

Floating Kelp Rafts as Indicators of Aggregation Zones within the San Juan Archipelago

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Key Points:

- Kelp raft density increased throughout fall 2023 in the San Juan Archipelago.
- 13.1% of the observed kelp rafts were occupied by gulls.
- Current strength, tidal range, and wind speed all significantly impacted the density and distribution of kelp rafts.

Abstract

Bull kelp forests line Salish Sea coastlines, providing important ecosystem services to shallow subtidal habitats. Each winter, bull kelp forests are dislodged by winter storms, setting “kelp rafts” adrift on currents. Changing climate conditions threaten to strengthen winter storms in the Pacific Northwest, which could both increase annual kelp forest dislodgement rates and the abundance of kelp rafts. The passive drifting behavior of kelp rafts is like that of plankton. Within the San Juan Archipelago, kelp rafts are often observed in high densities at tidal fronts, making them indicators of planktonic aggregation zones. Documenting kelp raft distribution patterns may provide insight into important aggregation areas for plankton and forage fish, as well as the distribution of important resting substrate for seabirds. This study investigated kelp raft distribution and density throughout the San Juan Archipelago and attempted to isolate driving factors behind kelp raft density and distribution. Kelp raft density was found to be highly correlated with both tidal amplitude and current strength but was not significantly correlated with proximity to the nearest kelp forest. Overall, 13.1% of all observed kelp rafts were occupied by gulls.

Introduction

Bull kelp forests provide important ecosystem services to subtidal habitats. Home to a vast array of commercially important fishes, invertebrates, understory algal assemblages, and marine birds and mammals, bull kelp forests offer protection from pelagic predators and play an important role in carbon and nutrient cycling (Berry et al. 2021, Krause-Jensen & Duarte 2016, Teagle et al. 2017, Duarte et al. 2005).

The Salish Sea is a fjord-like estuary of the Fraser River, spanning international waters between the Pacific Northwest United States and Canada (Spalding et al. 2007). The Salish Sea receives freshwater input from the Fraser, Nooksack, and Skagit Rivers, as well as seawater influences from deep Pacific Ocean water flowing east through the Strait of Juan de Fuca. Within the Salish Sea lies the San Juan Archipelago, a cluster of glacially carved islands with rich agricultural soils and rocky coastlines (Figure 1).

Bull kelp forests line San Juan Archipelago coastlines. An annual brown macroalgae, bull kelp grows from March until October in the Northern Hemisphere (Rigg 1912). Each winter, while a select few bull kelp sporophytes overwinter in protected coves, most bull kelp are dislodged by strong currents and winds associated with winter storms (Chenelot et al. 2001).

The spatial extent of Salish Sea bull kelp forests has recently declined (Berry et al. 2021), with marine heatwaves and overgrazing by sea urchins causing mass bull kelp mortality (Tolimieri et al. 2023, Hamilton et al. 2022). In the face of climate change, Salish Sea winter storms have been projected to worsen (Salathe et al. 2010), which could increase dislodgement of kelp forests throughout autumn and winter. Dislodged bull kelp often collect in tangled mats, referred to here as “kelp rafts” (Springer et al. 2010).

Kelp rafts provide rare physical structure to pelagic ecosystems. From each individual kelp sporophyte, blades extend several meters below the surface, creating a three-dimensional structure. The physical structure of kelp rafts has been shown to host a diversity of marine life, including herring, shrimp, nudibranchs, and decorator crabs (Duggins et al. 2015, Brackett

2012). Further, seabirds have been observed feeding on the subsurface kelp raft community (Vandendriessche et al. 2007).

Kelp rafts are passive drifters, often travelling hundreds of kilometers across marine biogeographies before washing ashore (Gibson et al. 2006, Layton et al. 2022). Therefore, kelp rafts can act as vectors for non-native species and marine pathogens, leading to the introduction of invasive species into fragile ecosystems (Avila et al. 2020, Mabey et al. 2021, Helmuth et al. 1994). Despite the threats posed to marine ecosystems, the annual advection of kelp rafts has been shown to be important for gene flow between marine biogeographies and crucial to the long-distance dispersal of marine algae and invertebrates (Waters et al. 2018).

Within the San Juan Archipelago, kelp rafts may act as indicators of plankton aggregation zones. Often observed in the highest densities at tidal fronts, the drifting behavior of kelp rafts is like that of plankton. Unlike plankton, however, kelp rafts are conspicuous. Documenting kelp raft distribution patterns may provide insight into important, if ephemeral, aggregation areas for plankton and forage fish.

This study investigated kelp raft distribution and density throughout the San Juan Archipelago. Specifically, this study aimed to answer the following questions: *How are kelp rafts distributed throughout the San Juan Archipelago? Does this distribution relate to currents, tidal amplitude, storm events, or proximity to nearby kelp forests? How does the density of kelp rafts change throughout autumn? What does this tell us about pelagic ecosystem function of the San Juan Archipelago?*

Methods

To analyze kelp raft distribution and density, this study used a combination of transect surveys aboard the interisland ferry and aboard the *R/V Kittiwake* and *R/V Rachel Carson*. Correlation analyses were used to isolate combinations of oceanographic and meteorological factors that are thought to be responsible for kelp raft distribution. Further, this study offers a predictive generalized additive model of kelp raft distribution.

Transects were surveyed using a pair of Nikon 8x42 binoculars from either the port or starboard side of the boat. Observations of seabirds, marine mammals, and floating kelp rafts (within 200 meters of the vessel) were recorded every minute for the duration of the transect (Figure 2). Seabirds and marine mammals were identified to the species level. Individuals unidentifiable to the family level were marked as “unidentified” by the recorder.

