**Title: A Spatio-Temporal Characterization of Pinniped Stranding and Human Interaction Cases along the Oregon and Washington Coasts, 1989 - 2016**

**Abstract**

Marine mammal strandings can be used as a proxy to assess pinniped health and the impacts of anthropogenic activities in the local marine environment. Stranding response network data from Washington and Oregon between 1989-2016 were used to examine regional and temporal patterns in strandings and human interaction cases across age and sex for six species. Over the study period, 14,939 pinnipeds stranded along the coasts of Washington and Oregon, 11% of which were documented as human interaction cases. Gunshot wounds and fisheries entanglements constituted the majority of human interaction cases (37% and 21%, respectively), though the prevalence of these cases varies across species. The number and prevalence of reported human interaction cases has increased over time in certain regions. The spatial distribution of strandings is highly dependent on species, with a higher proportion of California sea lions, Steller sea lions, and northern elephant seals stranding in Oregon whereas the majority of strandings in Washington were harbor seals. Pups, adults, and males stranded in higher numbers than females and other age classes, though these patterns varied across species and regions. Stranding hotspots are different across species and types of human interactions, likely due to the differential distribution of species and human activities along the coast. Despite the challenges and uncertainties inherent in using stranding data as an indicator of pinniped health and anthropogenic impacts, modeling spatio-temporal patterns will be useful for stranding response practitioners and natural resource managers in evaluating the scope and magnitude of threats to pinniped populations in a changing environment.

Keywords: pinnipeds, stranding, human interactions, spatio-temporal hotspots, wildlife health, anthropogenic impacts.

**Introduction**

Pinnipeds are subject to a wide range of natural and human-related causes of illness or injury, and studying the spatio-temporal patterns of pinniped strandings can provide insight into the dynamic and interconnected factors influencing the health of populations vulnerable to human activities. Pinnipeds live at the land-sea interface and are often considered sentinels of ocean health (Aguirre and Tabor 2004; Bossart 2006; Ross 2006; Moore 2008; Bossart 2011), as they strand onshore exhibiting direct evidence of the threats they encounter in their environment. However, factors influencing where and when an animal strands are diverse, numerous, and interdependent, including ocean conditions, prey availability, susceptibility to disease, and changes in abundance, pupping season, or species range (Woodhouse 1991; Brabyn & McLean 1992; Wilkinson & Worthy 1999; Norman et al., 2004; Pyenson et al., 2010; Osinga et al., 2012; Berini et al., 2015; Johnston, 2015). Stranding records can therefore provide insight into the animals themselves and how their environment is changing due to natural fluctuations or human-related activities. This study examines strandings across six pinniped species in the Pacific Northwest from 1989-2016 to investigate trends in sex, age class, and human interaction cases, and how those patterns vary over time and space.

Stranding records have been used around the world as a means of learning more about the demographics of wild populations, how a population may be affected by environmental conditions, the vulnerabilities of certain demographic groups, and how specific threats or conditions may be changing over time. In many cases, strandings of both pinnipeds and cetaceans have been found to correlate with prevailing oceanographic conditions, changing local abundance and distribution of species, and increased reporting effort (Norman et al., 2004; Jepson, 2005; Leeney et al., 2008; Berini et al., 2015; Huggins et al., 2015a). Gray, hooded, harp, and harbor seal strandings in the northeast U.S. increased from the late 1990s to early 2000s likely due to a combination of these factors (Harris & Gupta, 2006; Johnston, 2015). Similarly, gray and common seal strandings in the Netherlands increased likely due to growing populations and the resulting changes in seasonal and spatial distribution (Osinga et al., 2012).

On the West Coast, researchers have extensively studied trends in stranding causes across age and sex classes in California sea lions, northern elephant seals, and harbor seals in central California, and have generally found that strandings and documented human interaction cases have increased over time, that males and pups strand in greater numbers than females or adults, and that strandings have been elevated during El Nino conditions (Steward & Yochem, 1987; Goldstein et al., 1999; Greig et al., 2005; Melin et al., 2000, 2008, 2010; Moore et al., 2009; Keledjian & Mesnick, 2013). In the Pacific Northwest, considerable information has been gathered about pinniped haul-out locations (Jeffries et al., 2000), and researchers have used stranding data to identify mortality rates and causes, primarily for harbor seals (Stroud & Roffe, 1979; Huggins et al., 2013; Lambourn et al., 2013). Norman et al. (2004) identified cetacean stranding hotspots in the Pacific Northwest and attributed the observed summer peak in reported strandings to the seasonal rise in beach attendance and a greater cetacean presence in the area due to seasonal inshore upwelling. Patterns in harbor porpoise and orca strandings have been used to examine long-term mortality trends and highlight the importance of consistent stranding response effort and data collection protocols in the region (Barbieri et al., 2013; Huggins et al., 2015a). However, few spatio-temporal analyses have been conducted on long-term stranding patterns for pinnipeds.

The quantity and consistency of information contained within stranding records can vary over time and across regions, particularly in an area such as the Pacific Northwest that is characterized by diverse and sometimes remote or isolated beaches covered by a large number of response networks. In this region, identifying and responding to strandings relies heavily on reports from the public, which can vary by subregion due density of residential development, public awareness, and community interest (Huggins et al., 2015b). This illustrates the importance of acknowledging and contextualizing the uncertainty and variability inherent in stranding data when using it as a window into the health, status, or threats facing pinniped populations. However, despite these caveats, stranding records are often the best and only available data, representing the realities of what we know, what we don’t know, and what we might be able to learn in the future.

Data from stranding response networks were used to characterize spatio-temporal trends in age, sex, species, and human interaction cases in Oregon and Washington over a longer time period than has been assessed to date. This study provides an initial investigation into the complexities of overlapping human and pinniped uses of a diverse and changing coastal landscape over time, which is particularly relevant given recent and future predicted anomalous ocean conditions in the area. These analyses are critical to natural resource managers tasked with assessing and monitoring pinniped populations and additionally useful to ensure that stranding network practitioners have the necessary resources to study, collect, and evaluate stranded marine animals.

**Methods**

*Species and Region*  
Six pinniped species inhabit coastal and inland waters of the Pacific Northwest for some or all of their lives, each with unique life history characteristics, behavioral traits, local abundance, and dynamic population trends that influence their presence within the study area, and therefore their prevalence in stranding data over time and space. Each of these species will be briefly described below. The coastlines of Oregon and Washington are also variable, ranging in natural landscape (inaccessible rocky intertidal zones, sandy beaches, estuarine embayments, etc.) and socioeconomic development (residential and commercial districts, shipping channels, ports, fishing activities, ecotourism, etc.).

Harbor seals - Harbor seals (*Phoca vitulina*) are the most abundant and widely distributed pinniped in Washington State waters and are found throughout coastal areas along the U.S. West Coast. Harbor seals are separated into five stocks: California, Oregon/Washington Coast, and newly delineated inland stocks of Southern Puget Sound, Washington Northern Inland Waters, and Hood Canal (Huber et al., 2012; Carretta et al., 2016). The Oregon/Washington Coast stock has been presumed to have reached carrying capacity, and the inland stocks are thought to be stable. Based on a survey conducted in 1999, the coastal stock is estimated to be the largest, followed by the Northern Inland Waters stock, with much smaller estimates for the Hood Canal and Southern Puget Sound stocks (Carretta et al., 2016). Harbor seals exhibit moderate haul-out fidelity and choose sites depending on time of day, tides, season, or food availability (London et al., 2012). Harbor seals are known to make smaller localized movements to forage opportunistically as opposed to making longer seasonal migrations, with movement patterns depending on prey availability and oceanographic conditions. The timing of peak pupping varies for different areas, ranging from mid-April in the Columbia River, mid-May along the Oregon coast, and late summer and early fall throughout Puget Sound (Jeffries et al., 2000).

California sea lions - California sea lions (*Zalophus californianus*) are the most abundant pinniped off the coast of California, with an annual growth rate of 5.4% and an abundance estimated at nearly 300,000 individuals (Carretta et al., 2016). Female adults remain near to the primary rookeries off the coast of southern California throughout the year, making shorter local foraging trips until pups are weaned (Melin et al., 2008). Adult and subadult males make winter migratory foraging trips as far north as Alaska and return south in late spring (Lowry & Forney, 2005). Due to these life history and migratory patterns, individuals generally found in the Pacific Northwest are males utilizing feeding areas in fall, winter, and spring months, though an increasing number of females have been sighted in the area and even into Alaska in recent years (Maniscalco et al., 2004).

