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Spatial and temporal analysis of killer whale (*Orcinus orca*) strandings in the North Pacific Ocean and the benefits of a coordinated stranding response protocol

Michelle M. Barbieri,[1, 2] UC Davis Wildlife Health Center–Orcas Island Office, 942 Deer Harbor Road, Eastsound, Washington 98245, U.S.A.; **Stephen Raverty**, British Columbia Ministry of Agriculture and Food, Animal Health Center, 1767 Angus Campbell Road, Abbotsford, British Columbia V3G 2M3, Canada and University of British Columbia, 2202 Main Mall, Vancouver, British Columbia V6T 1Z4, Canada; **M. Bradley Hanson**, NOAA/NMFS/Northwest Fisheries Science Center, 2725 Montlake Boulevard, East Seattle, Washington 98112, U.S.A.; **Stephanie Venn-Watson**, Epitracker Analytics, 2165 Historic Decatur Road, San Diego, California 92106, U.S.A.; **John K. B. Ford**, Pacific Biological Station, Fisheries and Oceans Canada, 3190 Hammond Bay Road, Nanaimo, British Columbia V9T 6N7, Canada; **Joseph K. Gaydos**, UC Davis Wildlife Health Center–Orcas Island Office, 942 Deer Harbor Road, Eastsound, Washington 98245, U.S.A.

Abstract

Killer whales (*Orcinus orca*) are widely distributed throughout the world's oceans, yet little has been documented about their stranding patterns. Knowledge of stranding patterns improves our ability to examine and sample carcasses and provides a foundation for understanding killer whale natural history, diet, reproduction, anthropogenic stressors, emerging diseases, and patterns of unusual mortality. We compiled published and unpublished killer whale stranding data to describe stranding patterns in the North Pacific Ocean. Between 1925 and 2011, 371 stranded killer whales were reported in Japan (20.4%), Russia (3.5%), Alaska (32.0%), British Columbia (27.4%), Washington (4.0%), Oregon (2.7%), California (5.1%), Mexico (3.8%), and Hawaii (0.8%). Strandings occurred at all times of year, but regionally specific seasonal differences were observed. Mortality and annual census data from Northern and Southern Resident populations were extrapolated to estimate that across the North Pacific, an average of 48 killer whales die annually. However, over the last two decades, an average of only 10 killer whale carcasses were recovered annually in this ocean, making each event a rare opportunity for study. Publication of a standardized killer whale necropsy protocol and dedicated funding facilitated the number of complete postmortem necropsies performed on stranded killer whales from 1.6% to 32.2% annually.

Key words: killer whales, *Orcinus orca*, stranding, North Pacific Ocean, disease, necropsy.

[1]Corresponding author (e-mail: barbierim@TMMC.org).
[2]Current address: The Marine Mammal Center, 2000 Bunker Road, Sausalito, California 94965, U.S.A.

Killer whales (*Orcinus orca*) are cosmopolitan cetaceans (Dahlheim and Heyning 1999). Despite their worldwide distribution and the history of intense study of some populations, few analyses of killer whale stranding patterns have been conducted.

Historically, strandings have been an important method for studying marine mammals. They have demonstrated the existence of new marine mammal species, provided details on prey preference, growth rates, age at maturity, gestation, reproductive seasonality, longevity, and have expanded our understanding of marine mammal mortality factors including infectious diseases and toxins (Geraci and Lounsbury 2005, Morin *et al.* 2010). More recently, information gained from stranded marine mammals has enhanced our understanding of the impacts of sonar and underwater detonations (Jepson *et al.* 2003, Fernandez *et al.* 2005, Danil and St. Leger 2011) and further characterized injuries caused by vessel-whale collisions (Campbell-Malone *et al.* 2008). Stranding data have proven to be an early warning system for identifying the impacts of fishing bycatch in species like bottlenose dolphins (*Tursiops truncatus*; Byrd *et al.* 2008). Also, over sufficiently long time intervals, stranding records have even been shown to yield a richer assemblage of species than line transect survey methods (Pyenson 2010) and could be capable of detecting population declines sooner than survey data (Gulland 2006). Advances in both technology (*e.g.*, polymerase chain reaction [PCR]) and expertise have helped identify novel and emergent pathogens in stranded specimens and evaluate their potential impact on reproduction and population health (*e.g.*, Gibson *et al.* 2011, Nymo *et al.* 2011). Marine mammal stranding patterns can also reflect exposure to stressors such as biotoxins, contaminants, and climate change and help elucidate the synergistic effects of environmental perturbations and emerging pathogens (Krahn *et al.* 2004, Flewelling *et al.* 2005, Fire *et al.* 2007, Moore 2008, Van Bressem *et al.* 2009, Bossart 2011). As long-lived top predators, marine mammals are sentinel species for recognizing the cumulative impacts of such stressors and facilitate our overall understanding of aquatic ecosystem health (Jessup *et al.* 2004, Wells *et al.* 2004, Evans *et al.* 2005, Moore 2008, Bossart 2011). Thus, strandings offer opportunities to collect data on marine mammal biology and health, which are particularly central to conservation and management decisions for declining populations.