Transects were broken down into zones intended to divide the transect into equal areas with similar biogeographic and oceanographic characteristics. Aboard the *R/V Kittiwake*, six zones (1-6) divided the San Juan Channel and Strait of Juan de Fuca (Table 1). Aboard the interisland ferry, five zones (A-E) divided the northern San Juan Channel, Harney Channel, and Upright Channel.

This study considered four environmental covariates (current strength, tidal range, wind speed, and proximity to nearest kelp forest), all of which were potential drivers of kelp raft density and distribution. Current strength was approximated from the NVS-NANOOS Ways Water Moves Current Model and was collected on an hourly timescale for each zone. Tidal range isolated the effect of spring and neap tides on kelp raft density and was obtained through the National Oceanic and Atmospheric Administration’s publicly available tidal database. One-

Day Lag Maximum Wind Speed was calculated from data collected by the Friday Harbor Weather Station and served as a proxy for the impact of storms on kelp raft density. Proximity to nearest kelp forest attempted to evaluate whether kelp rafts were observed densely near kelp forests. Kelp forest spatial extent data was collected by the Washington Department of Natural Resources and was clipped to the study region (Figure 4).

A correlation analysis in R was used to test for significance and describe the degree of correlation between the observed kelp raft density and each factor thought to be driving kelp raft density distribution (environmental covariates).

A generalized additive model (GAM) incorporated existing observations of kelp raft density and of each environmental covariate listed above. By characterizing the relationship between kelp raft density and each environmental covariate, the GAM offered a prediction of kelp raft density throughout the San Juan Archipelago. To increase the predictive resolution of the GAM, kelp raft density observations were broken down to the micro-zone level (Figure 3).

Results

Seasonal Changes in Kelp Raft and Gull Density

Kelp raft density increased over the course of fall 2023. East San Juan Island (East SJI), Friday Harbor, Point Caution, Turn Island, and West Sound all showed an increase in kelp raft density during fall 2023 (Figure 5A). Kelp raft density remained relatively constant in all other zones, except for Lopez Island and Park's Bay. Lopez Island and Park's Bay oscillated between high and low kelp raft densities during fall 2023. The density of gulls associated with kelp rafts remained relatively constant for all zones throughout fall 2023, except for Point Caution (Figure 5B). Point Caution showed an increase in gulls associated with kelp rafts in late fall.

Friday Harbor and Point Caution had the highest density of kelp rafts overall, followed closely by Turn Island (Figure 6A). West Sound, Turn Island, and Squaw Bay had the highest density of gulls using kelp rafts, while Friday Harbor had comparatively fewer gulls associated with kelp rafts (Figure 6B). Overall, 13.1% of all observed kelp rafts were occupied by gulls.

Seasonal Trends in Environmental Covariates Influencing Kelp Raft Density Distribution

While the distance from each kelp raft to the nearest kelp forest remained constant for each zone, atmospheric and oceanographic parameters influencing kelp raft distribution oscillated throughout fall 2023 (Figure 7). Current strength increased in Crane's Bay, Point Caution, Turn Island, and in East SJI over the course of the fall (Figure 7A). Current speed decreased in Lopez Island, Griffin Bay, and Cattle Pass over the course of fall. Tidal range fluctuated in tandem with the spring-neap tidal cycle (Figure 7B), with the highest tidal range occurring during spring tides (October 20th, 31st, and November 16th). Lagged maximum windspeed peaked during the storm on October 26th, then decreased throughout the remainder of the season (Figure 7C).

Current strength, tidal range, and wind speed all influenced the observed distribution and density of kelp rafts in fall 2023. A generalized additive model was applied to each environmental covariate to describe the effect on kelp raft density. Kelp raft density was

positively correlated with both current strength and tidal range (Figure 8 A & B). Kelp raft densities were predicted to be highest at intermediate wind speeds and at intermediate distances from nearby kelp forests (Figure 8 C & D).

Statistical Significance

A correlation analysis revealed the highly significant relationship between the density of kelp rafts and tidal range ($r=0.19$, $p<0.001$) (Table 2). Kelp raft density and current strength, as well as wind speed, were also found to be significantly correlated, though at a lower statistical significance threshold ($r=0.20$, $p<0.01$ & $r=-0.16$, $p<0.01$). Kelp raft density was not significantly correlated, however, with the estimated distance to nearby kelp forests.

A GAM characterized the effect of each environmental covariate on kelp raft density and deserves further application and validation. Several combinations of environmental covariates were evaluated as potential GAMs. The GAM that was chosen for its lowest Akaike Information Criterion (AIC) score, however, incorporated all environmental covariates (Figure 9).

Discussion

Overall, kelp raft density, as well as the density of gulls associated with kelp rafts, increased throughout fall 2023 in the San Juan Archipelago. Kelp raft density likely increased during fall in response to the increased frequency of kelp forest dislodgement by storms (Chenelot et al. 2001). The October arrival of Bonaparte's gulls, as well as the increased density of kelp rafts throughout fall, are potential explanations for the autumnal increase in the density of gulls associated with kelp rafts.

Kelp raft distribution was influenced by a combination of oceanographic and meteorological variables. Current strength was found to be the main driver of kelp raft density and distribution. Quantitatively, current strength and tidal range were highly correlated, which was expected given the effect of higher tidal ranges on the quantity of water moving through San Juan Archipelago ecosystems (Marmer 1924). Kelp raft densities were highest at intermediate wind speeds but declined at high wind speeds. This may be due to the kelp rafts washing ashore during major wind events (Waters & Craw 2018).

Together, these observations and analyses suggest that kelp rafts may have occurred in higher densities during spring tides or following a windy day. Understanding the potential driving factors behind the distribution of kelp rafts may aid in modeling their distribution elsewhere throughout Salish Sea pelagic ecosystems.

