1. Introduction

Collision with ships is a significant cause of mortality among endangered whales. Collision lethality increases with vessel speed and mitigation includes slowing ships in whale dense areas. The 2181 km² Stellwagen Bank National Marine Sanctuary (SBNMS) is a site of numerous whale/ship collisions. To understand how speed reduction measures reduce lethal collisions, we used GIS to apply hypothetical speed reductions to observed ship traffic within SBNMS. During 2006, we collected complete AIS data from SBNMS vessel traffic. We created 1.85 km² grid cells covering SBNMS and determined each cell’s predicted probability of lethality (PLETH) from the cell’s mean speed and a mortality curve. We calculated average PLETH for the entire sanctuary (SPLETH), and used SPLETH to index status quo risk. We calculated average PLETH from SBNMS vessel traffic. We created 1.85 km² grid cells covering SBNMS and determined each cell’s predicted probability of lethality (PLETH) from the cell’s mean speed and a mortality curve. We calculated average PLETH for the entire sanctuary (SPLETH), and used SPLETH to index status quo risk. We applied speed limits of 16, 14, 12, and 10 knots on transits and recalculated SPLETH for each scenario. Our analysis included 2,079,867 AIS points to derive 74,638 cell transits by 502 ships (>295 t). Sanctuary mean ship speed, by cell transit, was 13.5 knots (SD 4.3, range 0.1–42.2). The choice of speed restriction had a major impact on SPLETH: 16 knots = –3.7%, 14 knots = –11%, 12 knots = –29.4%, 10 knots = –56.7%. The conservation benefit of speed restrictions is influenced by the status quo speed of ships from which risk must be reduced. As most areas lack such data our results can provide managers with a better understanding of how speed restrictions might reduce risk in their waters.

Published by Elsevier Ltd.
to whales of collisions with ships (Laist et al., 2001; NOAA, 2008; Pace and Silber, 2005; Vanderlaan and Taggart, 2007; Silber et al., 2010).

While reducing ship speeds is a viable tool for mitigating the biological impact of whale/ship collisions, little is known about the actual reductions in lethality that are achieved by implementing specific speed restrictions. This is because an understanding of the conservation value of particular speed limits requires knowledge of the speeds traveled by the vessels being restricted. For example, if a speed limit is chosen that is near or above the status quo transit speed of shipping, then little conservation benefit is realized by implementing that limit.

The Stellwagen Bank National Marine Sanctuary (Stellwagen Sanctuary or sanctuary) is a 2181 km² federally designated marine protected area located in the southern Gulf of Maine, off the coast of Massachusetts and New Hampshire, USA (Fig. 1). The Stellwagen Sanctuary is seasonally dense with endangered North Atlantic right, humpback (Megaptera novaeangliae), and fin (Balaenoptera physalus), whales (Mussoline et al., submitted; Pittman et al., 2006), and is the main fairway for ships accessing the port of Boston, Massachusetts, USA, a major metropolitan area. As a result, numerous whale/ship collisions have occurred there (Jensen and Silber, 2003). The sanctuary also overlaps Critical Habitat for right whales and two areas designated by the US National Oceanic and Atmospheric Administration (NOAA) as right whale Seasonal Management Areas (SMA), and is near a third SMA (Fig. 1). SMAs are sections of the ocean where NOAA has implemented a speed restriction of 10 knots or less for vessels of >65 ft (19.8 m) to reduce the threat of ship collisions with North Atlantic right whales (NOAA, 2008). However, NOAA’s regulation and choice of speed threshold are controversial and include a ‘sunset’ clause that will cause the regulation to expire in 2013. In this paper, we used data on the actual speed of ships >295 metric tons (t) transiting the Stellwagen Sanctuary to model the lethal risk reduction that can be expected by limiting ships to thresholds speeds of 16, 14, 12, and 10 knots (29.6, 25.9, 22.2, and 18.5 km/h, respectively). Because most ships travel at a relatively constant speed in coastal oceans such as that occupied by the Stellwagen Sanctuary, our results might be applicable to other areas where interests exist for using speed restrictions to protect whales, but in situ ship speed data are lacking. Furthermore, this paper demonstrates an approach to evaluating the conservation impact of a general mitigation measure to a highly heterogeneous geographic area.

