Salish Sea Marine Mammal Density in Response to Increasing Sea Surface Temperature and Trophic Level Changes

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Abstract

The San Juan Archipelago is situated in the state of Washington, south of the Strait of Georgia and east of Vancouver Island. In this biodiverse region resides an abundance of marine mammal species, including harbor porpoises, harbor seals, and Steller sea lions. Near the top of the trophic food chain, these animals rely on fish for prey while avoiding the predator at the very top: the transient killer whale. Marine mammals such as these pinnipeds act as ecosystem sentinels; their behaviors provide obvious, visible responses to environmental stressors and serve as warnings for underlying problems in the ecosystem.

Marine mammal surveys were conducted aboard a research vessel over the course of 17 years, from 2008 to 2024. Species of mammal and number present were recorded. Sea surface temperatures, zooplankton samples, and catch per unit effort of Pacific sand lance were obtained, as well as a dataset from the Whale Museum on transient orca sightings and Pacific herring spawn counts from Fisheries and Oceans Canada herring stock. Our results imply that rising sea surface temperatures are related to decreases in marine mammal density. While prey abundance could also be a factor, the data so far indicates it is unlikely. Whether rising sea surface temperature is impacting lower trophic levels and causing marine mammals to redistribute would entail further study. This study aims to address whether climatic factors, particularly sea surface temperature and the 2014-2015 marine heat wave, and prey abundances affect marine mammal density in the San Juan Archipelago. The report also examines the presence of transient killer whales in relation to pinnipeds over the years 2012 to 2019.

Introduction

The Salish Sea is a 16,925 km^2 inlet shared by Washington State, U.S. and British Columbia, Canada (Gaydos & Pearson, 2011). Within the Salish Sea is the San Juan Archipelago, a biodiverse region with the Georgia Strait to the northeast and the Strait of San Juan de Fuca to the south end. West of the archipelago lies Vancouver Island, and beyond that, the Pacific Ocean. Surrounding the San Juan Archipelago are the San Juan Islands, which include several important biological areas, from kelp forests occupying coastal shelves to shallow bays providing residence for a variety of animals (Lewis & Sharpe, 1985).

The Salish Sea's ecosystems are vulnerable to a changing climate, as global ocean surface waters have warmed between 0.5 and 1.0°C since 1970 (Sobocinski, K.L., 2021). More specifically, the North Station (48°35'N, 123°02.54'W) and South Station (48°25.20'N, 122°56.60'W) of the San Juan Channel have been steadily increasing ovefr time (Pagliaro, 2024). In addition to long-term warming, the Salish Sea also experiences short bursts of warm spells. From 2014 to 2016, a marine heat wave (MHW) known as the "Blob" occurred in the North Pacific Ocean. Temperatures increased up to 3.9°C above average, harming marine animals due to depletion of nutrition and abundance in the marine food web (Sobocinski, K.L., 2021). Other marine heatwaves have occurred in western North America, including one in July 2021, which surpassed existing Pacific Northwest temperature records (Schumacher et al., 2022). Such events can be caused by both anthropogenic influences (Hayashi et al., 2020) and natural variations (Oliver et al., 2018). Additionally, warming waters can stem from El Niño years. El Niño events are characterized by anomalous warming in the eastern equatorial Pacific Ocean occurring over subdecadal periods (Yeh et al., 2009).

Numerous species of marine mammals reside within the San Juan Archipelago, feeding off a diverse array of wildlife. These animals can be classified as ecosystem sentinels due to their ability to respond to changes in an obvious, observable manner and, because of this, can inform humans of any threats to the environment and/or human health. Deteriorating conditions in the population health in marine mammals reflects weakening conditions at lower trophic levels, indicative of changes at the ecosystem level (Plön et al., 2024c). Human-induced changes are rapidly affecting climatic processes and wildlife population dynamics, so indicators such as these are growing increasingly necessary (Plön et al., 2024c).

Marine mammals play critical roles in shaping their ecosystems, as apex predators or consumers of low-level trophic organisms like zooplankton (Ford, 2014). Zooplankton are key organisms in the marine pelagic ecosystem, at the interface of the lower primary production level (phytoplankton) and upper trophic levels (Carlotti & Poggiale, 2009). While plankton lay the groundwork, the next level up is also pivotal to the functioning of the ecosystem. Pelagic forage fish consume zooplankton, occupying a crucial intermediate trophic level (Sisson & Baker, 2017). In the San Juan Archipelago, fish that fill this niche include the Pacific sand lance (*Ammodytes personatus*), silver surf perch (*Hyperprosopon ellipticum*), and Pacific herring (*Clupea pallasii*) (Burke, 2014). Small, planktivorous fish such as these are a source of food for larger predatory fish, such as the pink salmon (Beacham, 1986). Pinnipeds such as Steller sea lions and harbor seals then feed on these larger fish (Ford, 2014). Varying levels of the ocean food chain are intrinsically connected and heavily reliant upon each other for food and healthy population levels.

Many of the indirect effects of climate change on marine mammals can be observed through shifts in prey availability (Gibson, Atkinson, & Gordon, 2006, p. 432). Often, marine mammal populations have distribution “hotspots,” or locations with high prey abundance and availability (Brough et al., 2018). While mammals can thermoregulate and exhibit behavioral adaptations against environmental shifts, habitat changes can still impact their distribution and population size (Evans, Pierce, & Panigada, 2010).

Another possible cause for changes in marine mammal density is top-down predation. Two ecotypes of killer whales reside in the Salish sea: the Southern Resident orcas and the transient orcas. While the Southern Resident orcas feed on salmon, the transient orca diet is made up on marine mammals, often including harbor porpoises, harbor seals, and Steller sea lions (J. K. Ford et al., 1998). A 2018 study from the Orca Behavior Institute found a continued significant increase in mammal-eating killer whale presence in the Salish Sea from 2011 to 2017 (Shields et al., 2018). This can result in behavioral changes in pinnipeds, such as moving from open water to spend more time in haul-out locations to reduce risk of predation (Bengtson & Cameron, 2004). At the top level, orcas can keep the trophic system in check, but if there exists an imbalance in the lower levels, predation could potentially become problematic and endanger other species of marine mammals.

This study aims to address whether climatic factors affect marine mammal density in the San Juan Archipelago. Is there an interannual trend in marine mammal density due to climatic factors, such as sea surface temperature and the MHW? A previous study conducted in the San Juan Channel found that the Blob had a significant impact on the densities of all recorded mammal species (Mayer, 2020). Considering this, are marine mammal populations recovering from the Blob? In addition to these questions, this study will examine the presence of transient killer whales in relation to harbor seals, harbor porpoises, and Steller sea lions over the years 2012 to 2019. Do higher abundances of transient killer whales correlate with lower abundances of these prey species? By answering these questions, we can develop a better understanding of marine mammals' resilience in an ocean that is rapidly changing due to natural and anthropogenic causes.

Methods

Data Collection Methods, Part I: Marine Mammal Counts

The first portion of data collection was conducted in six zones of the San Juan Channel, over the course of six research cruises. The first marine mammal survey was taken aboard the R/V *Rachel Carson*, and the later five were taken aboard the R/V *Kittiwake*. Research cruises from 2008 to 2019 used different vessels than the R/V *Kittiwake*, but the same methods of data collection were used. Each cruise covered six different zones, with the northernmost as Zone 1 and the southernmost as Zone 6 (Figure 1). Coordinates are listed in Table 2. The North-to-South surveys began at Zone 1 and stopped at Zone 6, and the South-to-North surveys started at Zone 6 and ended at 1. Surveys occurred on the following dates in 2024: October 1, October 8, October 15, October 22, October 29, and November 5.

For each zone, two observers on the port side of the vessel and two on the starboard side counted mammals and reported the numbers, species, and time to data recorders below deck via radio. All data collected came from observations within 200 meters of either side of the vessel, for a total of 400 meters surrounding the boat, using Bushnell 10x42 binoculars, and was recorded in one-minute intervals.

