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Trends in Propeller Strike-induced Mortality in Harbor Seals (*Phoca vitulina*) of the Salish Sea

Jennifer K. Olson,[1,6] Dyanna M. Lambourn,[2] Jessica L. Huggins,[3] Stephen Raverty,[4] Alyssa A. Scott,[1] and Joseph K. Gaydos[5] [1]The Whale Museum, 62 1st Street N, PO Box 945, Friday Harbor, Washington 98250, USA; [2]Washington Department of Fish & Wildlife, Marine Mammal Investigations, 7801 Phillips Road SW, Tacoma, Washington 98498, USA; [3]Cascadia Research Collective, 218 W 4th Avenue, Olympia, Washington 98501, USA; [4]Animal Health Center, 1767 Angus Campbell Road, Abbotsford, British Columbia V3G 2M3, Canada; [5]SeaDoc Society, UC Davis Karen C. Drayer Wildlife Health Center–Orcas Island Office, 942 Deer Harbor Road, Eastsound, Washington 98245, USA; [6]Corresponding author (email: jenolson@everettcc.edu)

ABSTRACT: Documenting human impacts on marine mammals is critical for understanding and mitigating harm. Although propeller strike injuries in small marine mammals are often debilitating and fatal, little is known about the occurrence or demographics of these types of injuries in pinniped populations. Using data of stranded harbor seals (*Phoca vitulina*) in the Salish Sea from 2002–19, we identified 27 cases of fatal propeller strikes. Weaned pups were the most frequently affected (64% of cases) with a much higher rate of propeller strikes than expected for the age class. Although they do represent animal welfare concerns, harbor seals in the Salish Sea probably are not threatened by these types of injuries at the population level; nevertheless, propeller strike cases increased significantly over the time of this study period, indicating increased interactions between boats and seals in the region. Continued monitoring and increased efforts to consistently quantify vessel traffic in the area are recommended to create and monitor long-term effectiveness of mitigation measures.

Key words: Harbor seal, human interaction, marine mammal stranding data, *Phoca vitulina*, propeller strike, Salish Sea, sharp trauma.

Identifying and understanding anthropogenic effects on marine mammals is a critical first step toward mitigating harm. Globally, vessel-induced morbidity and mortality has been well documented in large and small cetaceans (Laist et al. 2001; Van Waerebeek et al. 2007). For large cetaceans, vessel collisions can be major causes of mortality and, for some species, a threat at the population level (Kraus et al. 2005). The impact of vessels on pinnipeds is less well documented, despite their heavy use of nearshore habitat and proximity to dense human populations. Case studies have demonstrated propeller strikes in New Zealand fur seal (*Arctocephalus forsteri*), gray seals (*Halichoerus grypus*), and harbor seals (*Phoca vitulina*; Byard et al. 2012; Moore and Barco 2013); however, population-wide analyses needed to reduce propeller strikes are lacking.

The Salish Sea, an urban inland sea in Washington, US, is home to more than 8 million people and experiences high levels of commercial shipping, recreational boating, whale watching, and sport, commercial, and tribal fisheries (Dismukes et al. 2010). Despite heavy vessel traffic, little is known about the impact of propeller strikes on marine mammals. We retrospectively analyzed harbor seal stranding data and pathology findings to evaluate spatiotemporal trends in propeller strike mortality in these waters.

We evaluated harbor seal stranding and necropsy records from 2002 through 2019 in well-covered stranding-response areas of the Salish Sea: San Juan County (SJC) and South Puget Sound (SPS), in which consistent funding since the early 2000s (Ashley et al. 2020) has facilitated stable marine mammal stranding response and necropsy (Fig. 1). Data evaluated included stranding date, location, level of decomposition, age class, sex, length, weight, and findings of human interaction (National Oceanic and Atmospheric Administration 2020). In addition, we reviewed necropsy reports and analyzed gross findings, histopathology, and ancillary test results (Ashley et al. 2020).

Vessel strikes can cause sharp or blunt trauma. Although blunt trauma from boats can be confounded with other causes, such as predation by killer whales (*Orcinus orca*; Ashley et al. 2020), sharp trauma from

