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 the rates and causes of entanglement in Steller and California sea lions on the north coast of Washington state from 2010-2018 and to determine if the entanglements caused population impacts. We conducted small boat surveys to count sea lions and to 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 majority of entangled Steller sea lions were adults (77%), 32.4% of which were male and 63.3% were female; only 17.1% were juveniles, 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, with somewhat elevated entanglements also seen in November. 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, 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), 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 64 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). We also included instances where materials are internally or externally embedded (e.g. hooking injuries). Quantifying the effects of entanglement is a challenging undertaking, as affected individuals may spend more time at sea as a result of their greater energy expenditure or die at sea without being observed [4,8,9]. Even harder to detect are invisible entanglements, where an animal may swallow a hook and suffer internal damage as a result [10]. Any estimates of entanglement rates in a population therefore likely underestimate both the prevalence and potential impact of entanglement.

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. Much of the debris that enters the marine environment is made of synthetic materials and either floats or is neutrally buoyant, increasing the odds that a marine mammal encounters it. Otariids are especially curious of new objects, and can become entangled in debris while attempting to explore or play with them [11,12]. While it seems they are occasionally able to shed entangling materials, the frequency and mechanisms with which animals are able to escape unharmed from entanglement are not well understood [11,12]. 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 [13,14]. 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 [15–18].

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 [1,4,8,19–21]. 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

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). 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 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. 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 sites 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 : 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.

## 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 average 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).

Table : 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)** |

## Entanglement Rates

Our goal was to calculate an average annual entanglement rate for California and Steller sea lions for the northern Washington coast. Entanglement rates were calculated using the counts of the total number of individuals observed during surveys of the four main haulout complexes and the counts of entangled individuals, including both active and inactive entanglements, taken from photographs and survey notes. Our survey effort was greatest during the summer and early fall when sea conditions were most predictable. 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 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 average 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 average entanglement rates.

## 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 100cm 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 includes fishing lures (not attached to flashers) and longline gear, both of which are found hooked externally on the entangled individual. Rubber bands are thick black bands cut from truck tire inner tubes that are often used in crab fisheries to secure trap doors. The netting category includes 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 adhering to standardized debris monitoring procedures developed by NOAA’s Marine Debris Program [22]. 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.

# 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 significantly greater than all other months and statistically indistinguishable from each other (Single-Factor ANOVA, df = 11, F = 3.58, p = 0.00047; Tukey-Cramer HSD, df = 72, q = 0.84, p = 0.99).

