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Short communication

# Modeling speed restrictions to mitigate lethal collisions between ships and whales in the Stellwagen Bank National Marine Sanctuary, USA

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ABSTRACT

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 km$^2$ 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 km$^2$ ($N = 810$) 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 (SD4.3, 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.

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## 1. Introduction

Collision with ships is a key mortality factor for large whales, many of which are endangered. The problem is global in scale, (Jensen and Silber, 2003; Laist et al., 2001) including Australia (Kemper et al., 2008), Canada (Williams and O'Hara, 2010), the Canary Islands (Carillo and Ritter, 2008), the Mediterranean (Panigada et al., 2006), Spain (De Stephanis and Urquiol, 2006) and the United States (Kraus et al., 2005; Lammers et al., 2007; Wiley et al., 1995). In some cases lethality, defined as mortality or serious injury (Vanderlaan and Taggart, 2007), from collisions with ships is sufficient to reduce the viability of species; e.g. the North Atlantic right whale (*Eubalaena glacialis*) (Caswell et al., 1999; Fujiwara and Caswell, 2001; Kraus et al., 2005) or sub-populations; e.g. sperm whales (*Physeter macrocephalus*) in the Mediterranean (Panigada et al., 2009). An increase in the rate of detected collisions between whales and ships in the past few decades corresponds to an increase in the number, size and speed of ships over the same time period (Vanderlaan et al., 2009). Without intervention the problem is expected to exacerbate as already high levels of oceanic shipping continue to rise. Schwehr and McGillivary (2007) projected a sustained 3% annual increase in worldwide traffic, spurred by a global economy dependent on ships to move goods.

Lethality of collisions increases with ship speed (Pace and Silber, 2005; Vanderlaan and Taggart, 2007: Silber et al., 2010). Vanderlaan and Taggart (2007) found the probability of a lethal strike increased from 20% to 100% at speeds between 9 and 20 knots (16.7 and 37 km/h), and that lethality from ship strike increased most rapidly between 10 and 14 knots (18.5 and 25.9 km/h): 35–40% at 10 knots (18.5 km/h), 45–60% at 12 knots (22.2 km/h) and 60–80% at 14 knots (25.9 km/h). Similar results were reported by Pace and Silber (2005). In addition, Silber et al. (2010) found that increased vessel speed increased the hydrodynamic draw of vessels that could result in right whales (and likely other species) being pulled towards vessels making them more vulnerable to collisions and increasing the magnitude of impact. Therefore, slowing ship speeds in whale dense areas is a practical mitigation measure to reduce the severity

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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 km$^2$ 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