2. Methods

To understand how various speed reduction measures might reduce the potential for lethal collisions we used ArcGIS (ESRI, 2006) to apply hypothetical speed reductions to observed ship traffic within the Stellwagen Sanctuary. Ship traffic and speed data were acquired from the US Coast Guard’s Automatic Identification System (AIS). The United Nation’s International Maritime Organization (IMO) mandates that all commercial marine traffic >295 t carry AIS transmitters (Federal Register, 2003; IALA, 2004). The AIS transmitter broadcasts a suite of data that includes time, vessel identification and speed over ground (SOG) as often as every 2 s. We used data from AIS receivers installed by the Stellwagen Sanctuary in Cape Cod, MA, Cape Ann, MA and Scituate, MA, USA (Fig. 1) to...
To quantify the probability of lethality (PLETH) resulting from a collision between a whale and a ship, we gridded the Stellwagen Sanctuary into 810 cells of 1 min latitude and longitude (1.85 km²). Gridding was used because of heterogeneity in the data. For example, while most ships transited at a constant speed, some slowed as they approached port or to wait for tide or offloading conditions to be more favorable. For each cell we calculated its PLETH by using AIS data to calculate the mean speed of each ship transit (to 0.1 knot/h) in the cell and using a speed/lethality curve (Pace and Silber, 2005) to derive that transit's corresponding probability if a collision with a whale were to occur, the result would be lethal for the whale. We then summed these values for all cell transits and divided by the number of transits to obtain the mean PLETH value of that cell. We calculated the average PLETH value for the entire sanctuary (SPLETH), by summing the PLETH for all cells and dividing by the number of cells in the sanctuary (810), and used SPLETH as an index of status quo risk. We specifically chose this approach to allow equal influence of all areas of the sanctuary despite heterogeneity in vessel traffic characteristics among cells. We then applied hypothetical speed limits of 16, 14, 12, and 10 knots on transits by selecting all AIS points above the limit and replacing them with the limited speed. For example, if the hypothetical speed limit was 16 knots, each AIS point above 16 knots was selected and replaced with the value 16. We then recalculated SPLETH for each scenario.

To provide an understanding of the ship traffic transiting the Stellwagen Sanctuary, we used the AIS Vessel Type field to bin ships into five categories: cargo/container, tanker, tug, service/research, passenger, and fishing. For each category, we calculated the number of ships, number of transits, percent total (ships and transits), average minimum speed over ground (knots), average maximum speed over ground (knots), and average speed over ground (knots).

### Table 1

The probability of lethality resulting from a collision between a whale and ship in the Stellwagen Bank National Marine Sanctuary and percent risk reductions achieved by limiting ship speed to thresholds of 16, 14, 12, or 10 knots (29.6, 25.9, 22.2, and 18.5 km/h, respectively).

<table>
<thead>
<tr>
<th>Threshold speed (knots)</th>
<th>Probability of lethality associated with threshold speed (from: Pace and Silber, 2005)</th>
<th>Probability of lethality to a whale struck by a ship in the sanctuary (SPLETH)</th>
<th>Percent reduction (observed-status quo SPLETH)/status quo SPLETH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Status quo</td>
<td>NA</td>
<td>0.67</td>
<td>NA</td>
</tr>
<tr>
<td>16</td>
<td>0.865</td>
<td>0.645</td>
<td>-3.7</td>
</tr>
<tr>
<td>14</td>
<td>0.765</td>
<td>0.597</td>
<td>-11.0</td>
</tr>
<tr>
<td>12</td>
<td>0.622</td>
<td>0.473</td>
<td>-29.4</td>
</tr>
<tr>
<td>10</td>
<td>0.454</td>
<td>0.29</td>
<td>-56.7</td>
</tr>
</tbody>
</table>

### Table 2

Characteristics of vessel traffic (502 unique vessels) in the Stellwagen Bank National Marine Sanctuary for the year 2006. Data derived from the US Coast Guard’s Automatic Identification System.

