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Entanglement rates and population trends of Steller (<i>Eumetopias jubatus</i>) and California (<i>Zalophus californianus</i>) 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, 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 entangled individuals. Rates of entanglement and entangling material occurrence were compared with records of 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 entangled Steller sea lions was 77% adults (32.4% male, 63.3% female), 17.1% juveniles, 5.9% unknown age, and no pups. All entangled California sea lions were adult males except for one juvenile. Steller sea lion entanglements showed no seasonality, but California sea lions experienced an entanglement rate peak in June and July. The majority of identifiable entanglements were packing bands, followed by salmon flashers, which only occurred in June – September during the peak of the local ocean salmon troll fishery, and monofilament line. Counts of packing bands in debris surveys correlated with entanglements caused by packing bands observed on haulouts (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 rate of increase at the study haulouts, 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 a welfare issue for individual sea lions.
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Competing Interests Use the instructions below to enter a competing interest statement for this submission. On behalf of all authors, disclose any competing interests that could be perceived to bias this work—acknowledging all financial support and any other relevant financial or non-financial competing interests. This statement **will appear in the published article** if the submission is accepted. Please make sure it is accurate. View published research articles from *PLOS ONE* for specific examples.	EA and JS both work for the Makah FIsheries Management Department of the Makah Tribe. Furning for this project was provided by the Species Recovery Grant to Tribes that is administered by the National Marine Fisheries Service. EA and JS also receive funding from the Bonneville Power Administration Tribal Capacity Building Grant, the National Science Foundation through a subaward granted to the University of Chicago, and the John H. Prescott Marine Mammal Rescue Assistance Grant administered by the National Marine Fisheries Service. Author JS has also received funding support through the Saltonstall-Kennedy Grant Program, the Bycatch Reduction Engineering Program, the Preserve America Grant, and a NOAA Cooperative Research Grant which are all administered by the National Marine Fisheries Service; the Bureau of Indian Affairs; Washington SeaGrant; and the North Pacific Coast Marine Resource Committee. Funders played no role in the development, implementation, or analysis of the work completed for this manuscript.

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To Whom It May Concern,

Jonathan Scordino and I are pleased to provide for your review for publication in PLOS ONE a research article on the population trends and entanglement rates of sea lions in northern Washington titled, “Entanglement rates and population trends of Steller (*Eumetopias jubatus*) and California (*Zalophus californianus*) sea lions on the north coast of Washington state.” This study presents population trends, entanglement rates, and entangling material proportions for two pinniped species in a region with no previous studies of entanglements. Entanglement rates are contextualized through comparison to trends in counts conducted at sea lion haulouts and through comparison to the stranding record to understand the impacts of entanglement on sea lion health and survival. Entanglement rates and material proportions are also compared to beach debris surveys conducted along the Washington coast to analyze patterns in material occurrence and entanglement susceptibility. We also situate our entanglement rates and material proportions in existing literature through a literature review of otariid entanglement rates globally. The entanglement rates observed in this study are the highest recorded rates for Steller sea lions and the second highest recorded rates for California sea lions globally. The work in this manuscript has not been submitted or published elsewhere and is the original work of the authors.

Appropriate Academic Editors to handle this manuscript in order of relevance would be Robert Schick, Songhai Li, or Andrew Hoskins.

Thank you for your consideration of this research article. We think it will make an important contribution to the current knowledge on pinniped entanglement and fishery interactions, as well as aid in the development of more targeted mitigation strategies. Furthermore, I am very excited to submit this manuscript as it is my first time submitting my work for peer-reviewed publication.

Respectfully,

Elizabeth Allyn

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, 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 entangled individuals. Rates of entanglement and entangling material occurrence were compared with records of 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 entangled Steller sea lions was 77% adults (32.4% male, 63.3% female), 17.1% juveniles, 5.9% unknown age, and no pups. All entangled California sea lions were adult males except for one juvenile. Steller sea lion entanglements showed no seasonality, but California sea lions experienced an entanglement rate peak in June and July. The majority of identifiable entanglements were packing bands, followed by salmon flashers, which only occurred in June – September during the peak of the local ocean salmon troll fishery, and monofilament line. Counts of packing bands in debris surveys correlated with entanglements caused by packing bands observed on haulouts (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 rate of increase at the study haulouts, 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 a welfare issue for individual sea lions.

Introduction

The prevalence of man-made 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 [6–8]. For pinnipeds specifically, entanglement has been documented for more than half of the existing species [2,4,9]. 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, torso, 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. Entangling debris can come from terrestrial and marine pollution, and from derelict and active fishing gear. Any marine debris that form loops that can ensnare or sharp objects that can embed, such as hooks, pose an entanglement risk. 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 derelict gear 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 [10,11]. Otariids are especially curious of novel objects, and can become entangled in debris while attempting to explore or play with them [12,13]. 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 [9,14–17].

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 [1,4,9,18–20]. 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. We also compared entanglement rates with beach debris survey data to discern patterns in entanglement occurrence due to material availability, and with the stranding record to briefly explore the impacts of entanglement on health and survival. 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

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 from the United States Fish and Wildlife Service for all land-based survey activities conducted on haulouts within the Flattery Rocks National Wildlife Refuge.

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 these surveys. Surveys were conducted year-round with more effort from late spring through early fall 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 were still photographed to identify the source and nature of the injury. Entanglement and count data are publicly available through Mendeley Data [21].