Kelp rafts are conspicuous, planktonic organisms. Qualitative observations revealed kelp rafts frequently occurring along tidal fronts, current boundaries, or collecting in current eddies (R/V Kittiwake & Interisland Ferry Observations, PEF 2023). The latter observations are of relevance to our ability to identify planktonic aggregation zones. High kelp raft density zones, which tend to occur along regions of current mixing, could indicate aggregation zones of lower trophic groups. These aggregation zones may attract higher trophic predators, such as salmon, which are commercially important to regional fisheries.

Future studies should investigate high resolution, high frequency mapping of kelp raft and kelp forest distribution throughout the San Juan Archipelago. A more precise understanding

of the spatial distribution of kelp forests may result in a higher observed correlation between kelp raft density and proximity to the nearest kelp forest. Additionally, future research into the application and validation of predictive kelp raft density models is highly encouraged.

Figures and Tables

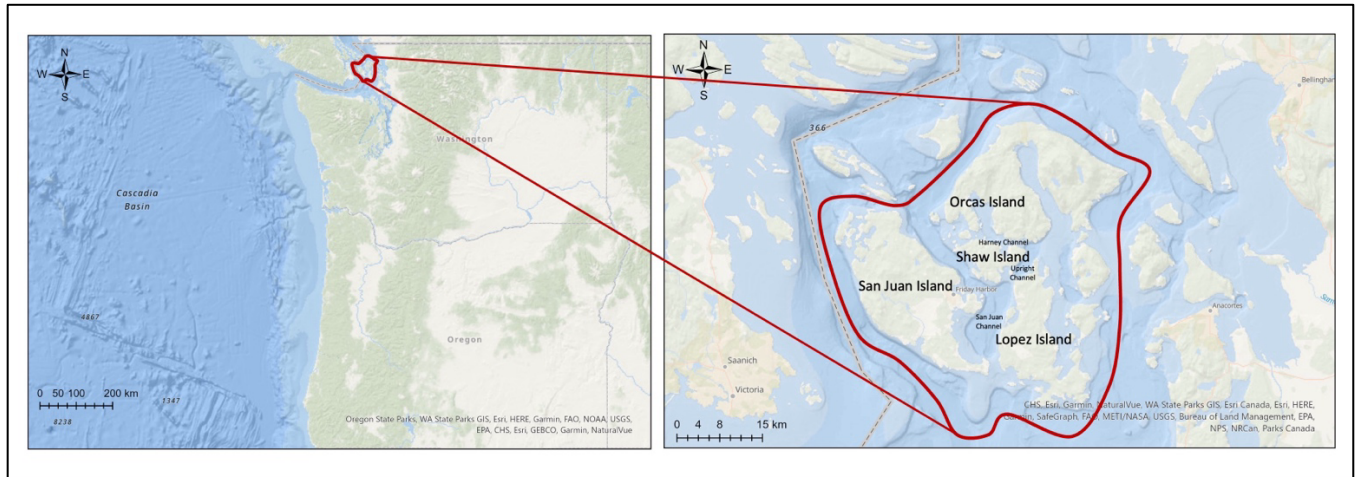


Figure 1. Contextualizing the San Juan Archipelago study region within the Pacific Northwest. The study region includes bathymetric features such as the San Juan, Harney, and Upright Channels, which were surveyed throughout the study.

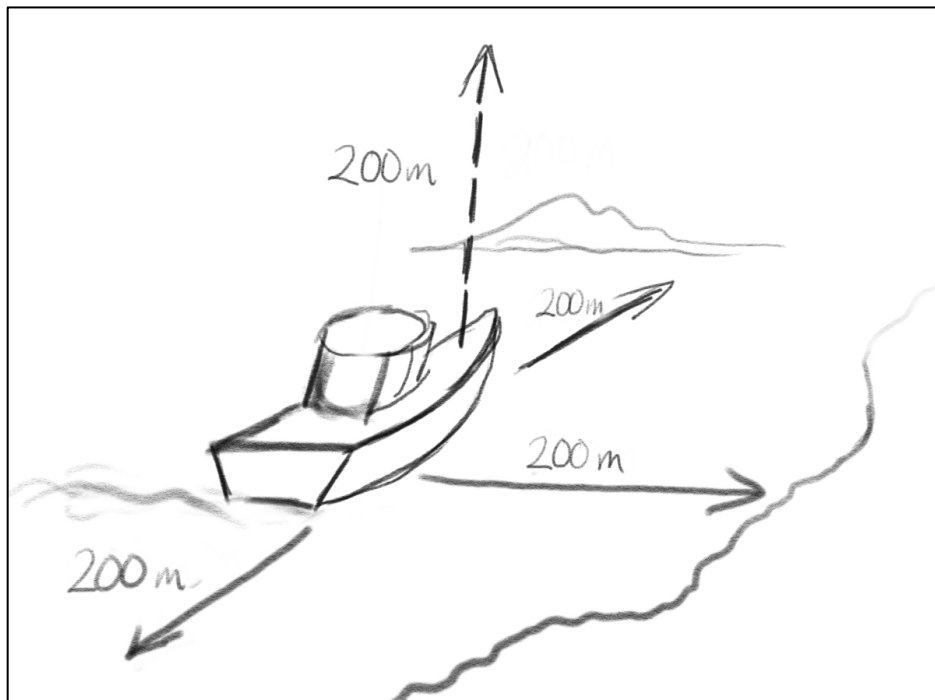


Figure 2. Transects were surveyed from either the port or starboard side of the boat. Observations within 200 meters of the vessel were recorded every minute for the duration of the transect.