<table>
<thead>
<tr>
<th>Vessel category</th>
<th>Number of unique vessels</th>
<th>Percent of total vessels</th>
<th>Number of transits</th>
<th>Percent of total transits</th>
<th>Average speed over ground (maximum and minimum) in knots</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cargo/container</td>
<td>141</td>
<td>28</td>
<td>645</td>
<td>26</td>
<td>16.2 (16.1–16.4)</td>
</tr>
<tr>
<td>Fishing</td>
<td>4</td>
<td>1</td>
<td>12</td>
<td>1</td>
<td>10.7 (10.3–11.0)</td>
</tr>
<tr>
<td>Passenger</td>
<td>76</td>
<td>15</td>
<td>214</td>
<td>8</td>
<td>14.4 (14.1–14.8)</td>
</tr>
<tr>
<td>Service/research</td>
<td>29</td>
<td>6</td>
<td>156</td>
<td>6</td>
<td>10.0 (9.3–11.0)</td>
</tr>
<tr>
<td>Tanker</td>
<td>161</td>
<td>32</td>
<td>943</td>
<td>37</td>
<td>14.0 (13.9–14.1)</td>
</tr>
<tr>
<td>Tug</td>
<td>91</td>
<td>18</td>
<td>548</td>
<td>22</td>
<td>8.5 (8.4–8.8)</td>
</tr>
</tbody>
</table>

### 3. Results

#### 3.1. Reduction in lethal risk

Our analysis included 2,079,867 AIS points to derive 74,638 cell transits by 502 ships (>295 t) making 2518 sanctuary transits. Sanctuary mean ship speed, by cell transit, was 13.5 knots (SD = 4.3, range 0.1–42.2), equating to a mean risk of lethality to a whale struck by a ship in the sanctuary (SPLETH) of 0.67, with 1.0 being a 100% chance of whale death if struck. The choice of speed restriction had a major impact on SPLETH: 16 knots = -3.7%, 14 knots = -11%, 12 knots = -29.4%, 10 knots = -56.7% (Table 1).

#### 3.2. Characteristics of ship traffic

The largest percentage of ships were cargo/container ships (28%) and the least was fishing vessels (1%). The fastest were cargo/container ships (average speed 16.2 knots (30 km/h) and the slowest were tug vessels (8.6 knots 15.9 km/h) (Table 2). The largest percentage of transits was tanker ships (37%) and the least was fishing vessels (1%).

### 4. Discussion and conclusion

When evaluating the effectiveness of mitigation measures on a biological reserve or any other delineated geographic space, the choice of summary metrics may greatly influence the perceived conservation value. In particular, if the activities being mitigated are heterogeneously distributed across the reserve, two choices for summarization are possible: by activity or by area. We evaluated mitigation on its overall effect to Stellwagen Sanctuary, a well defined geographic area. Thus, we thought it most informative if zones within the sanctuary not influenced by speed restrictions (low traffic volume above 10 knots) be given equal weight to areas greatly influenced so as to provide a geographic perspective to the evaluation process. Although completing an event-based analysis (e.g. counting the number of percent events where speed was reduced) might portray higher levels of threat reduction, those gains may be highly overstated for the reserve as a whole.