Twelve different species of marine mammals were observed and recorded over the course of the dataset: the harbor porpoise (*Phocoena phocoena*), Dall's porpoise (*Phocoenoides dalli*), harbor seal (*Phoca vitulina*), orca (*Orcinus orca*), humpback whale (*Megaptera novaeangliae*), gray whale (*Eschrichtius robustus*), minke whale (*Balaenoptera acutorostrata*), Pacific white-sided dolphin (*Lagenorhynchus obliquidens*), sea otter (*Enhydra lutris*), river otter (*Lontra canadensis*), Steller sea lion (*Eumetopias jubatus*), and California sea lion (*Zalophus californianus*).

Data Collection Methods, Part II: Sea Surface Temperature

Sea surface temperatures (within 0.5-1 meter of the surface, depending on the dataset) were collected via a Conductivity, Temperature and Depth (CTD) instrument that was deployed on each of the research cruises at North and South Station. From 2008 to 2018, data was collected on the R/V *Centennial* Seacat Model SBE-19 CTD. In 2019, the R/V *Magister* was used with the Sea-Bird SBE 25 CTD, and the R/V *Rachel Carson* with a Sea-Bird SBE 911plus CTD. From 2020 to 2024, use of the R/V *Rachel Carson* continued, along with the R/V *Kittiwake*, which was equipped with a Sea-Bird 19plus CTD. All devices collect temperature information at varying depths but can vary in precision and sampling speed.

Data Collection Methods, Part III: Zooplankton

To obtain zooplankton, a zooplankton net with a 0.7-meter diameter opening and a 153-µm mesh cod end was vertically towed from the vessel, at both North and South Stations. Before deployment, the flow meter was set to zero. The net was lowered to the bottom of the water column and then brought back to the surface. A clinometer was used to measure the angle of the main line as the net was retrieved. The flow meter was read after the net was brought back up to note and record the number of revolutions. The net was rinsed with a seawater hose to capture any remaining zooplankton and move them into the cod-end. Zooplankton were then moved from the cod-end and stored in a labeled jar. The seawater containing zooplankton was mixed with 60 mL buffered formalin to preserve the specimens.

Data Collection Methods, Part IV: Forage Fish

Forage fish were collected via Van Veen grabs. The Van Veen device covers 0.12 m^2 of surface area per drop and penetrates to a depth of 22 cm. If the sampler successfully closed and retained sediment, the grab was counted. The device was hauled up to the vessel, and fish were counted. If the fish was split by the device, it was still counted in the dataset. For the purposes of this study, prey abundance was measured using catch per unit effort (CPUE). These values were averaged across the fall season each year from 2012 to 2024.

Data Collection Methods, Part V: Transient Orcas

A prior PEF study by James Leifer in 2019 utilized a dataset from the Whale Museum on San Juan Island on transient orca sightings from 2012 to 2019. This same dataset was used for this study. Orca sightings were compared with harbor porpoise, harbor seal, and Steller sea lion sightings in the San Juan Channel.

Statistical Analysis Methods

Marine mammal density was calculated for each year. This value was obtained by taking the total number of animals in each area and dividing it by the area measured, to obtain the number of animals per kilometer squared. Transient orca sightings data from 2012 to 2019 was provided by the Whale Museum.

Zooplankton density was calculated using the following formula:

$$D = \frac{N * S}{V(f * a)}$$

where D = density (individuals/m^3), N = the count of all organisms in the subsample, S = the split volume (mL), f = the split dilution fraction, a = the aliquot volume (mL), and V = total tow volume of water (m^3).

RStudio was used to create a series of graphs to assess whether there was a correlation between variables. CTD data was used to analyze changes in sea surface temperature over the course of 17 years. The shallowest collected temperature values were used, which ranged from 0.5 – 1 meter deep. These values were averaged across each of the cruises for each year and then compared via a linear model graph. To test for significant relationships between variables, R^2 values and p-values were calculated. For this study, an R^2 value of 0.3 is considered a moderate relationship between two variables, and a p-value of 0.05 or less is considered significant (a 95% confidence interval). Interactive Poisson models were also created, which also entailed the use of a p-value to test for significance.

Results

Temperature and Marine Mammal Density

A series of linear models were constructed in RStudio, based on the 2008-2024 temperature and mammal density data. Temperature plotted against year yielded an R^2 of 0.296, indicating a moderate relationship between the two values, and a p-value of 0.014, indicating a significant upward trend in sea surface temperature (Figure 2). Density against year was also plotted, with an R^2 value of 0.755 and a low p-value of $3.6*10^{-6}$, suggesting a strong decline in marine mammal density over time (Figure 3).

Density modeled with temperature revealed an R^2 of 0.41 and a p-value of 0.0032 (Figure 4). These values indicate a relationship between the two variables and a significant trend of decreasing marine mammal density with increasing temperature.

Density Changes of Specific Marine Mammal Species Over Time

The densities of all twelve species of marine mammals from 2008-2024 were graphed (Figure 5). Densities dropped in 2014 and did not recover to their original levels. To better understand changes in density of certain species over time, densities of the three most frequently observed marine mammal species were compared. Annual values of harbor seal, Steller sea lion, and harbor porpoise densities were graphed individually (Figures 6, 7, and 8) and together (Figure 9).

All three species decreased in density during the years of the Blob, with Steller sea lion density dropping from 0.584 animals/km² in 2013 to 0.416 in 2014, and harbor porpoise density decreasing from 1.48 animals/km² in 2013 to 0.207 in 2014. Harbor seal density dropped from 2.4 animals/km² to 1.19 in 2015. All species increased slightly in density in 2016 after the MHW but declined again in 2017 and have not made a return to their original population levels since. Bar graphs of these individual species densities from 2008 to 2024 all revealed p-values of less than 0.1.

Zooplankton Density

Linear models of zooplankton density vs. time and zooplankton density vs. marine mammal density were constructed. Zooplankton density plotted from 2008 to 2024 produced an R^2 value of 0.291 and a p-value of 0.022 (Figure 10). Based on these results, density had a moderate relationship to time and an increasing trend. This dataset excludes the years 2017 and 2020, as zooplankton densities were not collected.

Zooplankton density vs. marine mammal density revealed an R^2 value of 0.354 and a p-value of 0.011 (Figure 11), indicating that marine mammal density has a positive relationship with zooplankton density; marine mammal density is experiencing a downward trend in relation to a downward trend in zooplankton density.

Forage Fish Catch Per Unit Effort and Pacific Herring Spawn Numbers

A single-factor comparison of interannual marine mammal density and sand lance catch per unit effort (Figure 12) revealed an adjusted R^2 value of 0.305 and a p-value of 0.029. These values suggest a correlation between the two and a significant increase in marine mammal density with an increase in fish CPUE.

Pacific Herring (*Clupea pallasii*) spawn numbers, provided by Fisheries and Oceans Canada herring stock assessments, do not show a decrease over time from 2008 to 2023, with a p-value of 0.02 and adjusted R^2 value of 0.259 (Figure 14). Moreover, there is a lack of trend between marine mammal density and total spawn number, with a p-value of 0.0722 and adjusted R^2 value of 0.16 (Figure 15).

Orca Predation

A linear model was constructed to explore orca abundance in relation to prey abundance (Figure 16). The model plotted transient orca sightings vs. prey sightings (harbor seal, Steller sea lion, and harbor porpoise) from the years 2012 to 2019. The plot revealed an adjusted R^2 of 0.48

and a p-value of 0.0352. These results indicate a strong predator-prey relationship as well as a significant decline in prey species density over time.

Interactive Model

Interactive Poisson models were run to determine if marine mammal density is impacted by a combination of factors: sea surface temperature, zooplankton density, orca abundance, and fish CPUE. None of the interaction variables were significant when combined with each other in a main effect model, nor were they significant in an interactive model. Upon testing the effects of these various factors, only a single-factor comparison with zooplankton yielded significant results.

