

Synthesis of Existing Data

A report from the 2024-2026 kelp resilience project

The Kelp Resilience Project – Synthesis Team

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December 12, 2025

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Preface

This report is a product of the 2024-2026 kelp resilience project. The focus of the overall project is understanding the factors leading to the pattern of floating kelp loss and resilience observed in the inner marine shoreline of Washington State. The project team spans many institutions and both ecological science and natural resource management perspectives.

This report is a collection of three chapters each produced by different teams. The purpose of the chapters is to synthesize existing data in three different areas of investigation. The three areas are the benthic habitat, environmental conditions, and kelp distribution and condition. For each area, specific datasets were selected for synthesis:

1. Benthic habitat
 - Reef Check dataset of benthic habitat dive surveys
2. Environmental conditions
 - Dept. of Ecology marine water monitoring dataset
 - Salish Sea Model 2014 solution current data
3. Kelp
 - Large number of datasets that span aerial and satellite remote sensing, observations from kayak, motorboat and helicopter, and historical maps.

This project is funded by the EPA through the HSIL program – a program jointly managed by the Washington State Departments of Fish and Wildlife, and Natural Resources. The project formally started in November 2023 and runs through June 2026.

1 Synthesizing Reef Check Washington's benthic data to inform kelp loss and resilience research

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Photo: Friday Harbor Laboratories

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This data synthesis was made possible by the Reef Check Foundation, specifically the Reef Check Washington chapter, whose volunteers spent countless hours collecting these data. This publication would not have been possible without their contribution.

We would also like to thank the following people who assisted with preparing this report:

- Kindall Murie and Ande Fieber (University of Washington) for providing advice on data cleaning and analysis
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1.1 Introduction

This report was designed to synthesize existing data on Washington State’s kelp forests. Specifically, it synthesized subtidal data, provided by the Reef Check Foundation. Reef Check is a citizen scientist organization which trains recreational scuba divers to collect monitoring data on shallow reef communities using their standardized protocols. Reef Check protocols survey fish, invertebrate, and algae communities, as well as the composition of the abiotic substrate. Since Reef Check specifically selects sites where at least some hard substrate is present to form a reef environment, their surveys cover important habitats for floating (canopy) and understory kelps, which mostly rely on hard substrate for attachment (Dayton 1985). The Washington chapter of Reef Check began monitoring in 2021, and by 2023 had established 43 sites across eight regions within Washington’s Salish Sea (Figure 1-1). All Reef Check sites in Washington State (with the exception of sites in Hood Canal) currently support or historically supported bull kelp (*Nereocystis luetkeana*), the only floating kelp species found within the majority of the Salish Sea.

This analysis of Reef Check data was part of multiple synthesis efforts by the HSIL Kelp Loss and Resilience project to understand the drivers of floating kelp dynamics in Washington State. The Kelp Loss and Resilience project identified Reef Check data as a potential method for linking floating kelp abundance (specifically *Nereocystis luetkeana* abundance) with benthic composition. Washington State’s coastline has previously been classified based on local floating kelp trends (Kelp Forest Monitoring Alliance of Washington State 2024). Reef Check sites represent locations experiencing a range of trends in floating kelp (Figure 1-2).

The goals of this synthesis were to:

- Describe the benthic composition of reef sites associated with *Nereocystis luetkeana* across Washington State’s Salish Sea
- Identify patterns in benthic composition across these sites
- Investigate environmental drivers which could explain these patterns in benthic composition
- Consider findings in the context of *N. luetkeana* dynamics

Through this synthesis, we aimed to identify benthic and environmental characteristics associated with positive and negative outcomes for *N. luetkeana*, to better understand what is driving both resilience and loss in this species in Washington State.

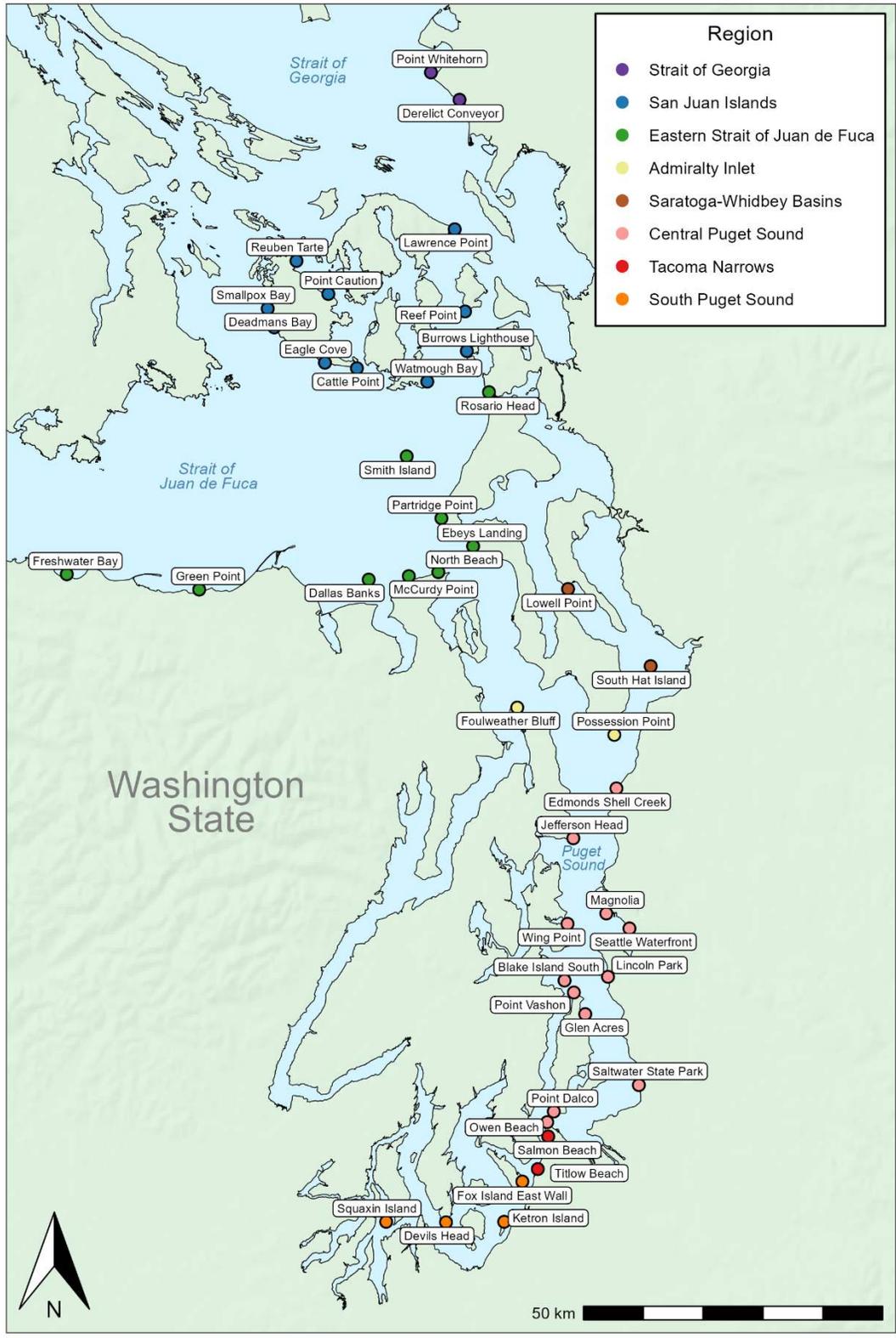


Figure 1-1. Sites surveyed by Reef Check Washington in 2023 shown by region.

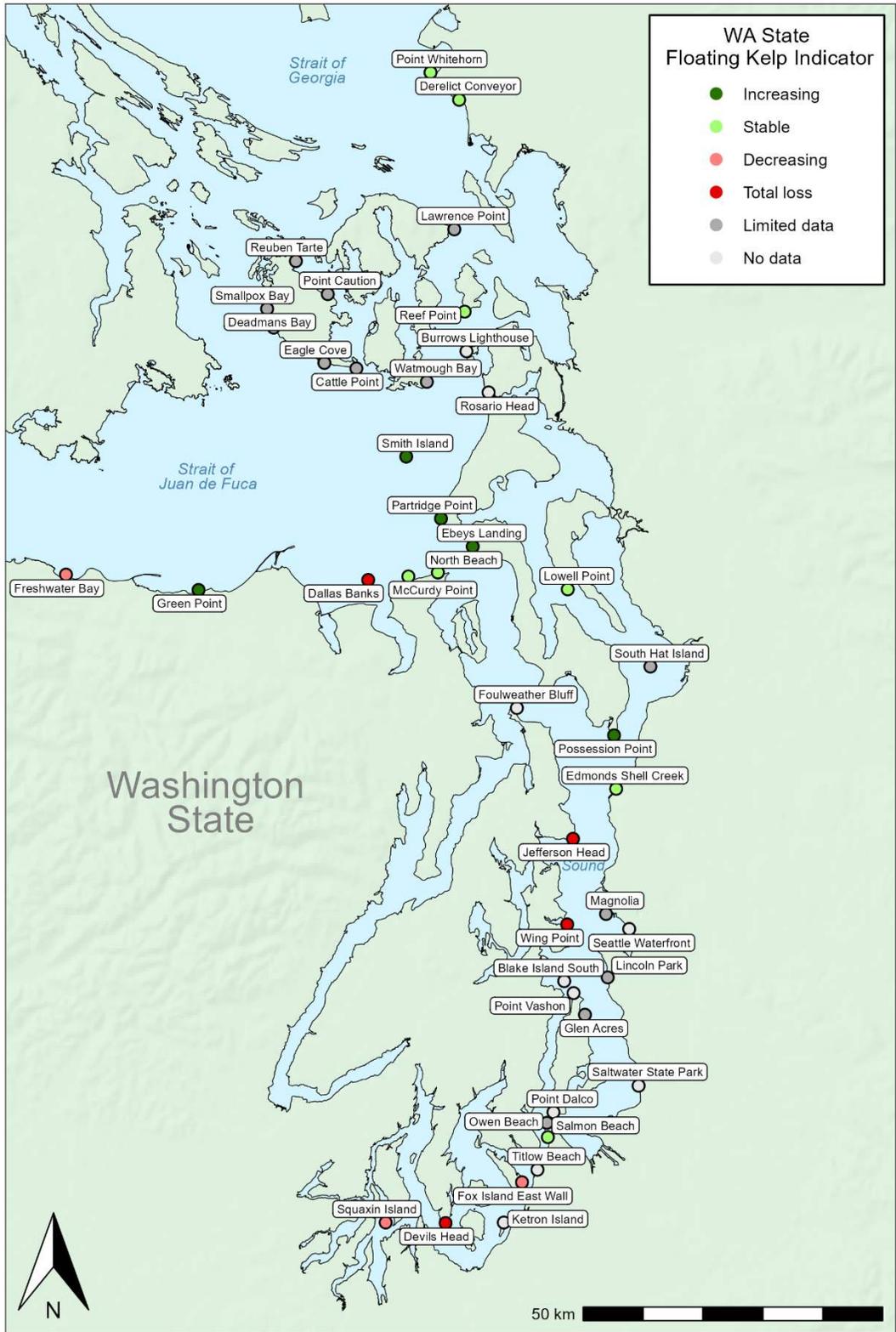


Figure 1-2. Sites surveyed by Reef Check Washington in 2023 shown by WA State Floating Kelp Indicator trend.

1.1 Methods

All graphing was done in RStudio with R version 4.3.1 (R Core Team 2023). Spatial analyses were done in ArcGIS Pro version 3.3.0 (ESRI 2024).

1.1.1 Benthic community composition

To describe benthic community composition across sites in Washington’s Salish Sea, we used the Reef Check dataset (Reef Check Foundation 2024). Reef Check Washington provided all raw survey data from the 2021-2023 dives to the Kelp Loss and Resilience project for this report. Only data from 2022 and 2023 were included in this report, because so few sites were sampled in 2021 (Table 1-1). Given our project’s focus on benthic composition and factors that could directly impact kelp, we did not include fish data in our data synthesis. We also excluded sites from Hood Canal from our analyses, since Washington’s two species of floating kelp are absent from this region (Figure 1-1). The trend in floating kelp canopy at each Reef Check site was extracted from the WA State Floating Kelp Indicator’s interactive map (Kelp Forest Monitoring Alliance of Washington State 2024) (Figure 1-2). Trends described changes in floating kelp abundance at each site, either “Increasing” for a significant positive trend, “Decreasing” for a significant negative trend, “Stable” for no significant trend, and “Total loss” if floating kelp was no longer present. Sites with fewer than five years of data were classified as “Limited data”, while sites with no data were classified as “No data”.

All data were collected using Reef Check protocols, as described in Freiwald et al. (2021), adapted for Washington following Selbitschka and Abbott (2024). In brief, six 30 m transects were laid at each site, three at shallower depths and three at deeper depths, roughly parallel to shore, and roughly equally spaced. Two types of surveys relevant to this report were performed on each transect: Uniform Point Contact (UPCs), and swath counts. For swath counts, the number of individuals within a 2 m swath (1 m on either side of the transect) was counted for 43 invertebrate and macroalgal taxa. For UPCs, a point was haphazardly selected on the benthos every 1 m along the transect, and the abiotic substrate, relief (the amount of slope and/or substrate heterogeneity), biotic cover, and biotic superlayer (macroalgal blades or mobile invertebrates covering the underlying substrate) under that point was identified. For this report, only abiotic substrate and biotic cover were analyzed, because preliminary analysis suggested superlayer did not vary meaningfully across sites, and relief, a categorical variable describing a wide range of slope and substrate conditions using only four categories, was tightly correlated with substrate. Substrate was categorized into ten cover types (Clay, Sand, Shell Hash, Pebble (0.5-5 cm), Cobble (5-15 cm), Rock (15-25 cm), Small Boulder (25-50 cm), Large Boulder (50 cm-1 m), Reef (> 1 m, including bedrock), and Other). Biotic cover was categorized into 10 cover types (Kelp Holdfast, Other Brown Algae, Red Algae, Encrusting Red Algae, Articulated Coralline Algae, Crustose Coralline Algae, Green Algae, Seagrasses, Sessile Invertebrates, and None). If multiple biotic substrates existed under a single point, only the “top” biotic

substrate was identified (e.g. a barnacle growing on a patch of crustose coralline algae would be recorded as “Sessile Invertebrates”).

Raw survey data from Reef Check were transformed as follows: invertebrate and macroalgal counts were converted to density using the area of Reef Check’s standard transects (2 m by 30 m), while substrate composition and biotic community composition were converted to percent cover using the number of points sampled on each transect. For most analyses, data were averaged across all six transects for each site.

To describe how substrate composition, biotic composition, and density of benthic taxa differed between sites, we conducted Principal Coordinates Analysis (PCoA) using a Bray-Curtis dissimilarity matrix and compared site groupings by latitude and by floating kelp trend. To further identify patterns in substrate and biotic composition, we graphed percent cover by site in 2023 for both categories. We also calculated mean cover of all rocky substrates (which included Rock, Small Boulder, Large Boulder, and Reef) for all sites across 2022 and 2023.

To describe the distribution of benthic taxa of interest, specifically invertebrates classified as grazers, macroalgae classified as understory, and the floating kelp *Nereocystis luetkeana*, we compared mean density of these taxa between sites. Macroalgae and invertebrate taxa found at fewer than 3 sites were excluded from these analyses.

To compare the distribution of *N. luetkeana* with floating kelp trends, we graphed mean densities for all sites with a positive (“Stable” and “Increasing”) or negative (“Decreasing”, “Total loss”) trend.

To compare the distribution of *N. luetkeana* with that of other taxa, we calculated Pearson correlation coefficients between transect-level density of *N. luetkeana* and transect-level density of all grazers and understory macroalgae using the “ggcorrplot” package (Alboukadel 2023). P-values were interpreted using an adjusted alpha value (0.05 corrected for the number of tests run).

Table 1-1. Sites included in this synthesis and the years they were surveyed.

Region	Site	2021	2022	2023
Strait of Georgia	Point Whitehorn		x	x
	Derelict Conveyor		x	x
San Juan Islands	Lawrence Point			x
	Reuben Tarte		x	x
	Point Caution		x	x
	Smallpox Bay		x	x
	Reef Point			x
	Deadmans Bay		x	x
	Burrows Lighthouse		x	x
	Eagle Cove			x
	Cattle Point			x
	Watmough Bay*			x
Eastern Strait of Juan de Fuca	Rosario Head		x	x
	Smith Island			x
	Partridge Point		x	x
	Ebeys Landing		x	x
	North Beach	x	x	x
	Freshwater Bay	x	x	x
	McCurdy Point		x	x
	Dallas Banks			x
Green Point			x	
Saratoga-Whidbey Basins	Lowell Point	x	x	x
	South Hat Island		x	x
Admiralty Inlet	Foulweather Bluff		x	x
	Possession Point			x
Central Puget Sound	Edmonds Shell Creek	x	x	x
	Jefferson Head		x	x
	Magnolia	x	x	x
	Wing Point	x	x	x
	Seattle Waterfront		x	x
	Lincoln Park		x	x
	Blake Island South		x	x
	Point Vashon		x	x
	Glen Acres			x
	Saltwater State Park			x
	Point Dalco			x
	Owen Beach			x
Tacoma Narrows	Salmon Beach			x
	Titlow Beach			x
South Puget Sound	Fox Island East Wall			x
	Squaxin Island		x	x
	Ketron Island		x	x
	Devils Head		x	x

1.1.1 Environmental drivers

To describe the depths at which benthic composition was surveyed, the minimum and maximum depth of each transect at each site in each year was extracted from the Reef Check dataset.

To describe the currents experienced at each Reef Check site, we used spatial interpolation of data from the Salish Sea Model (Khangaonkar et al. 2018), adapting methods described by (McKenna et al. 2022). For all Salish Sea Model nodes within 25 km of Reef Check sites ($n = 7109$) we calculated mean daily maximum current speeds for surface layer currents, which we then converted to a raster layer using the Spline with Barriers tool with 10 m cells. For each site, we took the maximum of mean daily maximum current speeds within a 45 m radius buffer (to approximate the 90 m sampling extent of Reef Check surveys) of the site's geographic coordinates as our final metric for current speed.

To describe the wind exposure experienced at each Reef Check site, we adapted methods described in Hill et al. (2010) to calculate relative openness. Using the “waver” package (Marchand and Gill 2023), we calculated openness as the sum of fetch in 48 directions up to 300 km for each Reef Check site. We then relativized this metric to the greatest openness calculated for any of our sites, which produced a metric bounded by 0 and 1. To identify patterns in currents and openness, we compared these metrics by site and by floating kelp trend.

To describe sea surface temperature and nitrate concentrations at each Reef Check site, we summarized data available from Washington State's Marine Monitoring Program (Washington State Department of Ecology 2024), again using methods adapted from (McKenna et al. 2022). Using measurements taken between 2013 and 2023 we calculated mean maximum monthly temperatures and mean minimum nitrate concentrations in the summer (May to August) for surface waters (depths < 3 m below the sea surface) at 30 stations for temperature (Figure 1-3a) and 22 stations for nitrate concentration (Figure 1-3b). We converted these station measurements to raster layers using the Spline with Barriers tool with 10m cells, then for each site calculated the mean value within a 45 m radius of each site's geographic coordinates.

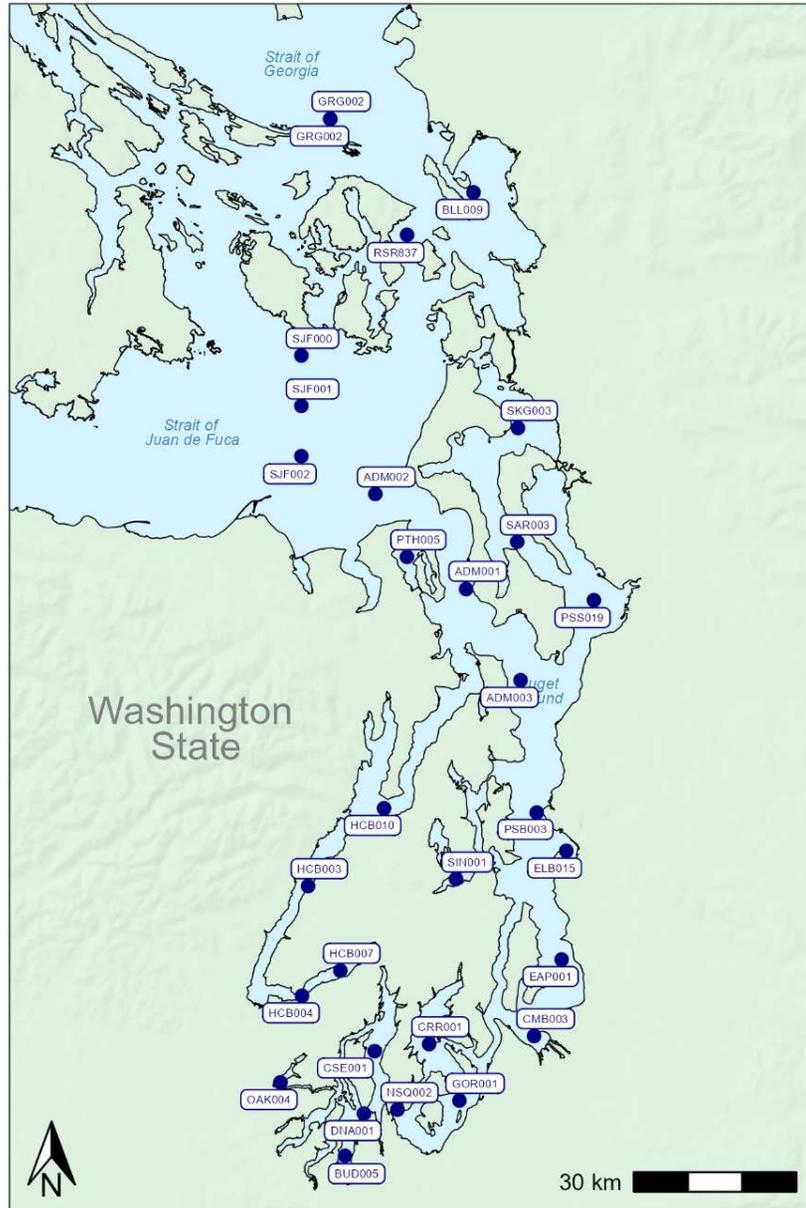
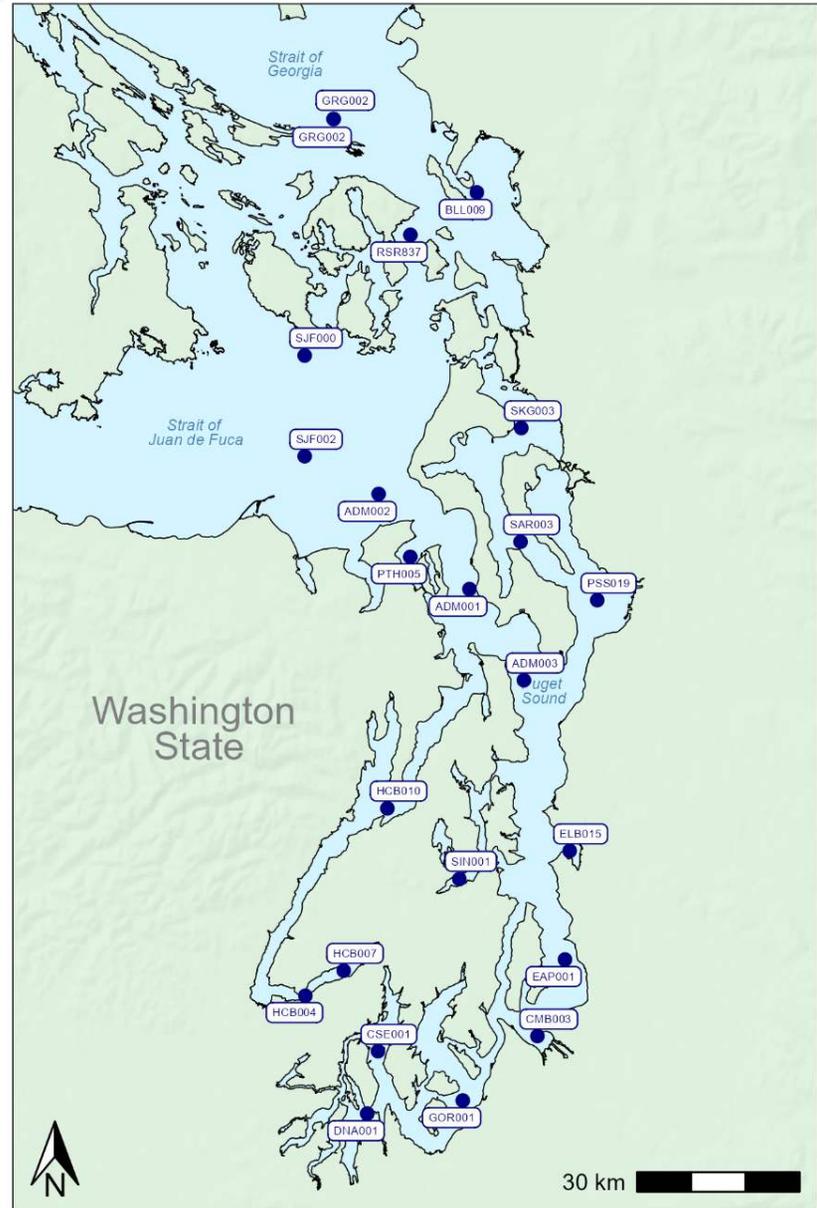
a**b**

Figure 1-3. Locations of water sampling by Washington State Department of Ecology used in this study to calculate a) temperature and b) nitrate concentration.

To identify patterns in sea surface temperature and nitrate concentrations, we compared these metrics by site and by floating kelp trend. Because the Department of Ecology Marine Water Monitoring program does not have any stations west of Dungeness for the Olympic Peninsula, we excluded the two Reef Check sites (Freshwater Bay and Green Point) from this region from these comparisons.

To identify similarities between patterns in water movement metrics (maximum current speed and relative openness), water quality metrics (maximum temperature and minimum nitrate) and geography (latitude), we calculated Pearson correlation coefficients using the “ggcorrplot” package (Alboukadel 2023). P-values were interpreted using an adjusted alpha value (0.05 corrected for the number of tests run).

1.1.2 Environmental drivers and *N. luetkeana* density

To describe *N. luetkeana* distribution across survey depths, we compared transect-level densities by mean transect depth for each site. For each transect within a site, we also divided density by the maximum density at that site, producing a site-relativized density metric to better compare density distributions within sites.

To identify patterns in *N. luetkeana* density across water movement metrics, we compared maximum density across maximum current speed and relative openness for all Reef Check sites.

1.2 Results

1.2.1 Benthic composition

In terms of substrate composition, sites grouped moderately by latitude (Figure 1-4a). Sites outside of Puget Sound proper (i.e. seaward of Admiralty Inlet) tended to have greater reef and medium rock cover than sites inside Puget Sound, which tended towards small rock and sand (Figure 1-4a, Figure 1-5). However, there were exceptions; the two northernmost sites, Point Whitehorn and Derelict Conveyor (located in the Strait of Georgia), as well as one site in the San Juan Islands (Cattle Point) and one site in the eastern Strait of Juan de Fuca (Dallas Banks) were sandier and grouped more with the Puget Sound sites in terms of substrate, while three sites from within Puget Sound (Seattle Waterfront in the central Sound, Salmon Beach in Tacoma Narrows, and Fox Island just south of Tacoma Narrows) were rockier and grouped more with the San Juan Islands and eastern Strait of Juan de Fuca sites. Pooling substrate categories larger than cobble showed similar groupings, with rocky sites more common outside Puget Sound, and sandy sites more common inside Puget Sound (Figure 1-6). However, the Strait of Georgia sites, despite having a sandier composition overall, still had a similar proportion of rocky cover to San Juan Islands/eastern Strait of Juan de Fuca sites.

Sites also grouped moderately well by kelp canopy indicator in terms of abiotic substrate composition (Figure 1-4b). Sites with “Decreasing” or “Total Loss” floating kelp trends tended towards cobble, pebble, shell hash and sand. This also reflected regional patterns, since five of the seven sites classified as “Decreasing” or “Total Loss” are inside Puget Sound, which tended towards these smaller substrates as described above. However, two sites classified as “Decreasing”, Freshwater Bay (in the eastern Strait of Juan de Fuca) and Fox Island East Wall (adjacent to Tacoma Narrows) had a higher proportion of rocky cover (Figure 1-6). Most sites with “Stable” and “Increasing” kelp trends were also rocky, which may also have reflected regional patterns since the majority of these were San Juan Islands, eastern Strait of Juan de Fuca, or Strait of Georgia sites.

In terms of biotic community composition, sites grouped somewhat by latitude (Figure 1-7a). Sites in the San Juan Islands (except Cattle Point) and eastern Strait of Juan de Fuca were characterized by crustose coralline and encrusting red algae, as well as brown macroalgae and kelp holdfasts. Sites in Puget Sound were more associated with sessile invertebrates or a lack of biotic cover, however crustose coralline algae, encrusting red algae, brown macroalgae and kelp holdfasts were still present and even highly abundant at many of these sites (Figure 1-8). Two southern sites, Salmon Beach and Wing Point, had very high encrusting red algae and brown macroalgal cover combined with lower sessile invertebrate cover, and grouped more with the San Juan Islands/eastern Strait of Juan de Fuca sites.

Sites showed very little grouping by floating kelp trends in terms of benthic biotic composition (Figure 1-7b).

Patterns in site groupings for macroalgae and invertebrate density were similar to those for biotic composition. The majority of the San Juan Islands/eastern Strait of Juan de Fuca sites plus Fox Island East Wall and Point Dalco (sites adjacent to Tacoma Narrows) grouped together and were characterized by multiple understory kelp species as well as brown macroalgae in the genus *Desmarestia* and the red urchin, *Mesocentrotus franciscanus* (Figure 1-9a). The majority of Puget Sound sites as well as the two Strait of Georgia sites, meanwhile, were associated with the understory kelps *Saccharina latissima*/*Hedophyllum nigripes*.

As with biotic composition, sites showed very little grouping by floating kelp trends in terms of macroalgae and invertebrate density, beyond what was linked to geographic patterns in floating kelp trends (Figure 1-9b).

Taxon-specific density patterns occurred for understory macroalgae in different regions. Three species of kelp, *Pterygophora californica*, *Pleurophycus gardneri*, and *Cymathere triplicata* largely occurred in the eastern Strait of Juan de Fuca and the San Juan Islands, with a few additional populations in central Puget Sound (Figure 1-10). Another kelp species, *Alaria marginata*, was more widespread across study sites but occurred at higher densities in the eastern Strait of Juan de Fuca and the San Juan Islands. The sieve kelps *Agarum clathratum*/*Neoagarum fimbriatum* showed a similar pattern to *A. marginata*, with fairly widespread distribution but higher densities in the San Juan Islands and at two sites at the southern end of Tacoma Narrows (Titlow Beach and Fox Island East Wall) (Figure 1-11). The introduced brown macroalga *Sargassum muticum*, meanwhile, occurred across regions but was more common in the Strait of Georgia and northern San Juan Islands, as well as central and south Puget Sound. Finally, the most widespread brown macroalgae were the kelps *Costaria costata* and *S. latissima*/*H. nigripes*, and brown macroalgae in the genus *Desmarestia* (Figure 1-12). While there was no clear geographic pattern in density for *C. costata*, *S. latissima*/*H. nigripes* densities were highest in central Puget Sound. The distribution of *Desmarestia* spp. was not clearly associated with regions, however it tended to reach higher densities near the north and south entrances to both Admiralty Inlet and the Tacoma Narrows.

Taxon-specific density patterns also occurred for grazing invertebrates. Two urchin species, *M. franciscanus* and *Strongylocentrotus purpuratus* were restricted to sites in the San Juan Islands and eastern Strait of Juan de Fuca (Figure 1-13). The green/white urchins *S. droebachiensis* and *S. pallidus* commonly occurred in these same northern regions but were also found at sites in central Puget Sound and Tacoma Narrows. *Cryptochiton stelleri*, the giant chiton, had a similar distribution to the green/white urchins, occurring frequently at northern sites but occasionally in Puget Sound as well (Figure 1-14). Both adult and juvenile kelp crabs in the genus *Pugettia*, meanwhile, were widespread at Reef Check sites, with densities peaking in south and central Puget Sound.

In general, the *N. luetkeana* densities obtained via Reef Check surveys concurred with the independently determined WA Floating Kelp Indicator. The density of *N. luetkeana* in 2023 varied widely across Reef Check sites (Figure 1-15). It was present across all regions and occurred at moderate to high densities (> 1 individual/m²) at sites in most of the study regions (Strait of Georgia, San Juan Islands, eastern Strait of Juan de Fuca, central Puget Sound, and Tacoma Narrows). Of the eight study sites where *N. luetkeana* was absent in 2023, three were in south Puget Sound (Fox Island East Wall, Ketron Island, and Devils Head) and three were in central Puget Sound (Jefferson Head, Wing Point and Saltwater State Park), while the remaining two were in eastern Strait of Juan de Fuca (Dallas Banks) and the San Juan Islands (Reuben Tarte).

When *N. luetkeana* density was compared by floating kelp trend, most sites with “Increasing and “Stable” trends had higher density than those with a “Decreasing” trend (Figure 1-16). The exception was Freshwater Bay, a “Decreasing” site whose *N. luetkeana* density was similar to the highest densities measured at any of the “Stable” sites, and Possession Point and Green Point, “Increasing” sites whose densities were similar to the lowest “Decreasing” sites. *Nereocystis luetkeana* was absent from all sites with a “Total loss” trend.

When the densities of understory macroalgae and grazing invertebrates were compared to *N. luetkeana* density, five species had significant correlations (Table 1-2). There were positive correlations between *N. luetkeana* density and two kelps (*C. costata* and *C. triplicata*), one other brown macroalgae (*Desmarestia* spp.), and two grazers (*S. droebachiensis/pallidus* and *Cryptochiton stelleri*). Despite being significant, all of these correlations were weak in strength.

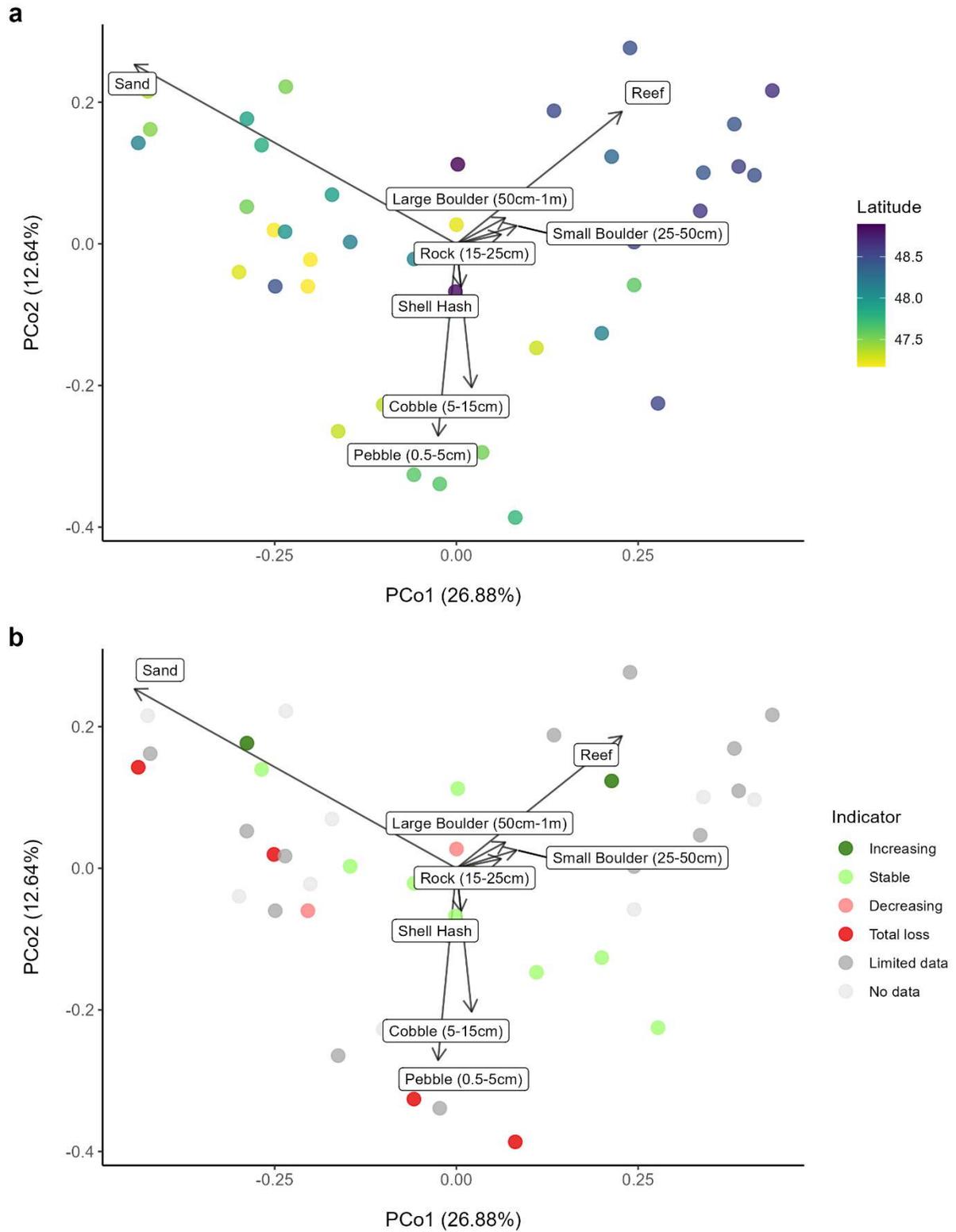


Figure 1-4. Principle coordinates analysis (PCoA) for substrate composition at Reef Check sites in 2022 and 2023, quantified as Bray-Curtis dissimilarity. Sites were classified by a) latitude and b) WA State Floating Kelp Indicator trend. Arrows represent important substrate categories used in surveys.

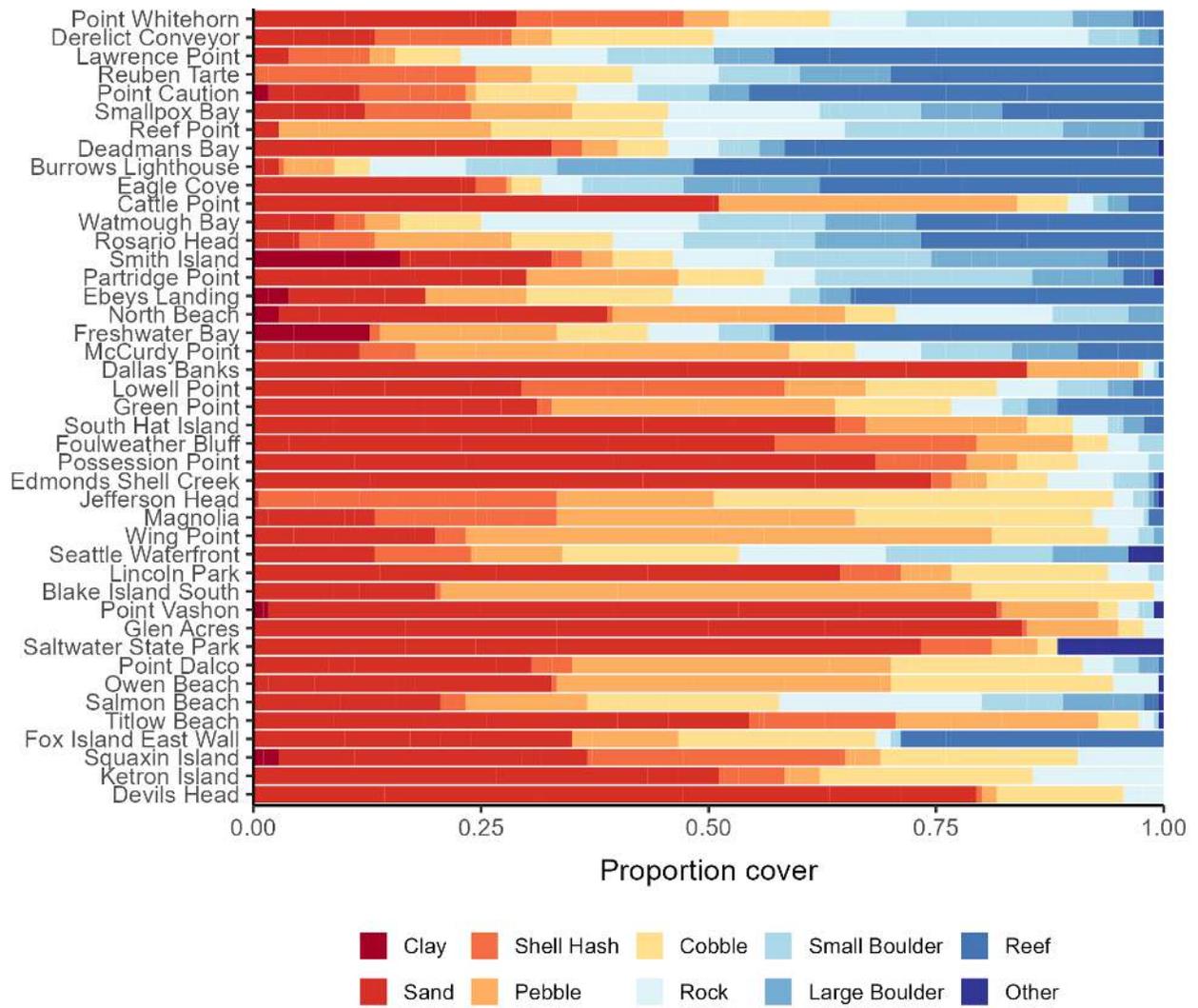


Figure 1-5. Proportion of substrate by cover type across all transects at Reef Check sites in 2023. Sites are arranged by latitude (north to south).

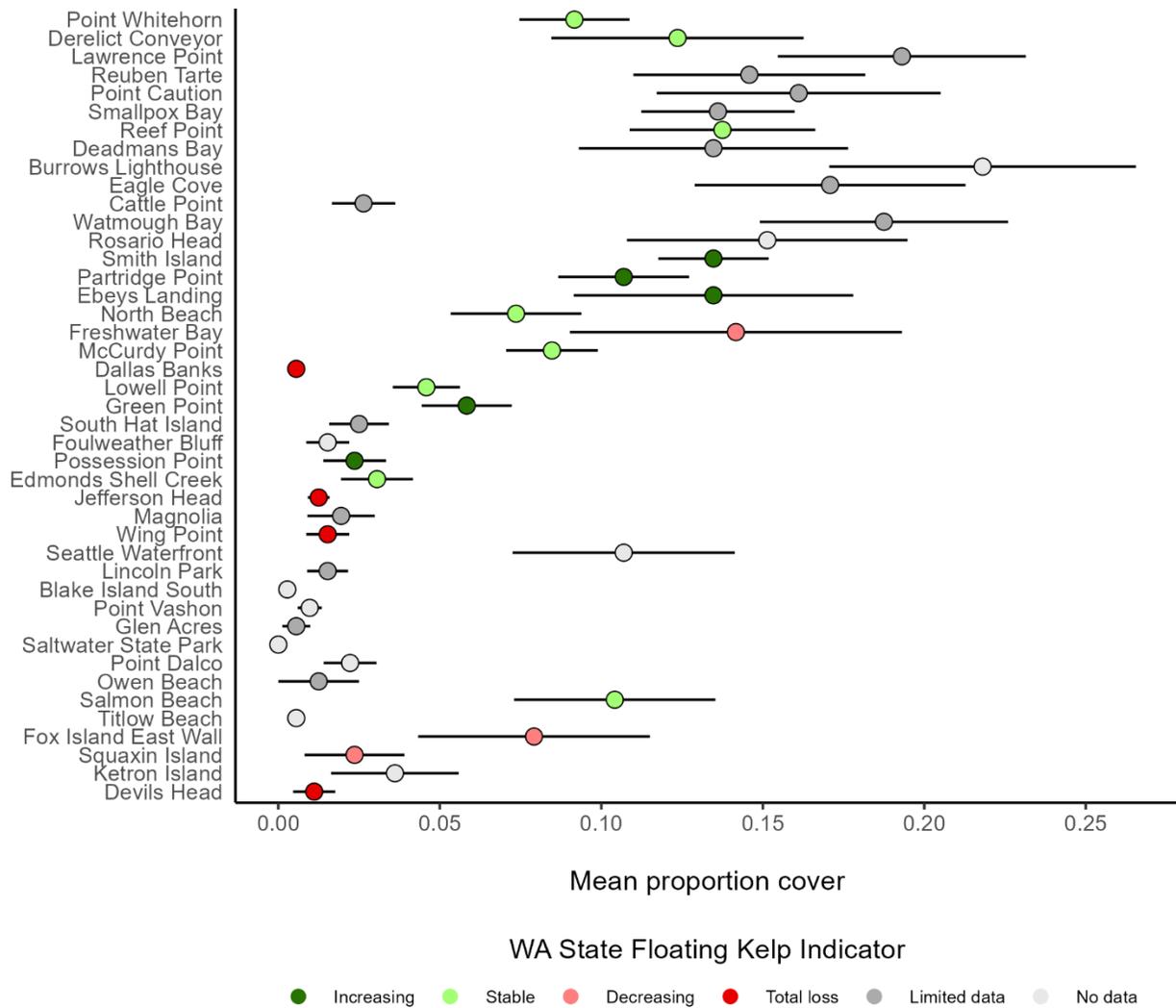


Figure 1-6. Mean proportion cover of rocky substrates (Rock (15-25cm), Small Boulder (25-50cm), Large Boulder (50cm-1m), and Reef) at Reef Check sites. Proportions were averaged across transects and years (2022 and 2023) for each site. Sites are arranged by latitude (north to south)

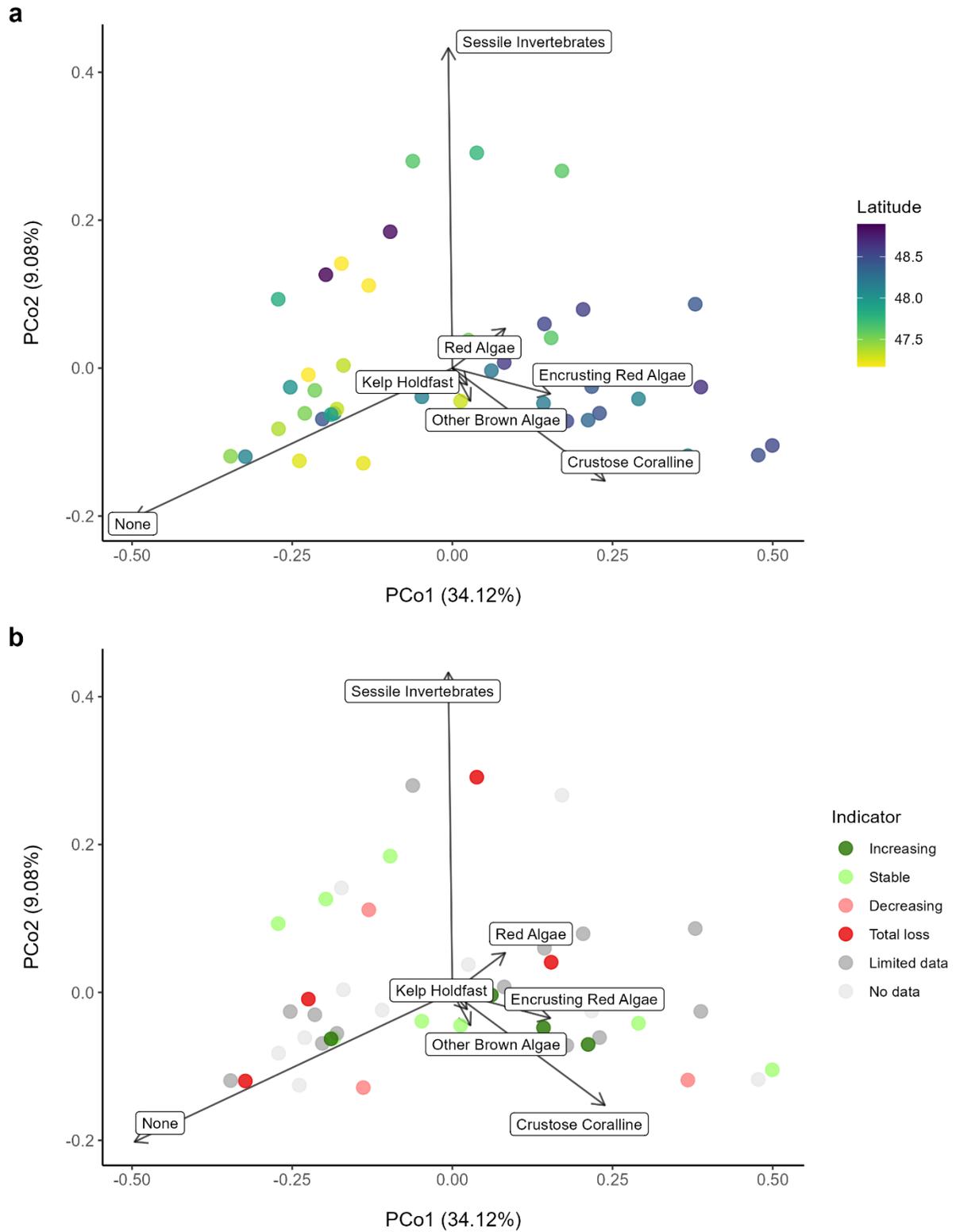


Figure 1-7. Principle coordinates analysis (PCoA) for biotic composition at Reef Check sites in 2022 and 2023, quantified as Bray-Curtis dissimilarity. Sites were classified by a) latitude and b) WA State Floating Kelp Indicator trend. Arrows represent important biotic cover categories used in surveys.

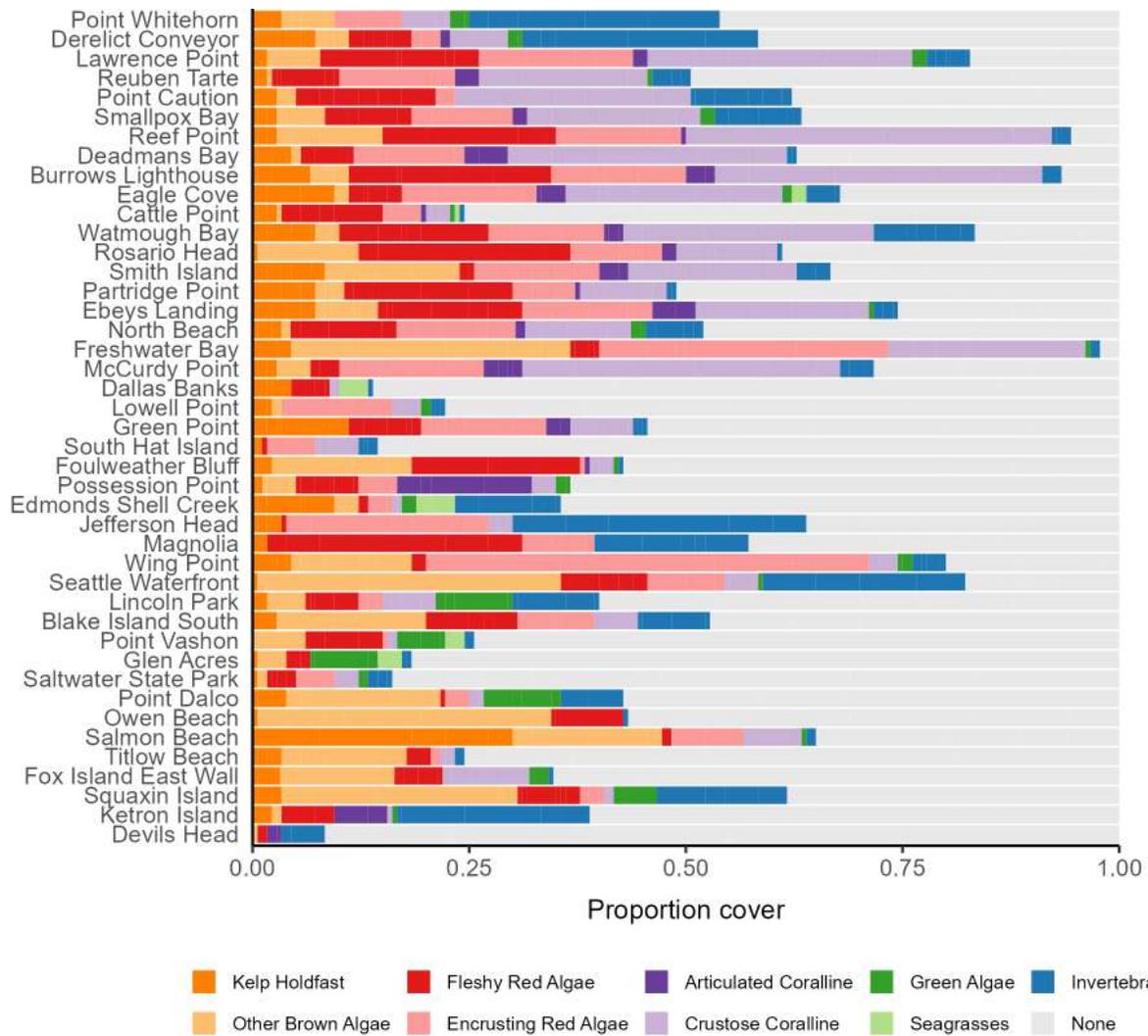


Figure 1-8. Proportion of biotic cover by cover type across all transects at Reef Check sites in 2023. Sites are arranged by latitude (north to south).