We used actual speeds from transiting ships (>295 t) to model the conservation benefit that can be expected to occur from speed reductions meant to diminish the likelihood of lethal collision between ships and whales. The use of data derived from actual ship transits is important because, while lethality curves provide a good indicator of risk reduction, the ultimate conservation benefit is also dependent on the status quo speed of ships transiting the management area from which risk must be reduced. For example, Laist et al. (2001) recommended reducing ship speed to less than 14 knots as a mitigation measure. If 14 knots became policy, our data indicate that little reduction in lethality might occur. In the
case of the Stellwagen Sanctuary, such a policy would result in a
decrease of only 11% from the current level of risk in the sanctuary.
In the Gibraltar Strait, a voluntary speed limit of 13 knots has been
recommended to reduce the lethality of collision with sperm
whales (Notice to Mariners published on January 2007 by the
“InstitutoHidrografico de la Marina” (Spanish Navy Hydrographical
Institute under the Ministry of Defense)). While we did not specif-
ically model a 13 knot speed, if shipping in the Gibraltar Strait is
similar to that transiting the Stellwagen Sanctuary, the conserva-
tion benefit might be less than expected because many ships
would not have to slow and many others would slow only minor
amounts.
It could be argued that ships that are already traveling near the
chosen speed threshold would not need to slow because they
would already account for minor risk to whales. However, if cur-
rent levels of lethality are the impetus for new management action,
then choosing a speed limit that did not result in most ships slowing
would be unlikely to achieve the goal of reducing risk. Again,
understanding the conservation benefit of specific speed reduc-
tions is dependent on knowledge of the current speeds used by
the ships being managed.
In lieu of such data, comparing and contrasting the composition of
ships in an area being considered for management to that con-
tained in this paper can provide a guide as to whether transit
speeds could be expected to be faster or slower. For example, an
area dominated by container ships might result in faster average
speed and greater risk reduction than we calculated and one dom-
inated by tugs-in-tow might have slower speeds and less risk
reduction. To that end, we have provided data on the characteris-
tics of ships using the study area and included in our analysis
(e.g., vessel categories, number of ships and transits, mean transit
speeds). A detailed 2006 description of vessel use in the Stellwagen
Sanctuary plus a 9.3 km buffer, including vessel type by tonnage,
number of transits, total transit distance, and transit time can be
found in Hatch et al. (2008). However, Hatch et al. (2008) over-
represents slow tug-in-tow vessels, which heavily use the 9.3 km buff-
er zone to the west of the sanctuary, an area not included in our
study. If areas being considered for management are closer to ports
than that used in our study, then ship speeds might be slower than
those we quantified as vessels would reduce headway to make
port. However, vessels departing ports are under no such limitation
and can be expected to quickly reach top transit speed.
An important aspect of attempting to apply a fitted biological
response within the evaluation of conservation measures is that
there may be considerable uncertainty within the biological re-
sponse model. For example, analyses such as ours are influenced
by the mortality curves used to predict risk reduction. Vanderlaan
and Taggart (2007) present several curves, simple logistic and lo-
gistic fitted to bootstrap predicted probabilities, to calculate
the risk of lethality. While the lethality curves presented in Pace
and Silber (2005) and used in this analyses are very similar to those
identified by Vanderlaan and Taggart (2007), there are differences.
For example, at 10 knots, Vanderlaan and Taggart (2007),
calculated risk of lethality as ~0.31 using a simple logistic curve and
~0.32 when using the bootstrapped method, while Pace and Silber
(2005) calculated ~0.45. At 16 knots, Vanderlaan and Taggart
(2007), calculated risk of mortality as ~0.86 using a simple logistic
curve and ~0.92 when using the bootstrapped method, while Pace
and Silber (2005) calculated 0.865. This suggests that when a ves-
sel reduces its speed from 16 to 10 knots it reduces it predicted
lethality by 47.5% in our model as compared to 64% and 65%
in the two Vanderlaan and Taggart (2007) models.
Our results are also impacted by the universe of vessels it con-
tains. For example, in our analysis we included all vessels in the area,
some of which were already operating at below the chosen thresh-
old speed. Including vessels that are operating below the threshold
lowers the calculated efficacy of the reduction because their behav-
ior is not changed. We chose to retain those vessels in our analysis
because our goal is to demonstrate the effectiveness of a speed
restriction rule on a particular piece of ocean where the actual com-
position and transit speed of the vessels is known with a high degree
of certainty (a rare occurrence), not on a set of vessels.
To protect North Atlantic right whales, one of the world’s rarest
large mammals, from the effects of ship strike, NOAA (2006) con-
sidered speed limits of 14, 12 and 10 knots in SMAs, before finally
implementing a 10 knot restriction (NOAA, 2008). Since three of
the largest and longest duration SMAs overlap (Cape Cod Bay
and Off Race Point) or are near (Great South Channel) the Stellwagen