Discussion

Results revealed a strong correlation between sea surface temperature and marine mammal density. There appears to be an increase in sea surface temperature over the 17-year time scale and a decrease in marine mammal density over that same period. Both variables are statistically related to each other, and therefore it is likely that increases in sea surface temperature are indeed a factor in the changing distributions of marine mammals in the San Juan Archipelago. Temperature also affects other trophic levels, such as zooplankton, altering zooplankton abundance and community dynamics (Francis et al., 2012) and fish, influencing growth and distribution (Lehodey et al., 2006). It is possible, then, that both sea surface temperature and prey abundance variables could interact with each other.

It is also evident that the 2014-2015 marine heat wave impacted the density of all marine mammal species (when all species counts are combined). Species also struggled to make a return to their original densities after this major climatic event. Changes in weather systems can cause changes in currents and upwellings that affect primary production and, in turn, how zooplankton and forage fish are distributed. El Niño events are associated with warmer waters that may result in a northward shift in distribution of marine mammals and prey (Ford, 2014). Perhaps during the MHW, these animals behaved similarly in response to warming waters. Harbor seals, harbor porpoises, and Steller sea lions all decreased in density during the Blob years. Steller sea lion and harbor porpoise densities dropped in 2014, and harbor seal densities dropped in 2015. None of these three species have made a recovery since the Blob. In particular, harbor porpoises experienced an extreme decrease in density during the MHW and were at their lowest levels in 2023 and 2024.

Increased temperatures can have negative impacts on prey abundance. For example, increases in water temperature have been shown to increase juvenile Chinook salmon susceptibility to disease (Dietrich, Van Gaest, Strickland, & Arkoosh, 2014), therefore reducing availability to predators. Additionally, warming will lead to changes in the distribution of fish stocks, likely with fish distributions shifting toward the poles; a study on elephant seals expects that these pinnipeds will change their distribution accordingly (McIntyre et al., 2011). It is predicted that colder water species will shift their distribution towards the poles, which will likely result in a reduced global range of marine mammals (Simmonds & Isaac, 2007). This could partially explain the change in marine mammal densities seen in the San Juan Archipelago.

The most important determinants of marine mammal distribution are food and the need to produce offspring (Ford, 2014). The decrease in zooplankton provide evidence that food availability is decreasing for marine mammals in the San Juan Archipelago. This reduction could be tied to climatic factors, since we now know that SST has decreased over the 17-year dataset.

However, the sand lance CPUE and Pacific herring spawn data did not reveal a significant decrease in fish populations over the studied time period. Therefore, we cannot conclude that the reduction in marine mammal density is related to these factors.

In addition to rising sea surface temperature, the decline in marine mammal sightings appear to have a strong tie to the increase in orca sightings. With the 2014-2015 marine heat wave came a decrease in density of marine mammal species, so perhaps the remaining populations were made even more vulnerable to transient orca predation. However, we recognize that the orca sightings provided by the Whale Museum are annual numbers rather than seasonal, and the transient orca data was collected from 2012-2019 rather than the course of the entire marine mammal density dataset.

Cumulative effects can disrupt ecological connectivity toward groups of ecosystem engineers like cetaceans (Plön et al., 2024c). While some effects, such as increased orca predation, are natural and exist as a function of the food web, climate change could also be altering predation behaviors. Further study is needed to better understand climate change's impacts on apex predator behavior. Additional study could also prove beneficial in understanding how much the decrease in marine mammal density is due to sea surface temperature alone and how much is due to climate change's effects on prey.

Finally, studies on pinniped haul-out behavior would be beneficial; it is possible that since this study is limited to a 400-meter boat width, we are simply not seeing animals present in the region. Additionally, with increasing orca populations, marine mammal prey species may be spending more time in haul-out zones in order to avoid predation. Further observational study on marine mammal distributions in the biodiverse San Juan Archipelago can help us better prepare for a globally changing climate and its potential impacts on other marine life.

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Figures

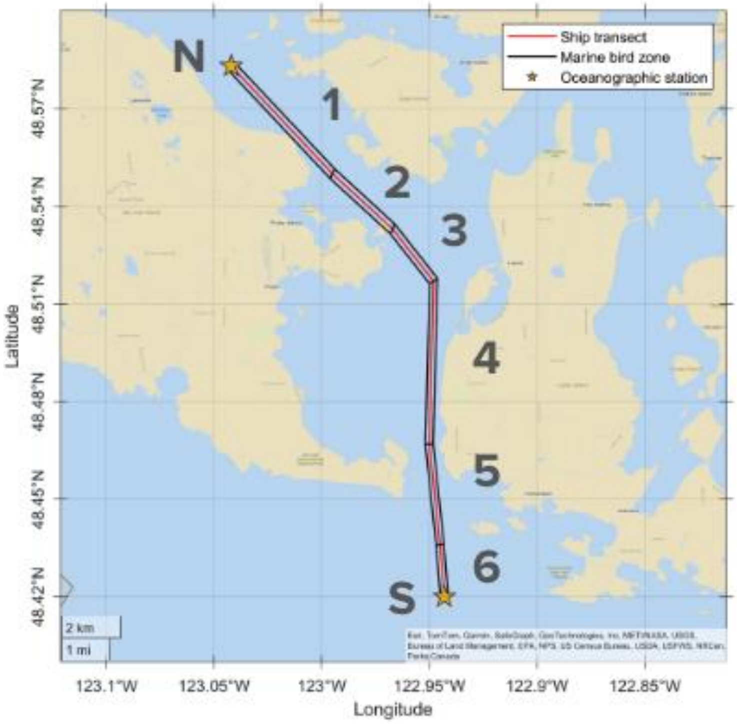

Figure 1. Map of the San Juan Channel, with six different zones. North and South Stations are marked with stars. Image courtesy of PEF apprentice Tim Iringan (2024).

Zone #	**Coordinates**
North Station	48°35’N, 123°02.54’W
1	48°35’N, 123°02.54’W
2	48°33’N, 122°59.67’W
3	48°32’N, 122°58’W
4	48°31’N, 122°56.89’W
5	48°28’N, 122°57’W
6	48°26’N, 122°56.72”W
South Station	48°25.20’N, 122°56.60’W

Table 1. The coordinates of North and South Station and the start of each zone.

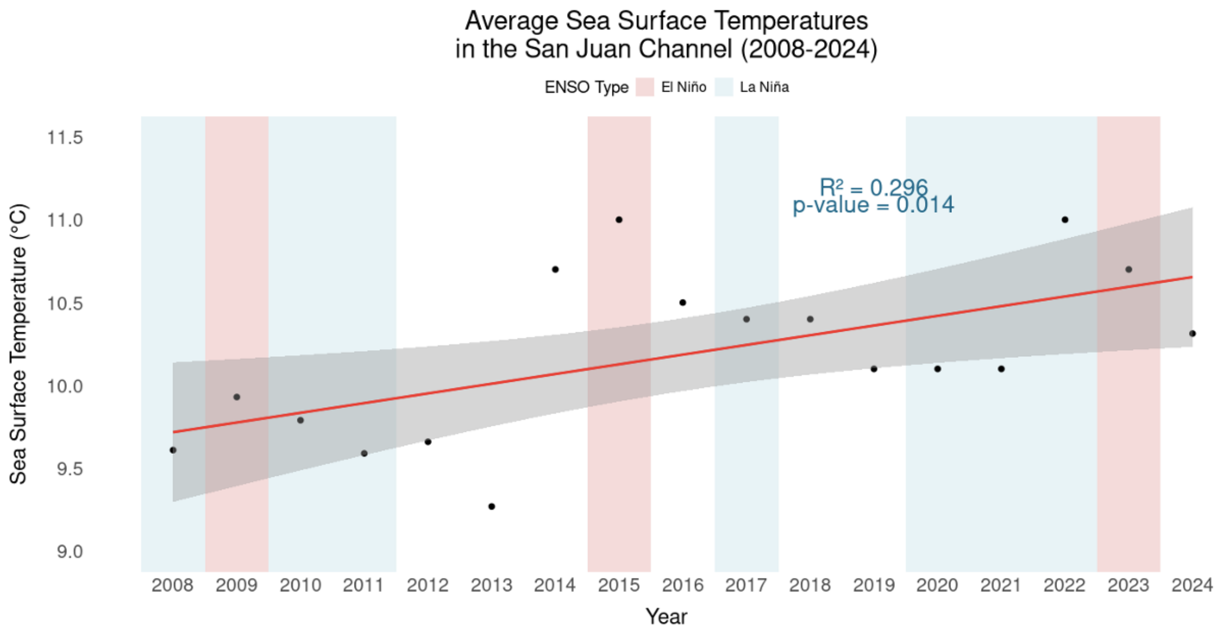

Figure 2. Average sea surface temperatures in the San Juan Channel from 2008 to 2024.