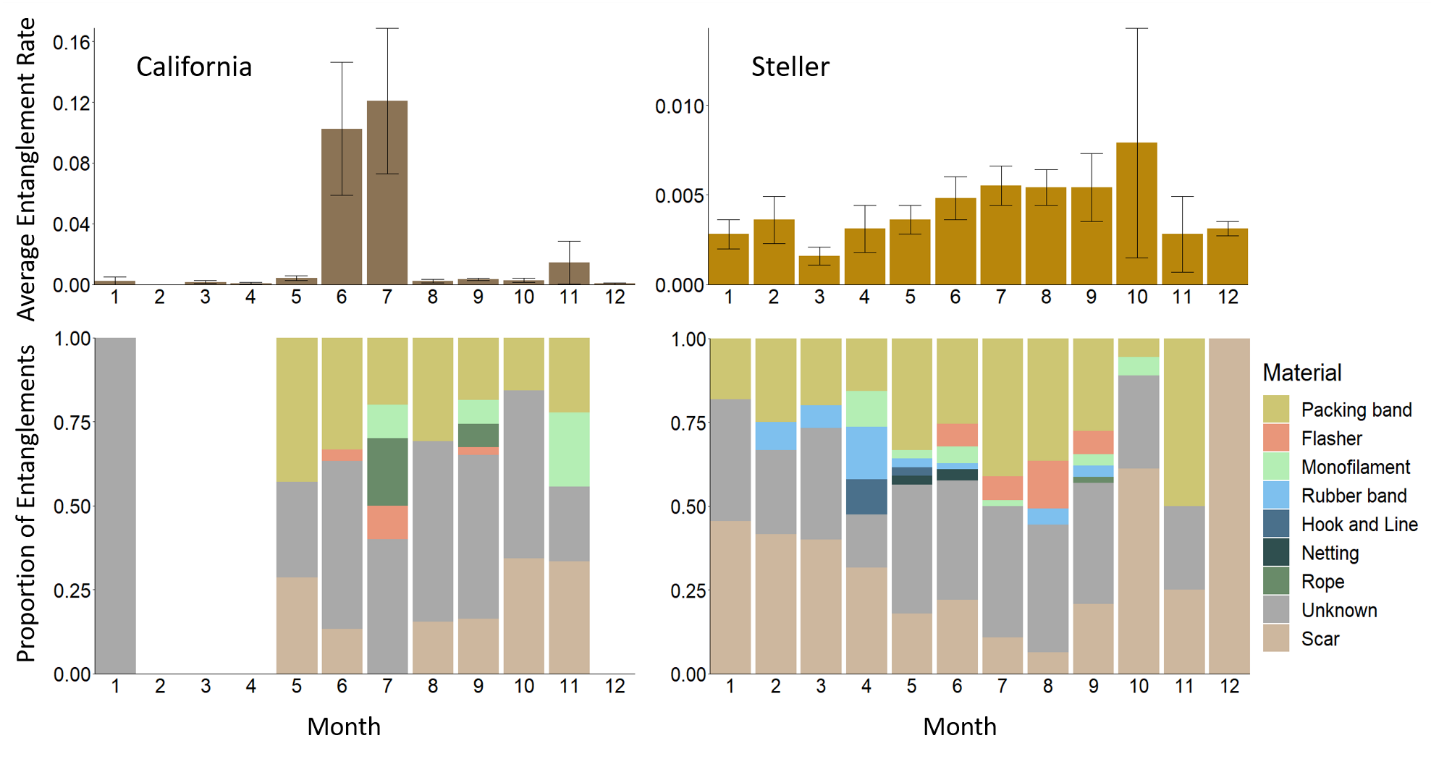


Fig 2: Average entanglement rates (expressed as entanglements per individual) and entangling material proportions for Steller and California sea lions in northern Washington from 2010-2018 by month. Entanglement rate calculations only included entangled individuals observed at one of four major haulout 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, much 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

Description automatically generated

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 correlate with the annual occurrence of packing bands observed during OCNMS beach debris surveys (Pearson’s R=0.81; Fig 5).

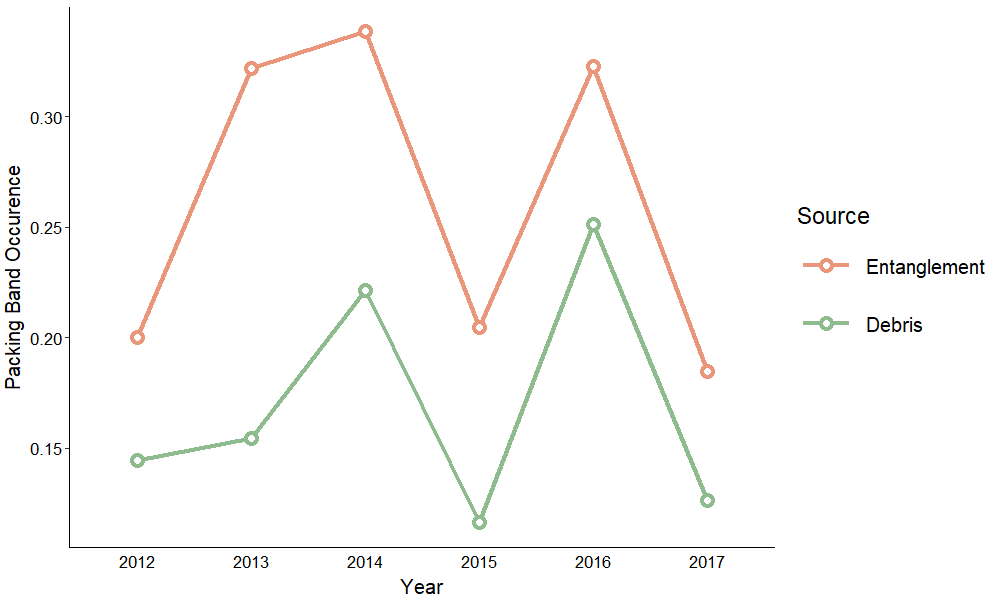


Fig 5: The proportion of entanglements caused by packing bands for sea lions at haulouts in northern Washington and the number of packing bands per survey recorded in beach debris surveys along the north Pacific coast of Washington conducted by the Olympic Coast National Marine Sanctuary.

## 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 0.91% for Steller sea lions and 0.19% for California sea lions. The majority 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. 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 haulouts. The average annual population growth of Steller sea lions in northern Washington 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).