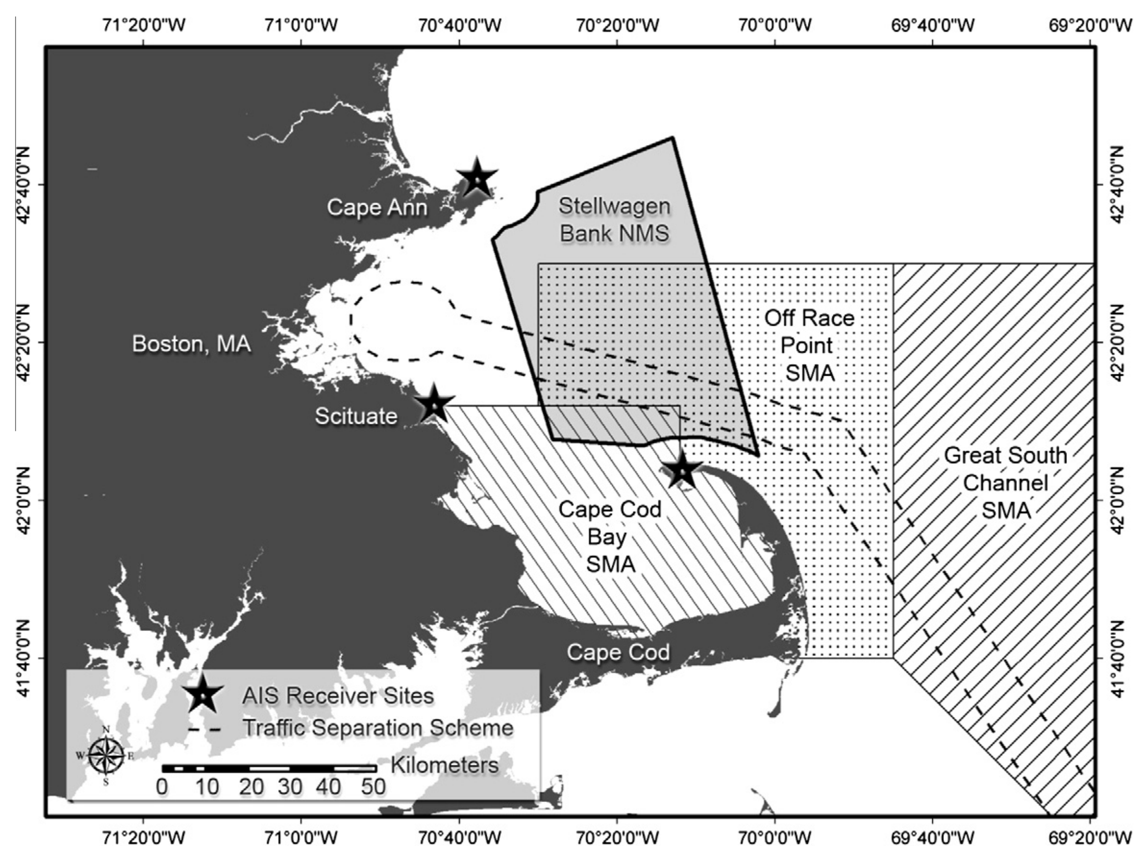


**Fig. 1.** The Stellwagen Bank National Marine Sanctuary study area and seasonal management areas (SMA) for endangered North Atlantic right whales (*Eubalaena glacialis*): Cape Cod Bay SMA, Off Race Point SMA and Great South Channel SMA. SMAs employ speed restrictions (⩽10 knots; 18.5 km/h) on vessel transits to reduce the risk of lethal strikes to that endangered species. In addition to the proximity of the SMAs to the Stellwagen Bank National Marine Sanctuary, note that the Traffic Separation Scheme accessing the port of Boston, Massachusetts traverses the sanctuary, Off Race Point SMA and Great South Channel SMA, indicating that many of the same ships would use each area. Therefore, speed based reductions in lethality modeled in the sanctuary are indicative of the results that might be expected in those SMAs.

collect data from all AIS carriage vessels transiting the sanctuary for the year 2006.

To quantify the probability of lethality (PLETH) resulting from a collision between a whale and ship, we gridded the Stellwagen Sanctuary into 810 cells of 1 min latitude and longitude (1.85 $km^2$). 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).

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

## 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 was 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

**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.

| Vessel category | Number of unique vessels | Percent of total vessels | Number of transits | Percent of total transits | Average speed over ground (maximum and minimum) in knots |
|---|---|---|---|---|---|
| Cargo/container | 141 | 28 | 645 | 26 | 16.2 (16.1–16.4) |
| Fishing | 4 | 1 | 12 | 1 | 10.7 (10.3–11.0 |
| Passenger | 76 | 15 | 214 | 8 | 14.4 (14.1–14.8) |
| Service/research | 29 | 6 | 156 | 6 | 10.0 (9.3–11.0) |
| Tanker | 161 | 32 | 943 | 37 | 14.0 (13.9–14.1) |
| Tug | 91 | 18 | 548 | 22 | 8.6 (8.4–8.8) |

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 "*InstitutoHidrográfico de la Marina*" (Spanish Navy Hydrographical Institute under the Ministry of Defense)). While we did not specifically model a 13 knot speed, if shipping in the Gibraltar Strait is similar to that transiting the Stellwagen Sanctuary, the conservation 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 current 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 reductions 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 contained 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 dominated by tugs-in-tow might have slower speeds and less risk reduction. To that end, we have provided data on the characteristics 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 buffer 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 response 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 logistic fitted to bootstrapped 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 leathality 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 vessel 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 contains. For example, in our analysis we included all vessels in the area, some of which were already operating at below the chosen threshold speed. Including vessels that are operating below the threshold lowers the calculated efficacy of the reduction because their behavior 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 composition 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) considered 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 management of those areas. An additional reason for our data to be representative 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 terminals would pass through all three areas. Thus, using shipping in the Stellwagen Sanctuary as a proxy for those areas, had NOAA implemented 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 severity 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 Stellwagen 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 vulnerable to collisions (Nowacek et al., 2004). In addition, passive acoustic 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 additional 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 record 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., Moller 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 mangers are contemplating ways to evaluate broad-scaled mitigation measures across locally heterogeneous threats.

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