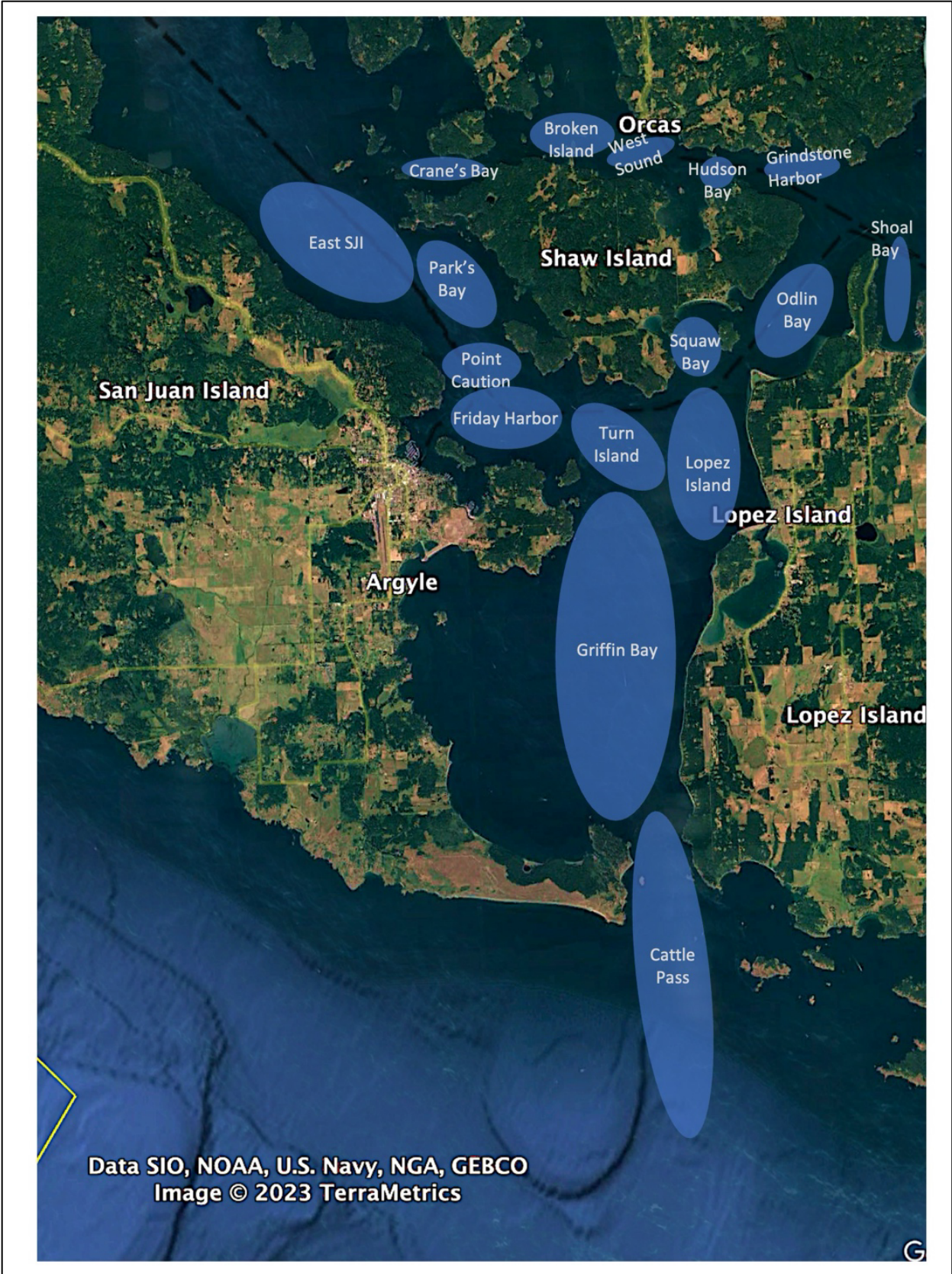


Figure 3. Study area broken down by zones. Zone identification aided by the NVS-NANOOS Ways Water Moves Current Model.