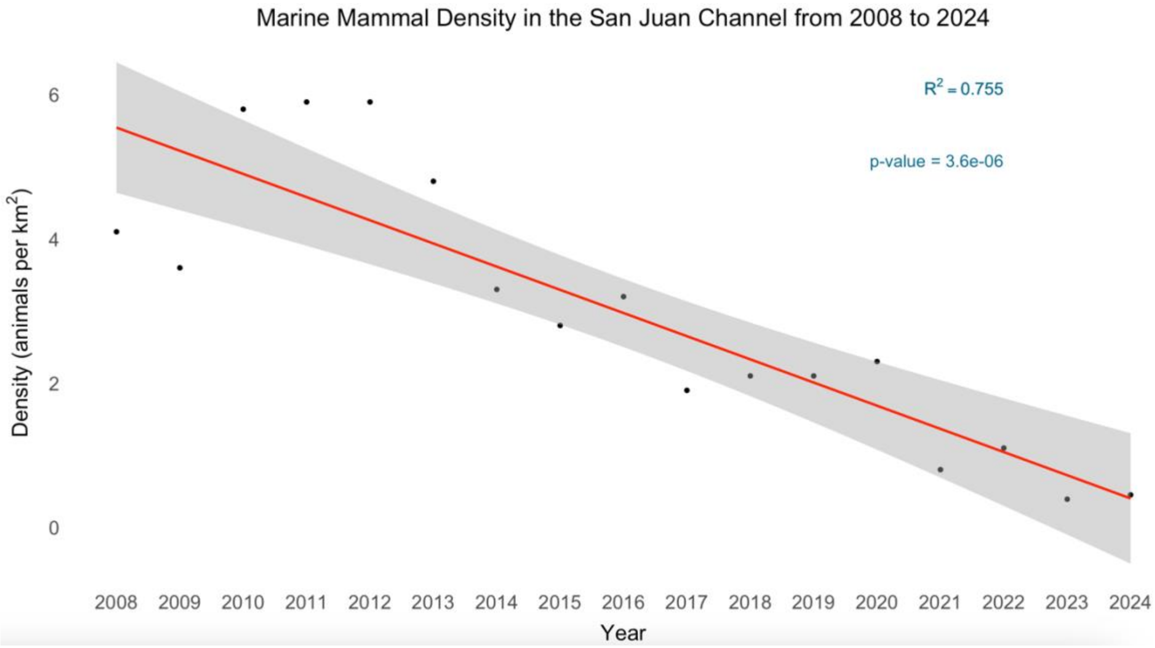

Figure 3. Marine mammal density in the San Juan Channel from 2008 to 2024.

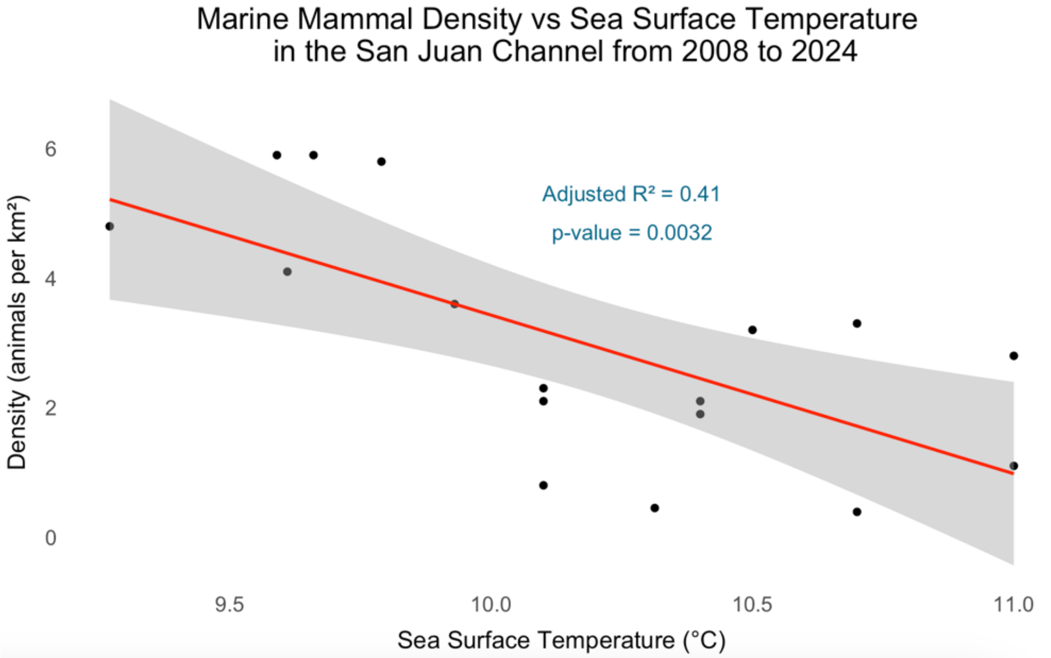

Figure 4. Marine mammal density from 2008 to 2024 has a moderate relationship to sea surface temperature with a significant trend.