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.

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 of the average number of Steller and California sea lions using the four major haulout complexes over the study duration. The observed change in annual counts were calculated for each year using the formula

$$r_t = \ln\left({}^{N_{t+1}}/_{N_t}\right)$$

where r_t is the realized per capita rate of population change, t is year, and N is the average count for the year. The annual rates of change were then averaged over all study years to produce the overall average rate of change in haulout counts for each species. We excluded 2018 data from 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 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)**

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, which were analyzed using single-factor ANOVA and Tukey-Kramer post-hoc tests. An overall average entanglement rate was calculated for each species by taking the average of the monthly mean entanglement rates. We used a paired two-tailed t-test to compare the average entanglement rate for Steller and California sea lions with monthly averages (n=12) as our sampling unit. We conducted a literature review to catalog published entanglement rates for California and Steller sea lions along with other otariid species to provide a comparison to our calculated 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 a number of physical characteristics, including 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.

Entangling materials 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 – 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 entangled individuals. Rubber bands are thick black bands cut from truck tire inner tubes that are often used in crab fisheries to secure trap doors. Packing bands are thin plastic strips attached at the ends to form loops that are used to increase the integrity of containers generally made of cardboard. The netting category included both gillnets made of monofilament line and trawl netting made of nylon or synthetic lines. Monofilament lines are commonly used in recreational fisheries and for leaders in commercial salmon fisheries and were differentiated from gillnets by the absence of knotted webbing. Active entanglements where the material could not be identified were 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 summarized and reported over months and years to observe trends in material occurrence.

Packing Band Analysis

Annual packing band entanglement occurrence was compared to 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 annual trend analysis due to low sea lion survey effort after the month of June. OCNMS conducted 1,548 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 [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. The annual proportion of entanglements caused by packing bands observed during surveys was analyzed for correlation with the number of packing bands per beach debris survey.

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 stranded individuals bearing evidence of entanglement. 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 entanglement-related injuries without entangling material present were marked 'Scar', and animals showing probable but inconclusive evidence of entanglement were marked 'Possible'. For active entanglements, the entangling material was determined using notes and comments accompanying the stranding record and assigned to one of the categories used during our live surveys (e.g. packing band or flasher). Entanglements marked "Possible" were excluded from summary statistics due to inconsistencies in reporting suspicious lesions as potential entanglement evidence.

Statistical Analysis

All statistical analyses were conducted in Microsoft Excel. Figures 2-6 were created with R Statistical Program version 3.6.1 using ggplot2 [23,24].

Results

Population Trends

There were 92 survey days from 2010-2017 where counts were recorded at all four major complexes. The average annual rate of change at the haulout complexes in northern Washington for Steller sea lion counts was 7.9% ± 3.2 (95% CI), and for California sea lion counts was 7.8% ± 4.2 (95% CI; Fig 2).

Fig 2: 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.

Entanglement Rates

There were 648 active and inactive entanglements observed in the survey area from 2010-2018, 611 (433 Steller, 178 California) of which were documented at the four major haulout complexes. 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 or California sea lions (Fig 3). However, California sea lions experienced high rates of entanglement in 2014, and both species experienced somewhat elevated rates of entanglement in 2015. California sea lions also exhibited some seasonal variability with a peak in entanglement rates in the summer, coinciding with the lowest months for haulout counts (Fig 4). While other months exhibited elevated rates of entanglement (November: 1.5%) or comparatively low average haulout counts (February: 168, March: 218), June and July were the only months to exhibit both low average haulout counts and high entanglement rates (June: 167, 10.2%; July: 35, 12.1%).

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 observed hauled out anywhere along the survey route.

Fig 4: Average pooled counts at the four major haulouts, 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 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 observed hauled out anywhere along the survey route.

Material Analysis

There were 502 (357 Steller, 145 California) sightings of entanglements with photos of a quality sufficient for analysis. For Steller sea lions, active entanglements comprised 77.9% of all entanglements and of those only 55.4% (n = 154) were identifiable. The majority of identifiable entanglements were caused by packing bands (67.5%) and salmon flashers (13.6%). Other materials comprised less than 10% of identifiable entanglements: rubber bands (7.8%), monofilament line (6.5%), netting (1.9%), hook and line (1.9%), and rope (0.6%). For California sea lions, 80.0% of all entanglements were active, and 41.4% of active entanglements were identifiable. Packing bands made up the majority of entanglements (70.8%), followed by monofilament line (12.5%), rope (10.4%), and salmon flashers (6.3%). For both species salmon flashers were only observed in the months of June – September coinciding with the local recreational and commercial ocean salmon troll fishery (Fig 4). In all cases where the entangling material could not be identified or was no longer present 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 age composition of entangled Steller sea lions was 77% adults (32.4% male, 63.3% female), 17.1% juveniles, 5.9% unknown age, and no pups. 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 5). 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 single juvenile male was entangled in a packing band, and the remaining adult males exhibited entanglements in the same proportions as what was seen for California sea lions overall in the survey area.

Fig 5: 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 positively correlated with the annual occurrence of packing bands observed during OCNMS beach debris surveys (Pearson's R=0.81; Fig 6).

Fig 6: 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 outer 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, 7 were adults (4 females, 3 males), one subadult, and one unknown. 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.