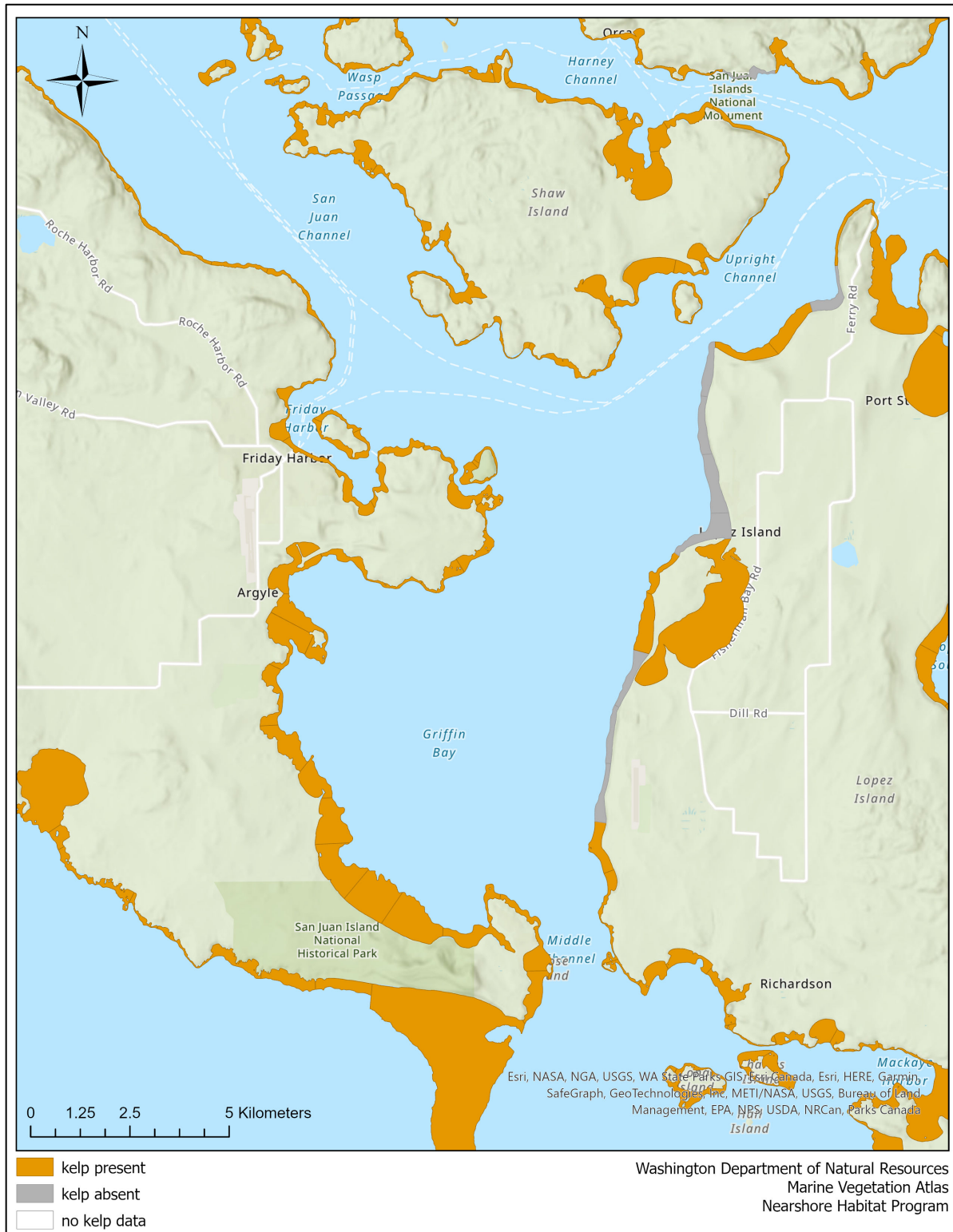


Figure 4. Kelp forest extent (orange) within the study region. Where kelp forests are absent, the coastline is shown in gray. Regions with no kelp data are shown in white. Kelp forest spatial extent surveys and data courtesy of the Washington Department of Natural Resources.

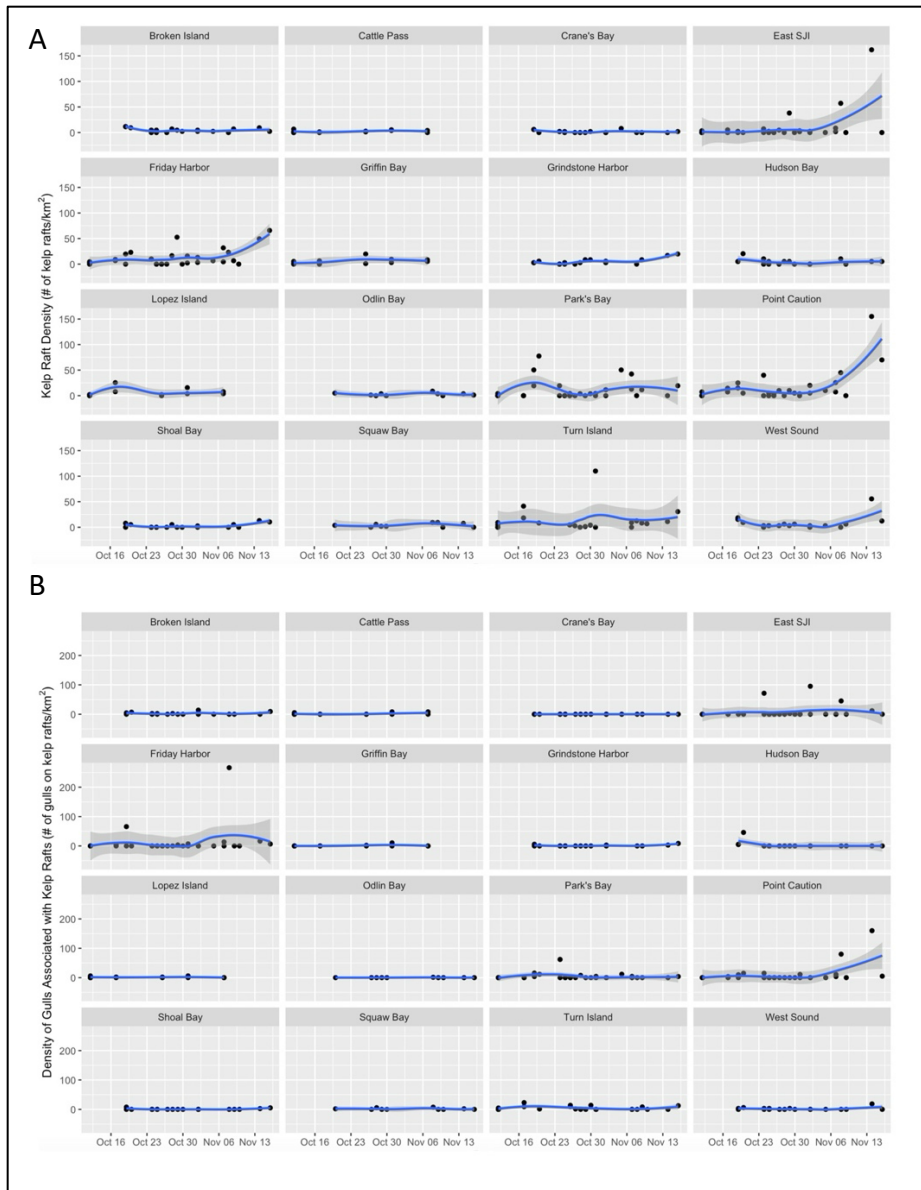


Figure 5. Density of A. kelp rafts (# of kelp rafts/km²) and B. gulls associated with kelp rafts (# of gulls associated with kelp rafts/km²) in the San Juan, Harney, and Upright Channels within the San Juan Archipelago during fall 2023. Zones identified in Figure 3. A locally weighted regression was applied to the data, using the Loess Statistical Smoothing Method (Cleveland 1979), to highlight seasonal trends.