The U.S. National Marine Fisheries Service (2008) mandated improved killer whale stranding response as part of a comprehensive effort to better define causes of killer whale mortality and inform conservation efforts in the case of the Southern Resident killer whale distinct population segment (DPS) in the eastern North Pacific. This killer whale DPS is listed as endangered in the United States (U.S. Federal Register 2005) and Canada (Baird 2001, Committee on the Status of Endangered Wildlife in Canada 2008). Concomitant with this designation, a comprehensive killer whale necropsy and disease testing protocol (Raverty and Gaydos 2004), designed to improve killer whale stranding response, was released. One objective of the present study was to compare the level of killer whale stranding response before and after the publication and circulation of this protocol to evaluate the effectiveness of this tool.

Threats to killer whales can be better understood through comprehensive stranding investigations, particularly when combined with long-term population monitoring studies, such as those conducted for resident killer whales in the North Pacific. These threats include prey limitation, environmental contaminants, disease, vessel disturbance, and a small population size (Gaydos *et al.* 2004, Wiles 2004, U.S. National Marine Fisheries Service 2008, Ford *et al.* 2010). Gross and microscopic examinations of stranded carcasses are the cornerstone of comprehensive stranding investigations, but should be interpreted in the context of spatial and temporal patterns in mortalities. Norman *et al.* (2004) examined the seasonality of 16 killer whale strandings in Washington and Oregon; however, despite the potential value, no comprehensive ocean-wide analysis of killer whale strandings has been published. The present study used published and unpublished data to summarize and illustrate the spatial and temporal aspects of killer whale strandings in the North Pacific Ocean since 1925.

Increased stranding preparedness will improve data collection on diseases, contaminants, and causes of mortality for this endangered population and for killer whales worldwide. In the case of Southern Resident killer whales (SRKW), contaminant burden is thought to contribute to their decline (Wiles 2004, U.S. National Marine Fisheries Service 2008). In fact, SRKW and sympatric killer whales of the marine mammal eating ecotype (Ford *et al.* 1998) have been found to harbor some of the highest levels polychlorinated biphenyls (PCBs) among all cetaceans (Ross *et al.* 2000). Although results from chemical analyses of biopsied blubber samples can provide valuable information when carefully interpreted (Ross *et al.* 2000, Krahn *et al.* 2004), internal organ and multiple, full-thickness blubber samples can be obtained from stranded animals (Yordy *et al.* 2010). This allows a more thorough assessment of whole body contaminant burden and associated potential health impacts.

In the mid-1990s, the Northern and Southern Resident killer whale populations (NRKW and SRKW, respectively) experienced 7% and 18% declines, respectively, which correlated with a coast-wide decline in Chinook (*Oncorhynchus tshawytscha*) salmon stock abundance indices (Ward *et al.* 2009, Ford *et al.* 2010). Observations of malnourished animals, however, were rare, suggesting that mortality might not have been a direct result of malnourishment. In the face of reduced prey availability, the mobilization of lipid stores to provide energy also mobilizes contaminants that have the potential to reduce immune function and increase disease susceptibility (Ross *et al.* 2000; Krahn *et al.* 2007, 2009).