Steller sea lions - Steller sea lions (*Eumetopias jubatus*) range from Japan throughout the North Pacific and south into California, with two recognized distinct population segments (DPS): Western and Eastern. The Western DPS is listed as Endangered under the ESA while the Eastern DPS, with an estimated 60,000 to 75,000 individuals (DeMaster, 2014; Carretta et al., 2016), was delisted in 2013. Breeding and haul-out sites for the Eastern DPS are located along the coast of southeast Alaska, British Columbia, Washington, Oregon, and California. Population demographic rates vary by region, with populations decreasing at California rookeries in recent years but increasing in the northern part of their range (Carretta et al., 2016). During the summer breeding season, adult males remain ashore while females and juveniles make short foraging trips (National Marine Fisheries Service [NMFS], 2013).

Northern elephant seals - Northern elephant seals (*Mirounga angustirostris*) range from Mexico to the Aleutians, making seasonal migrations from rookeries in California and Oregon to feeding areas in Alaska and the central North Pacific. Females and males have vastly different energy demands and therefore different seasonal migration patterns, with males making spring and fall feeding trips and females making an initial two-month foraging trip after pups are weaned in late winter, followed by the summer molting period, and then another eight-month foraging trip during gestation before returning to the rookery to give birth and breed (Le Beouf et al., 2000). The California breeding stock was estimated to be 179,000 individuals in 2010, with a growth rate of 3.8% in recent decades (Lowry et al., 2014).

Northern fur seals - Northern fur seals (*Callorhinus ursinus*) range from southern California far into the North Pacific, with two recognized stocks: California and Eastern Pacific. Primary rookeries are located on the Pribilof and Bogoslof Islands, and to a lesser extent islands off southern California (the latter comprising just 1% of the population during the summer breeding season) (Gelatt et al., 2015). Individuals may also haul out along the coast in the Pacific Northwest or British Columbia outside of the breeding season. Adults remain ashore throughout the summer breeding season and then remain at sea for seven to eight months, with adult females and pups from both stocks migrating to foraging areas off the West Coast (Lea et al., 2009; Orr et al., 2012). Population growth and demographics of the California stock are changing due to the co-occurrence of emigration and El Nino events.

Guadalupe fur seals - Guadalupe fur seals (*Arctocephalus townsendi*) were hunted nearly to extinction in the late 1800s, with the remaining population centered around islands off the coast of Baja California, Mexico. The population is listed as Threatened under the ESA but has been rebuilding, increasing by 13% to 21% each year (Esperon-Rodriguez & Gallo-Reynoso, 2012). Individuals have been sighted in the Channel Islands and strandings have occurred as far north as Oregon and Washington, suggesting recolonization and expansion of their historic range (Hanni et al., 1997; Lambourn et al., 2015). Similar to other otariids, pupping occurs in early summer, and then females remain close to the rookeries, making brief foraging trips for approximately eight months until pups are weaned (Figureroa-Carranza, 1994).

*Data Sources and Characterization*  
Data for this analysis were drawn from the NOAA National Marine Fisheries Service national stranding database (accessed February 2017) that contains standardized "Level A" information submitted by stranding responders, including a field ID number, observation date, stranding location, latitude and longitude coordinates, age, sex, species, stranding condition (live or dead), and other observational comments including visible evidence of injury or illness. The total number of pinnipeds stranded along the coasts of Oregon and Washington from 1989 to 2016 (n = 14,939) were characterized according to sex, age class, and species, and then aggregated by month, year, and stranding location. For this analysis, we assume stranding location can be used as a relative approximation for where strandings and human interactions occurred, though carcasses in stages of advanced decomposition can drift for some time before making landfall, and non-lethally entangled animals can migrate with entangling debris from a different region. Inland Washington waters were distinguished from coastal Washington counties because the species that live and strand in these two subregions are very different.

In addition to examining total stranding cases (both live and dead), the number of human interaction cases were also examined. Human interaction (HI) cases are recorded on the Level A stranding intake form, with "Yes," "No," or "could not be determined (CBD)" designations for whether there is evidence of fisheries entanglements, gunshot wounds, boat collisions, or "other" human interactions. Descriptions of "other" human interactions include but are not limited to indeterminate blunt trauma, missing body parts, dog bites, debris entanglement, oil staining, and humans harassing or illegally relocating animals. Records for dead or decomposed animals can be missing certain fields, resulting in "Unknown" or "Unidentified" designations, and were therefore only included in analyses where possible.

Therefore, the prevalence of HI cases must be calculated as a proportion of total strandings rather than the total number of HI cases.

We analyzed two measures of the prevalence of HI cases: (1) the percent composition of human interaction cases (*e.g.*, number of fisheries entanglements divided by total human interaction cases), which could suggest what type of anthropogenic activity has a higher impact on a given age, sex, or species), and (2) the changing annual prevalence of both combined and individual human interaction types among all stranding cases over time (*e.g.*, number of fisheries entanglements divided by total stranding cases), which could reveal changes in the overall prominence of human interactions independent of changes in population demographics. However, stranding response networks that have the capacity to conduct necropsies on a higher percentage of stranded individuals likely have a higher incidence of positive HI findings, while those that conduct fewer necropsies may have a higher incidence of CBD findings. Results examining the spatial differences in the prevalence of HI cases must be interpreted within this context, though we expect that these network differences average out and therefore still yield useful information at a broader regional level.

*Statistical Analysis*  
Age class, sex, and species - To determine whether mean strandings were significantly different across categorical variables such as age class, sex, species, or location, we conducted Kruskal-Wallis Nemenyi tests (posthoc.kruskal.nemenyi.test function in the PMCMR R package) with age class, sex, and species as independent variables and mean stranding cases as the dependent variable. Summary statistics were examined both at the regional level for management-relevant patterns and on a more local level useful for stranding response practitioners.

Temporal patterns - To determine whether strandings and HI cases have changed over the study period, we examined both the *number* and *prevalence* over time. We used negative binomial GLM regressions (glm.nb function in the MASS R package) for mean annual stranding cases against year to account for overdispersion and correct for standard error estimates that might be biased downwards in a Poisson regression model. This analysis was repeated for total strandings and HI cases for each species. Regression coefficients reported using this technique were back-transformed, resulting in a "fold increase" (*e.g.* y = 1.051x being equivalent to a 5.1% increase per year). Time series trend figures were fit with a loess regression line ("locally weighted regression", Cleveland & Devlin, 1988) to allow for a dynamic, changing, and unknown relationship between explantory and response variables over time, which could arise from changes in stranding network capacity and reporting effort over the study period. To examine changes in the prevalence of human interaction cases over time, we used a binomial logistic GLM regression with the logit link function, resulting in untransformed regression coefficients.

The presence of seasonal patterns were tested using post-hoc pairwise Kruskal-Wallis Nemenyi tests, as above, with month as the independent variable and mean monthly stranding cases as the dependent variable. We also tested for the presence of a seasonal effect with ANOVA comparisons of negative binomial GLM regression models with and without stranding month as an interaction term. Any monthly analyses were conducted on the subset of individuals that were recorded as being either alive or freshly dead at the time of observation in order to best capture the temporal component of the stranding event.

Spatial patterns - To determine possible spatial patterns in overall strandings and HI cases, we again used negative binomial GLM regression and post-hoc Kruskal-Wallis Nemenyi tests using stranding location (county) as the independent variable and mean monthly stranding cases as the dependent variable. Stranding hotspot maps were generated with a kernel density estimation (Gatrell et al., 1996) derived from the ggplot2 function geom\_density2d in R. Because this function does not take into account the fact that strandings occur only on the coast, these maps are intended as a qualitative visualization rather than a statistical probability for predicting the spatial distribution of stranding cases. Further refining the parameters of the kernel density function or using saTScan analysis (Kulldorff & Nagarwalla, 1995; Kulldorff, 2001, 2005) could be explored in the future to refine these hotspot maps.

**Results**

From 1989-2016, local stranding response networks identified and recorded 14,939 stranded pinnipeds along the coast of Oregon and Washington. The majority of these strandings were harbor seals (58% of all cases) and California sea lions (19%), followed by a smaller number of Steller sea lions (7%), northern elephant seals (3%), Guadalupe fur seals (1%), and northern fur seals (1%) (Table 1). Approximately 28% were alive and 31% were freshly dead at the time of recovery, with the remaining being in various states of decomposition. Evidence of human interaction was present in 11% of all stranding cases over the study period, including fisheries entanglements (n = 336, 21% of all human interaction cases), gunshot wounds (n = 598, 37% of all human interaction cases), boat collision injuries (n = 76, 5% of all human interaction cases), and "other" (n = 648, 40% of all human interaction cases).