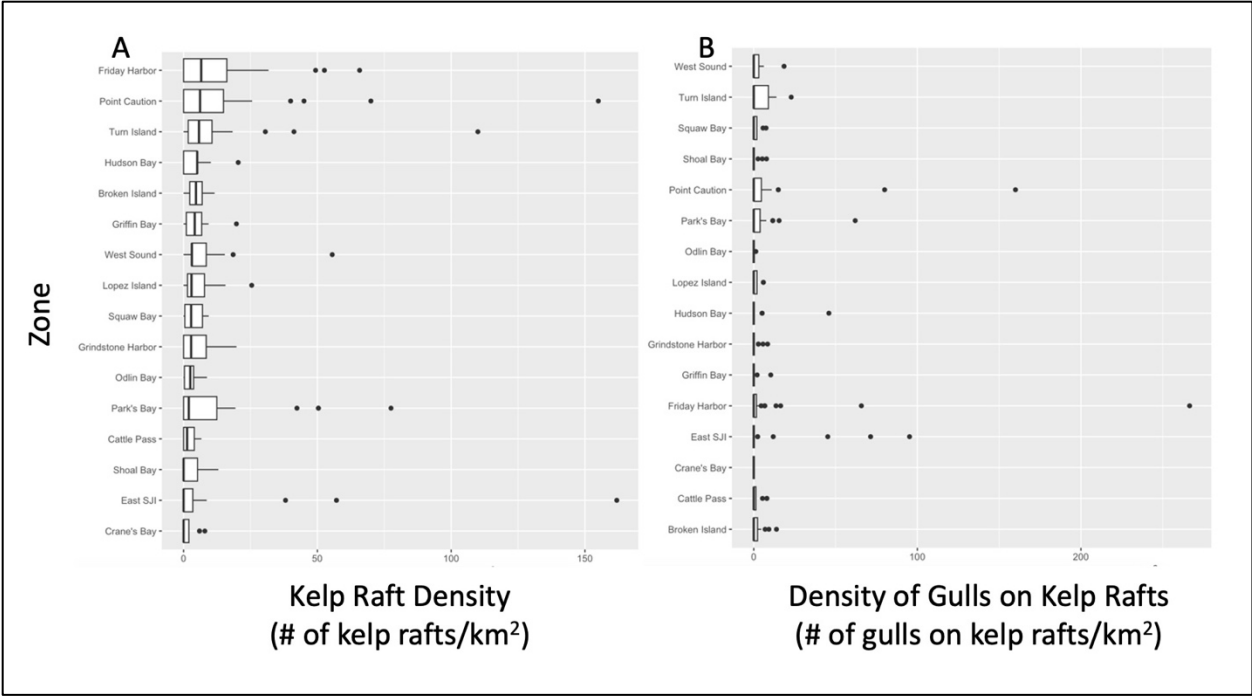


Figure 6. Density distribution of A. kelp rafts (# of kelp rafts/km²) and B. gulls associated with kelp rafts throughout the San Juan, Harney, and Upright Channels within the San Juan Archipelago in fall 2023. Zones ordered by kelp raft density (highest densities at top, lowest densities at bottom).

