Entanglement rates and population trends of Steller (*Eumetopias jubatus*)and California (*Zalophus californianus*) sea lions on the north coast of Washington state

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# Abstract

Entanglements affect marine mammal species around the globe, and for some species, those impacts are great enough to cause population declines. This study aimed to document rates and causes of entanglement in Steller and California sea lions on the north coast of Washington from 2010-2018 and to determine if entanglements caused population impacts. We conducted small boat surveys to count sea lions and document and photograph entangled individuals. Rates of entanglement and entangling material occurrence were compared with records collected from stranded individuals on the Washington and Oregon coast and with packing bands recorded during beach debris surveys. California sea lions experienced a higher rate of entanglement than Steller sea lions (2.13% and 0.41%, respectively). The age composition of Steller sea lions was 77% adults (32.4% were male and 63.3% female), 17.1% juveniles, 5.9% unknown age, and no pups. Steller sea lion entanglements showed no seasonal patterns, but California sea lions experienced a peak in entanglement rates in June and July. The majority of identifiable entanglements were packing bands (68.3%) followed by salmon flashers (11.3%), which only occurred in the summer months of May – September during the peak of the local ocean salmon troll fishery. The occurrence of packing bands in beach debris surveys correlated with the occurrence of entanglements caused by packing bands observed during haulout surveys (Pearson’s R=0.81). However, no packing band entanglements were observed in the stranding record, and the overall proportion of stranded animals exhibiting evidence of entanglement was lower than expected. During the study period, Steller sea lions exhibited a 7.9% ± 3.2 population growth rate, which was similar to that seen in California sea lions (7.8% ± 4.2) suggesting that the high observed entanglement rates did not have population level consequences, though they are still an issue for the welfare of individual sea lions.

# Introduction

The prevalence of marine debris is of global concern and has been gaining attention from media, researchers, and the public in recent decades as the impact to marine life becomes better understood [1–5]. Many marine organisms are affected by marine debris through entanglement. Instances of entanglement have been recorded for at least 32 species of marine mammals globally [4], and for some, like the northern fur seal (*Callorhinus ursinus*) and the endangered Hawaiian monk seal (*Monachus schauinslandi*), entanglement was thought to have contributed to population declines [6,7]. For pinnipeds specifically, entanglement has been documented for more than half of the existing species [2,4,8]. In this study, entanglement is defined as the presence of marine debris attached to an animal’s body, including materials that are looped around the appendages or neck (e.g. netting or packing bands) and instances where materials are internally or externally embedded (e.g. hooking injuries).

The mechanisms by which an animal becomes entangled are almost as varied as the entangling materials themselves. Any marine debris that form loops that can ensnare or sharp objects, such as hooks, that can embed pose an entanglement risk. Entangling debris can come from terrestrial and marine pollution, and from derelict and active fishing gear. The mechanism of entanglement can often be determined by identifying the entangling material. Packing bands, rubber bands, and monofilament line are likely encountered passively as debris, while net fragments can be a sign of either passive encounters with floating debris or a sign of interaction with an actively fished net. Salmon flashers and other hook and line gear are likely encountered as actively fished gear and are evidence of fishery depredation behaviors, which cause harm both to the entangled animal and to the fisher’s catch [9,10]. Otariids are especially curious of new objects, and can become entangled in debris while attempting to explore or play with them [11,12]. The factors leading to entanglement in any given location are therefore governed by both local and regional dynamics, as ocean currents, upwelling patterns, fishing effort and gear types, prey distributions, abundance of pinnipeds, and marine traffic patterns all may contribute to both the distribution of entangling materials and the behavior of pinnipeds in the area [8,13–16].

The objective of this study was to characterize the rates and causes of entanglement in Steller (*Eumetopias jubatus*)and California (*Zalophus californianus*) sea lions in northern Washington state and to evaluate if the observed entanglements were negatively impacting the populations. We described temporal trends in entanglement occurrence and determined the most commonly observed entangling materials. Based on previous studies, we expected to see entanglements caused by mainly packing bands and netting [1,4,8,17–19]. We expected little change in annual entanglement occurrence but anticipated that there would be a peak in entanglements observed in the mid- to late-summer months due to these being the peak months for recreational and commercial fishing effort. Understanding the patterns behind entanglement occurrence will enable the development of more targeted prevention and response efforts and a more accurate understanding of the impacts of entanglement on local populations.

# Methods

## Data Collection

All necessary permits were obtained for the described study, which complied with all relevant regulations. The National Marine Fisheries Service reviewed and approved our research methodologies and granted Marine Mammal Protection Act research permits 14326, 13430, and 19430. We also obtained Special Use Permits for all land-based survey activities conducted on haulouts within the Flattery Rocks National Wildlife Refuge from the United States Fish and Wildlife Service.

Observations of hauled out Steller and California sea lions were carried out from small boats along the north coast of Washington from 2010 –2018 focusing on four major haulout complexes (Fig 1). Occasionally, surveyors were landed on haulouts to conduct the surveys. Surveys were conducted year-round with more effort from late spring through early fall than in other months of the year due to availability of survey days with suitable weather and sea conditions. Surveys often did not include all haulouts during a day due to logistical challenges such as sea conditions and daylight. During surveys, we counted actively entangled individuals and individuals showing evidence of past entanglement (e.g. scarring) and counted the total abundance of the two sea lion species at each haulout. We attempted to photograph all entangled sea lions and those that appeared entangled with a digital SLR camera with a 100-400 mm lens for later assessment. Entangled individuals encountered along the survey route in locations other than the four major haulout complexes were excluded from entanglement rate calculations due to the lack of reliable and regular total counts of hauled individuals, but they were still documented for inclusion in the analysis of entangling materials.

A close up of a map

Description automatically generated

Fig 1: Map of the four major Steller and California sea lion haulout complexes surveyed for entangled individuals: Tatoosh Island, the Bodelteh Islands, Carroll Island, and Sea Lion Rock.

## Entanglement Rates

Our goal was to calculate an average annual entanglement rate for California and Steller sea lions for the northern Washington coast. Our survey effort was greatest during the summer and early fall when sea conditions were most predictable (Table 1). In order to ensure that our calculated entanglement rate was representative of the year, and not biased to time periods when we had more surveys, we calculated average yearly entanglement rates using a multistep process. Counts of the total number of individuals hauled out and counts of entangled individuals, including both active and inactive entanglements taken from photographs and survey notes, were pooled across haulout complexes within survey days, and an entanglement rate was calculated for each survey day by dividing the total number of entangled individuals by the total count. Average entanglement rates were then calculated for each month of the nine-year study period. The mean rates for each month of the study were then averaged across years for each month and across months for each year to discern seasonal and annual patterns. An overall average entanglement rate was calculated for each species by taking the average of the monthly mean entanglement rates.