*Species*  
As would be expected, average annual strandings are significantly different across species over the study period (chi-sq = 9.8, p < 0.01), ranging from 5 per year for northern fur seals to 312 per year for harbor seals (Figure 1a, Table 1). As noted above, annual harbor seal strandings (58%) and California sea lions (19%) were significantly higher than the other species. Similar to all strandings, harbor seals constituted the majority of HI cases (54%) followed by California sea lions (28%) and Steller sea lions (12%).

Differences between species are particularly evident when examining the prevalence of human interaction cases (*i.e.*, percentage of cases with evidence of human interaction divided by total number of cases for a given species), and the percent composition of HI cases for each species (*i.e.*, the proportion of human interaction cases involving gunshot wounds versus fisheries entanglements for a given species). The prevalence of HI cases ranges from 8% for northern elephant seals up to 18% for Steller sea lions and 25% for northern fur seals, the latter two being among the more depleted species occurring in the study area (Table 1). The composition of HI cases by type varies considerably across species (Table 1). Gunshot wounds amounted to 74% of human interaction cases for Steller sea lions and 58% for California sea lions, but only 21% for harbor seals. In contrast, fisheries interactions constituted a lower proportion of human interaction cases for those three species but amounted to 65% and 75% of human interaction cases for Guadalupe and northern fur seals, respectively (Table 1). Boat collision injuries are encountered much less frequently than the other types of human interaction cases but are most prevalent in northern elephant seals, amounting to 11% of HI cases (Table 1 and Figure 1b). The changes in these rates over time are detailed below.

*Sex and Age Class*  
All stranding cases - Annual average strandings were significantly different across both sex (chi-sq = 119.3, p < 0.001) and age class (chi-sq = 232.6, p < 0.001), but remained relatively consistent throughout the study period. From 1989-2016, 34% of all stranding cases were male, 17% female, and 49% unidentified (Table 2). Across all strandings, the majority were pups (28%) and adults (23%), with significantly fewer yearlings (7%) and subadults (6%), with the remainder being unidentified (Table 2). Pairwise comparisons showed that mean annual strandings for pups and adults were significantly higher than yearlings and subadults.

Additionally, the sex composition of strandings varies depending on age class and species, with the proportion of females ranging from 12% for subadults to 26% for pups and the proportion of males ranging from 27% of pups to 61% of adults (Table 2). For California sea lions, the majority of identified strandings (those assigned a species or age class designation) were male, while the sex composition was more equal for the other species (Table 3). For California sea lions and Steller sea lions, more than half of identified strandings were adults, while the majority for the other four species were pups and yearlings (91.5% for Guadalupe fur seals) (Table 3).

Human interaction cases - Similar to overall strandings, the *number* of HI cases is significantly higher for males compared to females (chi-sq = 119.2, p < 0.001), but the *prevalence* of human interaction cases is similar for males and females (approximately 16%). The prevalence of fisheries interactions and boat injuries is similar between males and females, though gunshot wounds are more prevalent for males (Table 4). For specific age classes, the number and prevalence of HI cases is significantly higher in pups, adults, and subadults and lowest for yearlings (Table 4). Fisheries interactions are the most common type of HI case for yearlings (39% of all yearling HI cases) and significantly less prominent for pups and adults (17%). Gunshot wounds, however, are most prominent for adults (58% of adult HI cases) and subadults (51%) and less problematic for pups (4%). Boat collisions comprise a small proportion (5-7%) of HI cases for all age classes (Table 4).

*Temporal Patterns*  
All stranding cases - Since 1989, the number of reported stranding cases has increased significantly over time (y = 1.048x, z = 5.4, p < 0.001), suggesting a 4.8% increase per year. An annual average of 328.8 individuals stranded per year throughout the 1990s and 666 per year since 2000. However, annual strandings are changing differently over the study period for each species; significantly increasing for harbor seals (y = 1.057x, z = 6.2, p < 0.001), California sea lions (y = 1.098x, z = 7.7, p < 0.001), Steller sea lions (y = 1.143x, z = 8.3, p < 0.001), Guadalupe fur seals (y = 1.159x, z = 2.0, p < 0.05), and northern fur seals (y = 1.044x, z = 2.2, p < 0.05) (Figure 2). Examining these trends separately for the Oregon coast, Washington coast, and inland Washington waters would likely indicate different rates of change.

Human interaction cases - The overall *number* of HI cases has increased significantly from 1989-2016 (y = 1.10x, z = 7.8, p < 0.001), signifying a 10% increase per year. An annual average of 20.5 cases were documented throughout the 1990s and 82.5 per year since 2000. Specifically, data show an increasing number of gunshot wounds (y = 1.073x, z = 4.6, p < 0.001), fisheries entanglements (y = 1.090x, z = 8.3, p < 0.001), and boat injuries (y = 1.087x, z = 3.3, p < 0.01) over the study period (Figure 3b). The *prevalence* of HI cases has also increased overall (y = 0.06x, z = 15.5, p < 0.001) and specifically for gunshot wounds (y = 0.039x, z = 6.4, p < 0.001), fisheries entanglements (y = 0.043x, z = 5.3, p < 0.001), and boat injuries (y = 0.087x, z = 4.2, p < 0.001), with the prevalence of combined HI cases exceeding 20% in 2012, 2013, and 2015 (Figure 4b).

Examining whether human interaction cases are changing over time is most meaningful at the species level. Similar to overall strandings, the *number* of documented HI cases increased for harbor seals (y = 1.114x, z = 8.7, p < 0.001), California sea lions (y = 1.099x, z = 6.3, p < 0.001), Steller sea lions (y = 1.095x, z = 5.3, p < 0.001), and Guadalupe fur seals (y = 1.173x, z = 2.1, p < 0.05) (Figure 3a). The *prevalence* of HI cases has increased for harbor seals (y = 0.06x, z = 11.4, p < 0.001), California sea lions (y = 0.03x, z = 3.8, p < 0.001), and northern elephant seals (y = 0.09x, z = 3.5, p < 0.001) (Figure 4a). More specifically, data show that the prevalence of gunshot wound cases increased significantly for California sea lions, fisherines entanglement cases increased for California sea lions and harbor seals, and boat-related injuries increased for harbor seals.

On a seasonal basis, total strandings are significantly different across months of the year (chi-sq = 4615, p < 0.001), with greater total strandings occurring May through October. However, the timing of this peak is different for each species. Examining pairwise Tukey comparisons showed that harbor seal strandings are significantly higher from June through September. Though not statistically significant, California sea lion strandings exhibit a peak in May and again from August through November. The age class composition of stranded animals varies seasonally, ranging from 10-20% pups when strandings are lower in the winter to 60% when strandings are higher during July and August. The month of the stranding observation is a significant predictor of strandings by age class, with pups exhibiting significantly higher strandings from June through September (chi-sq = 503.8, p < 0.001), with the majority of these likely being harbor seals, as noted above. None of the other age classes exhibited statistically significant seasonal stranding patterns. Seasonal patterns were similar across male and female strandings.

The *number* of human interactions cases peaks significantly in the summer (July), but is evident only for harbor seals and pups (Figure 5). The *prevalence* of HI cases shows a seasonal peak, ranging from 11% to 23% of cases depending on the month. The proportion of gunshot wounds is higher in March (constitute an average of 13% of all cases) than other months (4% of all cases), while boat injuries and gunshot wounds do not change significantly throughout the months of the year.

*Spatial Patterns*  
Over the study period, more strandings occurred inland Washington and Oregon compared with along the Washington coast. The percentage of annual strandings in Oregon ranged from 8% to 58% and averaging 35% for the whole study period (Figure 6). In contrast, annual strandings along the Washington coast ranged from 2% to 23% and averaging 8% for the whole study period. The distribution of HI cases between these three regions is similar to that of overall strandings, with 35% of all HI cases occurring in Oregon, 53% in inland Washington waters, and the remaining 12% along the Washington coast. The distribution of specific types of HI cases are also disperately distributed between the three regions, with only 31% of boat collisions and 16% of "other" cases occurring in Oregon and 68% and 72% occurring in inland Washington waters. The higher percentage of "other" HI cases in inland WA is likely due to the fact that the majority of those cases are harbor seal pups, and a disproportional number of harbor seal stranding occurs in Washington, as described above. The higher percentage of boat-related injuries in inland Washington could be attributed to the prevalence ferry and shipping traffic and recreational boating opportunities throughout Puget Sound and the Salish Sea. The most prevalent type of human interaction case reported on the Washington coast was gunshot wounds, amounting to 25% of gunshot wounds during the study period.