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 California sea lions in this study experienced the second highest rate for any otariid population in the published literature and the highest otariid entanglement rate documented in the United States (Table 2). Our observed count increase rate for California sea lions (7.8%) was similar to the range-wide population growth estimate for 1975-2014 (7%) [25]. The entanglement rate observed in this study for Steller sea lions was almost double other published rates [18,26], and the count increase rate calculated for Steller sea lions in this study (7.9%) was close to double the population growth rate observed by Pitcher et al. [27] and the National Marine Fisheries Service [28] for the eastern distinct population segment of Steller sea lions.

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 without caution. Species are listed using the first letters of their genus and species: Af - Arctocephalus forsteri, Ag – Arctocephalus gazella, Ap – Arctocephalus pusillus, Apd – Arctocephalus pusillus doriferus, App – Arctocephalus pusillus pusillus, At – Arctocephalus tropicalis, Cu – Callorhinus ursinus, Ej – Eumetopias jubatus, Nc – Neophoca cinerea, Zc – Zalophus californianus.

Year	Reference	Location	Species	Rate (%)
1988-1989	[20]	Channel Islands, CA	Cu	0.00
1997-2013	[29]	Bass Strait, Australia	App	0.002-0.019
1988-1997	[30]	Livingston Island, Antarctica	Ag	0.024
1996-2002	[31]	Bouvetøya	Ag	0.024-0.059
2001-2005	[1]	Point Reyes, CA	Zc	0.03

1982-1984	[32]	St Paul Island, AK	Cu	0.04$^{\sim}$
1985	[26]	Aleutian Islands, AK	Ej	0.07
1978	[33]	Namibia & South Africa	Ap	0.11*
1977	[33]	Namibia & South Africa	Ap	0.12*
1979	[33]	Namibia & South Africa	Ap	0.12*
1991-1996	[34]	Marion Island, Australia	Ag & At	0.15
2006	[35]	Pribilof Islands, AK	Cu	0.17*
1983-1984	[20]	Channel Islands, CA	Zc	0.18
2005	[35]	Pribilof Islands, AK	Cu	0.18*
2006	[35]	St Paul Island, AK	Cu	0.20
1988-2000	[36]	Kangaroo Island, Australia	Nc	0.20
1988-1989	[20]	Channel Islands, CA	Zc	0.22
1985-1986	[20]	Channel Islands, CA	Cu	0.24
1996-1999	[34]	Marion Island, Australia	Ag & At	0.24
2001-2007	[18]	SEAK & northern BC	Ej	0.26
1985-1986	[20]	Channel Islands, CA	Zc	0.27
1986-1988	[20]	Channel Islands, CA	Zc	0.27
1986-1988	[20]	Channel Islands, CA	Cu	0.28
1988-1989	[37]	Bird Island, South Georgia	Ag	0.4
1989-2000	[36]	Kangaroo Island, Australia	Af	0.4
2010-2018	[21]	Northwest Coast, WA	Ej	0.43
1991-1995	[38]	Gulf of California, Mexico	Zc	0.49
1995-2005	[39]	Kaikoura, New Zealand	Af	0.6-2.84
1983	[40]	St Paul Island, AK	Cu	0.75*
1984	[41]	St Paul Island, AK	Cu	0.78*

2001-2002	[36]	Kangaroo Island, Australia	Af	0.9
2001	[36]	Kangaroo Island, Australia	Nc	1
2002	[36]	Kangaroo Island, Australia	Nc	1.3
1989-1991	[42]	Bass Strait, Australia	Apd	1.9
2010-2018	[21]	Northwest Coast, WA	Zc	2.86
1992	[16]	Los Islotes, Mexico	Zc	3.9-7.9
2000	[43]	Los Islotes, Mexico	Zc	8.75
1998	[43]	Los Islotes, Mexico	Zc	9.9
1992	[43]	Los Islotes, Mexico	Zc	10.4

* Harvest data, only subadult males

~ Rookery data during breeding season

While the entanglement rates we observed were high, the low number of recorded mortalities from entanglement in the literature and in the local stranding record 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 out of 1,599 total strandings. The proportion of dead stranded sea lions that exhibited evidence of entanglement (0.81%) was of a similar order of magnitude to the proportion of live sea lions observed with signs of entanglement from survey effort (0.41% Steller, 2.13% California). In the literature there are also very few records of animals observed dead with signs of entanglement [19,44]. 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, it suggests that this was not the case.

There are two plausible 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 [45]. Studies on tagged subadult male northern fur seals on St. Paul Island, Alaska found that entangled individuals had a similar return rate the following year as the general harvest population, suggesting that entanglement, at least for the harvestable segment of the population, had little to no impact on survival [41,46]. However, the probability of survival might be largely dependent on the animal's ability to shed the entangling material [41]. 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 [47], a female Hawaiian monk seal with a nursing pup who freed herself from a tangle of monofilament and polypropylene line [48], nursing female northern fur seals who freed themselves from 200g trawl net fragments [49], multiple Hawaiian monk seals who seemed to entangle and disentangle themselves in beached netting [44], and several Steller sea lions, including a few branded individuals, observed shedding salmon flashers in Alaska (Alaska Department of Fish and Game, unpublished data). 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 [18,20,35]. However, not a single sea lion stranded dead on the Washington or Oregon coast from 2010-2018 while 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 with an identifiable entanglement, a much higher proportion than what was seen in live observations (13.6% Steller, 6.3% California), 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 June – 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% of all documented entanglements) and in other studies [16,20,41] is another testament both to the ability of animals to self-shed entangling materials and to survive even severely wounding entanglements.