Disease is a major mortality factor for many marine mammal species and has been the cause of numerous mortality events worldwide. Gulland and Hall (2007) reported an increasing global trend in the reporting of marine mammal infectious diseases and in the documenting of mass mortalities, which are likely associated with an increase in scientific research and in the number of researchers in this field. Despite this, little is known about diseases of free-ranging killer whales (Gaydos *et al.* 2004). Deviations in killer whale strandings from baseline levels suggest unusual mortality events, but are impossible to evaluate without knowledge of common temporal and spatial stranding patterns by region (Gulland 2006).

Materials and Methods

Peer-reviewed and gray literatures were searched for data on killer whale strandings throughout the North Pacific Ocean. Records were sought as far back as possible. Direct correspondence with major marine science centers, government agencies, and killer whale biologists was also undertaken to solicit unpublished killer whale stranding and necropsy information. Specifically, we requested the following: stranding date and location, the number of animals involved, individual animal identification, ecotype, pod, age or age class, total length, sex, whether or not a gross necropsy was performed, a list of ancillary tests that were performed, whether or not a diagnosis was made, and the name of the lead biologist and/or pathologist.

Using the information gathered, we rated the level of postmortem examination performed on a stranded carcass. Where no information was provided, or little or nothing was done to determine cause of death, the necropsy was classified as "no rating." If a gross necropsy was conducted and biological specimens were collected, the response was rated as "intermediate." For carcasses receiving gross examination, microscopic examination of tissues, as well as bacteriology, toxicology, and other ancillary tests, the necropsy was rated as "complete." Animals that stranded alive and survived were not included in this portion of the analysis.

Locations were categorized into the following nine regions of the North Pacific Ocean: Japan, Russia, Alaska, British Columbia, Washington, Oregon, California, Mexico, and Hawaii. While it is preferable to use total length to classify animals into age classes, these data were not consistently available so for the purposes of this study, animals were broadly categorized as either "adult" or "subadult." If an animal was qualitatively described as immature, neonate, calf, juvenile, or subadult, it was categorized as "subadult." In rare cases, no descriptive terminology was given, but a total length was provided. For these animals, females >490 cm and males >550 cm were labeled as "adult" (Mitchell 1975 as cited in Nowak 1999). Dates were categorized by month, year, and season north of the equator (Winter: January–March, Spring: April–June, Summer: July–September, and Fall: October–December). The data also were queried to describe the occurrence of mass strandings, which are defined as those involving at least two animals of the same species, excluding cow-calf pairs (Geraci and Lounsbury 2005).

Descriptive and univariate analyses were performed. For univariate analyses, categorical variable comparisons were conducted using chi-square tests with appropriate contingency tables; categorical and numerical variable comparisons were conducted using general logistic or general linear models. To compare the likelihood of stranding events by region and season, a general linear model was used with *post hoc* intergroup comparisons using the Scheffe's method. Statistical significance was defined as $P \leq 0.05$.

Killer whale stranding density was calculated for each of the nine North Pacific regions. To compare trends in stranding density across regions, values were standardized by 500 km units. The denominator of 500 km was chosen because it is a round number less than the maximum coastline length of the smallest region (Oregon).

Each individual mortality in a mass stranding was counted separately for this analysis, and carcasses that were observed floating offshore were excluded. Shoreline lengths for each of the whale strandings regions were calculated, using ESRI ArcMap 10 software, from polygon shapefiles that are included in the ESRI "Maps & Data" collection, 2009 version. The two shapefiles used were "as_cntry.shp" and "na_cntry.shp." The shoreline for each region was extracted from the polygon shapefile and converted to a polyline shapefile. Line segment lengths were then calculated using the "Calculate Geometry" function. The segment lengths were then summed using the "Statistics" function. The Russia region includes all of the shoreline north of the Russia–China border and terminates at the 180° meridian. The Mexico region includes the Baja Peninsula and mainland Mexico to 70 km south of Puerto Vallarta.

Results

Data on 371 killer whales that stranded in 234 events in the North Pacific between 1925 and 2011 were obtained (Table 1, Table S1, Fig. 1). Data on sex, age, and

Table 1. Demographic data on stranded killer whales in the North Pacific, 1925–2011.