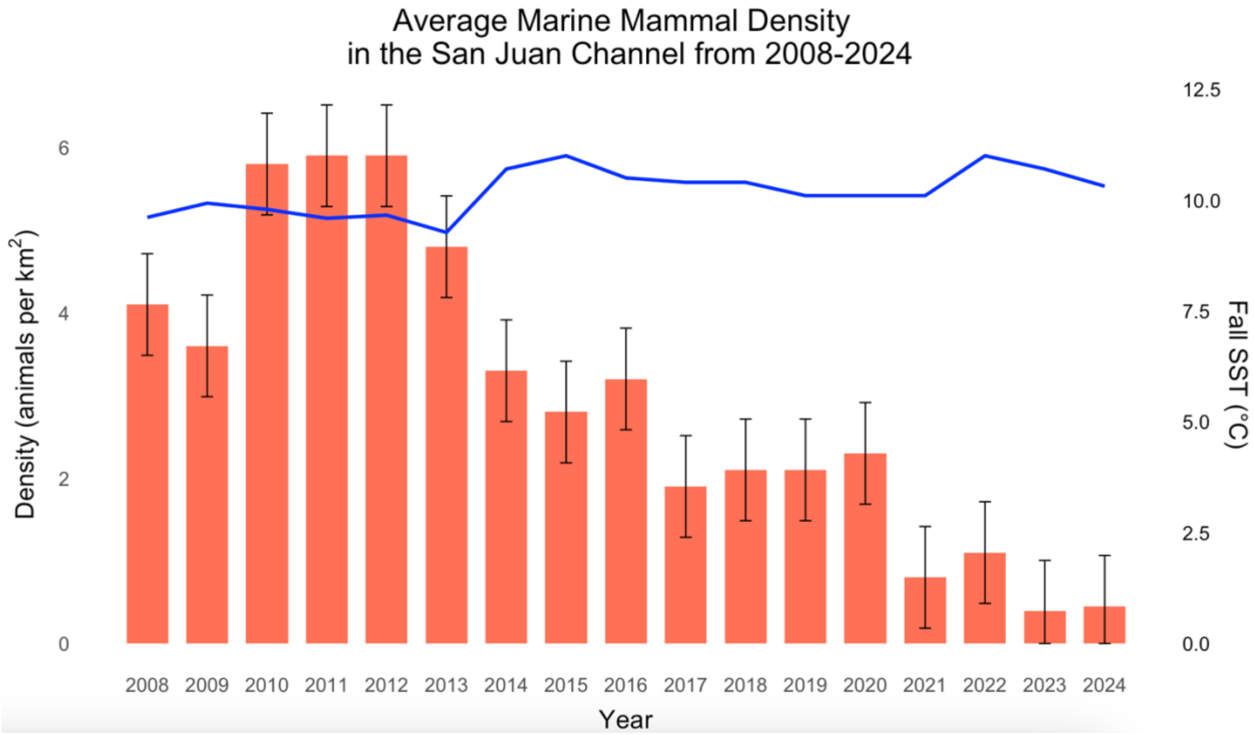

Figure 5. Marine mammal density in the San Juan Channel from 2008 to 2024.

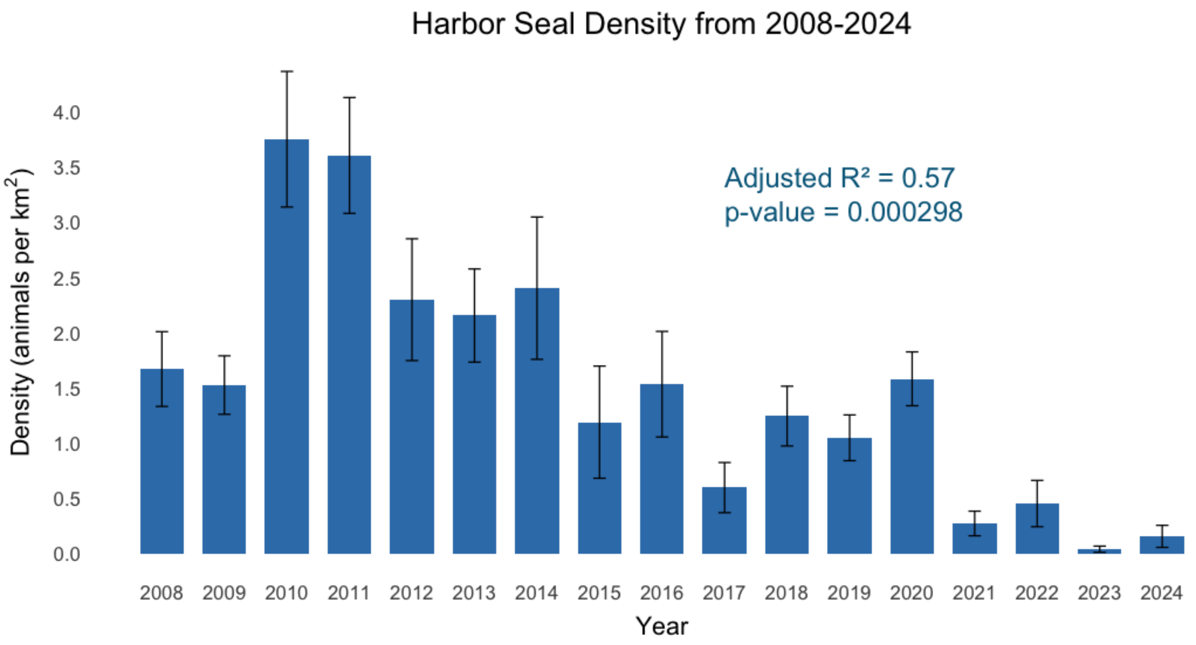

Figure 6. Harbor seal density in the San Juan Channel from 2008 to 2004.

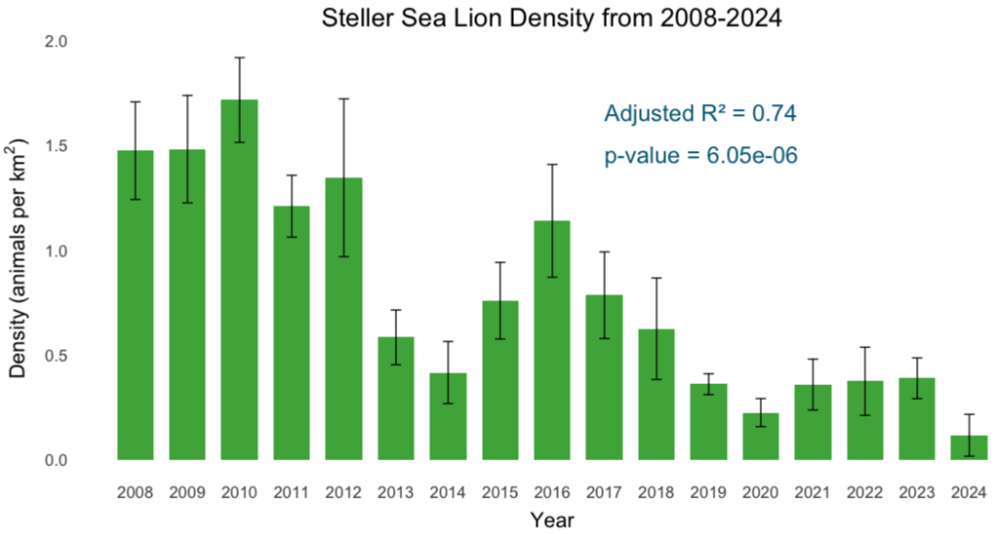

Figure 7. Steller sea lion density in the San Juan Channel from 2008 to 2024.

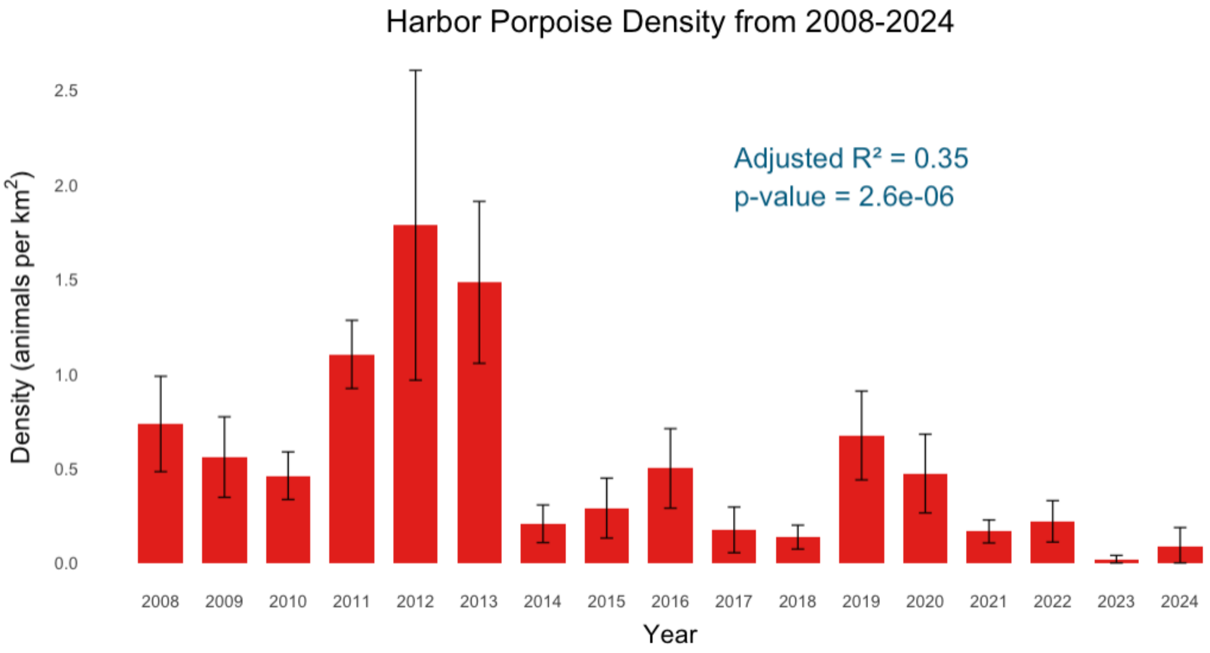

Figure 8. Harbor porpoise density in the San Juan Channel from 2008 to 2024.