Table 1: The number of surveys conducted in each month of the study period 2010-2018 with the number of complete surveys where all four major haulout complexes were visited in parentheses. Note that no complete surveys were conducted after June in 2018.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Month** | | | | | | | | | | | | | | |
|  |  | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **Total** |
| **Year** | 2010 |  | 1 | 1 | 1 | 3(1) | 2 | 3(1) | 5(3) | 8(2) | 2 | 2(1) |  | 28(8) |
| 2011 | 1 | 2(1) | 2 | 4(1) | 6(3) | 5(2) | 4(2) | 6(2) | 3(2) | 4(1) | 3(1) |  | 40(15) |
| 2012 |  | 2 | 2(1) | 2(1) | 3(2) | 5(4) | 8(1) | 4(2) | 5(2) | 2(1) | 3(1) | 2(1) | 38(16) |
| 2013 | 2(1) | 1(1) | 2(1) | 2(1) | 3(1) | 4(3) | 3(2) | 3(2) | 3(1) | 3 | 2 |  | 28(13) |
| 2014 |  |  |  | 2 | 2(1) | 3(2) | 4(2) | 4(1) | 4(3) | 2 |  |  | 21(9) |
| 2015 | 3(2) | 2(1) | 1 | 3 | 2 | 2 | 4(1) | 5(2) | 4(1) | 1 | 1 |  | 28(7) |
| 2016 | 1(1) |  | 4 | 1 | 5(3) | 1(1) | 4(2) | 4(2) | 3(3) | 3(1) |  | 1(1) | 27(14) |
| 2017 | 1(1) | 2(1) | 1 |  |  | 3(3) | 1 | 4(3) | 3(1) | 1(1) |  |  | 16(10) |
| 2018 |  | 1 | 3(1) | 2(1) | 1(1) | 3(2) | 3 | 3 | 3 | 1 |  |  | 20(5) |
|  | **Total** | **8(5)** | **11(4)** | **16(3)** | **17(4)** | **25(12)** | **28(17)** | **34(11)** | **38(17)** | **36(15)** | **19(4)** | **11(3)** | **3(2)** | **246(97)** |

## Photo Analysis

We assessed photographs of sea lions with evidence of entanglement to determine if the entanglement was active or inactive, identify the entangling material, and record the age and sex of the entangled individual. Entangled individuals were assigned to demographic groups by age as adult, juvenile, pup, or unknown, and by sex for adults based on body size and shape, whisker length, and presence of secondary sexual features. The proportion of entangled individuals in each sex and age class were calculated.

Entanglements were identified to one of nine categories: packing band, salmon flasher, rubber band, monofilament line, hook and line, netting, rope, scar, or unknown. Salmon flashers are plastic or metal attractants attached to a line with a 60 to 200cm leader ahead of the lure or baited hook. The hook from the lure or baited hook is often swallowed leaving the flasher to dangle out of the mouth by the leader. The hook and line category included fishing lures (not attached to flashers) and longline gear, both of which are found hooked externally on the entangled individual. Rubber bands were thick black bands cut from truck tire inner tubes that are often used in crab fisheries to secure trap doors. The netting category included both gillnets made of monofilament line and trawl netting made of nylon or synthetic lines. Monofilament lines are lines that are commonly used in recreational fisheries and for leaders in commercial salmon fisheries; monofilament lines were differentiated from gillnets by the presence of knotted webbing in the gillnet. Any active entanglement where the material could not be identified was recorded as unknown. Animals with evidence of a previous entanglement but where no debris was observed on the sea lion were recorded as scar. The proportion of entanglements that were active or inactive and the proportion exhibiting each entangling material were calculated over months and years to analyze trends in material occurrence.

## Packing Band Analysis

Annual packing band entanglement occurrence was further analyzed for correlation with data from marine debris surveys conducted by the Olympic Coast National Marine Sanctuary (OCNMS) to discern patterns in material availability in the environment. The year 2018 was excluded from analysis of annual trends due to low sea lion survey effort after the month of June. OCNMS conducted 1,548 monthly beach debris surveys in the Olympic Coast region from 2012-2017, covering 17 beaches in Washington State, from Roosevelt Beach (47.1770**°** N, 124.1972**°** W) to Wa’atch Beach (48.3441**°** N, 124.6792**°** W). Surveys were conducted by volunteers in an OCNMS citizen science program adhering to standardized debris monitoring procedures developed by NOAA’s Marine Debris Program [20]. The number of packing bands encountered each year in beach debris surveys was divided by the total number of surveys conducted in that year to correct for variation in survey effort.

## Stranding Analysis

The West Coast Marine Mammal Stranding Network, overseen by the West Coast Regional Office of NOAA’s Protected Resources Division, has recorded opportunistic sightings of marine mammal strandings since the early 1980’s. Data on Steller and California sea lions that stranded dead on the Washington and Oregon coast from 2010-2018 were analyzed to determine the occurrence of evidence of entanglement on stranded individuals. Entanglements were assigned to three categories depending on the nature of the entanglement evidence: animals that stranded with the entangling material still present were marked as “Active”, animals with evidence of lesions or other entanglement-related injuries but no entangling material present were marked “Scar”, and animals showing possible but inconclusive evidence of entanglement were marked “Possible”. For active entanglements, the entangling material was determined using notes and comments accompanying the stranding record according to the same material categories used to categorize the entangled individuals observed live on haulouts. Entanglements marked “Possible” were excluded from summary statistics due to inconsistencies in reporting suspicious lesions as potential entanglement evidence.

## Population Trends

Population trends were calculated using a three-step process. First, for each species we pooled the counts from the four major haulout complexes on days when all four haulouts were visited. Next, we averaged all complete survey days within a month for a monthly average. Last, we averaged the mean monthly counts for an annual estimate and a monthly estimate of average number of sea lions using the four major haulout complexes over the study duration for Steller and California sea lions. The observed change in annual counts were calculated for each year using the formula where *t* is year and *N* is the average count for the year, then averaged over all study years to produce the overall average population growth rate for each species (Figure 2). We excluded data from 2018 in the analysis because there were no survey days that covered all four haulout sites after June, potentially biasing the counts by not including the full range of seasonal variation (Table 1).