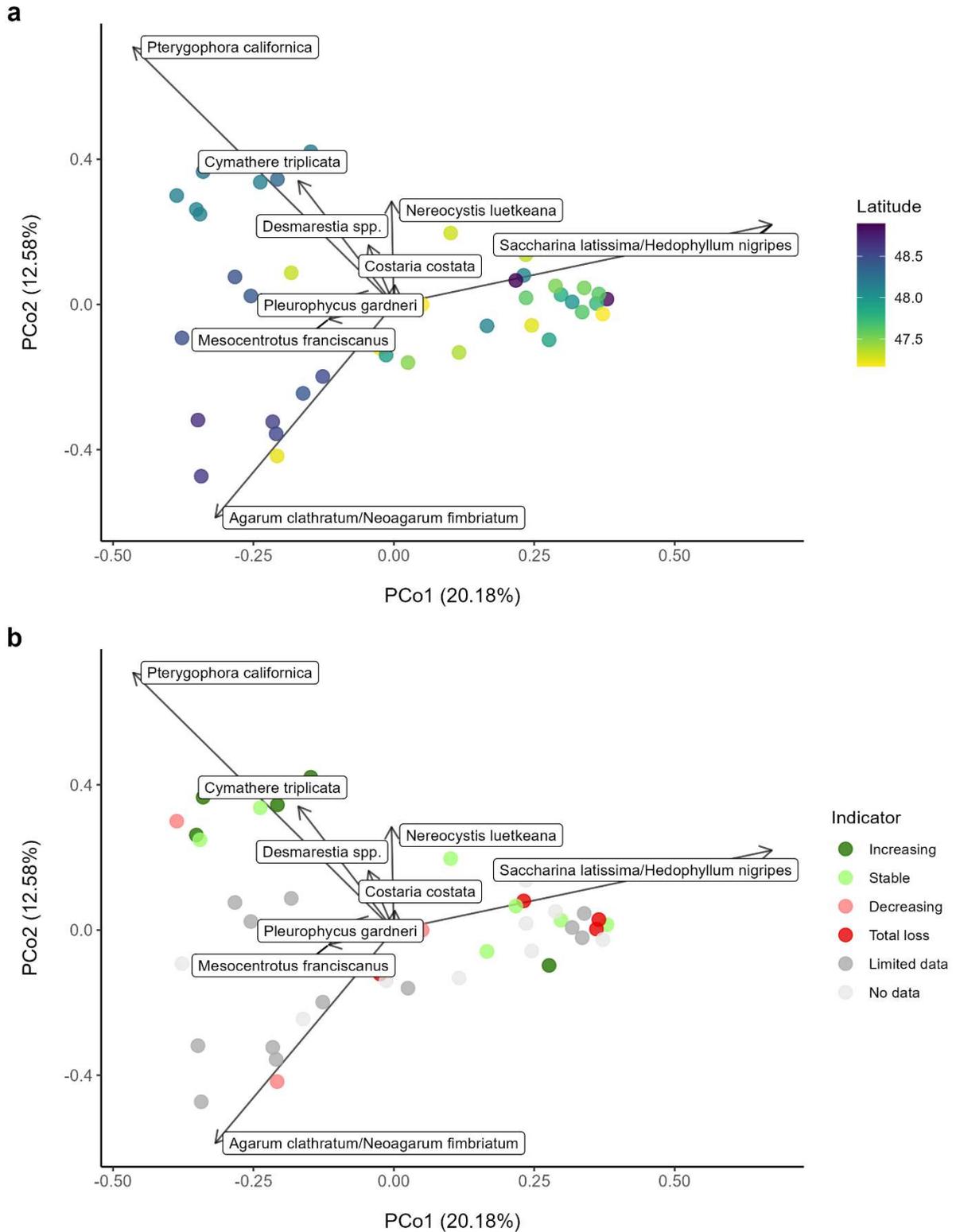


Figure 1-9. Principle coordinates analysis (PCoA) for invertebrate and macroalgae density at Reef Check sites in 2022 and 2023, quantified as Bray-Curtis dissimilarity. Sites were classified by a) latitude and b) WA State Floating Kelp Indicator trend. Arrows represent important taxa observed in surveys.

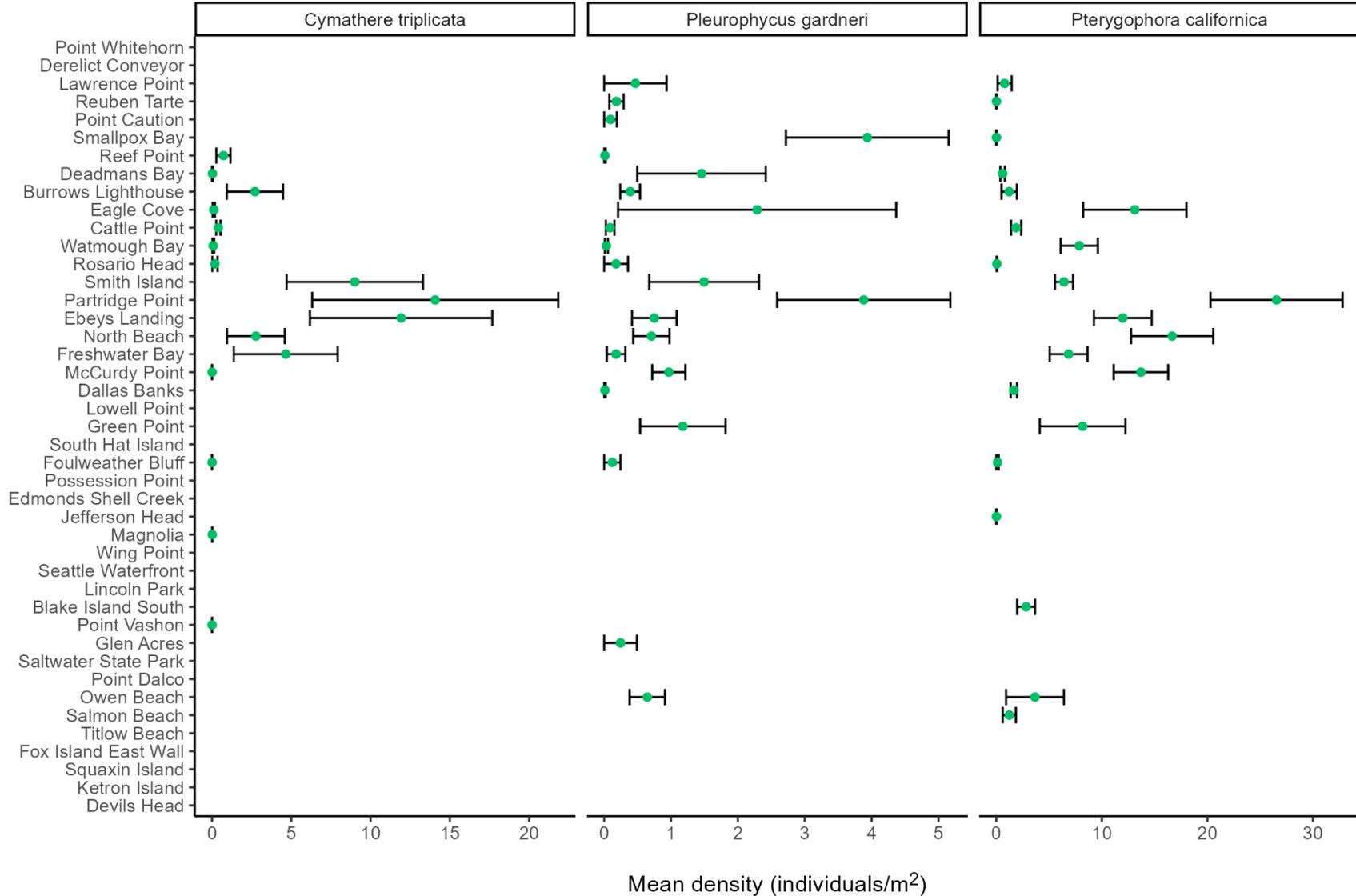


Figure 1-10. Mean density of three understory brown algae taxa (*Cymathere triplicata*, *Pleurophycus gardneri*, and *Pterygophora californica*) at Reef Check sites in 2022 and 2023. Densities were averaged across all transects for each site. Sites are arranged by latitude (north to south).

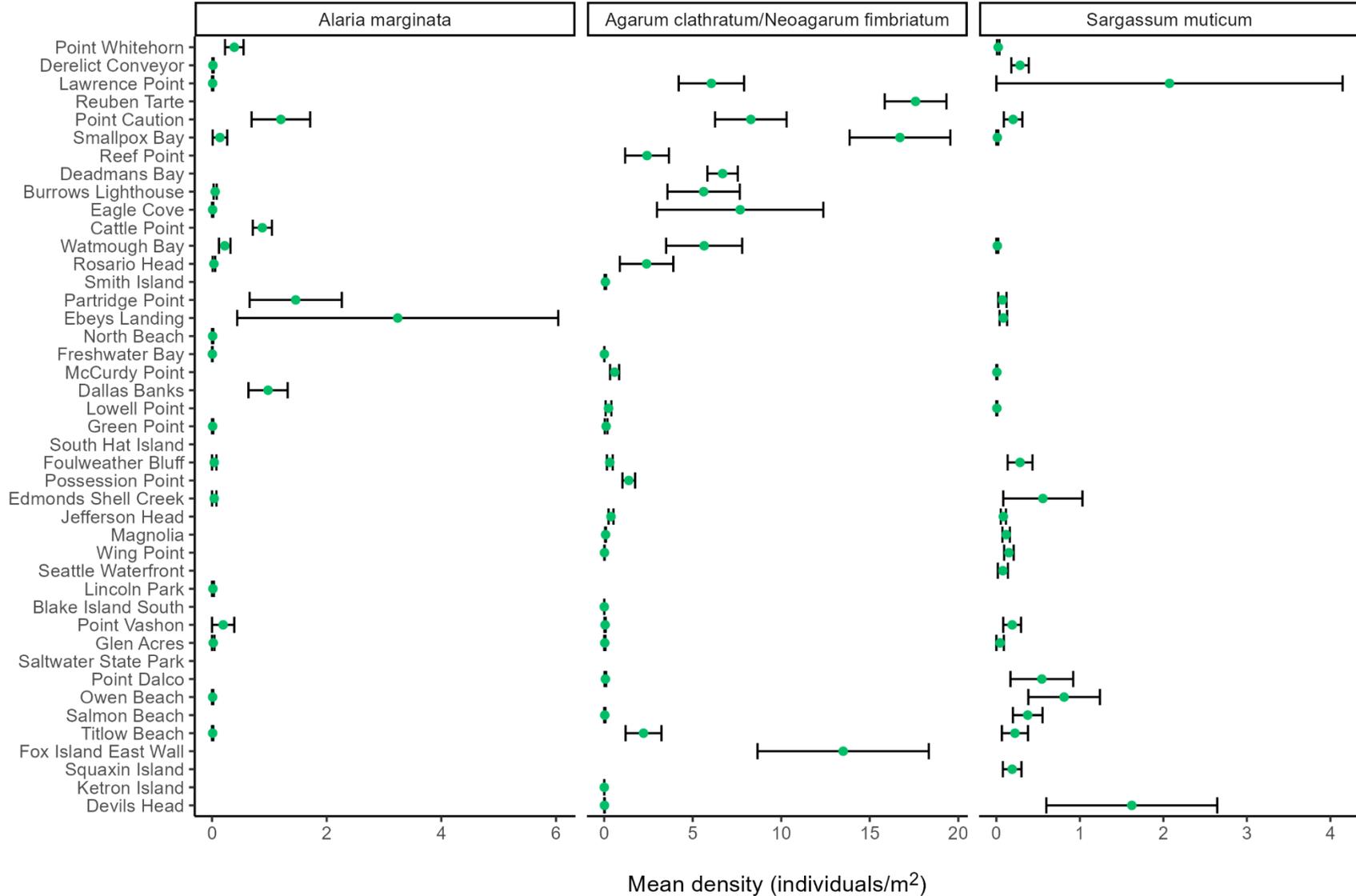


Figure 1-11. Mean density of three understory brown algae taxa (*Alaria marginata*, *Agarum clathratum* and *Neoagarum fimbriatum*, and *Sargassum muticum*) at Reef Check sites in 2022 and 2023. Densities were averaged across all transects for each site. Sites are arranged by latitude (north to south).

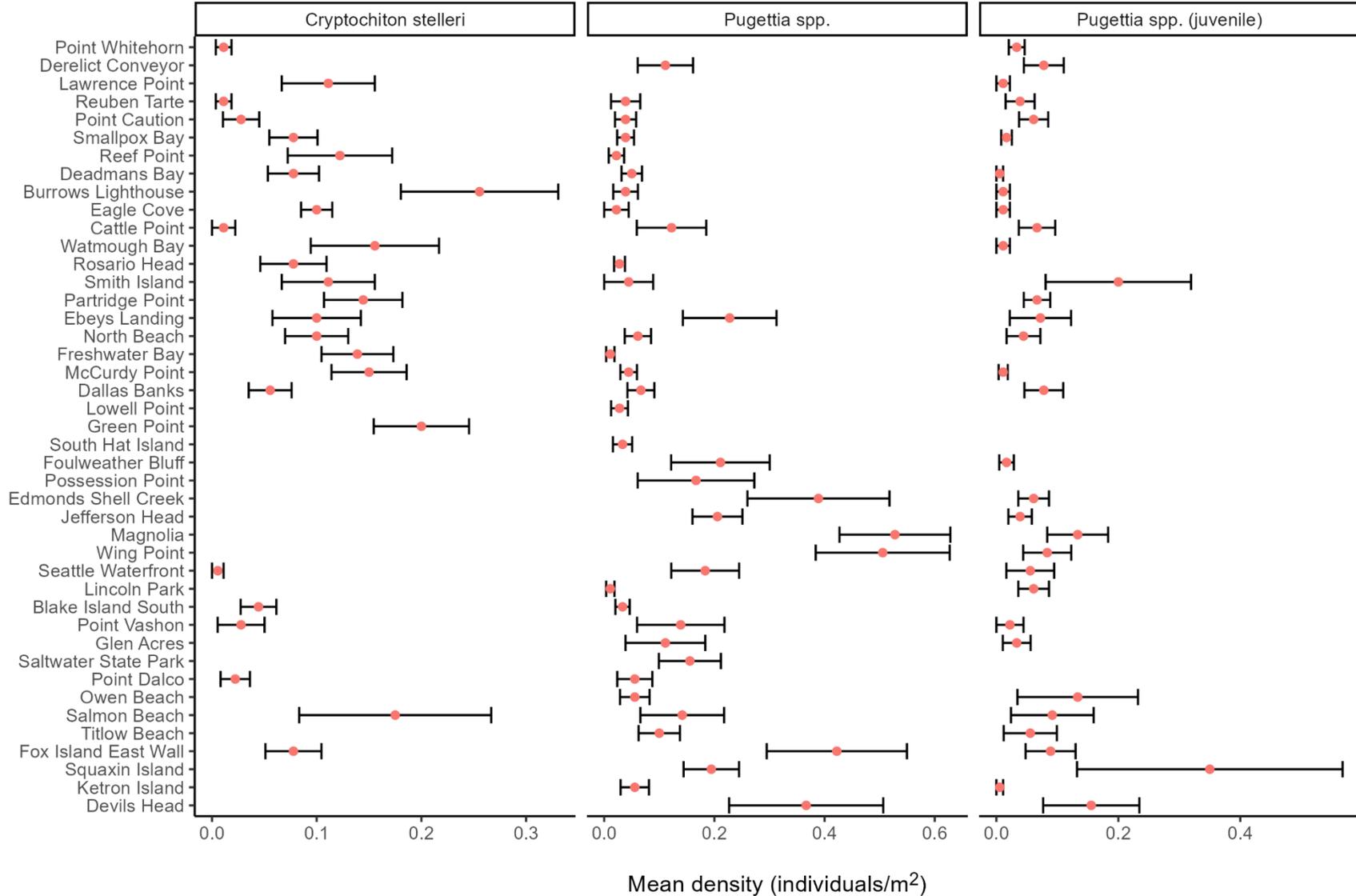


Figure 1-12. Mean density of three understory brown algae taxa (*Costaria costata*, *Saccharina latissima*/*Hedophyllum nigripes*, and *Desmarestia* spp.) at Reef Check sites in 2022 and 2023. Densities were averaged across all transects for each site. Sites are arranged by latitude (north to south).

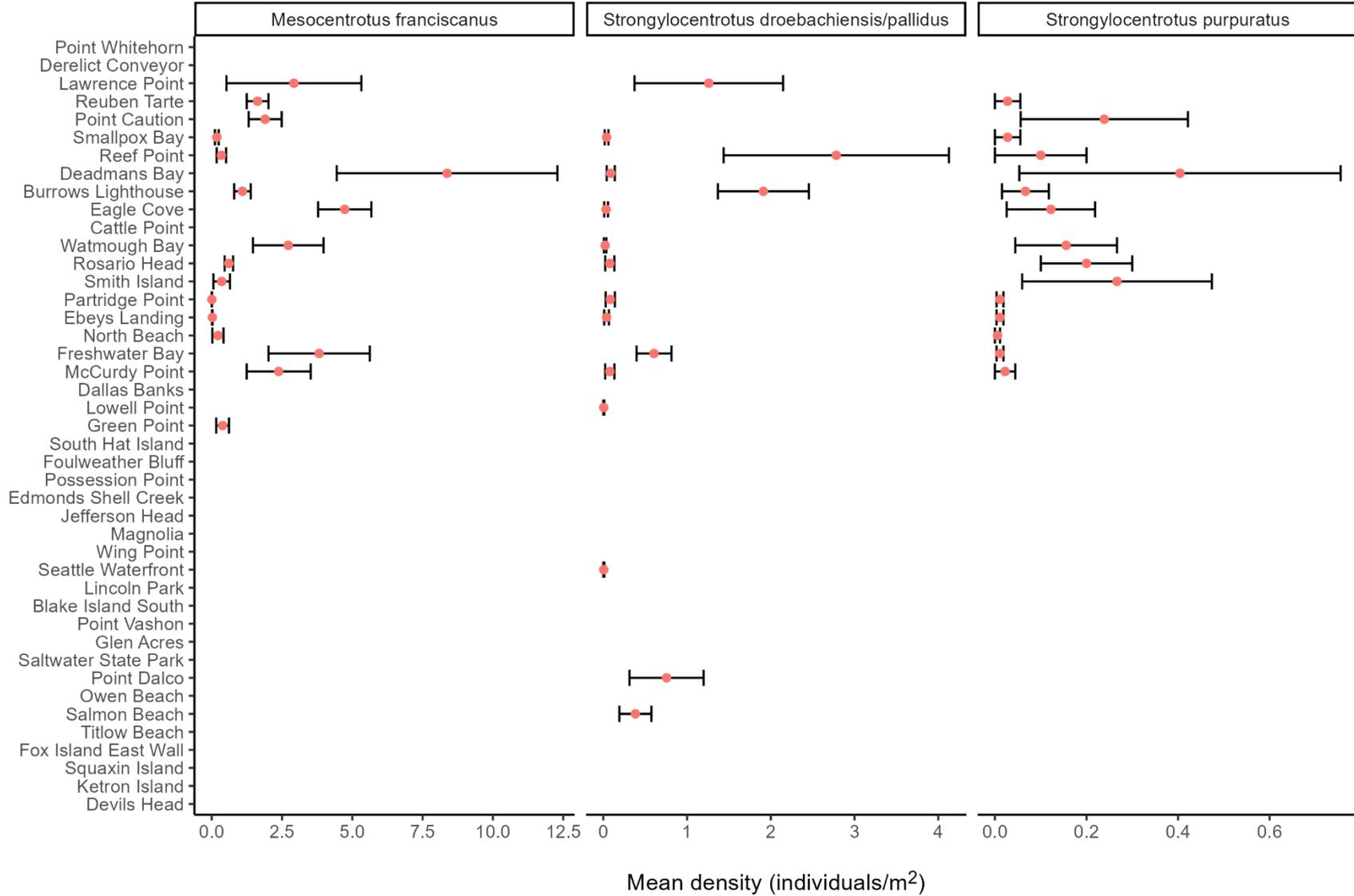


Figure 1-13. Mean density of three urchin taxa (*Mesocentrotus franciscanus*, *Strongylocentrotus droebachiensis* and *S. pallidus*, and *S. purpuratus*) at Reef Check sites in 2022 and 2023. Densities were averaged across all transects for each site. Sites are arranged by latitude (north to south).

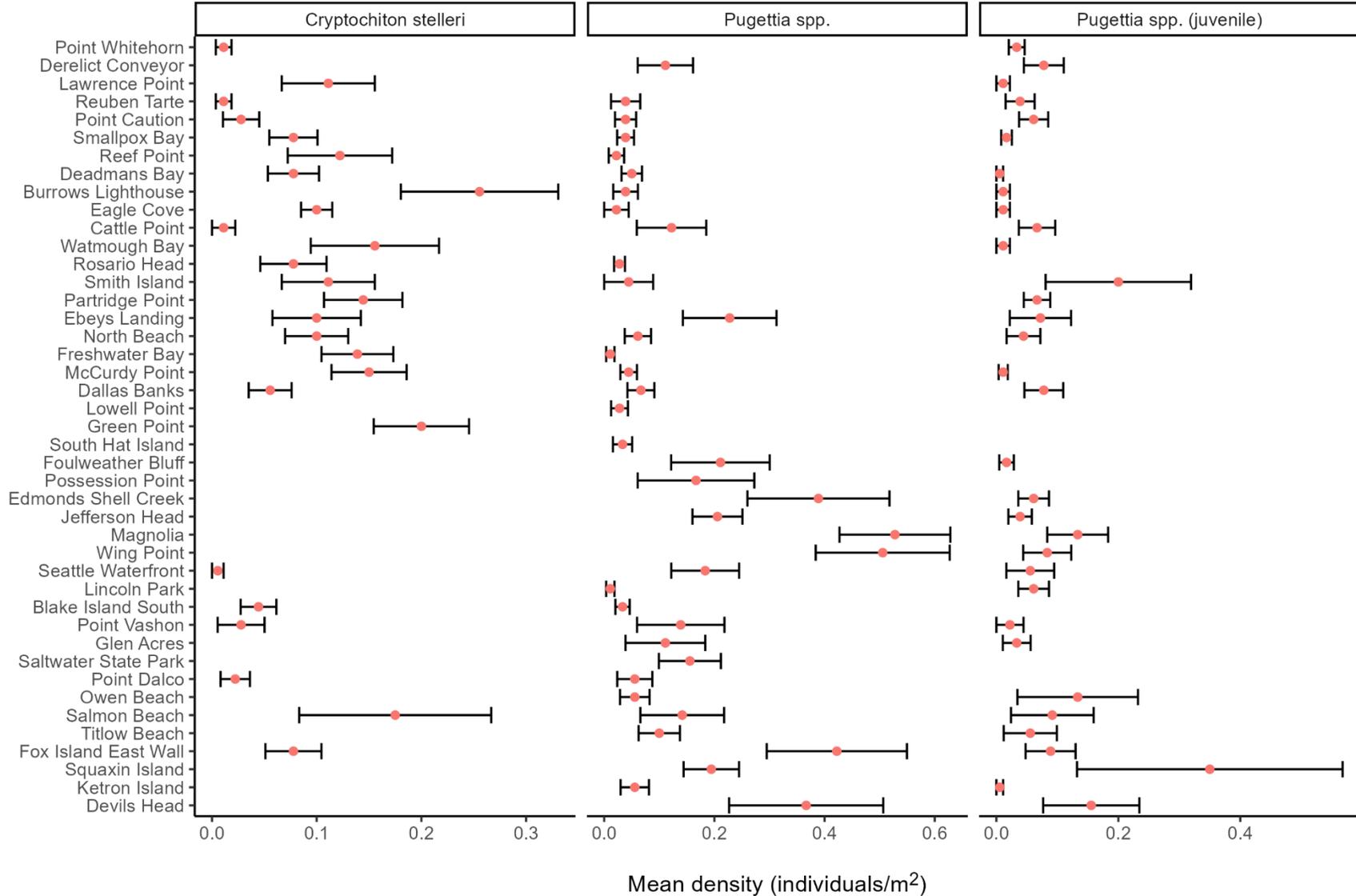


Figure 1-14. Mean density of two grazing invertebrate taxa (*Cryptochiton stelleri*, and *Pugettia* spp., subdivided into adults and juveniles) at Reef Check sites in 2022 and 2023. Densities were averaged across all transects for each site. Sites are arranged by latitude (north to south).

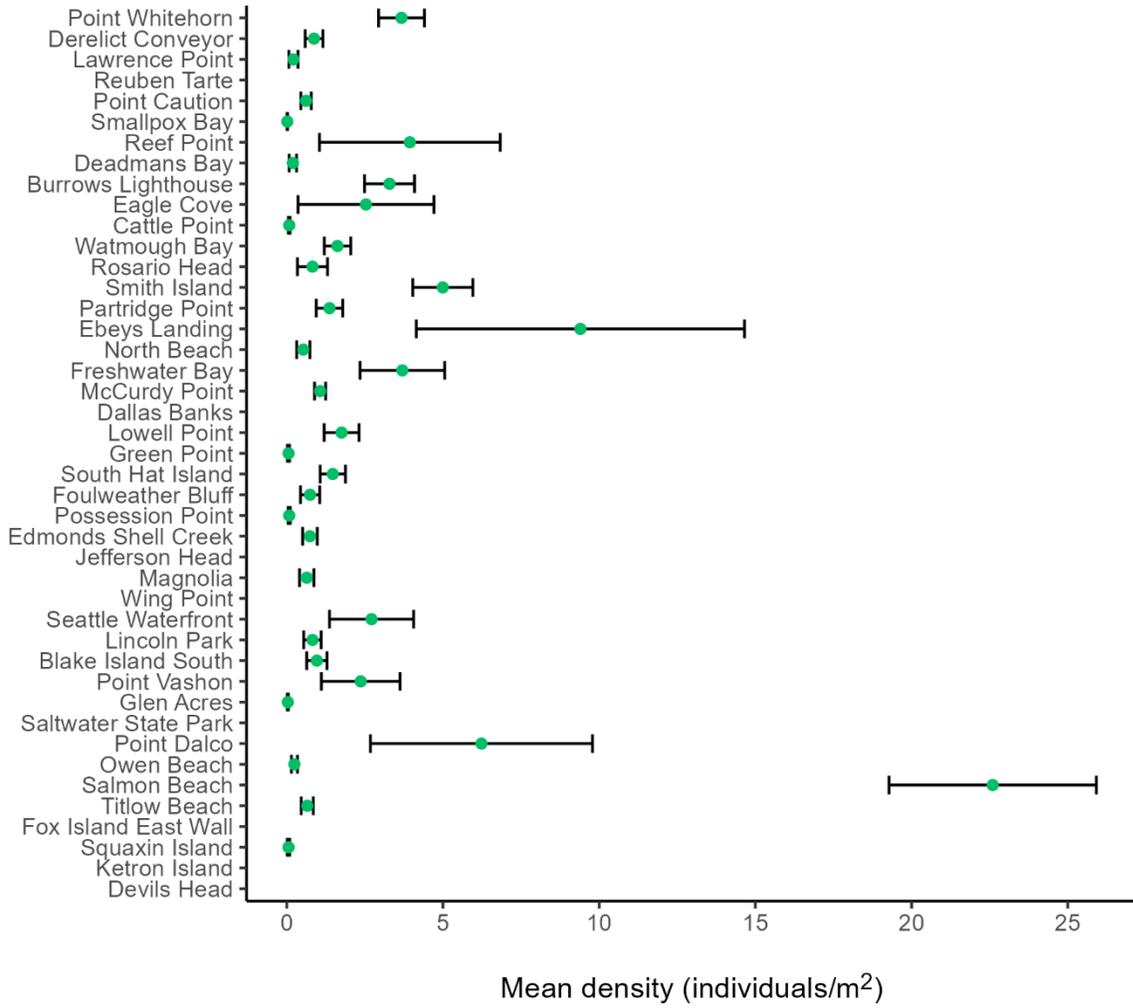


Figure 1-15. Mean density of the floating kelp *Nereocystis luetkeana* at Reef Check sites in 2022 and 2023. Density was averaged across all transects for each site. Sites are arranged by latitude (north to south).

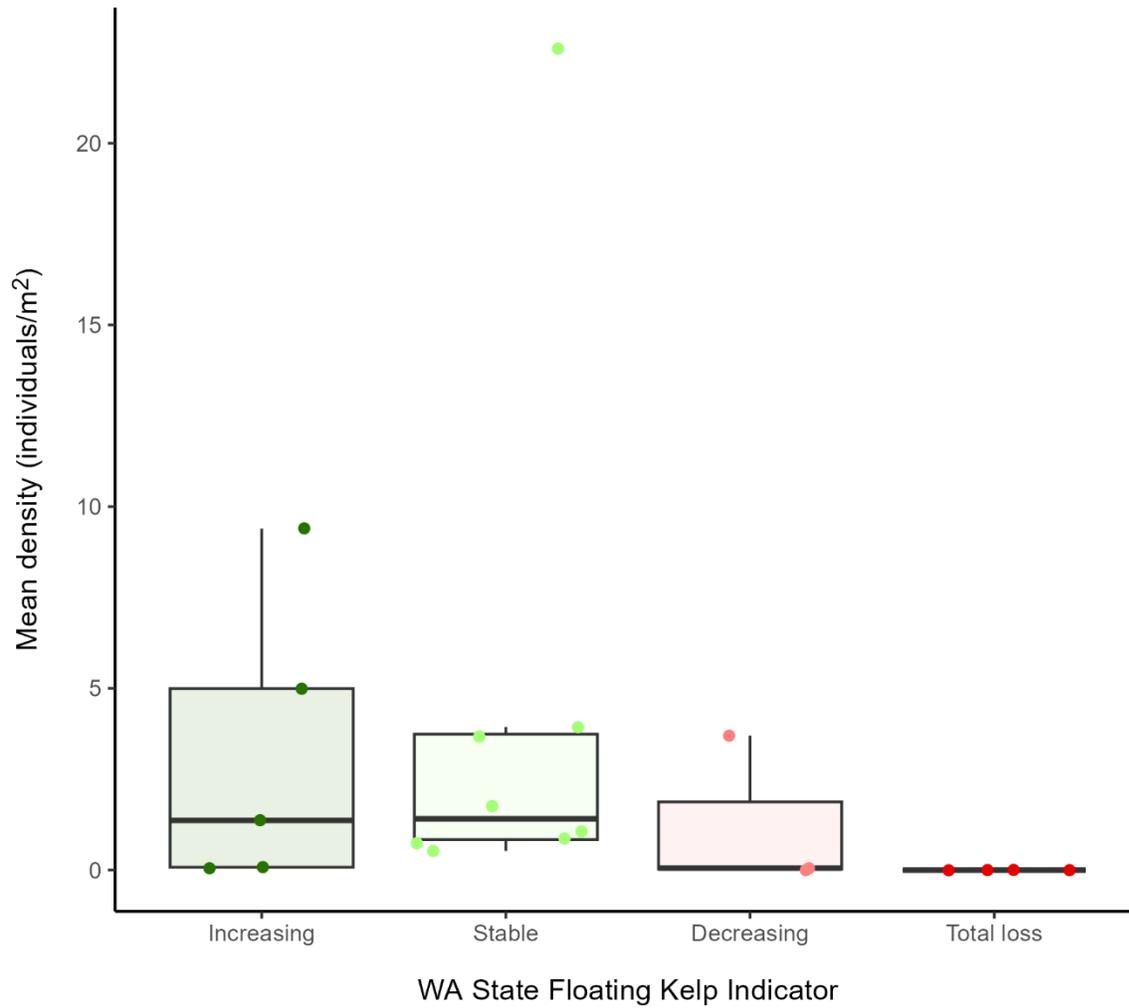


Figure 1-16. Mean density of *Nereocystis luetkeana* at Reef Check sites, grouped by sites' WA State Floating Kelp Indicator trend. Density was averaged across all transects for each site surveyed in 2022 and 2023.

Table 1-2. Correlations between the density of understory macroalgae and grazing invertebrates and *Nereocystis luetkeana* density. Correlations were calculated using data from all transects surveyed by Reef Check Washington in 2022 and 2023. Only macroalgae and grazing invertebrates with significant correlations were included.

Taxon	Correlation	P-value
<i>Costaria costata</i>	0.3665	< 0.001
<i>Desmarestia</i> spp.	0.2226	< 0.001
<i>Strongylocentrotus droebachiensis/pallidus</i>	0.1853	< 0.001
<i>Cryptochiton stelleri</i>	0.1796	< 0.001
<i>Cymathere triplicata</i>	0.1772	< 0.001

1.2.2 Environmental drivers

The depths surveyed by Reef Check varied between sites, but with no consistent geographic patterns. Minimum transect depth ranged between 0.9 and 5.8 m below MLLW, while maximum transect depths ranged between 1.8 and 19.2 m below MLLW (Figure 1-17). Water movement metrics also varied between sites. Mean daily maximum current speed was highest in the San Juan Islands, eastern Strait of Juan de Fuca, and near the Tacoma Narrows, and lower at sites within Central and South Puget Sound (Figure 1-18a). In comparison, relative openness, a metric of wind fetch, was highest at sites in the Strait of Georgia and eastern Strait of Juan de Fuca (as well as sites on the west side of San Juan and Fidalgo Islands), but lowest in Tacoma Narrows and south Puget Sound (Figure 1-18b).

This spatial variation was reflected in but not explanatory for floating kelp trend. While all sites with an “Increasing” kelp trend had moderate current speeds, and most sites with a “Total Loss” trend had low current speeds, there were no clear patterns for “Stable” and “Decreasing” sites. In terms of openness, most sites with “Decreasing” or “Total loss” trends had low openness, consistent with being Puget Sound sites. While most sites with an “Increasing” trend had moderate to high openness, “Stable” sites included both high and low openness sites.

Water quality metrics also showed spatial variation. Mean maximum monthly summer temperature peaked at Squaxin Island in south Puget Sound (exceeding temperatures at all other sites by 2 °C) but was also high in the Strait of Georgia and in and around the Saratoga-Whidbey basins (Figure 1-19a). The lowest temperatures occurred in the southern San Juan Islands, near the Strait of Juan de Fuca. Mean minimum summer nitrate concentrations, meanwhile, were generally the inverse of temperature patterns (Figure 1-19b). The highest nitrate concentrations occurred in the southern San Juan Islands near the Strait of Juan de Fuca, and the lowest occurred at Squaxin Island and sites in or around the Strait of Georgia and Saratoga-Whidbey basins. However, sites in or near the Tacoma Narrows had higher nitrate minima than all other Puget Sound sites, despite being similar in temperature.

Maximum temperature and minimum nitrate concentration varied less consistently by kelp canopy trend. Negative canopy trends (“Decreasing” and “Total Loss”) mostly occurred at sites with moderate to high temperatures and moderate to low nitrate, however positive trends (“Stable” and “Increasing”) occurred over a wide range of temperatures and nitrate concentrations.

When water movement and water quality metrics were compared, along with latitude, multiple correlations were identified (Figure 1-20). Maximum temperature was significantly negatively correlated with all other metrics, but only strongly with minimum nitrate concentration (all other correlations with temperature were moderate in strength). Maximum current speed, meanwhile, was the only metric not significantly correlated with latitude, and was only weakly positively correlated with relative openness. It was, however, moderately positively correlated with minimum nitrate concentration.

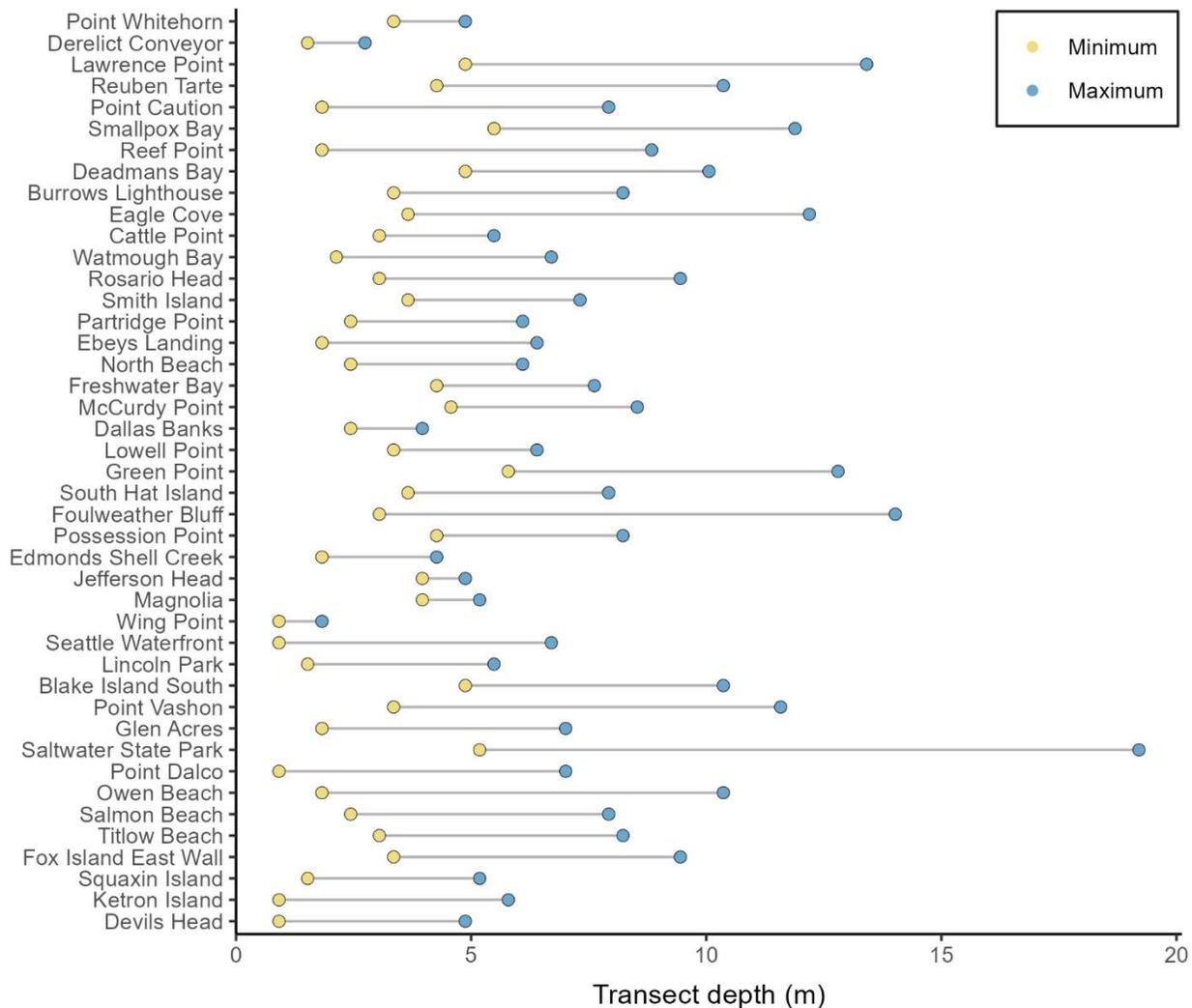


Figure 1-17. Minimum and maximum depth across all transects at Reef Check sites in 2023. Depth was calculated as depth below MLLW. Sites are arranged by latitude (north to south).

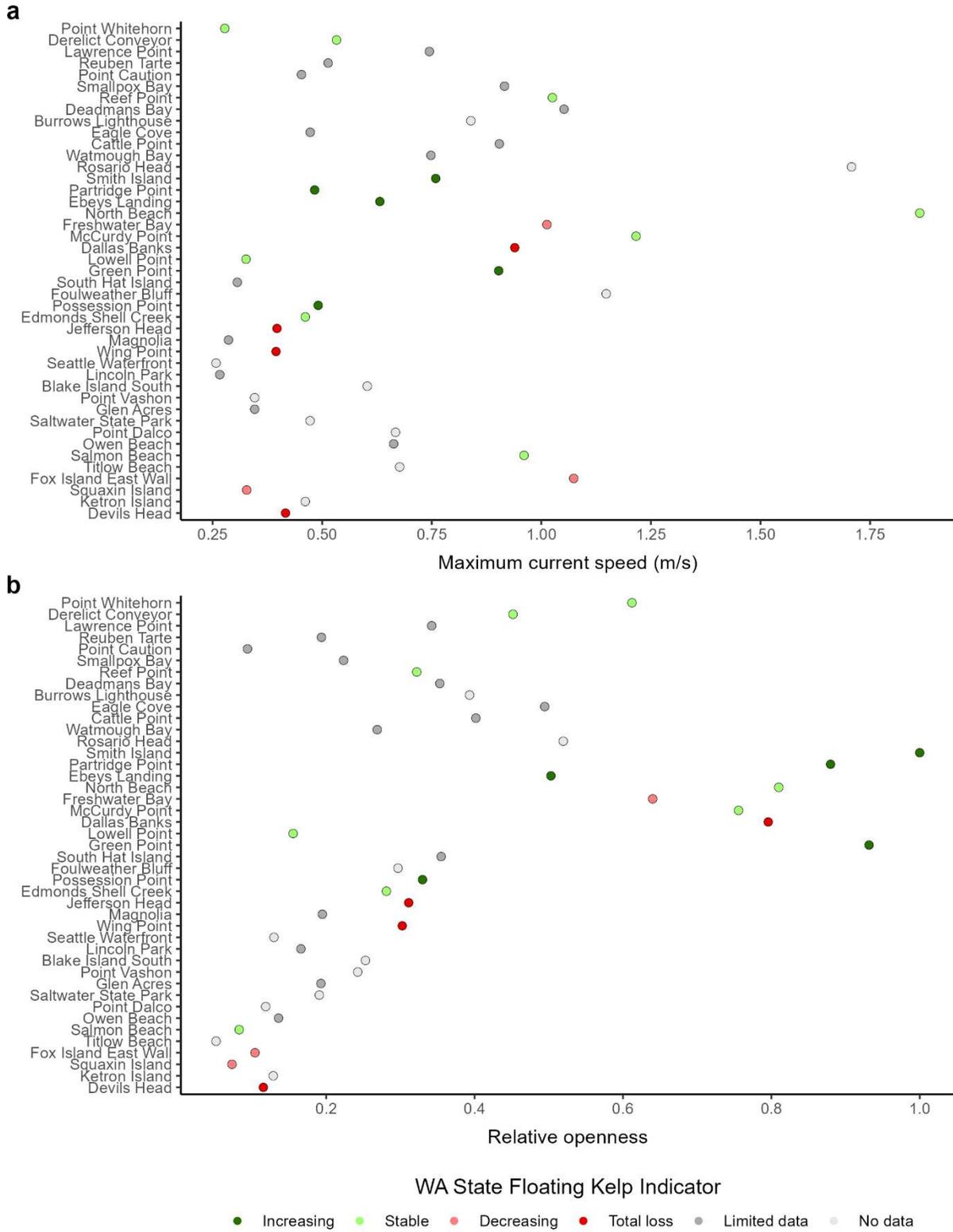


Figure 1-18. Mean daily maximum current speed and relative openness of Reef Check sites, classified by sites' WA State Floating Kelp Indicator trend. Sites are arranged by latitude (north to south).

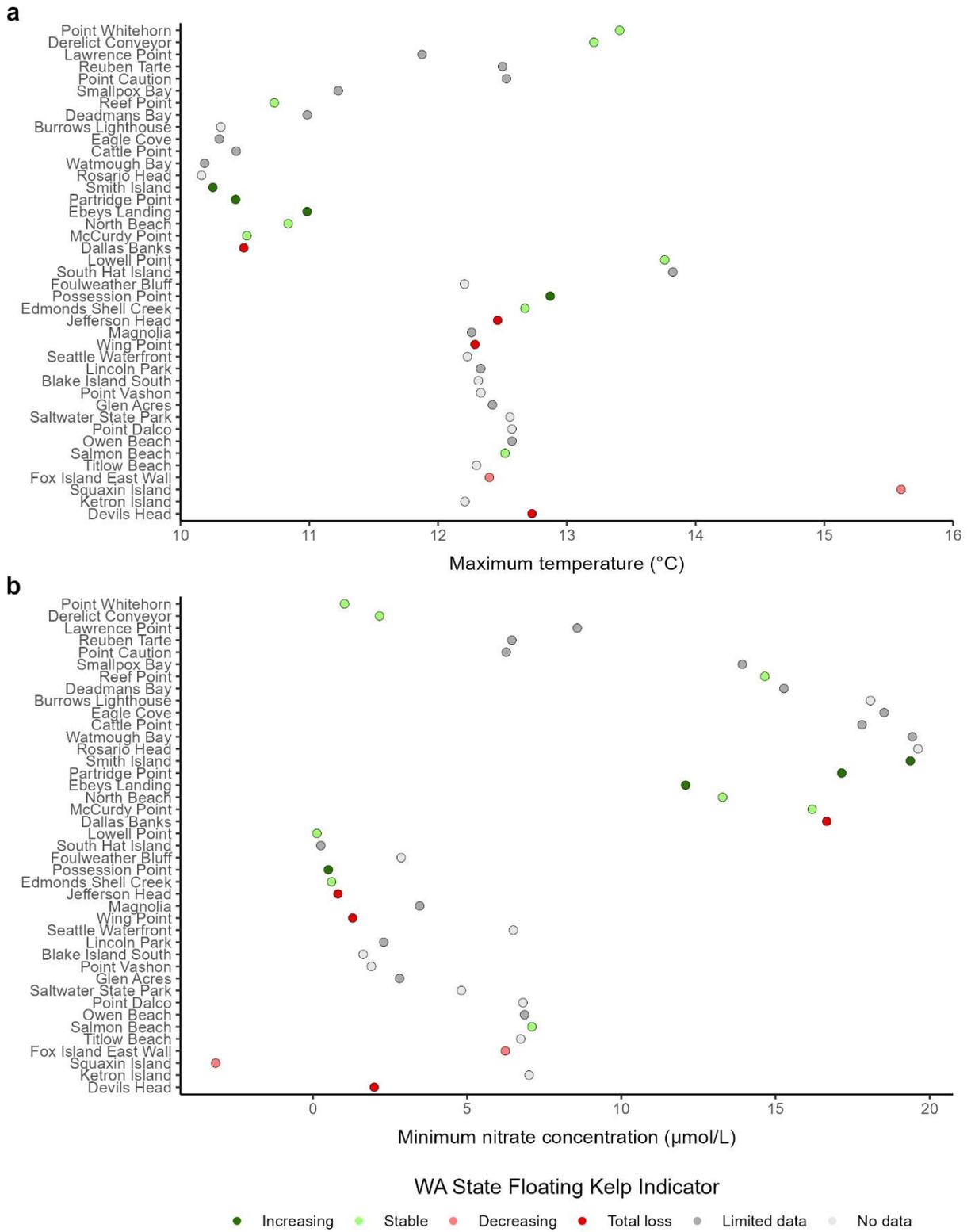


Figure 1-19. Mean maximum monthly temperature and mean minimum nitrate concentration for Reef Check sites, classified by sites' WA State Floating Kelp Indicator trend. Sites are arranged by latitude (north to south). Sites from the Olympic Peninsula west of Dungeness were excluded due to a lack of data.

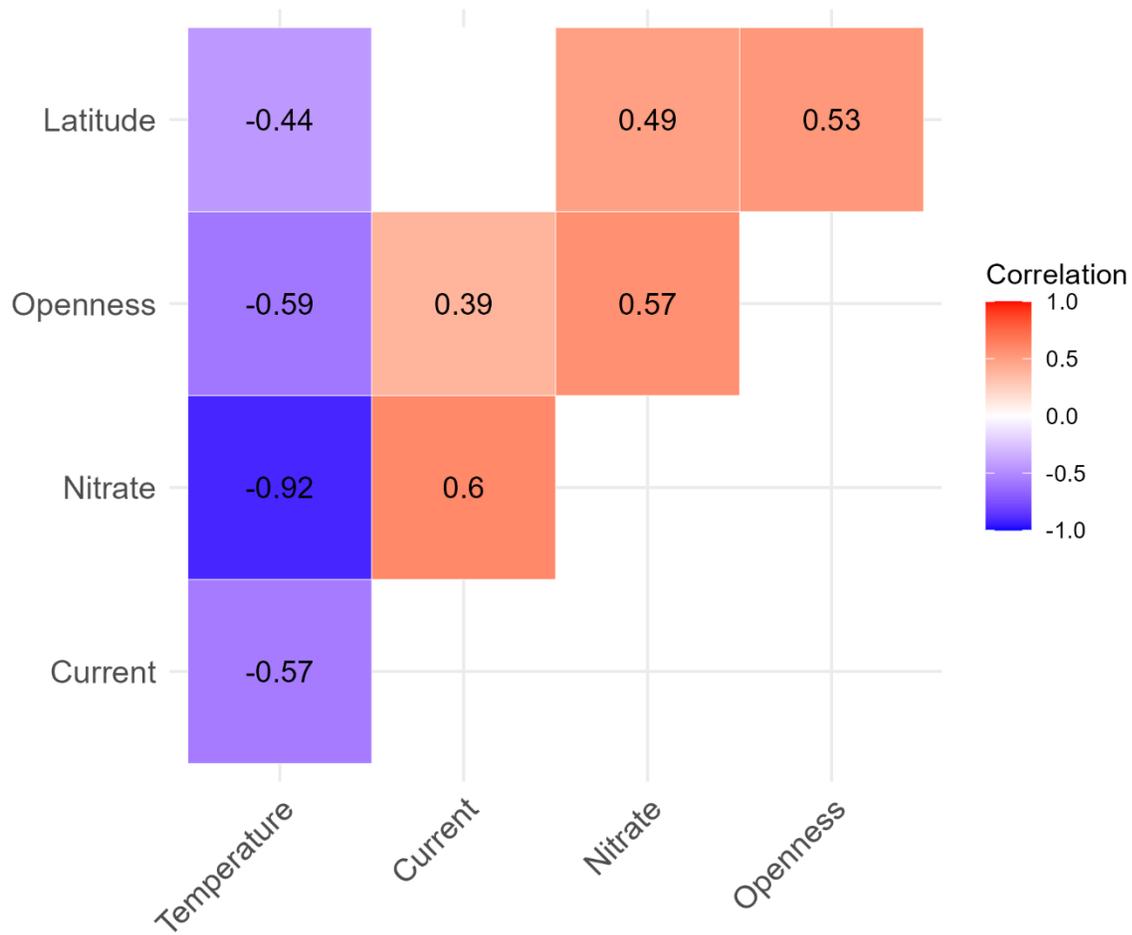


Figure 1-20. Correlations between the mean daily maximum current speed, relative openness, mean maximum monthly temperature, mean minimum nitrate concentration, and latitude of Reef Check sites. Only significant correlations were included in the plot. Sites from the Olympic Peninsula west of Dungeness were excluded due to a lack of data.

1.2.3 Environmental drivers and *N. luetkeana* density

Nereocystis luetkeana density varied across depths, although with few consistent patterns among sites (Figure 1-21a). *Nereocystis luetkeana* was present on transects ranging from 1 to 12 m below MLLW, with deep and shallow living bull kelp found at sites across regions. Across sites, the highest densities occurred between 2 and 7 m below MLLW. Within sites, the greatest relative densities occurred at a wide variety of depths (Figure 1-21b). Most often, relative density peaked on the shallower transects surveyed, however in a few northern sites (Point Whitehorn, Smallpox Bay, Cattle Point, and Smith Island) density peaked on the deeper transects.

Nereocystis luetkeana density varied inconsistently with water movement metrics. The highest densities across all Reef Check sites occurred at moderate current speeds (Figure 1-22) and low to moderate openness (Figure 1-22b). The lowest densities occurred across the full range of current speeds and openness, although absence was most common at low values of both metrics.

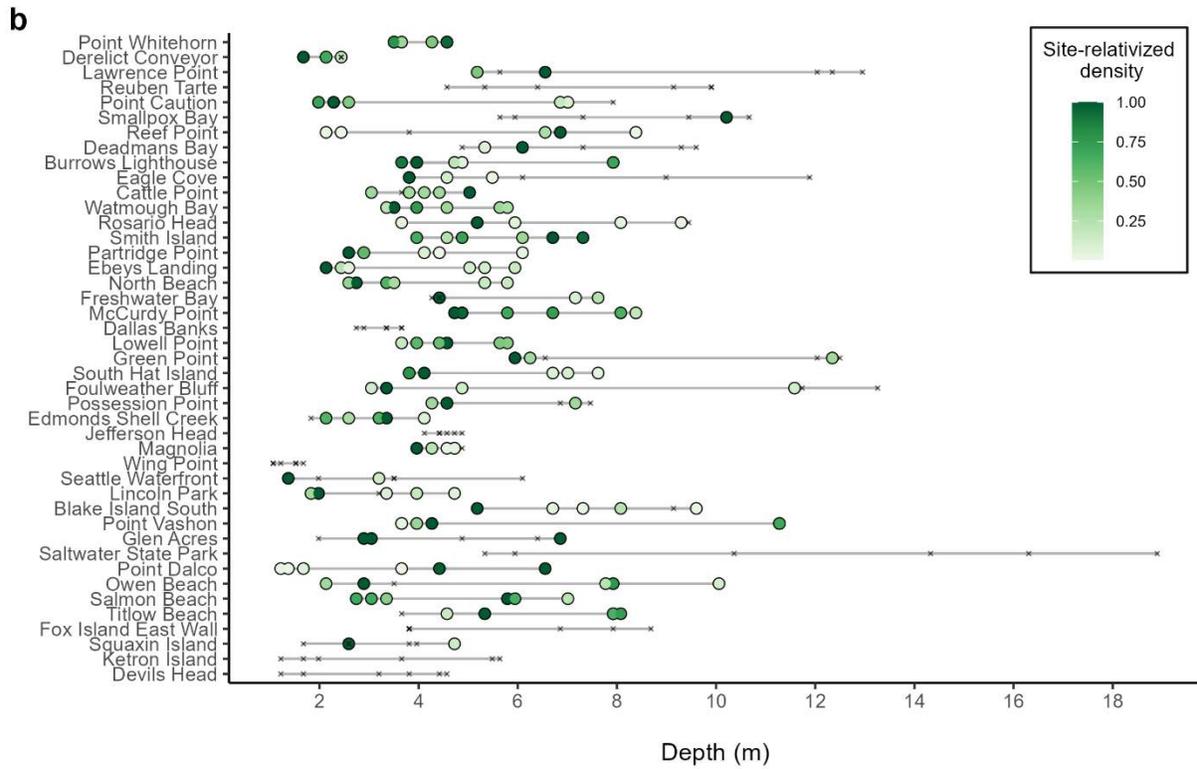
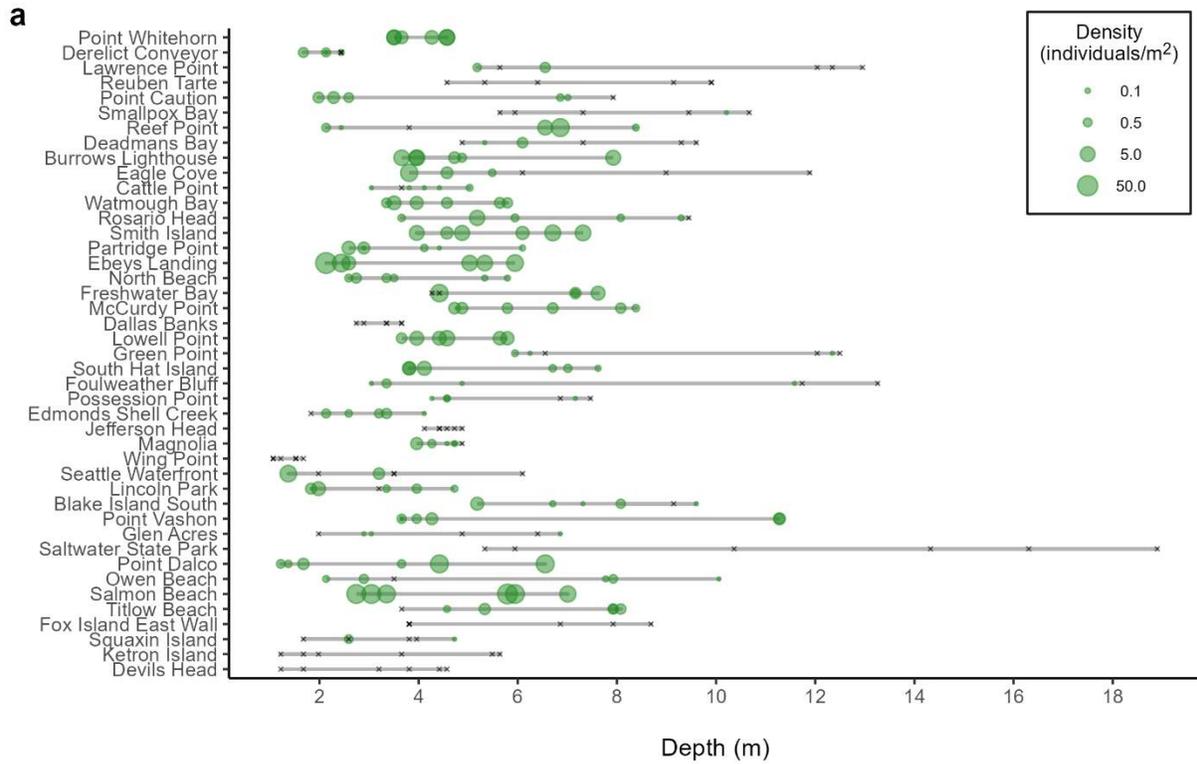


Figure 1-21. Transect-level a) density and b) site-relativized density of *Nereocystis luetkeana* across depth at Reef Check sites in 2023. Transects with no *N. luetkeana* present are marked with an x. Sites are arranged by latitude (north to south).