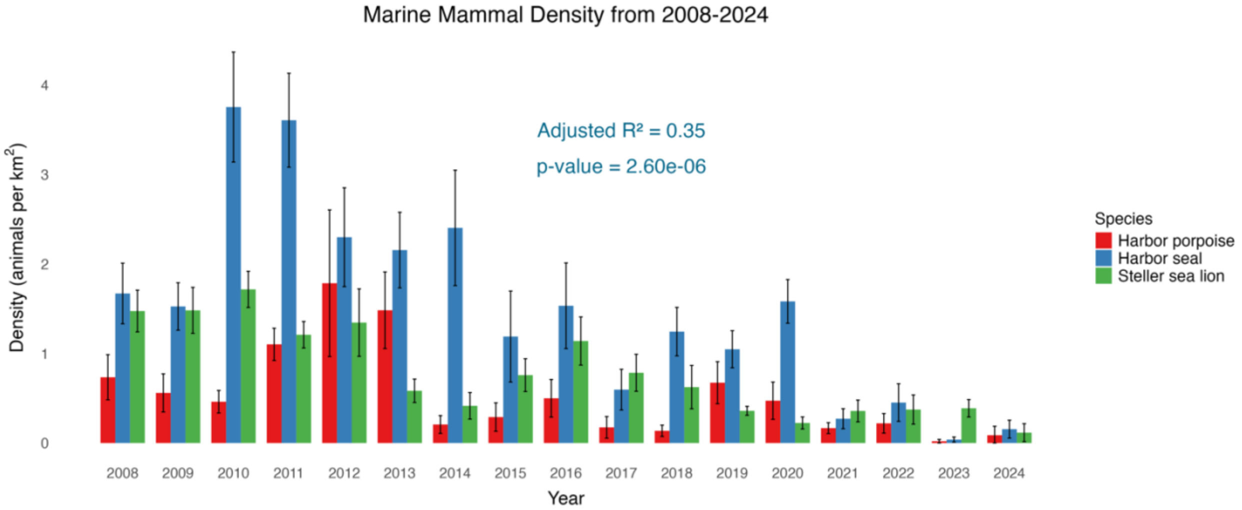

Figure 9. Density of harbor porpoises, harbor seals, and Steller sea lions in the San Juan Channel from 2008 to 2024.

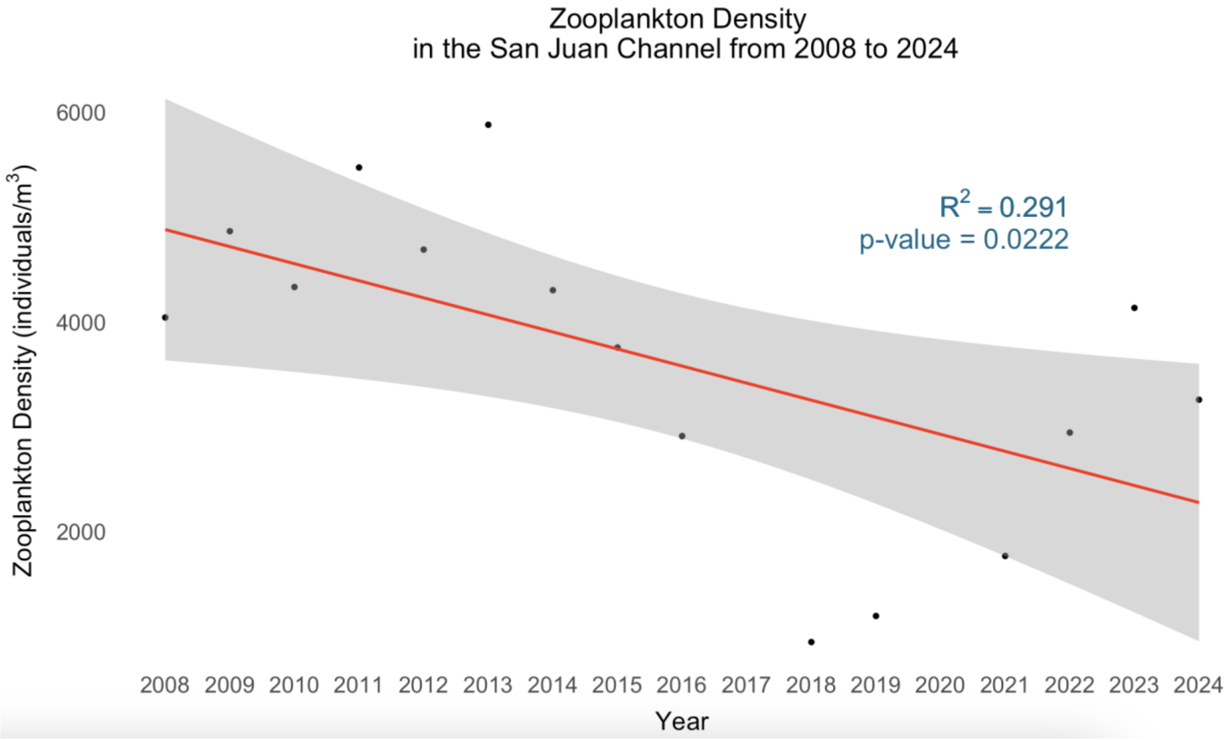

Figure 10. Zooplankton densities from 2008 to 2024 (excluding 2017 and 2020) reveals a moderate relationship between density and time and a significant decline in density over time.