At the county level, strandings were not evenly distributed along the coast (chi-sq = 1191.3, p < 0.001). In Washington, strandings were highest in San Juan, Island, King, Pierce, and Grays Harbor counties (Figure 7). Similarly, the number of HI cases were significantly higher in Grays Harbor, Pierce, and Pacific counties, with a disproportionately higher number of cases in Pacific county compared with all strandings, the majority of which were gunshot wounds. Combined human interaction cases increased in Pierce (y = 1.069x, z = 3.0, p < 0.01) representing a 6.9% increase per year, Pacific (y = 1.073x, z = 2.7, p < 0.01) representing 7.3% increase per year, King (y = 1.053x, z = 2.7, p < 0.01), Whatcom (y = 1.066x, z = 3.0, p < 0.001), and Jefferson (y = 1.076x, z = 2.2, p < 0.05) counties. Kernel density plots show different hotspot areas for different human interaction types, with boat collision injuries and fisheries interactions largely occurring in Puget Sound and gunshot wounds additionally occurring at the Columbia River (Figure 8).

In Oregon, the majority of strandings occurred in Clatsop, Tillamook, Coos, and Lincoln counties (Figure 7). These counties were also where the majority of HI cases occurred, though a disproportionately higher number occurred in Clatsop, the majority of which where gunshot wounds. Combined human interaction cases increased in Clatsop county (y = 1.095x, z = 3.9, p < 0.001), representing 9.5% increase per year. Kernel density plots show fisheries interaction and boat injury cases as being concentrated along the northern Oregon coast, while gunshot wounds are distributed further south (Figure 9).

Species - Individual species strandings were not equally distributed between the three subregions, highlighting their differing distributions and life history characteristics. Guadalupe fur seal, northern elephant seal, and northern fur seal strandings were distributed approximately 60% in Oregon and 40% in Washington while California sea lion and Steller sea lion strandings were approximately 70% in Oregon and 30% in Washington. In contrast, harbor seal strandings were approximately 15% in Oregon and 85% in Washington (Figure 7, Table 1). Stranding hotspots were apparent in Puget Sound, along the northern tip of the Olympic Peninsula, and at the mouth of the Columbia River for northern elephant seals, California sea lions, and Steller sea lions, whereas northern and Guadalupe fur seal strandings only exhibited hotspots along the outer coast and harbor seals primarily in Puget Sound (Figure 10). In Oregon, Guadalupe fur seals and Steller sea lion strandings were distributed along the coast while stranding hotspots for the other four species were concentrated in the northern part of the state (Figure 11).

**Discussion**

pasting from methods: These response network members have grown in their capacity and coverage over the study period, particularly in the mid-2000s with the implementation of the Prescott grant program, which could in part account for a rise in reported strandings. Not all historical records prior to the implementation of this grant program have been digitized, and may therefore be excluded from this analysis. One of the challenges of using data from this compilation of stranding response networks is that beach coverage, response capacity, and even data-reporting protocols vary between members and over time, and any apparent patterns must be interpreted in the context of those challenges. However, when combined, these data illustrate what is known and what remains uncertain about strandings throughout the region.

Our results highlight spatio-temporal stranding hotspots in Oregon and Washington from 1989-2016. Our data show that harbor seals are the most commonly stranding species in Washington while the other species strand more frequently in Oregon, that strandings exhibit a seasonal peak, that more males have stranded than females though the sex composition varies by age, that the prevalence of human interactions varies by sex, age class, and species, that the number of strandings and human interactions has changed over time, and that strandings and specific human interaction types are clustered in certain counties along the coast. Though Huggins et al. (2015b) found that stranding reporting rates both changed over time and were different across species, seasons, and network areas, this variation likely remains relatively consistent over time and space (*i.e.*, any given reporting biases that have arisen were probably rooted in logistical issues specific to a given place or situation, and remain true to that area). Therefore, while reported strandings at minimum underestimate the true volume of strandings, the long-term spatio-temporal patterns across sex and age class and the relative changes in the prevalence of human interactions cases reflect and can be explained by natural and anthropogenic characteristics of the region and respective species, as described in more detail below.

*Age Class and Sex*  
Patterns in the age class and sex of strandings remained relatively constant over time, with males, pups, and adults stranding in higher numbers overall and the sex composition varying across age classes and species. These findings are similar to other studies that have found a higher proportion of males in overall strandings compared to females (Colegrove et al., 2005, Greig et al., 2005; Soulen et al., 2013). Many studies have found that males of various age classes (but particularly young animals) had a greater number of human interaction cases (Greig et al., 2005, Delong et al., 1990, Kiyota & Baba, 2001; Kaplan Dau et al., 2009), while here we found that while there were a higher *number* of male HI cases, the *prevalence* of human interaction cases was similar for both males and females (~16%). Our results here also must be interpreted with the knowledge that strandings of pups in inland Washington may be higher due to dedicated surveys of haul-out areas not publicly accessible.

Adults constituting a higher percentage of overall strandings compared to other age classes differs from others where young animals have comprised the majority of strandings and human interaction cases (Greig et al., 2005; Goldstein et al., 1999; Hanni & Pyle, 2000; Kaplan Dau et al., 2009). This higher proportion of adults is likely due to having more adults migrating through or hauling out in the region compared to other study regions such as California where there are a higher prevalence of pups near the rookeries. Similarly, the slightly higher prevalence of HI cases in adults and subadults rather than pups and yearlings (16% versus 8-11%) as in other studies is likely due to the spatial distribution of different age classes for each species, as noted above.

*Species*  
Looking more closely at the composition of age class and sex of strandings is more informative at the species level considering that the different demographic and behavioral characteristics of each species largely determines when and where pupping, weaning, and foraging occur along the coast. For example, the majority of California sea lion strandings were male, reflecting the fact that many females largely stay around the rookeries in California. Our findings were similar to that of Lee (2016), where California sea lions were primarily males while Steller sea lions were more equitably distributed between males and females. Further analysis of each individual species could potentially elucidate the connections between patterns in strandings and the seasonal use of important reproductive and foraging habitat at a finer spatio-temporal scale using known haul-outs (Jeffries et al., 2000), proxies for upwelling, wind and current patterns, or specific prey distributions.

The overall prevalence of human interaction cases for all species over the study period was approximately 11%, similar to the prevalence found in California (7.5-16%) and Cape Cod (10%) (Goldstein et al., 1999; Kaplan Dau et al., 2009; Moore et al., 2009; Bogomolni et al., 2010; Keledjian & Mesnick, 2013). Similar to other studies (Moore et al., 2009; Bogomolni et al., 2010), the prevalence of HI cases varied considerably across species, being highest for northern fur seals, Steller, and California sea lions, and lower for northern elephant seals and harbor seals (Table 1). This disparity is likely due to a combination of the different age classes prevalent for each species and each species having different foraging habits, behavioral tendencies, and different levels of examination or necropsy for different species (*i.e.*, listed and infrequently stranding species such as the northern fur seal would likely garner greater scientific interest and therefore more extensive examinations that would reveal evidence of human interaction).

*Temporal Patterns*  
We examined mean annual strandings and human interaction cases, and the prevalence of each human interaction type over the study period. Our results indicate that total annual reported strandings significantly increased over the study period, though this pattern is different for each species. Harbor seals and California sea lion strandings increased over time, while strandings of the other species slightly decreased over time. This observed increase in the number of reported strandings likely reflects increasing abundance and increasing stranding response effort rather than being symptomatic of declining population health. The noticeable and extended seasonal peak in harbor seal strandings likely reflects that these strandings are primarily pups, and pupping in Washington occurs from April to October depending on the area.

The *number* of HI cases increased over the study period for harbor seals and California sea lions, mirroring the rise in overall strandings. Additionally, the *prevalence* of HI cases has increased significantly over time for California sea lions and northern fur seals, and decreased for northern elephant seals. More specifically, the prevalence of gunshot wounds has decreased in recorded strandings of harbor seals and northern elephant seals and documented fisheries entanglements have increased in northern fur seal and Guadalupe fur seal stranding records. In California, human interaction cases increased over time throughout the 1990s, averaging 7.5% (Goldstein et al., 1999), which is lower than results presented here. Over a longer time period in California, the prevalence of human interaction cases amounted to 16% of California sea lion strandings from 1983-2010, with fisheries interactions and gunshot wound cases significantly increasing over time (Keledjian & Mesnick, 2013). It is difficult to theorize about potential explanations for these observed trends because both the pinniped populations and human activities can be simultaneously changing over time and space.