The second plausible 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 [4,9,50,51]. 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 [49,51,52]. 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 [53]. 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 [54]. At-sea mortality, internal injuries, and derelict gear are just a few types of entanglement-related mortality unlikely to be accurately documented and included in published entanglement rates.

The age, size, and foraging experience of the sea lion may dictate the materials they become entangled in, and therefore the outcome of the entanglement [9,55,56]. 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 [57] could have caused entanglements to bury deep into the flesh where they are not readily observed [49]. Age and body size therefore impact 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 June and July, but the few animals that stayed during those months 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 [51,52] or compromised body condition. 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, and abandoned their pups more frequently than unentangled females [49,58]. However, records of three entangled female California sea lions successfully weaning pups in Los Islotes, Baja California [16] demonstrate that the impacts of entanglement on all aspects of pinniped population dynamics are poorly understood.

Entanglement rates also appear to be impacted by the availability and distribution of entangling materials in the immediate environment [4,9]. 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 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 [59], and with northern fur seal pups which show higher rates of entanglement in areas on

St. Paul Island, Alaska with higher concentrations of debris in the nearshore [56]. 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 [14,15,38]. 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 [60], the impacts of which were seen well into 2016 [61]. 2014 and 2015 were years of high entanglement rates for California and Steller sea lions in our study area, and 2014 - 2016 were years of elevated large whale entanglements [17,62]. It is possible that these anomalous ocean conditions changed the distribution of fishing effort, entangling debris, and prey items important to cetaceans 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 [30,31,47]). 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 [16,63]. However, in Australia, large-scale efforts by the government and local fishermen to reduce entanglement failed to prevent entanglement rates from continuing to increase [36]. Page et al. (2004) 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. (2004) also commented that laws that fall short of mandating the use of redesigned materials to prevent entanglement risk, such as biodegradable packing bands, may fail to cause an effective change in observed entanglement rates. Similarly, while deterrents exist or are in development that could prevent animals from interacting with various types of actively fished gear [64,65], it can be a challenge to find a solution that balances effectiveness, cost, and reducing potential harm to the ecosystem [66–68]. While preventing entanglements altogether is likely an impossible task, small actions such as encouraging fishers to cut packing bands could decrease the impact of entanglement on the welfare of local pinniped species.