Demographic	Number (% of reported)	Total reported
Sex		195
Female	96 (49.0)	
Male	99 (50.7)	
Age category		228
Subadult	100 (43.7)	
Adult	128 (56.1)	
Median length	554 cm (range 120–1,000)	153
Region		371
Japan	76 (20.4)	
Russia	13 (3.5)	
Alaska	119 (32.0)	
British Columbia	102 (27.4)	
Washington	15 (4.0)	
Oregon	10 (2.7)	
California	19 (5.1)	
Mexico	14 (3.8)	
Hawaii	3 (0.8)	

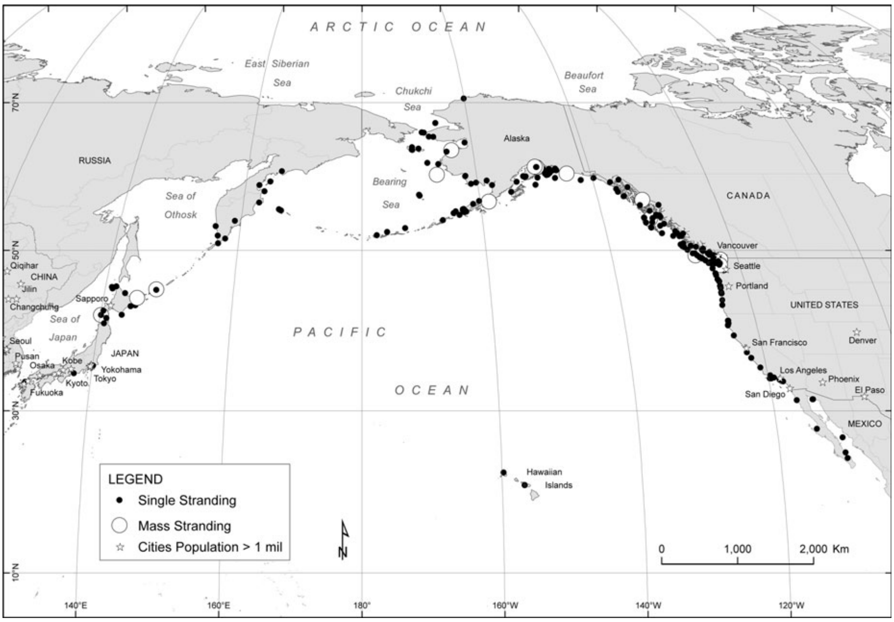

Figure 1. Killer whale strandings in the North Pacific, 1925–2011. Cities with human populations greater than one million people are noted.

length were provided for a subset of the stranded animals (Table 1). Strandings were described by region as follows: Japan (20.4%), Russia (3.5%), Alaska (32.0%), British Columbia (27.4%), Washington (4.0%), Oregon (2.7%), California (5.1%),

Table 2. Killer whale stranding density (strandings per 500 km of shoreline) in nine North Pacific regions. Carcasses observed floating offshore were excluded from analysis.

Region	Number of strandings	Coastline length (km)	Strandings per 500 km
Japan	76	18,240	2.08
Russia	13	37,200	0.17
Alaska	110	61,180	0.90
British Columbia	98	19,250	2.55
Washington	15	3,320	2.26
Oregon	10	940	5.32
California	19	2,970	3.20
Mexico	14	9,200	0.76
Hawaii	3	1,944	0.77

Mexico (3.8%), and Hawaii (0.8%). The highest density of killer whale strandings occurred in Oregon (5.3 whales/500 km shoreline), followed by California, British Columbia, and Washington (Fig. 1, Table 2). Data over the past two decades (1990–2010) suggest that on average, 10 killer whale strandings are reported each year in the North Pacific. No significant sex bias in strandings was noted in the 195 carcasses for which this information was reported ($P = 0.77$).

Data on total length and/or age class were available for 228 stranded animals. Overall, the number of adult killer whale strandings (56.1%) exceeded that of subadults (43.7%; $P = 0.05$). This finding is likely driven by the similar pattern found specifically in Alaska, as no significant differences were observed between age classes across any other region. Of the 67 Alaskan stranding records for which age class was provided, 65.7% were adults and 34.3% were subadults ($P < 0.01$).