*Spatial Patterns*  
As expected, overall strandings and HI cases are not distributed equally along the coast at the state and county levels, likely due to the distribution of both the animals and stranding response network effort. From 1989-2016, more pinnipeds stranded in Washington, though the proportion between the two states varied over the study period for each species.

Overall strandings - The number and relative distribution of species stranded along the coasts of Oregon and Washington (Table 1) can be largely explained by the local abundance and demographic characteristics of each species. The number and relative distribution of strandings are different across species, and stranding hotspots are similar to those that have been previously identified for cetaceans and pinnipeds (Norman et al., 2004; Lee, 2016). In Washington, harbor seals primarily strand in Puget Sound due to the area having a large number of haul-outs, rookeries, and people reporting strandings. Guadalupe fur seal stranding hotspots do not occur north of the Columbia River (Figure 10), as few individuals likely range farther north or into inland Washington waters. Similarly, northern fur seal strandings did not exhibit clustering in northern Washington or Puget Sound, possibly due to individuals spending more time foraging offshore or near rookeries in Alaska. Approximately two-thirds of Steller sea lion strandings during the study period occurred in Oregon, likely due to the three large breeding sites along the coast. These results align with findings from other coastal areas where patterns in marine mammal strandings reflect either local abundance or seasonal distribution of species (Woodhouse et al., 1991; Norman et al., 2004; Maldini et al., 2005; Leeney et al., 2008; Pyenson et al., 2010; Peltier et al., 2014; Frungillo et al., 2014; Johnston, 2015).

Human interactions - These species each have different behaviors, preferred prey, foraging strategies, and adaptability to changes in their environment that could affect their likelihood of encountering human activities and becoming entangled, shot, struck by a vessel, or ingesting marine debris. It is therefore unsurprising that the prevalence of HI cases varies across species, age classes, and sex (Table 1 and Table 4). California sea lions and male pups have been cited as being particularly inquisitive and therefore more likely to become entangled, though California sea lions were second to northern fur seals and Steller sea lions in this study. Similar to our findings, studies have noted northern fur seals as having a relatively high prevalence of entanglement, evident in rookery field surveys and stranding data (Fowler 1987, Delong et al., 1990; Antonelis et al., 2006). Additionally, Colegrove et al. (2005) found the prevalence of human interaction cases in central California varied annually, but was higher in harbor seals than northern elephant seals, also similar to the results presented here.

In Washington, human interactions were disproportionately higher in San Juan and Pierce counties, where nearly one-quarter of HI cases were gunshot wounds. In Oregon, human interactions were disproportionately higher and increased over time in Lincoln, Tillamook, Coos, and Clatsop counties. Nearly half of all HI cases in Oregon were recorded in Clatsop, the majority of which were gunshot wounds. Clatsop county includes Astoria, an economically important fishing port, and the area has seen an increased number of fisheries interactions in recent years (Lee, 2016), particularly with animals foraging up into the Columbia River. However, this higher number of HI cases could also be attributed to the higher necropsy rate in the northern part of the state (Lee, 2016).

*Future Directions*  
This characterization and hotspot mapping analysis is important for informing management and conservation measures and can support decision-making for stranding response practitioners. Though these results present one of the most comprehensive summary statistics of human interactions cases for pinnipeds in this region, further analysis of each individual species could ascertain whether it is likely that certain age classes overlap to a greater extent in time and space with anthropogenic activities in areas we identified as hotspots for human interaction cases. While strandings and human interaction cases can coincide with or have a higher reporting rate from dense human population centers, they can also occur offshore or in more isolated areas, and therefore go undetected. More refined spatio-temporal cluster modeling that includes measures of pinniped abundance, prey abundance or distribution, and proxies for oceanographic conditions (such as Evans et al., 2005, Soulen et al., 2013, Truchon et al., 2013, Peltier et al., 2014, and Berini et al., 2015) could further elucidate and even predict the magnitude and spatial distribution of strandings, and therefore areas or species that are at a higher risk for human impacts and therefore in need of enhanced management attention.

**Conclusion**  
Spatio-temporal patterns in the age and sex of pinniped strandings in Oregon and Washington since varied for each of the six species that are found in the study area. The distribution and number of strandings along the coast and throughout the year are likely due to the local abundance and demographic characteristics of each species, with harbor seal pups stranding primarily throughout Puget Sound and the Salish Sea during pupping season, and other species strand more broadly across all age classes and along the coast. The number of strandings and the prevalence of human interaction cases has increased over time, largely attributed to a combination of changing population dynamics, enhanced stranding response effort and public awareness, and continued coastal socioeconomic development. Stranding hotspot maps show discrete areas of high-density strandings, which are different across species and types of human interaction cases. Stranding data may contain gaps and inconsistencies, but are an invaluable resource for conservation and management of these marine mammal species. More refined spatio-temporal modeling techniques could further elucidate the connections between stranding clusters, forage species availability, prevailing oceanographic conditions, and anthropogenic activities that all impact the short and long-term health of these pinniped populations in a changing environment.

**Figures and Tables**

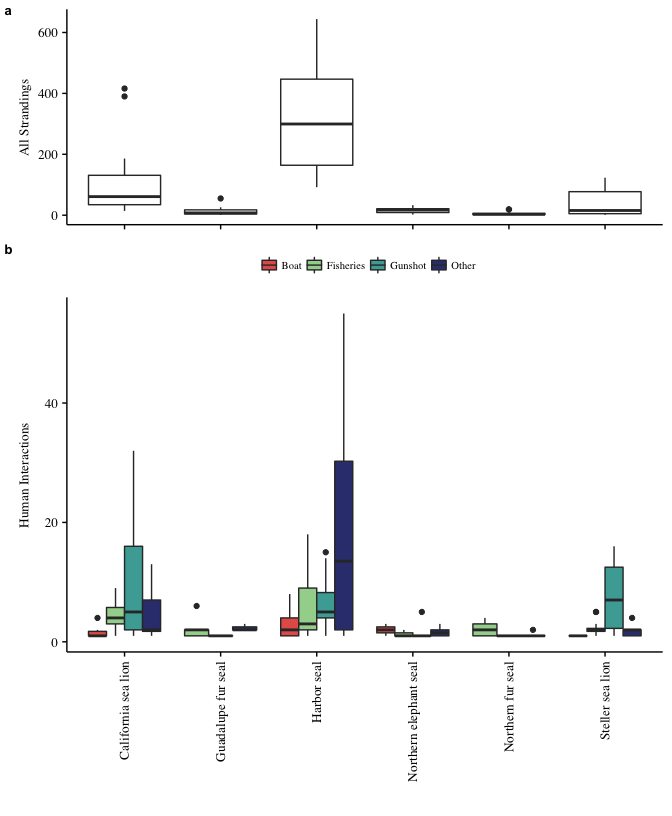


Figure 1: (a) Annual stranding cases for each species showing higher average strandings for harbor seals and California sea lions; and (b) annual human interaction cases showing a high number of gunshot wounds for California sea lions and Steller sea lions and Other cases for harbor seals.

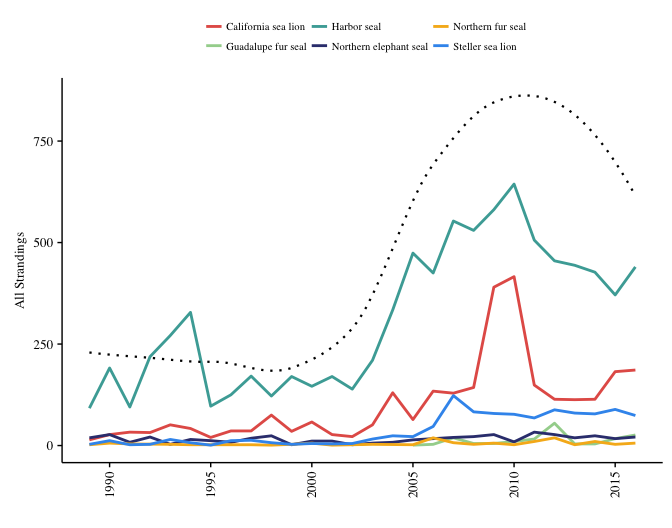


Figure 2: Increasing total reported annual strandings (n = 14,939) over the study period (black dotted loess regression line) likely at least in part due to Prescott Grant funding beginning in the mid-2000s; and increasing stranding reports of harbor seals (y = 1.057x, z = 6.2, p < 0.001), California sea lions (y = 1.098x, z = 7.7, p < 0.001), Steller sea lions (y = 1.143x, z = 8.3, p < 0.001), Guadalupe fur seals (y = 1.159x, z = 2.0, p < 0.05), and northern fur seals (y = 1.044x, z = 2.2, p < 0.05).