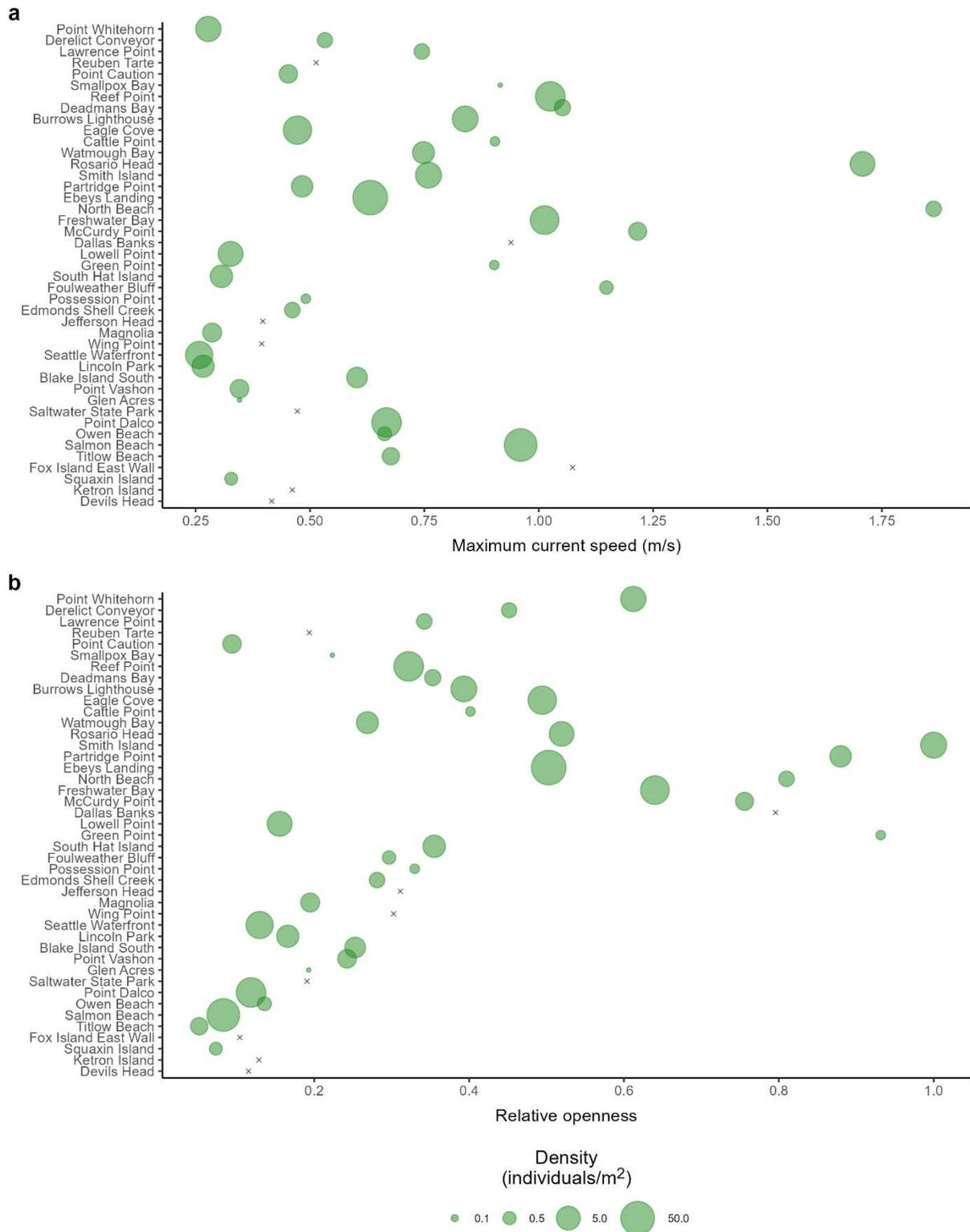


Figure 1-22. Mean density of *Nereocystis luetkeana* versus a) mean maximum current speed and b) relative openness at Reef Check sites in 2023. Transects with no *N. luetkeana* are marked with an x. Sites are arranged by latitude (north to south).

1.3 Discussion

In this synthesis, we aimed to describe the reefs which support Washington State's kelp forests, and assess how reef benthic composition, environmental conditions, and the state of the floating kelp *N. luetkeana* are interrelated. We found that benthic composition of reef sites varied across Washington State's Salish Sea. We identified spatial patterns in abiotic and biotic benthic composition across these sites, which are likely explained by spatial patterns in environmental drivers such as current, wind exposure, and temperature and nutrients. However, we did not identify consistent links between those benthic composition and environmental driver patterns and *N. luetkeana* density or persistence over time.

1.3.1 Patterns in benthic composition

Benthic substrate and community composition exhibited clear patterns within regions. Sites in the northern, adjoining regions of eastern Strait of Juan de Fuca and San Juan Islands tended to be rocky, with a benthic community dominated by coralline and fleshy encrusting algae, and brown macroalgae, including kelp. These sites had an understory made up of multiple kelps and related brown macroalgae, including *P. californica*, *P. gardneri*, *C. triplicata*, and *Desmarestia* spp., and a grazer assemblage that included urchins (especially *M. franciscanus*) and the giant chiton *C. stelleri*.

However, non-adjoining regions also shared similar within-region patterns. Strait of Georgia sites, which are geographically closer to eastern Strait of Juan de Fuca and San Juan Islands, more closely resembled sites within Admiralty Inlet, the Saratoga-Whidbey basins, and central and south Puget Sound. Sites in all these regions tended towards cobbly, pebbly and sandy benthic substrates, with less biotic cover overall and more sessile invertebrates, even though many benthic taxa were still present. The understory at these sites was dominated by sugar kelps (*S. latissima* and *H. nigripes*), which reached their highest densities at such sites, and *Pugettia* spp. kelp crabs were the only abundant grazer surveyed. The similarity between sites in the Strait of Georgia and in Puget Sound suggest that they share similar environmental conditions, despite being separated by other bodies of water.

Benthic composition at sites in and adjacent to the Tacoma Narrows resembled a mix of Puget Sound and eastern Strait of Juan de Fuca/San Juan Islands characteristics. Salmon Beach and Fox Island East Wall, for example, were rockier with fewer invertebrates and more encrusting algae and brown macroalgae than most Puget Sound sites. Along with Owen Beach and Point Dalco, they also supported understory kelp and grazing invertebrate taxa largely otherwise restricted to the Strait of Juan de Fuca and San Juan Islands sites. Tacoma Narrows therefore only somewhat resembled geographically close sites in Puget Sound, because their benthic composition also resembled the geographically distant sites of the eastern Strait of Juan de Fuca and the San Juan Islands. This suggests that Tacoma Narrows experiences a mix of environmental conditions, with some conditions resembling

those experienced in the rest of Puget Sound, while others more closely resembling conditions in the Strait of Juan de Fuca and San Juan Islands.

There were other exceptions to within-region patterns. These included Cattle Point in the San Juan Islands, which was sandier and lower in biotic cover than most sites in that region, the Seattle Waterfront, which was rockier than most central Puget Sound sites and supported urchins and chitons, and Wing Point, which had lower sessile invertebrate cover and more encrusting algal and brown macroalgal cover. These exceptional sites demonstrate the importance of substrate in determining biotic composition, since their regionally atypical substrate produced regionally atypical biotic cover. These patterns likely reflect local geography or bathymetry in the case of Cattle Point and Wing Point, and human activity in the case of Seattle Waterfront, and could provide further insights through comparisons with nearby sites that experience similar environmental drivers but more regionally-typical substrate and species composition.

Overall, our results indicated that kelp forest benthic communities exist in a number of forms across Washington State's Salish Sea. This is consistent with previous studies of these regions, which noted large compositional differences between *N. luetkeana* forests between southern Salish Sea regions (Shaffer and Parks 1994; Shaffer 2000). Communities in most of Puget Sound and the Strait of Georgia supported only a few understory macroalgae, one of which (*S. latissima*) was highly abundant, and a single genus of surveyed grazing invertebrates (*Pugettia* spp.). Communities in the San Juan Islands and eastern Strait of Juan de Fuca supported these same understory and invertebrate taxa plus others not found in Puget Sound, including multiple grazers from two additional phyla. Consequently, the biotic interactions occurring in these regions likely differ in strength. While more understory taxa are competing for light and substrate in the San Juan Islands and eastern Strait of Juan de Fuca, grazing pressure on the substrate is likely much higher as well and likely plays a greater role in community composition. In comparison, in Puget Sound and the Strait of Georgia, fewer understory taxa are present to compete for space, however with less rocky substrate available and few grazers to free up space, competition may be a more important factor in community composition.

1.3.2 Benthic composition and environmental drivers

Environmental drivers also exhibited clear regional patterns, similar to those identified for benthic composition. The majority of sites in the adjoining San Juan Islands and eastern Strait of Juan de Fuca regions experienced moderate to high water movement as a result of current speed, openness, or a combination of both. These conditions likely favoured similar substrates, since moderate to high water movement creates a net export of sediment, leaving rocky substrates exposed instead of buried by silt, sand, or smaller rocks (Airoldi 2003). Clear rocky substrates provide suitable habitat to the benthic organisms which are characteristic of both regions, such as calcified and non-calcified encrusting red algae, grazing invertebrates which prefer rocky substrate for locomotion (i.e. *C. stelleri*, *S. purpuratus*, and *M. franciscanus*) (Schroeter 1978; Yates 1989; Starko et al. 2022), and brown macroalgae which need more stable substrate for anchoring (i.e. *P. californica*)

(Rose 1979; Connell 2005; Rubin et al. 2017). Most sites in in the San Juan Islands and eastern Strait of Juan de Fuca also experienced lower maximum sea surface temperatures and higher minimum nitrate concentrations. These conditions, alongside water movement are highly suitable for growth and survival of the previously listed kelp taxa, which are typically found in cooler, mixed, and rocky environments (Luning and Freshwater 1988; Konar and Roberts 1996; Gaylord and Denny 1997). Conditions which favour growth of these kelp may also favour the grazing invertebrates listed above by increasing food availability (Harrold and Reed 1985; Watanabe and Harrold 1991).

Patterns in environmental drivers also explained patterns in benthic composition in other regions, including non-adjoining ones. Most sites in Puget Sound (including Admiralty Inlet and the Saratoga-Whidbey basins but not the Tacoma Narrows) and sites in the Strait of Georgia had higher sea surface temperatures and lower nitrate concentrations. These conditions may not be favourable to the previously mentioned kelp species but clearly allow other macroalgae such as *C. costata*, *S. latissima*/*H. nigripes*, and *Desmarestia* spp. to persist (Luning and Freshwater 1988; North et al. 1990). These species may be more physiologically tolerant, or they may grow and reproduce more rapidly, to avoid the high temperatures and low nutrient concentrations experienced in these regions during peak summer (Luning and Freshwater 1988; Maxell and Miller 1996; Johannessen et al. 2021; Fales et al. 2023). As well as water quality, the low to moderate water movement in these regions is consistent with their benthic communities. As a result of low current speed or low relative openness in Puget Sound, and low currents and moderate openness in the Strait of Georgia, sediments would regularly accumulate, reducing the availability of any hard substrate present and leading to lower biotic cover all, as observed in these regions (Neushul 1967; Airoidi 2003; Mullan 2017; Mantelatto et al. 2022). The lack of hard substrates would explain why encrusting algae were less abundant at Strait of Georgia and Puget Sound sites, and why several invertebrate and macroalgal taxa found in rockier regions were excluded entirely. The brown macroalgae which were present in these regions, such as *Costaria costata* and *S. latissima* may be better suited to surviving on unconsolidated or unstable substrates (Dayton 1985; Maxell and Miller 1996; Rubin et al. 2011; Picard et al. 2022). These species were often seen living attached to pebbles or totally unattached over sand at sites in these regions surveyed in 2024 (R. Hansen, pers. common).

The one study region with benthic composition patterns that were a mix of those common in adjoining regions (Puget Sound) and non-adjoining regions (San Juan Islands/eastern Strait of Juan de Fuca) regions also experienced intermediate environmental conditions. Sites in and around the Tacoma Narrows, most of which were rockier than sites in other parts of Puget Sound, experienced higher water movement than most Puget Sound sites, as a result of higher currents. This corresponded to greater cover by encrusting algae and brown algae and the presence of understory macroalgal taxa and grazing invertebrates that were more common in the San Juan Islands and eastern Strait of Juan de Fuca.

There were exceptions to this complementarity between environmental drivers and benthic composition. Sites in the northern San Juan Islands, closer to the adjoining Strait of Georgia

region, had warmer and more nutrient poor water conditions. However, their community composition was still typical of the San Juan Islands region. Similarly, while nitrate concentrations in the Tacoma Narrows were higher than those in the rest of Puget Sound, maximum temperatures were also higher than most Puget Sound sites, yet the communities which occurred at several Tacoma Narrows sites resembled those of cooler regions. This may indicate that temperature is less important in determining community composition than water movement and substrate. This may also reflect limitations in the interpolation method used to infer local temperatures from water quality data sampled in other waterbodies, discussed below.

Overall, our analyses of the Reef Check dataset suggest that Washington's kelp forests currently occur across a wide range of environmental conditions, and these conditions shape the benthic composition of these ecosystems. The geography of the southern Salish Sea produces an inherently variable marine environment via spatial differences in bathymetry, wind fetch, tidal currents, and riverine inflow (Masson 2006; Sutherland et al. 2011; Banas et al. 2015; Mullan 2017; Yang et al. 2019). These differences produce spatial gradients in light, temperature, nutrient concentrations, salinity, and substrate composition (Masson and Peña 2009; Peña et al. 2016; Mullan 2017). For example, less mixing of surface waters with deep waters in basins such as the Strait of Georgia, the Saratoga-Whidbey basins and south and central Puget likely explained the higher temperatures and lower nutrient concentrations we reported for these regions, relative to better mixed waterbodies like the Strait of Juan de Fuca, the channels of the San Juan Islands, Admiralty Inlet, and the Tacoma Narrows (Moore et al. 2008; Masson and Peña 2009). These oceanographic differences between basins and channels explain why sites and regions which are geographically close may not resemble each other in terms of benthic composition and may instead resemble more distant sites and regions.

However, current environmental conditions also reflect anthropogenic influences. Climate change has resulted in gradual warming of sea surface temperatures, meaning the maximum temperatures reached at sites now are likely warmer than the maxima reached historically (Masson and Cummins 2004; Pfister et al. 2018). Climate change has also increased frequency of extreme climate events, like the 2014-2017 Northeast Pacific Marine Heatwave, which increased surface ocean temperatures in the Salish Sea (by as much as 2.3 °C in Puget Sound) while reducing nutrient concentrations in surface waters (Khangaonkar et al. 2021). More localized human activities may also have influenced conditions experienced at our study sites. Basins like Puget Sound are at a higher risk of nutrient loading, because of input of pollutants from a high number of coastal communities (including large cities) and long residence times which reduce flushing of nutrient inputs out of the region (Mackas and Harrison 1997; Khangaonkar et al. 2012). A combination of local human activities releasing sediment and climate change related changes in precipitation may also have affected sediment dynamics in our study regions, by increasing sediment inputs via rivers and runoff, and increasing coastal erosion (Shaffer 2000; Airoldi 2003; Syvitski et al. 2005; Lee et al. 2016; Rubin et al. 2017).

Considering variation in benthic composition and environmental conditions as both a historical reality and the product of our current realities is important for contextualizing our results. Some benthic communities described in this report closely resemble past assemblages (e.g. low grazer diversity in Puget Sound, reported by Andrews (1925) in (McLean 1962)), while others may have experienced considerable changes. Little or no comparable historical subtidal data exist for sites in this report (although see Vadas (1968) , (Maxell and Miller 1996) Shaffer and Parks (1994), Maxell and Miller (1996), and Rubin et al. (2011)), meaning we cannot establish a baseline for benthic composition, we can only document spatial variation and compare this variation to better documented changes, such as floating kelp canopy extent.

1.3.3 *Nereocystis luetkeana* density and dynamics

Sites with concerning temporal trends in *N. luetkeana* exhibited some definable patterns in terms of benthic composition, environmental conditions, and region. Most sites with zero *N. luetkeana* recorded by Reef Check in 2023 and a negative floating kelp trend (“Decreasing” or “Total Loss”) for floating kelp were located in Puget Sound, and many of these were in south Puget Sound specifically. Most of these sites were dominated by smaller, sandier substrates and had low openness, high sea surface temperatures, and low nitrate concentrations, which are all characteristics consistent with broader Puget Sound conditions. However, negative floating kelp trend sites varied widely in biotic community composition and current speed.

In comparison, sites with positive temporal trends for *N. luetkeana* exhibited very few patterns in terms of benthic composition, environmental conditions, and region. Sites with a positive floating kelp trend (“Stable” or “Increasing”) were found in every region except south Puget Sound, and sites with moderate densities of *N. luetkeana* in 2023 were found in every region except south Puget Sound and Admiralty Inlet. While most sites had higher proportions of rocky substrate and many had moderate to high openness, they varied widely in terms of biotic community composition, current speed, maximum temperature, and minimum nitrate concentration.

This suggests that the persistence of *N. luetkeana* is limited by different environmental conditions across different regions and sites. While conditions such as high temperatures, low nutrient concentrations, and low water movement are clearly challenging for *N. luetkeana* (Berry et al. 2021; Fales et al. 2023; Mora-Soto et al. 2024a), its historical presence across reefs which experience a wide range of these conditions naturally suggests that to a certain degree, these conditions do not necessarily prevent *N. luetkeana* from persisting. The region with the worst *N. luetkeana* outcomes, south Puget Sound, did experience high temperatures and low nutrients. However, sites in the Strait of Georgia and Saratoga-Whidbey basins exhibited positive outcomes despite experiencing comparable water quality conditions. While temperatures have increased as a result of anthropogenic climate change, it is unclear whether the effects of gradual warming on current temperatures pose a challenge to *N. luetkeana*, or whether the losses of *N. luetkeana* we

see currently are the largely the result of extreme temperatures (and low nutrient concentrations) during the 2014-2017 marine heatwave (Khangaonkar et al. 2021). It is also unclear whether conditions during that extreme event exhibited parallel spatial patterns, or whether regions like south Puget Sound experienced more severe effects. Without baseline data for the full range of temperature and nutrient conditions that *N. luetkeana* historically survived, it is challenging to determine where and when these conditions have led to loss or resilience.

The natural variation in benthic composition across our study also makes it challenging to identify characteristics associated with certain outcomes for *N. luetkeana* sites. While hard substrate availability likely limits *N. luetkeana* under some circumstances, our results show *N. luetkeana* can exist at considerable densities where hard substrate availability is low (e.g. Lowell Point, Point Dalco, Point Vashon) and can struggle even where hard substrate availability is high (e.g. Freshwater Bay, Fox Island East Wall). A previous study of a Puget Sound *N. luetkeana* population following a coastal landslide found that *N. luetkeana* survived moderate sedimentation and turbidity (Shaffer and Parks 1994). While sedimentation may have increased as a result of human activity, without baseline data for historical benthic substrate composition, it is hard to assess whether loss of *N. luetkeana* has occurred alongside increased sedimentation, or whether these conditions have been a historical reality for *N. luetkeana*. Similarly, *N. luetkeana* persisted across a wide range of biotic communities, most of which included understory macroalgae, and many of which also included grazing invertebrates. Urchin grazing can even be an important mechanism for *N. luetkeana* persistence, because it prevents competitive dominance by perennial kelp (Vadas 1968; Duggins 1980). While herbivory and competition for space and light can affect *N. luetkeana* density (Vadas 1972) , without historical baselines, it is hard to determine if either of these processes have become more negative within the Salish Sea. While a change in the density of competitors or herbivores over time at sites with poor *N. luetkeana* outcomes would suggest these processes contributed to kelp loss, the data currently available only inform us that certain regions are more likely to be affected by these processes.

For example, competition between *N. luetkeana* and understory macroalgae for space and light may be more of a concern where hard substrate is limited, and where grazers of younger macroalgal life stages like urchins and chitons are absent, such as central and south Puget Sound. In this region, large losses of *N. luetkeana* during the 2014-2017 marine heatwave could have reduced the shading effects of *N. luetkeana* and allowed understory algae to become dominant, whereas in regions like the San Juan Islands and eastern Strait of Juan de Fuca, the presence of grazers could have kept understory algae low, allowing *N. luetkeana* populations to re-establish once conditions were cooler. Without baseline data, however, this cannot be demonstrated through monitoring data, like those collected by Reef Check surveys.

1.3.4 Limitations

Reef Check surveys provided comprehensive benthic monitoring data for a large number of sites across almost all regions of Washington’s Salish Sea. However, surveys did not sample across depths consistently, limiting their use for assessing variation in depth distributions of *N. luetkeana* and other subtidal species. Variation in the depths surveyed reflected variation in where rocky reef habitat occurred, since reef extent determined where Reef Check surveys occurred (Jackie Selbitschka, pers. comm). Reef Check surveys also occurred across multiple months in the growing season, meaning their estimates of macroalgal density do not always represent peak density across all sites.

As a SCUBA-based method, Reef Check surveys also covered relatively small areas of coastline, and in some cases may have surveyed outside of the main floating kelp bed as a result of site access issues (Jackie Selbitschka, pers. comm.). Previous efforts to identify environmental conditions associated with *N. luetkeana* resilience or loss have succeeded using aerially-mapped canopy extent instead (Mora-Soto et al. 2024a; Mora-Soto et al. 2024b). Since site-specific measurements of most environmental metrics are not available, broader but coarser aerial maps of *N. luetkeana* abundance may be scaled appropriately to the relatively coarse estimates of wind exposure, current, temperature, and nutrients used in our analyses. The small-scale nature of Reef Check’s SCUBA surveys may also have led to some spatial mismatches between each site’s *N. luetkeana* density estimate and floating kelp trend, since the floating kelp indicator was assessed using floating canopy data, which can be collected over a much larger area (Kelp Forest Monitoring Alliance of Washington State 2024).

Currently, Reef Check data also lack a historical baseline for comparison. Surveys in Washington began five years after the 2014-2017 Marine Heatwave, meaning they did not capture the immediate effects of this event. Lag effects following heat stress are common, meaning the surveys which have occurred may still reflect the effects of this stressor (Schroeder et al. 2019; Selgrath et al. 2024). If surveys continue into the future, however, the data analyzed in this report will act as a baseline for assessing future changes to kelp forests in Washington, whether those changes be recovery or continued loss.

The WA State Floating Kelp Indicator provided a succinct descriptor of *N. luetkeana* dynamics across the study regions. However, many Reef Check sites were classified as either “No data” or “Limited data”, meaning they did not inform our assessment of patterns in benthic composition and environmental conditions across positive and negative outcomes of *N. luetkeana*. In particular, all but one site in the San Juan Islands, and half of sites in central Puget Sound were classified as “Limited” or “No data”, meaning there was greater uncertainty in our understanding of how benthic composition relates to *N. luetkeana* dynamics in these regions. Continuing to collect data to inform this index would help improve our understanding of these patterns. Another limitation of the kelp indicator is the timespan of data available for defining trends in floating kelp. The monitoring data used to measure change in *N. luetkeana* density have only been collected since 2013, and many sites have only been monitored starting in more recent years (Kelp Forest Monitoring

Alliance of Washington State 2024). This means that sites classified as “Stable” may still have supported much higher floating kelp densities in the past, but any losses before the first year of monitoring cannot be captured by the indicator. Using historical data to establish earlier baselines, as demonstrated by Berry et al. (2021), remains an important part of understanding kelp losses over time.

Spatial limitations of the water movement and water quality data used in this report also affected our findings. Current speeds were calculated using the Salish Sea Model’s mesoscale nodes, which may not accurately capture fine-scale variation in currents (Danielle Claar, pers. comm.). For example, we found that the Squaxin Island site had lower current speeds than other sites in south Puget Sound, despite local knowledge suggesting currents are high at this site (Julia Ledbetter, pers. comm.). Temperature and nutrient data, meanwhile, were obtained from the Department of Ecology water monitoring program which has low spatial coverage outside of Puget Sound. Several sites on the Olympic Peninsula could not be analyzed at all, while in the San Juan Islands values for sites within smaller passages where mixing likely occurs were interpolated from distant stations in larger waterbodies (Mullan 2017). Even within Puget Sound in areas of high oceanographic complexity, there was a lack of data from within the Tacoma Narrows proper, meaning values were partially interpolated from the Port of Tacoma area, which may be different from the Narrows themselves. Supplementing Department of Ecology data with other local temperature and nitrate measurements or with remote sensing data would increase the accuracy of our analyses. Alternatively, using more complex interpolation methods that are informed by oceanographic information, not just physical proximity, could also improve the accuracy of water quality metrics.

Temporal limitations of the water quality data used in this report also limited what analyses were possible. Measurements were typically recorded once a month at each station for temperature, and once every two months at each station for nitrate concentration. Lack of continuous data, especially through the marine heatwave years, meant we could not assess how often (if at all) temperatures exceeded physiological thresholds for *N. luetkeana*, and when and where this co-occurred with low nutrient levels. If these data were available, analyses similar to Pontier et al. (2024) would allow us to assess how often conditions were suitable for growth at each site, which would be very useful for assessing how much these factors currently limit *N. luetkeana* persistence in different regions.

1.3.5 Future directions

Establishing baselines that are broad both spatially and temporally should be a focus of future research. Subtidal studies done within Washington’s Salish Sea in the second half of the 20th century, such as those led by researchers at Friday Harbor Laboratories, could provide data on the past substrate and biotic community composition of our study regions. Other sources of information could be historical imagery, information from the grey literature i.e. government and industry reports, as well as the private documents (e.g. dive logs) of SCUBA divers (or their estates) from that time period. Increasing site-specific

historical knowledge, while not likely to be possible for all Reef Check sites could provide valuable information at a subset of sites.

Another goal of future research should be supporting observed correlations with experimental manipulations. Experiments at specific sites could test where factors such as competition, herbivory, or substrate limitation may be influencing *N. luetkeana* populations at a local level. For example, in regions where *Sargassum* spp. occurred at higher densities i.e. the Strait of Georgia, northern San Juan Islands, and central and south Puget Sound, experimental removals of *Sargassum* could demonstrate whether this introduced and possibly invasive alga has a negative impact on *N. luetkeana* at specific sites, as predicted (Berry et al. 2021). While experiments alone would not confirm whether a specific factor was responsible for the observed historical changes, if paired with the historical research suggested above, it would lead to more definitive conclusions.

Finally, accounting for *N. luetkeana* dynamics during the spore and gametophyte life phases, when visual census methods like those used by Reef Check cannot detect *N. luetkeana* should also be a focus of future research. Sampling substrates using eDNA methods could provide a metric of presence/absence for *N. luetkeana* gametophytes (Schoenrock et al. 2021) and modelling studies of propagule dispersal in regions with low adult *N. luetkeana* density (e.g. south Puget Sound) could identify sites where low connectivity may limit *N. luetkeana* recovery.

1.3.6 Conclusions

The spatial heterogeneity of Washington's Salish Sea has produced a diversity of shallow benthic habitats that can support kelp forests. These forests, only some of which occur on true reef (bedrock) habitat, include both floating and understory kelps, alongside multiple grazing invertebrates. These biotic communities form under a range of wave, current, temperature and nutrient conditions, which are reflected in the benthic composition of each forest. While this variation is natural and valuable, it makes identifying the characteristics which make sites prone to resilience or loss of floating kelp very challenging. When so many benthic composition and environmental conditions can support kelp forests, it is hard to determine which factors affect floating kelp at a given site, and whether these factors represented a recent change in ecosystem dynamics. Understanding what kelp forests look like now, studying the factors that could be at play for floating kelp persistence, and continuing to monitor these kelp forests into the future represent our best hope for conserving these important ecosystems.

1.4 Bibliography

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2 Summary of Two Existing Environmental Datasets

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This chapter analyzes two existing environmental datasets. These datasets are:

1. Washington Department of Ecology Marine Water Monitoring
2. Salish Sea Model 2014 solution currents

2.1 Ecology Marine Water Monitoring

The Washington State Department of Ecology (Ecology) initiated a marine water monitoring program in 1967 with stations distributed in Puget Sound, Willapa Bay and Gray’s Harbor. The focus of the program has changed over time with initial focus on municipal and industrial discharges giving way to quantifying “ambient water quality in the context of the estuarine physical processes” (Pool et al., 2025). Ecology currently distributes data starting from 1999 through their public web site.

Our understanding is that in the past, float planes were used for monthly field visits to the monitoring stations. Now, research vessels are used (Pool et al. 2025). Field activities include in-situ marine water measurements and water sample collection through the water column with a CTD (conductivity-temperature-depth) instrument. Water samples are used for laboratory analysis of physical and biotic parameters.

The R code used here for data integration, transformation, summary and visualization are available in a public repository:

https://github.com/WA-Nearshore/Ecology_marine_water_monitoring_processing

A public web app was constructed for the purpose of easy browsing of the dataset prepared from the downloaded Ecology monitoring dataset:

<https://experience.arcgis.com/experience/94aa60295f53496fbd6327c829d18d8a>

2.1.1 Data Acquisition

On Ecology’s web page for Marine Monitoring Unit⁶, a link to ‘download marine water column data’ directs users to Ecology’s public facing data repository – Environmental Information Management (EIM) – for data access.

In June 2024, we downloaded all available marine water monitoring data from EIM in a series of separate files. Once these data were integrated, we found that the latest data included was from 2017. There was no data from more recent years.

In response to an email inquiry, Ecology explained that the EIM was not being updated due to limited program resources, but that the complete dataset, including the more recent

⁶ <https://ecology.wa.gov/research-data/monitoring-assessment/puget-sound-and-marine-monitoring>

data, was available from a different web page⁷ in netCDF format (Suzan Pool, personal communication, June 2024).

In June 2024, we downloaded all available annual netCDF files which spanned 1999 through 2023, although 2023 data was not complete.

We also included data from a previous download from Ecology in 2018 as part of a different project (Berry et al. 2021). This data was collected at a station in the Tacoma Narrows, NRR001. The data for this station was limited and older (Nov. 1989 through Sept. 1991) and is not included in the currently available netCDF download files (or in EIM). Despite these limitations, given the importance of the Tacoma Narrows for floating kelp, the previously acquired water temperature data for station NRR001 was included as source data for this project.

The following sections include dataset preparation (section 2.1.2), data characteristics (section 2.1.3) and station comparisons (section 2.1.4) based on the data described above. This data has a time span of 1999 to 2023 with a limited data from 1989-1991.

The trend analysis (section 2.1.5) was conducted much later in September 2025. In order to have data from 2024 included in the analysis, the most recent netCDF data files were downloaded from Ecology that extended the time span of the dataset through 2024 (complete) and into 2025 (incomplete).

2.1.2 Dataset Preparation

All data was extracted from the annual netCDF files in the form of one-dimensional vectors. The annual vectors were concatenated for each variable extracted. These concatenated vectors were grouped based on vector length and organized into related tables containing records for measurements, profiles and stations (Figure 2-1). Another table compiles attributes for each variable.

The data for the Tacoma Narrows station previously acquired in 2018 was formatted to match the more recent data format and integrated with the data acquired in 2024.

Stations outside the study area for this kelp resilience project were removed. These removals included stations in Hood Canal, Gray's Harbor and Willapa Bay.

Different indicators of problematic data values were consolidated under the convention of assigning NA (not available) for the measured data value. This consolidated the following cases:

- the measurement data value was already NA (in which case the value was retained).

⁷ <https://ecology.wa.gov/Research-Data/Monitoring-assessment/Puget-Sound-and-marine-monitoring/Water-column-data>

- the measurement data value was the missing data value (-99999.99).
- the value of the QA variable associated with the measured variable was either 1 (fail) or 0 (no QA value available). Data available for analysis then only includes cases where the QA variable is 2 (pass).

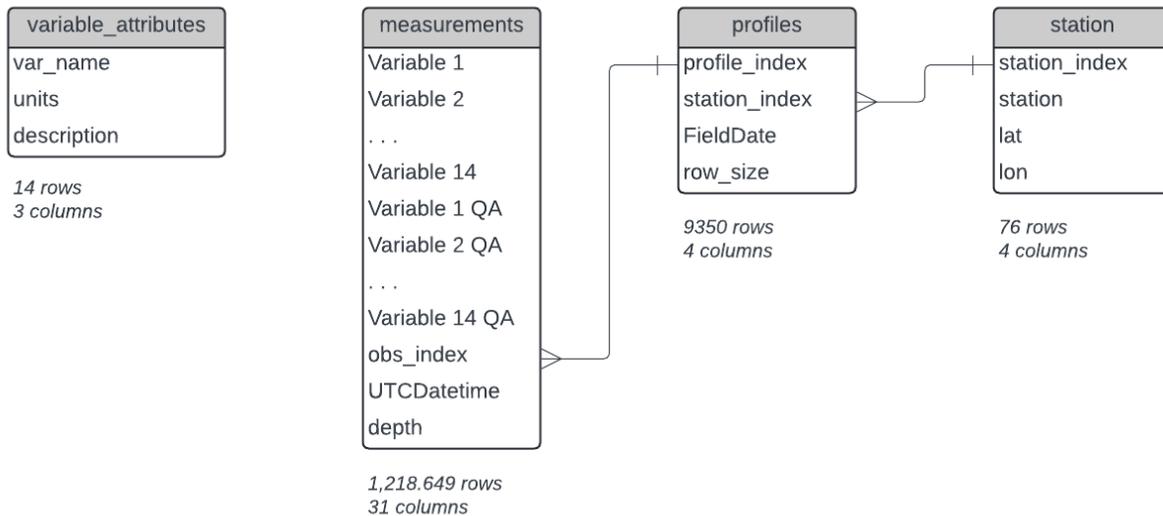


Figure 2-1. An entity-relationship diagram of the data tables assembled from the vectors as extracted from the Ecology marine water monitoring netCDF data files. Four tables are shown with column names in a list. The table connectors show the related keys in the tables and the one-to-many relationships. This version of this dataset downloaded in June 2024 includes measurements of 14 variables at 1,218,649 discrete points organized into 9,350 profiles across 76 stations. The contents of the *variable_attributes* table are shown in Table 2-1.

To make the measurements table more convenient for later analysis, the station information was joined onto it. First the stations table was joined to the profiles table using *station_index* as the shared key. Then the result of this join was joined onto the measurements table using *obs_index* and *profile_index* as keys.

2.1.3 Overview of the Data

The data include 14 measured variables (Table 2-1) and 14 matching QA variables that take values 0 (no QA value available), 1 (fail) or 2 (pass).

The five nutrient variables (phosphate, silicate, ammonium, nitrite, nitrate) are based on laboratory analysis of discrete water samples collected typically at several depths. The other variables are based on various in-situ sensor measurements made through the water column at 0.5 meter depth increments (CTD casts).

Table 2-1. The measured variables contained in the Ecology marine water monitoring dataset as compiled from 1999-2023 netCDF files with variable name, units and short description as contained within the data files. Each measured variable has a companion QA variable (not shown) that can take one of the values 0 (no QA value), 1 (fail) and 2 (pass).

	Variable name	Units	Description
1	PO4	micromoles L ⁻¹	Discrete phosphate
2	SiOH4	micromoles L ⁻¹	Discrete silicate
3	NH4	micromoles L ⁻¹	Discrete ammonium
4	NO2	micromoles L ⁻¹	Discrete nitrite
5	NO3	micromole L ⁻¹	Discrete nitrate
6	Xmiss_25cm	%	In situ seawater light transmission using a 25-cm path length
7	BatC	1 m ⁻¹	In situ beam attenuation in seawater
8	FluorAdjusted	mg m ⁻³	In situ chlorophyll fluorescence in seawater
9	Turb	NTU	In situ seawater turbidity
10	DOAdjusted	mg L ⁻¹	Concentration of in situ dissolved oxygen in seawater; adjusted for sensor drift.
11	Salinity	PSU	in situ seawater salinity
12	Density	kg m ⁻³	in situ seawater density in sigma-t, kg/m ³
13	Cond	S m ⁻¹	in situ seawater conductivity
14	Temp	degree_C	in situ seawater temperature

There are 55 stations in the dataset used for this study (Figure 2-2). These include the 76 stations in the Ecology dataset acquired in June 2024 plus the addition of NRR001 data acquired in 2018 and the removal of 22 stations that were outside the study area for this project.

Data availability varied by station and by variable. Figure 2-3 illustrates for temperature how some stations have relatively unbroken monthly data in the 1999-2023 period while other stations have only been sampled on a rotational basis for a year at a time. Other stations have only been sampled in one discrete interval, typically a year.

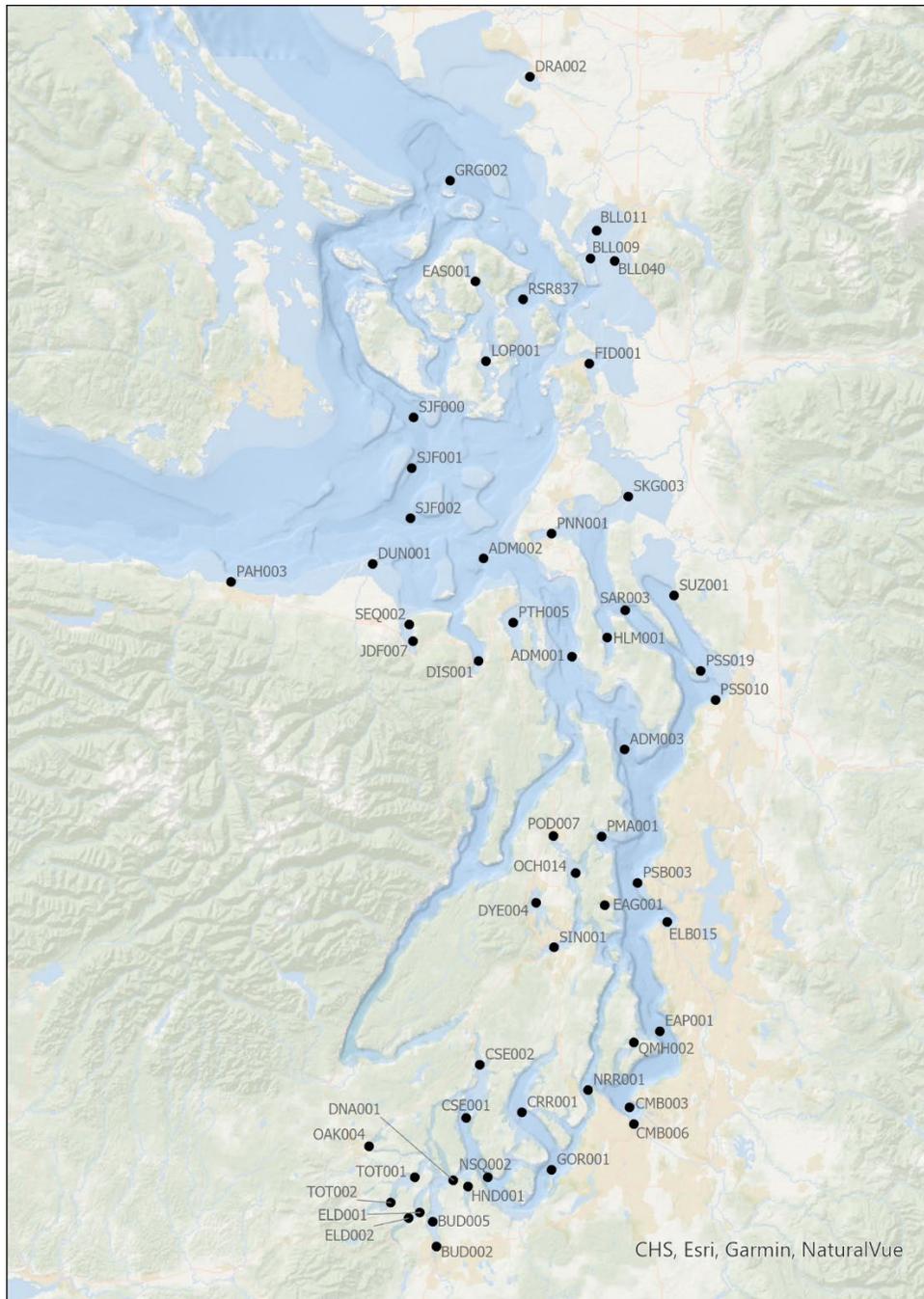


Figure 2-2. The 55 Ecology marine water monitoring stations used in this study. This includes stations contained in the data downloaded from Ecology in June 2024 with two modifications: (1) data from station NRR001 in the Tacoma Narrows was added from an earlier download in 2018 and (2) stations outside the study area were removed, including stations in Hood Canal, Gray's Harbor and Willapa Bay.

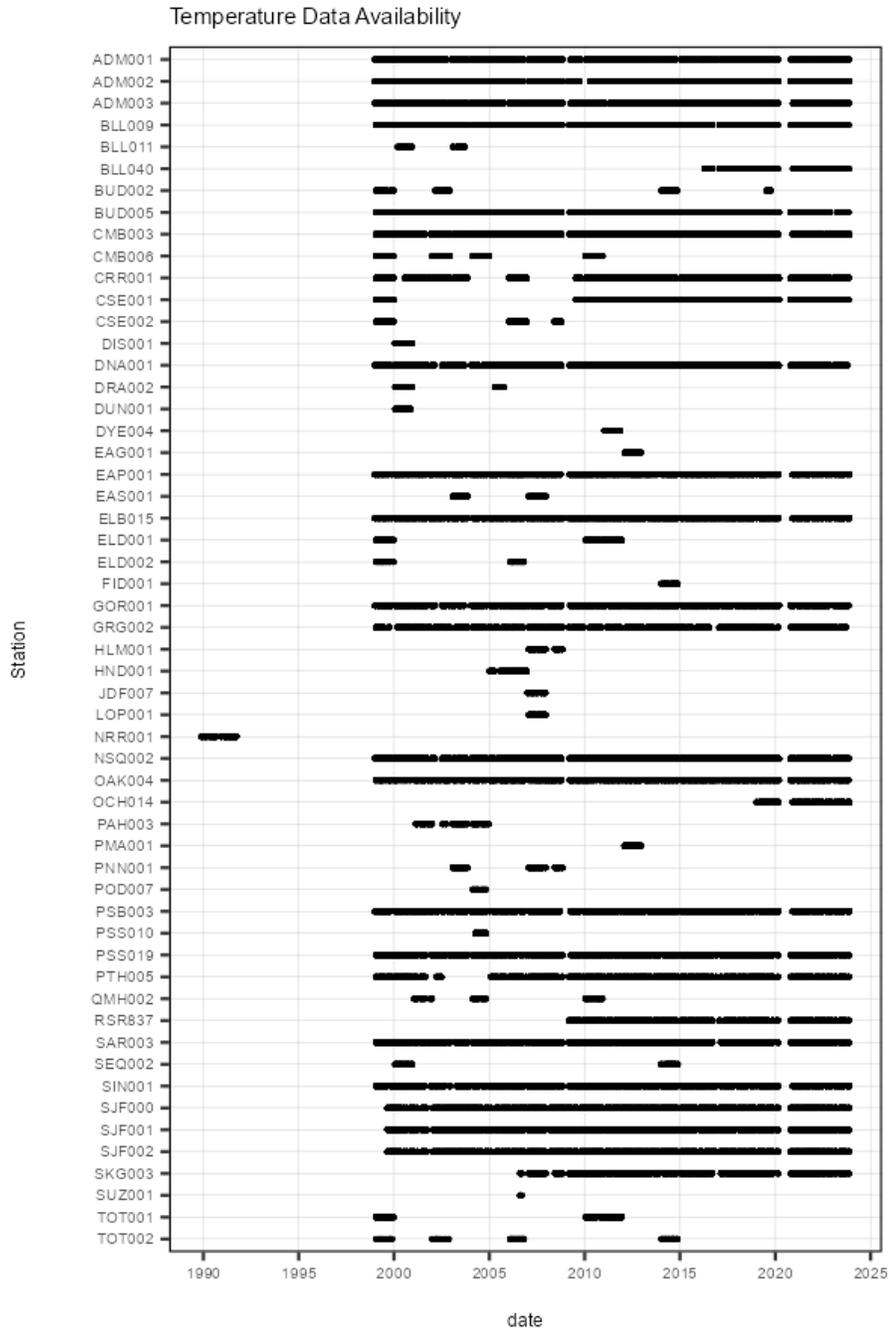


Figure 2-3. Temperature data availability for the 55 Ecology marine water monitoring stations assembled for this study. Note that the data for station NRR001 (1989 – 1991) precede the other data acquired from Ecology in 2024 that start in 1999. The general pattern in this figure reflects data availability for the other 13 variables except that data from station NRR001 are only available for temperature, density, salinity, dissolved oxygen and transmission. Also, turbidity measurements were not introduced until 2009.

This pattern of data availability for temperature is also representative of the other variables except that this assembled dataset only contains a subset of variables for station NRR001 (temperature, salinity, density, dissolved oxygen and transmission). Also, data for turbidity

is only available starting in 2009. A similar data availability graph is available for all the variables on the public web app⁸ created for this project to browse the Ecology dataset. The sampling effort is well distributed through the study area (Figure 2-4).

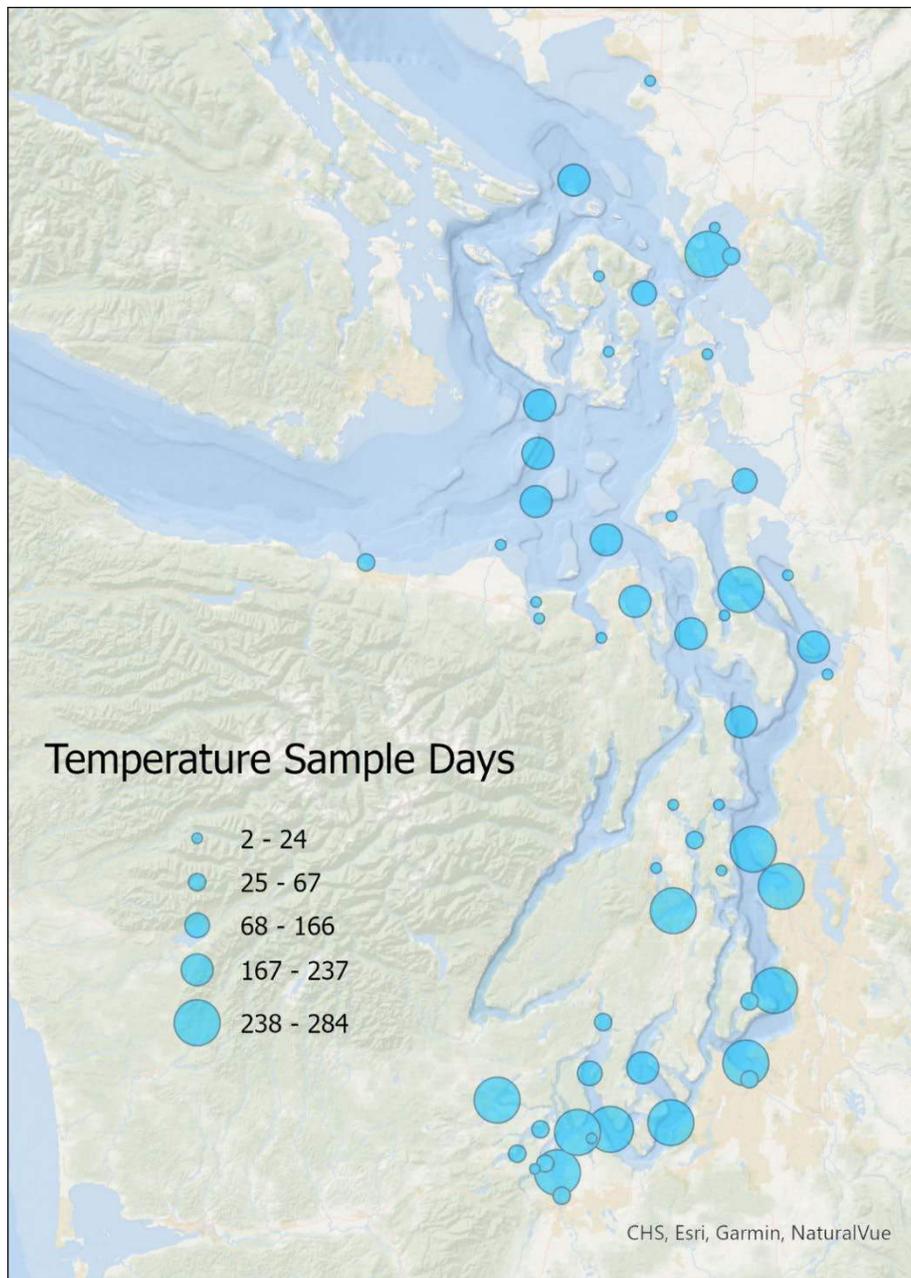


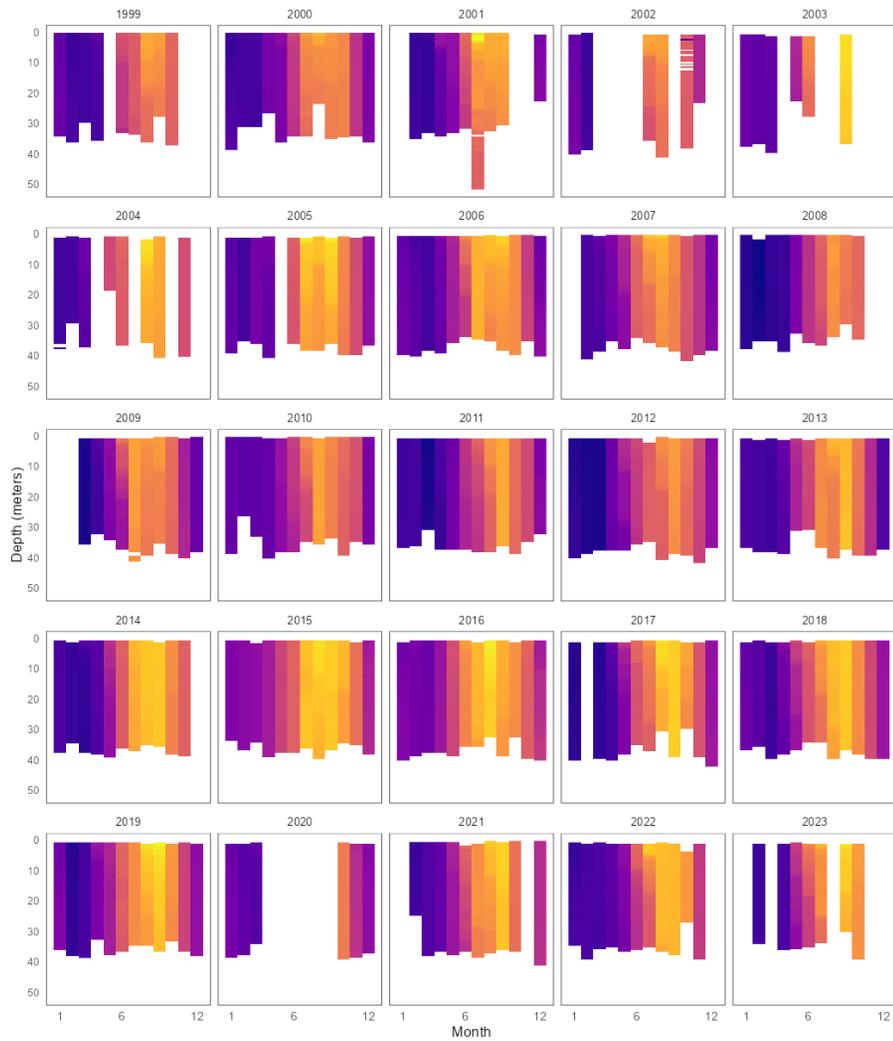
Figure 2-4. The amount of temperature data by station as measured by the number of sample, or data collection, days.

⁸ <https://experience.arcgis.com/experience/94aa60295f53496fbd6327c829d18d8a>

Data availability also varies across water depth. This is apparent when we visualize individual monthly profiles. To visualize profiles on a monthly basis, we must first address cases with multiple profiles at a station in a given month. While the general monitoring design calls for profile data collection monthly, there are 45 cases in the dataset of multiple profiles for a station in a given month, including one case of 5 profiles in a single month. These cases represent less than 1% of the station-months, and here we handle these cases by randomly selecting one profile to represent the month.

The resultant profiles clearly illustrate the contrasting data availability by depth for the CTD variables compared to the nutrient variables from discrete water samples (Figure 2-5). The depth of profiles varies across stations, and for a given station there is some variability in the depth reached by each monthly profile. Also, there is some variability in the depth sampled for nutrients. Figure 2-6 shows the data distribution by depth when all stations are pooled.

Monthly Temp Profiles - Station DNA001



Monthly NO3 Profiles - Station DNA001

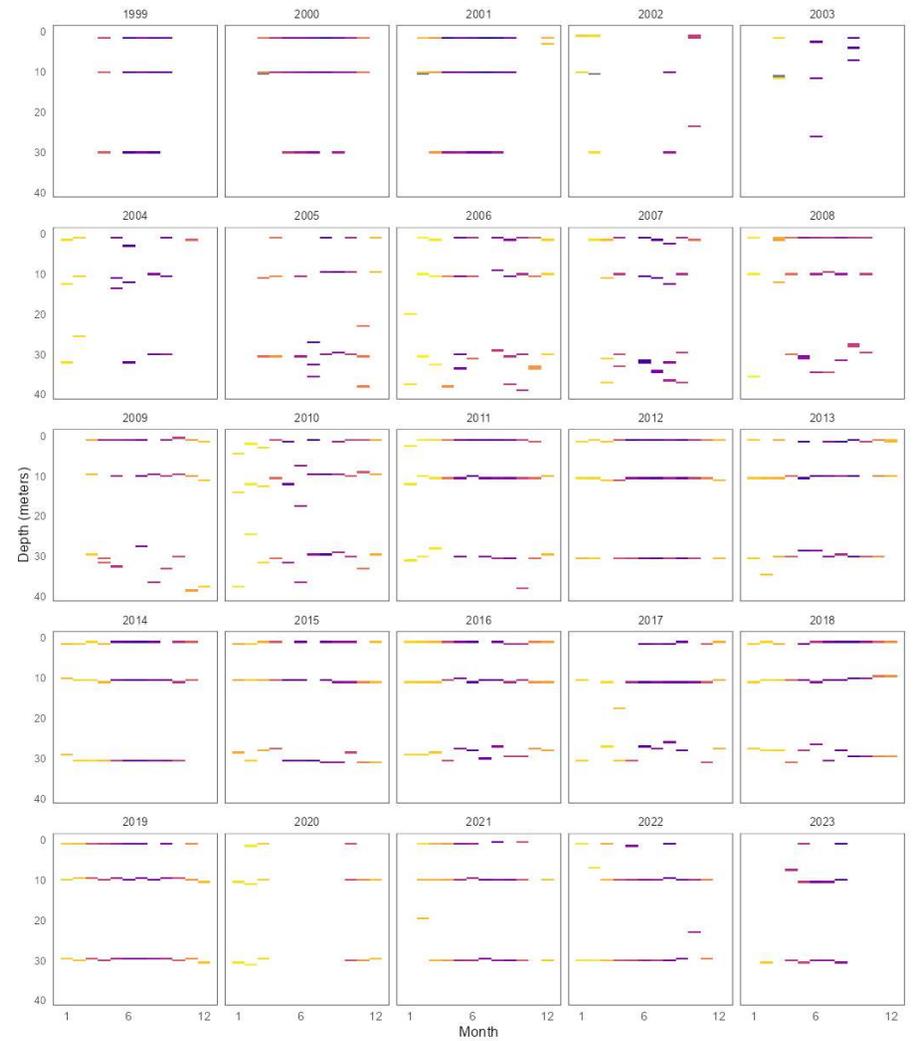


Figure 2-5. Examples of data distribution by depth for: Left: CTD variables (temperature shown); Right: nutrient variables from discrete water samples (nitrate shown). This data is from the Dana Passage station (DNA001).