Annual stranding data suggest that the number of reported killer whale strandings has increased over time (Fig. 1), however this is likely confounded by increased surveillance effort. Throughout the North Pacific Ocean, the greatest number of strandings occurred in May ($P < 0.01$; Fig. 2). When analyzed by region, significant seasonal differences were observed in Alaska, California, Japan, and Mexico. (Table 3, Fig. 3). Stranding events were more likely to occur or be reported in fall and summer in Alaska ($P < 0.0001$), fall in California ($P = 0.0006$), winter in Japan ($P < 0.0001$), and summer in Mexico ($P = 0.02$). As a whole, the model suggested at least one significant seasonal difference among strandings in British Columbia ($P = 0.05$). However, specific *post hoc* comparisons of strandings by season did not identify any significant differences in this region. No significant differences were observed in the seasonality of strandings in Russia ($P = 0.27$), Washington ($P = 0.81$), Oregon ($P = 0.63$), or Hawaii ($P = 0.66$), although samples were limited in some of these regions. As a whole, the general linear model indicated significant differences among the regions compared ($P = 0.05$), but no significant *post hoc* intergroup comparisons were identified using Scheffe's method.

Twenty-three (9.8%) of the 234 reported stranding events were mass strandings. Mass stranding events were reported in five regions (Japan, Alaska, British Columbia, Washington, Mexico) but the majority occurred in Alaska ($n = 10$ events) and Japan ($n = 6$ events). Of the 160 individuals that mass stranded, at least 122 mortalities (76.3%) occurred. On average, there were approximately six mortalities per mass stranding (range 2–21 animals).

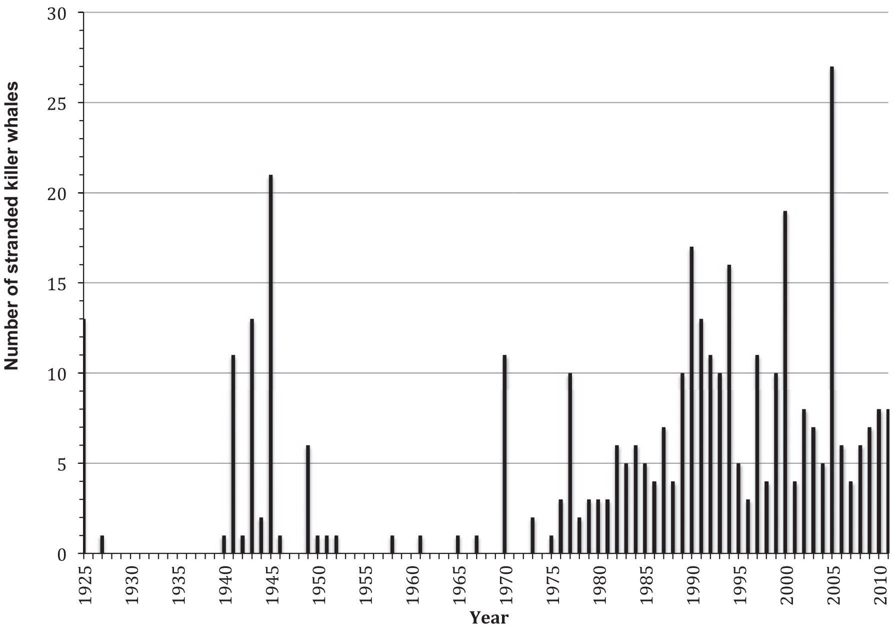

Figure 2. Annual reported killer whale strandings in the North Pacific, 1925–2011.

Table 3. Comparisons of stranding event likelihood by region and season.

Region	*P*	Significant intergroup comparisons
Alaska	<0.0001	fall, summer > spring, winter
British Columbia	0.05	none
California	0.006	fall > summer, winter
Hawaii	0.66	n/a
Japan	<0.0001	winter > spring, fall, summer
Mexico	0.02	summer > winter
Oregon	0.63	n/a
Russia	0.27	n/a
Washington	0.81	n/a

Of the 371 stranded killer whales reported, 328 mortalities were documented. The postmortem examinations of 24 of these individuals were rated as complete and 46 were rated as intermediate. Examinations of the remaining 258 carcasses were given "no rating." Since the 2004 publication of a coordinated killer whale stranding response and necropsy protocol and increased efforts and funding by NOAA Fisheries to respond to killer whale strandings, stranding response rates increased significantly ($P = 0.02$) and a significantly higher number ($P < 0.0001$) of complete necropsies have been performed. Prior to publication of the necropsy protocol, an average of only 1.6% of carcasses received complete postmortem examinations each year. Since the beginning of 2004, this value has increased to an average of 32.2% per year.