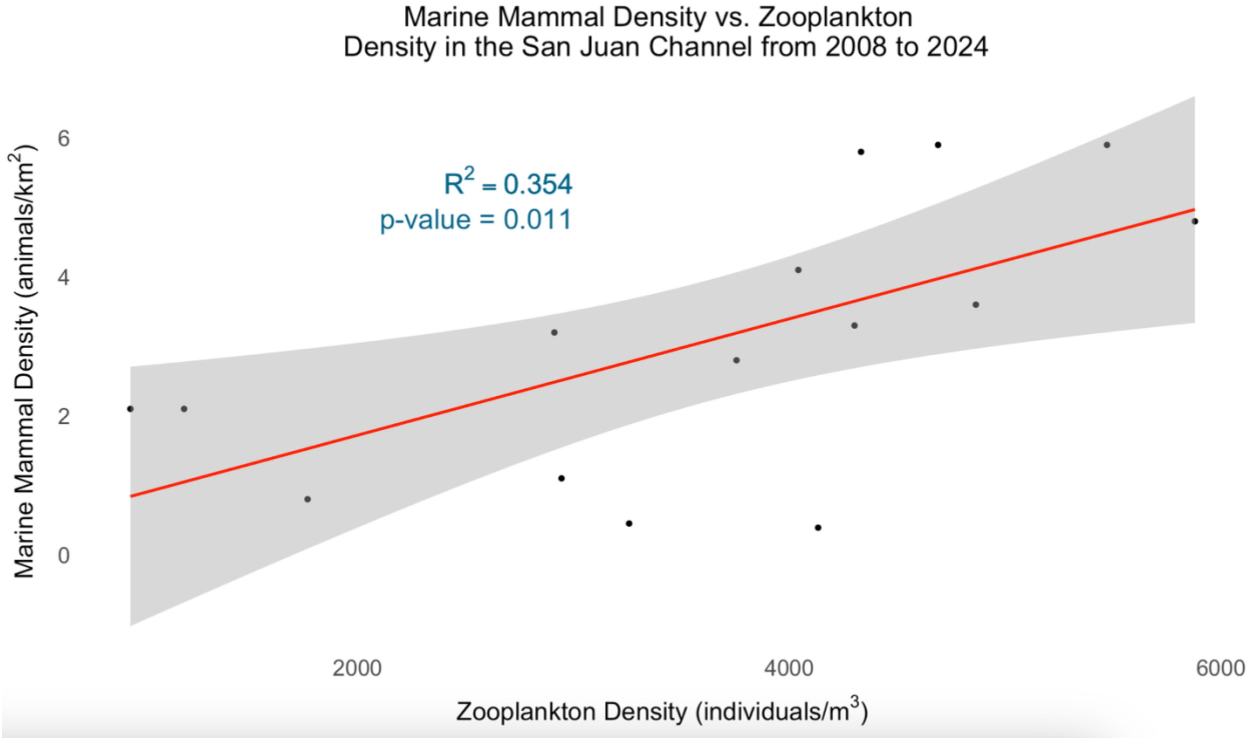

Figure 11. Marine mammal density vs. zooplankton density in the San Juan Channel from 2008 to 2024. Zooplankton densities were not collected in 2017 and 2020.

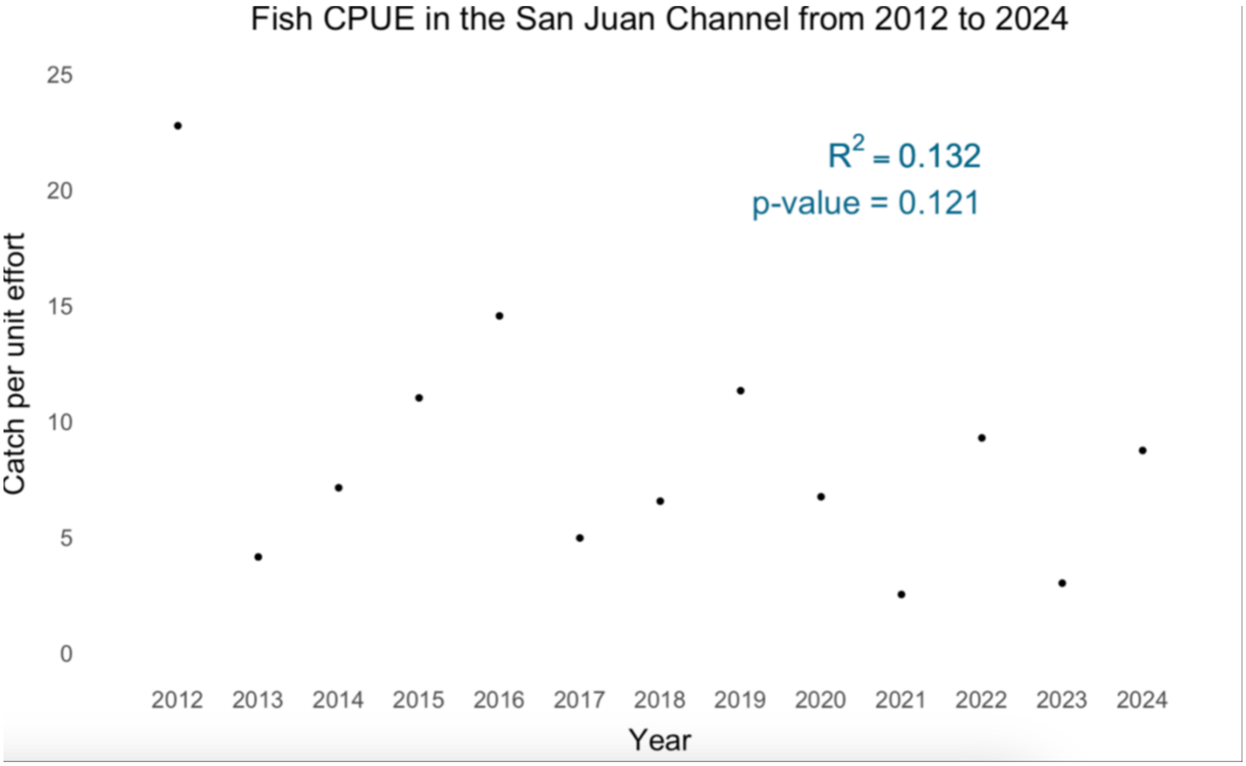

Figure 12. Annual Pacific sand lance catch per unit effort from 2012 to 2024.

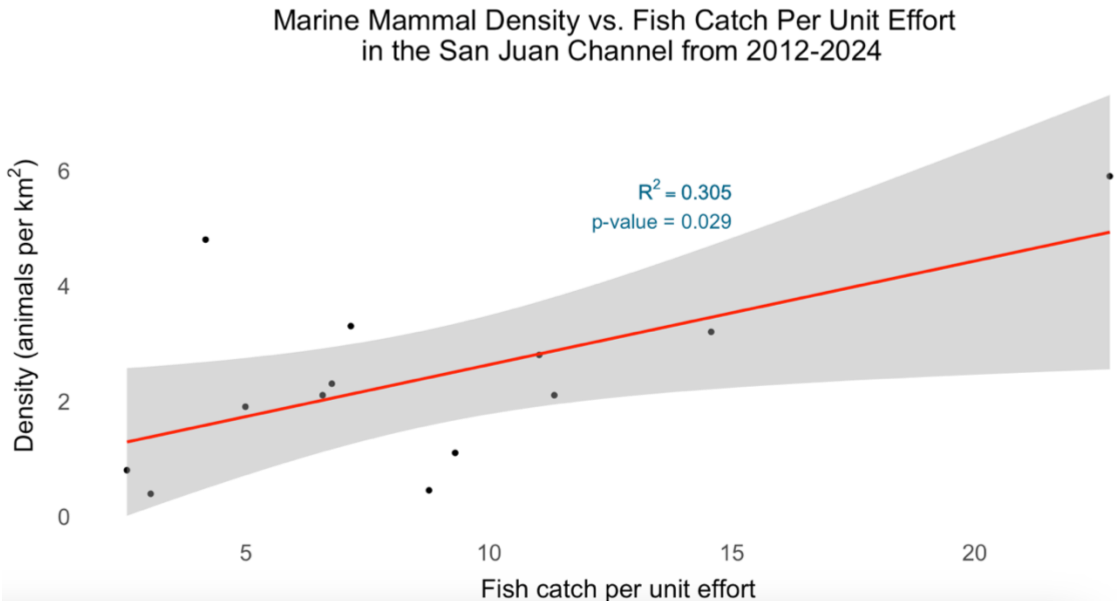

Figure 13. Marine mammal density plotted against Pacific sand lance catch per unit effort from 2012 to 2024.