Sanctuary it is likely that shipping in our study area is similar to
that in those SMAs and our results could be applicable to the man-
agement of those areas. An additional reason for our data to be rep-
resentative of those areas is that the Traffic Separation Scheme
accessing the port of Boston MA passes through the Stellwagen
Sanctuary, Off Race Point SMA and Great South Channel SMA
(Fig. 1). Therefore many ships calling on or departing Boston termi-
nals would pass through all three areas. Thus, using shipping in the
Stellwagen Sanctuary as a proxy for those areas, had NOAA imple-
mented a 14 knot restriction a risk reduction of ~11% could have
been expected and a 12 knot restriction would have yielded a
~30% reduction. NOAA’s ultimate choice of 10 knots for the SMA
restrictions resulted in a substantial risk reduction of almost 60%.
While we have modeled the goal of reducing the physical sever-
ity of whale/ship collisions by focusing on the likelihood of a whale
being killed or seriously injured when it is struck by a ship, a more
ideal goal would focus on the prevention of ship strike to whales.
A number of mitigation measures to reduce the risk of whales being
struck have been proposed including rerouting traffic to less whale
dense areas, sonic deterrents placed on ships to move whales away
from ships, active sonar or human observers to detect whales in the
path of ships so whales can be avoided, and acoustic detection buoys
that can alert operators to the existence of whales ahead. However,
many of these measures have inherent problems. Rerouting ships,
such as done in the Bay of Fundy, Canada and Stellwa-
gen Sanctuary, requires long term data on the distribution of
whales that are often unavailable. Active acoustic deterrents and
SONAR devices add to oceanic noise pollution, an area of increasing
concern for large whales (NRC, 2003; Hatch et al., 2008) or can
cause whales to move to the surface, where they are more vulner-
able to collisions (Nowacek et al., 2004). In addition, passive acous-
tic whale detectors can only identify acoustically active whales and
human observers on ships are of limited effectiveness at night or in
rough seas. Given these problems, when whales and ships cannot
be separated in time and space through rerouting, mitigation by
slowing ship speeds remains the most attractive and viable tool
for reducing the impact of whale/ship collisions. Speed restrictions
have the additional advantage of providing whales and ships addi-
tional time to avoid collision, although it is not clear that either
will do so.
When possible, decisions concerning the speed limit chosen to
protect whales should be based on empirical data that includes the
speed of ships transiting the management area. Such speed
can be derived from AIS transmitters carried by ships (>295 t)
as required by the IMO. However, AIS was devised by the IMO as a
collision avoidance system rather than an archival data base that
can be used for post hoc analysis such as we have done. Collection
of such data requires the proper placement of receivers that can re-
cord and store/transmit data and specialized software to retrieve
and analyze it. While use of AIS data is becoming more common
in conservation (e.g., Möller et al., 2005; Hatch et al., 2008;
Lagueux et al., 2011; McGillivary et al., 2009; Vanderlaan
and Taggart, 2009) our modeling of threat reduction based on the
actual speed of ships transiting the Stellwagen Sanctuary can be
useful for managers lacking such data, but seeking to choose the most appropriate speed for managing the risk to whales in their waters. It can also be of use to managers and stakeholders needing to have confidence in the choice of speed thresholds used for management. For example, in the case of the North Atlantic right whale, conservation interests need to have confidence that the speed threshold chosen (10 knots) will result in real risk reduction, shipping interests need to know that they are not being hindered without benefit to the species and managers need to demonstrate that their decision has value. In fact, this condition was the basis for NOAA’s Ship Strike Reduction Rule expiring and potentially being reconsidered for renewal in 2013 (NOAA, 2008). Our results indicate that the choice of a 10 knot threshold for speed resulted in considerably more risk reduction than alternatives (16, 14, and 12 knots) and that the level of risk reduction (nearly 60%) should benefit the species. Our case study also provides an example of how scientists and managers might investigate the value of speed restrictions in their area and provide incentive for expanded use of AIS data for environmental decision-making.

Finally, our work stands as a case study for a more generally applicable evaluation strategy. That is, we evaluated the reduction in threats across a large geographic area by applying a biological response curve to localized threat conditions to measure and average the local condition. We then modified the threats or risks to examine the overall impact of potential management measures across the area. As evaluating the efficacy of conservation strategies and policies is an important aspect of management (Wiley et al., 2008), our approach should have wide appeal when reserve managers are contemplating ways to evaluate broad-scaled mitigation measures across locally heterogeneous threats.

Acknowledgements
We thank Craig MacDonald and Patrick Ramage for support. Funding was provided by the International Fund for Animal Welfare, NOAA’s Office of National Marine Sanctuaries and National Marine Fisheries Service/Northeast Regional Office.

References