# Results

## Entanglement Rates

There were 648 active and inactive entanglements observed in the survey area from 2010-2018, 611 of which were documented at the four major haulout complexes: 433 Steller and 178 California sea lions. The average entanglement rate for California sea lions (2.13%) was greater than for Steller sea lions (0.41%), but the difference was not statistically significant (Paired t-test, df = 11, t = 1.41, p = 0.19). There were no annual or seasonal trends of statistical significance in entanglement rates for Steller sea lions, but California sea lions exhibited a peak in entanglement rate in the summer (Fig 2, Fig 3). The average entanglement rates for California sea lions in June (10.2%) and July (12.1%) were at least an order of magnitude greater than all other months, and the month with the next highest rate (November: 1.5%) still an order of magnitude greater than the others (average 0.19%, range 0-0.41%), though the sample size was too small for any definitive statistical differences (n=84).

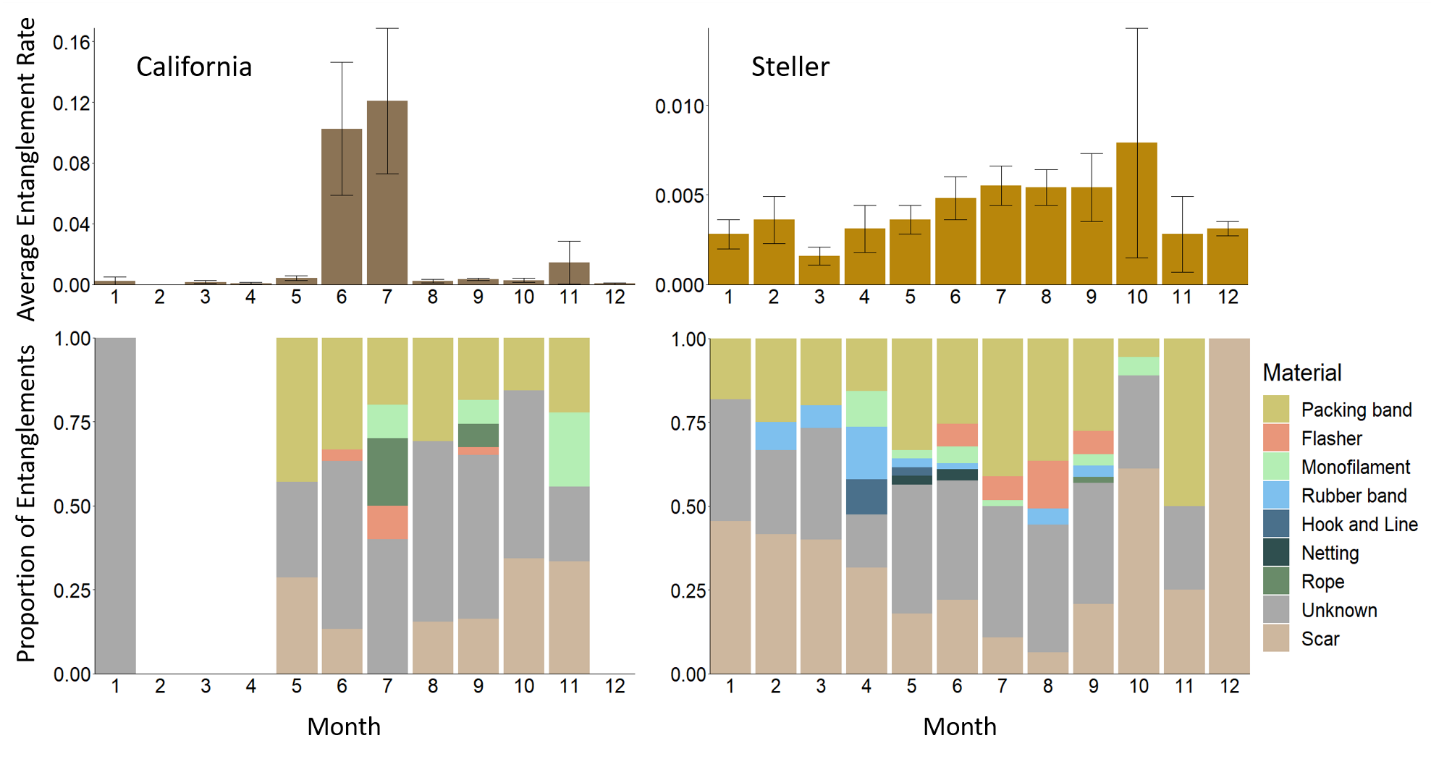


Fig 2: Average entanglement rates (expressed as entanglements per individual) and entangling material proportions for Steller and California sea lions in northern Washington from 2010-2018 by month. Entanglement rate calculations only included entangled individuals observed at one of four major haulout complexes. Entangling materials were analyzed for any entangled individuals with photos of sufficient quality.

*A screenshot of a cell phone

Description automatically generated*

Fig 3: Average entanglement rates (expressed as entanglements per individual) and entangling material proportions for California and Steller sea lions in northern Washington from 2010-2018 by year. Entanglement rate calculations only included entangled individuals observed at one of four major haulout complexes. Entangling materials were only analyzed for individuals with photos of sufficient quality.

## Material Analysis

There were 502 sightings of entanglements with photos of a quality sufficient for analysis. Active entanglements comprised 78.5% of all entanglements, but the entangling material was only identifiable for 48.7% (n = 202) of them. The majority of identifiable entanglements (n=202) were caused by packing bands (68.3%) and salmon flashers (11.8%). The salmon flashers were only observed in the months of May – September coinciding with the local recreational and commercial ocean salmon troll fishery (Fig 2). Other materials comprising less than 10% of identifiable entanglements were monofilament line (7.9%), rubber bands (5.9%), rope (2.9%), netting (1.5%), and hook and line (1.5%). In all cases where the entangling material could not be identified, the entanglement scar or wound was located on the neck, indicating that those entanglements were caused by an encircling material, such as a packing band, rubber band, monofilament line, or netting.

## Sex and Age

For Steller sea lions both the sex and age could be identified for 74.5% of entanglements, and either the sex or the age could be identified for an additional 19.9% for the 357 Steller sea lions analyzed. The majority of the entangled individuals were adults (77.0%), 32.4% of which were male and 63.3% were female; only 17.1% were juveniles, and no entangled pups were observed. For the most part, entangling materials were evenly distributed among sex and age classes, but 16.4% of entangled juveniles exhibited a flasher and 11.5% exhibited rubber bands, higher percentages than any other sex or age class grouping (Fig 4). The sex and age could be identified for 98.6% (n = 143) of entangled California sea lions, 142 of which were adult males, with one juvenile male. The juvenile male was entangled in a packing band, but the overall entangling material proportions are otherwise equivalent to the material proportions for adult male California sea lions.