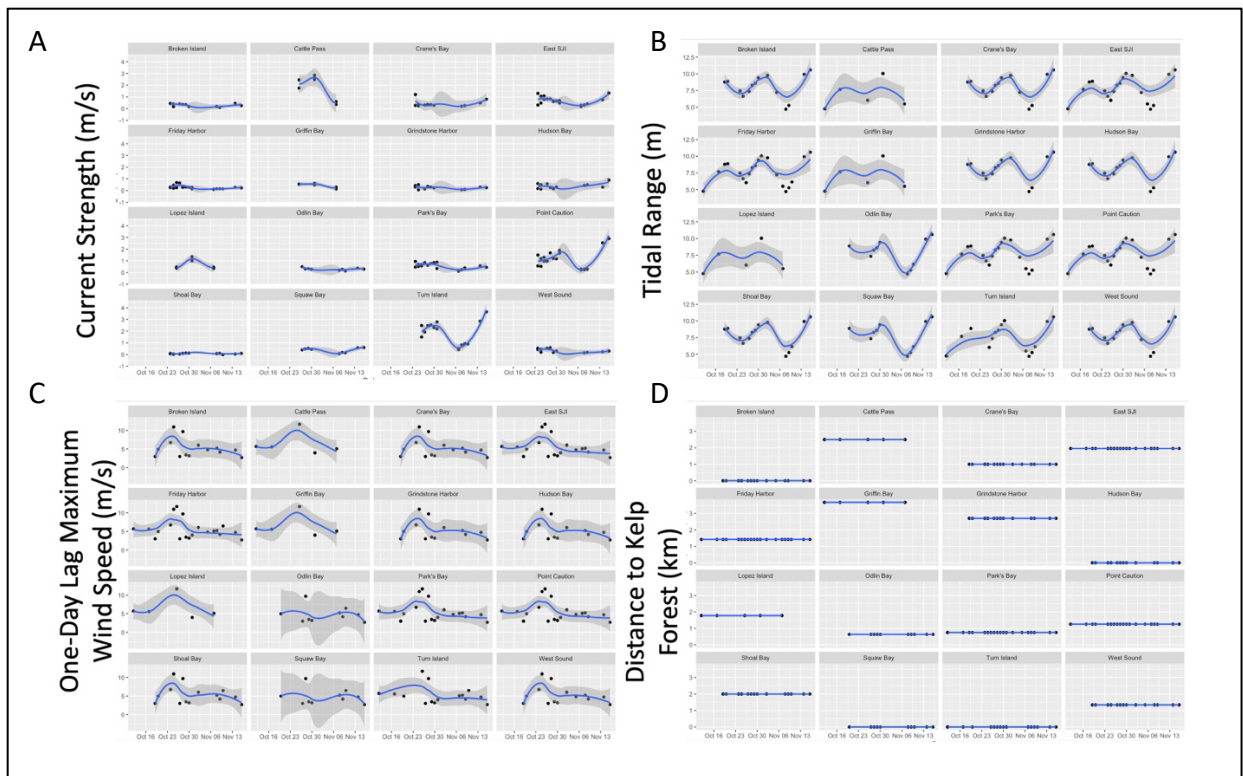


Figure 7. Seasonal trends in A. current strength (m/s), B. tidal range (m), C. one-day lag maximum wind speed (m/s), and D. distance to nearest kelp forest (km) throughout the San Juan, Harney, and Upright Channels within the San Juan Archipelago. A locally weighted regression was applied to the data, using the Loess Statistical Smoothing Method (Cleveland 1979), to highlight seasonal trends.

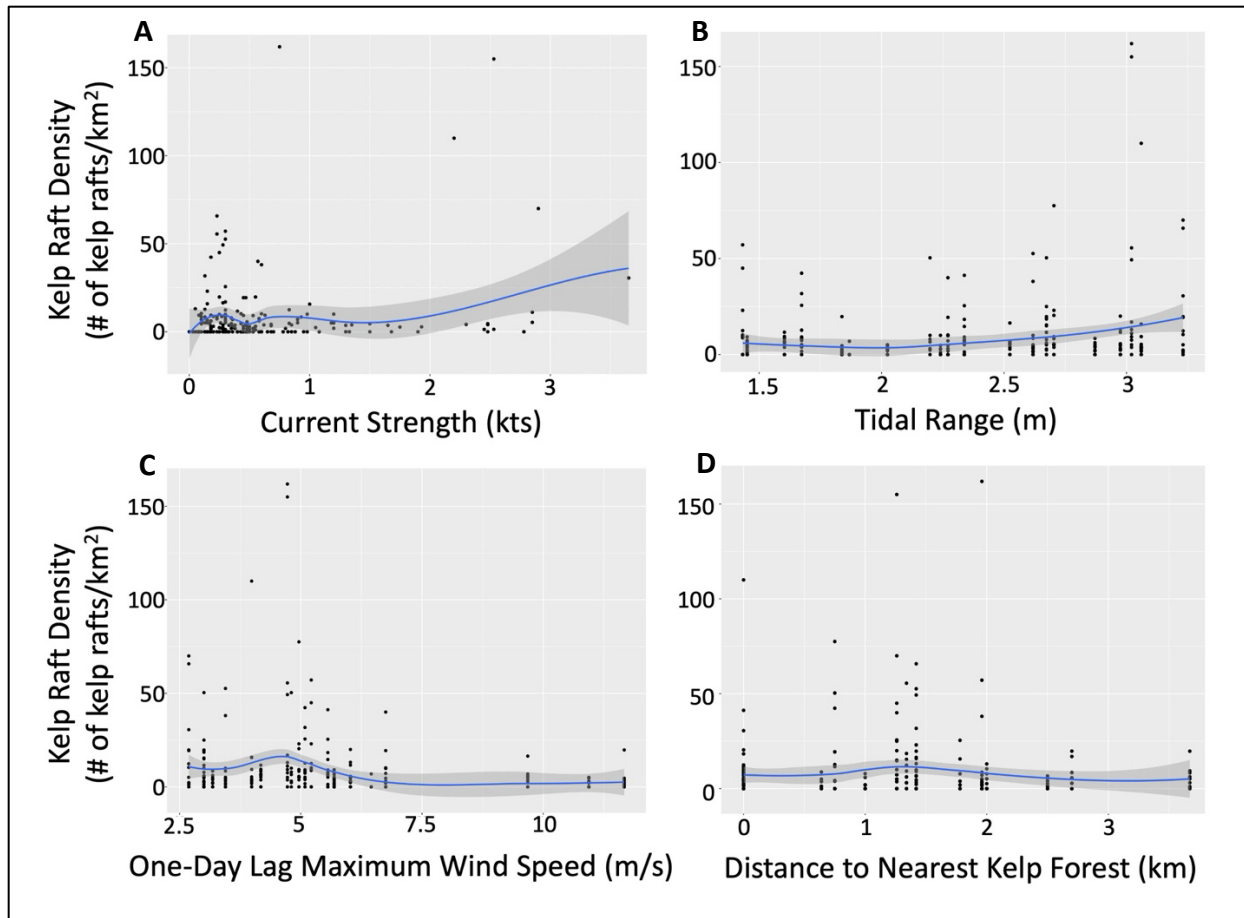


Figure 8. Kelp raft density (# of kelp rafts/km²) as it relates to A. current strength (m/s), B. tidal range (m), C. one-day lag maximum wind speed (m/s), and D. distance to nearest kelp forest (km) throughout the San Juan, Harney, and Upright Channels within the San Juan Archipelago. A locally weighted regression was applied to the data, using the Loess Statistical Smoothing Method (Cleveland 1979), to highlight seasonal trends.