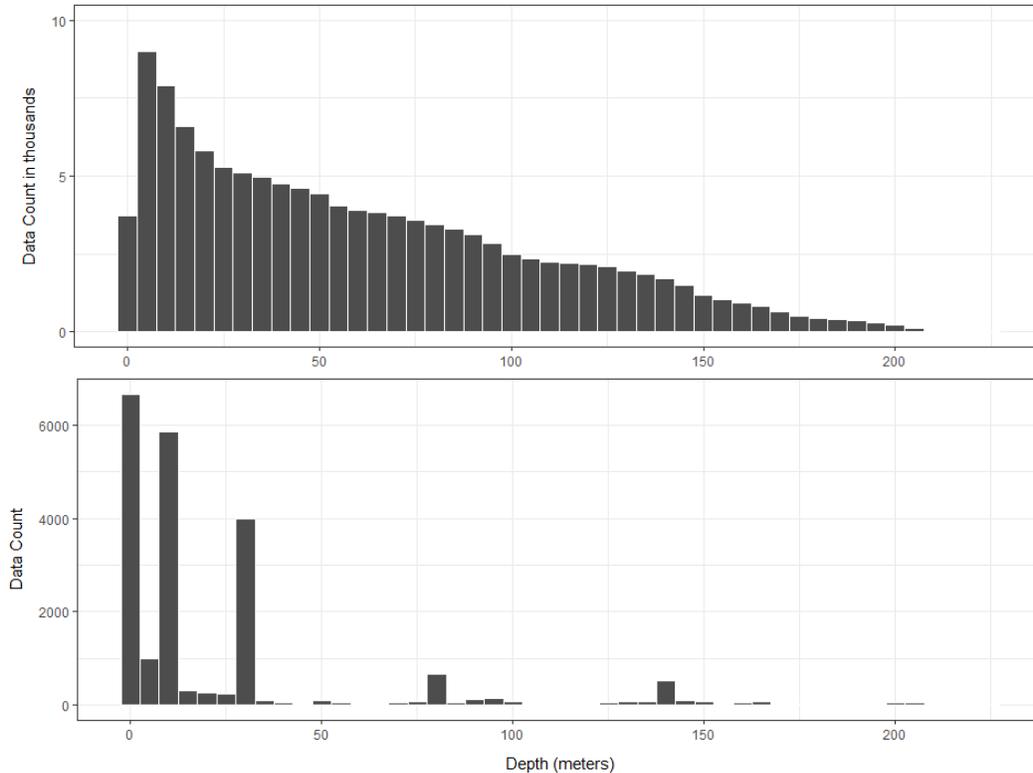


Figure 2-6. Distribution of Ecology marine water monitoring data by water depth when all stations are pooled. Top: typical distribution for CTD variables. Distribution for temperature data is shown. Bottom: typical distribution for discrete water sample variables. Distribution of nitrate data is shown.

2.1.4 Station Comparisons

When making station comparisons, it is useful to have an understanding of the data precision. The Ecology dataset contains relatively high precision data of instantaneous conditions at a point, given the use of high-quality instrumentation and the well-documented sample handling procedures (Pool et al., 2025).

But as a measure of mean monthly conditions, the data are low precision estimates as compared, for example, to any monthly statistics derived from continuously recording instrument data. In the context of this project, the unique strength of the Ecology dataset is not its precision but the multi-year data record. This provides temporal context for the data collected as part of the kelp resilience project.

In this section we ignore the temporal sequence of the annual measurements but instead focus on station differences in central tendency and we use the multiple annual measurements to assess variability. The observed variability reflects both the real variability of in-situ conditions across years as well as sampling error associated with sampling the month at one point in time.

To simplify station comparisons, we reduce each profile to a single value. Many profiles reach 100m depth or greater, but we are more interested in the top of the profile where floating kelp is found. One approach when comparing stations is to compare just the surface measurements (0.5m depth) from the profiles. For example, Figure 2-7 compares the seasonal pattern of surface temperature at two contrasting stations with some of the warmest and coolest summer surface temperatures within the dataset. The precision of the monthly measurements, as represented by the dispersion in a station's annual curves, is more than sufficient to clearly distinguish these stations in terms of spring, summer and fall surface temperatures. Winter surface temperatures are indistinguishable.

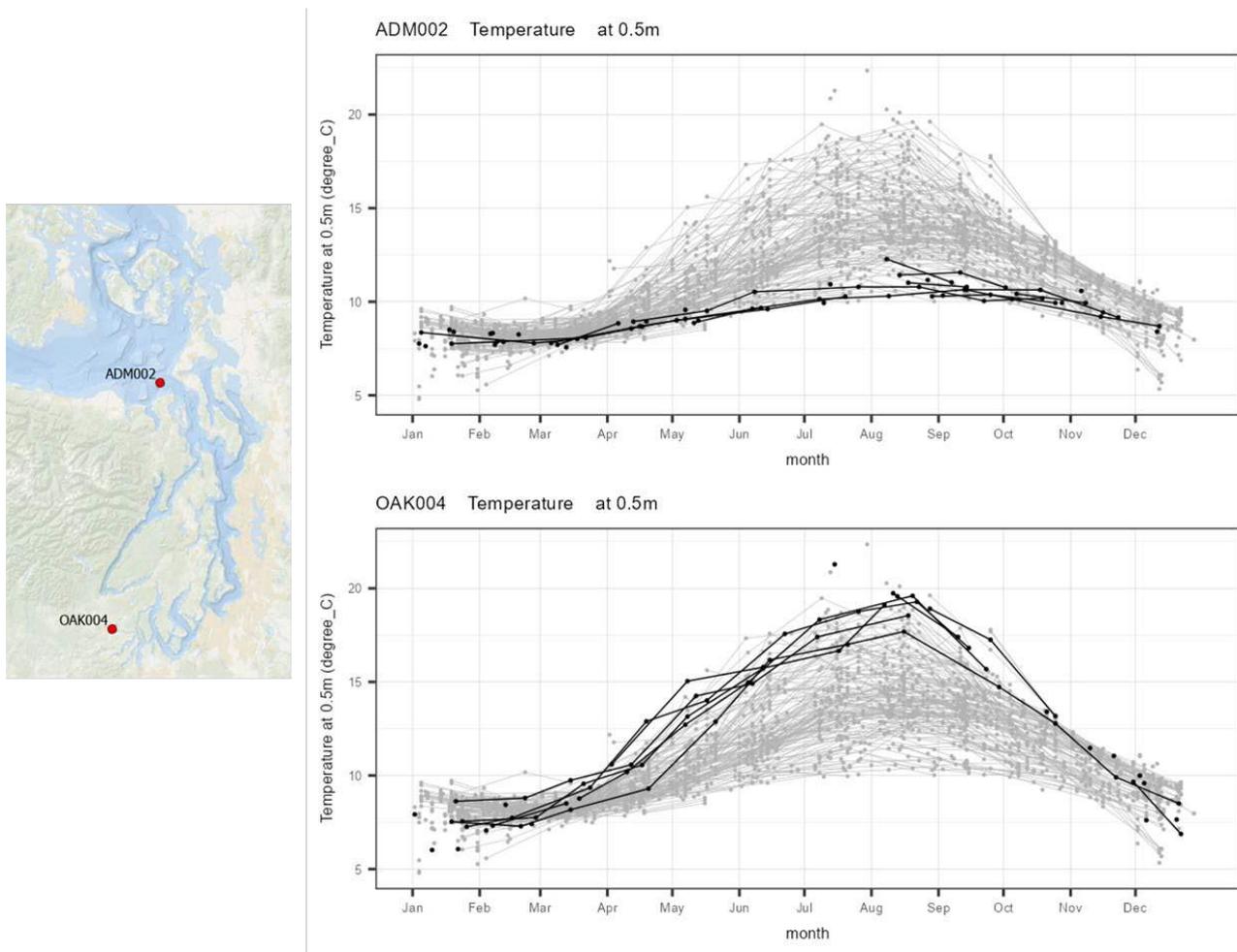


Figure 2-7. The seasonal pattern of surface water temperature (0.5m depth) over all annual cycles at two strongly contrasting stations with OAK004 reaching much higher summer temperatures than ADM002. The data for the specified stations are shown in black over a background of all seasonal cycles of surface temperature in the assembled Ecology dataset (all 55 stations and all years where surface data is available, shown in gray).

Alternatively, we can reduce the profile data to single values by calculating the mean of all profile measurements within a depth band, instead of just using the surface value. Figure

2-8 shows the results of this approach for mean water temperature in the 0 to 5m depth band at two nearby stations. There is more overlap between the seasonal curves at the two sites, but the two stations are still distinguishable in July and August temperatures. For summer temperature at least, the monthly sampling is sufficient to detect station differences between these nearby stations in the dataset.

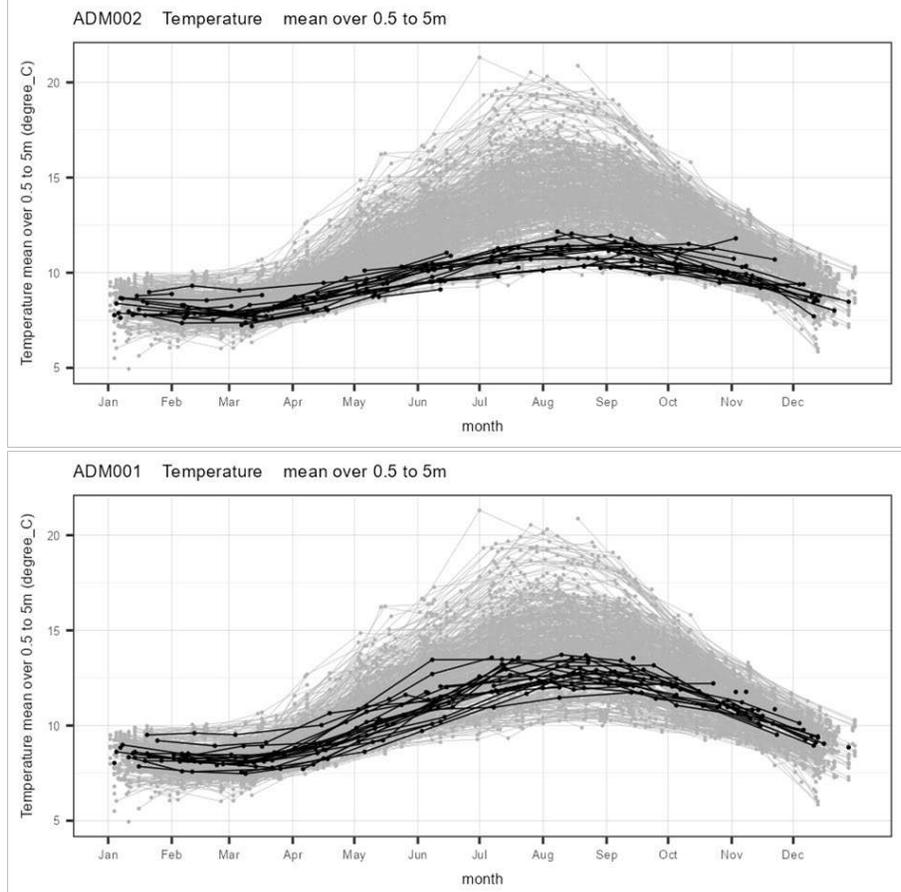


Figure 2-8. The seasonal pattern of the average of water temperature measurements in the 0.5 to 5m depth range. Multiple annual cycles are displayed in black for two proximal stations, ADM001 and ADM002. The gray data in the background show all seasonal cycles in the assembled Ecology dataset (all 55 stations, all years).

Profile reduction using the mean over the 0.5 to 5m depth band has the benefit of representing a much greater number of profiles since almost all profiles have measurements within this band, while many profiles do not have a surface (0.5 m) measurement (Figure 2-6). This is evident in the contrasting density of background data in Figure 2-7 and Figure 2-8.

It is useful to see the dispersion and the seasonal pattern of station data (Figure 2-7, Figure 2-8) but if we reduce the data further we can make more direct station comparisons using summary statistics.

Here we group months into four 3-month 'seasons', starting with Jan-Feb-Mar and compare season statistics across the stations. We also expand the depth band of interest to 0 - 10m depth. When using statistics for summarization, we need to pay attention to sample size especially since we know there are large station discrepancies in sample size (e.g., Figure 2-3 and Figure 2-4, pp. 58-59). If we look at sample size (the number of sample dates within each season at each station) for temperature data, i.e. 4 seasons * 55 stations = 420 instances of sample size, there is a clear separation between station-seasons with more than 25 sample dates and those with 20 or less sample dates (Figure 2-9).

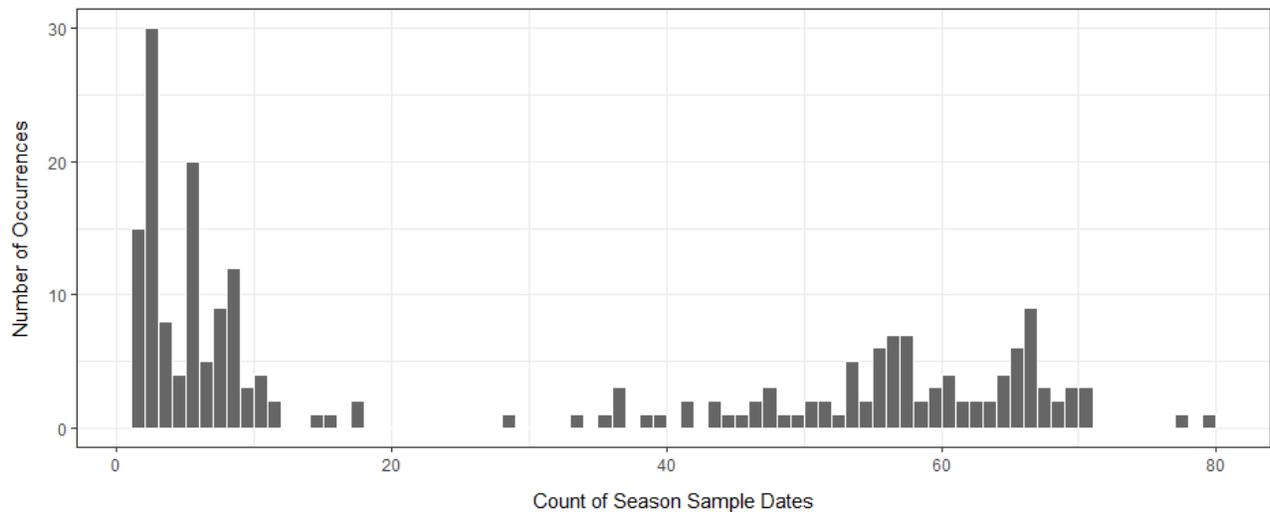


Figure 2-9. Distribution of station seasons (55 stations x 4 seasons) by the number of sample dates within the season. This indicates the distribution of sample sizes for seasonal statistics where the sample can include data from each month of the season and from all the years available for a given station.

Six variables were selected for closer examination. As shown below, the data for these variables have varying levels of skew, but all have strong central tendencies. Based on this, a minimum sample size of 8 was subjectively selected for station comparisons by season. Imposing this sample size requirement removes 25 small-sample stations so that out of the 55 stations (Figure 2-2, p.57), 30 stations remain for comparisons.

For each of the six selected variables, we plot the median temperature and total temperature range for each station and season, as follows:

- Temperature (Figure 2-10, p.68)
- Salinity (Figure 2-11, p.69)
- Nitrate (Figure 2-12, p.70)
- Light transmission over 25 cm (Figure 2-13, p.71)

Beam attenuation (Figure 2-14, p.72)
Turbidity (Figure 2-15, p.73)

2.1.4.1 Temperature

The temperature median and range across all sites clearly reflect warm summers, cool winters with spring and fall being intermediate (Figure 2-10).

In all four seasons, the station median temperature tends to be higher with distance from the ocean. This pattern is very subtle in winter (Jan-Feb-Mar) where median temperatures across all stations are similar with reduced variability. This pattern is most pronounced in the summer (Jul-Aug-Sep) where there is a near-monotonic pattern of increasing median temperature with distance from ocean.

The temperature data are approximately normal with little skew (Figure 2-10).

Where the median line is offset from the center of the range, this indicates the occurrence of relatively rare anomalies with large departures from the central tendency. There are a few instances of cold anomalies in the autumn (Oct-Nov-Dec) in the Saratoga-Whidbey area (stations SKG003, SAR003, PSS019). There are many more cases of warm anomalies, particularly in the spring (Apr-May-Jun) and summer (Jul-Aug-Sep).

2.1.4.2 Salinity

Autumn tends to have the highest median salinities across stations, closely followed by summer with winter and spring tending toward low salinity (Figure 2-11).

There are a small number of stations with anomalously low median salinities across seasons. These stations are presumably more strongly subject to freshwater inputs: SKG003, SAR003, PSS019, TOT001, OAK004.

In each season, there are many stations that have relatively rare low salinity observations with strong departures from the median. In these cases, the median indicator is far to the upper part of the range.

Overall, the distribution of salinity data skewed left. The bulk of the distribution was above the mean with an extended tail below the mean.

2.1.4.3 Nitrate

Across all stations, the highest median nitrate concentrations were in the winter, closely followed by autumn with spring and summer having clearly lower concentrations (Figure 2-12).

In winter, median nitrate concentrations tend to be higher with distance from the ocean. In all other seasons, there tends to be a lower concentration with distance from ocean.

There are cases of stations with relatively rare low concentration events (median closer to top of range) as well as high concentration events (median closer to bottom of range).

In general, there is high variability across years (wide range) relative to the differences in the median across stations.

2.1.4.4 Light transmission

There is a weak tendency for greater median light transmission in the spring (Figure 2-13).

There are clearly lower median transmission levels in the far southern inlets, the Saratoga-Whidbey area, and at Commencement Bay. In contrast, transmission is relatively high in the Strait of Juan de Fuca.

There is a persistent pattern across stations and seasons of relatively rare low light transmission events (median value closer to top of range).

Overall the transmission data is left-skewed with the bulk of the distribution above the mean but with a long tail at lower levels of transmission.

2.1.4.5 Beam attenuation

There is a tendency for lower beam attenuation in the autumn and somewhat less so in winter (Figure 2-14). Spring and summer tend to have greater levels of attenuation.

Attenuation tends higher in the southern inlets and higher in the Strait of Juan de Fuca.

For almost all stations and seasons, there are relatively rare high attenuation events with strong departures from the median (median much closer to bottom of range).

Overall, the attenuation data have a strong central tendency with less dispersion than a normal distribution.

2.1.4.6 Turbidity

The turbidity data do not exhibit a strong pattern across seasons (Figure 2-15).

In most cases, stations have relatively rare events of high turbidity, including cases of large departures from the median (median close to bottom of range).

Both SKG003 and OAK004 have anomalously high median turbidity values in all seasons.

Overall, the distribution of turbidity data is right skewed but the departure from a normal distribution is not large.

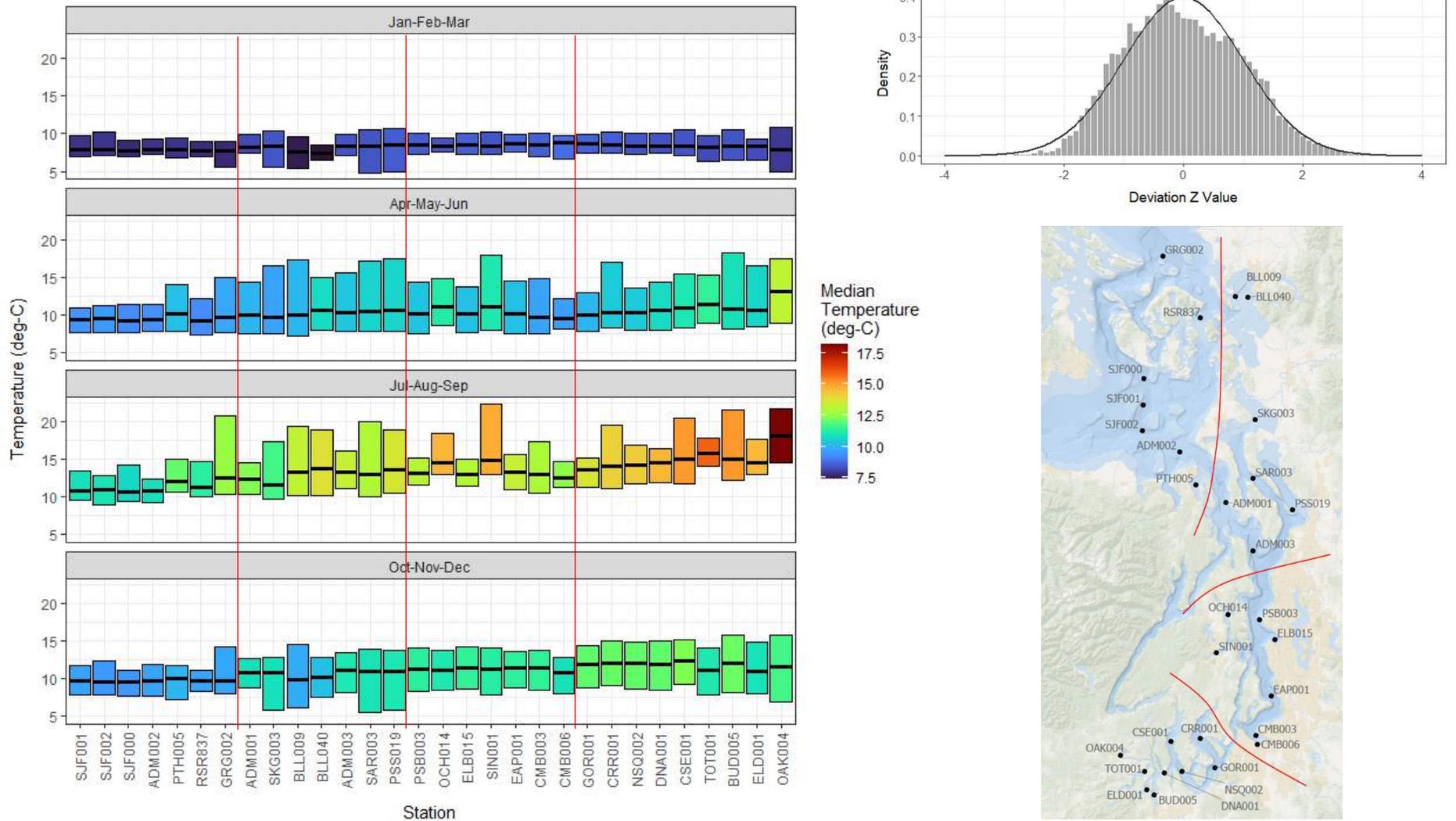


Figure 2-10. Comparison of temperature data within the Ecology dataset across stations and seasons. The bar charts (left) show stations ordered by distance from ocean, with each bar indicating the range observed in mean temperature in the 0-10m depth band for each of the 3-month seasons. The horizontal black lines indicate the median temperature. The bars are colored by the median temperature. The histogram (upper right) indicates the distribution of residuals of monthly values about the season mean for each station and season with a normal curve shown for reference. The residuals were converted to z-values to normalize all to the same scale. The red lines on the bar charts and on the map separate the stations into four sets of stations grouped by distance from ocean. These stations ($n=30$) have a minimum of 8 sample dates for each season in the bar charts.

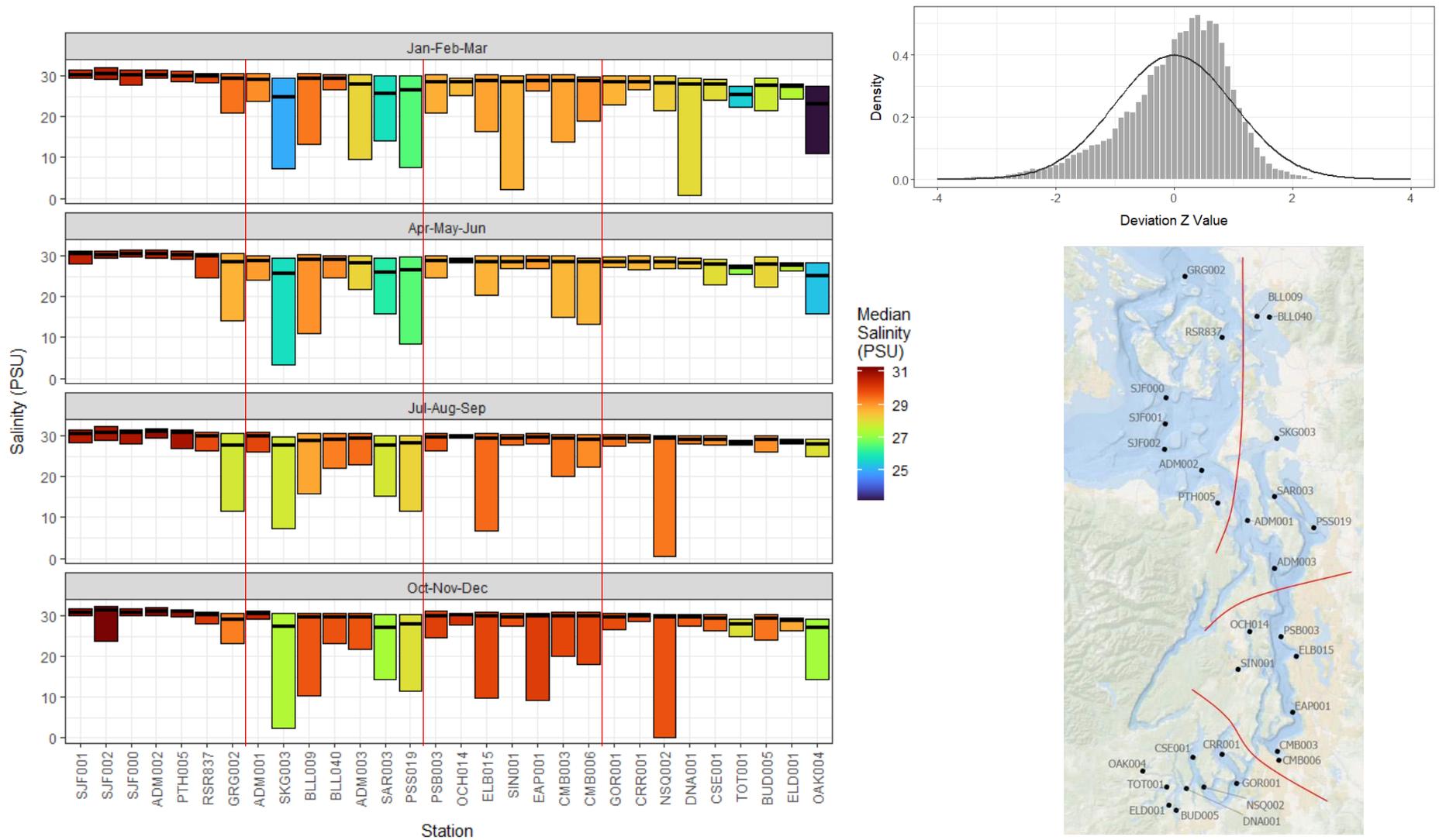


Figure 2-11. Comparison of salinity data within the Ecology dataset across stations and seasons. The bar charts (left) show stations ordered by distance from ocean, with each bar indicating the range observed in mean salinity in the 0-10m depth band for each of the 3-month seasons. The horizontal black lines indicate the median salinity. The bars are colored by the median salinity. The histogram (upper right) indicates the distribution of residuals of monthly values about the season mean for each station and season with a normal curve shown for reference. The residuals were converted to z-values to normalize all to the same scale. The red lines on the bar charts and on the map separate the stations into four sets of stations grouped by distance from ocean. These stations (n=30) have a minimum of 8 sample dates for each season in the bar charts.

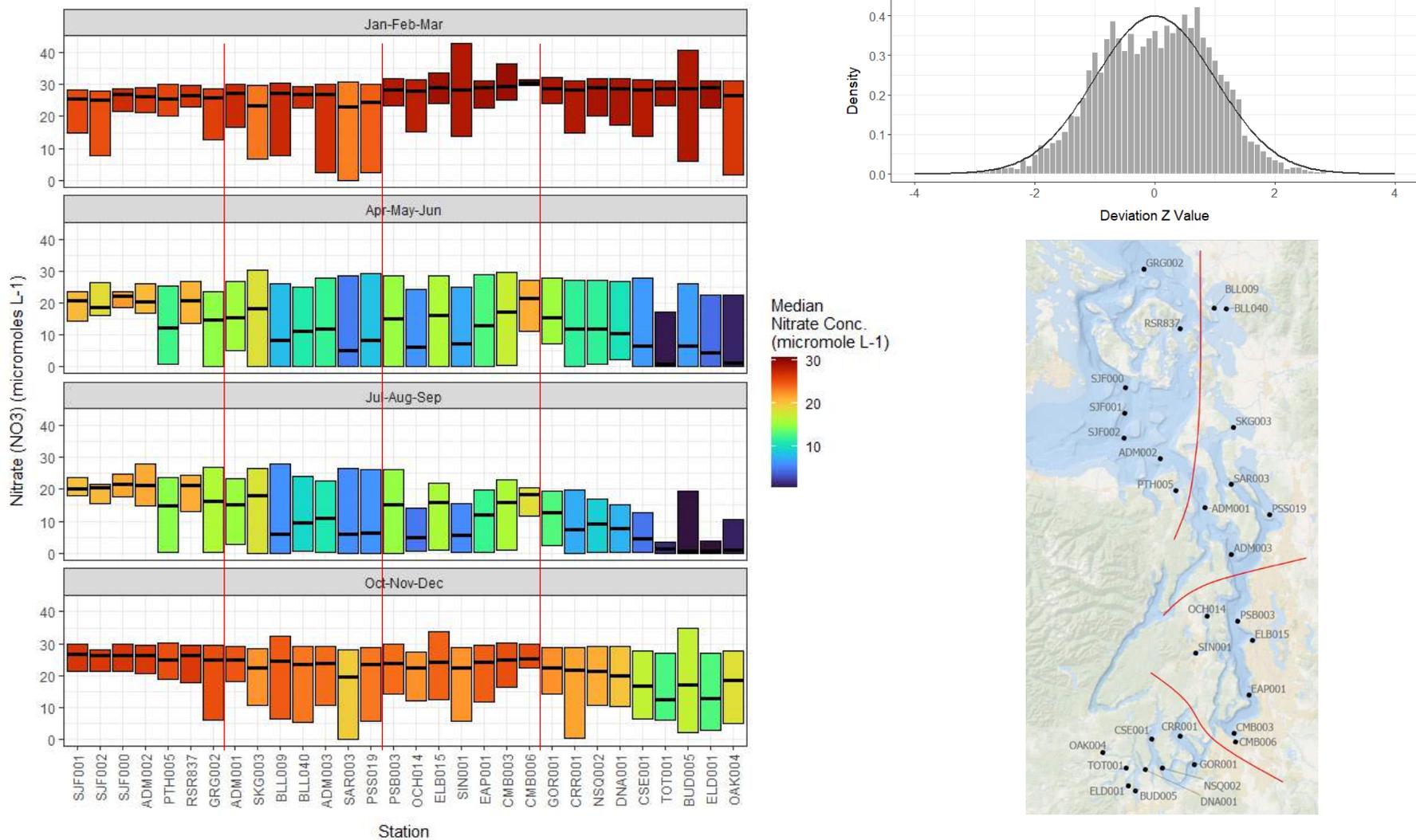


Figure 2-12. Comparison of nitrate concentration data within the Ecology dataset across stations and seasons. The bar charts (left) show stations ordered by distance from ocean, with each bar indicating the range observed in mean nitrate concentration in the 0-10m depth band for each of the 3-month seasons. The horizontal black lines indicate the median concentration. The bars are colored by the median concentration. The histogram (upper right) indicates the distribution of residuals of monthly values about the season mean for each station and season with a normal curve shown for reference. The residuals were converted to z-values to normalize all to the same scale. The red lines on the bar charts and on the map separate the stations into four sets of stations grouped by distance from ocean. These stations (n=30) have a minimum of 8 sample dates for each season in the bar charts.

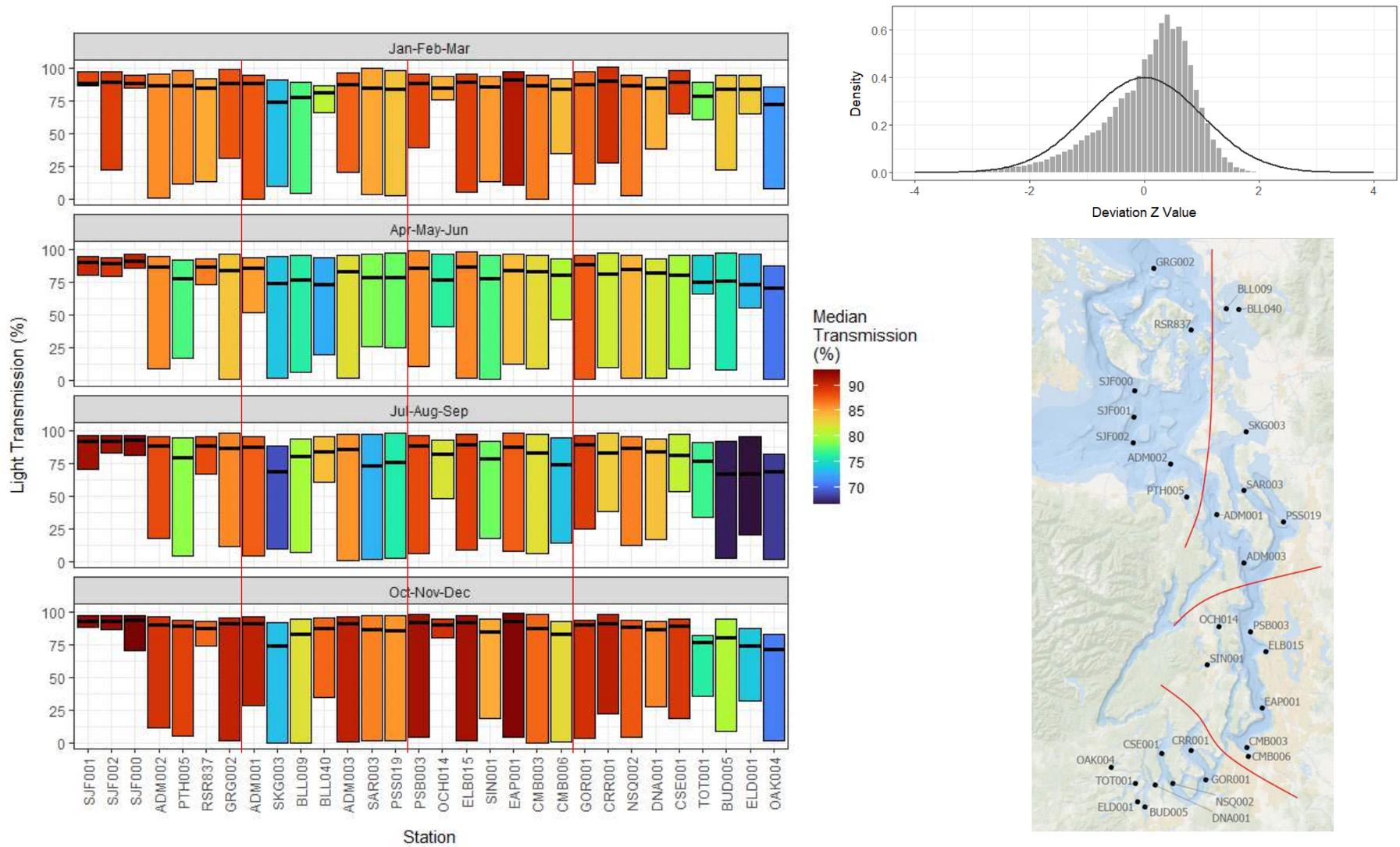


Figure 2-13. Comparison of light transmission data within the Ecology dataset across stations and seasons. The bar charts (left) show stations ordered by distance from ocean, with each bar indicating the range observed in mean transmission in the 0-10m depth band for each of the 3-month seasons. The horizontal black lines indicate the median transmission. The bars are colored by the median transmission. The histogram (upper right) indicates the distribution of residuals of monthly values about the season mean for each station and season with a normal curve shown for reference. The residuals were converted to z-values to normalize all to the same scale. The red lines on the bar charts and on the map separate the stations into four sets of stations grouped by distance from ocean. These stations (n=30) have a minimum of 8 sample dates for each season in the bar charts.

2.1.5 Trends

In this section, we focus on station trends over time for individual months. As discussed earlier (p.54), a second data acquisition from the Ecology web site was conducted to extend the data record for trend analysis through 2024.

To address the very wide variation in sample size, we imposed a filter on the data for each station and month: a minimum of 8 years of data for the month. This filter reduces the number of stations available for analysis from 55 (Figure 2-2, p.57) to 26 (Figure 2-16).



Figure 2-16. Map of the 26 Ecology marine water monitoring stations that were used for Spearman correlation analysis for trend. These stations passed the filter applied to the 55 stations (see Figure 2-2, p.57) that removed stations with less than 8 monthly values or with data that spanned less than 8 years.

To focus the analysis, six variables were selected for trend analysis out of the 14 variables in the dataset: chlorophyll fluorescence, temperature, salinity, nitrate, light transmission over a 25cm path, and turbidity.

To assess the presence of trend we evaluate the Spearman rank correlation coefficient and statistical significance using the `corr.test` function in the `psych` R package. We selected Spearman because of its flexibility – it does not rely on assumptions of normality or linearity. Since we conducted a large number of correlations (6 variables x 26 stations x 12 months), the Type I error rate was controlled with the R function `p.adjust` using the Holm method.

We have not conducted a power analysis, but it is possible that the power of this trend detection is limited due to the use of a single observation to represent a month and due to the large number of tests used that necessitate adjustments to test significance. On the other hand, the data record is substantial (1999-2025), which should bolster the power to detect trend.

We focus on significant correlations at the 0.05 and 0.01 levels, rather than focusing on the strength of the correlations (i.e. the correlation coefficients themselves). The variables with the highest occurrence of significant trends were temperature and light transmission (Figure 2-17).

Of the 26 stations tested, four had increasing temperature trend in October. Three stations had increasing trends in August. There were two other significant trends – one in May and one in November. In addition, of the non-significant cases, there were more positive trends than negative trends, by a large margin. For example, each of the 26 stations without exception had more positive trends than negative trends within the months with non-significant trends. This suggests that the scope of positive trends is greater than that suggested by the significant trends detected with the testing presented here. Other approaches to significance testing could be devised to capture this, but these are not pursued here.

Light transmission has the greatest number of occurrences of significant trends and they are all positive trends, indicating increasing water clarity over time (Figure 2-17). These occurrences are spread broadly over many sites and many months.

Aside from temperature and light transmission, the other variables have a small number of occurrences of significant trends (Figure 2-17).

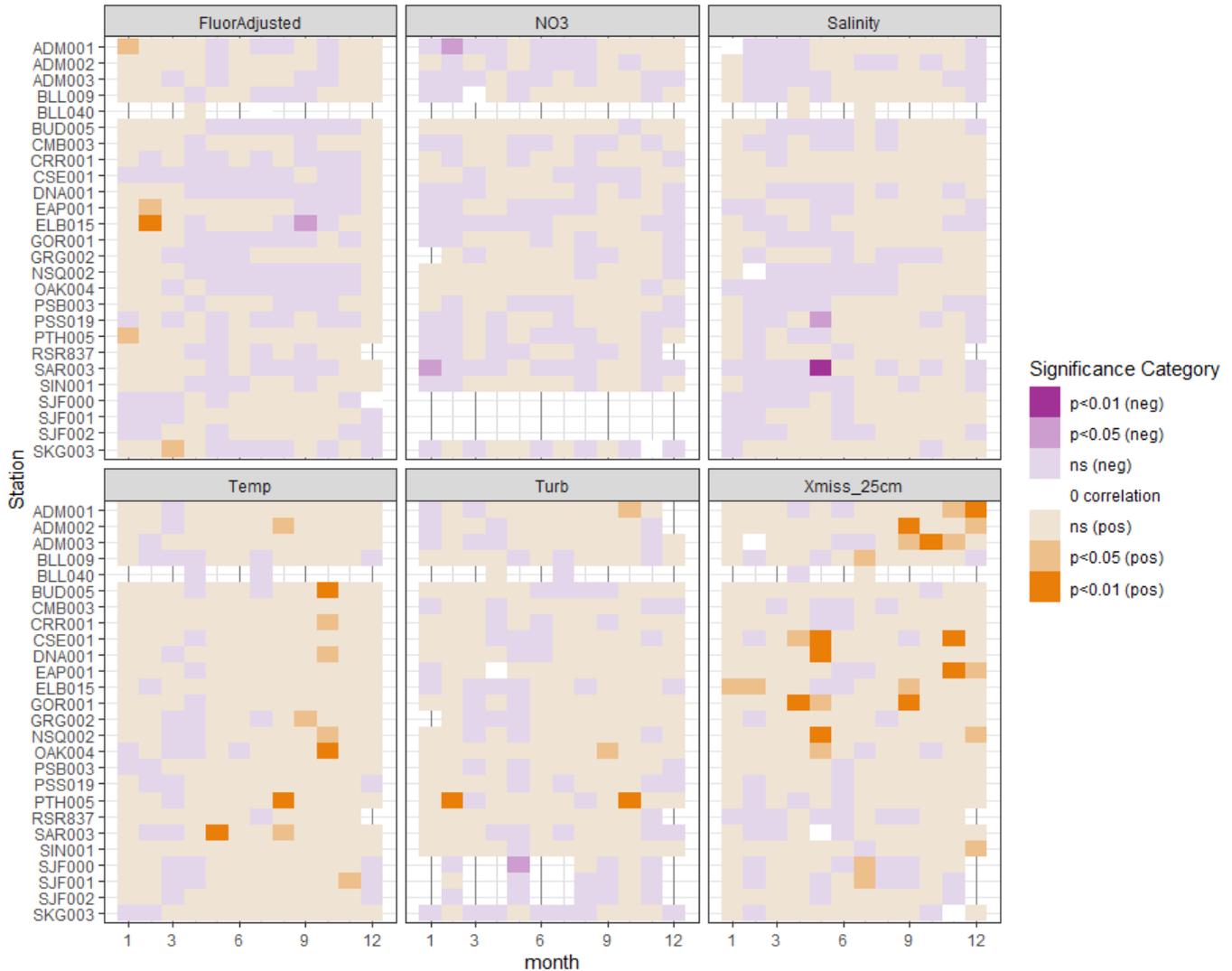


Figure 2-17. Summary of the Ecology marine water monitoring station trend results from the Spearman correlations of monthly mean (0-10m depth) water temperature with time. Results are only presented for six selected variables: adjusted chlorophyll fluorescence, nitrate concentration, salinity, temperature, turbidity and light transmission over a 25cm path (Xmiss_25cm). These results present the significance and sign of the Spearman correlations, not the correlation values themselves.

The Spearman correlations give us results with monthly granularity (Figure 2-17), but these results mask year-to-year patterns. Given this help resilience project will have detailed data on specific sites mostly confined to one year (2024), it is relevant to ask to what extent does year-to-year variation reflect effects of a particular station and to what extent does this variation reflect effects of year. It is also relevant to ask how does 2024 fit within the data record?

We explore this further qualitatively with just the temperature variable. And given the concentration of significant station trends in October, we will first focus on October.

The time series of October temperatures for the 26 stations clearly shows a pattern of increasing temperatures over the data record (Figure 2-18). This is most easily seen in the range of temperatures across the stations in the first year (1999) compared to the much greater range in the last year reaching higher temperatures (2024). This visual comparison holds for the first and last three years, or even the first half of the data record compared to the second half.

Not all stations appear to have the same pattern of increasing temperature trend (Figure 2-18). The greater range in October temperatures seen in 2024 as compared to 1999 is due to some stations that reach much higher temperatures, but there are many stations at the cooler end of the range with temperatures at 1999 levels. This emphasizes that there are strong station-to-station differences that should presumably be captured in the single-year data (2024) collected by the kelp resilience project.

Another pattern seen in the October time series is occurrence of annual transitions that exhibit coherent, or shared, response across stations from one year to the next. For example, between 1999 and 2000, October temperatures increased for almost all stations. Between 2006 and 2007, all stations had a decrease in October temperatures. There are several years, or even a sequence of years, where stations, or sometimes a subset of stations, display similar patterns of change.

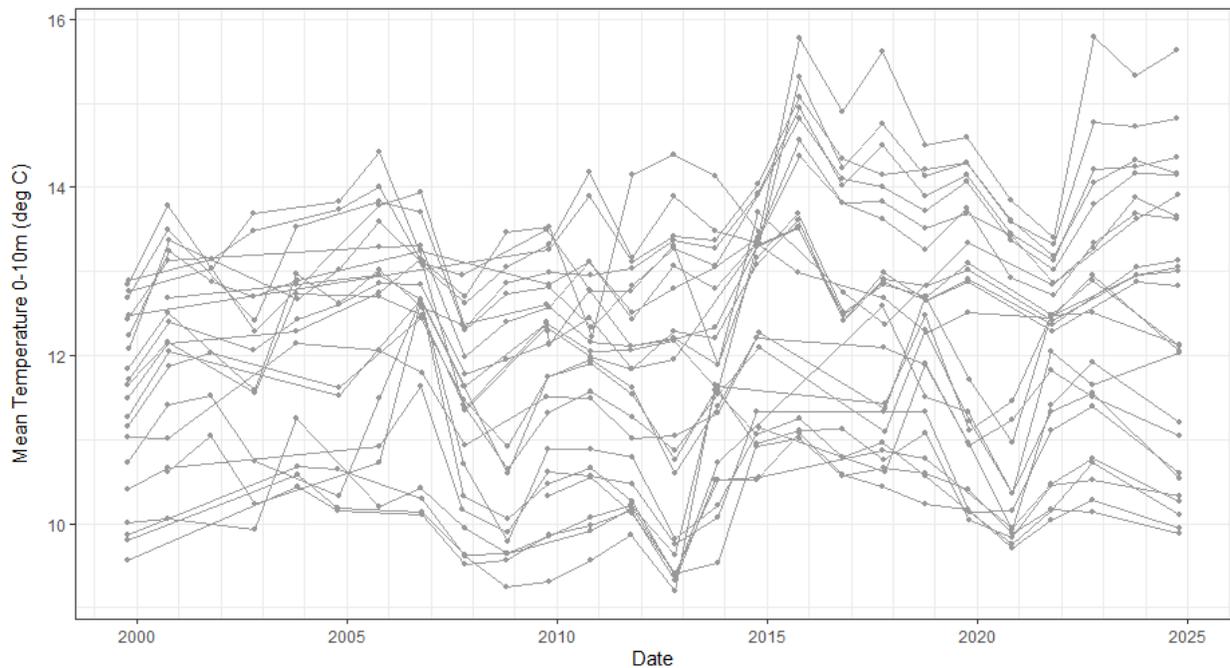


Figure 2-18. Time series of October temperatures over the Ecology marine water monitoring dataset for the 26 stations subject to trend analysis using Spearman correlation with time (see Figure 2-16). Temperature values are the mean temperature within the 0-10m depth layer.

But there is also substantial variation that doesn't follow a larger pattern and appears as noise in Figure 2-18. Some of this could be due to the fact that variation in the time series reflects both station-to-station variability and year-to-year variability.

To better isolate year-to-year variability, the October temperature values were converted to z-scores (Figure 2-19). These z-scores represent departures from the station mean October value over the data record with the magnitude of the departure scaled by the station standard deviation. This view of the data reveals a strong year effect with clear periods with predominantly negative temperature departures (2007-2012) and periods of strong positive departures that include a signal presumably from the blob (2014-2018). We can conclude that there is a strong correlation across stations – there are warm years and cool years and station departures tend to vary together across years, if not in complete unison.

In terms of the October temperature departures (Figure 2-18), 2024 was an unremarkable year with stations with both positive and negative departures. As a group, the station departures were well within the mix seen across the data record.

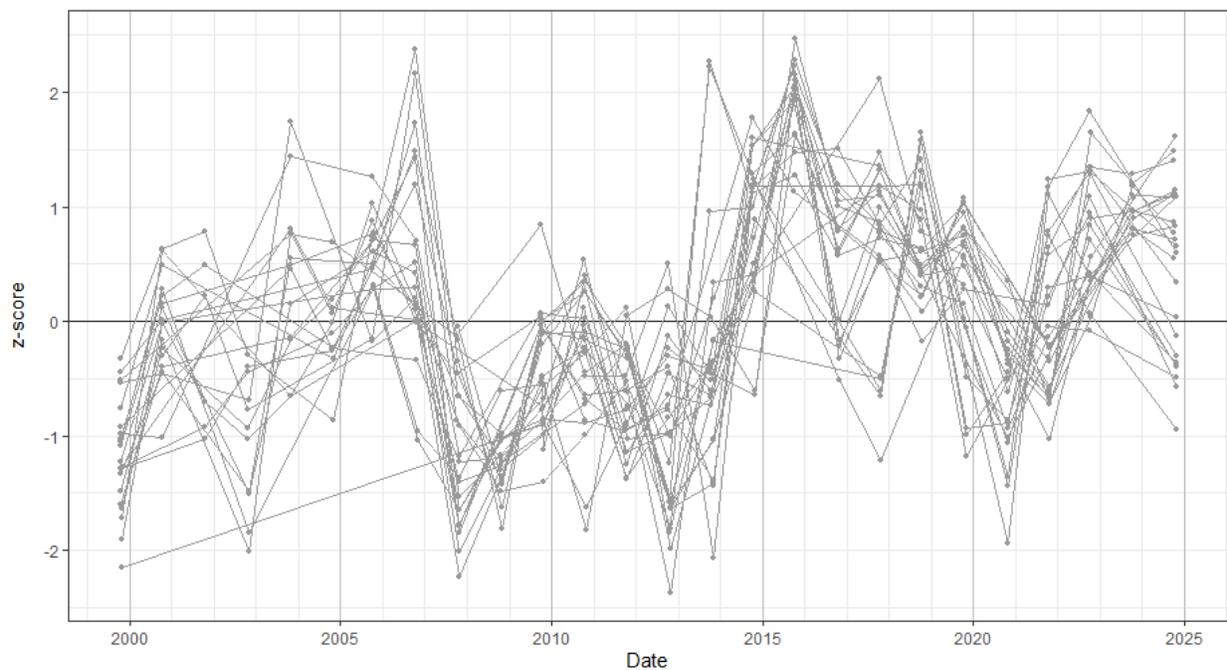


Figure 2-19. October temperature departures in the Ecology marine water monitoring dataset for the 26 stations subject to trend analysis using Spearman correlation with time (see Figure 2-16). Departures are presented as station z-scores (relative to station mean over the data record and relative to station variance) of mean temperature values in the 0-10m depth layer.

To expand the scope of this analysis beyond October, we first put October in the context of the previous two months to capture the summer to early autumn transition (Figure 2-20).

August and September display a similar pattern of years with predominantly negative temperature departures (e.g. 2007 – 2012) and years with predominantly positive departures (e.g. 2014 – 2018). But there appears to be greater variability in August and September. The interannual signal is stronger in October – i.e. the correlation across stations appears stronger.

As in October, the August and September temperature departures as a whole appear unremarkable in 2024, with a mix of positive and negative departures and a range that is well within the mix seen across the data record.

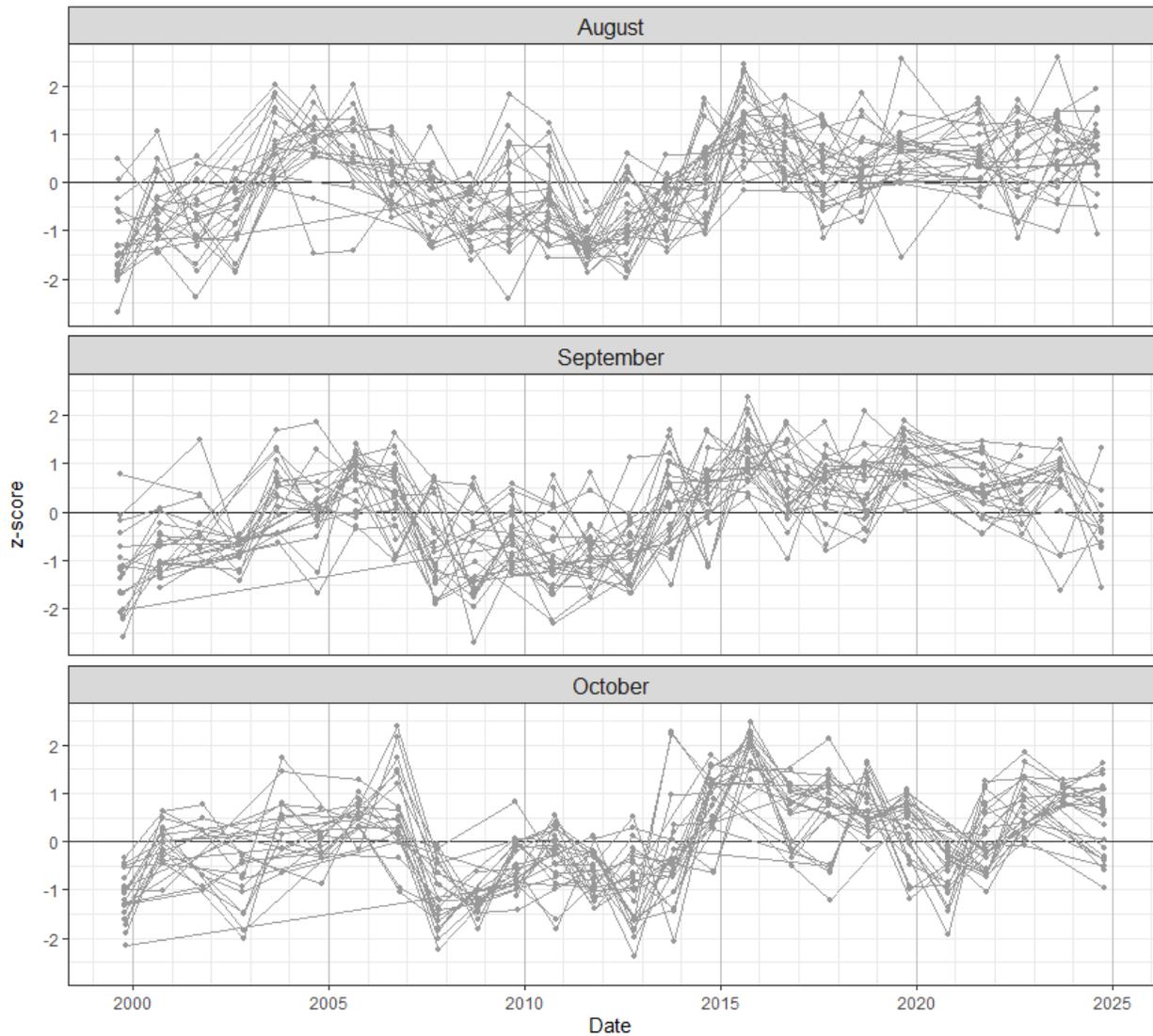


Figure 2-20. August, September and October temperature departures in the Ecology marine water monitoring dataset for the 26 stations subject to trend analysis using Spearman correlation with time (see Figure 2-16). Departures are presented as station z-scores (relative to station mean over the data record and relative to station variance) of mean temperature values in the 0-10m depth layer.