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Haulout Map

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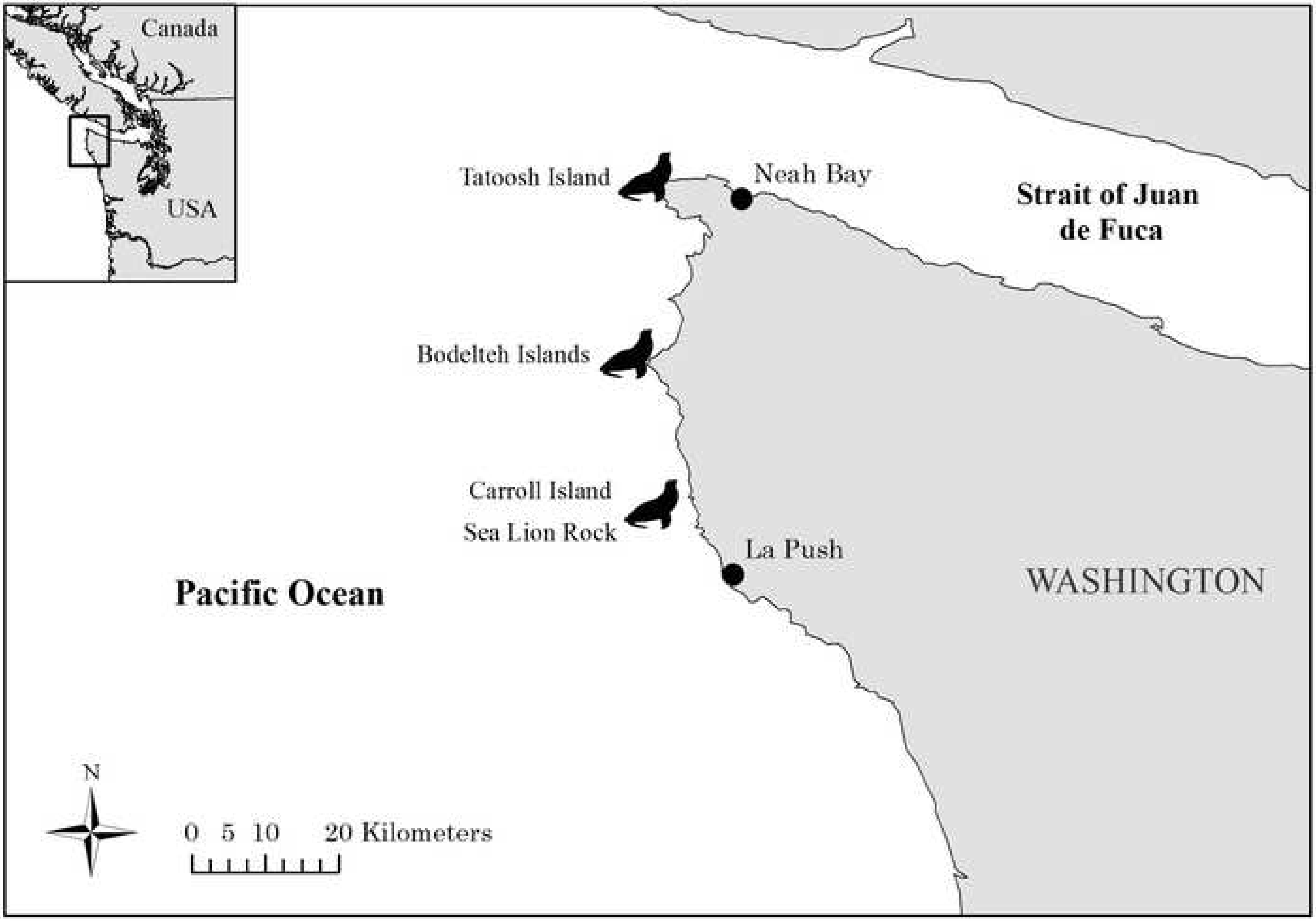
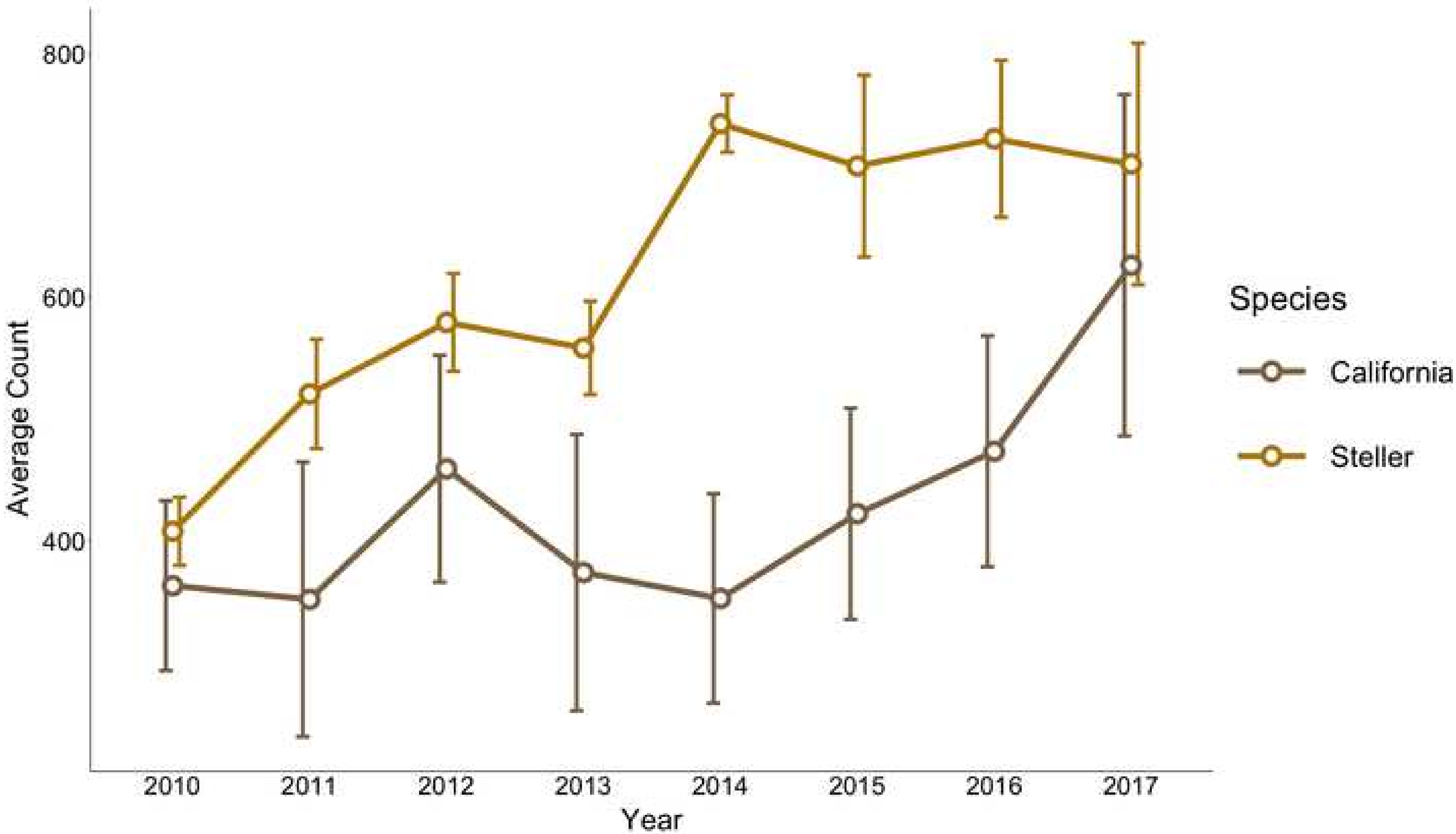