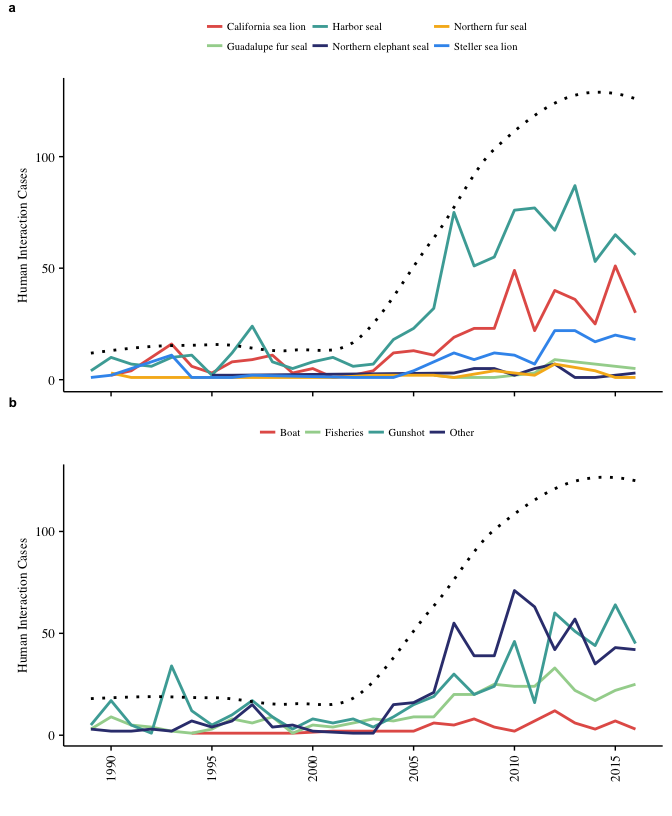


Figure 3: (a) Annual combined HI cases overall (denoted by black loess regression line) and for each species shows increasing cases for harbor seals (y = 1.114x, z = 8.7, p < 0.001), California sea lions (y = 1.099x, z = 6.3, p < 0.001), Steller sea lions (y = 1.095x, z = 5.3, p < 0.001), and Guadalupe fur seals (y = 1.173x, z = 2.1, p < 0.05) and (b) increasing number of gunshot wounds (y = 1.073x, z = 4.6, p < 0.001), fisheries entanglements (y = 1.090x, z = 8.3, p < 0.001), and boat injuries (y = 1.087x, z = 3.3, p < 0.01).

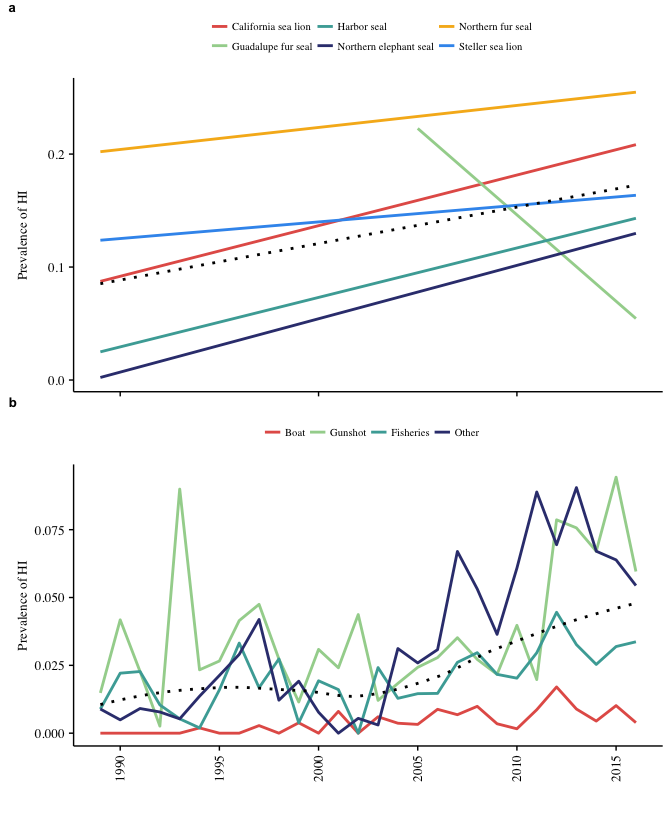


Figure 4: Prevalence of human interaction cases (a) increasing for all combined species (black dotted regression line, y = 0.06x, z = 15.5, p < 0.001) and significantly increasing for harbor seals (y = 0.06x, z = 11.4, p < 0.001), California sea lions (y = 0.03x, z = 3.8, p < 0.001), and northern elephant seals (y = 0.09x, z = 3.5, p < 0.001); (b) increasing for all types combined (black dotted regression line, y = 0.06x, z = 15.5, p < 0.001) and for each HI case type: gunshot wounds (y = 0.039x, z = 6.4, p < 0.001), fisheries entanglements (y = 0.043x, z = 5.3, p < 0.001), and boat injuries (y = 0.087x, z = 4.2, p < 0.001).

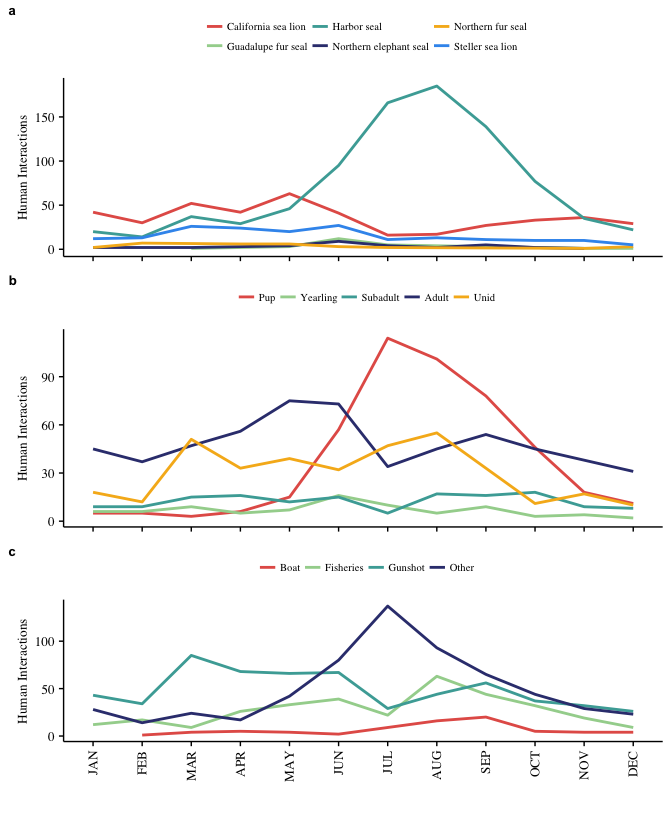


Figure 5: Sum of human interaction cases across years for each month according to (a) species showing summer peak for harbor seals; (b) age class, showing summer peak for human interaction cases for pups; and (c) human interaction type, showing a high number of Other cases in the summer and gunshot wounds in March.

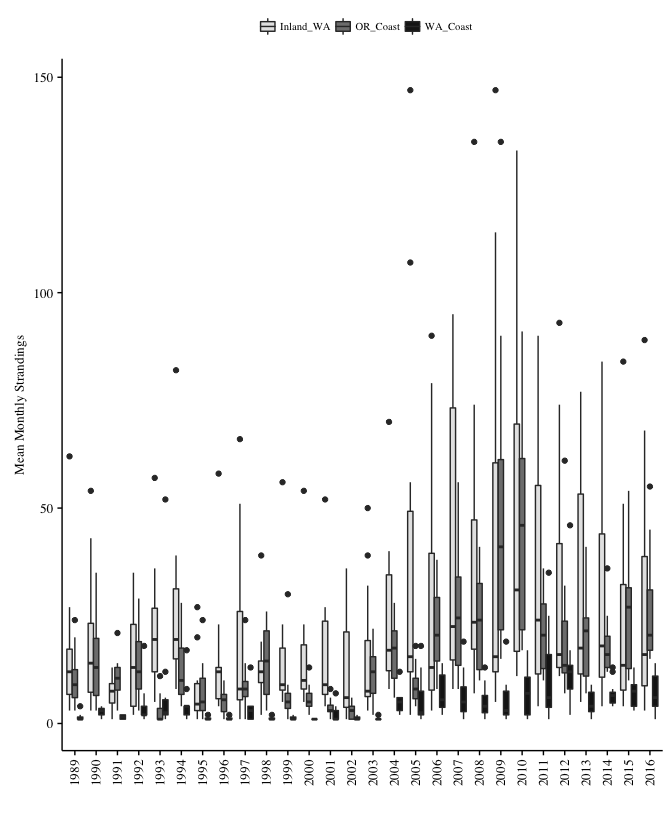


Figure 6: Mean monthly strandings over the study period shows greater strandings in Oregon and inland Washington waters, with increasing numbers and variability over time.