We further examined the station temperature departures in the early season, from winter transitioning into spring (Figure 2-21). In these months, the stations are even more highly correlated with stations departures appearing to change somewhat in unison.

The same interannual pattern seen in Aug-Sep-Oct is visible in the early season but it is a weaker pattern with strong differences. For example, the 2007-2012 period of predominantly negative temperature departures in Aug-Sep-Oct is punctuated by a strong shift to positive departures in 2010 in the early season. Similarly, the 2014-2018 period of predominantly positive temperature departures in Aug-Sep-Oct is shortened in the early season with a strong shift to more negative departures in 2017.

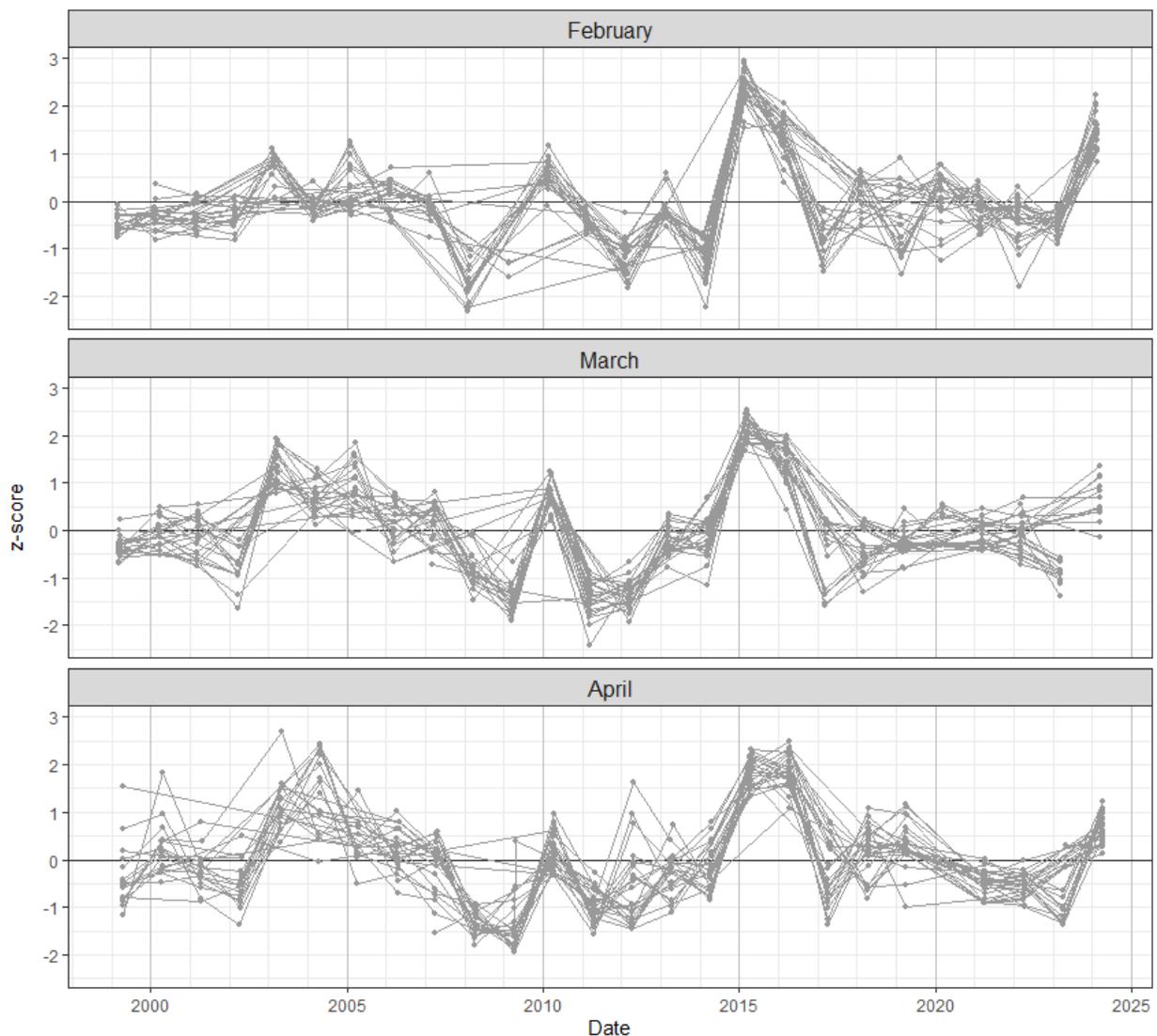


Figure 2-21. February, March and April temperature departures in the Ecology marine water monitoring dataset for the 26 stations subject to trend analysis using Spearman correlation with time (see Figure 2 16). Departures are presented as

station z-scores (relative to station mean over the data record and relative to station variance) of mean temperature values in the 0-10m depth layer.

Another difference seen in the early season is that 2024 appears to be more unique in station temperature departures. In March and April, the station departures are all positive with one exception, but the magnitudes of these z-score departures are moderate. In February however, all departures are again positive, but the z-score departure magnitudes are greater. When all stations are considered together, 2024 had the most anomalously warm February in the 25-year record except for 2015 when the signal from the blob was at its peak. In absolute terms, the February temperature departures are mostly between +0.5 and +1.0 degrees C, but a few stations have departures greater than 1 degree C (Figure 2-22).

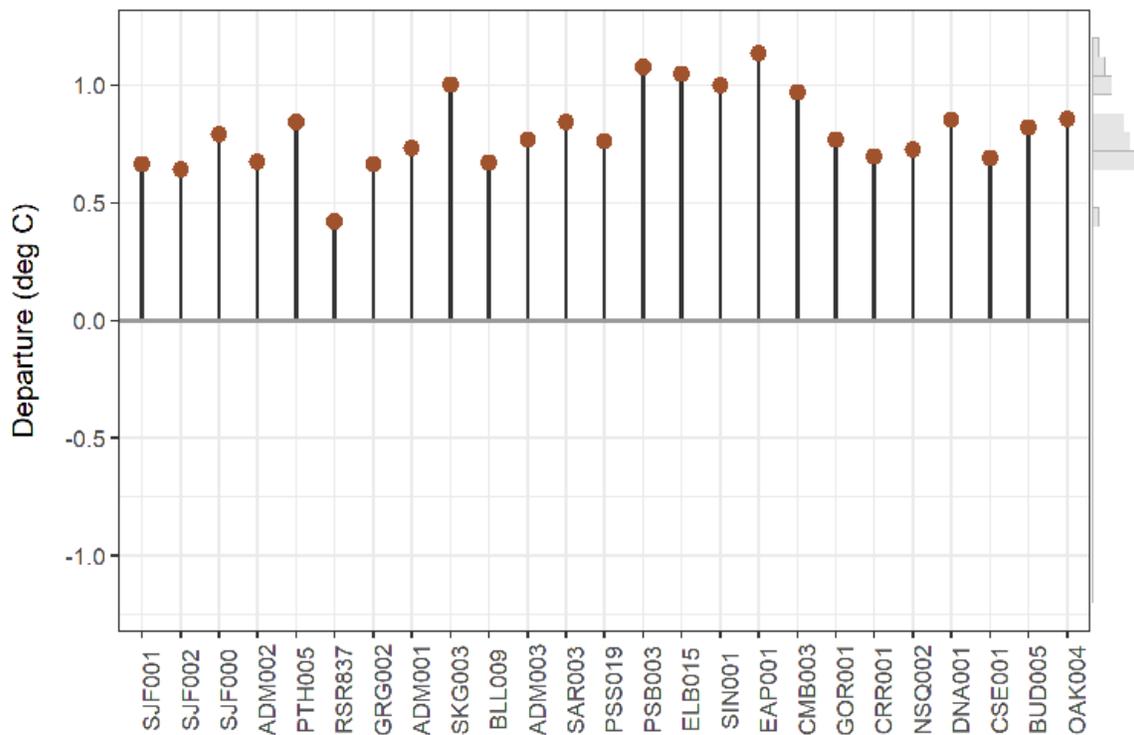


Figure 2-22. February 2024 temperature departures from station means for February derived from the 1999-2024 data record. The frequency distribution of departure values is shown as a marginal histogram along the right side of the graph.

2.2 Salish Sea Model Currents

Current speed has been shown to have a positive relationship with both floating kelp photosynthesis rates (Wheeler, 1980) and survival (Bunting et al. 2025). Current speed was used in Chapter 1 (p.9) as an environmental predictor variable, based on extraction of

current data from the 2014 model solution of the Salish Sea Model (SSM). The 2014 model solution⁹ of the SSM (Khangaonkar et al. 2021) is publicly available and is a unique resource in that it has comprehensive spatial and temporal coverage across the Salish Sea for all 2014 at an hourly time step.

We had two purposes with the work reported in this section. First, we wanted to expand on the characterization of current speed in Chapter 1 based on the 2014 model solution. There, each model grid cell was reduced to the maximum current speed on a daily basis for the surface layer (each model grid cell has 10 depth layers). We wanted to expand the analysis to look at the distribution of current speeds. Also, in Chapter 1 the SSM grid of daily maximum current speeds was spatially interpolated to a 10m grid. This downscaling should be treated with caution as it does not use any ancillary data to assist in the downscaling (Atkinson 2013), and we opt instead to work here with data at the scale of the model grid cells.

Our second purpose here was to conduct some basic assessment of the reliability of the model current data. We have heard skepticism expressed about the reliability of the SSM in the nearshore. To understand the nature of this skepticism, consider the following points, all based on personal communications with other nearshore scientists:

- We have heard nearshore ecologists express general concern that the spatial resolution of the model grid is too coarse to capture current patterns at the finer scales relevant to the location and morphology of nearshore vegetation beds.
- One study discontinued the use of nearshore temperature data from the 2014 SSM solution after identifying inconsistencies between SSM output and measured data.
- The SSM project lead, Tarang Khangaonkar, is currently working with his team on a second generation SSM. One of the stated goals is to improve model reliability in the nearshore through the use of a much finer grid and through changes to the treatment of hydrodynamics in the model. This implicitly acknowledges that the reliability of the first generation SSM in the nearshore has limitations.

To address these concerns, we visualize the SSM model grid at specific sites and we present an intercomparison with current data originating from NOAA. We proceed to compare the distributions of current speeds from the SSM 2014 solution across the 15 project sites, culminating in a simple classification of sites based on current regime.

2.2.1 The 2014 Model Solution

The Salish Sea Model (SSM) is a 3D hydrodynamic model linked with a water quality model. The 2014 solution from the SSM is distributed by the Pacific Northwest National

⁹ The 2014 model solution of the Salish Sea Model is made available by the Pacific Northwest National Laboratory at <https://www.pnnl.gov/projects/salish-sea-model/data-portal>.

Laboratory⁹. The Department of Ecology has been closely involved in model development¹⁰ and University of Washington now hosts the Salish Sea Modeling Center¹¹.

The 2014 model solution was downloaded in May 2025 for this study. It is distributed as a series of 365 daily netCDF files for each day of 2014. Each netCDF file contains hourly data values for 16,012 grid cells and 10 depths at each cell. Each netCDF file contains 11 data objects that include one-dimensional vectors, and 2D and 3D data objects (Table 2-2).

Table 2-2. The variables contained in the netCDF files distributed as the 2014 SSM model solution.

variables	description	data object dimension
u, v, w	Current speed in three data arrays in m/s: u is speed in North(+)/South(-) dimension v is speed in East(+)/West(-) dimension w is speed in up(+)/down(-) dimension	[16012, 10, 24] containing values for 16012 nodes, 10 depth levels and 24 hours.
h	Depth of substrate surface at each node from smoothed bathymetry in meters.	[16012]
zeta	Water surface elevation in meters relative to NAVD88.	[16012, 24]
temp	Temperature in degrees C	[16012, 10, 24]
salinity	Salinity in ppt.	[16012, 10, 24]
time	Seconds since 1/1/2014 00:00:00	[24]
siglay	Vertical dimension of a grid cell layer as percentage of depth at each node.	[10]
x, y	Node coordinates in meters in a UTM Zone 10N projection.	[16012]

The spatial grid for the 2014 model solution is distributed as nodes, or points, that are the centroids of the grid cells. The grid cells are described as triangular in shape, but here for the purposes of visualization, we have represented grid cells as Thiessen polygons (Figure 2-23) simply because this was straightforward to do within ArcGIS Pro. While the shape of grid cells do not match that described for the SSM, the number and density of cells will be the same, and, on average, grid cell area will be the same (Figure 2-23).

The horizontal components of the current vector (u, v speeds) were converted to a total horizontal speed and an azimuth angle representing the current direction. Horizontal speed was calculated as

$$\text{horizontal speed} = \sqrt{u^2 + v^2}$$

¹⁰ <https://ecology.wa.gov/research-data/data-resources/models-spreadsheets/modeling-the-environment/salish-sea-modeling>

¹¹ <https://ssmc-uw.org/>

Azimuth was calculated by first identifying the quadrant of the velocity vector based on the sign of u and v . Then an interim azimuth, θ_0 , was calculated by forcing the velocity vector into the first quadrant (u and v positive) as

$$\theta_0 = \tan^{-1} \left(\frac{|v|}{|u|} \right)$$

and this was converted to degrees on a 0-360 scale based on θ_0 and the quadrant.

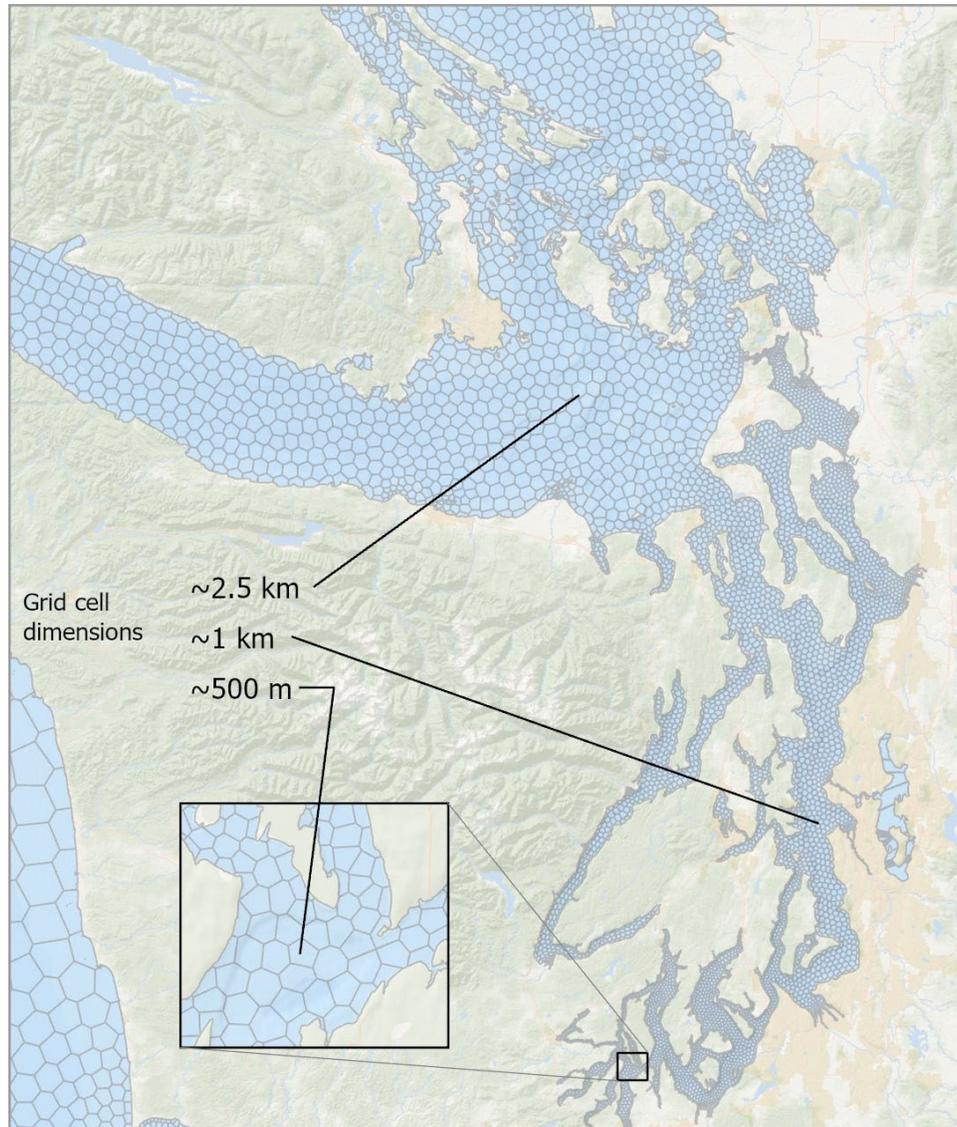


Figure 2-23. Spatial resolution of the 2014 model solution generated by the Salish Sea Model. The distributed model solution includes the spatial grid as a set of centroid points or nodes. Here, Thiessen polygons have been generated so there is one polygon for each point while the actual grid cells used in the modeling are triangular. The number, density and mean area of the cells are the same within any subarea.

2.2.2 Data Intercomparison

NOAA's Center for Operational Oceanographic Products and Services (CO-OPS) distributes both current measurements and current predictions through its Tides & Currents web site¹². The current measurement data is limited to discrete efforts, typically of 1-2 years duration. No current measurement data was available for 2014 within our study area.

We therefore use NOAA current prediction data for an intercomparison with SSM current speeds. The prediction data will vary from actual conditions that reflect, in addition to tidal forcing, oceanographic and meteorological weather conditions. But the NOAA current prediction data is a widely used and well-known data source for many uses, including within nearshore field ecology. The NOAA current prediction data is therefore useful as a reference point for assessing the SSM current data.

2.2.2.1 NOAA Current Prediction Data

NOAA makes available current predictions for a network of 128 stations within the study area (Figure 2-24). Current prediction data can be retrieved using the CO-OPS API for Data Retrieval¹³. Data about stations, including the numbering of depth bins and their depths, can be retrieved using the CO-OPS Metadata API¹⁴.

Our approach was to construct URLs and call the API's from within R code. The data was retrieved as data frames and the metadata was retrieved as xml objects and then parsed using the R package xml2.

The initial plan was to conduct intercomparisons at the nearest NOAA stations to each of the 15 project sites. This plan was abandoned when inspection of the depths of the current predictions showed poor coverage of the shallow depths that are of interest here (Figure 2-25).

Based on the availability of shallow current predictions among all 128 NOAA stations (Figure 2-26), a threshold of 3 m depth was used to filter for stations with shallow current predictions to use in the intercomparison. Out of the 128 stations, 19 include current predictions at 3 m depth or shallower (Figure 2-27).

¹² <https://tidesandcurrents.noaa.gov/>

¹³ CO-OPS API for Data Retrieval: <https://api.tidesandcurrents.noaa.gov/api/prod/>

¹⁴ CO-OPS Metadata API: <https://api.tidesandcurrents.noaa.gov/mdapi/prod/>

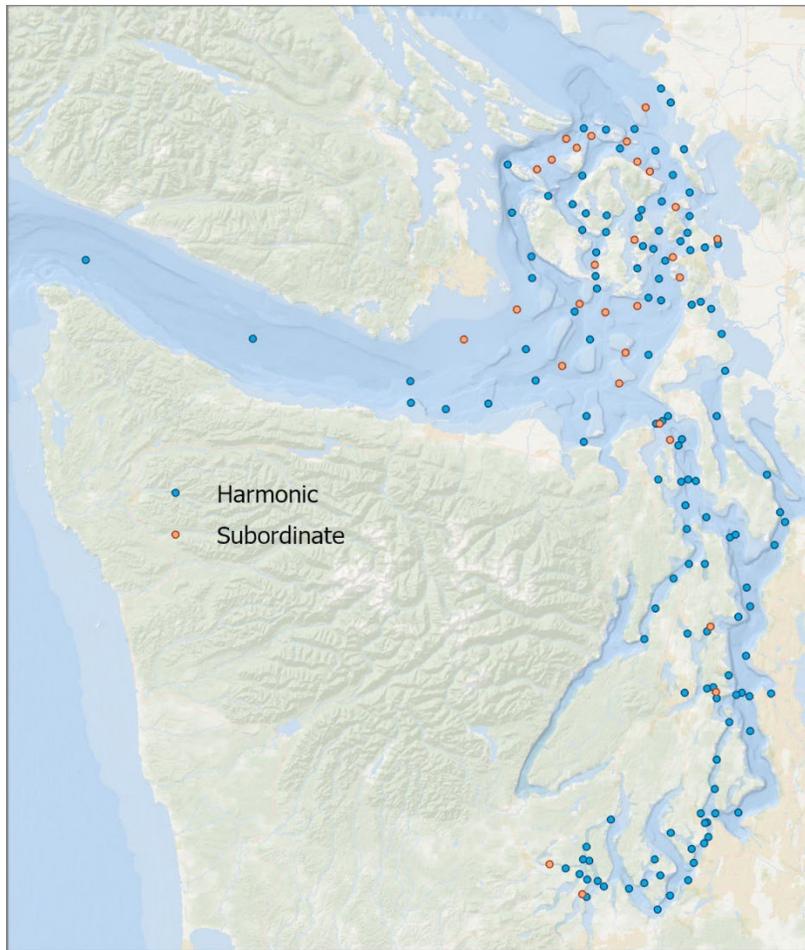


Figure 2-24. Map of all NOAA tide and current prediction stations categorized by whether predictions are based on harmonics or using offsets from the harmonic stations (subordinate).

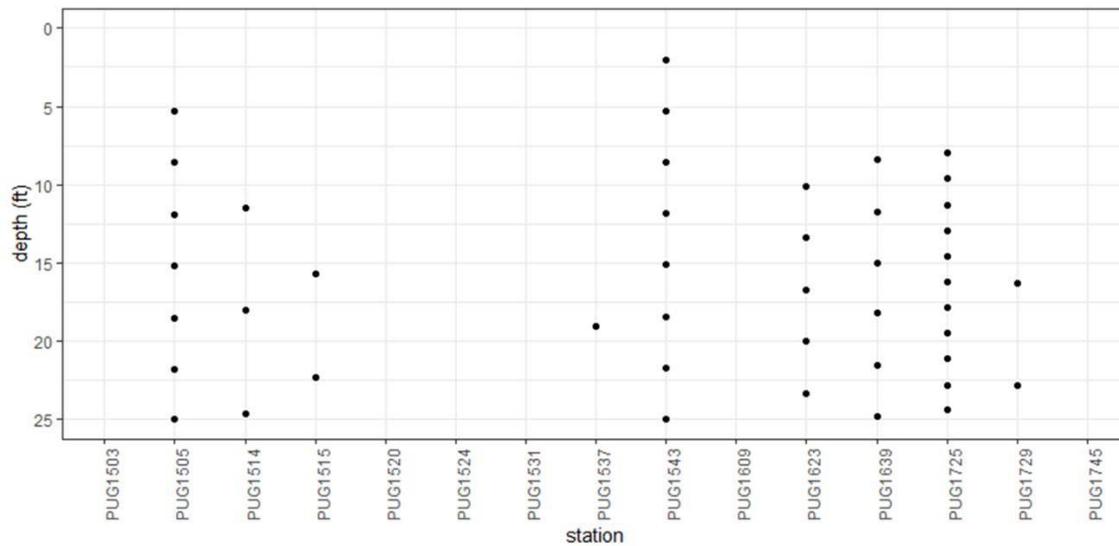


Figure 2-25. Depths at which NOAA current predictions are available in shallow waters for the 15 NOAA stations nearest to the 15 project sites. These reflect general station metadata applicable to all available data for a station, rather than a summarization of 2014 predictions which could have less availability than that depicted here.

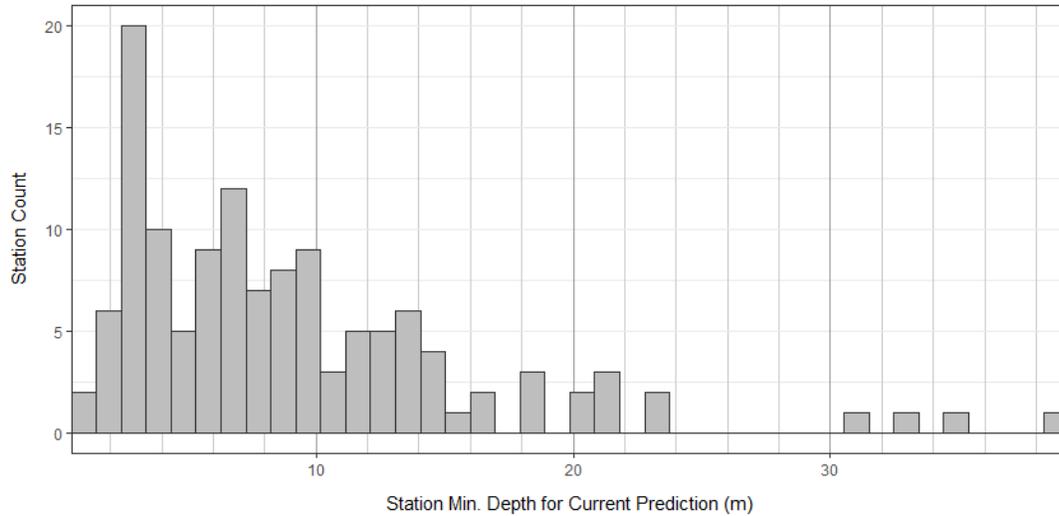


Figure 2-26. Frequency of NOAA current prediction stations (y-axis) with different values of minimum depth at which predictions are made. All 128 NOAA stations are included. Based on this distribution, the 19 NOAA stations with current predictions within the top 3 meters of the water column were selected for further analysis.

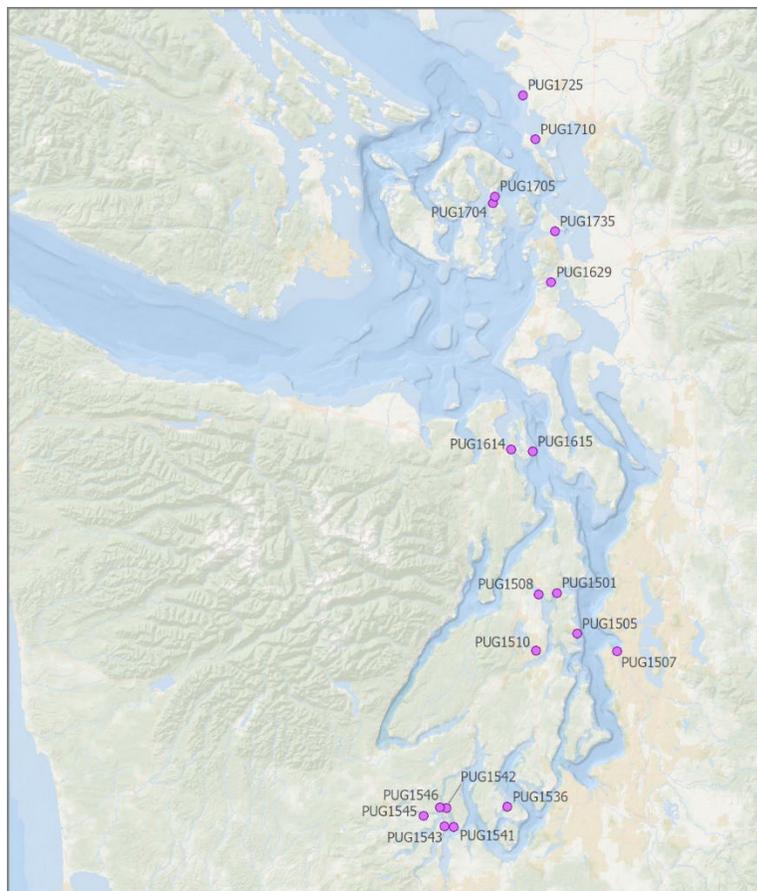


Figure 2-27. The 19 NOAA current prediction stations selected for comparisons of NOAA current predictions and Salish Sea Model current output. Only these 19 stations out of the 128 NOAA stations have predictions that include shallow ($\leq 3m$) depths.

2.2.2.2 Intercomparison of Current Speeds at 19 Stations

The data used for the intercomparison at the 19 stations is presented in Figure 2-28. At each station, the current speeds for all hours of 2014 are summarized in a pair of frequency histograms. One histogram is derived from NOAA predicted currents in the shallowest depth bin (≤ 3 m depth) and the other histogram is derived from SSM 2014 surface layer model solution currents for the SSM grid cell containing the NOAA station.

A subjective summary of the agreement between the NOAA and SSM data sources for the 19 stations is as follows:

- 8 stations: good agreement (e.g. PUG1541)
- 7 stations: reasonable agreement with SSM missing high currents relative to NOAA predictions (e.g. PUG1510)
- 3 stations: reasonable agreement with SSM having more high currents relative to NOAA predictions (e.g. PUG1615)
- 1 station: categorical disagreement (PUG1614).

We conclude from these intercomparisons that the SSM surface currents in the 2014 model solution have value for coarse characterizations of current regimes in individual grid cells. But there are discrepancies that suggest these results should be used with caution.

The case with categorical disagreement in the current speed distribution (NOAA station PUG1614 and SSM cell 5921, Figure 2-28) has unique spatial characteristics that might explain this disagreement and allow us to set this case aside. The NOAA prediction station is at the narrowest point of constriction, roughly 100 m across, that connects two larger water bodies (Port Townsend and Oak Bay) (Figure 2-29). The SSM grid cell contains this constriction but also areas of more open water which would be expected to have very different current conditions (this likely holds even when considering that the actual model grid cells are triangular in shape).

There are other cases where there are constricted channels but with much better agreement between the SSM and NOAA-based current distributions. For example, at NOAA station PUG1510 in Port Washington leading to Dyes Inlet, the channel is long enough that the encompassing SSM grid cell is entirely in the channel. The two current distributions (NOAA PUG1510 and SSM 11624) are in reasonable agreement (Figure 2-28).

Let us consider the use of the SSM current distributions for a simple categorization of locations into predominantly low speed currents, say with $\geq 90\%$ of the current distribution below 0.5 m/s, and locations with a substantial portion of 2014 currents with higher speeds (> 0.5 m/s). Under this categorization, the SSM and NOAA-based results would agree in 16 out of the 19 stations tested, based on visual inspection of Figure 2-28. If we screen for unusual shoreline spatial situations (i.e. PUG1614 with categorical disagreement), then the SSM and NOAA-based results would agree in 16 of 18 cases (84% agreement).

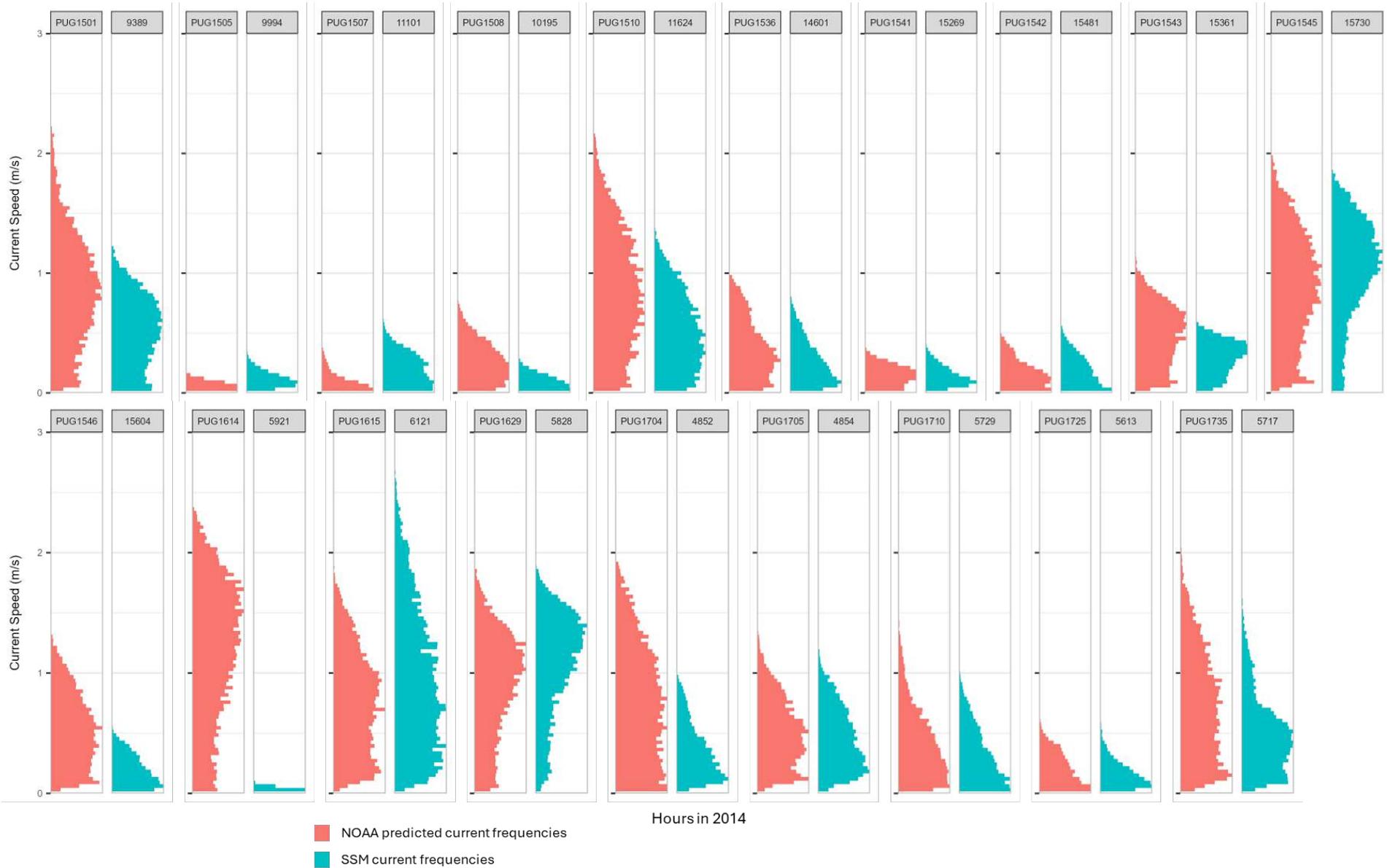


Figure 2-28. Intercomparison of distributions of 2014 current speeds from the Salish Sea Model surface layer, and from the NOAA predicted currents in the shallowest depth bin (≤ 3 m depth) for the 19 locations with shallow NOAA current predictions (Figure 2-27). Each distribution at a NOAA station (e.g. station PUG1501) is paired with the current distribution from the SSM grid cell containing the NOAA station (e.g. grid cell 9389).

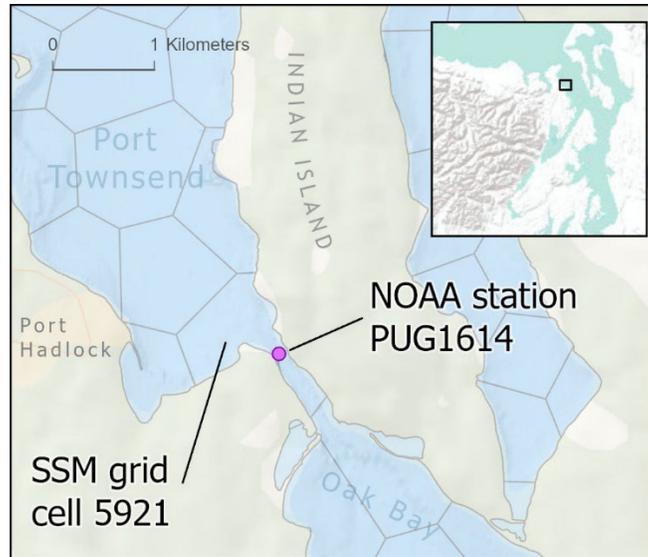


Figure 2-29. The one location where the 2014 current speed distribution from SSM grid cell 5921 was in categorical disagreement with the distribution from NOAA current predictions at station PUG1614, contained within the SSM grid cell.

The two cases where a simple low/high current categorization would disagree when based on NOAA vs SSM data are to the west of Squaxin Island (Figure 2-30). We find nothing obvious about the spatial characteristics of these locations that would suggest they would be problematic. There are stations to the east of Squaxin Island and in Hammersley Inlet where SSM and NOAA-based current categorizations would agree (Figure 2-30).

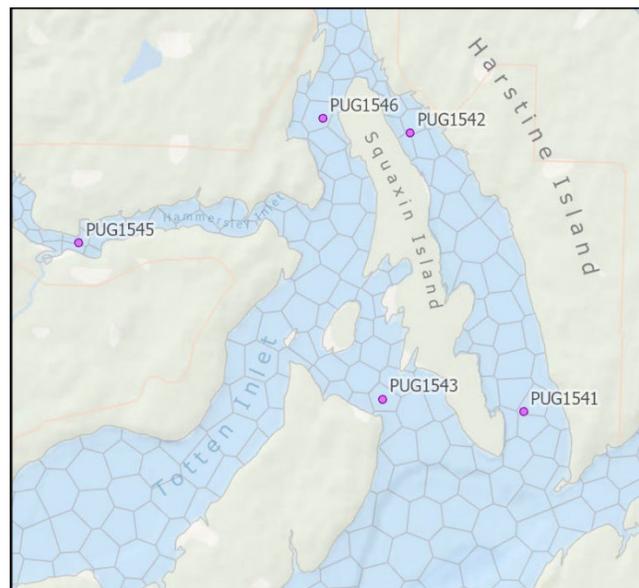


Figure 2-30. Locations of the two NOAA current prediction stations to the west of Squaxin Island (PUG1546 and PUG1543) where a simple categorization of locations into low/high currents (see p.88) would be different when based on SSM 2014 solution currents or NOAA predicted currents. The two stations to the east of Squaxin Island, as well as the station in Hammersley Inlet would be categorized the same with SSM or NOAA data.

2.2.3 Site Current Distributions

We generated the current speed frequency histograms derived from the surface layer of the SSM 2014 model solution. We did this for grid cells containing the 15 project sites (Figure 2-31, Figure 2-32). There is clear separation among sites. North Beach, Salmon Beach and Fox Island have substantial occurrences of high current speeds that have no occurrences at the other sites.

Let us again consider the use of 0.5 m s^{-1} as a current speed threshold. The proportion of the hours in the year with current speeds above this threshold will be used as a metric for a coarse site classification (Figure 2-33). The idea is that higher current speeds have better nutrient delivery, whereas lower current speeds are subject to local depletion of nutrients.

We can use this threshold for a simple binary (high/low) classification by classifying a site as ‘high’ current if less than 10% of all hours over the year have current speeds below this threshold. All other sites that do not meet this criterion are classified as ‘low’ current sites. This results in 7 “high” sites and 8 “low” sites (Table 2-3).

The pattern of cumulative time with current speeds above 0.5 m s^{-1} suggests an alternative classification of sites into three classes based on the visible breaks (Figure 2-33). This classification gives 3 “high” sites, 4 “moderate” sites and again 8 “low” sites (Table 2-3).

Given the distributions of current speeds over an entire year, many different approaches to site classification with respect to current speed are possible. The two classifications presented here (Table 2-3) are simple options based only on hypothesized stress on kelp associated with low current speeds.

A more sophisticated classification scheme might also consider very high currents as potentially stressful, possibly with an interaction with substrate type. The idea here is that different substrates, at least when unconsolidated, will have different critical current speeds where the substrate becomes mobile, thereby introducing potential stress.

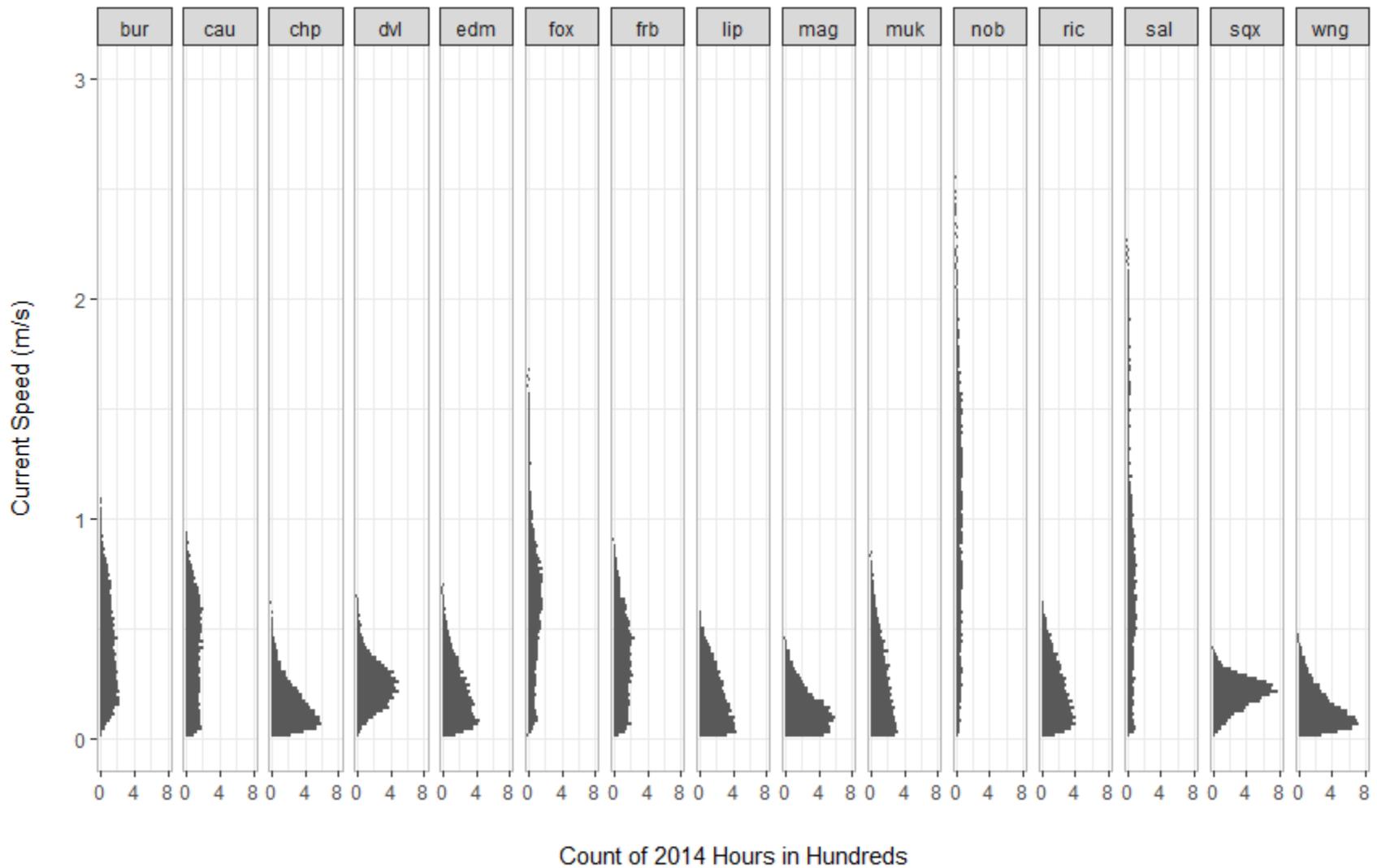


Figure 2-31. Frequency of current speeds over all hours in 2014 as represented in Salish Sea Model output for model cells containing the 15 project sites. The x-axes are labelled in hundreds of hours so label range of 0 to 8 represents 0 to 800 hours. The panels are ordered by site name as follows: Burrows Lighthouse, Pt. Caution, Cherry Point, Devel's Head, Edmonds, Fox Island, Freshwater Bay, Lincoln Park, Magnolia, Mukilteo, North Beach, Rich Passage, Salmon Beach, Squaxin Island and Wing Point.

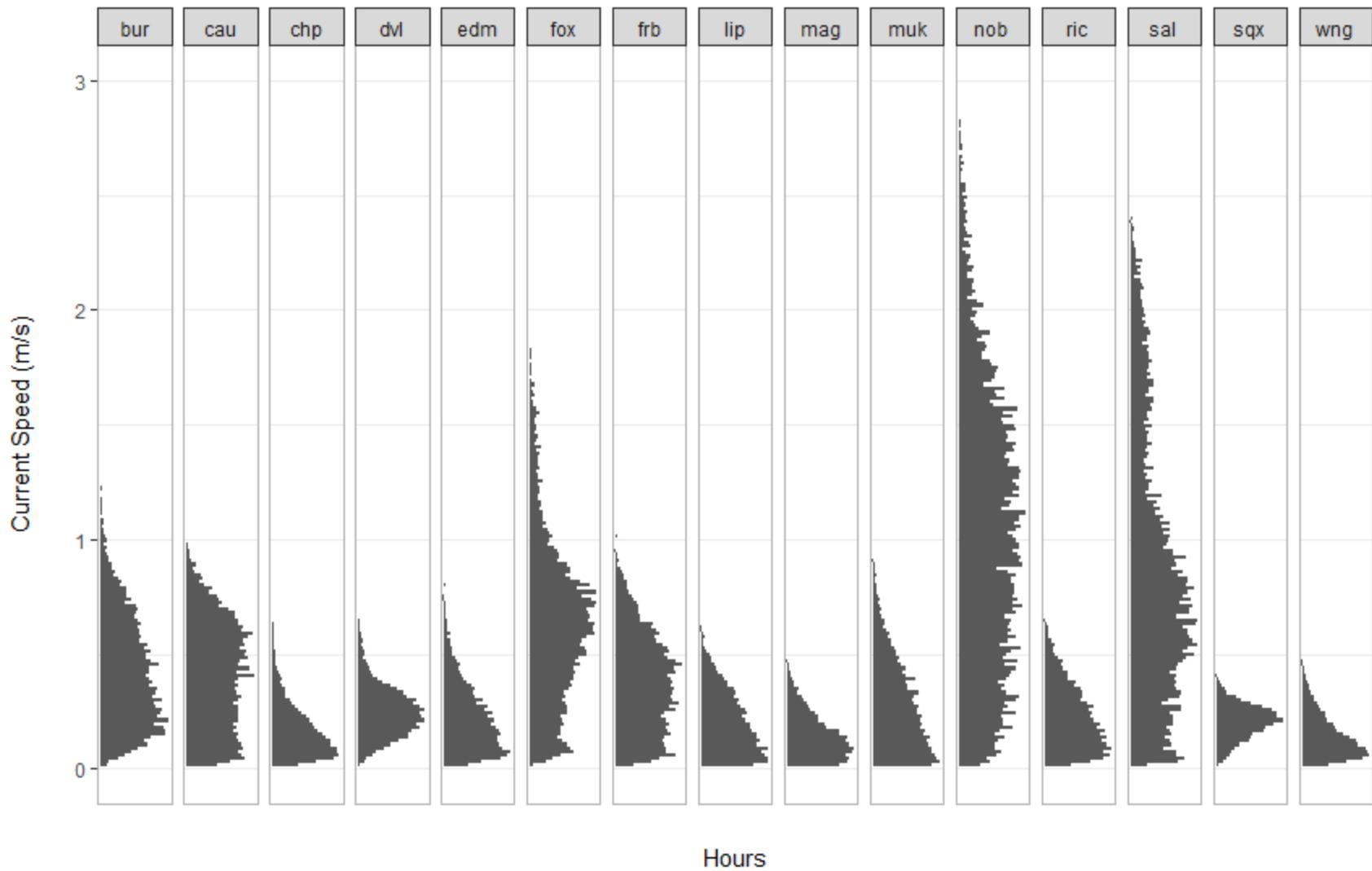


Figure 2-32. Frequency of current speeds over all hours in 2014 as represented in Salish Sea Model output for model cells containing the 15 project sites. These are the same histograms as in Figure 2-31, except the x-axes are now scaled separately for each site to maximize visibility of each histogram.

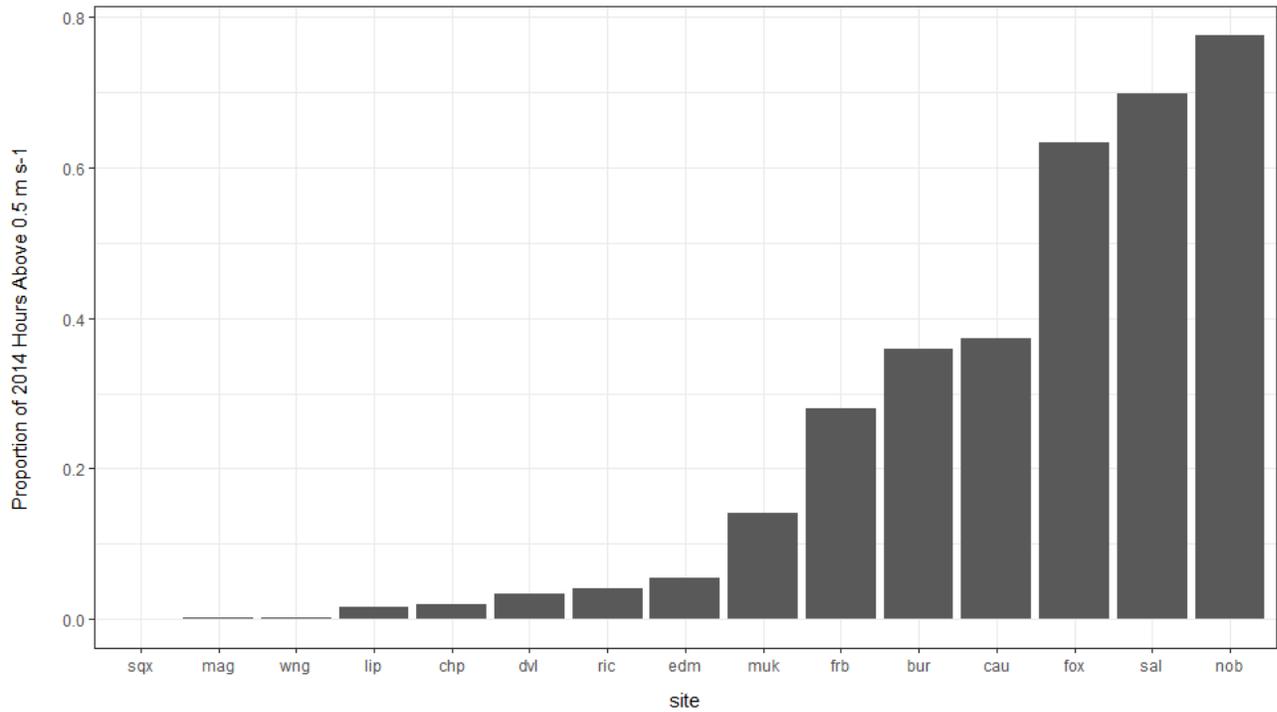


Figure 2-33. Proportion of all 2014 hours with current speeds above 0.5 m s^{-1} at the 15 project sites. This is a summary of the top depth layer of the SSM 2014 model solution for the 15 grid cells containing the project sites.

Table 2-3. Coarse site classification by current speed. Two alternative classifications are given based on the proportion of time over the year with current speeds above 0.5 m s^{-1} (Figure 2-33).

site code	site name	% above 0.5 m s^{-1}	Site Classifications by Current Speed	
			High/Low	High/Moderate/Low
sqx	Squaxin Island	0.01%	low	low
mag	Magnolia	0.2%	low	low
wng	Wing Point	0.3%	low	low
lip	Lincoln Park	1.7%	low	low
chp	Cherry Point	2.0%	low	low
dvl	Devil's Head	3.4%	low	low
ric	Rich Passage	4.0%	low	low
edm	Edmonds	5.5%	low	low
muk	Mukilteo	14%	high	moderate
frb	Freshwater Bay	28%	high	moderate
bur	Burrow's Lighthouse	36%	high	moderate
cau	Pt. Caution	38%	high	moderate
fox	Fox Island	63%	high	high
sal	Samon Beach	70%	high	high
nob	North Beach	78%	high	high

While we have demonstrated the use of the SSM 2014 model solution for classification of the project sites by current regime, we must retain some caution in the use of such results. To some extent the whole-year frequency distributions are a highly aggregated view of the SSM data and likely to be less sensitive to limitations in model precision. But even so, when using the simple binary classification, we did not have complete agreement when the classification was based on a different widely used data source, the NOAA current predictions. In 2 out of 18 cases (16%) there was disagreement.

Notably, the two cases of disagreement were in the vicinity of the Squaxin Island kelp bed where the SSM currents speeds were markedly lower than the NOAA predictions. Field observations from the Squaxin Island kelp bed suggest this is generally a high current site, in contrast to the characterization from the SSM 2014 model solution. Caution may be warranted in SSM-based characterization of the Squaxin Island site in particular.

2.3 References

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3 Existing bull kelp data

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Executive Summary

This report was produced as part of a project designed to advance our understanding of factors associated with patterns of bull kelp loss and resilience within the Washington State waters of the Salish Sea. The project involves coordinated monitoring, research, and synthesis of existing data conducted by a coalition of organizations led by the Washington State Department of Natural Resources (DNR), the University of Washington, and the University of Chicago.

This chapter was compiled by the Washington State Department of Natural Resources (DNR). DNR manages 2.6 million acres of state-owned aquatic lands for the benefit of current and future residents of Washington State. As part of this responsibility, DNR's Nearshore Habitat Program (NHP) monitors populations of nearshore marine vegetation including floating kelp forests along Washington's shorelines.

This synthesis of existing data consists of this compendium of available information on bull kelp canopies (*Nereocystis luetkeana*) in the study area with some information on giant kelp (*Macrocystis pyrifera*). Data includes canopy kelp distribution, abundance, and trends based on information collected by DNR and partners contributing to the new floating kelp indicator – an element of the Puget Sound Vital Signs coordinated by the Puget Sound Partnership. This canopy kelp synthesis report is paired with two additional components that synthesize available information on benthic habitats (Chapter 1) and marine environmental data (Chapter 2).

3.1 Introduction

Floating kelp forests are a critical nearshore habitat in Washington waters. In greater Puget Sound (Puget Sound plus the San Juan Islands and the U.S. portion of the southern Strait of Georgia), the primary canopy-forming floating species is bull kelp (*Nereocystis luetkeana*), while the outer coast and western Strait of Juan de Fuca also includes giant kelp (*Macrocystis pyrifera*). Floating kelp beds create three-dimensional habitat structure that supports an abundance of marine life, including salmon, forage fish, orcas, and other species of cultural, economic, and ecological significance (Schroeder 2019, Shaffer et al. 2020). Rapidly growing kelp functions as a primary producer and nutrient cyclers, creating a food source for numerous species of fish and invertebrates (Chittaro et al. 2023).

WA Department of Natural Resources (DNR) Nearshore Habitat Program and many collaborators conduct monitoring of floating kelp beds throughout the state using a variety of methods, including fixed-wing aerial imagery, uncrewed aircraft systems (UAS) imagery, and kayak-based surveys. In recent years, a diverse group of partners have synthesized floating kelp monitoring efforts across the state to better understand how its distribution has changed over time in the Washington State Floating Kelp Indicator project, a component of the Puget Sound Vital Signs program (Berry et al. 2023).