A screenshot of a cell phone

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Fig 4: The proportion of entanglements caused by each material type for Steller sea lion juveniles, adult females, and adult males in northern Washington, 2010-2018.

## Packing Band Analysis

Annual trends in the proportion of entanglements caused by packing bands from 2012-2017 correlated with the annual occurrence of packing bands observed during OCNMS beach debris surveys (Pearson’s R=0.81; Fig 5).

A close up of a map

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Fig 5: The proportion of entanglements caused by packing bands for sea lions at haulouts in northern Washington (primary axis) and the number of packing bands per survey recorded in beach debris surveys along the north Pacific coast of Washington conducted by the Olympic Coast National Marine Sanctuary (secondary axis).

## Stranding Analysis

There were confirmed stranding records of 551 dead Steller sea lions and 1,048 dead California sea lions on the coast of Washington and Oregon from 2010-2018. The proportion of dead strandings exhibiting evidence of entanglement was 1.6% for Steller sea lions and 0.38% for California sea lions. All four entangled California sea lions that stranded dead were adult males. Of the nine dead stranded entangled Steller sea lions, 8 were adults (4 females, 3 males, 1 unknown), and one was a subadult. Of the 13 total entanglements observed, five were entangled in salmon flashers and other assorted hook and line gear. There was also a single Steller sea lion entangled in rope, and another exhibiting scars indicative of entanglement, the remaining six records did not have enough detail to determine the status of the entanglement or the entangling material. No sea lions stranded dead were observed entangled in packing bands.

## Population Trends

There were 189 survey days from 2010-2017 where counts were recorded at all four major complexes. The average annual population growth of Steller sea lions in northern Washington at the haulout complexes was 7.9% ± 3.2 (95% CI), and California sea lions exhibited a similar average annual rate of change, 7.8% ± 4.2 (95% CI; Fig 6).

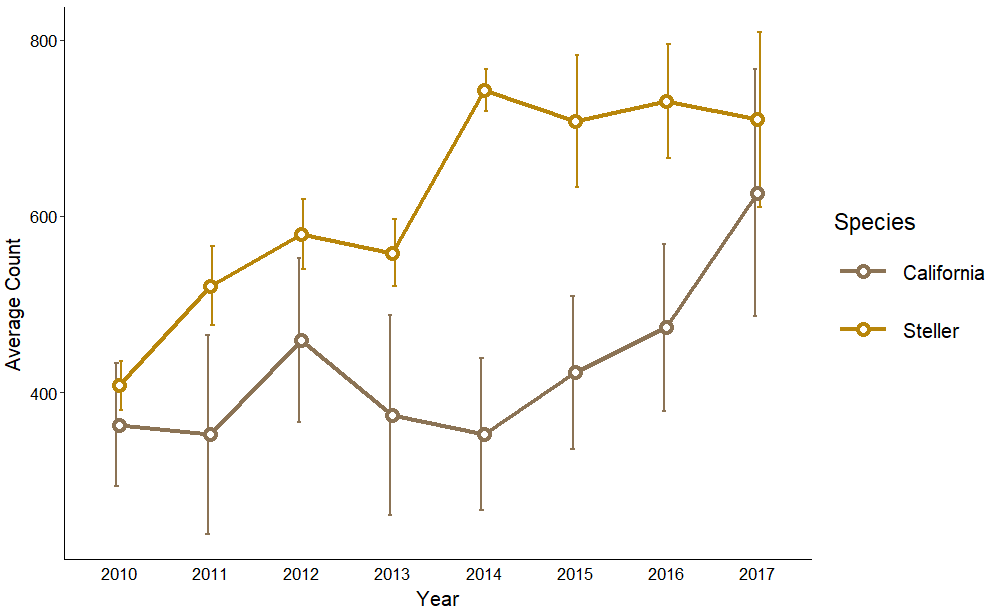


Fig 6: Trends in average annual counts of Steller and California sea lions present at four major haulout complexes on the north coast of Washington from 2010-2017.

# Discussion

Despite exhibiting high rates of entanglement, populations of both California sea lions and Steller sea lions exhibited high rates of growth in northern Washington, suggesting that entanglements did not affect the population dynamics of either species in this area enough to cause concern. The entanglement rate observed for California sea lions in this study was the second highest rate documented for any pinniped in the published literature and the highest pinniped entanglement rate documented in the United States (Table 2), and our observed growth rate for California sea lions (7.8%) was similar to the range-wide estimate for 1975-2014 (7%) [22]. The entanglement rate observed in this study for Steller sea lions was almost double other published rates [17,21], and the population growth rate calculated for Steller sea lions in this study (7.9%) was close to double the rate observed by Pitcher et al. [23] and the National Marine Fisheries Service [24] for the eastern distinct population segment of Steller sea lions. However, Maniscalco et al. [25] cautioned that the eastern Gulf of Alaska population of Steller sea lions was much more sensitive to declines in juvenile and adult survival, which are potentially impacted by entanglement, than changes to fecundity, so understanding the effects of entanglement on juvenile and adult survival is critical.