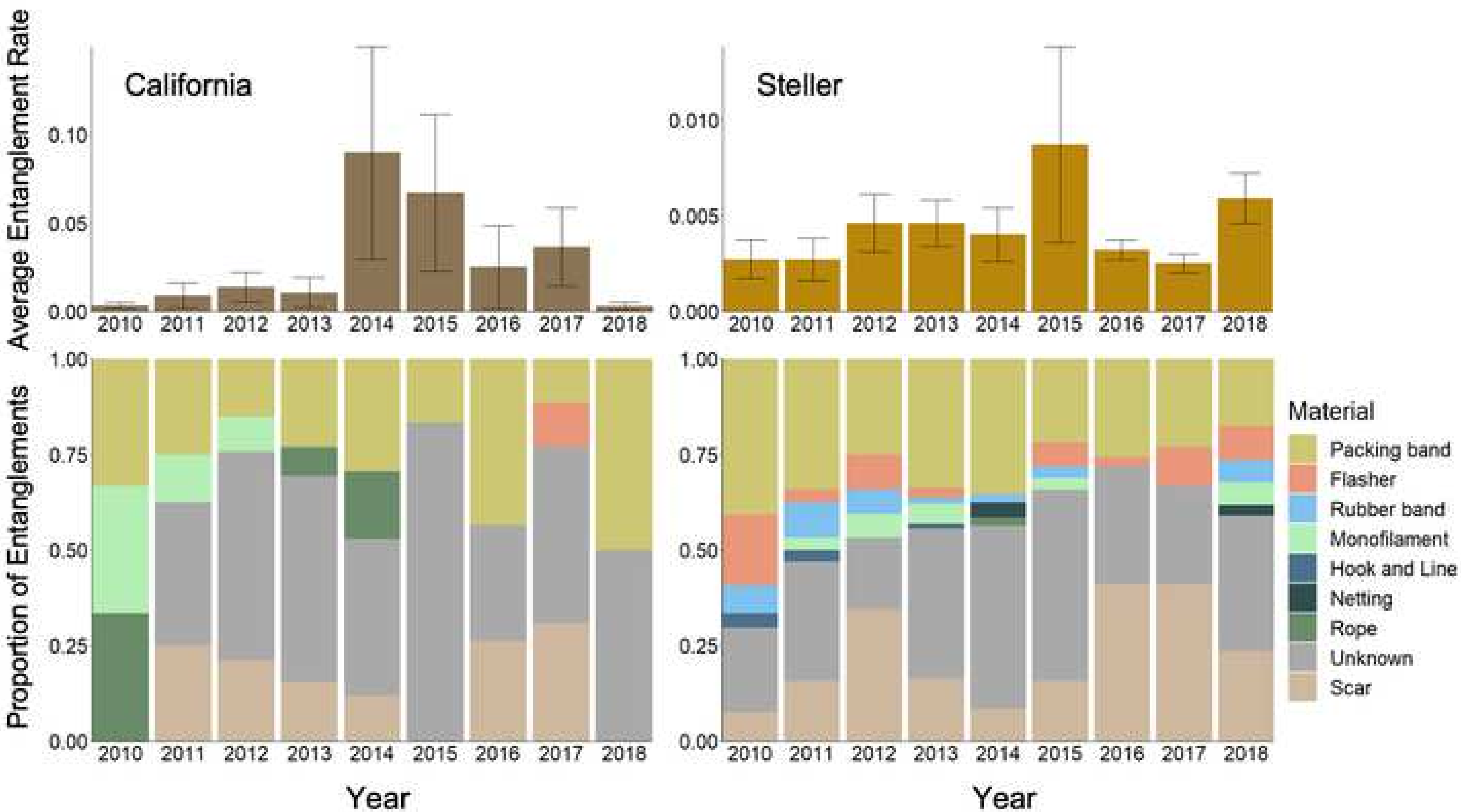
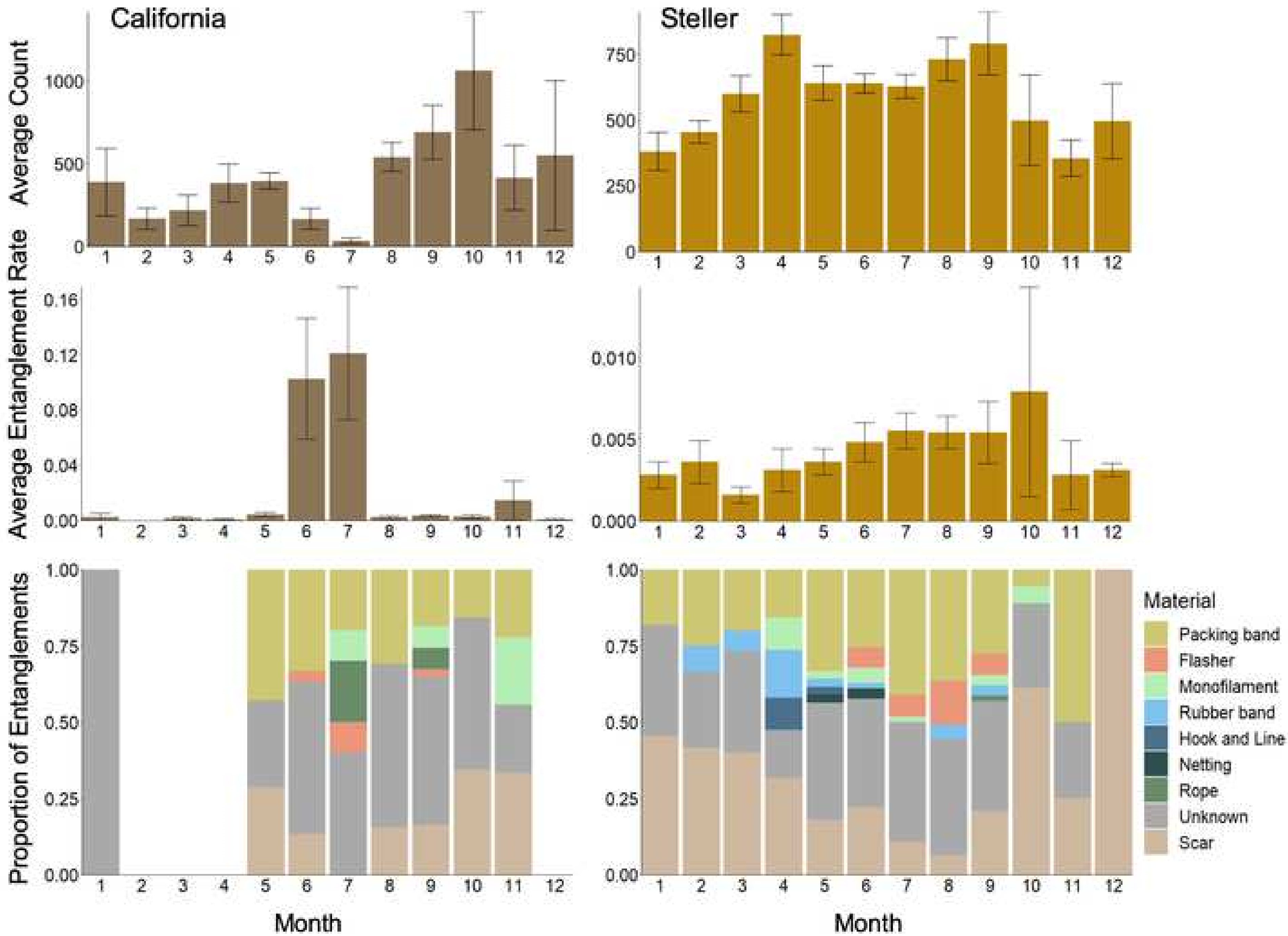
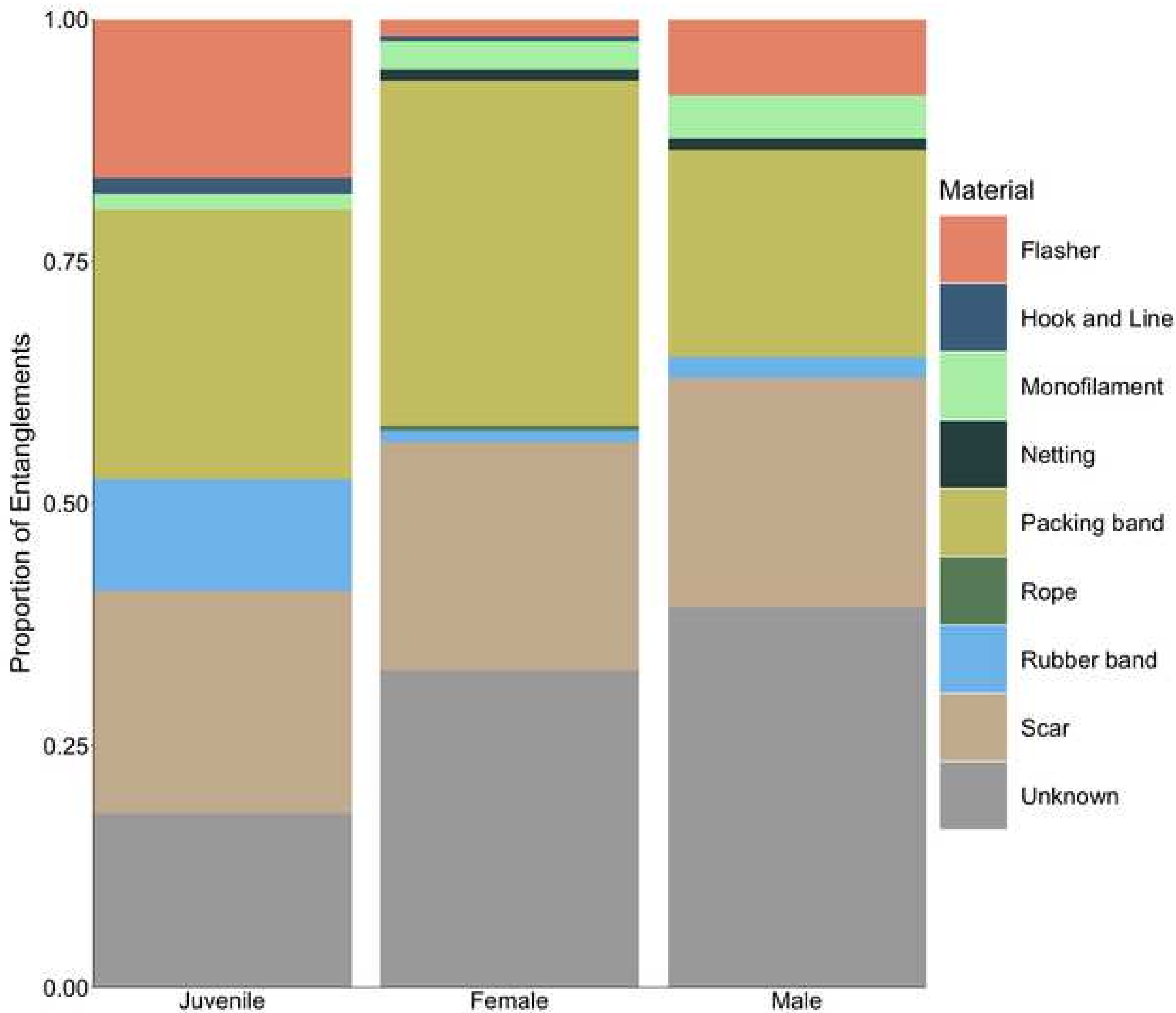