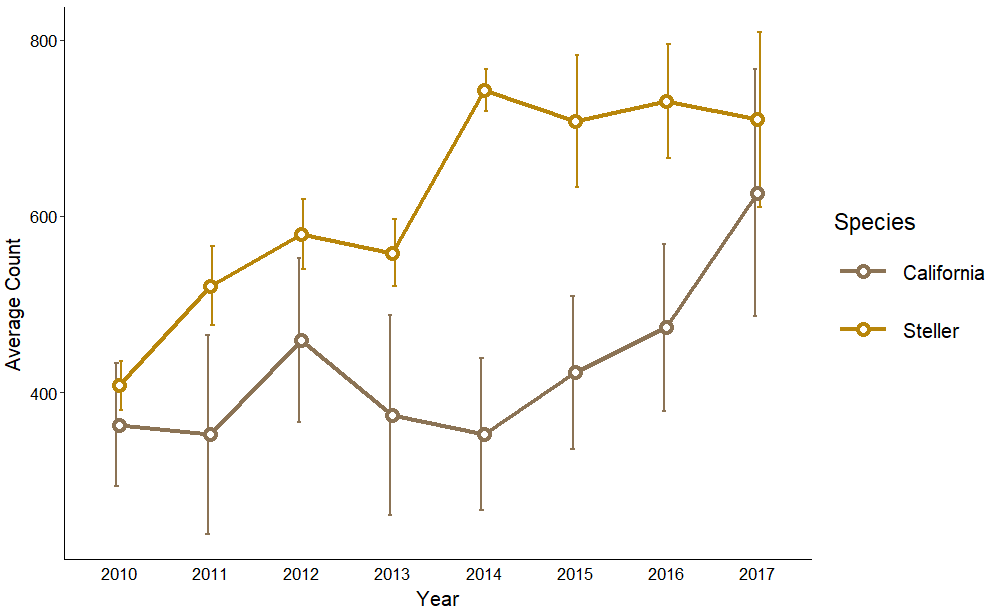


Fig 6: Trends in average annual counts of Steller and California sea lions present at four major haulout complexes on the north coast of Washington from 2010-2017.

# Discussion

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). The entanglement rate observed in this study for Steller sea lions was almost double other published rates [19,23]. 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 population growth rate calculated for Steller sea lions in this study (7.9%) is lower than the 9.2% growth rate from 1989-2002 calculated by Pitcher et al. [24] and the 9.13% rate from 1989 to 2013 for Washington state calculated by [25], and higher than the 4.18% population growth rate estimated for the entire eastern DPS from 1979-2010 by . All three estimates are lower than the theoretical Rmax, which is 12%, indicating that there are potentially still significant factors limiting population growth, though it is unclear what role entanglement may play in dampening population growth, and how that effect may vary regionally [26]. Maniscalco et al. (2015) also noted that the eastern Gulf of Alaska population 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 Steller sea lion populations could be critical to monitoring their return to historic levels [27]. For California sea lions, the population growth rate calculated in this study (7.8%) is similar to the range-wide estimate for 1975-2014 (7%) [28].

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 | [21] | Channel Islands | CA | Cu | 0\* |
| 2003 | [1] | Point Reyes | CA | Zc | 0.03 |
| 1983 | [29] | St Paul Island | AK | Cu | 0.04~ |
| 1999 | [30] | Bouvetøya | Antarctica | Ag | 0.024-0.059 |
| 1985 | [31] | Northwest Islands | HI | Ms | 0.06 |
| 1985 | [23] | Aleutians | AK | Ej | 0.07 |
| 1978 | [32] | Cape Cross | South Africa | Ag | 0.11^ |
| 1993 | [33] | Marion Island | Australia | Ag & At | 0.15 |
| 2006 | [34] | St Paul Island | AK | Cu | 0.17^ |
| 1983 | [21] | Channel Islands | CA | Zc | 0.18 |
| 2005 | [34] | St Paul Island | AK | Cu | 0.18^ |
| 1994 | [35] | Kangaroo Island | Australia | Nc | 0.2 |
| 1989 | [21] | Channel Islands | CA | Zc | 0.22 |
| 1983 | [21] | Channel Islands | CA | Ma | 0.24 |
| 1985 | [21] | Channel Islands | CA | Cu | 0.24 |
| 1998 | [33] | Marion Island | Australia | Ag & At | 0.24 |
| 2004 | [19] | SEAK and NBC | AK | Ej | 0.26 |
| 1985 | [21] | Channel Islands | CA | Zc | 0.27 |
| 1987 | [21] | Channel Islands | CA | Zc | 0.27 |
| 1987 | [21] | Channel Islands | CA | Ma | 0.28 |
| 1989 | [21] | Channel Islands | CA | Ma | 0.28 |
| 1987 | [21] | Channel Islands | CA | Cu | 0.28 |
| 1985 | [21] | Channel Islands | CA | Ma | 0.36 |
| 1983 | [29] | St Paul Island | AK | Cu | 0.4 |
| 1988 | [36] | Bird Island | South Georgia | Ag | 0.4 |
| 1994 | [35] | Kangaroo Island | Australia | Af | 0.4 |
| 2004 | NA | Northwest Coast | WA | Ej | 0.43# |
| 1988 | [31] | Northwest Islands | HI | Ms | 0.48 |
| 1993 | [37] | Gulf of California | Mexico | Zc | 0.49 |
| 1978 | [32] | Cape Cross | South Africa | Ag | 0.6^ |
| 1990 | [7] | Northwest Islands | HI | Ms | 0.7 |
| 1975 | [29] | St Paul Island | AK | Cu | 0.71\*^ |
| 2001 | [35] | Kangaroo Island | Australia | Af | 0.9 |
| 2001 | [35] | Kangaroo Island | Australia | Nc | 1 |
| 2002 | [35] | Kangaroo Island | Australia | Nc | 1.3 |
| 1990 | [38] | Bass Strait | Tasmania | Af | 1.9 |
| 2000 | [39] | Kaikoura | New Zealand | Af | 0.6-2.84 |
| 2020 | NA | Northwest Coast | WA | Zc | 2.86# |
| 1992 | [17] | 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