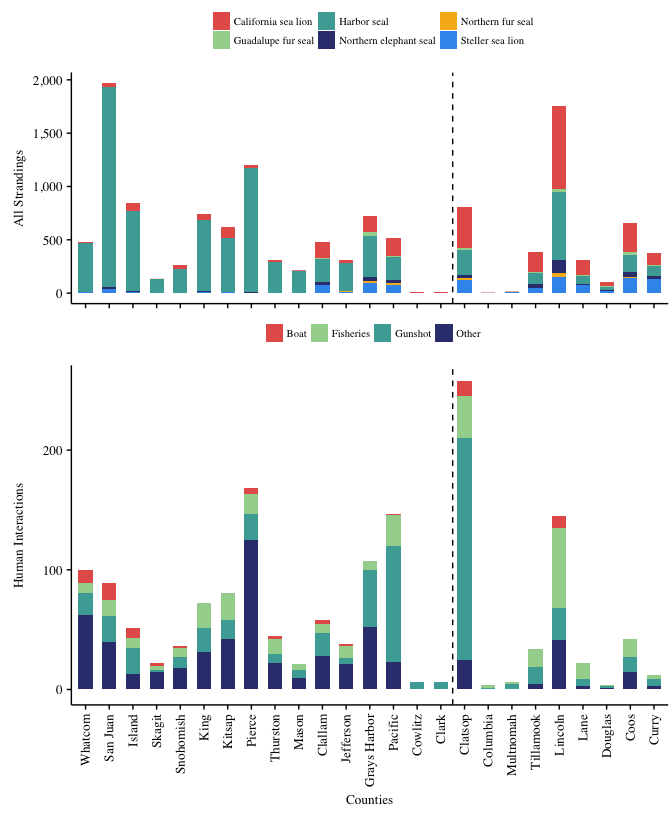


Figure 7: Total strandings (above) and human interaction cases (below) for counties in Washington (left of dashed line) and Oregon (right of dashed line) show higher strandings in Lincoln, San Juan, and Pierce, and proportionally higher HI cases in Clatsop and Pacific.

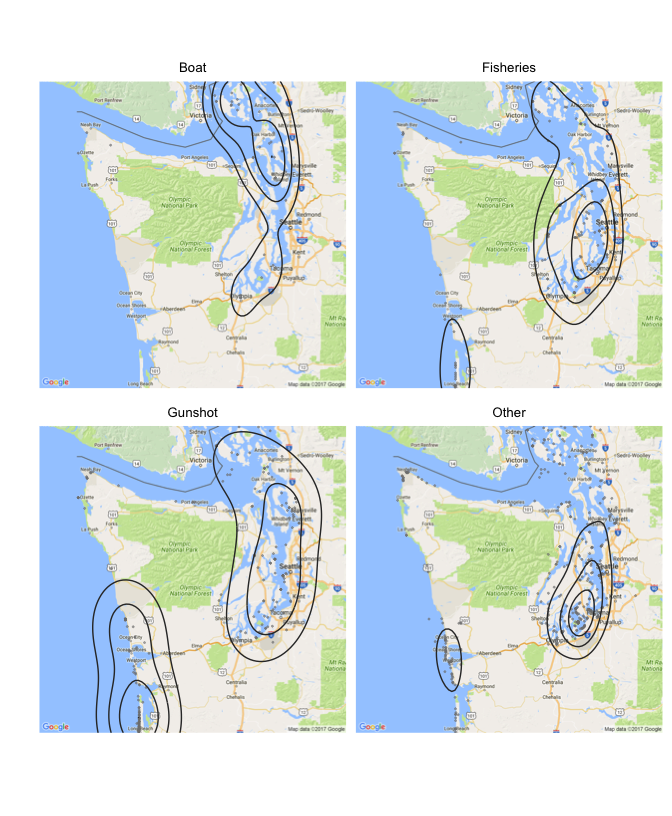


Figure 8: Kernel density plot showing hotspots of human interaction cases in Washington, with fisheries and boat collisions distributed throughout Puget Sound, and gunshot wounds occurring along the southern coast, particularly at the Columbia River.

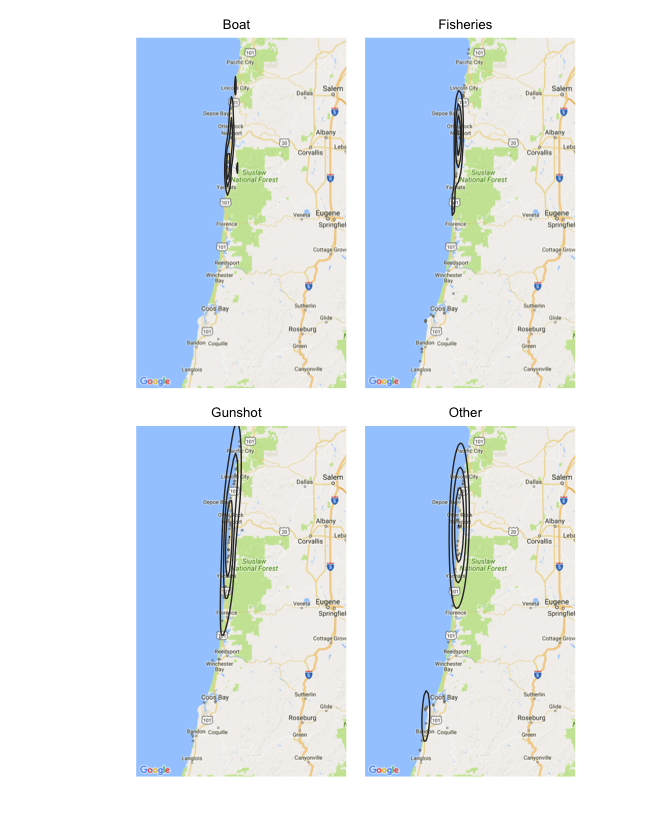


Figure 9: Kernel density plot showing hotspots of human interaction cases in Oregon, with fisheries and boat collisions distributed along the northern coast, and gunshot wounds focused near Astoria and the Columbia River.

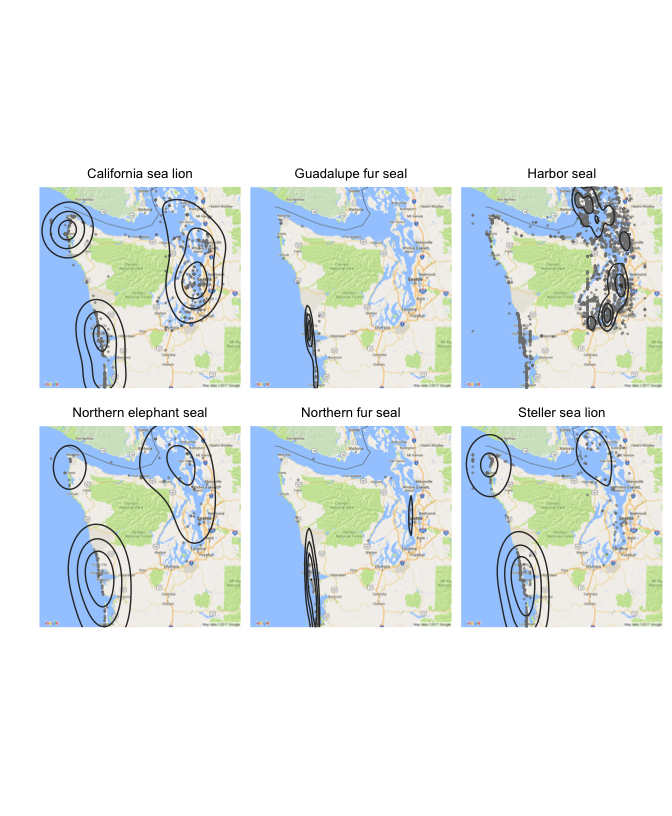


Figure 10: Kernel density plot of species stranding hotspots in Washington.