Average Count
800
600
400
2010
2011
2012
2013
2014
2015
2016
2017
Year
Species
California
Steller

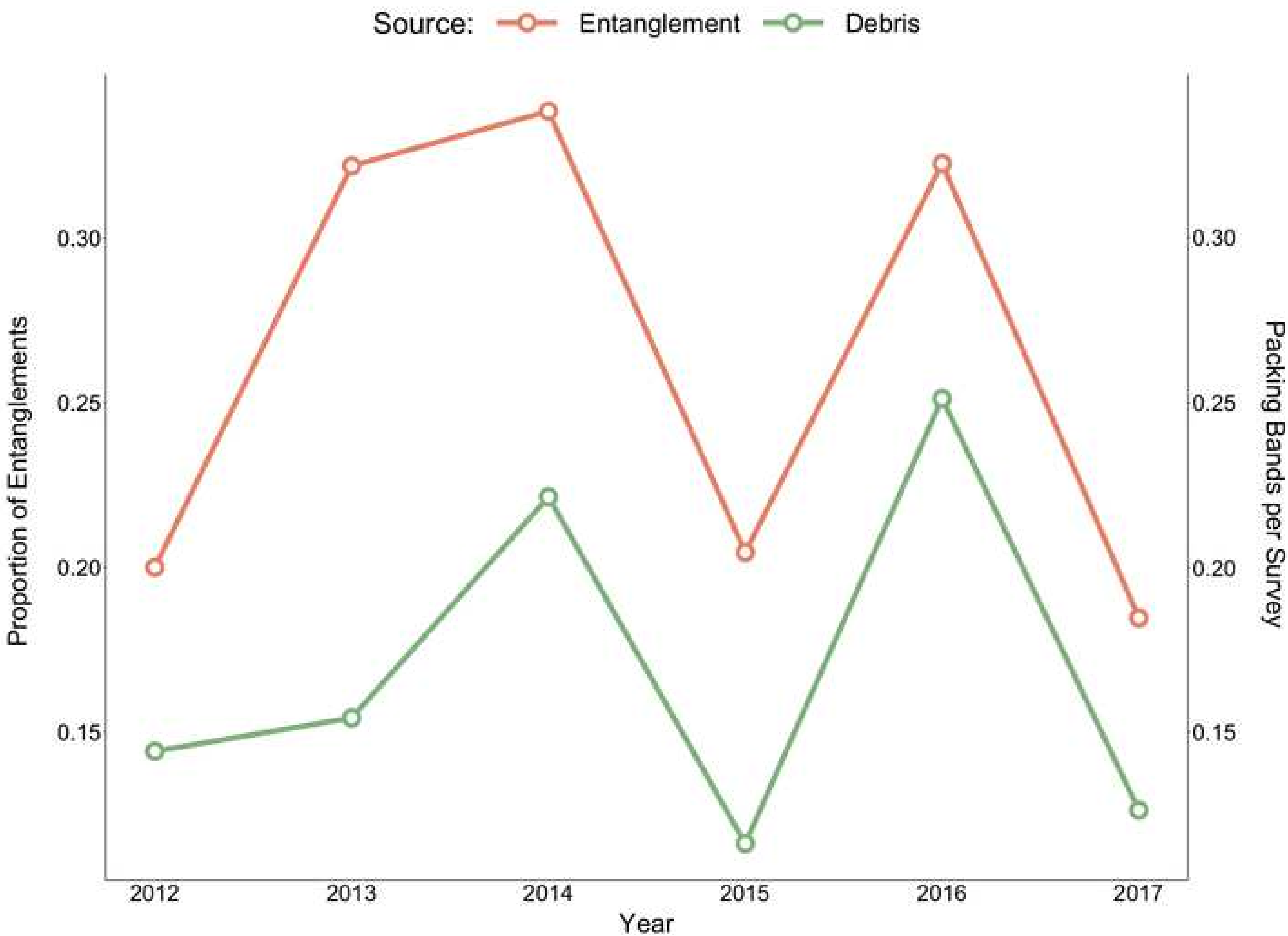

California
Steller
Average Entanglement Rate
0.10
0.05
0.00
0.010
0.005
0.000
2010
2011
2012
2013
2014
2015
2016
2017
2018
Proportion of Entanglements
1.00
0.75
0.50
0.25
0.00
Year
Material
Packing band
Flasher
Rubber band
Monofilament
Hook and Line
Netting
Rope
Unknown
Scar


California
Steller
Average Count
Average Entanglement Rate
Proportion of Entanglements
Month
Material
Packing band
Flasher
Monofilament
Rubber band
Hook and Line
Netting
Rope
Unknown
Scar

Ej MA



1.00
0.75
0.50
0.25
0.00
Proportion of Entanglements
Juvenile
Female
Male
Material
Flasher
Hook and Line
Monofilament
Netting
Packing band
Rope
Rubber band
Scar
Unknown



Source:
Entanglement
Debris
0.30
0.25
0.20
0.15
Proportion of Entanglements
0.30
0.25
0.20
0.15
Packing Bands per Survey
2012
2013
2014
2015
2016
2017
Year

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