Table 2: A review of pinniped entanglement rates in the published literature in ascending order of entanglement rate. Entanglement rates were calculated using many different methodologies based on many different data collection methods and are not meant to be directly comparable. Species are listed using the first letters of their genus and species: Af - Arctocephalus forsteri, Ag – Arctocephalus gazella, At – Arctocephalus townsendi, Cu – Callorhinus ursinus, Ej – Eumetopias jubatus, Ma – Mirounga angustirostris, Ms – Monachus schauinslandi, Nc – Neophoca cinerea, Zc – Zalophus californianus. U.S. states are abbreviated, other countries/regions are named fully.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Year | Reference | Location | Region | Species | Rate (%) |
| 1989 | [19] | Channel Islands | CA | Cu | 0\* |
| 2003 | [1] | Point Reyes | CA | Zc | 0.03 |
| 1983 | [26] | St Paul Island | AK | Cu | 0.04~ |
| 1999 | [27] | Bouvetøya | Antarctica | Ag | 0.024-0.059 |
| 1985 | [28] | Northwest Islands | HI | Ms | 0.06 |
| 1985 | [21] | Aleutians | AK | Ej | 0.07 |
| 1978 | [29] | Cape Cross | South Africa | Ag | 0.11^ |
| 1993 | [30] | Marion Island | Australia | Ag & At | 0.15 |
| 2006 | [31] | St Paul Island | AK | Cu | 0.17^ |
| 1983 | [19] | Channel Islands | CA | Zc | 0.18 |
| 2005 | [31] | St Paul Island | AK | Cu | 0.18^ |
| 1994 | [32] | Kangaroo Island | Australia | Nc | 0.2 |
| 1989 | [19] | Channel Islands | CA | Zc | 0.22 |
| 1983 | [19] | Channel Islands | CA | Ma | 0.24 |
| 1985 | [19] | Channel Islands | CA | Cu | 0.24 |
| 1998 | [30] | Marion Island | Australia | Ag & At | 0.24 |
| 2004 | [17] | SEAK and NBC | AK | Ej | 0.26 |
| 1985 | [19] | Channel Islands | CA | Zc | 0.27 |
| 1987 | [19] | Channel Islands | CA | Zc | 0.27 |
| 1987 | [19] | Channel Islands | CA | Ma | 0.28 |
| 1989 | [19] | Channel Islands | CA | Ma | 0.28 |
| 1987 | [19] | Channel Islands | CA | Cu | 0.28 |
| 1985 | [19] | Channel Islands | CA | Ma | 0.36 |
| 1983 | [26] | St Paul Island | AK | Cu | 0.4 |
| 1988 | [33] | Bird Island | South Georgia | Ag | 0.4 |
| 1994 | [32] | Kangaroo Island | Australia | Af | 0.4 |
| 2004 | NA | Northwest Coast | WA | Ej | 0.43# |
| 1988 | [28] | Northwest Islands | HI | Ms | 0.48 |
| 1993 | [34] | Gulf of California | Mexico | Zc | 0.49 |
| 1978 | [29] | Cape Cross | South Africa | Ag | 0.6^ |
| 1990 | [7] | Northwest Islands | HI | Ms | 0.7 |
| 1975 | [26] | St Paul Island | AK | Cu | 0.71\*^ |
| 2001 | [32] | Kangaroo Island | Australia | Af | 0.9 |
| 2001 | [32] | Kangaroo Island | Australia | Nc | 1 |
| 2002 | [32] | Kangaroo Island | Australia | Nc | 1.3 |
| 1990 | [35] | Bass Strait | Tasmania | Af | 1.9 |
| 2000 | [36] | Kaikoura | New Zealand | Af | 0.6-2.84 |
| 2020 | NA | Northwest Coast | WA | Zc | 2.86# |
| 1992 | [15] | Los Islotes | Mexico | Zc | 3.9-7.9 |

\* Not a representative value, included for comparison to extreme values.

^ Harvest data used to calculate entanglement rate

~ Rookery counts during breeding season used to calculate entanglement rate

# Entanglement rate from this study

While the entanglement rates we observed were high, the low number of recorded mortalities from entanglement in the literature highlights our poor understanding of the effects of entanglement on sea lion health and survival. In the stranding record for the Washington and Oregon coast only thirteen California and Steller sea lions were found dead with signs of entanglement from 2010-2018. The proportion of dead stranded sea lions that exhibit evidence of entanglement was similar to the proportion of live sea lions observed with signs of entanglement from survey effort. There are also very few records of dead stranded animals with clear evidence of entanglement in the literature [18,37]. Since dead stranded animals are a subset of the mortality experienced by a population, it is logical that if entanglement significantly affected the sea lion’s health and survival, the proportion of dead individuals with evidence of entanglement would be greater than for the live population at large. Since recorded mortality due to entanglement was lower than expected, we can conclude that this was not the case.

There are two possible explanations for the lack of recorded mortalities from entanglement. The first is that entanglement has a much smaller effect on the health of the affected animals than is assumed [38]. Studies on tagged subadult male Northern fur seals on St. Paul Island, Alaska found that entangled individuals had a similar return rate to the general harvest population, suggesting that entanglement, at least for the harvestable segment of the population, had little to no impact on survival [39,40]. However, Scordino et al. (1988) noted that the probability of survival might be largely dependent on the animal’s ability to shed the entangling material [39]. There are records of animals shedding entangling materials in the wild, including an adult female Antarctic fur seal (*Arctocephalus gazella*)that removed a tied loop of rope [41], a female Hawaiian monk seal with a nursing pup who freed herself from a tangle of monofilament and polypropylene line [42], a large territorial Steller bull who shed two salmon flashers (pers comm. Justin Jenniges), nursing female Northern fur seals who freed themselves from 200g trawl net fragments [43], and multiple Hawaiian monk seals who seemed to entangle and disentangle themselves in beached netting [37]. The likelihood of successfully shedding entangling materials may depend on the type of material. Packing bands were the most common entangling material in all study years for both Steller and California sea lions from live observations, similar to what was seen in other studies in the North Pacific [17,19,31]. However, not a single sea lion stranded dead on the Washington or Oregon coast from 2010-2018 entangled in a packing band. This could indicate that sea lions are able to shed packing bands at a higher rate than other materials. Flashers, on the other hand, made up one third of strandings where the entangling material was identifiable, a much higher proportion than what was seen in live observations, indicating that individuals with entanglements caused by a swallowed hook could have a higher mortality rate. The presence of flasher entanglements on live individuals only during May – September reinforces that sea lions either quickly shed the gear or die. Most sea lions were in good body condition when observed, suggesting it is more likely that they quickly shed the gear, though it is likely that some animals retain the hook internally after losing the visible flasher. The large proportion of individuals exhibiting entanglement-related scarring in our record (21.5%) and in other studies [15,19,39] is another testament both to the ability of animals to self-shed entangling materials and to survive even severely wounding entanglements.

The second possible explanation of the lack of recorded mortalities due to entanglement is that affected animals are dying at sea or otherwise away from areas where they might be detected [4,8,44,45]. Entanglement in a large entangling material, such as a trawl netting fragment, has been proven to increase the energy expenditure of affected animals, increase the time they spend at sea, and decrease the depth and duration of foraging dives, all of which could lead to reductions in health or survival and cause them to perish away from the scientific eye [43,45,46]. Internal entanglement injuries from swallowed and embedded hooks are also likely to go undetected and unrecorded. Three animals in the Oregon stranding record had hooks in their stomach and esophagus, but no external signs of entanglement, and one individual was found with a hook in the stomach and the attached flasher wedged in the esophagus, demonstrating that animals impacted by embedded hooks may have sustained severe injuries without showing any observable evidence of entanglement until necropsy [47]. Likewise, animals entangled in derelict fishing gear are unlikely to be discovered until the gear is recovered, so the impact of these entanglement mortalities is likely underestimated [48]. At-sea mortality, internal injuries, and derelict gear and just a few types of entanglement-related mortality that are unlikely to be accurately documented and included in entanglement rates, further demonstrating that both the rates and impacts of entanglement are likely underestimated in any published rate.