Impetus for the Washington State Floating Kelp Indicator came from multiple community, tribe, and agency efforts, including the Puget Sound Kelp Conservation and Recovery Plan (the “Kelp Plan”). The Kelp Plan was created in 2020 by the Northwest Straits Initiative and partners as a collaborative effort to provide “a research and management framework for coordinated action to improve understanding of kelp forest population changes and declines, while also working to implement and strengthen recovery and protective measures.” ([Kelp Plan website](#); Calloway et al. 2020). The Kelp Plan was created in response to the Rockfish Recovery Plan for Puget Sound and the Georgia Basin (NMFS 2017) due to the recognition of the importance of kelp forests as critical habitat for juvenile rockfish and long-term recovery. The Kelp Plan has been a nexus of collaboration, and an update was published in 2023 (Whitty and Oster 2023). One of the actions (3.3.4) within the Kelp Plan was to “Collaborate with the Puget Sound Partnership to expand the eelgrass Vital Sign to incorporate kelp indicators (such as kelp canopy area and understory kelp distributions).” The first Indicator to come from this effort is the Floating Kelp Bed Area Vital Sign Indicator.

The Washington State Floating Kelp Bed Area Vital Sign Indicator (hereafter, the “Indicator”) tracks changes in floating kelp bed area over time, including both *Nereocystis* and *Macrocystis* canopies. Floating kelp *bed area* is defined as the area of kelp individuals floating at the surface as well as the small spaces between individuals. Several of the datasets described in this report also measure *canopy area*, defined as only the area of the kelp individuals that is floating at the surface of the water. The Indicator reports on floating kelp *status* and *trends*. The following is a brief description of status and trends reporting (including Table 3-1), for more in-depth information, see the Indicator Monitoring Program

Design and Data Assessment Protocols document (Berry et al. 2023), the Indicator Summary Report (Claar et al. 2025), and the Indicator [interactive webmap](#). *Trends* are reported at the location scale, with ‘location’ size depending on the data type but generally ranging from approximately 1 km to 5-10 km of coastline. *Trends* are assessed quantitatively using linear regressions for locations that have at least five years of bed area data. *Status* is assessed at the sub-basin level, with ‘sub-basins’ defined based on large-scale geographic and oceanographic features. There are eleven sub-basins defined that encompass the entirety of Washington’s coast, nine of which have floating kelp present. *Status* is an integrated assessment that includes not only the *trends* at locations within the sub-basin but also other ways of knowing such as Indigenous Scientific Knowledge, citizen science, and historical surveys.

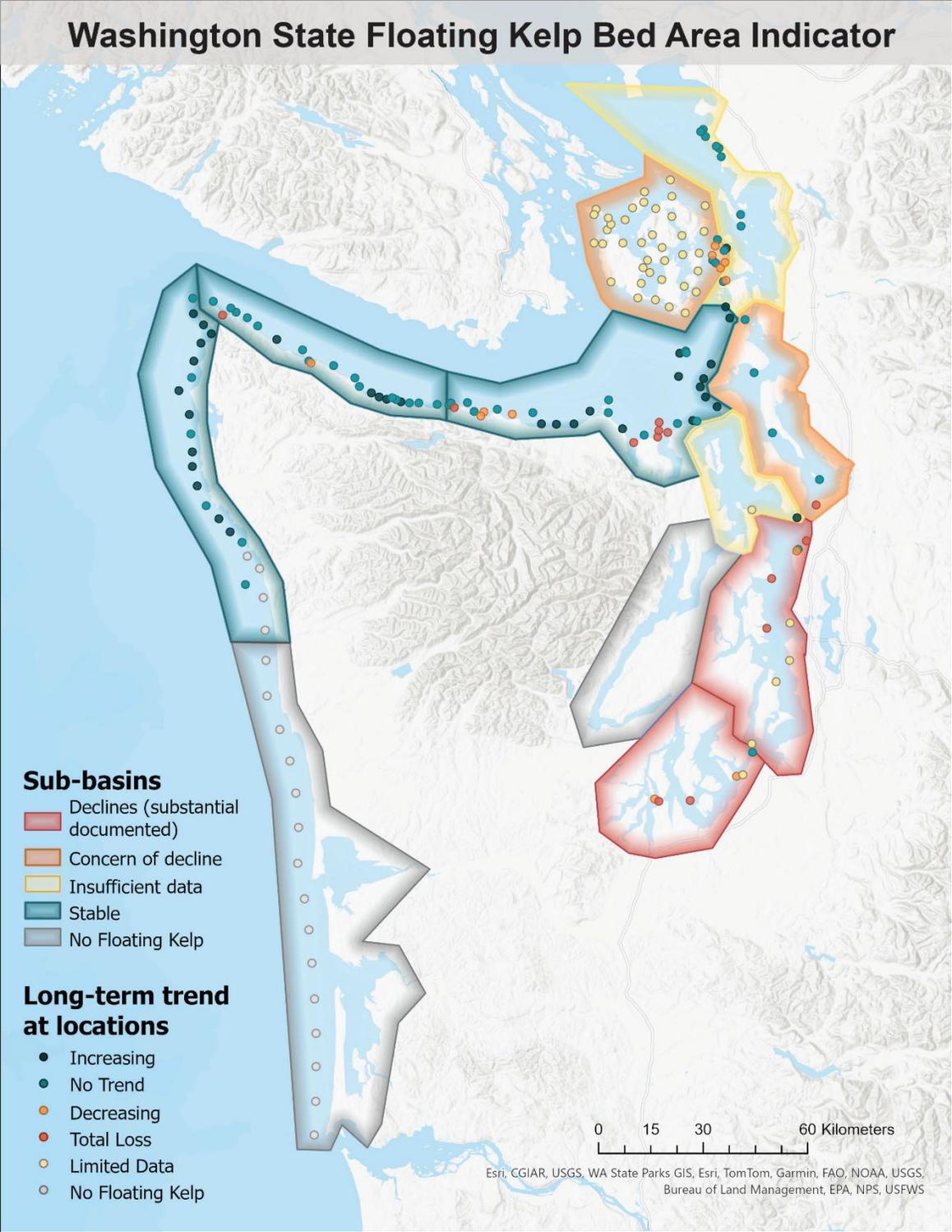


Figure 3-1. Floating kelp status in sub-basins (shaded polygons) and long-term trends at sampling locations (colored points), including data through 2023. Figure and caption from Claar et al. 2025.

Table 3-1. Key definitions from the WA Floating Kelp Bed Area Vital Sign Indicator Summary Report (Claar et al. 2025).

Location: the smallest spatial unit for trend assessment of floating kelp bed area with two types:

- Sites - individually identified areas, with a general size of ~1 km of shoreline. Surveyed by kayak.
- Zones - spanning ~5-10 km of shoreline, with boundaries placed at geomorphic features such as headlands. Surveyed using aerial photography. Zones are currently defined within 5 of the 11 sub-basins (the southern and northern coast, western and eastern Strait of Juan de Fuca, the San Juan Islands and DNR Aquatic Reserves).

Location trend categories:

- Increasing – positive (statistically significant) change in area over time
- No trend – no statistically significant change in area over time
- Decreasing – negative (statistically significant) change in area over time
- Total loss – floating kelp was present in the data record but absent in the most recent year
- Limited data – quantitative data are available but are not sufficient to perform regression or assess long-term changes using alternative methods
- No floating kelp – all surveys show absence of floating kelp

Sub-basin: the largest spatial unit for status assessment, based on large-scale oceanographic features that are associated with environmental conditions. Eleven sub-basins are delineated within Washington.

Sub-basin status categories:

- Stable – no long-term change in extent over time
- Concern of decline – data sources suggest losses, but quantitative data lack sufficient spatial or temporal detail (low signal-to-noise ratio).
- Decline – data sources demonstrate major losses (high signal-to-noise ratio).
- Insufficient data – data sources do not provide sufficient spatial or temporal certainty to classify the sub-basin.
- No floating kelp– all available data sources show floating kelp has been absent historically and is currently absent.

Indigenous scientific knowledge – Indigenous science is about the knowledge of the environment and knowledge of the ecosystem that Indigenous Peoples have. It is the knowledge of survival since time immemorial and includes multiple systems of knowledge(s) such as the knowledge of plants, the weather, animal behavior and patterns, birds, and water among others. (definition from [Indigenous science – Canada.ca](#)).

Variability in stability and change of floating kelp canopies throughout the State has instigated focused attention on environmental drivers and anthropogenic stressors. The goal of this chapter is to produce a synthesis of floating kelp distribution and trends in Washington, and to describe how this information is related to the WA Floating Kelp Bed Area Vital Sign Indicator.

3.2 Methods

Floating kelp canopies have been surveyed using a number of different methods, including aerial imagery (sections 3.2.1, 3.2.2, 3.2.5), kayak surveys (section 0), UAS (drone) surveys (section 3.2.4), boat surveys (section 3.2.7), satellite imagery (section 3.2.6) and synthesis of historical data such as charts and maps (section 3.2.8). Although these methods produce differing products (e.g., due to different resolutions and survey methodologies), many of these datasets can be compared to one another in a meaningful way.

Consequently, four of these datasets have been used in the quantitative synthesis of floating kelp *trends* for the Washington Floating Kelp Bed Area Vital Sign Indicator (i.e., WA DNR COSTR/AQRES, Samish aerial data, MRC kayak data, and WA DNR kayak data). The other datasets included in this document are incorporated into the *status* metric that is synthesized at the sub-basin scale, and some will likely be included in quantitative trend calculations once more years of data have been collected. The following sections represent brief summaries of each program/method, for more in-depth information visit the data sources and documentation listed in section 3.3.3.

3.2.1 Aerial imagery (fixed-wing aircraft)

3.2.1.1 WA DNR COSTR/AQRES

Department of Natural Resources' air photo-based monitoring of the open coast and Strait of Juan de Fuca (DNR-COSTR) and at three DNR Aquatic Reserves (DNR-AQRES), collected by Ecoscan LLC. DNR-COSTR imagery has been collected annually between 1989 and 2025 (except 1993), totaling 36 years of kelp canopy area and bed area measurements for the open coast and Strait. DNR-AQRES has been collected annually between 2011 and 2025, totaling 15 years of kelp canopy and bed area measurements in three DNR Aquatic Reserves: Smith and Minor Island, Cypress Island, and Cherry Point. Imagery is collected in late summer, which coincides with maximum floating kelp extent each year.

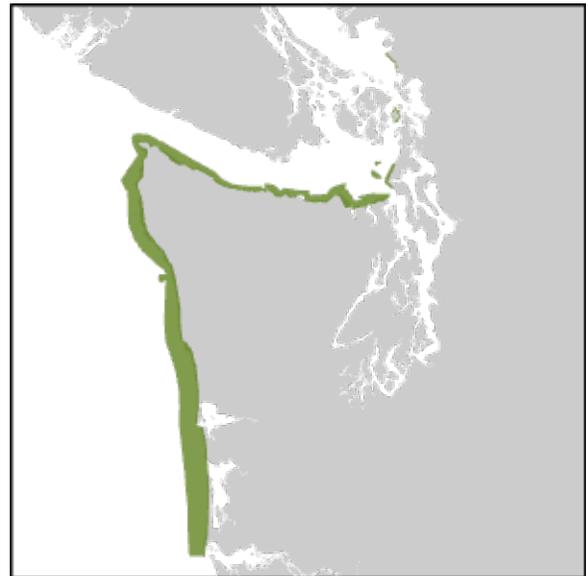


Figure 3-2. COSTR/AQRES survey extent.

Table 3-2. Description of DNR COSTR/AQRES dataset (modified from Floating Kelp Vital Sign Indicator COSTR/AQRES Dataset Description).

Spatial Extent:	Open coast and the Strait of Juan de Fuca to Point Wilson, Port Townsend (COSTR). DNR’s northern Aquatic Reserves (AR): Smith and Minor Island AR, Cypress Island AR, Cherry Point AR (AQRES). Note: Protection Island AR is included in the COSTR dataset.
Metric(s)	Canopy area with bed area and density determined from beds delineated as polygons; tabular data summarizing canopy area, bed area, relative density. In COSTR, estimates are sub-divided into giant kelp and bull kelp. In AQRES, only bull kelp is present.
Assessment Units	102 units (map indices) that comprehensively cover the study area
Survey years	1989-2025 (COSTR), 2011-2025 (AQRES)
Frequency	annual
Methods summary	Near-vertical low-tide color-infrared imagery is collected from a fixed wing platform during late summer. Imagery is projected onto 1:12,000 paper maps and kelp canopies are hand-delineated. Bed area is estimated by buffering canopy data with a 20-m radius of association. The hand-delineated paper canopy maps are scanned. Then tabular estimates of canopy area and bed area are produced and summarized at the scale of map indices (stretches of shoreline defined by geomorphic features such as headlands).
Access	All survey data is maintained by the Nearshore Habitat Program, in the Washington Department of Natural Resources (nearshore@dnr.wa.gov).

3.2.1.2 Kelp Aerial Monitoring (KAM): High-resolution aerial imagery

Department of Natural Resources’ air photo-based monitoring of Washington State floating kelp and eelgrass, collected by NV5-Geospatial. Imagery has been collected annually between 2022 and 2025. Imagery is collected during summer (mid-July – September), which coincides with maximum floating kelp extent each year.

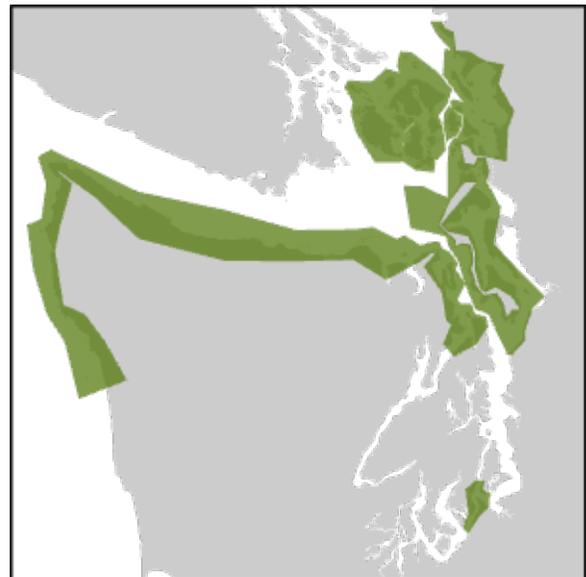


Figure 3-3. KAM survey extent.

Table 3-3. Description of DNR KAM high-resolution fixed-wing aerial imagery

Spatial Extent:	Nine areas of interest (AOIs) have been surveyed between 2022 and 2024: Open Coast, Strait of Juan de Fuca, Admiralty Inlet, North Puget Sound, San Juan Islands, Saratoga-Whidbey sub-basin, Tacoma Narrows, Squaxin Island, and Aquatic Reserves. Imagery covers approximately 750,000 acres of nearshore habitat each year.
Metric(s)	Canopy area quantified from 6-inch resolution, 4-band imagery (red, green, blue, near infrared) Derived products including bed area are currently under development.
Assessment Units	Comprehensive within study area
Survey years	2022, 2023, 2024, 2025 (data in progress)
Frequency	annual
Methods summary	Aerial photo acquisition was performed by Geoterra, in coordination with NV5 using UltraCam large-format cameras (Falcon Prime and Falcon Mark 2). The acquisition windows targeted sun angles between 25° and 45°, low tides (less than 1 ft MLLW), ocean swell less than 1.5 m, calm sea states (surface winds less than 10 knots) and cloud free or overcast conditions. Images were collected with 80% along-track overlap and 40% sidelap between frames, from an altitude of 8,200 ft AGL. Imagery was orthomosaicked and provided to WA DNR as GeoTIFF orthomosaics (full resolution), MrSID orthomosaics (lossy compression), and as the original image frames (TIFFs).
Access	All survey data is maintained by the Nearshore Habitat Program, in the Washington Department of Natural Resources (nearshore@dnr.wa.gov).

3.2.1.3 Samish Aerial data

The Samish Indian Nation delineated floating kelp beds using aerial photography in San Juan County in 2004/2006 in collaboration with WA DNR and the Friends of the San Juans and in 2016 & 2019 using imagery collected by Pictometry for San Juan County. In addition, they classified Skagit County and shorelines in 2019 using similar processing methods. In 2022, 2023 and 2024 (2025 in progress at the time of this publication), Samish Indian Nation measured floating kelp bed extent in the San Juan Islands using 4-band aerial imagery collected by Washington State DNR (KAM high-resolution imagery).

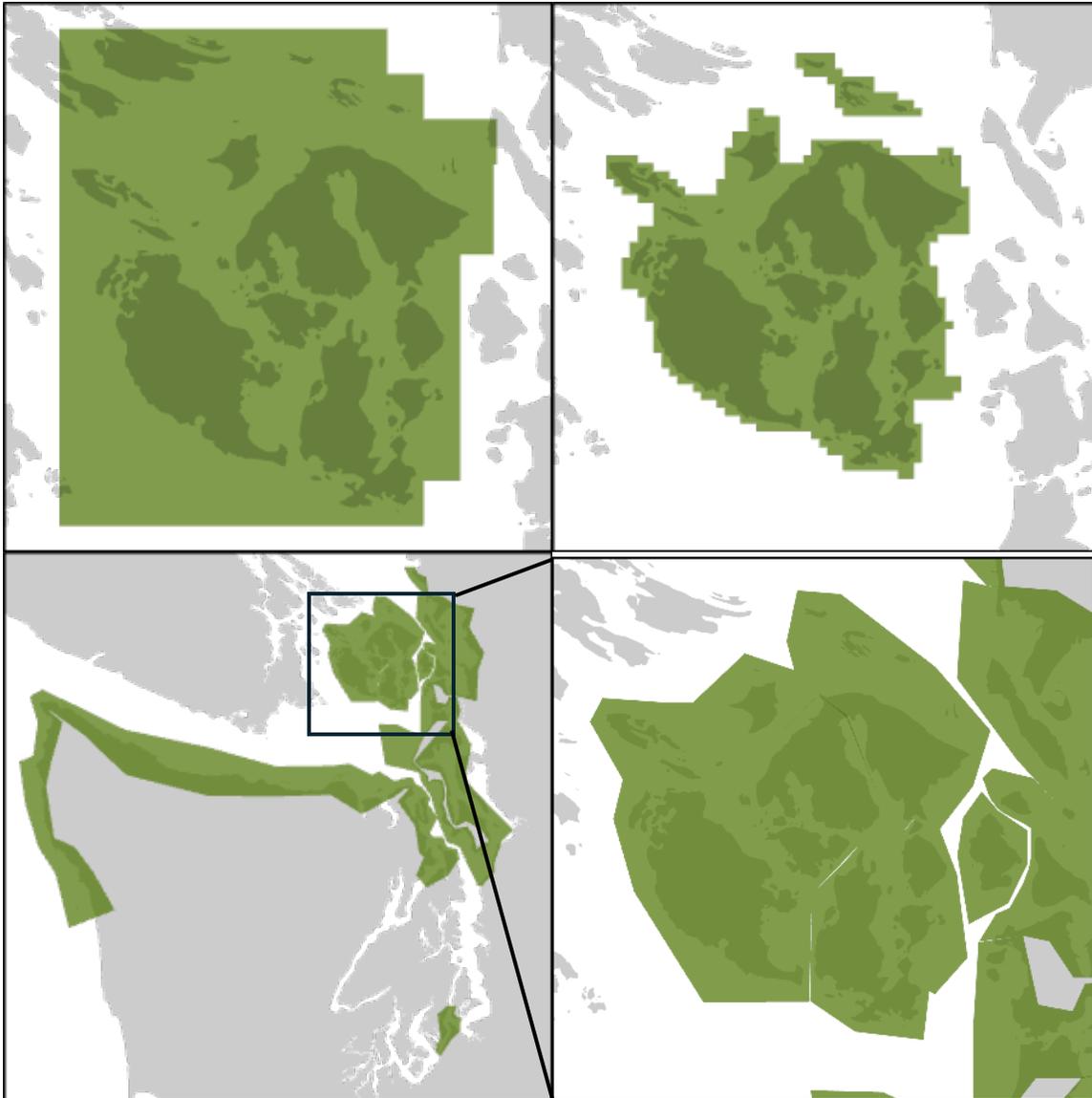


Figure 3-4. Top left: Friends of the San Juans/DNR fixed-wing aerial imagery extent (2004 & 2006). Top right: Samish Indian Nation survey extent 2016 and 2019. Bottom left: DNR Kelp Aerial Monitoring survey map, box shows San Juan Islands area (bottom right) collected as part of this survey in 2022, 2023, 2024 and 2025.

Table 3-4. Description of Samish Indian Nation dataset (modified from Floating Kelp Vital Sign Indicator Samish Indian Nation Aerial Dataset Description).

Spatial extent	San Juan County (SJC), Skagit County (SC).
Metric(s)	Kelp bed area (GIS polygons)
Assessment Units	Comprehensive delineation within the study area
Survey years	2004/2006 (SJC only, Western portion in 2004 and eastern portion in 2006), 2016 (SJC only), 2019, 2022 (SJC only)
Frequency	As funding is available.
Methods summary	<p>Beds were delineated to encompass areas with floating kelp canopies (including gaps within the canopy and rocks) using on-screen digitizing of aerial photography. Detailed methods are available from the Samish Indian Nation.</p> <p>Aerial imagery sources:</p> <ul style="list-style-type: none"> - 2004-2006 aerial photography: low-tide, color-infrared 9" x 9" negatives collected during joint DNR-Friends of the San Juans project. (Berry 2007). These photographs were originally used for surface canopy delineation using semi-automated classification of spectral band data. - 2016 and 2019 aerial photography: 6" resolution color imagery collected by Pictometry for San Juan County during May/June 2016. Variable tide and current levels. - 2019 photography from SC was collected at a different time than SJC photography - 2022-2025 low-tide, slack-current, 4-band imagery collected with a fixed-wing aircraft at 6" resolution. Imagery collected as part of a broader WA DNR Kelp Aerial Monitoring imagery program.
Accessibility	The 2006, 2016, and 2019 Samish aerial kelp surveys are generated and maintained by Samish Indian Nation DNR and are used as part of the Floating Kelp Vital Sign Indicator with permission. Access to raw data (including GIS files) can be done with a request to the Samish Indian Nation (contact).

3.2.2 Linear extent from 1984 imagery in Central Puget Sound

In 2024, WA DNR digitized and analyzed a collection of aerial images of the Seattle shoreline captured by Ron Thom in 1984. The color-infrared images span approximately 4km of shoreline along Magnolia Bluff and 6.5 km of shoreline in West Seattle, including the southern shoreline of Lincoln Park. Kelp presence and abundance data was extracted from the images and mapped onto the -6.1 m MLLW isobath to create a linear extent dataset.



Figure 3-5. Footprint of historical aerial imagery of Seattle shorelines from 1984.

Table 3-5. Description of the 1984 aerial imagery dataset.

Spatial Extent:	Central Puget Sound: Magnolia and West Seattle
Parameters	Floating kelp presence (linear data) and abundance classes (Table 3-6 Table 3-6).
Metric(s)	Linear extent of kelp presence, comprehensive within study area
Survey years	1984
Frequency	Once
Methods summary	The 1984 images were georeferenced using notable shoreline features but not rectified due to oblique image angles. Subject matter experts reviewed the images for kelp presence and abundance. Review results were mapped onto the -6.1 m MLLW isobath, approximating methods used in Berry et al. 2021. Methods are described in detail in McKenna et al. 2025.
Access	All survey data is maintained by the Nearshore Habitat Program, in the Washington Department of Natural Resources (nearshore@dnr.wa.gov).

Table 3-6. Kelp presence type and subtype classification system used to describe floating kelp presence in 1984 imagery. Incidental subtypes were grouped together for reporting results in this study. Table and caption from McKenna et al. 2025.

Type	Description	Subtype	Description
bed/forest	Sufficient density to form a multi-plant canopy spanning >10 m alongshore.	fringing	Narrow and linear, width consistently <20 m.
		wide	Conspicuous due to large size, width consistently > 20 m.
incidental	isolated individuals that do not form a multi-plan canopy	single	A single individual at a distinct location, or multiple individuals growing in a clump attached to a single location. Located at least > 20 m from other bull kelp (generally much farther away). These features were assigned an alongshore length of 4 m during data processing.
		multiple	Multiple spatially isolated individuals, generally < 20 m apart. This category often chosen through process of elimination; when individuals occur too close to be easily mapped as 'single' yet are not close enough to constitute a bed/forest.
absent	no bull kelp present	absent	None.

3.2.3 Kayak data

3.2.3.1 MRC kayak

Volunteers with Marine Resources Committees (MRCs) and Northwest Straits Commission (NWSC) began surveying floating kelp beds in 2015 and in subsequent years have now surveyed beds in all seven counties in northern Washington (Clallam, Island, Skagit, Jefferson, San Juan, Snohomish, Whatcom). The MRC site surveys range in temporal coverage. Volunteers follow a kayak-based survey protocol to record the perimeter of floating kelp canopies with handheld GPS units at select sites.

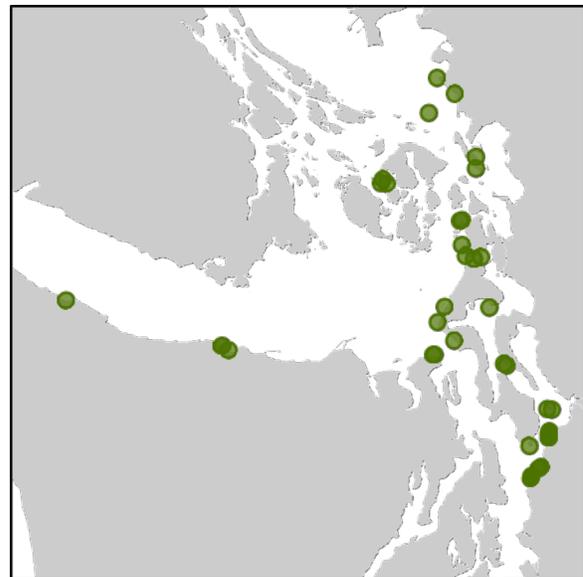


Figure 3-6. MRC Kayak survey sites.

Table 3-7. Description of MRC Kayak dataset (modified from Floating Kelp Vital Sign Indicator MRC Kayak Dataset Description).

Spatial Extent:	Seven northern counties in Puget Sound that are within the Northwest Straits Initiative (Clallam, Island, Skagit, Jefferson, San Juan, Snohomish, Whatcom).
Metric(s)	Bed area based on delineated bed perimeters
Assessment Units	Multi-year monitoring sites, most sites are at the approximate scale of 1 km of shoreline.
Survey years	2015 – 2025 total, many sites span a subset of years.
Frequency	Annual
Methods summary	<p>Kayak-based delineation of bed perimeter with handheld GPS. Minimum thresholds for inclusion: canopy width >5 m. Maximum distance among individuals (fronds or bulbs) for inclusion: 8 m between individuals (Bishop 2014, updated 2023).</p> <p>Volunteers collect data on additional parameters such as water temperature and kelp bed depth as well as visual observations and photo documentation following the monitoring protocol developed by the Northwest Straits Commission (NWSC) with guidance from scientists. The data are collected by volunteer kayakers and members of the Marine Resources Committees (MRCs).</p>
Access	All survey data are maintained by the Northwest Straits Commission and visible on SoundIQ. GPS data is available for download through SoundIQ or directly contacting the NWSC.

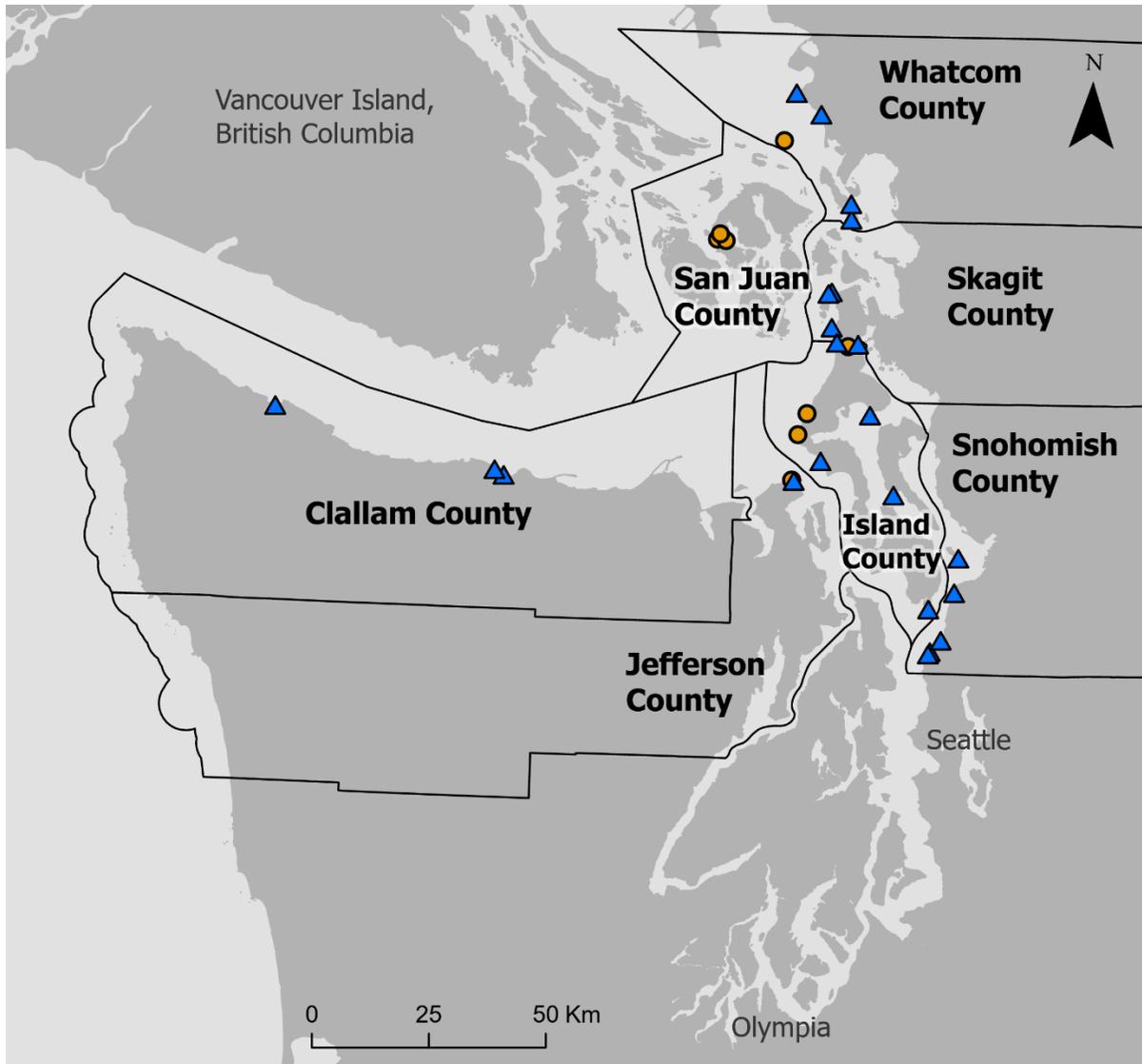


Figure 3-7. Marine Resources Committees (MRCs) kayak-based floating kelp monitoring sites in seven northern counties in Puget Sound, WA. Blue triangles represent sites surveyed in 2021 and orange circles represent sites no longer surveyed. Figure and caption from Ledbetter and Berry 2024.

3.2.3.2 WA DNR kayak

WA DNR scientists conduct annual monitoring of floating kelp beds at 13 core monitoring sites in South Puget Sound and Central Puget Sound using kayaks and handheld GPS units. Surveys assess bed area, depth range, density, morphometrics, and other parameters. Surveys began in 2013 at five monitoring sites. Additional surveys have been conducted opportunistically or as part of other projects at eight other sites.

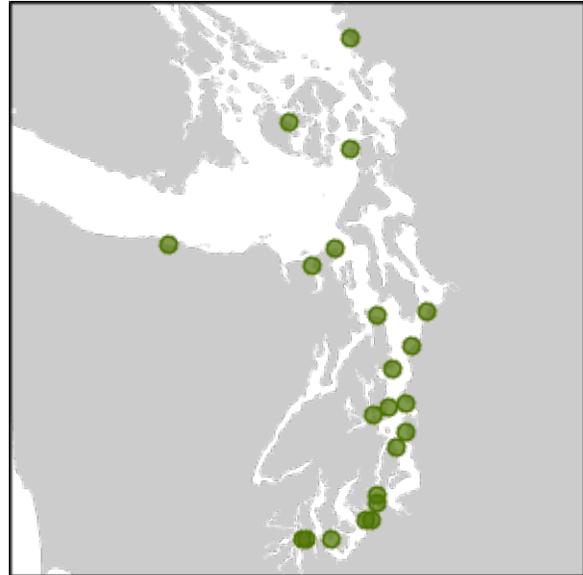


Figure 3-8. WA DNR Kayak survey extent, including core and focus sites.

Table 3-8. Description of WA DNR Kayak dataset (modified from Floating Kelp Vital Sign Indicator WA DNR Kayak Dataset Description).

Spatial Extent:	Sites within Central Puget Sound and South Puget Sound, as well as the Eastern Strait, North Puget Sound, and the San Juan Islands.
Metric(s)	bed (polygons), minimum/maximum depth
Assessment Units	13 sites with historical or current floating kelp, sites span approximately 0.5 – 1.0 km of shoreline each.
Survey years	2013, 2017-2025 (South Puget Sound), 2018-2025 (Salmon Beach), 2020-2025 (Central Puget Sound)
Frequency	Annual (core sites) or intermittent (opportunistic/project sites)
Methods summary	<p>Kayak-based delineation of bed perimeter with handheld GPS. Minimum abundance for inclusion: single bulb. Maximum distance among individuals for inclusion in a single bed: 25 m.</p> <p>At a subset of sites, assessed:</p> <ul style="list-style-type: none"> - density, percent cover, and morphometrics at grid of points along regularly placed across-shore transects, and minimum and maximum depth along regularly placed across-shore transects.
Access	<p>All survey data is maintained by the Nearshore Habitat Program, in the Washington Department of Natural Resources (nearshore@dnr.wa.gov).</p> <p>Kelp monitoring results and spatial/tabular data are available from: https://www.dnr.wa.gov/programs-and-services/aquatics/aquatic-science/kelp-monitoring</p> <p>Kelp Kayak Survey Data – bed perimeters 2013-2025 available at: https://services.arcgis.com/4x406oNViizbGo13/arcgis/rest/services/WADNR_Kelp_Kayak_Survey_Data/FeatureServer/2</p>

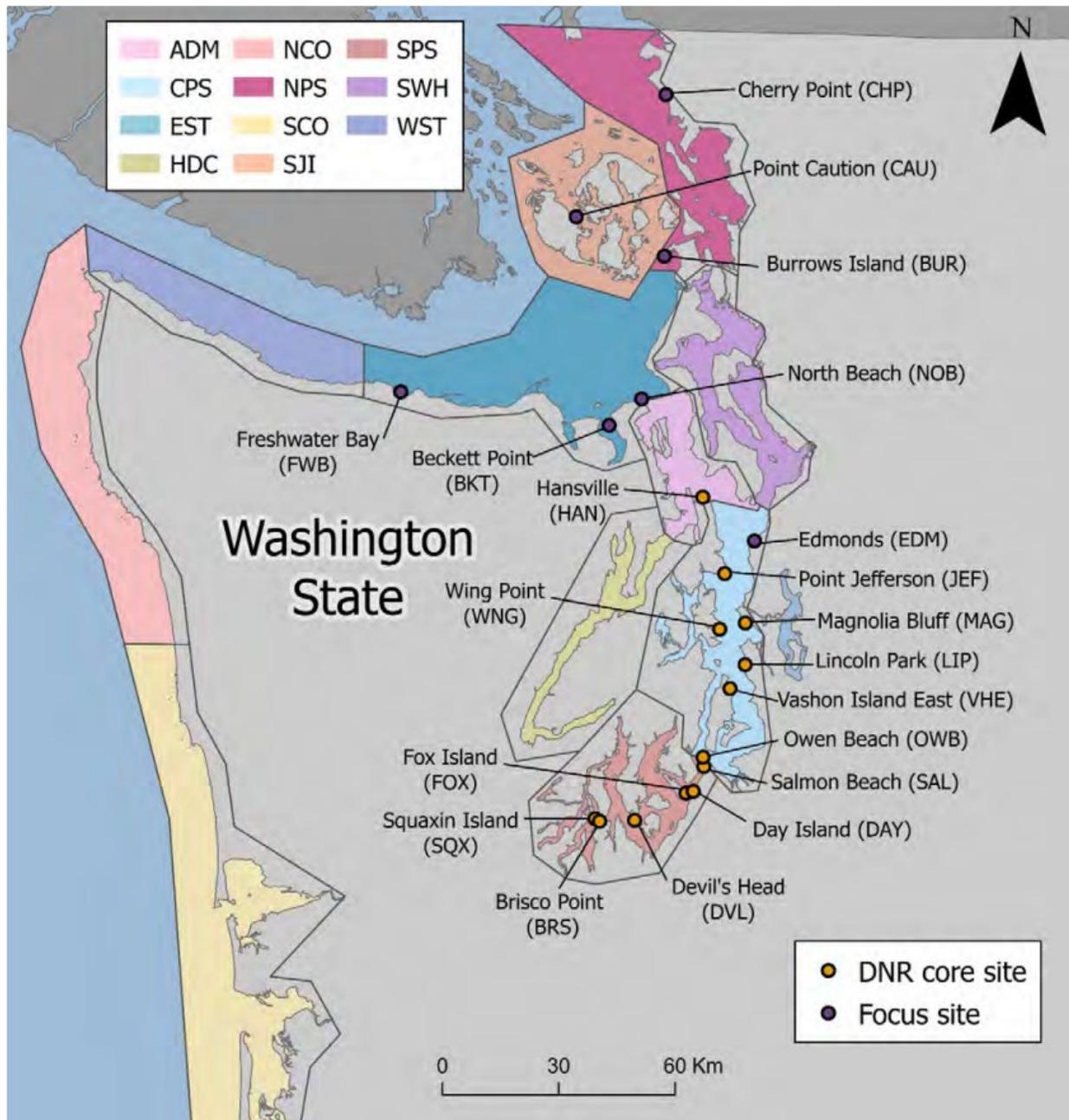


Figure 3-9. Map of the 20 DNR floating kelp monitoring sites. Orange points represent DNR Nearshore Habitat Program's core floating kelp kayak monitoring sites ($n = 13$) and the purple points represent sites where kayak data were collected for focus floating kelp studies ($n = 7$). Each sub-basin is outlined in gray and has a unique color; Admiralty Inlet (ADM), Central Puget Sound (CPS), Eastern Strait (EST), Hood Canal (HDC), North Coast (NCO), North Puget Sound (NPS), South Coast (SCO), San Juan Islands (SJI), South Puget Sound (SPS), Saratoga-Whidbey Basins (SWH), and Western Strait (WST). Modified from Ledbetter and Berry, 2024

3.2.4 UAS

3.2.4.1 WA DNR UAS monitoring surveys

WA DNR scientists have conducted annual surveys of floating kelp beds using uncrewed aircraft systems (UAS or “drones”) at approximately ten sites from 2020 to 2025. Additional ad hoc surveys have been conducted at six other sites during this time as well. Automated gridded surveys are executed to collect high-resolution multispectral imagery, with concurrent ground control points collected using a high-accuracy GNSS device. Collected imagery are stitched into continuous site-wide “orthomosaics” using structure-from-motion photogrammetry software. Orthomosaics are then analyzed using a spectral index-based approach to create classified maps from which floating kelp canopy area metrics can be derived (Cowdrey & Claar, 2024).



Figure 3-10. DNR NHP UAS monitoring extent

Table 3-9. Description of WA DNR UAS dataset

Spatial Extent:	Annual monitoring sites are distributed throughout Central and South Puget Sound, Admiralty Inlet, the eastern Strait of Juan de Fuca, and the southern Strait of Georgia. Additional ad hoc surveys have been conducted in Saratoga Passage, the western Strait of Juan de Fuca, and San Juan Islands.
Metric(s)	Spatial metrics derived from classified imagery currently include: <i>Canopy area</i> (includes only the area of kelp stipes, bulbs, and blades floating at or near the surface) <i>Bed extent</i> (including the overall perimeter of each kelp forest)
Assessment Units	Multi-year monitoring sites, most sites are at the approximate scale of 1 km of shoreline.
Survey years	2020-2025 total, many sites span a subset of years.
Frequency	Annual
Methods summary	In 2020, surveys were conducted using a DJI Mavic 2 Pro with an RGB camera (red, green, blue). Since 2021, UAS surveys have been conducted using the DJI Phantom 4 Multispectral (P4M) quadcopter with real-time kinematic (RTK) positioning and a five-band multispectral camera (blue, green, red, red edge, and near-infrared). Ground control points are collected using Trimble Geo7X and Emlid Reach RS2+ handheld GNSS receivers. Acquisition windows target sun angles between 25° and 45°, low tides at less than 1 ft MLLW, calm winds (ideally less than 10 knots), and cloud free or overcast conditions.

	<p>UAS imagery is collected at ~3-5 cm resolution with 70-80% overlaps, and combined into continuous orthomosaics using structure-from-motion software for use in generating spatial metrics of floating kelp distribution and abundance. <i>Bed extent</i> is manually delineated from the imagery, with kelp individuals within approximately 25 m of each other grouped together as 'beds.' <i>Canopy area</i> is identified using a spectral index threshold classification method based on blue-NDVI (Cowdrey & Claar, 2024). Additional spatial metrics derived from these two are in development.</p> <p>Between 2021-2023, multiple surveys were conducted at all annual monitoring sites during the same day and/or field season to evaluate sources of variability in canopy detection.</p>
Access	<p>All survey data is maintained by the Nearshore Habitat Program, in the Washington Department of Natural Resources (nearshore@dnr.wa.gov).</p>

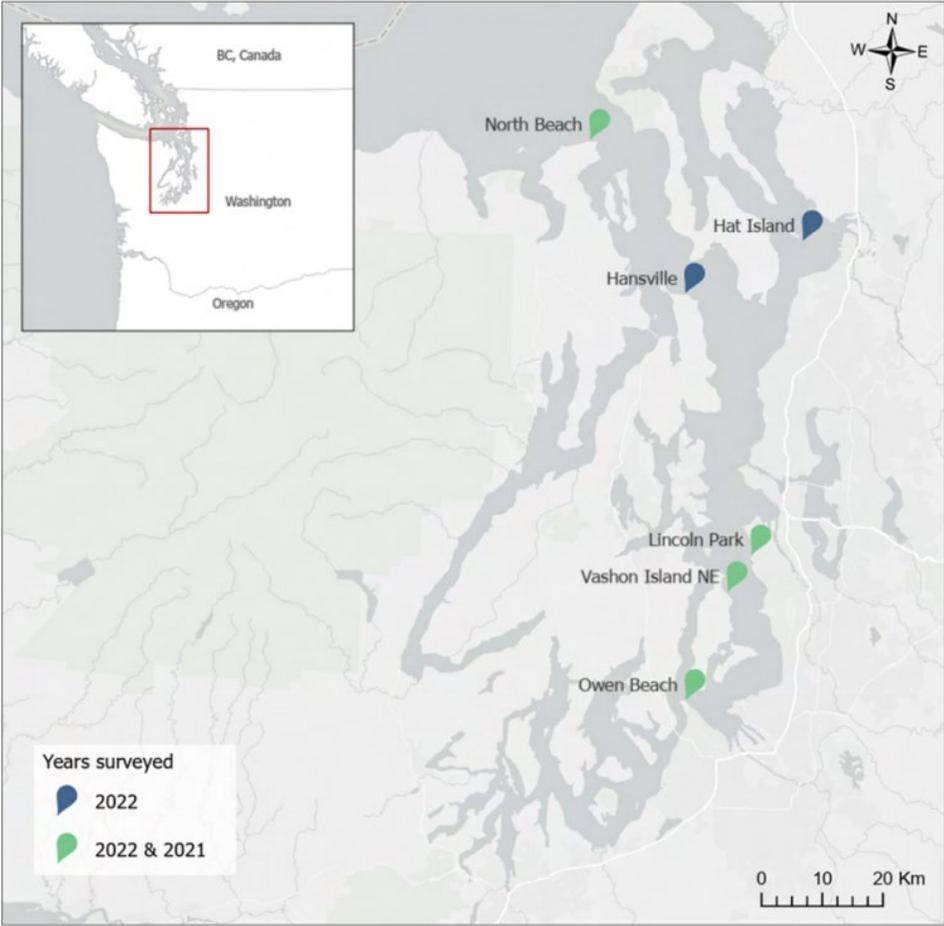


Figure 3-11. Map of the six bull kelp forest sites surveyed with UAS for Cowdrey & Claar, 2024. Sites are symbolized according to the number of years they were surveyed. Figure and caption from Cowdrey & Claar, 2024.

3.2.4.2 WA DNR/Suquamish UAS Surveys

WA DNR partnered with the Suquamish Indian Tribe of the Port Madison Reservation to survey all canopy forming kelp beds in Central Puget Sound (CPS) in 2023 and 2024, which is part of the Tribe’s Usual and Accustomed fishing grounds. WA DNR scientists used the methods described below to collect multispectral imagery at 29 kelp canopy sites using UAS (drones), and classify resulting orthomosaics to produce estimates of kelp bed area and canopy density. Additionally, WA DNR scientists on this project obtained airspace permissions to perform a survey in 2024 at Day Island in South Puget Sound, one of NHP’s kayak monitoring sites; plans are underway to begin including this site in the monitoring UAS work.

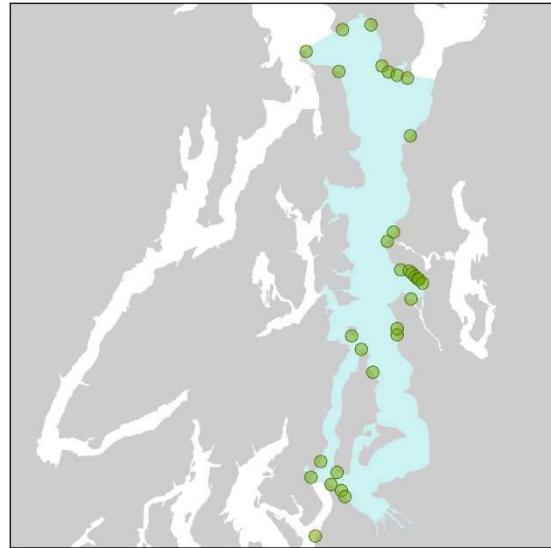


Figure 3-12. Suquamish UAS project study area (blue) and survey locations (green).

Table 3-10. Description of Suquamish UAS project dataset

Spatial Extent:	Surveys were performed at all locations classified “forest-wide” and “forest-fringing” in NHP’s 2019 Central Puget Sound boat-based survey data (Section 3.2.7). For the purposes of this project, CPS was defined as extending across Admiralty Inlet between Foulweather Bluff and Double Bluff, across the Tacoma Narrows, excluding waters west of Agate and Rich Passages, and northeast of Possession Point (Figure 3-12).
Metric(s)	Spatial metrics derived from classified imagery include: <i>Canopy area</i> : area of kelp stipes, bulbs, and blades floating at or near the surface; hectares. <i>Bed extent</i> : outer perimeter of kelp forest; hectares.
Survey years	2023-2024
Frequency	Once per site, 6 completed in 2023 and 23 completed in 2024.
Methods summary	Adapted from Cowdrey & Claar, 2024. Initial survey grids were generated for the classified linear extents of shoreline, extending from approximately the MHHW line offshore to the -6.5m MLLW contour, and cross-referenced with NHP’s kelp aerial monitoring imagery (section 2.1.2) where possible in Admiralty Inlet and north of the Tacoma Narrows. Prior to beginning surveys, scientists ground-truthed the actual outer extent of kelp canopy to the planned survey area and modified the offshore extent as needed, since several sites had kelp present beyond the -6.5m contour or/and 2023 aerial imagery. This project utilized the P4M UAS with 5-band multispectral sensor, and RTK enabled via the Washington State Reference Network. Surveys were completed using 70-80% overlap and sidelap, flown at altitudes between 60 m and 120 m resulting in ~3.5-6 cm resolution. Ground control points were collected using the Trimble Geo7X GNSS

	<p>receiver at all sites where shore access was possible, and synthetic ground control points were generated using georectified NAIP imagery in the areas where shore access was not possible. Surveys were completed during sun angles between 25° and 48° (averaging 37°), slack currents associated with tides below 1 ft MLLW, winds less than 12 kts, and cloud-free or overcast conditions.</p> <p>Continuous orthomosaics were produced using photogrammetry software, from which <i>bed extents</i> were manually delineated to include all kelps within 25 m and the perimeter falling within ~1 m of the kelp forest edges. <i>Canopy areas</i> were obtained by producing the BNDVI spectral index for the orthomosaic within the <i>bed extent</i> and performing binary threshold classification to produce pixel counts of kelp presence, multiplied by the corresponding survey resolution to produce estimates in hectares (following Cowdrey & Claar, 2024). Future work planned includes analyses of bed density (<i>canopy area/bed extent</i>), and exploration of alternative classification methods to the BNDVI threshold method.</p>
Access	<p>All survey data is maintained by the Nearshore Habitat Program, in the Washington Department of Natural Resources (nearshore@dnr.wa.gov).</p>

3.2.5 ShoreZone

The Washington State ShoreZone Inventory describes physical and biological characteristics of intertidal and shallow subtidal areas along Washington State's saltwater shorelines. This synoptic inventory includes more than 50 habitat characteristics, including physical features such as shoreline type, vegetation types such as kelp and eelgrass, and anthropogenic features such as bulkheads. It has been used in a wide range of planning and research projects.



Figure 3-13. ShoreZone survey extent.

Table 3-11. Description of ShoreZone dataset

Spatial Extent:	Entire shoreline for state of Washington (~4,900 km)
Parameters	Floating kelp qualified presence (continuous, patch) and absence, and over 50 other physical and biological characteristics of the shoreline.
Metric(s)	Shoreline units (primarily line segments with mean length 0.66 km)
Survey years	Aerial surveys took place between 1994 and 2000.
Frequency	Once
Methods summary	Inventory information was collected from a helicopter during low tides. Video imagery of the shoreline was recorded, along with locational information (GPS). From the helicopter a geomorphologist and a marine ecologist recorded continuous commentary on the physical and biological features along the shoreline. Following the survey, the videotapes were taken back to the office for interpretation and classification. The geomorphologist divided the shoreline into units on orthophoto maps and described each unit. Next the marine ecologist added information on the living resources in each unit. (Berry et al. <i>Washington State ShoreZone Inventory User's Manual</i>)
Access	Data is maintained by the Nearshore Habitat Program, in the Washington Department of Natural Resources (nearshore@dnr.wa.gov). Data and associated reports available online at: https://www.dnr.wa.gov/programs-and-services/aquatics/aquatic-science/nearshore-habitat-inventory

3.2.6 KelpWatch (Landsat satellite)

Landsat imagery has been analyzed to map floating kelp canopy from 1984 to the present from Baja California, Mexico, to the US Canada border, including the outer coast of Washington State and the western Strait of Juan De Fuca (Bell et al. 2023). Kelp canopy cover is reported at the 30-m pixel level. These data have been visualized in an interactive web app, KelpWatch.org (Bell et al. 2023). These data have been used in numerous large-scale studies on kelp dynamics, but higher resolution data is preferable for local-scale questions. Areas close to shore, with offshore rocks, or with sparse canopy presence are typically missed by this method, and heavy cloud cover reduces the availability of data in some years.

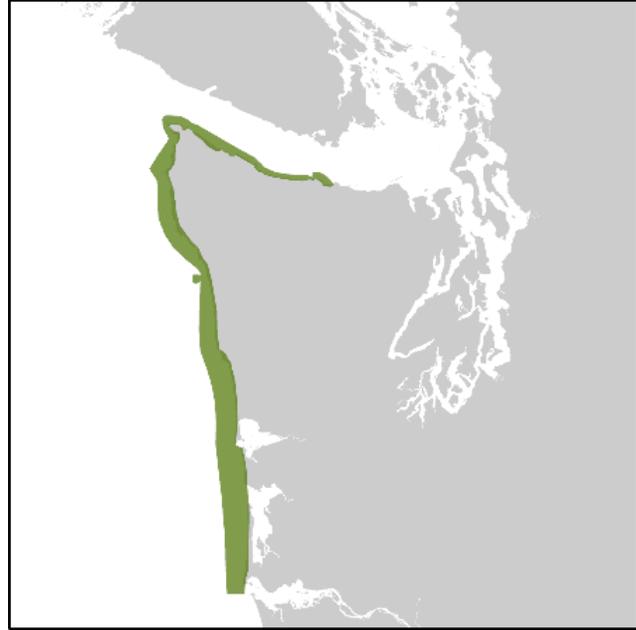


Figure 3-14. Survey extent of KelpWatch (Landsat)

Table 3-12. Description of KelpWatch dataset

Spatial Extent:	Outer coast and Western Strait of Juan de Fuca.
Parameters	Quarterly mean proportional cover of emergent kelp canopy
Metric(s)	Proportion kelp canopy area within 30-m pixels; comprehensive within the study area
Survey years	1984 – present
Frequency	Quarterly mean values are published regularly
Methods summary	Atmospherically corrected 30-m resolution multispectral imagery from five Landsat sensors is masked to remove land and intertidal areas. Pixels are then classified as water, cloud, land, or kelp canopy using a decision tree. For each pixel classified as kelp canopy, multiple endmember spectral mixture analysis is used to estimate fractional kelp canopy coverage. Images are averaged across quarters. Full methods are described in Bell et al. 2023.
Access	Data is maintained by Santa Barbara Coastal LTER. A visualization of the data is viewable at kelpwatch.org and the underlying data is available for download at https://doi.org/10.6073/pasta/a9071a2ce1b78242c2ad1dda5854ec78

3.2.7 CPS and SPS Boat Surveys

In South Puget Sound (SPS) and Central Puget Sound (CPS), comprehensive surveys identified shorelines with floating kelp, which are uncommon in these basins (in 2013 and 2017 in SPS, and 2019 in CPS). Both surveys recorded floating kelp presence along the -6 m subtidal bathymetry line, with a minimum threshold of a single individual. Both studies were paired with a multi-decadal synthesis of diverse data sources to summarize the presence/absence of floating kelp within 1-km shoreline segments. In SPS, the study noted presence, while in CPS presence was further categorized into abundance classes, ranging from isolated individuals to wide beds.



Figure 3-15. CPS (left) and SPS (right) Boat Survey extents.

Table 3-13. Description of WA DNR boat-based survey dataset (modified from Floating Kelp Vital Sign Indicator WA DNR Kayak Dataset Description).

Spatial Extent:	Central Puget Sound and South Puget Sound
Parameters	Floating kelp presence (linear data). Abundance classes (Central Puget Sound only).
Metric(s)	Linear extent of floating kelp presence, comprehensive within study area
Survey years	2013 and 2017 (South Puget Sound), 2019 (Central Puget Sound)
Frequency	Infrequent
Methods summary	Collected field observations of floating kelp presence by motoring along the shoreline in a small boat, in shallow water during low tide and slack currents. Summarized presence/absence by segmenting -6 m bathymetry contour. Minimum threshold for detection: a single individual. In Central Puget Sound, observations were further sub-divided to describe abundance, ranging from isolated individuals to wide, conspicuous beds.
Access	All survey data is maintained by the Nearshore Habitat Program, in the Washington Department of Natural Resources (nearshore@dnr.wa.gov).