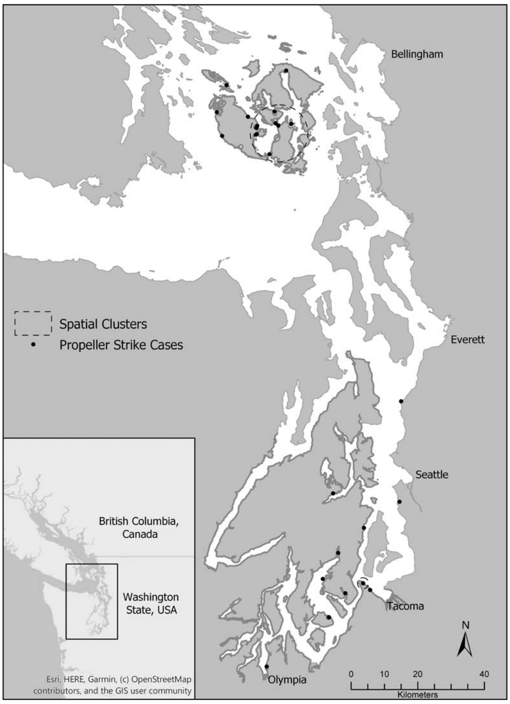

FIGURE 1. Locations of stranded harbor seals (*Phoca vitulina*) with propeller strike injuries in the Salish Sea, Washington, USA, from 2002–19. Response areas are indicated by darker shorelines. Significant spatial clusters (circular dotted lines) were determined by the Bernoulli model in SaTScan (version 9.6; Kulldorff 1997).

propellers results in characteristic lacerations that leave little doubt about their cause. We identified propeller strike injury based on observation of classic propeller lesions and established case definitions (Byard et al. 2013; Moore and Barco 2013). Specifically, this included multiple parallel, fenestrated, and equidistant linear, curvilinear, or sigmoid incisions. Wound depth was not diagnostic because it can vary with the proximity of the animal to the strike, startle response, angle of impact, blade slope and contour, and vessel speed and momentum. Deep incisions with clean margins on extremities and amputations were included, as large propellers or cases with minimal contact along an extremity may present as a single incision or chop wound (Costidis et al. 2013). Injury severity ranged from superficial to severe, including bone fractures, limb or digit amputations, penetration of the thoracic or abdominal cavity, and laceration of internal organs.

Each case was independently reviewed and designated as *confirmed*, *probable*, or *suspect*, according to Costidis et al. (2013); only cases that were examined by trained responders or with images typical of propeller strike were included. Microscopic subcutaneous edema, hemorrhage, and myocellular degeneration and necrosis were used to discriminate antemortem from postmortem trauma.

Harbor seals were assigned an age class category (adult, subadult, weaned pup, or nursing pup), based on length and stranding date (Ashley et al. 2020). Differences between the predicted and actual proportion of propeller strikes according to sex and age class were compared using the chi-squared test of independence. Change in propeller strike cases over time was assessed using a generalized linear model with a Poisson distribution. Change in total strandings over time was assessed using a negative-binomial generalized linear model, with preference over the Poisson distribution determined by a log-likelihood test. For both models, we used number of cases as the response variable and year as the explanatory variable; the model of best fit was determined using the lowest Akaike information criterion value. Significant spatial clusters ($P \leq 0.05$) were identified using a Bernoulli model in the program SaTScan (version 9.6; Kulldorff 1997).

We reviewed 3,633 records from harbor seals that stranded in SJC and SPS from 2002 to 2019 and an additional 275 opportunistic cases from outside those areas. Of all cases, 28 had evidence of propeller strike; 27 of which were fatal. Based on gross necropsy and histopathology, 20 cases were confirmed, five were probable, and three were suspect. Additionally, we identified a record of one healthy (not stranded) harbor seal observed in 2008 with documented evidence of a healing propeller strike wound.

Propeller strike injuries were found in males (61%) and females (39%) with no significant difference in predicted prevalence by sex (χ^2=0.911, P=0.34; Table 1). Propeller strikes were not, however, distributed evenly

TABLE 1. Expected and actual propeller strikes for stranded harbor seals (*Phoca vitulina*) of known sex and/or age class in the Salish Sea, Washington, USA, examined from 2002–19 with associated Pearson's adjusted residuals for chi-squared test of independence by sex and age class.

Age class and Sex	Actual strikes	Expected strikes	Total examinations	Adjusted residuals
Adult	3	4	521	−0.61
Subadult	1	2	219	−0.59
Weaned pup	18	5	655	5.47
Nursing pup	6	17	2033	−2.60
Male	17	14	1111	0.66
Female	11	14	1038	−0.69

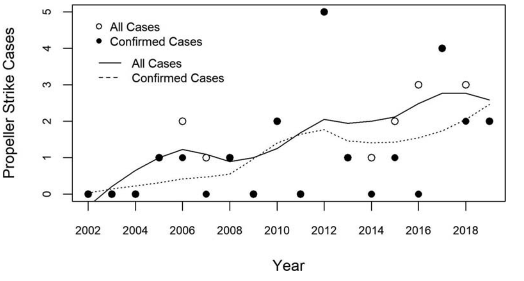

FIGURE 2. Cases of stranded harbor seals (*Phoca vitulina*) with evidence of propeller strike injury observed in the Salish Sea, Washington, USA, from 2002–19. All cases (confirmed, probable, and suspect), plus confirmed cases shown with locally estimated smoothing scatterplot fitted lines.

among age classes (χ^2=37.40, P<0.001). Most cases (86%) involved nursing (n=6) or weaned (n=18) pups, with far more strikes documented in weaned pups than expected (Table 1).