The age, size, and foraging experience of the sea lion may impact the materials they become entangled in, and therefore the outcome of the entanglement [8,49,50]. The high proportion of entangled Steller juveniles exhibiting flashers and rubber bands may be a function of their age: rubber bands may be too small to entangle a large adult, and flasher entanglement is a sign of a risky foraging behavior - depredating salmon troll fisheries. The small number of unidentifiable entangling materials on juveniles may be because of their smaller size, which causes the material to sit on the surface of the skin where it can be easily identified. This may also explain the large number of unidentifiable entangling materials on adult males, whose considerable seasonal growth [51] could have caused entanglements to bury deep into the flesh where they are not readily observed [43]. Pinniped life history therefore impacts both the entangling materials an individual is likely to encounter, and the severity of the wound caused by that entanglement.

Entanglement may also have an impact on pinniped life history and population dynamics. Most California sea lions migrate away from our survey area to their breeding grounds to the south during the summer months, but the few animals that stayed exhibited a much higher entanglement rate than in other months. It is therefore possible that entangled individuals were prevented from migrating because of restrictions imposed by the greater energy expenditure associated with entanglement [45,46]. Even for individuals that did arrive at their breeding grounds, entanglement could impact their reproductive success. Entangled nursing female Northern fur seals spent longer at sea, weaned smaller pups than unentangled females, and sometimes abandoned their pups altogether [43,52]. However, records of three entangled female California sea lions successfully weaning pups in Los Islotes, Baja California [15] demonstrate that the impacts of entanglement on all aspects of pinniped population dynamics are poorly understood.

Entanglement rates appear to also be impacted by the availability and distribution of entangling materials in the immediate environment [4,8]. In our survey area, the occurrence of packing bands in beach surveys was positively correlated with the proportion of entangled individuals exhibiting packing bands. A similar relationship has been observed in the Hawaiian Islands with Hawaiian monk seals, which frequently haul out on top of beached debris and therefore experience higher entanglement risk when more debris is present on the beach [53], and with Northern fur seal pups on St. Paul Island which show higher rates of entanglement at areas with higher concentrations of debris in the nearshore [50]. It is likely that both basin-wide circulation patterns and nearshore currents play a role in the concentration of entangling materials and therefore the distribution of entanglement hot spots. Studies have shown that warm anomaly ocean conditions, usually associated with an El Niño event, can cause changes to the distribution of marine debris, fishing effort, and pinniped prey items, all of which can impact rates of entanglement [13,14,34]. 2014 and 2015 were years of high entanglement rates for California and Steller sea lions in our study area (Figure 5), and 2014 - 2016 were years of elevated large whale entanglements [16,54]. In summer 2014, high sea surface temperatures associated with the warm anomaly referred to as “the Blob” reached the coast, causing the shortest upwelling season for the northern California Current on record [55], the impacts of which were seen well into 2016 [56]. It is possible that these anomalous ocean conditions changed the distribution of fishing effort, entangling debris, and prey items important to whales and pinnipeds, contributing to the high levels of entanglement seen for both taxa. Entanglement rates therefore seem to be driven somewhat by debris circulation conditions created both by normal ocean currents and abnormal ocean conditions.

While entanglement may not currently cause population-level concerns in Steller or California sea lions in Washington, it is still a significant welfare issue, especially considering that most entanglements are caused by humans , either through the creation of marine debris or through direct fishery interactions [4](except for animals collared by penguin skins [27,41]). The good news is that human-caused entanglements can be addressed through changes in human behavior. For entanglements caused by actively fished gear, outreach and education paired with deterrence strategies may prove effective, while marine debris requires tackling pollution sources or redesigning offending materials. In New Zealand and South Georgia, campaigns to encourage fishermen to cut packing bands before disposal led to declines in packing band entanglements [15,57]. However, in Australia, large-scale efforts by the government and local fishermen to reduce entanglement failed to prevent entanglement rates from continuing to increase [32]. Page et al. proposed that the debris could originate from areas outside of Australian waters and away from local fishing grounds, making national legislation ineffective at addressing the trans-boundary issue. A similar situation could complicate entanglement prevention efforts in northern Washington because of the close proximity to the Canadian border and the presence of large basin-wide currents just offshore. Page et al. also commented that laws that fall short of mandating the use of redesigned materials to prevent entanglement risk, such as biodegradable packing bands, may not cause an effective change in observed entanglement rates. Similarly, while deterrents exist or are in development for various types of gear that could prevent animals from interacting with actively fished gear [58,59], it can be a challenge to find a solution that balances effectiveness with reducing potential harm to the ecosystem [60–62]. While preventing entanglements altogether is likely an impossible task, small actions such as encouraging fishers to cut packing bands could decrease the impact on the welfare of local pinniped species.

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# References

1. Moore E, Lyday S, Roletto J, Litle K, Parrish JK, Nevins H, et al. Entanglements of marine mammals and seabirds in central California and the north-west coast of the United States 2001–2005. Mar Pollut Bull. 2009;58: 1045–1051. doi:10.1016/j.marpolbul.2009.02.006

2. National Oceanic and Atmospheric Administration. 2014 Report on the Entanglement of Marine Species in Marine Debris with an Emphasis on Species in the United States. Silver Spring, MD; 2014.

3. Dau BK, Gilardi KVK, Gulland FM, Higgins A, Holcomb JB, Leger JS, et al. Fishing gear-related injury in California marine wildlife. J Wildl Dis. 2009;45: 355–362. doi:10.7589/0090-3558-45.2.355

4. Laist DW. Impacts of Marine Debris: Entanglement of Marine Life in Marine Debris Including a Comprehensive List of Species with Entanglement and Ingestion Records. Coe J, Rogers D, editors. New York: Springer; 1997. doi:10.1007/978-1-4613-8486-1

5. Hofman RJ. The changing focus of marine mammal conservation. Trends Ecol Evol. 1995;10: 462–465. doi:10.1016/S0169-5347(00)89184-3

6. Fowler C. Marine debris and northern fur seals: A case study. Mar Pollut Bull. 1987;18: 326–335. doi:10.1016/S0025-326X(87)80020-6

7. Henderson JR. A pre- and post-MARPOL annex V summary of Hawaiian monk seal entanglements and marine debris accumulation in the Northwestern Hawaiian Islands, 1982-1998. Mar Pollut Bull. 2001;42: 584–589. doi:10.1016/S0025-326X(00)00204-6

8. Fowler CW. A review of seal and sea lion entanglement in marine debris. Proc North Pacific Rim Fish Conf Mar Debris 1987. 1988; 16–63.