Discussion

This is the first comprehensive description of the spatial and temporal attributes of historical killer whale stranding patterns in the North Pacific Ocean. While on average, only 10 stranded killer whales are observed annually in this region, it is likely that more killer whales die than are found or reported. The actual percentage of killer whales that die compared to those that are beach-cast and observed is unknown, but can be estimated using data from the well studied SRKW and NRKW populations found off the west coasts of the United States and Canada (Ford *et al.* 2000).

Using distinct physical markings and photographic identification, the Center for Whale Research (Friday Harbor, WA) has conducted an annual census of the SRKW population since 1976. Fisheries and Oceans Canada (Nanaimo, British Columbia, Canada), with help from the Vancouver Aquarium (Vancouver, British Columbia, Canada), has conducted an annual census of NRKW since 1973. According to one of the authors (JKBF), 96 SRKW and 176 NRKW are known to have died between 1974 and 2008. In that same time period, 19 confirmed SRKW and 5 confirmed NRKW carcasses were found, suggesting carcass recovery rates of 20% and 3% for the SRKW and NRKW populations, respectively. Using our estimated annual observation rate of 10 strandings/yr in the North Pacific Ocean, and the best-case scenario of a 20% carcass recovery rate (observed in the SRKW), we can extrapolate that throughout the entire North Pacific Ocean, at least 48 killer whales strand annually. This small number of animals further supports the need that every killer whale stranding should be investigated and represents a critical opportunity to learn more about the diseases and biology of killer whales in the North Pacific.

Mortality data gathered from the annual censuses of resident killer whales described above were compared to the recovery of resident killer whale carcasses from 1974 to 2008 (Fig. 4). As expected, annual census data documented more resident killer whale mortalities than stranding data alone, on average, by 4:1. An increase in resident killer whale mortality over time is evident in both the annual census and carcass recovery data. The 20% carcass recovery rate calculated for SRKW is the highest reported for any cetacean species to date (Williams *et al.* 2011). Despite this relatively high rate of carcass recovery, stranding data alone would have been insufficient to document the magnitude of this population decline. Although stranding investigations are key to documenting trends in and causes of mortality, they cannot replace long-term population assessments and demographic data acquired through long-term photo-identification studies. Rather, these two complementary methods of assessment should be used to best identify trends in killer whale population health and threats to their recovery.

Cumulative killer whale stranding density (strandings per 500 km of shoreline) was greatest in Oregon, California, British Columbia, and Washington. Insufficient data are available to infer that this represents a greater relative abundance of killer whales off the northwestern coast of North America, though killer whales are present year-round in Washington and British Columbia waters (Ford *et al.* 2000, Baird 2001, U.S. National Marine Fisheries Service 2008). The killer whale populations in these regions are also studied intensively and comparable survey effort has not been described in other North Pacific sites, such as Japan and Russia. Thus, the higher stranding density observed between California and British Columbia could be biased by a greater scientific focus on killer whales in these areas. Human population density and coastline accessibility, relative to killer whale abundance, also could explain the relatively higher stranding density in these regions. From 1930 to 2002, cetacean strandings in the northwest United States were most often reported in areas regularly visited by humans (Norman *et al*. 2004).

Shorelines in the northern portions of the study area are highly convoluted, but the additional shoreline length does not necessarily represent a larger habitat across which strandings can occur. It is therefore possible that stranding density along the northern North Pacific states is underestimated compared to regions with relatively straighter shorelines.

When examined on a monthly basis, killer whale strandings reported in the North Pacific are most common in May (Fig. 5). Areas in which discrete seasonal differences were observed include Alaska, California, Mexico, and Japan (Table 3, Fig. 3). Strandings peak in the summer and fall months in Alaska, which could reflect increased carcass surveillance in warmer months. No distinct pattern was observed across regions, but seasonality of stranding events may be used to guide stranding response efforts and resource allocation in these areas. Increased collection of stranding data in other regions would better help define trends and direct preparedness efforts in more disparate locations.