3.2.8 Historical data (from CPS and SPS analyses)

DNR reconstructed bull kelp presence over 145 years from navigation charts, government surveys, ecological studies and other historical documents. These maps provide a long-term view of kelp coverage in Puget Sound prior to the region’s industrialization.



Figure 3-16. Central (right) and South (left) Puget Sound. Note that historical data is not comprehensive within each sub-basin. See Berry et al. 2021 and Berry et al. in prep for additional maps and information.

Table 3-14. Description of WA DNR historical data analysis.

Spatial Extent:	Central Puget Sound and South Puget Sound
Parameters	Floating kelp presence (linear data).
Metric(s)	Varies based on survey, see Table 3-15 for more information.
Survey years	Between 1873 and 1999
Frequency	Based on accessible historical data sources
Methods summary	Synthesis of historical and modern <i>Nereocystis</i> surveys and examined presence/absence within 1-km segments along the shorelines of Central and South Puget Sound. Data sources noted the presence or absence of <i>Nereocystis</i> , including peer-reviewed publications, maps, charts, reports, and field surveys. The datasets were produced for a wide range of purposes, including navigation, harvest, resource management, land use planning, and ecological research. The spatial extent of data sources varied from a single location to the entire study area. Format and level of detail also varied widely, including text descriptions of presence or absence at a location, generalized cartographic symbols, delineations of bed perimeter, and phycological studies, which examined detailed plant metrics such as density and phenology.
Access	All survey data is maintained by the Nearshore Habitat Program, in the Washington Department of Natural Resources (nearshore@dnr.wa.gov).

Table 3-15. Synoptic *Nereocystis* surveys completed in South Puget Sound. Table and caption from Berry et al. 2021.

Survey Years	Purpose	Reference Year	Data Source Description	Scale
1873–1879	navigation	1878	Topographic sheets nos. 1327a, 1327b, 1671, 1672, 1674 1528 [59, 60, 62–65]. Surveyed in the field on plane tables [108]. Geo-referenced maps [109] were aggregated into a synoptic snapshot.	1:10,000
1911–1912	harvest	1911	Kelp beds suitable for harvest were identified as part of the west coast-wide Fertilizer Investigations [69]. Beds delineated on final maps were wider than actual bed width denoted on preparatory maps.	1:100,000
1935–1936	navigation	1935	Hydrographic surveys nos. 5931, 6102, 6103, 6104, 6105, 6106, 6107, 6108, 6197, 6198, 6199, 6202, 6203, 6204, 6205 [71–85]. The source data for navigation charts, included field surveys of soundings and aids to navigation. Multiple maps were aggregated into a synoptic snapshot.	1:10,000– 1:20,000
1978	habitat	1978	Washington Department of Wildlife field survey maps [92], annotated in pencil on a paper hydrographic chart, source for the Coastal Zone Atlas [110].	1:100,000
1997–1999	habitat	1999	WA State ShoreZone Inventory, based on low tide helicopter-based videography [30, 53]. Classified <i>Nereocystis</i> alongshore presence as patchy (<50%) or continuous (>50%) within geomorphically defined linear shoreline units	1:24,000
2013	habitat	2013	GPS-based small boat survey that noted presence of <i>Nereocystis</i> as a line feature along the -6.1 m bathymetry line and as a polygon feature for beds of concern.	1:12,000
2017	habitat	2017	GPS-based small boat survey that noted presence of <i>Nereocystis</i> as a line feature along the -6.1 m bathymetry line and as a polygon feature for beds of concern [103]. Minimum linear length of 3 m. A 10 m threshold between alongshore plants was applied to classify gaps as 'absent'. Threshold for <i>Nereocystis</i> presence was one bulb.	1:12,000

<https://doi.org/10.1371/journal.pone.0229703.t001>

3.3 Results

3.3.1 Indicator releases to date

The first release of the Washington State Floating Kelp Bed Area Vital Sign Indicator was in 2023, and it contained all available survey data through 2021. Subsequently, the Indicator has been updated in 2024 annually. The most recent Indicator release included data through 2023 (Figure 3-17).

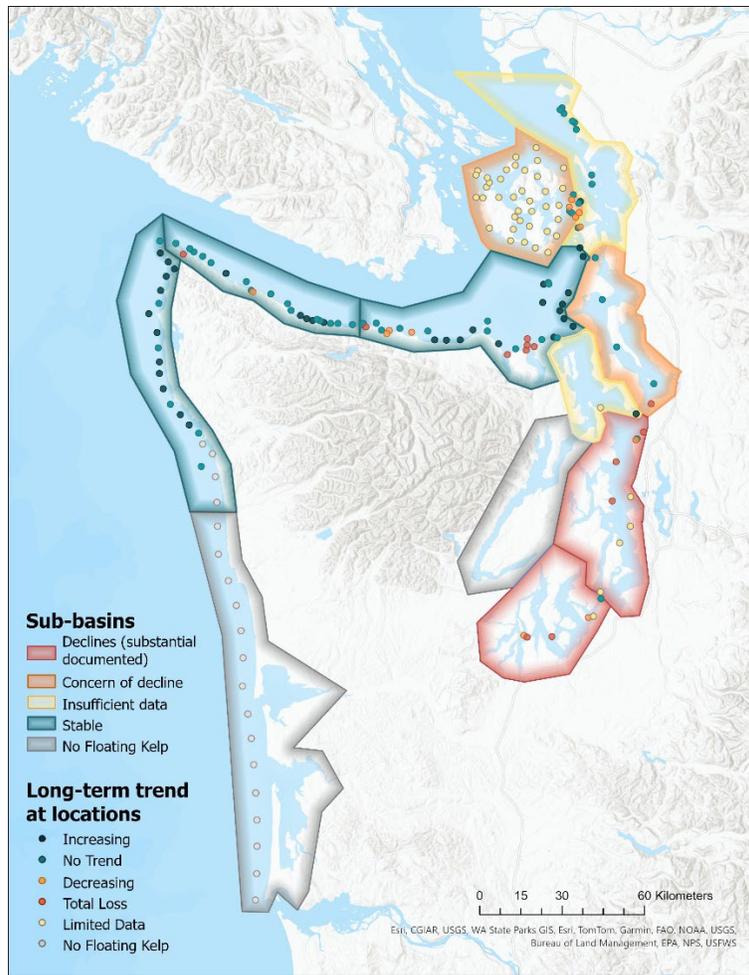


Figure 3-17. Floating kelp status in sub-basins (shaded polygons) and long-term trends at sampling locations (colored points), including data through 2023. Figure and caption from Claar et al. 2024.

The amount of available data in each sub-basin varies widely (Figure 3-18), with some sub-basins having <10 years of data (e.g., Admiralty Inlet) and others having 30 years of quantitative data or extensive historical data (e.g., South Puget Sound, eastern and western Strait of Juan de Fuca).

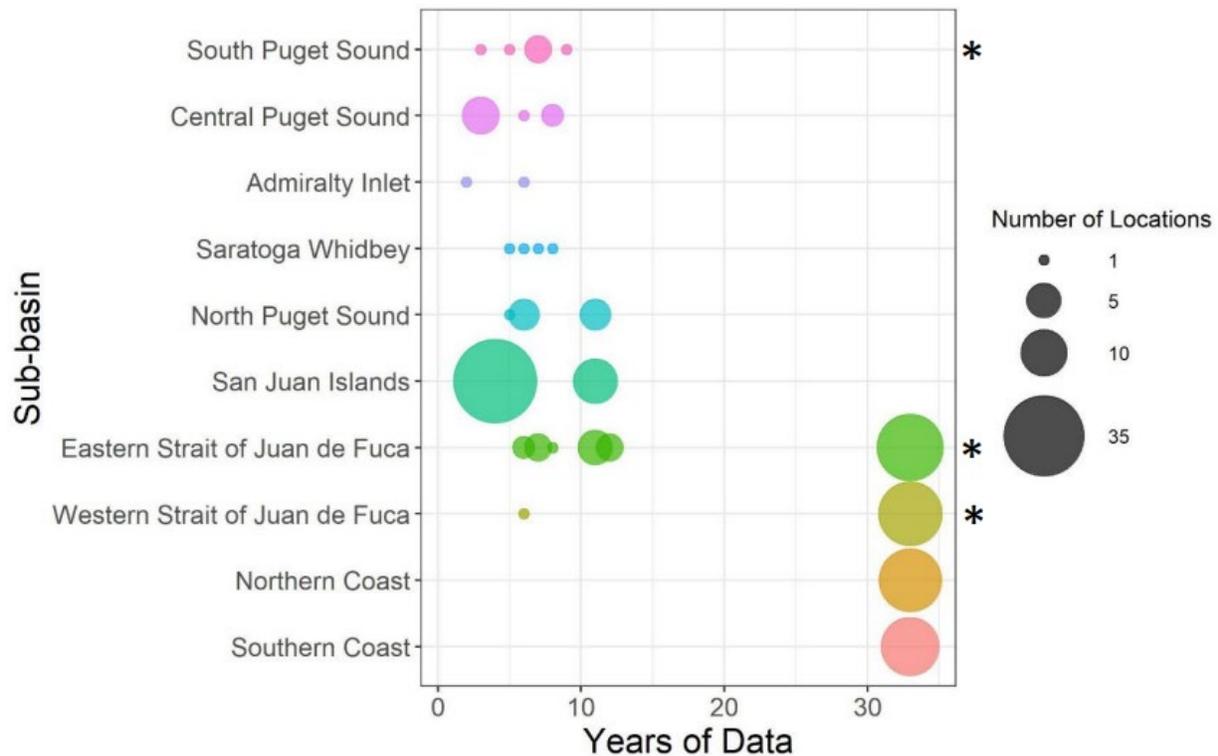


Figure 3-18. The number of years surveyed, and count of monitoring locations (sites or zones) included in the floating kelp indicator. Sub-basins with an asterisk (*) also have historic data comparison studies included in the indicator assessment. Hood Canal is not included, because floating kelp has not been documented in this sub-basin, nor has repeat surveying been conducted. Figure and caption from Claar et al. 2025.

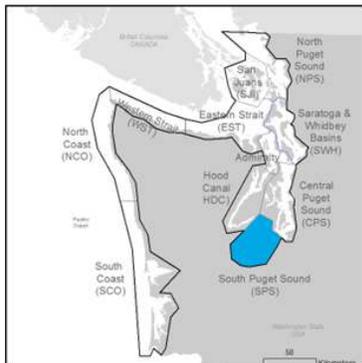
Long-term trends at individual locations are classified as *increasing*, *no trend*, *decreasing*, *total loss*, *limited data*, and *no floating kelp* (Figure 3-17). These *trend* classifications are woven together with other ways of knowing, such as historical studies, Indigenous Scientific Knowledge, and citizen science to assess *status* at the sub-basin scale (Figure 3-17; Table 3-16). A summary of each sub-basin status is provided as an appendix to the Indicator Summary Report (Claar et al. 2025), and as a pop-up on the Indicator interactive webmap (e.g., Figure 3-19).

Table 3-16. Summary of sub-basin status and kelp distribution for survey data through 2022. Figure and caption from Claar et al. 2025.

Sub-basin status	Number of sub-basins	Sub-basins	Total nearshore extent (ha (%))	Total linear extent (km at -6.1m isobath)	Range of statewide floating kelp bed area within each status category (mid-point)
Stable	3	Western Strait, Eastern Strait, North Coast	36,496 (20%)	513 (15%)	45-90% (67.5%)
Concern	2	San Juan Islands, Saratoga/Whidbey	21,090 (12%)	839 (24%)	6-25% (15.5%)
Decline	2	Central Puget Sound, South Puget Sound	21,818 (12%)	877 (25%)	2%
Insufficient Data	2	North Puget Sound, Admiralty Inlet	26,055 (15%)	565 (16%)	6-25% (15.5%)
No Floating Kelp	2	Hood Canal, South Coast	73,494 (41%)	737 (21%)	0

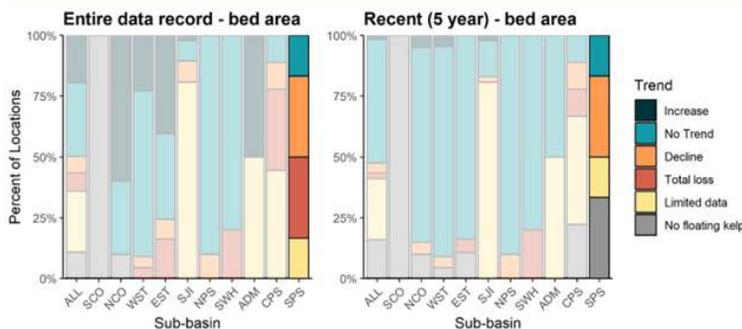
Sub-basin: South Puget Sound (SPS)

Sub-basin assessment: **substantial documented declines**



Key Findings:

- **Floating kelp is uncommon along the shorelines of South Puget Sound.** One species of floating kelp occurs here, bull kelp (*Nereocystis luetkeana*).
- **South Puget Sound is identified as sub-basin of concern due to substantial documented declines.** A [historical ecology study spanning 145 years](#) found that bull kelp disappeared from approximately 63% of the shorelines by 2017 (compared to the maximum cumulative extent of all observations).
- **Bull kelp has disappeared from most of the sub-basin.** It persists along shorelines near the Tacoma Narrows and at Squaxin Island.
- **Six locations are monitored annually for floating kelp.** At two locations, bull kelp has disappeared, at two locations it is declining, at one location there is no trend, and at one location the monitoring time span is too short for assessment.
- **Priorities in this sub-basin include addressing stressors and restoration, as well as conserving existing beds.**



The bar charts show the count of locations by trend category for two time periods (long-term on left, recent on right). Within each chart, the left-most bar includes all locations in WA state (all). Subsequent bars correspond to individual sub-basins, sorted spatially from coast (left) to innermost basin (right). The colors for this sub-basin are vibrant (others are muted).

Sub-basin details

number of locations monitored	6	
count of entire data record trends at locations	increasing	0
	no trend	1
	declining	2
	total loss	2
	limited data	1
no floating kelp	0	
Nearshore habitat (from -15 m to -1 m, MLLW) in sub-basin (ha)	12,219	
% of nearshore habitat monitored in sub-basin	<1%	
% of WA floating kelp beds in sub-basin	<1%	

This assessment includes updates through 2023.

Figure 3-19. Example sub-basin summary from the WA State Floating Kelp Bed Area Vital Sign Indicator.

3.3.2 Summary Plots and Tables, by project/program

3.3.2.1 WA DNR COSTR/AQRES

WA DNR has contracted with Ecoscan LLC annually since 1989 (except 1993) to collect floating kelp canopy maps in the Strait of Juan de Fuca and the open coast of Washington (Figure 3-20). In 2011, this program was expanded to include three DNR Aquatic Reserves: Smith and Minor Island Aquatic Reserve, Cypress Island Aquatic Reserve, and Cherry Point Aquatic Reserve (Figure 3-20).

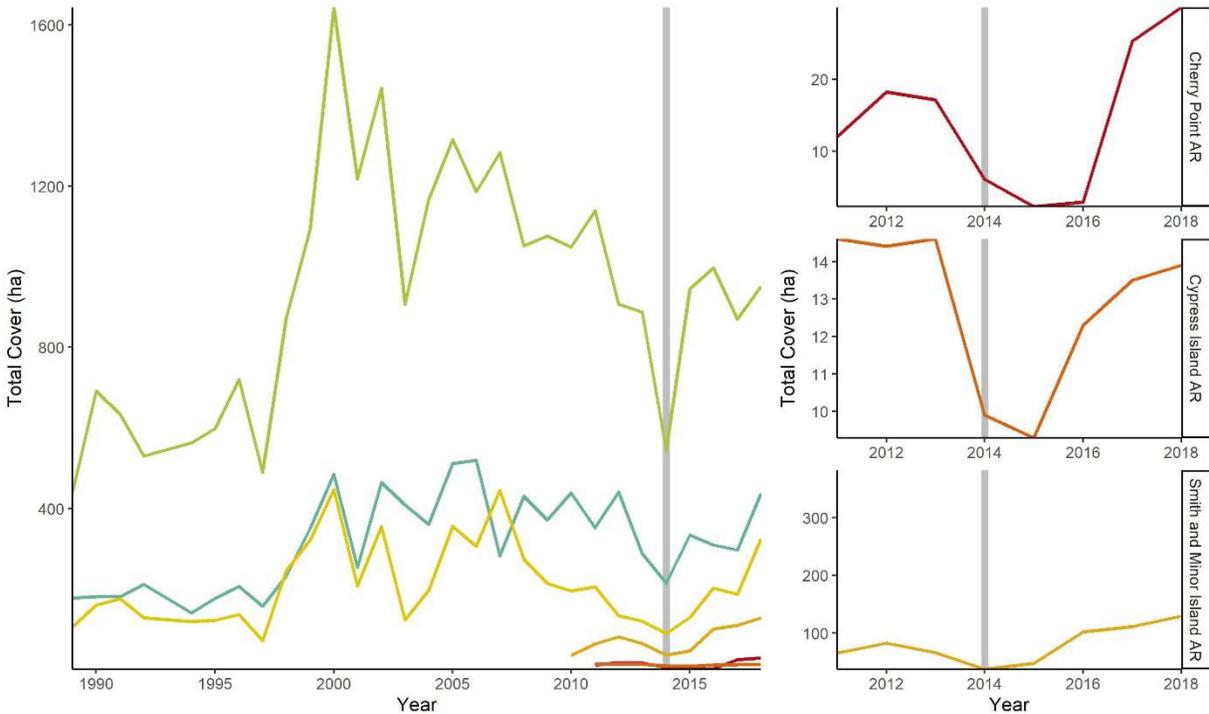


Figure 3-20. Total floating kelp bed area from the COSTR/AQRES datasets. Color corresponds to area surveyed: green = western Strait of Juan de Fuca, blue = open coast, bright yellow = eastern Strait of Juan de Fuca, dark yellow = Smith and Minor Island Aquatic Reserve, orange = Cypress Island Aquatic Reserve, and red = Cherry Point Aquatic Reserve. Grey line corresponds to the beginning of the 2014-2016 marine heatwave. Figure from Claar et al. 2025.

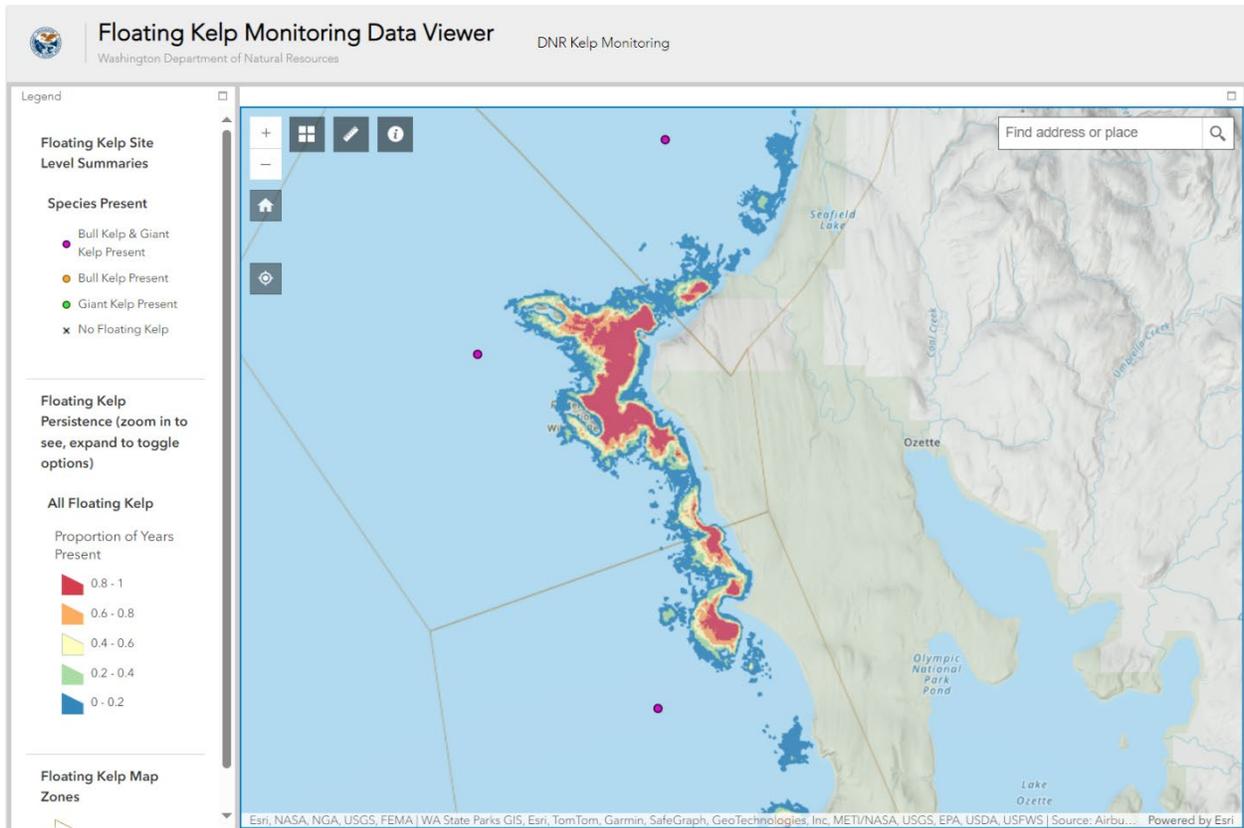


Figure 3-22. Screen Capture of the COSTR/AQRES Floating Kelp Monitoring Data Viewer

COSTR/AQRES maps include both bed area and canopy area, and distinguish between the two floating kelp species in Washington (*Nereocystis luetkeana* and *Macrocystis pyrifera*) in areas where they co-occur (Figure 3-23, Figure 3-24, Figure 3-25).

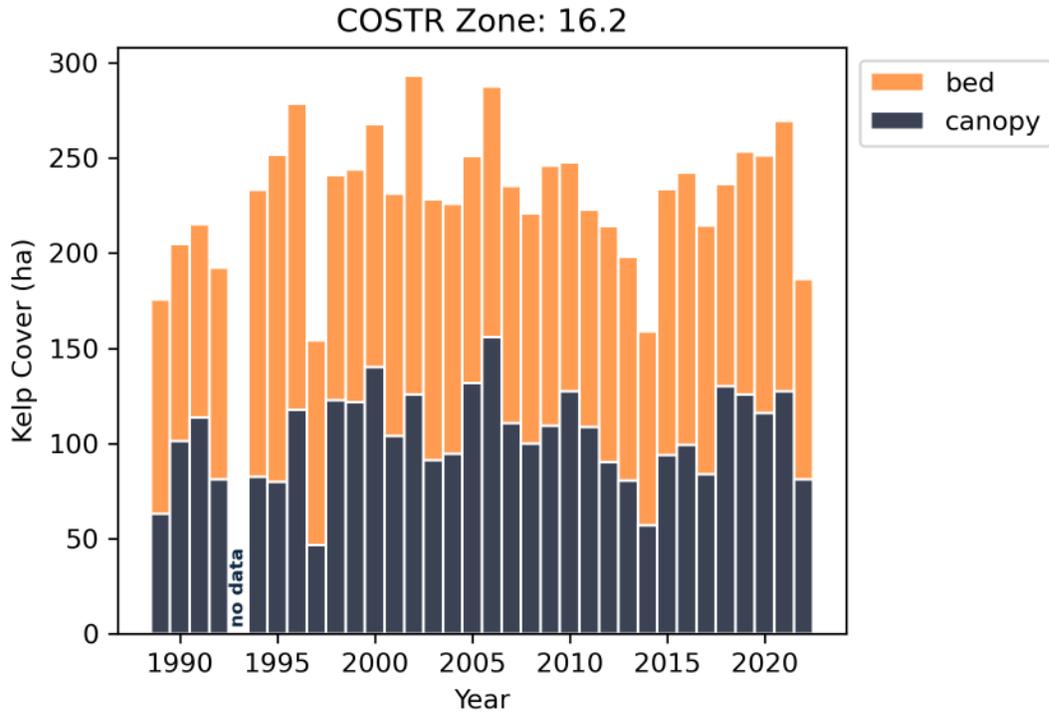


Figure 3-23. Example data for COSTR map index 16.2 (Cape Flattery – Koitlah Point). This map index has both bull kelp and giant kelp present.

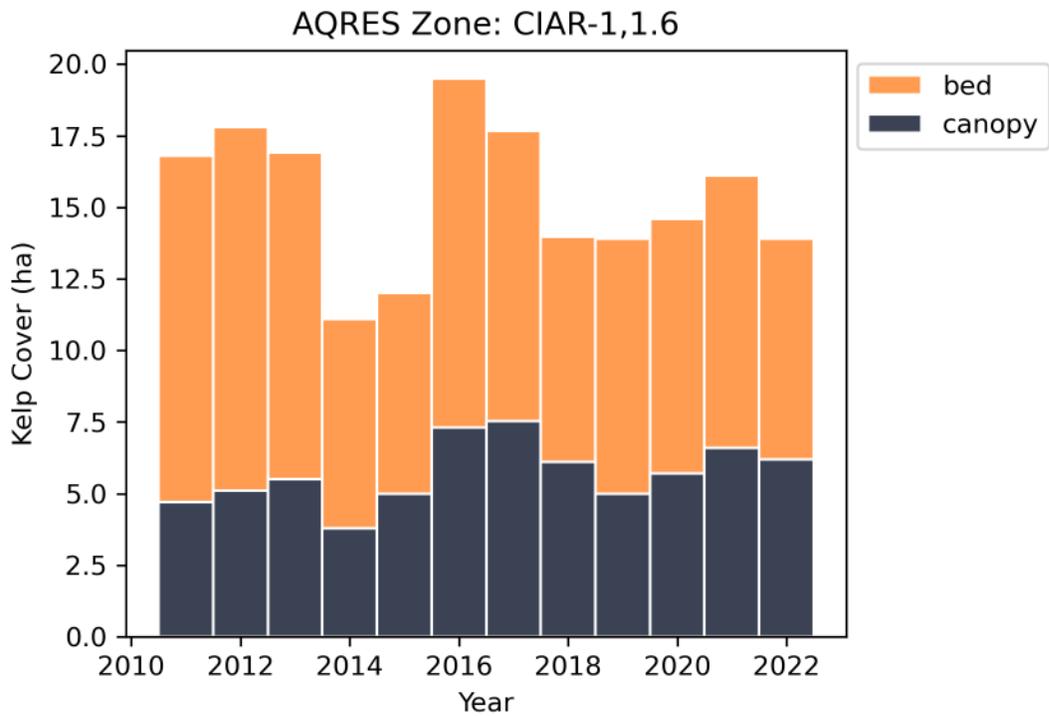


Figure 3-24. Example data for AQRES map index CIAR-1,1.6 (Cypress Island). This map index only has bull kelp present (no giant kelp).

Cape Flattery - Koitlah Pt

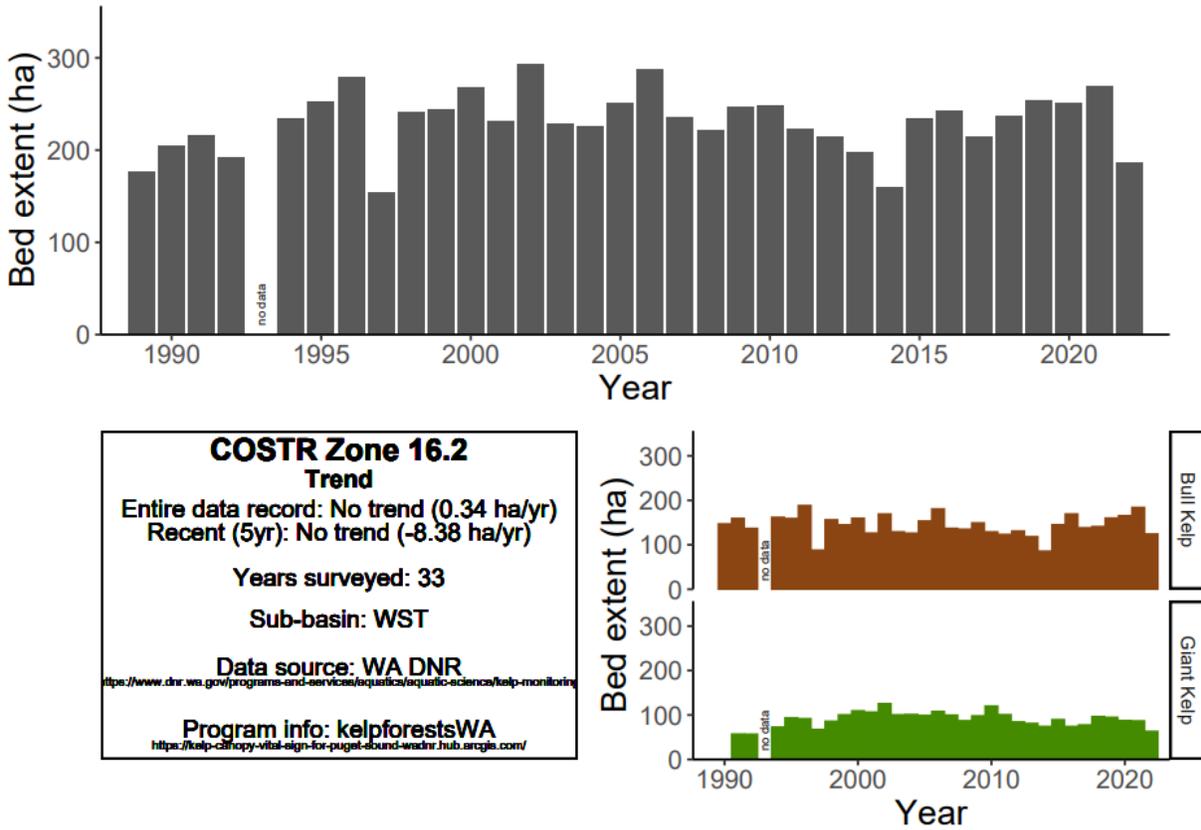


Figure 3-25. Example of a Location pop-up from the WA Floating Kelp Bed Area Vital Sign Indicator interactive webmap. The top plot shows changes in kelp bed extent by survey year, the panel on the bottom left shows information about that Location, and the bottom right shows bed extent data divided by kelp species (bull kelp = *Nereocystis luetkeana*, giant kelp = *Macrocystis pyrifera*).

3.3.2.2 Kelp Aerial Monitoring (KAM): High-resolution aerial imagery

In 2022, 2023, 2024 and 2025 DNR contracted with NV5-Geospatial to collect high-resolution (6-in) four-band (red, green, blue, near-infrared) imagery across large areas of Washington State (Figure 3-26, Figure 3-27, Figure 3-28, Figure 3-29). These surveys provide synoptic coverage of visible floating kelp canopies across the survey area. The AOIs (Areas of Interest) surveyed do not contain all floating kelp areas within the State (for example, floating kelp also exists in Central and South Puget Sound), but they do include most of the areas that are ideal for aerial surveys with a fixed-wing aircraft. All planned AOIs were successfully surveyed in 2022, 2024 and 2025 (Figure 3-26, Figure 3-28 and Figure 3-29, respectively). In 2023, weather conditions precluded collection of the Admiralty Inlet AOI and part of the Saratoga Passage AOI (Figure 3-27).

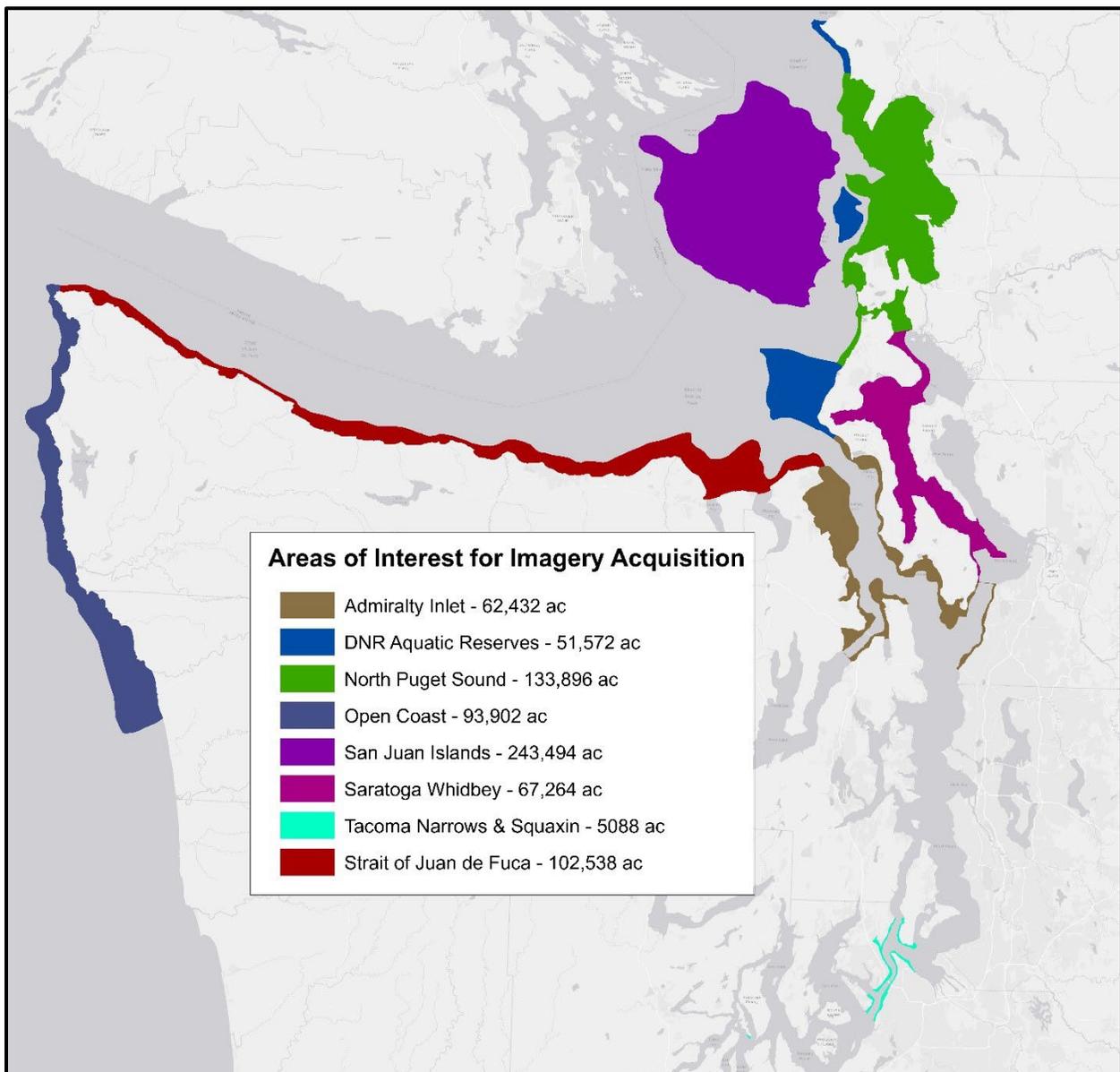


Figure 3-26. Areas of Interest (AOIs) captured in 2022 KAM surveys.

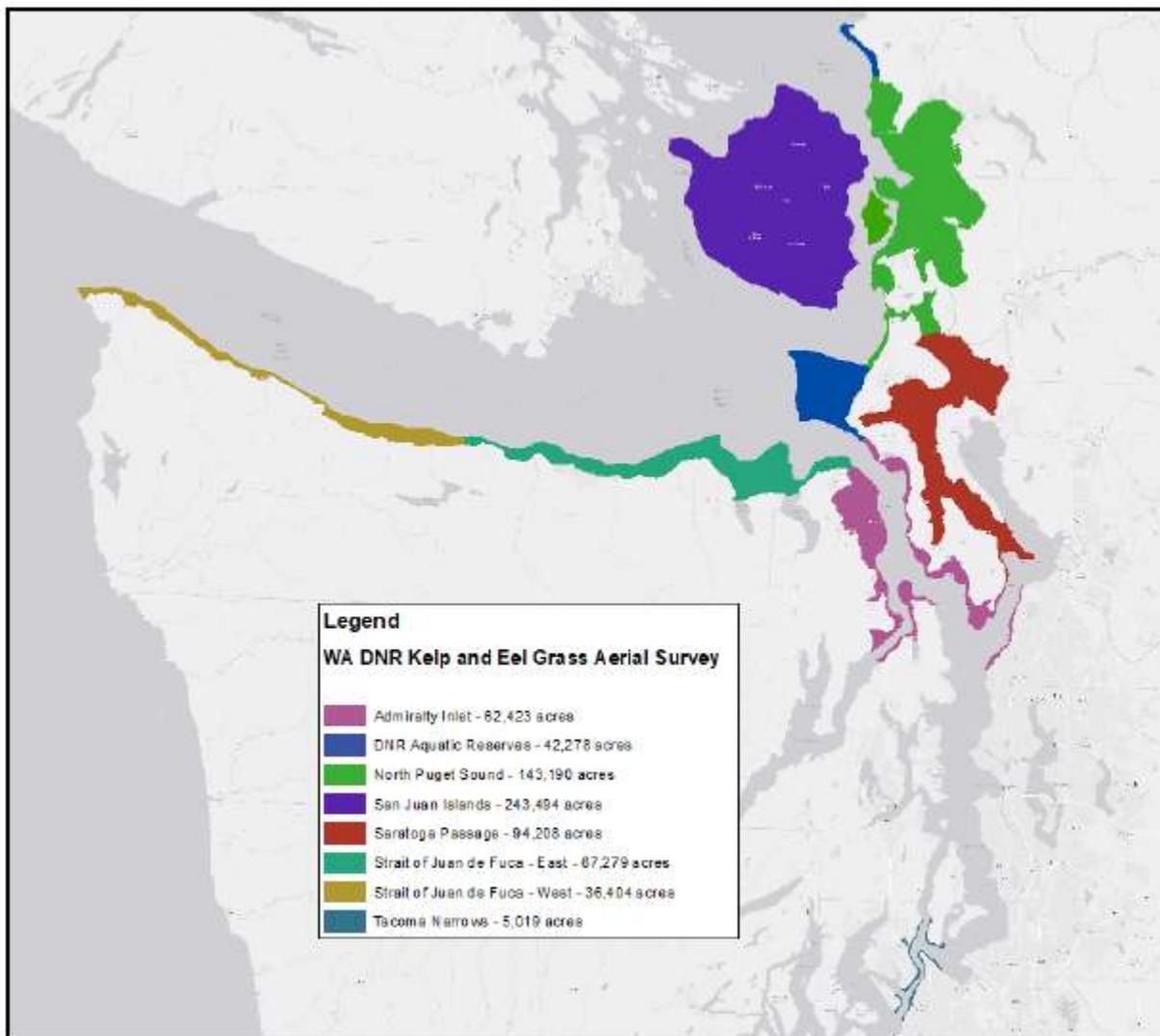


Figure 3-27. Areas of Interest (AOIs) planned for capture in 2023 KAM surveys. Note that Admiralty Inlet and part of Saratoga Passage were not sampled due to poor weather conditions that limited survey windows.

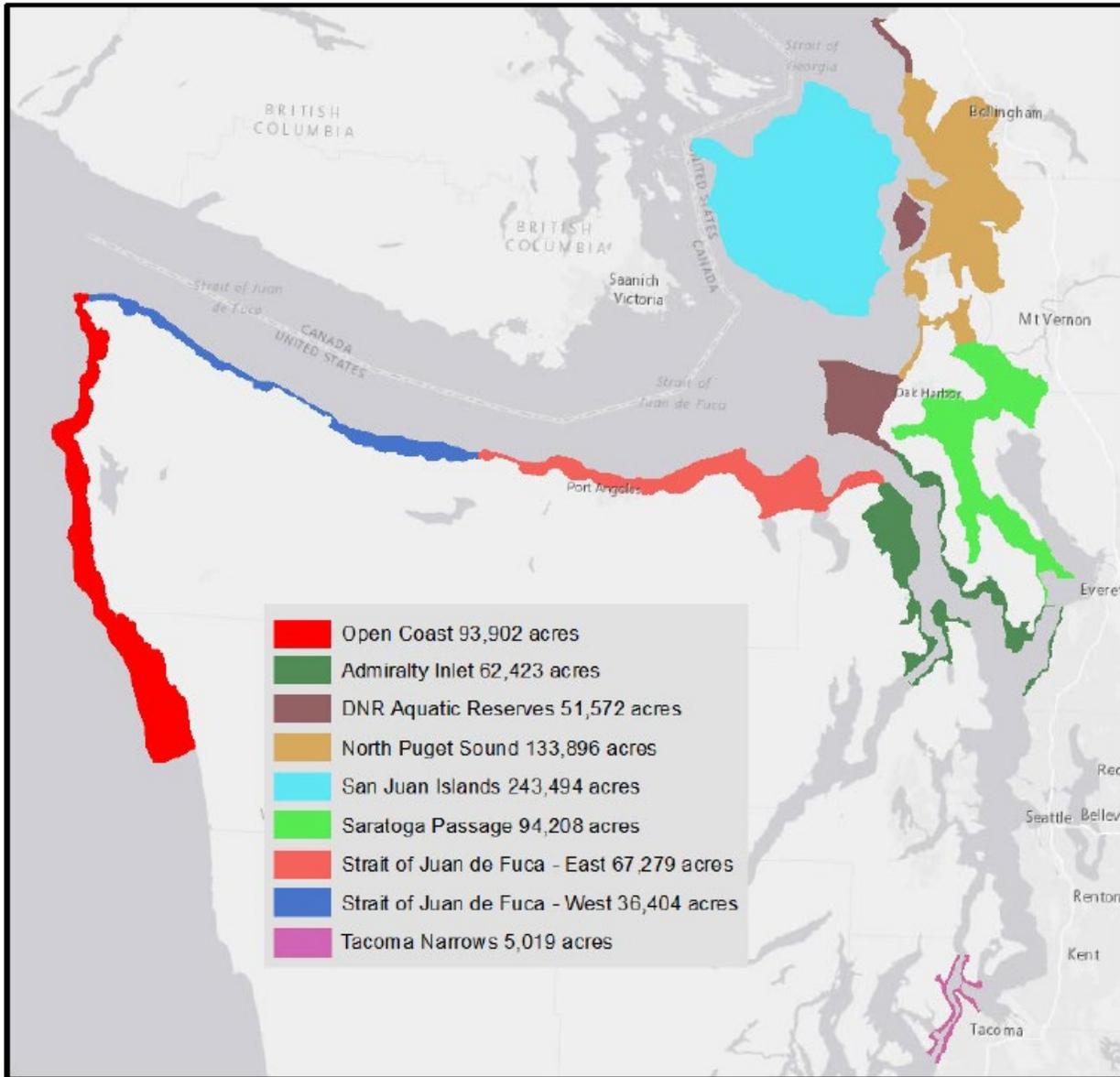


Figure 3-28. Areas of Interest (AOIs) captured in 2024 KAM surveys.

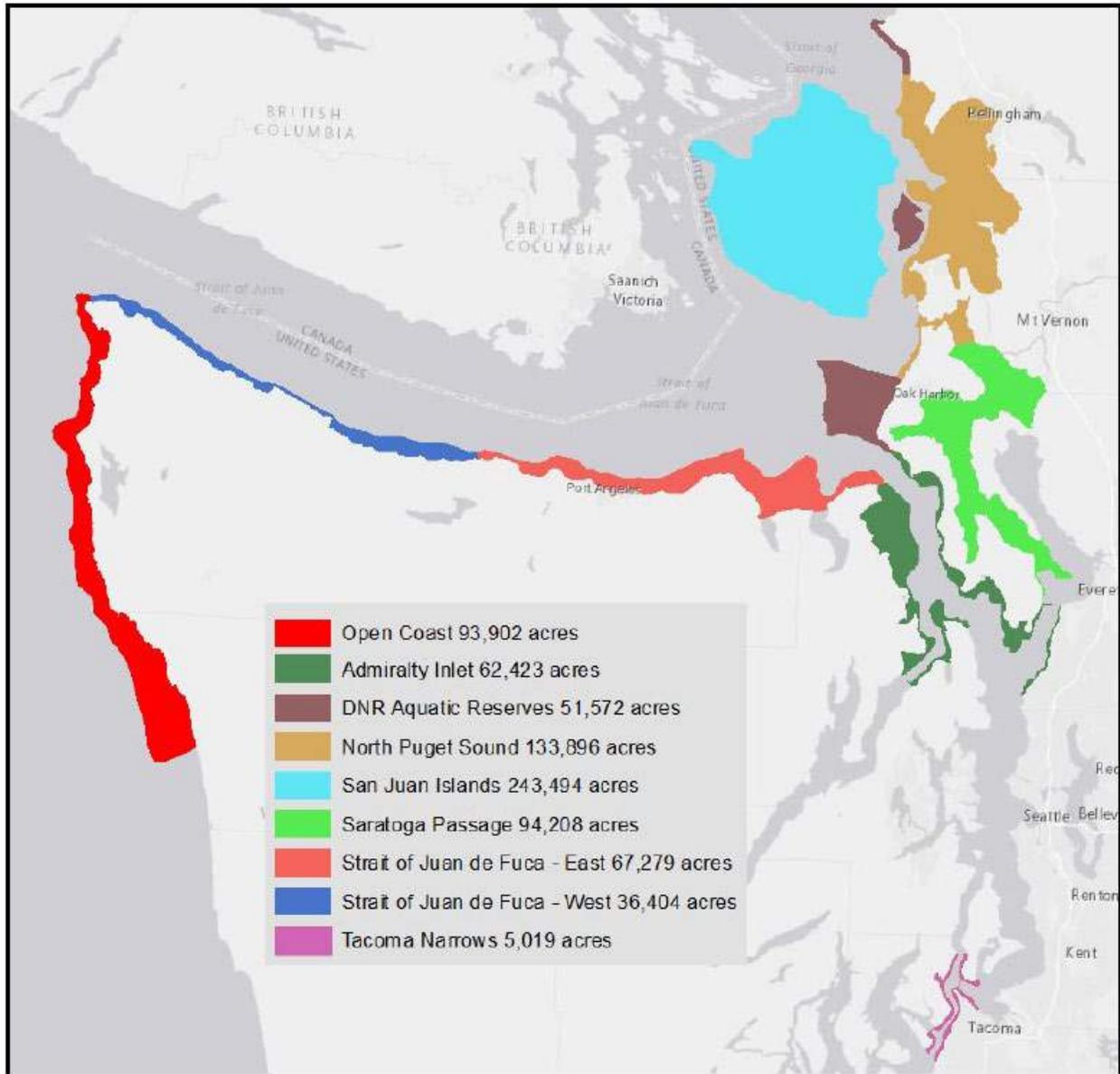


Figure 3-29. Areas of Interest (AOIs) captured in 2025 KAM surveys.

This aerial imagery can be visualized in ‘true color’ (red, green, blue bands; Figure 3-30), but floating kelp is most visible when imagery is visualized in ‘false color’ (near-infrared, green, blue bands; Figure 3-31).



Figure 3-30. RGB (red-green-blue bands) imagery example at Smith and Minor Island Aquatic Reserve. Floating kelp shows up as dark patches in the water. Imagery was collected in 2022.

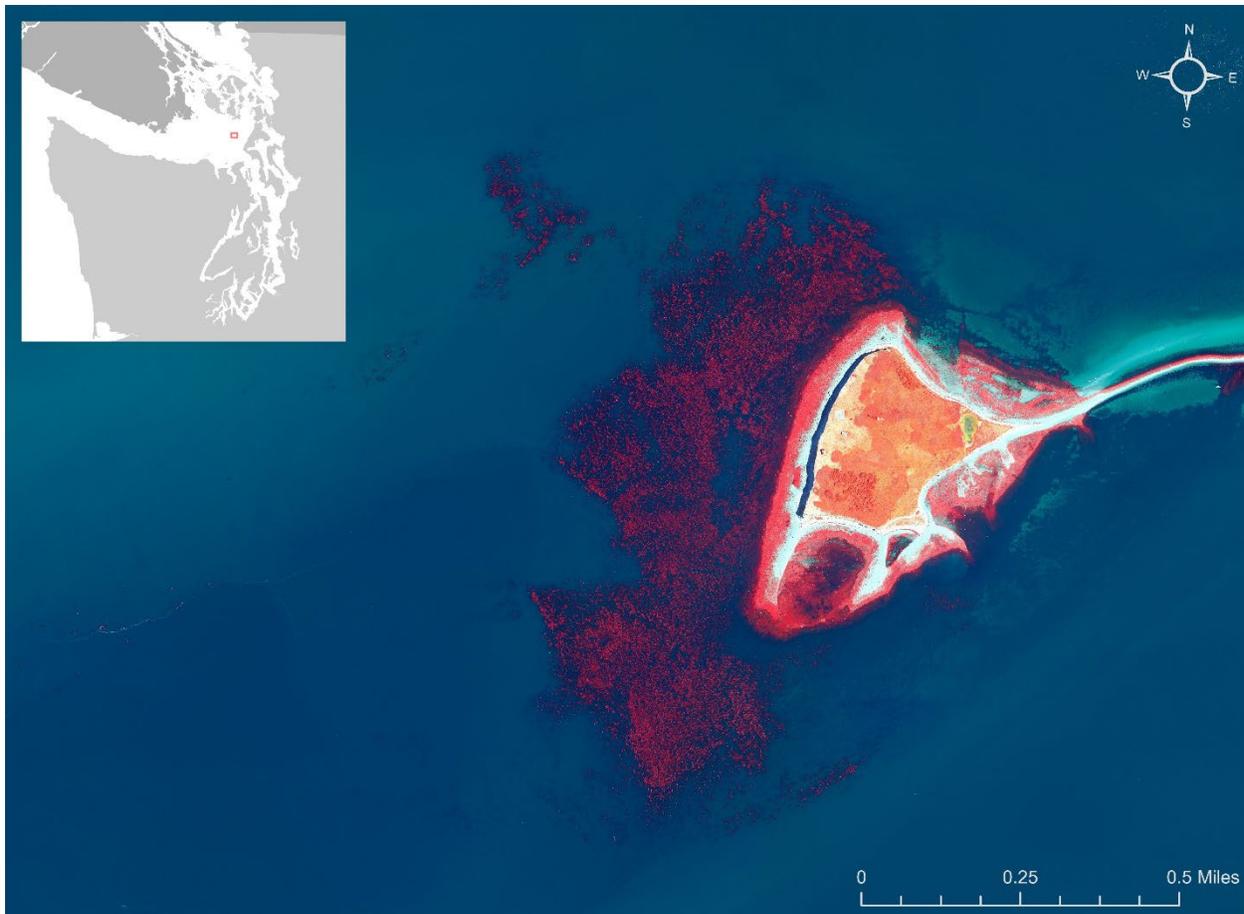


Figure 3-31. NIR-GB (near infrared-green-blue bands) imagery example at Smith and Minor Island Aquatic Reserve. Floating kelp shows up as pink/red patches in the water. Imagery was collected in 2022.

Imagery is manually masked (i.e., an expert observer creates polygon areas of interest that maximize inclusion of areas with floating kelp and exclusion of everything else, e.g., open water, wrack, intertidal algae, and seagrass) (Figure 3-32).

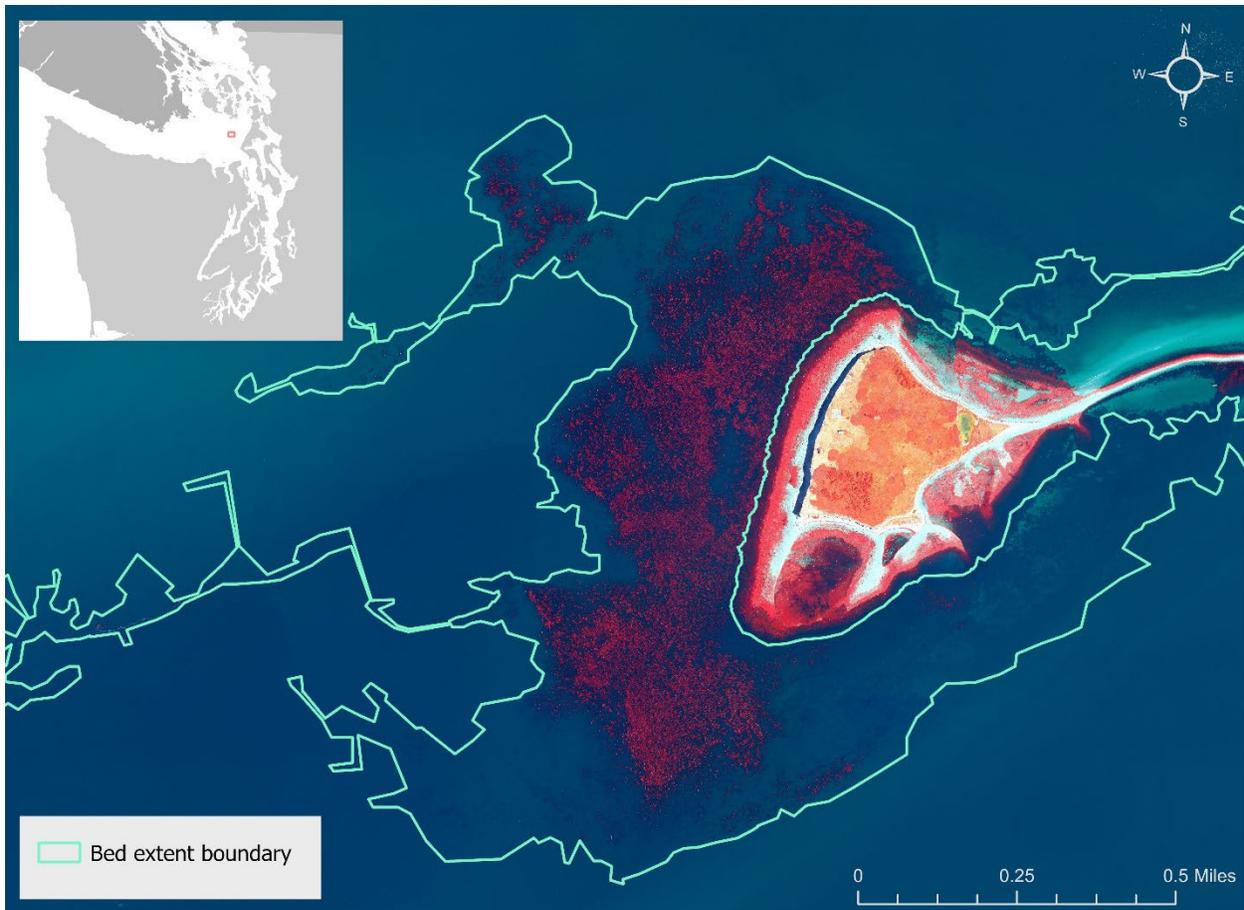


Figure 3-32. NIR-GB (near infrared-green-blue bands) imagery example at Smith and Minor Island Aquatic Reserve, showing manually delineated kelp bed extent. Floating kelp shows up as pink/red patches in the water. Imagery was collected in 2022.

To classify canopy area, both NIR-G-B imagery and BNDVI (Blue Normalized Difference Vegetation Index) are used. BNDVI is a spectral index calculated as $BNDVI = \frac{NIR - BLUE}{NIR + BLUE}$ with NIR and BLUE representing the near-infrared and blue spectral bands from the imagery. BNDVI maximizes visibility of floating kelp on the surface of the water and provides useful cues for both visual observation and automated classification (Figure 3-33).