In the stranding record for the Washington and Oregon coast only seven California and Steller sea lions were found dead with signs of entanglement from 2010-2018. The proportion of dead stranded animals that exhibit evidence of entanglement was similar to the proportion of live sea lions observed with signs of entanglement from survey effort. Since dead stranded animals are a subset of the mortality experienced by a population, it is logical that if entanglement was a significant cause of mortality, the proportion of dead individuals with evidence of entanglement would be greater than for the live population at large. That this was not true was an indicator that recorded mortality due to entanglement was lower than expected. There are also very few records of dead stranded animals with clear evidence of entanglement in the literature [20,40]. 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 [41]. There are a few records of animals shedding entangling materials, including an adult female Antarctic fur seal (*Arctocephalus gazella*)that removed a tied loop of rope [42], a female monk seal with nursing pup who freed herself from a tangle of monofilament and polypropylene line [43], a large territorial Steller bull who shed two salmon flashers (pers comm. Justin Jenniges), and multiple monk seals who seemed to entangle and disentangle themselves in beached netting [40]. There is also a large proportion of animals in our entanglement record exhibiting entanglement-related scarring (21.5%), further indicating that entanglement is not always fatal. The second possibility is that entangled animals are dying at sea or otherwise away from areas where they might be detected, and more dedicated survey efforts would be required to track the survivorship of entangled individuals. Likewise, animals entangled in derelict fishing gear are unlikely to be discovered until the gear is recovered, so the impact of these unrecorded entanglement mortalities is likely underestimated [44]. Records of three entangled female California sea lions successfully weaning pups in Los Islotes, Baja California [17] further demonstrates that the impacts of entanglement on all aspects of pinniped population dynamics are poorly understood, although it has been documented in whales that previously entangled individuals have lower birth rates [45].

There are potential differences in the outcome of an entanglement depending on the entangling material. Packing bands were the most common entangling material in all study years for both species from live observations, similar to what was seen in other studies in the North Pacific [19,21,34]. 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 25% 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 after losing the visible flasher. 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. Internally embedded hooks are just one type of entanglement-related mortality that is 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 also impact the materials they become entangled in, and therefore the outcome of the entanglement. The high proportion of entangled juveniles exhibiting flashers and rubber bands may be a function of their age: rubber bands may be too small to entangle a large adult male or female, 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 [46] could have caused entanglements to bury deep into the flesh where they are not readily observed. The Washington and Oregon stranding record also contains a larger proportion of adult males stranded dead with signs of entanglement than adult females or juveniles, though the sample size is too small to be definitive.

There is no clear annual trend in entanglement rates for either species, though there are a few interesting years worth noting. In 2014, California sea lions experienced elevated rates of entanglement, a larger proportion of which were caused by rope, and in 2015, both species experienced elevated rates of entanglement (Figure 5). 2014 - 2016 were also years of elevated large whale entanglements, raising the possibility that entanglements in sea lions and whales could be caused by similar conditions [18,47]. Other 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 [15,16,37]. 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 [48], the impacts of which were seen well into 2016 [49]. It is possible that these anomalous ocean conditions changed the distribution of fishing effort and prey items important to whales and pinnipeds, contributing to the high levels of entanglement seen for both taxa.

The high overall entanglement rate in California sea lions was also a product of the highly seasonal variability in entanglement rates, which peaked during June and July. During the summer months, California sea lions migrate away from our survey area to their breeding grounds to the south, and the few animals that stayed exhibited a much higher entanglement rate than in other months. It is therefore possible that entangled individuals were less likely to migrate to their breeding grounds, potentially because of restrictions imposed by the greater energy expenditure associated with entanglement [9].

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 (except for animals collared by penguin skins [30,42]). 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 [17,50]. However, in Australia, large-scale efforts by the government and local fishermen to reduce entanglement failed to prevent entanglement rates from continuing to increase [35]. 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 [51,52], it can be a challenge to find a solution that balances effectiveness with potential harm to the ecosystem [53–55]. While preventing entanglements altogether is likely an impossible task, small actions such as encouraging fishers to cut packing bands could decrease the impact on welfare of local pinniped species.

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