Overall, the majority of reported strandings (32%) and mass stranding events occurred in Alaska. Interestingly, a significant difference between age classes also was observed in this region, with a predominance of adult killer whales ($P < 0.01$). Thirteen of the 22 adult individuals that were involved in mass strandings in Alaska were either pushed back or were able to refloat themselves and swim away. When this subset of animals is excluded, there is no significant difference between age classes stranding in Alaska ($P = 0.7$). Accounts of suspected killer whale predation on beluga whales have been associated with live killer whale mass strandings in Cook Inlet, Alaska (Shelden *et al.* 2003). Thus, feeding strategies of adult killer whales could explain the predominance of adult strandings in this region.

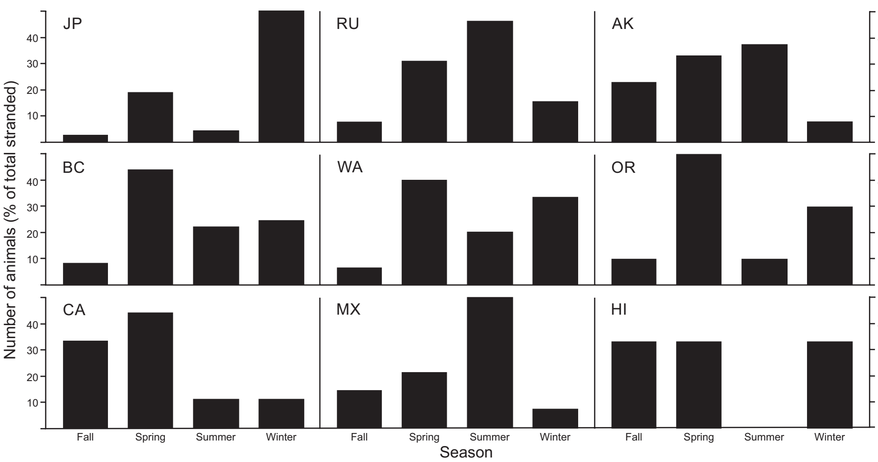

Figure 3. Regional killer whale strandings by season for each of the nine North Pacific regions, 1925–2011. For each region, the number of strandings per season is illustrated as a percent of the total strandings in that region. Seasons are defined as: winter (January–March), spring (April–June), summer (July–September), and fall (October–December). Regions are defined as: Japan (JP), Russia (RU), Alaska (AK), British Columbia (BC), Washington (WA), Oregon (OR), California (CA), Mexico (MX), Hawaii (HI).

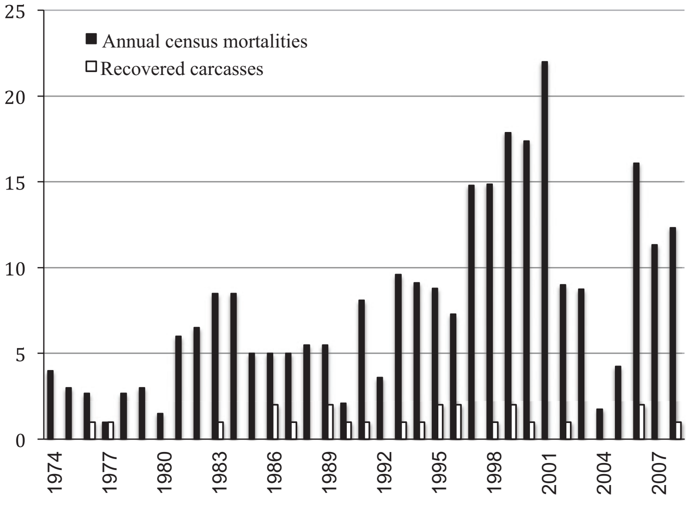

Figure 4. Comparison of carcass recovery data to mortality data obtained by annual censuses of Southern Resident and Northern Resident killer whales, 1974–2008.