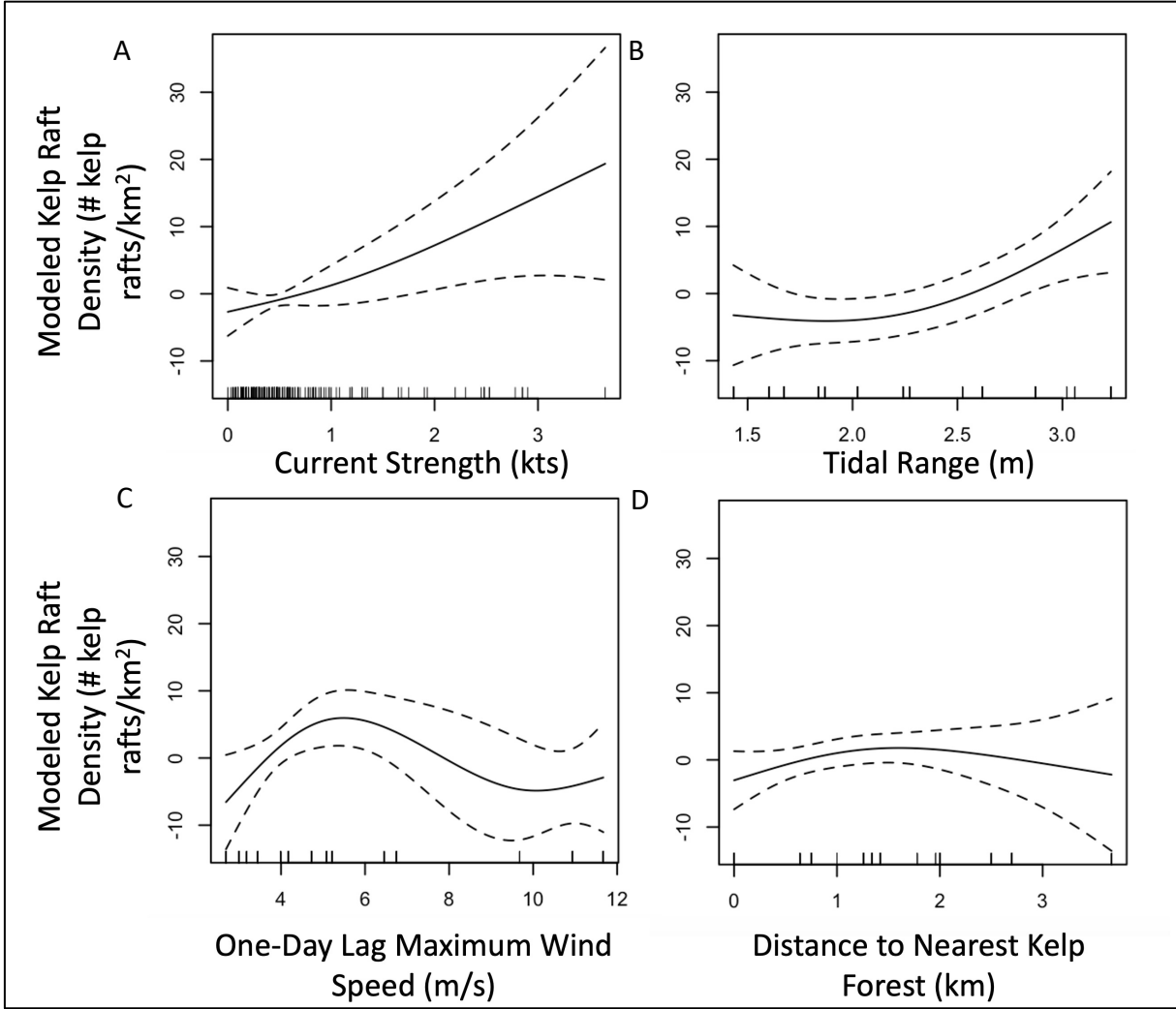


Figure 9. Modeled kelp raft density (# of kelp rafts/km²) as a function of A. current strength (m/s), B. tidal range (m), C. one-day lag maximum wind speed (m/s), and D. distance to the nearest kelp forest (km) for any location within the San Juan Archipelago. A generalized additive model was applied to the data (Hastie & Tibshirani 1986) to demonstrate the effect of each parameter on kelp raft density.

Table 1. Coordinates of zone changes for both R/V Kittiwake and Interisland Ferry Kelp Raft Density Surveys.

Zone Change	Coordinates
Beginning – Zone 1	48.583333° , - 123.004167°
Zone 1 to 2	48.55° , - 123.004167°
Zone 2 to 3	48.533333° , -122.966667°
Zone 3 to 4	48.516667° , -122.95°
Zone 4 to 5	48.466667° , -122.950556°
Zone 5 to 6	48.433333° , -122.954167°
Zone A to B	48.560389° , -123.004111°
Zone B to C	48.587222° , -123.016444°
Zone C to D	48.582083° , -122.900389°
Zone D to E	48.552889° , -122.923361°
Zone E to A	48.542667° , -123.009472°

Table 2. Degree of statistical correlation (r) between environmental covariates (tidal range, current strength, wind speed, and distance to nearest kelp forest) and kelp raft density, as well as density of gulls associated with kelp rafts.

Parameter	Correlation Coefficient (r)
Kelp Raft Density & Gulls on Kelp Rafts	0.37 ***
Kelp Raft Density & Tidal Range	0.19 ***
Kelp Raft Density & Current Strength	0.20 **
Kelp Raft Density & Wind Speed	-0.16 **
Kelp Raft Density & Distance to Nearest Kelp Forest	-0.036
Gulls on Kelp Rafts & Tidal Range	-0.00012
Gulls on Kelp Rafts & Current Strength	0.06
Gulls on Kelp Rafts & Wind Speed	-0.044
Gulls on Kelp Rafts & Distance to Nearest Kelp Forest	-0.0039
Tidal Range & Current Strength	0.30 ***
Tidal Range & Wind Speed	-0.34 ***
Current Strength & Wind Speed	-0.0013

*** $p < 0.001$

** $p < 0.01$

* $p < 0.05$

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