likely an ultimate cause of the changes in abundance of some species over the summer months, as species have preferred temperature ranges. Thus, systematic changes in SST over the 23 years of the study could potentially have caused the trends in species abundance. Despite much seasonal and interyear variation, measured SST did increase over the study period at a mean rate of 0.066 °C/year (95% CI 0.004–0.0128, from a general linear

model with calendar month as categorical covariate), which translates into an increase of 1.45 °C during the entire 23-year study. This rate is sufficiently slow that it is unlikely to have much affected the abundances of the seven cetacean species with significant trends listed in Table 4, which have SST tolerance ranges of approximately 20–37 °C (Kaschner 2004).

Much more likely as an environmental factor driving the trends in cetacean abundance in the Gully is prey abundance. There have been substantial recent changes in the ecology of the eastern Scotian Shelf (Frank et al. 2011). The earliest part of this study (1988–1992) coincided with the collapse of populations of large predatory fish, especially Atlantic cod (*Gadus morhua* L., 1758), largely a result of unsustainable fishing. This released a major increase in forage fish biomass that only began to dampen in about 2005, as the predatory fish stocks started to rebuild (Frank et al. 2011). Large zooplankton, such as euphausiid, biomass was low in the 1990s but increased from 2000 to 2008 (Frank et al. 2011). These dynamics of the eastern Scotian Shelf ecosystem may not relate directly to the cetacean trends in the Gully. The Scotian Shelf patterns primarily refer to the shallow shelf waters, while the Gully data are primarily from a deep canyon. Some species, such as white-sided dolphins, fin whales, and pilot whales, use both shelf and canyon habitats and so abundance in the Gully might indicate unfavourable conditions for them on the Scotian Shelf if habitat suitabilities in the two systems are not well correlated.

General diets of the species with abundance trends in the Gully are indicated in Table 4. Apart from the blue whale, which primarily eats euphausiids, and Sowerby's beaked whale whose diet is poorly known, the species have wide diets, including two or more of the large zooplankton, pelagic fish, and cephalopod groups. The increasing abundance of blue whales after about 2000 does generally match the dramatic rise in their presumed prey, large zooplankton, on the Scotian Shelf over this period (Frank et al. 2011). In a similar vein, the decreasing abundances of fin and humpback whales over the study might relate to the general decline in pelagic fish such as herring (*Clupea harengus* L., 1758). A similar argument could be made for white-sided and striped dolphins, although with less support, as we know less of their diets. We know nearly nothing of biomass trends in the mesopelagic where both Sowerby's beaked whales and pilot whales feed.

Competition

Species could be using the Gully more or less frequently in response to changes in the abundance of competitive species. This seems unlikely for the bulk feeding baleen whales whose resources come in large quantities, and there is no obvious concentration of competing species. The most likely competitors for mesopelagic-feeding Sowerby's beaked whales are pilot whales, whose abundance also increased, and bottlenose whales, whose abundance in the Gully has remained fairly stable over the study (COSEWIC 2011). Thus, decrease in competition seems an unlikely driver of the dramatic rise in the abundance of Sowerby's beaked whales. Competition cannot be ruled out among the delphinids, with the decrease in numbers of white-sided and striped dolphins perhaps being related to the increase in pilot whales.

Anthropogenic disturbance

Human presence in the study area, and associated disturbance, has generally decreased since 1988. Until the 1993 groundfish moratorium, there was considerable bottom trawling in the shallow waters around the Gully by large (>20 m) vessels (Breeze 2002). These activities are noisy (Rosen et al. 2012) and had a major effect on ambient noise levels in the Gully (personal observation). Pelagic and benthic longlining, which use smaller and quieter vessels than trawling, has occurred in the Gully region throughout the study (Breeze 2002), but all fishing has been banned from Zone 1 since the establishment of the MPA in 2004. Seismic explo-

ration activities have been sporadically intense on the Scotian Shelf, especially between 1998 and 2003 (Canada – Nova Scotia Offshore Petroleum Board 2006), but activity has been kept away from the Gully since it was declared a pilot MPA in 1998 and especially since it received full MPA status in 2004 (Westhead et al. 2012). Commercial shipping, while not banned from the Gully, has been warned away from it since the establishment of a "Whale Sanctuary" in 1994, and especially with the MPA in 2004. The sonic booms of the supersonic airliner Concorde, whose routes between Europe and New York passed over the Gully, were prominent acoustically both above and below the water, but these ended in 2003 when the Concorde ceased operations. Currently, the Gully MPA is traversed by about one commercial vessel per day, small longlining fishing vessels using its outer zones, and research vessels occasionally work in the area (personal observation). Overall human disturbance, indicated by ocean noise levels, has probably been generally decreasing over the study period.

A decrease in noise might have increased the attractiveness of the Gully for some species, especially as ocean noise has been generally increasing elsewhere (see citations in Weilgart 2007). Of the three species whose abundance has increased, changes in noise may be particularly significant for Sowerby's beaked whale (Table 4). Although little is known of Sowerby's, the beaked whales in general and other members of its *Mesoplodon* genus in particular are known to be especially sensitive to ocean noise (Aguilar Soto et al. 2006; Cox et al. 2006; Weilgart 2007). Thus, the reduction in noise is a tenable hypothesis for the remarkable increase in Sowerby's beaked whales in the Gully, as well as Shortland and Haldimand canyons which will have experienced similar decreases in ocean noise due to declines in fishing activities, seismic exploration, and supersonic flight.

Conclusion

Over the 23 years of this study, the Gully has changed. The humpback and finback whales that were frequently sighted are now rare. The large draggers working the shallow lips of the canyon are long gone. Sowerby's beaked whales, an unseen exotic in the early days, are now a staple part of the Gully biota. The waters have warmed a little, and a seascape studded with oil and gas leases is now a marine protected area.

The neighbouring eastern Scotian Shelf has also seen dramatic changes in ecology (Frank et al. 2011). These result from complex interplays between anthropogenic impacts, such as bottom trawling, and natural processes including regime shifts. Despite much study, the relative significance of different factors in the ecological dynamics of the eastern Scotian Shelf are disputed (Frank et al. 2011; Swain and Mohn 2012). Depending on the part of the ecosystem, events in the Gully may parallel those on the eastern Scotian Shelf, or approximate their inverse, for instance for species that move between shallow and deep waters depending on the relative food abundance in each. There are also a whole range of oceanographic processes that can affect cetacean abundance in deep canyons (Moors 2012).

Unravelling all this is very difficult. However, long time series of organismal abundance are a particularly valuable resource. They can be used for simple trend analysis, as in this paper. They can also be used for more direct testing of oceanographic and anthropogenic hypotheses for patterns of change, as in Burrows et al.'s (2012) analysis of a decade-long time series of marine mammal abundance in Monterey Bay, California. I plan, in the next phase of this research, to explore hypotheses for the patterns of abundance of cetaceans in the Gully by directly relating sighting rates to explanatory variables using generalized linear models or related methods. These explanatory variables will include oceanographic variables such as SST, measures of prey abundance, and indicators of human disturbance. However, extending the current time series for another two decades will likely be even more revealing.