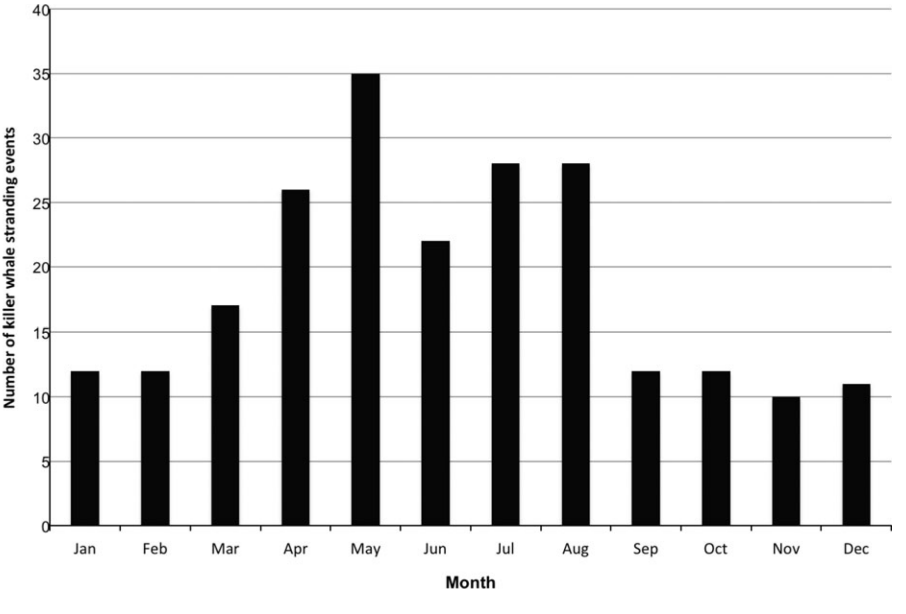

Figure 5. Killer whale stranding events in the North Pacific by month, 1925–2011.

Comprehensive stranding response enables the collection of data on marine mammal life history, genetics, and disease, in addition to causes of mortality. Collectively, the diversity of information gathered from stranded animals is essential in guiding population management and conservation measures. For example, vessel strikes are a leading cause of mortality in critically endangered North Atlantic right whales (*Eubalaena glacialis*) (Knowlton and Kraus 2001). Intensive stranding response efforts and postmortem data collection provided the explicit information used in the development of vessel speed restrictions to reduce the incidence of ship strikes to protect this endangered species (Moore *et al.* 2004, U.S. Federal Register 2008). The open access online stranding response and necropsy protocol developed for North Atlantic right whales (McLellan *et al*. 2004) likely facilitated these efforts.

Samples from stranded marine mammals also help determine genetic differences, which can inform stock structure and social organization (Hoelzel *et al.* 1998, Viricel *et al*. 2008, Morin *et al.* 2010, Foote *et al.* 2011). Samples from stranded killer whales that are used to evaluate genetic variation will have important management implications if the scientific community determines that *Orcinus orca* should be split into multiple species (Morin *et al.* 2010, Foote *et al.* 2011). Additionally, stranding data permit more complete assessments of environmental contaminant exposure (Krahn *et al.* 2004), and have been used to identify emerging killer whale pathogens including *Edwardsiella tarda* (Ford *et al*. 2000) and *Salmonella* Newport (Colegrove *et al*. 2010).

Investigation into the stranding of 12 killer whales entrapped in ice near Aidomari, Rause, Hokkaido, Japan, is one example of how multidisciplinary stranding response can document natural catastrophic environmental events and maximize opportunities for sample collection and study. Carcasses were screened for exposure to infectious diseases, heavy metals, and persistent organic pollutants and described by age and reproductive maturity (Uni *et al.* 2005, Endo *et al*. 2006, Kajiwara *et al.* 2006, Omata *et al*. 2006, Endo *et al*. 2007, Harino *et al.* 2008, Haraguchi *et al.* 2009, Amano *et al*. 2011).

Since 2004 there has been a 32% increase in the number of complete necropsies done on killer whales. The development of a killer whale necropsy and stranding response protocol (Raverty and Gaydos 2004), combined with U.S. federal interest and financial resources facilitated this improved response to killer whale strandings. The protocol is available electronically (Raverty and Gaydos 2004), and the development of similar protocols could improve data collection from other under-studied marine mammals. Stranding investigations are an integral component of a comprehensive population health assessment program, as they yield data on mortality trends, life history, and threats to conservation, such as contaminant exposure and infectious disease.

The historical data obtained in this study were used to describe monthly and seasonal trends in North Pacific killer whale strandings to guide stranding response efforts and resource allocation. While these data are likely incomplete, they represent the best current information on killer whale strandings in the North Pacific and illustrate the importance of continued time and resource allocation to investigate threats to free-ranging killer whales.

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Supporting Information

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Table S1. Killer whale strandings in the North Pacific, 1925–2011.