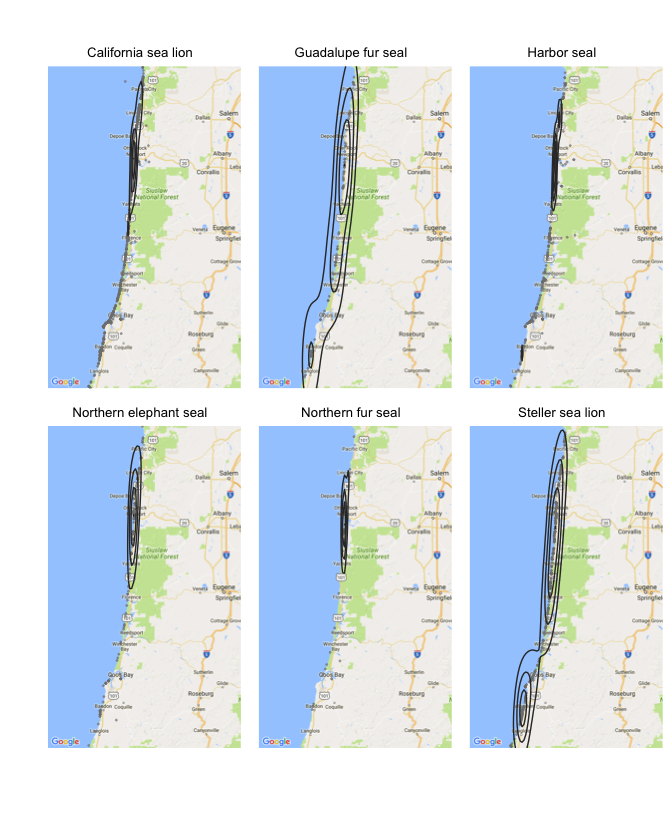


Figure 11: Kernel density plot of species stranding hotspots in Oregon.

Table 1: Species composition of all strandings (n = 14,939), the prevalence of human interaction cases (HI/all cases) for each species, regional distribution, and the composition of human interaction type (number of specific type/all HI cases) for each species.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Species | Total (n) | All Strandings (%) | OR (%) | WA Coast (%) | WA Inland (%) | Prevalence of HI (%) | Fisheries (%) | Gunshot (%) | Boat (%) | Other (%) |
| California sea lion | 2823 | 19 | 69 | 11 | 20 | 15 | 18 | 58 | 4 | 20 |
| Guadalupe fur seal | 165 | 1 | 61 | 34 | 5 | 14 | 65 | 4 | 0 | 30 |
| Harbor seal | 8730 | 58 | 15 | 7 | 78 | 10 | 19 | 21 | 6 | 55 |
| Northern elephant seal | 445 | 3 | 66 | 16 | 17 | 8 | 11 | 33 | 11 | 44 |
| Northern fur seal | 122 | 1 | 61 | 25 | 15 | 25 | 75 | 4 | 0 | 21 |
| Steller sea lion | 1040 | 7 | 67 | 17 | 16 | 18 | 16 | 74 | 2 | 8 |

Table 2: Number and percentage of male, female, and unidentified strandings at each age class across all years and the average sex composition of strandings across all age classes.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Age | Female (N) | Female (%) | Male (N) | Male (%) | Unid. (N) | Unid. (%) |
| Pup | 1085 | 26 | 1135 | 27.0 | 2022 | 48.0 |
| Yearling | 178 | 18 | 313 | 31.0 | 507 | 51.0 |
| Subadult | 109 | 12 | 523 | 56.0 | 304 | 32.0 |
| Adult | 606 | 18 | 2084 | 61.0 | 754 | 22.0 |
| Unid | 592 | 11 | 966 | 18.0 | 3761 | 71.0 |
| Average | -- | 17 | -- | 38.6 | -- | 44.8 |

Table 3: Age class and sex composition of all strandings (n = 14,939) by species shows very different composition according to species.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Species | Total (n) | Male (%) | Female (%) | Unid. Sex (%) | Pup (%) | Yearling (%) | Subadult (%) | Adult (%) | Unid. Age (%) |
| California sea lion | 2823 | 77.4 | 1.0 | 21.6 | 0.2 | 9.0 | 14.7 | 53.1 | 23.0 |
| Guadalupe fur seal | 165 | 31.5 | 30.9 | 37.6 | 1.2 | 91.5 | 2.4 | 2.4 | 2.4 |
| Harbor seal | 8730 | 24.5 | 23.2 | 52.3 | 45.3 | 4.4 | 3.7 | 14.3 | 32.3 |
| Northern elephant seal | 445 | 34.8 | 13.3 | 51.9 | 19.8 | 18.0 | 11.9 | 5.6 | 44.7 |
| Northern fur seal | 122 | 23.8 | 39.3 | 36.9 | 25.4 | 31.1 | 8.2 | 4.9 | 30.3 |
| Steller sea lion | 1040 | 41.6 | 33.3 | 25.1 | 13.5 | 7.7 | 11.7 | 54.7 | 12.4 |

Table 4: Sex and age composition of all strandings (n = 14,939), the prevalence of human interaction cases for each age class, and the composition of human interaction type for each age class.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Class | All Strandings (%) | Prevalence of HI (%) | Fisheries Interactions (%) | Gunshots (%) | Boat Injuries (%) | Other (%) |
| Female | 17 | 16 | 18 | 32 | 5 | 44 |
| Male | 34 | 17 | 15 | 47 | 5 | 33 |
| Unid. Sex | 49 | 5 | 35 | 19 | 3 | 42 |
| Pup | 28 | 11 | 17 | 4 | 7 | 72 |
| Yearling | 7 | 8 | 39 | 21 | 5 | 35 |
| Subadult | 6 | 16 | 21 | 51 | 5 | 23 |
| Adult | 23 | 17 | 16 | 58 | 5 | 21 |
| Unid. Age | 36 | 7 | 27 | 41 | 2 | 30 |

**Appendices: Additional Tables and Statistical Analyses**

Table 5: Proportion of all strandings, proportion of human interaction cases (%), and the composition of human interaction case types for each county in Washington (n = 9,413).

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| County | All Strandings (%) | Human Interactions (%) | Fisheries (%) | Gunshot (%) | Boat (%) | Other (%) |
| Clallam | 6 | 6 | 14 | 33 | 5 | 48 |
| Clark | 0 | 1 | 0 | 100 | 0 | 0 |
| Cowlitz | 0 | 1 | 0 | 100 | 0 | 0 |
| Grays Harbor | 8 | 10 | 7 | 45 | 0 | 49 |
| Island | 9 | 5 | 16 | 43 | 16 | 25 |
| Jefferson | 4 | 4 | 26 | 13 | 5 | 55 |
| Jefferson County | 0 | 0 | 0 | 0 | 50 | 50 |
| King | 9 | 7 | 29 | 28 | 0 | 43 |
| Kitsap | 8 | 8 | 28 | 20 | 0 | 52 |
| Mason | 2 | 2 | 24 | 29 | 0 | 48 |
| Pacific | 6 | 14 | 18 | 66 | 1 | 16 |
| Pierce | 13 | 16 | 10 | 13 | 3 | 74 |
| San Juan | 21 | 8 | 16 | 24 | 16 | 45 |
| Skagit | 2 | 2 | 18 | 5 | 9 | 68 |
| Snohomish | 3 | 3 | 22 | 25 | 3 | 50 |
| Thurston | 3 | 4 | 27 | 18 | 7 | 49 |
| Whatcom | 5 | 10 | 8 | 19 | 11 | 62 |

Table 6: Proportion of all strandings (%), the proportion of human interaction cases (%) and the composition of human interaction case types for each county in Oregon (n = 5,435).

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| County | All Strandings (%) | Human Interactions (%) | Fisheries (%) | Gunshot (%) | Boat (%) | Other (%) |
| Clackamas | 0 | 1 | 0 | 100 | 0 | 0 |
| Clatsop | 16 | 49 | 14 | 72 | 5 | 10 |
| Columbia | 0 | 1 | 75 | 25 | 0 | 0 |
| Coos | 13 | 8 | 36 | 29 | 0 | 36 |
| Curry | 8 | 2 | 25 | 50 | 0 | 25 |
| Douglas | 2 | 1 | 25 | 50 | 0 | 25 |
| Lane | 7 | 4 | 59 | 27 | 0 | 14 |
| Lincoln | 44 | 27 | 46 | 19 | 7 | 28 |
| Multnomah | 0 | 1 | 17 | 83 | 0 | 0 |
| Tillamook | 9 | 6 | 44 | 41 | 0 | 15 |

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