From 2002–19, the total number of stranded harbor seals examined annually remained stable (z=0.144, P=0.885). However, the total occurrence of propeller strike cases (confirmed, probable, and suspect), increased significantly over the course of this study (z=2.793, P=0.005) with the highest number of cases (n=5) documented in 2012 (Fig. 2). This increasing trend was further substantiated when only confirmed cases were analyzed (z=2.455, P=0.014). Seasonally, cases were documented in all months from May to December but were most frequent in August and September (76%). Although seasonal reporting biases exist, the timing of this peak aligns with the region's highest overlap between newly weaned pups and seasonal recreational vessel use.

Numerous coastal, oceanographic, and meteorological forces influence carcass dispersal and final stranding sites (Olson et al. 2020). Although stranding locations do not represent the exact location at which an animal was struck, spatial analyses showed that propeller strike cases were well distributed throughout the study area, with two significant spatial clusters: one of nine strandings in the inner-island shorelines of SJC (P=0.03), and another of three strandings at Owen's Beach in SPS (P=0.002; Fig. 1). Both clusters were located in heavy use areas with confined geography and were in proximity to large marinas (>400 slips), suggesting these areas may be greater-risk sites for collisions between vessels and marine mammals.

The cases identified represent an absolute minimum level of impact. The fact that only 10% (n=3) of cases in this study were accompanied by an eyewitness report suggests that propeller strike is underreported, possibly because of fear of prosecution, uncertainty as to whom to report the incident, or the boat operator being unaware of the strike. Furthermore, beach-cast marine mammal carcasses only represent a fraction of actual mortalities (Williams et al. 2011), and beach surveys on Washington's outer coast indicate that only 38% of stranded harbor seals are reported (Huggins et al. 2015). Thus, propeller strikes almost certainly occur at a much higher rate than reflected in the minimum numbers we report.

Our findings that weaned pups were the most frequently affected age class is consistent with previous work, suggesting that juveniles are particularly vulnerable to this type of injury (Byard et al. 2013; Costidis et al. 2013). This could be due to the lack of a fully developed awareness of marine vessels as a threat. We also found that subadult and adult seals with propeller strike injuries were more likely to have underlying or preexisting conditions that predisposed the animal to the trauma. All adults (n=3), as well as the only subadult, had severe preexisting infections (pyometra, bacteremia, and widespread abscessation; pyometra and perirenal abscessation with systemic microabscessation; encephalitis, gastritis, bronchopneumonia, and lymphadenitis; and bronchiolitis, lymphoid hyperplasia, and hepatitis, respectively), which probably decreased their awareness of propellers, delayed evasive responsiveness, and increased their risk of injury.

The increase in annual observed propeller strike cases that we noted occurred over a period of stable response effort and stranding frequency and in a harbor seal population at equilibrium (Ashley et al. 2020). This trend suggests increased interactions between boats and seals in the Salish Sea. Given the relationship between the size of the animals affected and the lesions noted, it is likely that most of our cases were the result of smaller recreational vessels as opposed to larger ships typically associated with lethal cetacean strikes (Laist et al. 2001). Unlike larger ships, recreational watercraft have unpredictable speeds and courses of travel, making them more difficult for smaller pinnipeds to avoid. These vessels are also more likely to transit shallower waters near haul-out sites or sites that overlap with popular harbor seal foraging areas. Unfortunately, limited data exist to track quantitative trends in regional recreational boat traffic because smaller vessels are not required to use automatic identification systems. Aerial surveys conducted in SJC in 2006 and 2010 showed a 7% increase in weekend vessel traffic and a 19% increase on weekdays (Dismukes 2006; Dismukes et al. 2010). Although more-recent aerial surveys are lacking, marine vessel traffic is increasing on a global scale (Tournadre 2014), and this trend is probably reflected at the local level, particularly with the human population growth observed in the Salish Sea region. Given the probable increasing overlap between recreational boats and pinnipeds that rely on coastal habitat, better quantification of recreational vessel traffic, spatially and temporally, is needed.

Harbor seals are believed to be at carrying capacity in the Salish Sea; the small proportion of animals affected by propeller strikes is unlikely to affect the population. Understanding and mitigating propeller strikes in a harbor seal population at carrying capacity is more of an animal welfare and human safety issue. If locations and times of increased strike can be identified, mitigation measures, such as mandatory propeller guards or vessel speed limits, could be used to reduce human-caused injury, pain, and mortality of harbor seals. We were unable to determine blunt force trauma mortality in this retrospective review, but marine mammals are also known to be hit by boat hulls as well as the lower unit of outdrives. Adding propeller guards will not settle all problems associated with vessel impact, but should help reduce sharp trauma. The unknown extent of vessel-induced blunt trauma in pinnipeds further emphasizes the need for expanded boat traffic data and continued monitoring of stranded pinnipeds in this urban ecosystem.

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