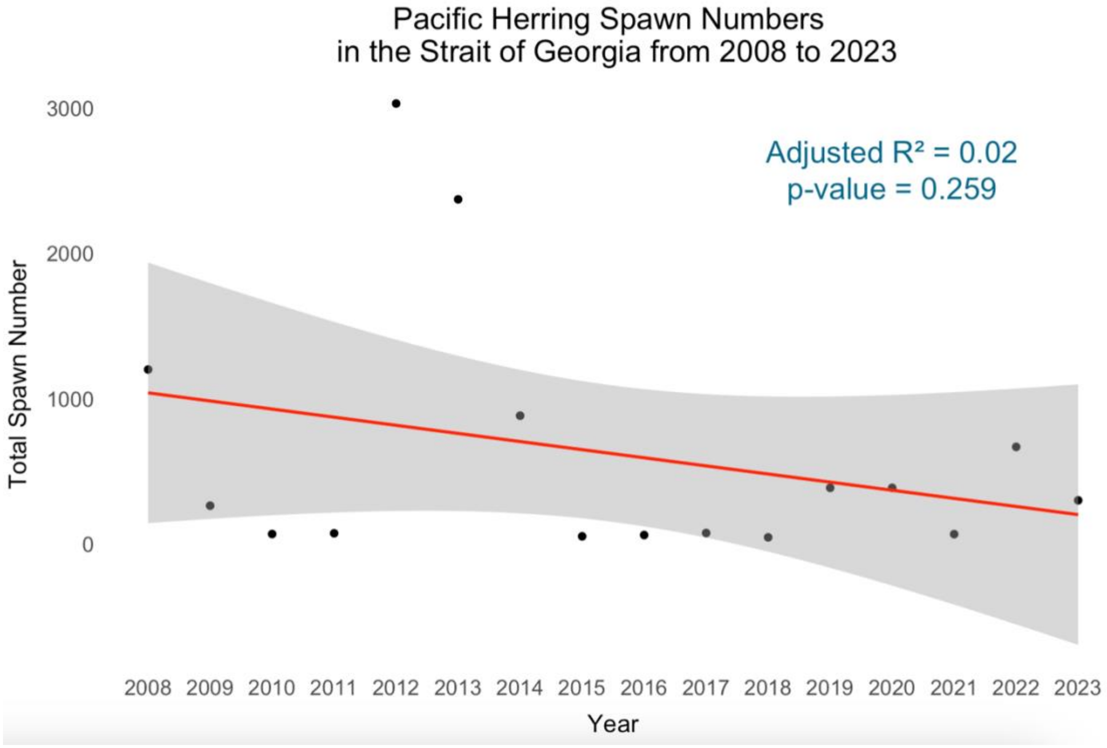

Figure 14. Annual total spawn numbers of Pacific herring in the Strait of Georgia from 2008 to 2023.

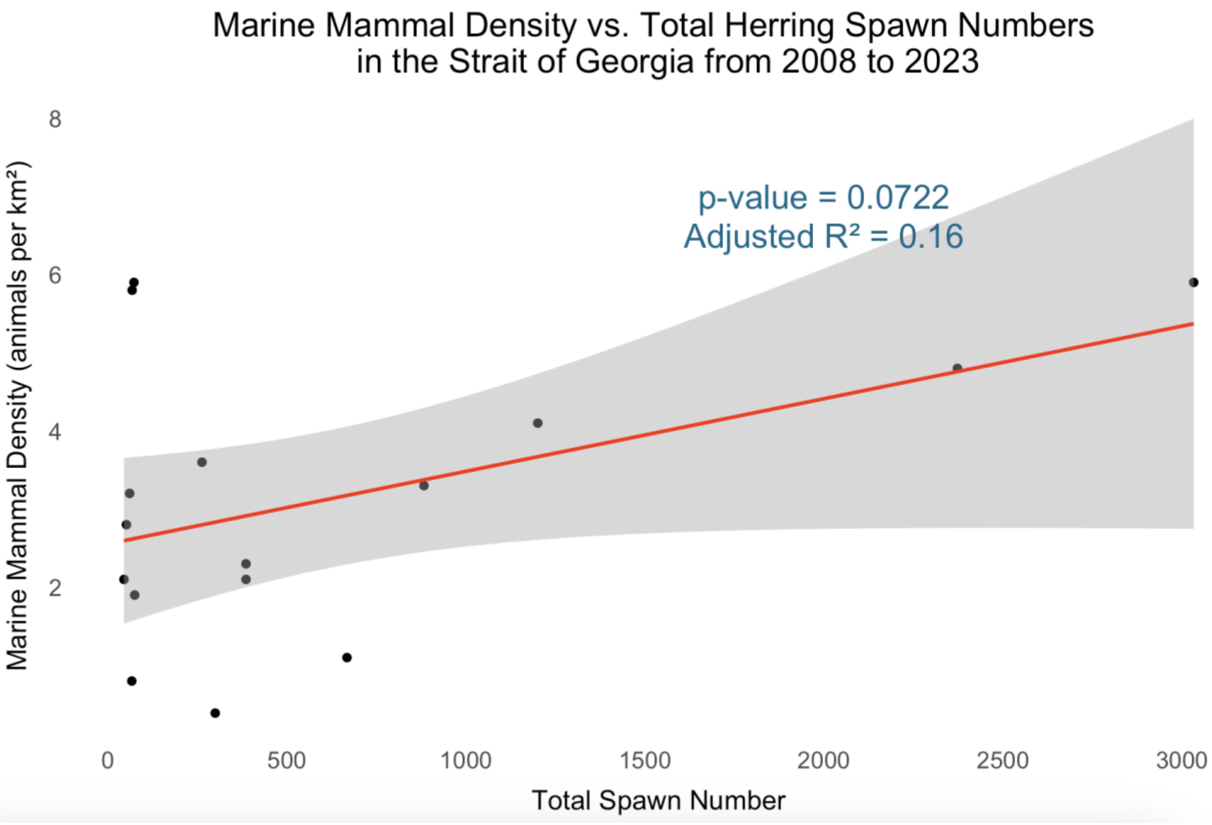

Figure 15. Marine mammal density plotted against annual total spawn numbers of Pacific herring in the Strait of Georgia from 2008 to 2023.

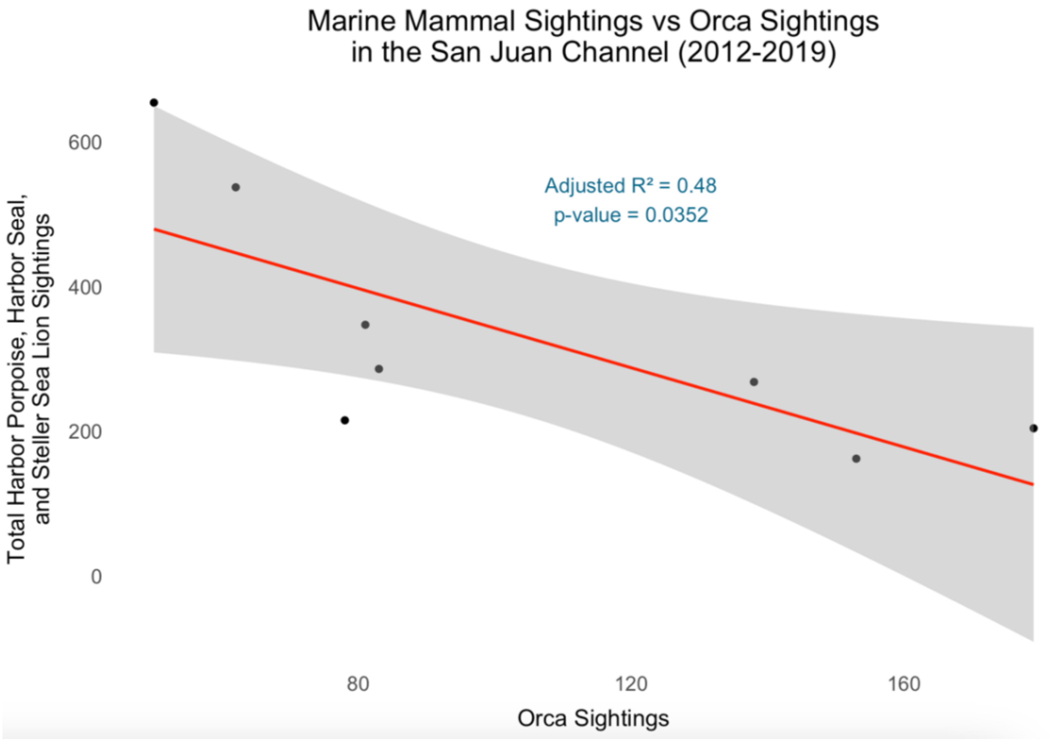

Figure 16. Total harbor porpoise, harbor seal, and Steller sea lion sightings in relation to transient orca sightings in the San Juan Channel from 2012 to 2019.

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