9. Read AJ. The looming crisis: interactions between marine mammals and fisheries. J Mammal. 2008;89: 541–548. doi:10.1644/07-mamm-s-315r1.1

10. Weise MJ, Harvey JT. Impact of the California sea lion (Zalophus californianus) on salmon fisheries in Monterey Bay, California. Fish Bull. 2005;103: 685–696.

11. Yoshida K, Baba N. The problem with fur seal entanglement in marine debris. In: Shomura RS., Yoshida HO, editors. Proceedings of the workshop on the fate and impact of marine debris, 27-29 November, 1984, Honolulu, HI, US. 1985. pp. 448–452.

12. Cawthorn MW. Entanglement in, and Ingestion of, Plastic Litter in Marine Mammals, Sharks, and Turtles in New Zealand Waters. Proceedings of the workshop on the fate and impact of marine debris, 27-29 November, 1984, Honolulu, HI, US. 1985.

13. Donohue MJ, Foley DG. Remote sensing reveals links among the endangered Hawaiian monk seal, marine debris, and El Niño. Mar Mammal Sci. 2007;23: 468–473. doi:10.1111/j.1748-7692.2007.00114.x

14. Keledjian AJ, Mesnick S. The impacts of el niño conditions on california sea lion (*Zalophus californianus*) fisheries interactions: Predicting spatial and temporal hotspots along the california coast. Aquat Mamm. 2013;39: 221–232. doi:10.1578/AM.39.3.2013.221

15. Harcourt R, Aurioles D, Sanchez J. Entanglement of California sea lions at Los Islotes, Baja California Sur, Mexico. Mar Mammal Sci. 1994;10: 122–125. doi:10.1111/j.1748-7692.1994.tb00399.x

16. Santora JA, Mantua NJ, Schroeder ID, Field JC, Hazen EL, Bograd SJ, et al. Habitat compression and ecosystem shifts as potential links between marine heatwave and record whale entanglements. Nat Commun. 2020;11. doi:10.1038/s41467-019-14215-w

17. Raum-Suryan KL, Jemison LA, Pitcher KW. Entanglement of Steller sea lions (*Eumetopias jubatus*) in marine debris: Identifying causes and finding solutions. Mar Pollut Bull. 2009;58: 1487–1495. doi:10.1016/j.marpolbul.2009.06.004

18. Hanni KD, Pyle P. Entanglement of pinnipeds in synthetic materials at South-east Farallon Island, California, 1976-1998. Mar Pollut Bull. 2000;40: 1076–1081. doi:10.1016/S0025-326X(00)00050-3

19. Stewart BS, Yochem PK. Pinniped Entanglement in Synthetic Materials in the Southern California Bight. Proceedings of the Second International Conference on Marine Debris, 2-7 April 1989, Honolulu, Hawaii. 1990. pp. 554–561.

20. Opfer S, Arthur C, Lippiatt S. NOAA Marine Debris Shoreline Survey Field Guide. NOAA Mar Debris Progr. 2012. Available: www.MarineDebris.noaa.gov

21. Loughlin TR. Assessment of Net Entanglement on Northern Sea Lions in the Aleutian Islands, 25 June - 15 July 1985. 1986.

22. Laake JL, Lowry MS, DeLong RL, Melin SR, Carretta J V. Population growth and status of california sea lions. J Wildl Manage. 2018;82: 583–595. doi:10.1002/jwmg.21405

23. Pitcher KW, Olesiuk PF, Brown RF, Lowry MS, Jeffries SJ, Sease JL, et al. Abundance and distribution of the eastern North Pacific Steller sea lion (*Eumetopias jubatus*) population. Fish Bull. 2007;107: 102–115.

24. National Marine Fisheries Service. Steller Sea Lion (*Eumetopias jubatus*): Eastern U.S. Stock. US Pacific Mar Mammal Stock Assessments. 2018.

25. Maniscalco JM, Springer AM, Adkison MD, Parker P. Population trend and elasticities of vital rates for Steller sea lions (*Eumetopias jubatus*) in the eastern Gulf of Alaska: A new life-history table analysis. PLoS One. 2015;10: 1–17. doi:10.1371/journal.pone.0140982

26. Shomura RS., Yoshida HO. Proceedings of the workshop on the fate and impact of marine debris, 27-29 November, 1984, Honolulu, HI, U.S. In: Shomura RS, Yoshida HO, editors. Proceedings of the workshop on the fate and impact of marine debris, 27-29 November, 1984, Honolulu, HI. Honolulu, HI; 1985. doi:NOAA-TM-NMFS-SWFC-54

27. Greg Hofmeyr GJ, Bester MN, Kirkman SP, Lydersen C, Kovacs KM. Entanglement of Antarctic fur seals at Bouvetøya, Southern Ocean. Mar Pollut Bull. 2006;52: 1077–1080. doi:10.1016/j.marpolbul.2006.05.003

28. Henderson JR. Recent entanglements of Hawaiian monk seals in marine debris. In: Shomura R, Godfrey M, editors. Proceedings of the Second International Conference on Marine Debris. Honolulu, HI: NMFS; 1990. pp. 540–553. doi:10.1109/TKDE.2011.223

29. Shaughnessy P. Entanglement of Cape Fur Seals with Man-made Objects. Mar Pollut Bull. 1980;11: 332–336.

30. Hofmeyer GJ, De Maine M, Bester MN, Kirkman SP, Pistorius PA, Makhado AB. Entanglement of Pinnipeds At Marion Island , Southern Ocean: 1991-2001. Aust Mammal. 2002;24: 141–146.

31. Zavadil PA, Robson BW, Lestenkof AD, Holser R, Malavansky A. Northern Fur Seal Entanglement Studies on the Pribilof Islands in 2006. 2007.

32. Page B, McKenzie J, McIntosh R, Baylis A, Morrissey A, Calvert N, et al. Entanglement of Australian sea lions and New Zealand fur seals in lost fishing gear and other marine debris before and after Government and industry attempts to reduce the problem. Mar Pollut Bull. 2004;49: 33–42. doi:10.1016/j.marpolbul.2004.01.006

33. Croxall JP, Rodwell S, Boyd IL. Entanglement in Man‐Made Debris of Antarctic Fur Seals At Bird Island, South Georgia. Mar Mammal Sci. 1990;6: 221–233. Available: http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?db=pubmed&cmd=Retrieve&dopt=AbstractPlus&list\_uids=8369427653589658751related:f-yKmRsuJnQJ

34. Zavala-González A, Mellink E. Entanglement of California sea lions, *Zalophus californianus californianus*, in fishing gear in the central-northern part of the Gulf of California, Mexico. Fish Bull. 1997;95: 180–184.

35. Pemberton D, Brothers NP, Kirkwood R. Entanglement of Australian fur seals in man-made debris in tasmanian waters. Wildl Res. 1992;19: 151–159. doi:10.1071/WR9920151

36. Boren LJ, Morrissey M, Muller CG, Gemmell NJ. Entanglement of New Zealand fur seals in man-made debris at Kaikoura, New Zealand. Mar Pollut Bull. 2006;52: 442–446. doi:10.1016/j.marpolbul.2005.12.003

37. Kenyon KW. No man is benign: The endangered monk seal. Oceans. 1980;May: 43–54.

38. Forney KA, Cole TVN, Eagle T, Angliss R, Long K, Barre L, et al. Differentiating Serious and Non-Serious Injury of Marine Mammals: Report of the Serious Injury Technical Workshop. 2008.

39. Scordino J, Kajimura H, Furuta A. Fur Seal Entanglement Studies in 1984, St. Paul Island, Alaska. Fur Seal Investig 1985. 1988.

40. Stewart BS, Bengtson JL, Baba N. Northern Fur Seals Tagged and Observed During Entanglement Studies St. Paul Island, Alaska. Fur Seal Investig 1986. 1989.

41. Bonner WN, McCann T. Neck collars on fur seals, *Arctocephalus gazella*, at South Georgia. Br Antarct Surv Rep. 1982;57: 73–77.

42. Henderson JR. Encounters of Hawaiian Monk Seals With Fishing Gear at Lisianski Island, 1982. Mar Fish Rev. 1984;46: 59–61.

43. DeLong RL, Gearin PJ, Bengtson JL, Dawson P, Feldkamp SD. Studies on the Effects of Entanglement on Individual Northern Fur Seals. Proceedings of the Second International Conference on Marine Debris, 2-7 April 1989. 1990. pp. 492–493.

44. Williams R, Gero S, Bejder L, Calambokidis J, Kraus SD, Lusseau D, et al. Underestimating the damage: Interpreting cetacean carcass recoveries in the context of the Deepwater Horizon/BP incident. Conserv Lett. 2011;4: 228–233. doi:10.1111/j.1755-263X.2011.00168.x

45. Feldkamp SD, Costa DP, G.K. D. Energetic and behavioral effects of net entanglement on juvenile northern fur seals. Fish Bull. 1989;87: 85–94.

46. Bengtson JL, Stewart BS, Ferm LM, DeLong RL. The Influence of Entanglement in Marine Debris on the Diving Behavior of Subadult Male Northern Fur Seals. Fur Seal Investig 1986. 1989.

47. Franco-Trecu V, Drago M, Katz H, Machín E, Marín Y. With the noose around the neck: Marine debris entangling otariid species. Environ Pollut. 2017;220: 985–989. doi:10.1016/j.envpol.2016.11.057

48. Good TP, June JA, Etnier MA, Broadhurst G. Derelict fishing nets in Puget Sound and the Northwest Straits: Patterns and threats to marine fauna. Mar Pollut Bull. 2010;60: 39–50. doi:10.1016/j.marpolbul.2009.09.005

49. Gearin PJ, Stewart BS, DeLong RL. Late Season Surveys for Entangled Northern Fur Seal Females and Pups St. Paul Island, Alaska. Fur Seal Investig 1986. 1989.

50. Stewart BS, Baba N, Gearin PJ, Baker J. Observations of Beach Debris and Net Entanglement on St. Paul Island, Alaska. Fur Seal Investig 1986. 1989.

51. Winship AJ, Trites AW, Calkins DG. Growth in Body Size of the Steller Sea Lion (*Eumetopias jubatus*). J Mammal. 2001;82: 500–519. doi:10.1644/1545-1542(2001)082<0500:gibsot>2.0.co;2

52. DeLong RL, Dawson P, Gearin P. Incidence and Impact of Entanglement in Netting Debris on Northern Fur Seal Pups and Adult Females, St. Paul Island, Alaska. Fur Seal Investig 1985. 1988; 58–68.

53. Donohue MJ, Boland RC, Sramek CM, Antonelis GA. Derelict fishing gear in the Northwestern Hawaiian Islands: Diving surveys and debris removal in 1999 confirm threat to Coral Reef ecosystems. Mar Pollut Bull. 2001;42: 1301–1312. doi:10.1016/S0025-326X(01)00139-4

54. National Marine Fisheries Service. 2018 West Coast Whale Entanglement Summary. NOAA Fish. 2019. Available: https://seagrant.oregonstate.edu/sites/seagrant.oregonstate.edu/files/wcr\_2018\_entanglement\_report\_508.pdf

55. Peterson W, Robert M, Bond NA. The warm Blob continues to dominate the ecosystem of the northern California Current. PICES. 2015;23: 44–46.

56. Gentemann CL, Fewings MR, García-Reyes M. Satellite sea surface temperatures along the West Coast of the United States during the 2014–2016 northeast Pacific marine heat wave. Geophys Res Lett. 2017;44: 312–319. doi:10.1002/2016GL071039

57. Arnould JPY, Croxall JP. Trends in entanglement of Antarctic fur seals (*Arctocephalus gazella*) in man-made debris at South Georgia. Mar Pollut Bull. 1995;30: 707–712. doi:10.1016/0025-326X(95)00054-Q

58. Forrest KW, Cave JD, Michielsens CGJ, Haulena M, Smith D V. Evaluation of an Electric Gradient to Deter Seal Predation on Salmon Caught in Gill-Net Test Fisheries. North Am J Fish Manag. 2009;29: 885–894. doi:10.1577/m08-083.1

59. Barlow J, Cameron GA. Field experiments show that acoustic pingers reduce marine mammal bycatch in the California drift gill net fishery. Mar Mammal Sci. 2003;19: 265–283. doi:10.1111/j.1748-7692.2003.tb01108.x

60. Götz T, Janik VM. Acoustic deterrent devices to prevent pinniped depredation: Efficiency, conservation concerns and possible solutions. Mar Ecol Prog Ser. 2013;492: 285–302. doi:10.3354/meps10482

61. Jefferson TA, Curry BE. Acoustic methods of reducing or eliminating marine mammal-fishery interactions: Do they work? Ocean Coast Manag. 1996;31: 41–70. doi:10.1016/0964-5691(95)00049-6

62. Götz T, Janik VM. Target-specific acoustic predator deterrence in the marine environment. Anim Conserv. 2015;18: 102–111. doi:10.1111/acv.12141