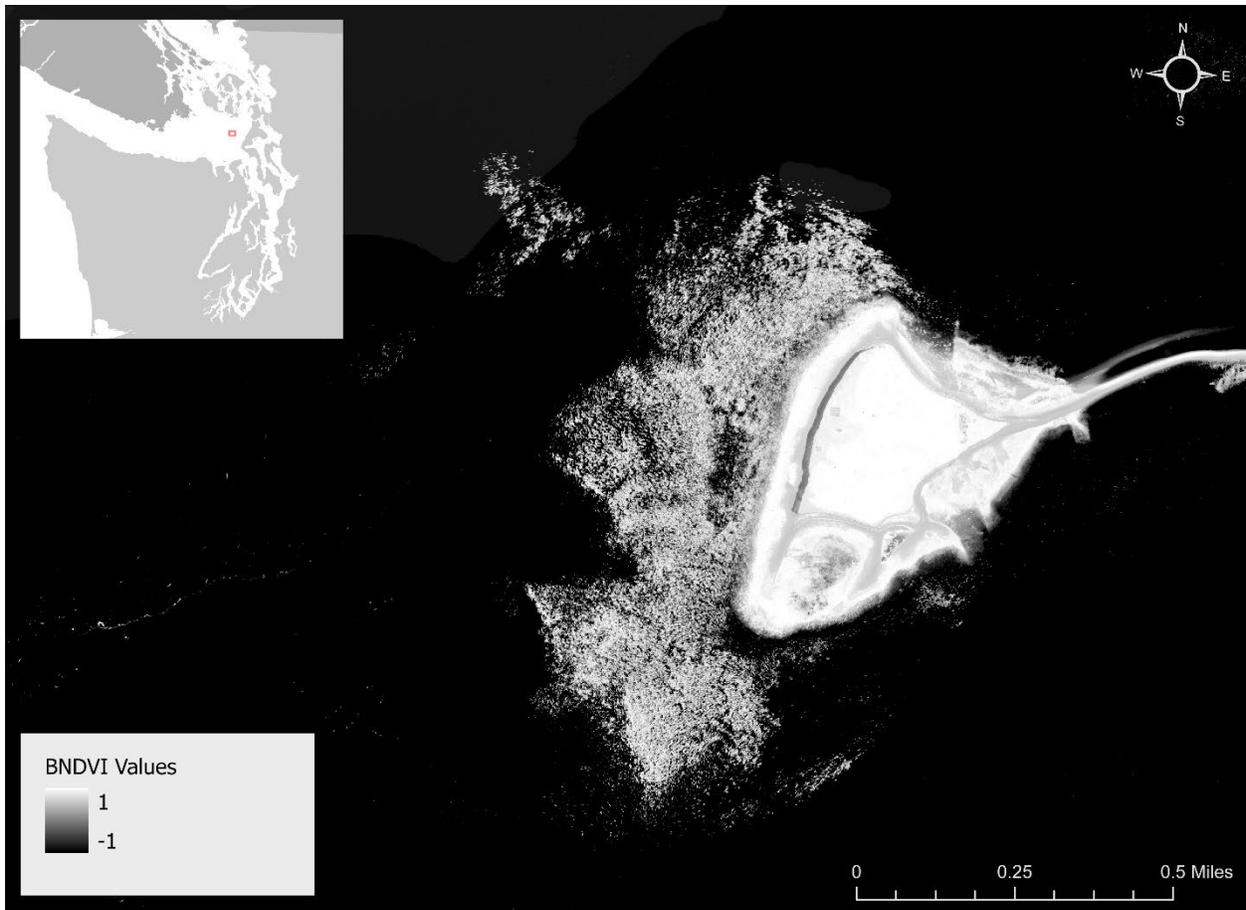


Figure 3-33. BNDVI (blue normalized difference vegetation index) example at Smith and Minor Island Aquatic Reserve. Floating kelp is visualized with BNDVI values close to 1, against open water which has values closer to -1. Imagery was collected in 2022.

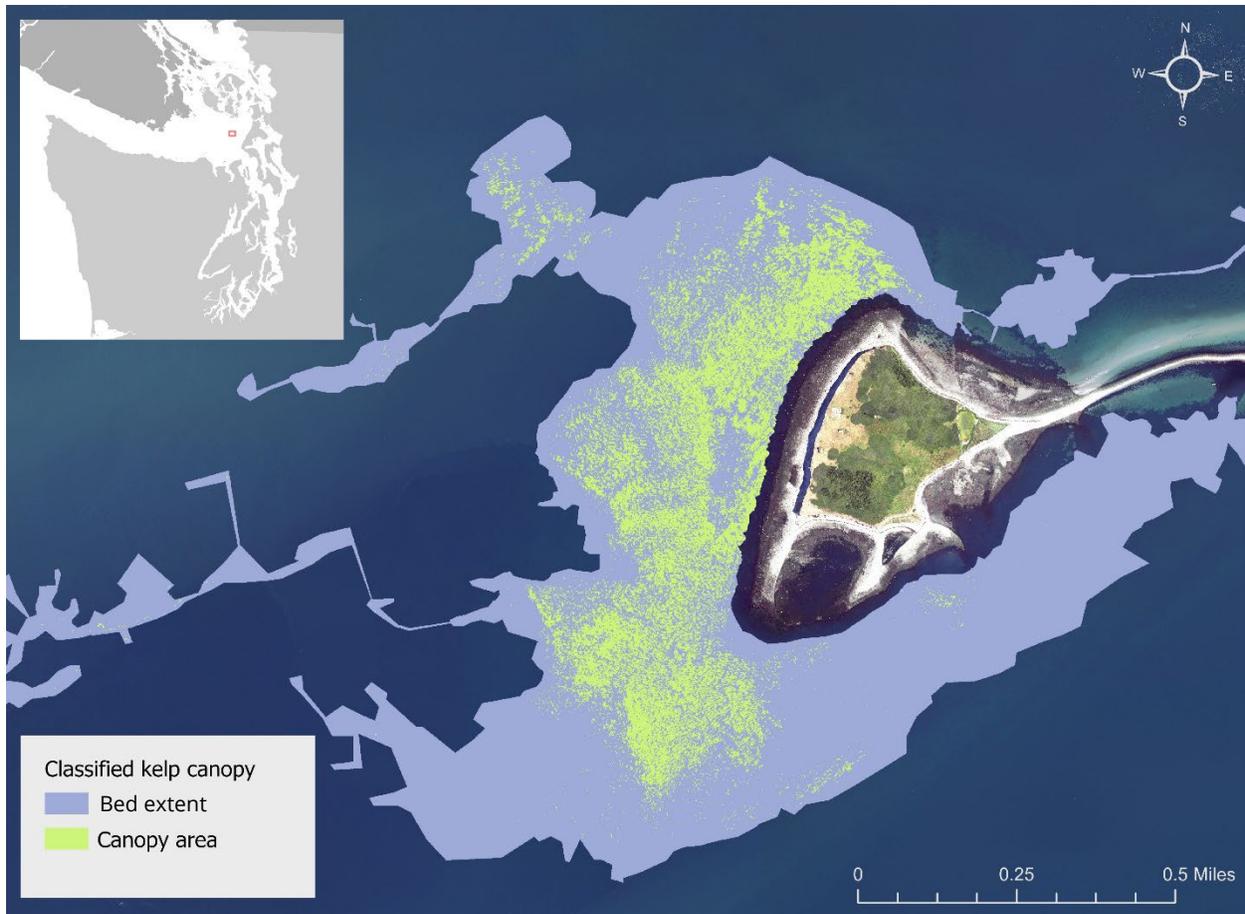


Figure 3-34. Classified kelp canopy area and bed extent at Smith and Minor Island Aquatic Reserve. Underlying imagery is RGB. Imagery was collected in 2022.

Classified kelp canopy area can be used to quantify the amount of floating kelp in an area of interest, or to assess relative density of kelp cover at the surface (Figure 3-34).

3.3.2.3 Samish aerial data

The Samish Indian Nation Department of Natural Resources has delineated kelp bed extent in the San Juan Islands over the past twenty years (including 2004, 2006, 2016, 2019, 2022, 2023, 2024 and 2025 (in progress)); Figure 3-35). These surveys have detected stability in some areas and warned of substantial losses in others. It is important to note that aerial surveys in 2016 and 2019 were not controlled for tides and currents. Therefore, those years must be interpreted with caution since tides and currents have a large effect on the amount of detectable kelp canopy (Britton-Simmons et al. 2008, Timmer et al. 2024).

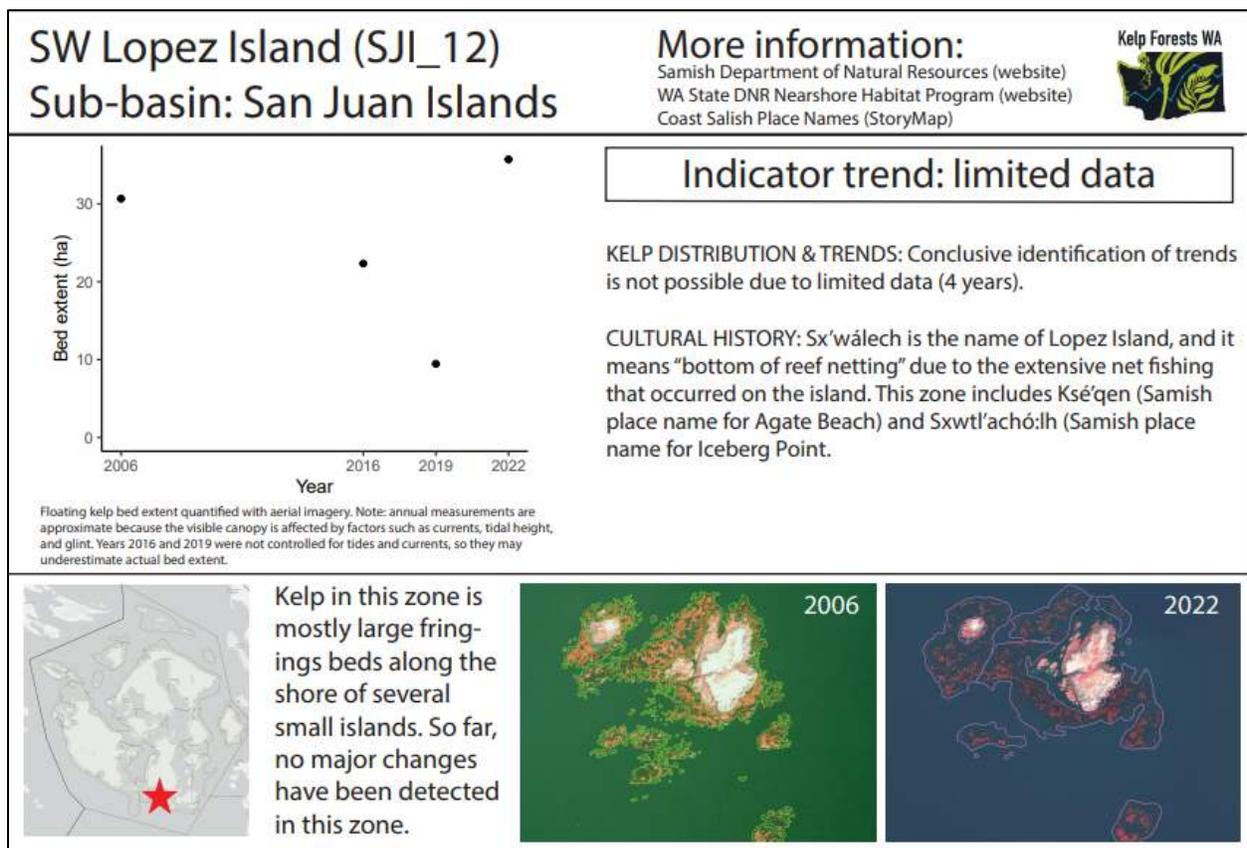


Figure 3-35. Example of a Location pop-up from the WA Floating Kelp Bed Area Vital Sign Indicator interactive webmap. The plot in the upper left shows changes in kelp bed extent by survey year, the map in the lower left shows the location on a map, and the bottom right shows example imagery and bed delineations for two survey years (2006 and 2022).

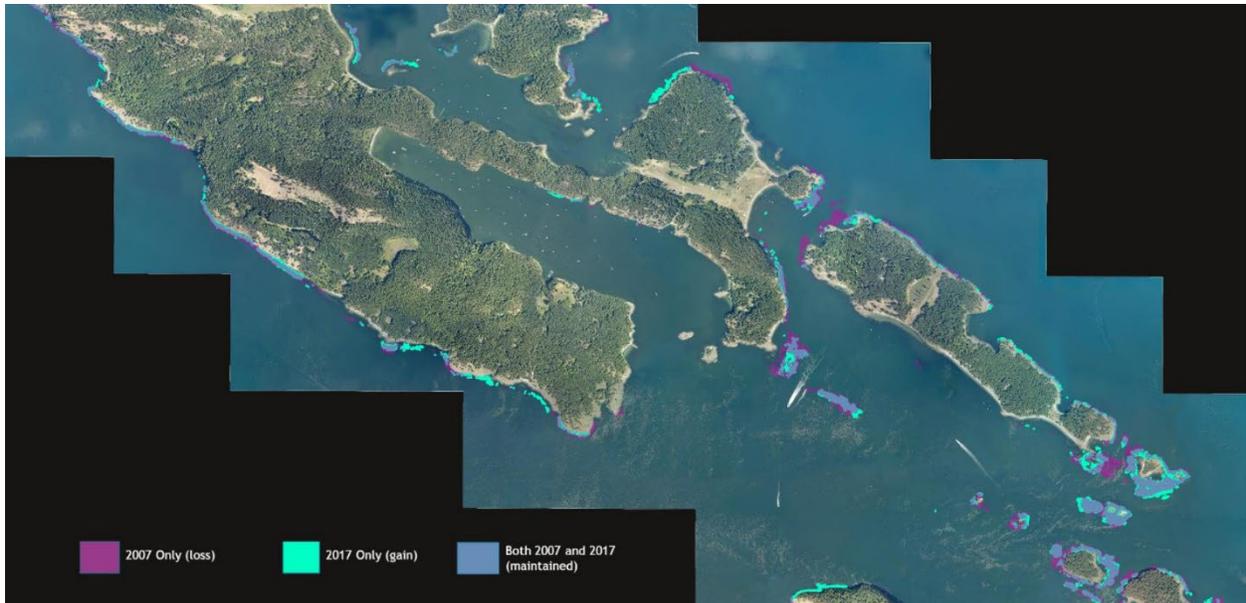


Figure 3-36. Stuart Island, San Juan Archipelago, Washington. Screenshot from *A Decade of Disappearance: Bull Kelp in the San Juan Islands* a [StoryMap](#) created by Samish DNR.

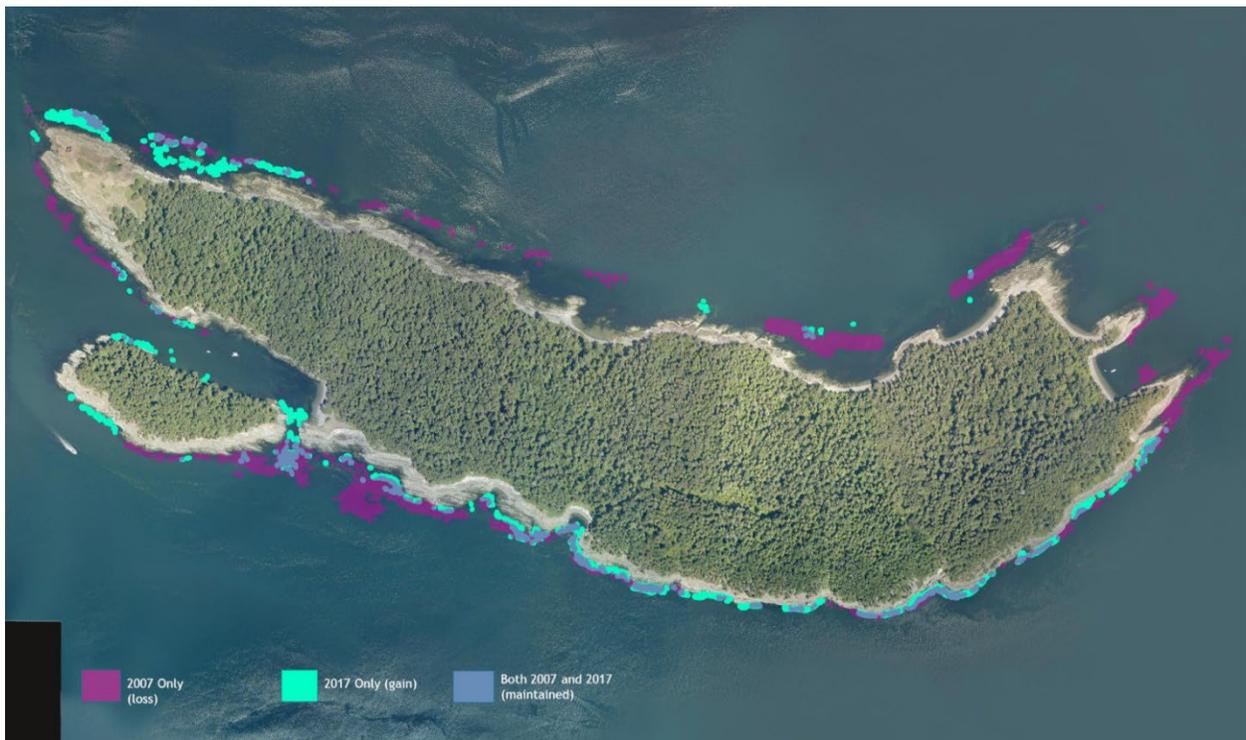


Figure 3-37. Patos Island, San Juan Archipelago, Washington. Screenshot from *A Decade of Disappearance: Bull Kelp in the San Juan Islands* a [StoryMap](#) created by Samish DNR.

3.3.2.4 Linear extent from 1984 imagery in Central Puget Sound

The goal of this project was to leverage a small collection of aerial images of the Seattle shoreline taken in 1984 (Figure 3-38) to fill a data gap in the historical distribution of floating kelp in Central Puget Sound. In doing so, the data source is now also usable in a larger historical kelp distribution study in this sub-basin. To achieve this, the 1984 photographs were spatially referenced and reviewed by a group of experts to generate an estimate of the linear extent of floating kelp in 1984. This project also includes a change analysis between the 1984 results and a 2019 boat-based survey of kelp extent in Central Puget Sound (Berry et al. *in prep*), which provides a snapshot of how kelp forests have changed in these sections of shoreline over the last four decades. The dataset resulting from this project provides an important source for a more comprehensive analysis of historical floating kelp distribution in Central Puget Sound.

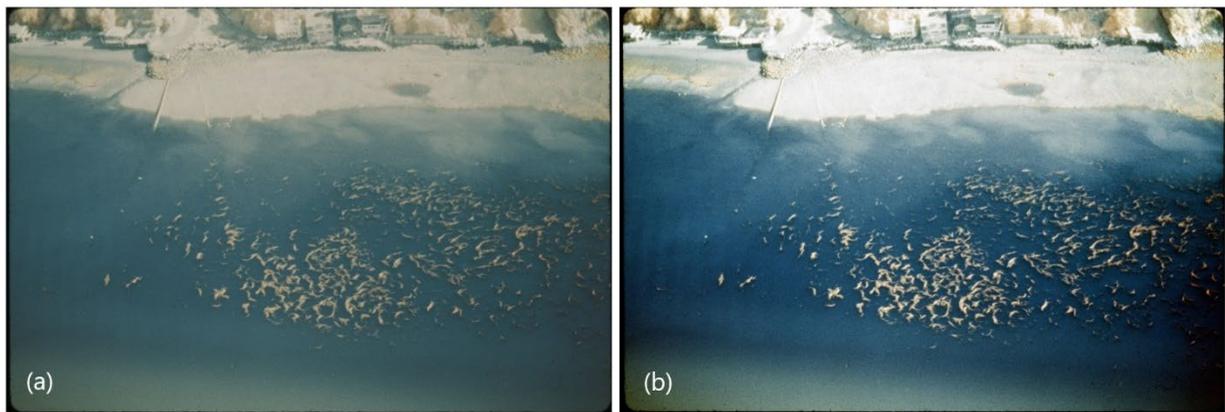


Figure 3-38. Example of (a) Raw scanned image and (b) Color-corrected image provided by Archive Washington. Images shows 32nd Ave beach in Magnolia. Figure and caption from McKenna et al. 2025.

Since the images were collected at an oblique angle (rather than nadir), images could be roughly georeferenced to the shoreline (Figure 3-39) but could not be fully georectified or used for kelp canopy area calculations. Therefore, linear extent (i.e., distance along the -6m bathymetry line) was mapped for the three areas for which aerial images were available (Magnolia, West Seattle, and Lincoln Park; Figure 3-40)



Figure 3-39. View of 1984 images placed along shoreline at Magnolia. Images have been moved, rotated, and scaled to maximize alignment of notable shoreline features with reference imagery and with neighboring images, but the imagery have not been spatially adjusted for the oblique angle of image capture. Underlying imagery is 2019 NAIP Natural Color Imagery Basemap (Esri, USDA Farm Service Agency). Figure and caption from McKenna et al. 2025.

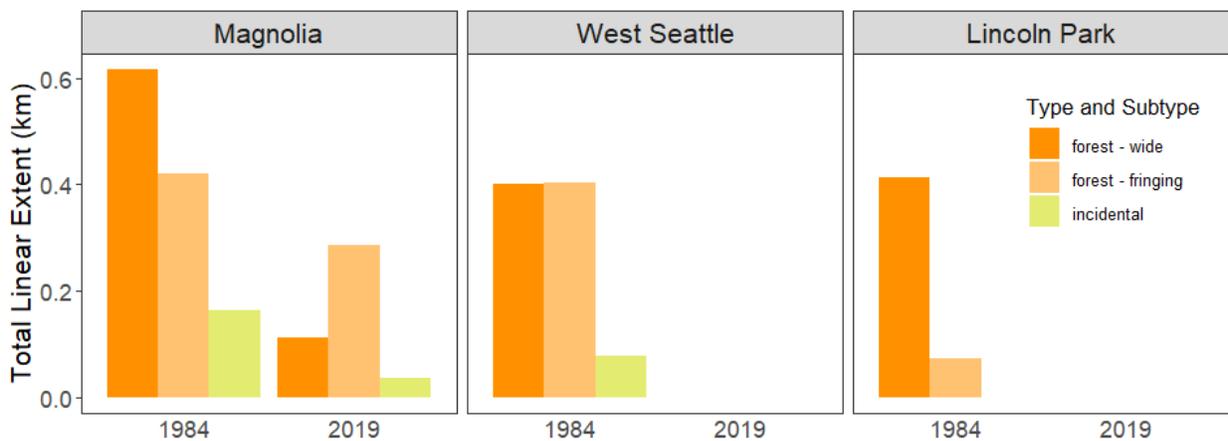


Figure 3-40. Linear extent (km) of floating kelp at each site in 1984 (left) and 2019 (right) grouped by type and subtype; dark orange = forest wide, light orange = forest fringing, yellow = incidental (single and multiple). See Table 1 for category definitions. Figure and caption from McKenna et al. 2025.

By comparing the linear extent from the 1984 aerial imagery with a boat survey conducted in 2019, losses in floating kelp extent were detected in all three areas (Magnolia, Lincoln Park, and West Seattle; Figure 3-41; Figure 3-42). At Magnolia, major losses occurred due

to the construction of the Elliott Bay Marina, although smaller kelp canopies have persisted in the areas around the Marina (Figure 3-41).



Figure 3-41. Maps of linear extent of floating kelp along Magnolia in 1984 derived from aerial imagery (top) and 2019 derived from boat-based linear extent mapping (bottom). Floating kelp presence is symbolized by type/subtype: dotted grey = absent, wide orange line = forest (wide), narrow orange line = forest (fringing), yellow line = incidental (multiple), yellow dot = incidental (single). See Table 1 for category definitions. Figure and caption from McKenna et al. 2025.

At Lincoln Park and West Seattle, there was a total loss of bull kelp canopies throughout the areas surveyed in the 1984 imagery (Figure 3-42). It is worth noting that other areas in this stretch of shoreline (e.g., areas of Lincoln Park that were not surveyed in 1984) do still

have kelp canopies (as of 2025; DNR kayak surveys). However, as a whole this stretch of shoreline has experienced substantial losses.

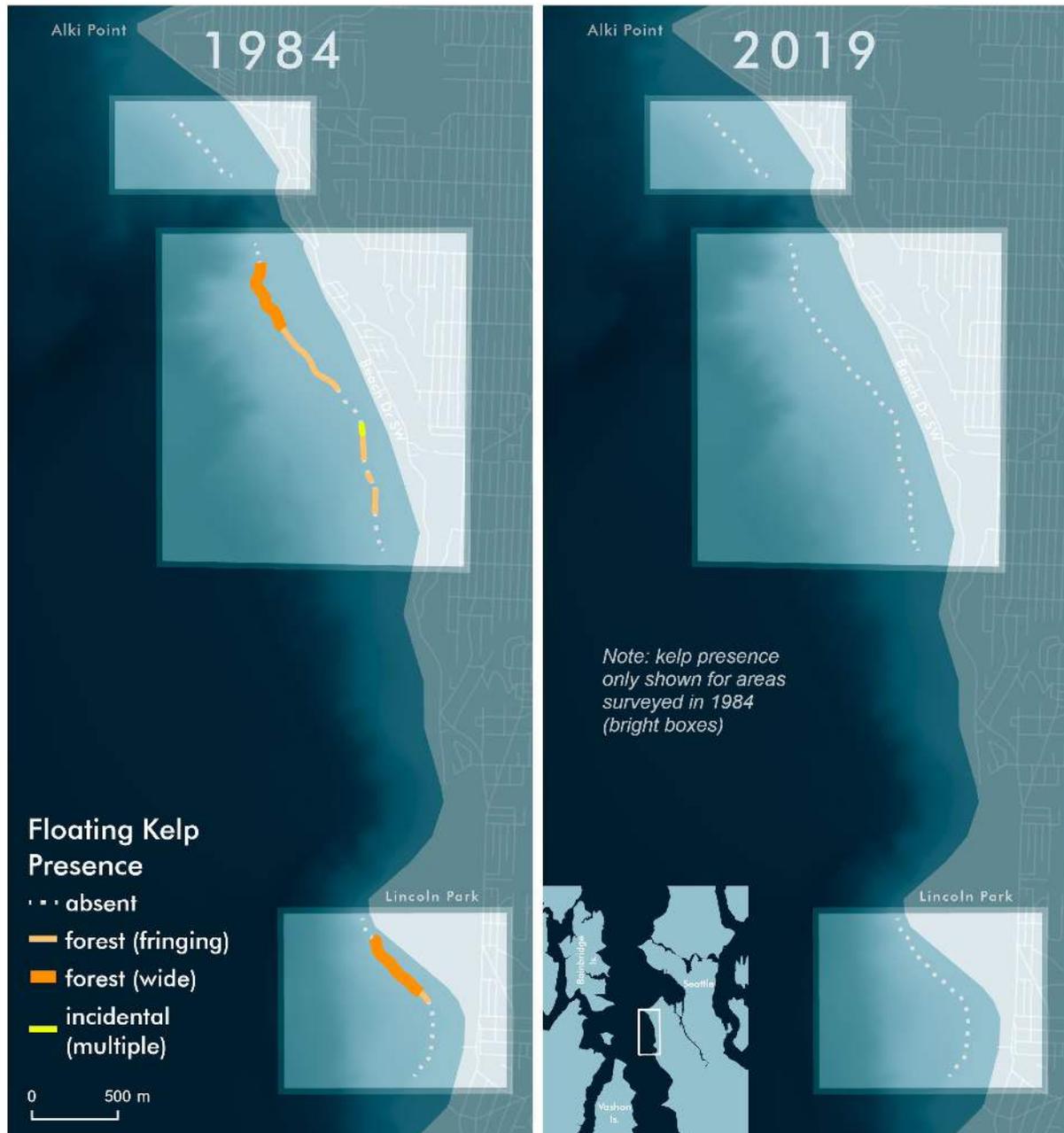


Figure 3-42. Floating kelp presence in West Seattle and Lincoln Park in 1984 derived from aerial imagery (left) and 2019 derived from boat-based linear extent mapping (right). Floating kelp presence is symbolized by type/subtype: dotted grey = absent, wide orange line = forest (wide), narrow orange line = forest (fringing). Highlighted areas show areas surveyed by both datasets; kelp presence is not reported in this study in darkened areas, although 2019 dataset covers entire shoreline. See Table 1 for category definitions. Figure and caption from McKenna et al. 2025.

3.3.2.5 MRC Kayak surveys

The MRC kelp monitoring program has surveyed a total of 44 kelp beds at 31 distinct sites throughout all seven MRC counties. Since program inception in 2015, some monitoring sites have been dropped and new ones have been added. At each monitoring site, MRC volunteers collect floating kelp bed perimeters (Figure 3-43), as well as depth and temperature measurements on the shallow and deep edges of the beds. Other metrics and observations are collected based on county interests. During the 2024 monitoring season, there were 23 sites surveyed in six counties (no sites are currently surveyed in San Juan County) (Figure 3-44).

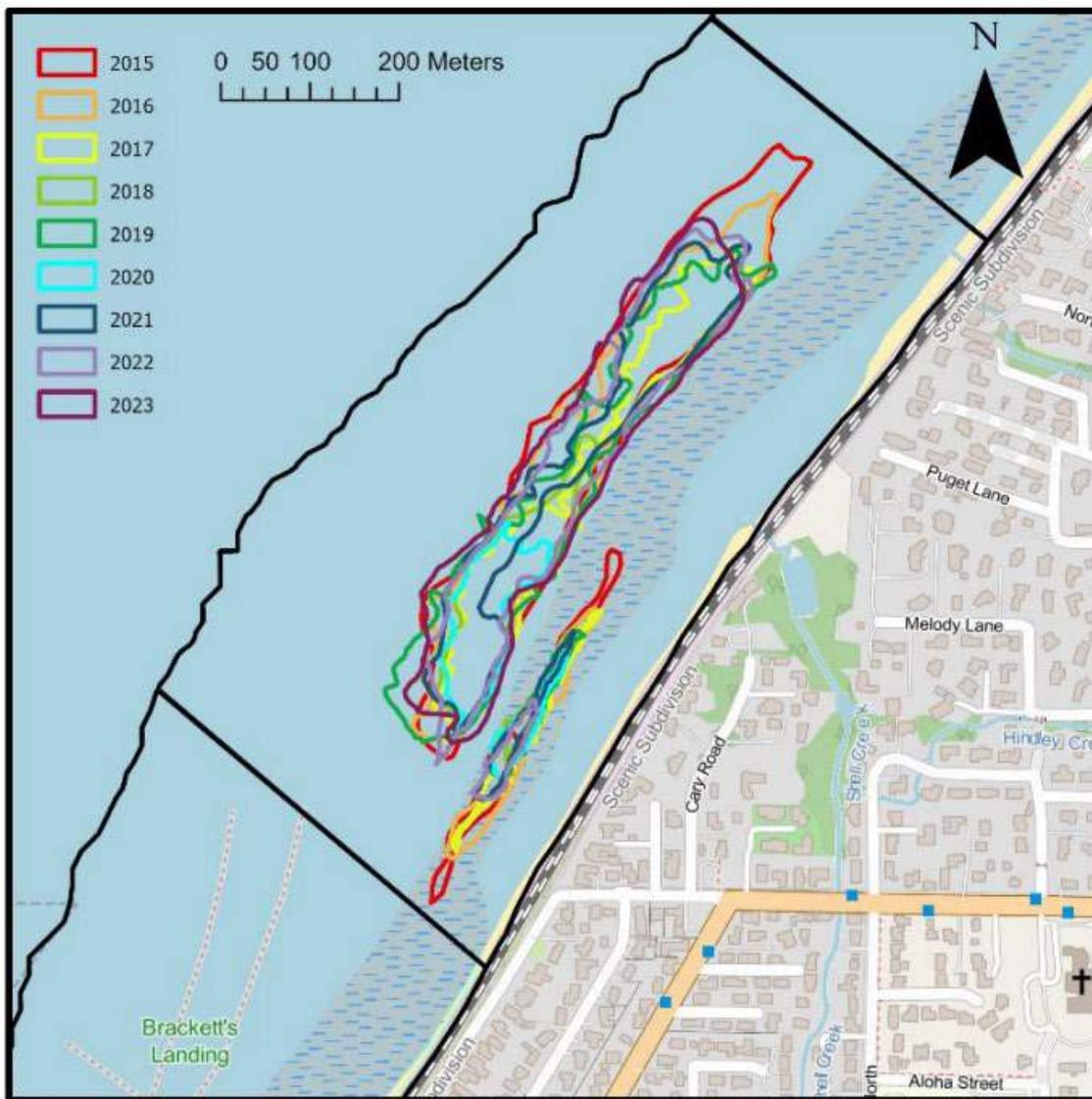


Figure 3-43. Example of annual maximum floating kelp bed perimeters collected at Edmonds North in Snohomish County.

Vital Sign Site Name	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	VS Status
Ebey's Landing	x	x	x	x	x	x	x	x	x	x	Included
Edmonds North	x	x	x	x	x	x	x	x	x	x	Included
Meadowdale	x	x	x	x	x	x	x	x	x	x	Included
Mukilteo	x	x	x	x	x	x	x	x	x	x	Included
North Beach Main	x	x	x	x	x	x	x	x	x	x	Included
Polnell Point		x	x	x	x	x	x	x	x	x	Included
Lummi SW		x	x	x	x	x	x	x	x	x	Included
Coffin Rocks		x	x	x	x	x	x	x	x	x	Included
Freshwater Bay		x	x	x	x	x	x	x	x	x	Included
Observatory Point		x	x	x	x	x	x	x	x	x	Included
Biz Point			x	x	x	x	x	x	x	x	Included
Cherry Point			x	x	x	x	x	x	x	x	Included
Edmonds-Dive Park			x	x	x	x	x	x	x	x	Included
Hat Island			x	x	x	x	x	x	x	x	Included
Possession Point			x	x	x	x	x	x	x	x	Included
Shannon Point-East			x	x	x	x	x	x	x	x	Included
Shannon Point-West			x	x	x	x	x	x	x	x	Included
Aiston Preserve				x	x	x	x	x	x	x	Included
Lowell Point		x	x			x	x	x	x	x	Included
Hoypus Point		x	x	x			x	x	x	x	Included
Clallam Bay			x	x	x	x	x	x			Included
Point Whitehorn		x			x	x	x		x		Included
Alden Bank				x	x	x					Excluded
Ben Ure		x	x	x							Excluded
Pole Pass	x	x	x								Excluded
North Beach West	x				x		x				Excluded
Freshwater Bay 3				x				x		x	Pending
Fawn Island		x	x								Excluded
Reef Island		x	x								Excluded
Hat Island West										x	Pending
Lone Tree Point										x	Pending
Camano Island 2		x									Excluded
Hastie Lake	x										Excluded
Libbey Beach	x										Excluded
North Beach 2					x						Excluded

Years of data:	10 yrs	9 yrs	8 yrs	7 yrs	6 yrs	5 yrs	3 yrs	2 yrs	1 yr
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Figure 3-44. MRC kayak surveys, showing which sites were surveyed during each year between 2015 and 2024. VS Status refers to whether the site is included in the WA Floating Kelp Bed Area Vital Sign Indicator.

Most MRC kelp monitoring sites exhibit substantial year to year variation in kelp bed area, however four sites have exhibited increases (Biz Point, Coffin Rocks, Ebey’s Landing, Possession Point), four site have exhibited declines (Clallam Bay, Freshwater Bay, Shannon Point East, Edmonds Dive Park), and two sites have been lost completely (Meadowdale and Mukilteo) (Figure 3-45, Figure 3-46, Figure 3-47).

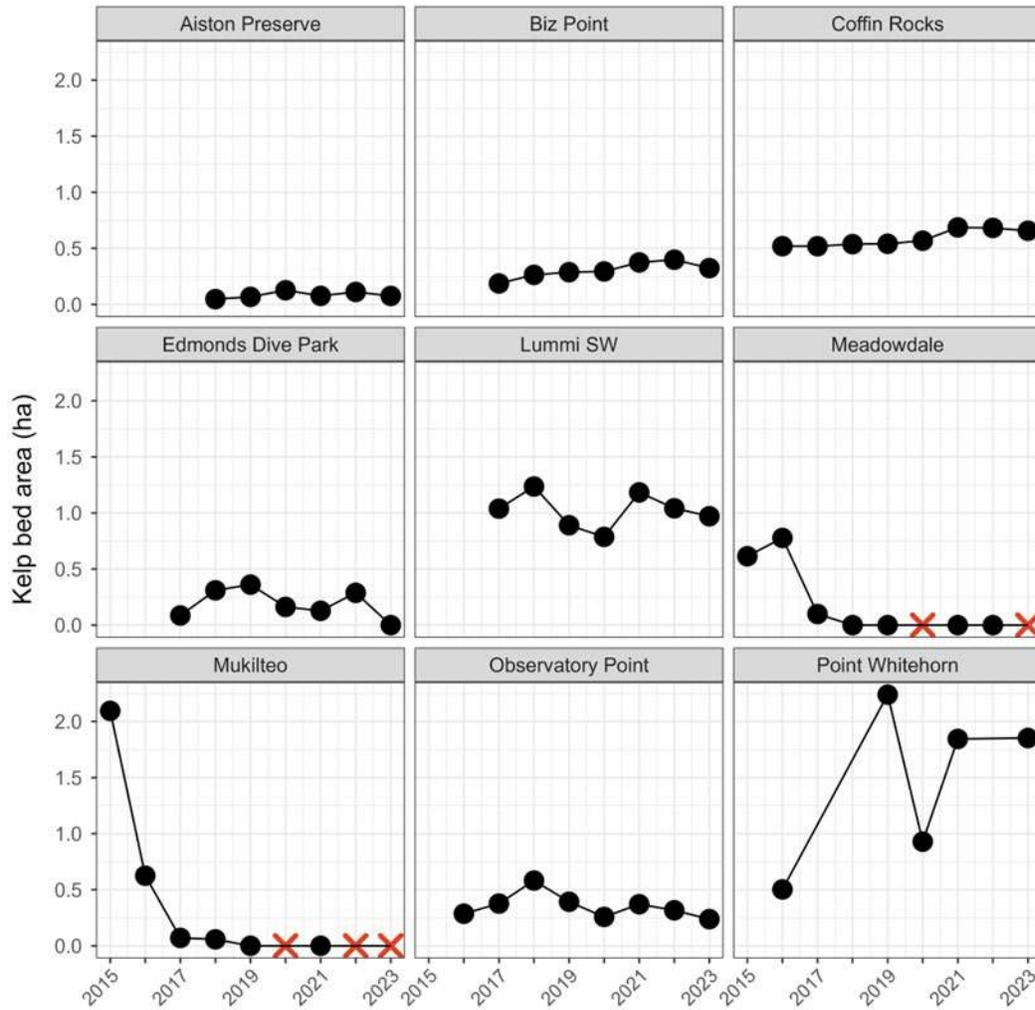


Figure 3-45. Floating kelp bed area at MRC kelp monitoring sites less than 3 ha in size. Data through 2023. Black points represent floating kelp present, and red x's denote no floating kelp.

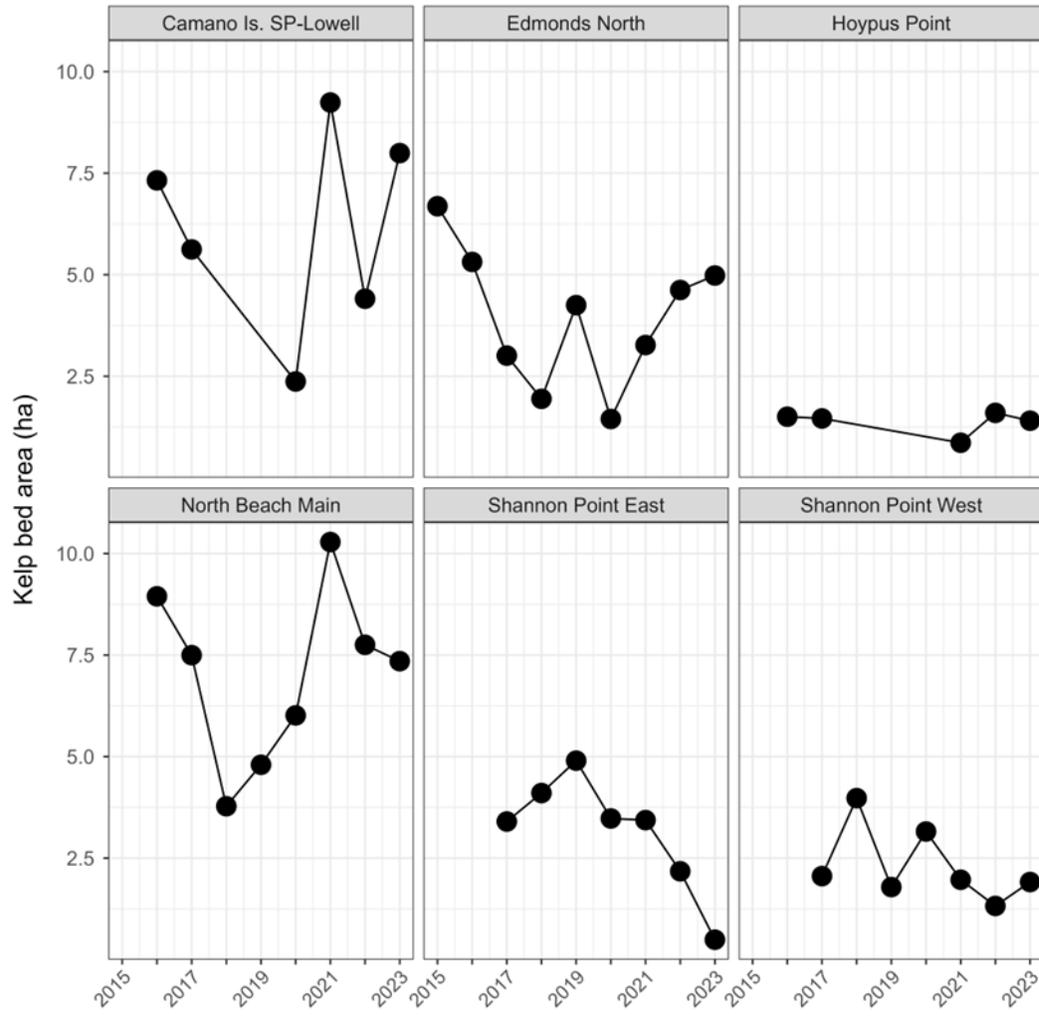


Figure 3-46. Floating kelp bed area at MRC kelp monitoring sites ranging in size between 2 ha and 10 ha. Data through 2023.

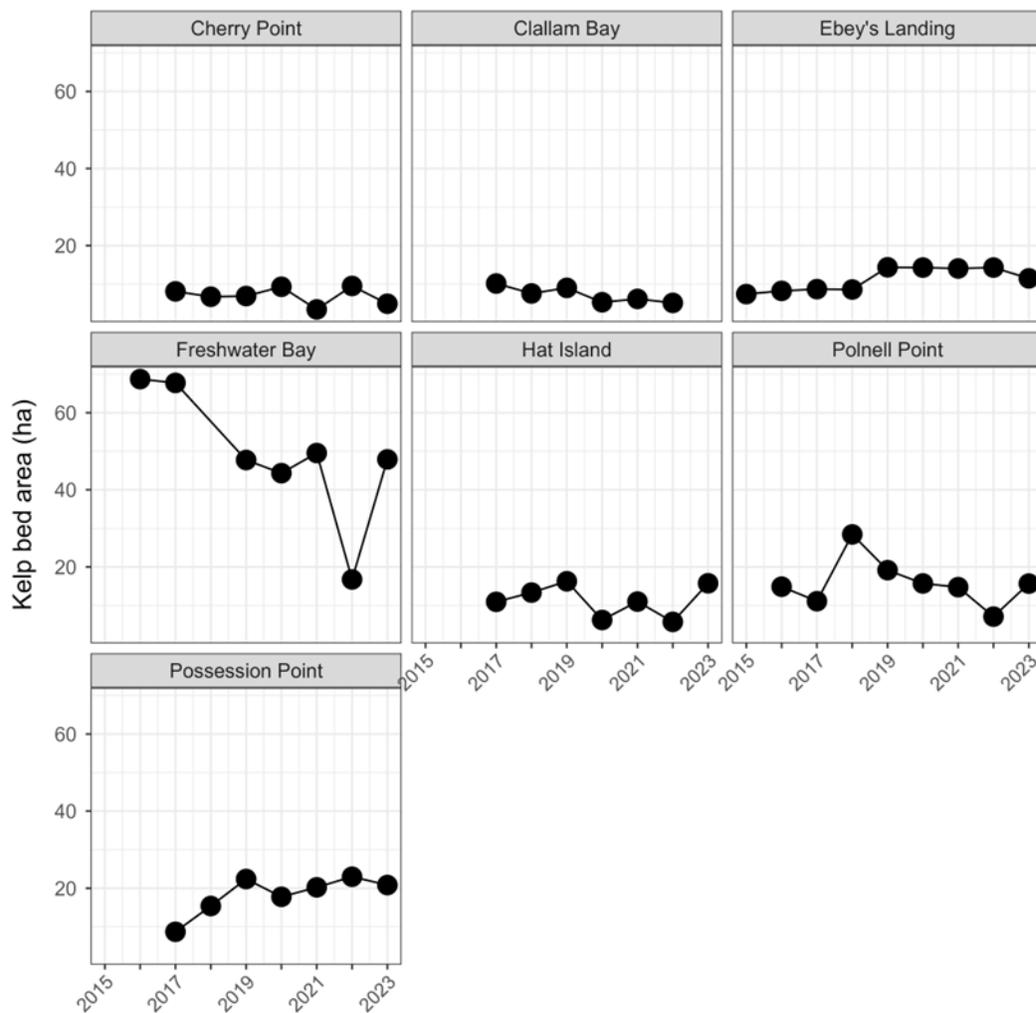


Figure 3-47. Floating kelp bed area at MRC kayak monitoring sites greater than 10 ha. Data through 2023.

The recent and long-term trends in kelp bed area were determined for each site using linear regression, along with an assessment of survey line maps, graphs of the maximum bed area per year, survey notes, and volunteer interviews. Of the 18 MRC sites incorporated into the Indicator in 2021, the trend analysis classified two sites as *increasing*, one site as *decreasing*, two sites as *total loss*, and 13 sites as *no trend* (Figure 3-48). Most sites exhibit substantial year to year variation in kelp bed area, which resulted in many sites classified as *no trend*. In 2023, the number of sites included in the Indicator has increased to 22. Information about the MRC kayak surveys is included as part of the Indicator Summary Report (Claar et al. 2025), and as pop-ups on the [Floating Kelp Indicator interactive webmap](#) (Figure 3-49).

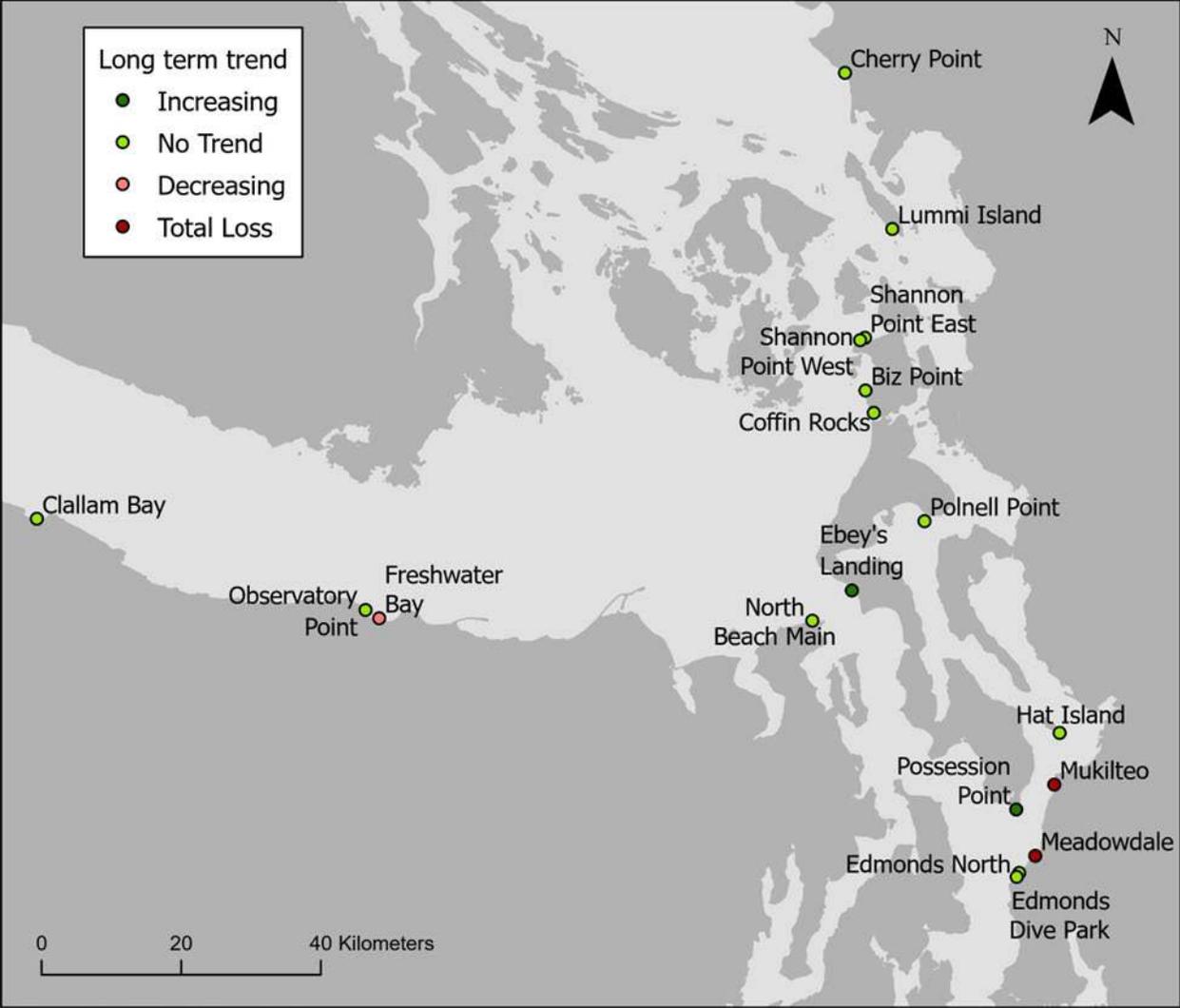
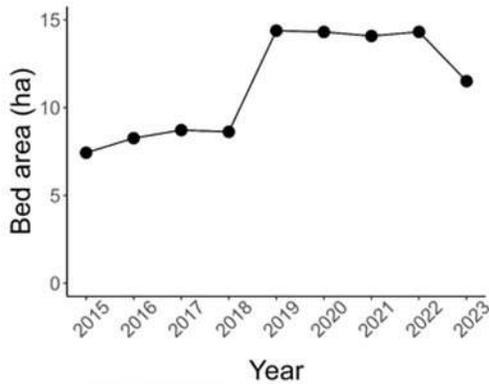


Figure 3-48. Long-term trend classifications for each site of the 18 MRC sites included in the Floating Kelp Bed Area Indicator. Figure and caption from Ledbetter and Berry 2024.

Location: Ebey's Landing (EBL)

Sub-basin: Eastern Strait

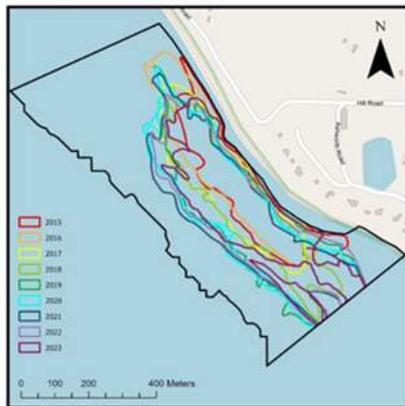
More information:
[Island County MRC](#)
[NW Straits Commission](#)



Recent (5 yr) bed trend: **No trend**

Entire data record: **Increasing**

Island County Marine Resources Committee (MRC) volunteers have monitored Ebey's Landing since 2015. Bed area increased in 2019. Volunteers have observed the bed to expand into deeper water and extend further south, merging with a kelp bed to the southeast. A hole developed in the NW part of bed in 2023. Trend results at this site span a limited number of years, continuing to collect data will enrich our understanding.



To explore the spatial data visit [Sound IQ](#)



Figure 3-49. Example of a Location (Ebey's Landing) pop-up from the WA Floating Kelp Bed Area Vital Sign Indicator interactive webmap. The pop-ups include a plot of bed area over time (top left), a map of bed area footprint over time (bottom left), trend information and summary (top right) and photo (bottom right).

3.3.2.6 WA DNR Kayak surveys

WA DNR has conducted kelp kayak surveys annually since 2013, with eight new sites in 2020 for a total of 14 core sites that are surveyed annually as of 2024 (Figure 3-50).

Site Name	2013	2014	2016	2017	2018	2019	2020	2021	2022	2023	2024	VS Status	
Squaxin Island	x	x	x	x	x	x	x	x	x	x	x	Included	
Brisco Point	x			x	x	x	x	x	x	x	x	Included	
Devil's Head	x			x	x	x	x	x	x	x	x	Included	
Fox Island	x			x	x	x	x	x	x	x	x	Included	
Salmon Beach					x	x	x	x	x	x	x	Included	
Day Island							x	x	x	x	x	Included	
Hansville							x	x	x	x	x	Included	
Lincoln Park							x	x	x	x	x	Included	
Magnolia							x	x	x	x	x	Included	
Owen Beach							x	x	x	x	x	Included	
Point Jefferson							x	x	x	x	x	Included	
Vashon Island SE							x	x	x	x	x	Included	
Wing Point							x	x	x	x	x	Included	
Beckett Point										x	x	Pending	
Years of data:	11 yrs		9 yrs			7 yrs			5 yrs		2 yrs		

Figure 3-50. WA DNR Nearshore Habitat Program kayak surveys at core sites, showing which sites were surveyed during each year between 2013 and 2024. VS Status refers to whether the site is included in the WA Floating Kelp Bed Area Vital Sign Indicator.

WA DNR has also conducted surveys at additional sites that are either sampled opportunistically or as part of another funded project (Figure 3-51). For example, the HSIL funding that is supporting this funding included surveys at eight additional sites in 2024 (Figure 3-51).

Site Name	2013	2014	2016	2017	2018	2019	2020	2021	2022	2023	2024	VS Status
Burrows Island										x	x	Not included
Point Caution										x	x	Not included
Cherry Point										x	x	Not included
Edmonds										x	x	Not included
Freshwater Bay										x	x	Not included
North Beach										x	x	Not included
Mukilteo											x	Not included
Rich Passage											x	Not included

Figure 3-51. WA DNR Nearshore Habitat Program kayak surveys at additional sites, showing which sites have been sampled opportunistically or as part of another funded project. VS Status refers to whether the site is included in the WA Floating Kelp Bed Area Vital Sign Indicator.

DNR kelp canopy kayak surveys have detected changes in floating kelp bed area over the past ten years (Figure 3-52; Ledbetter and Berry 2024).

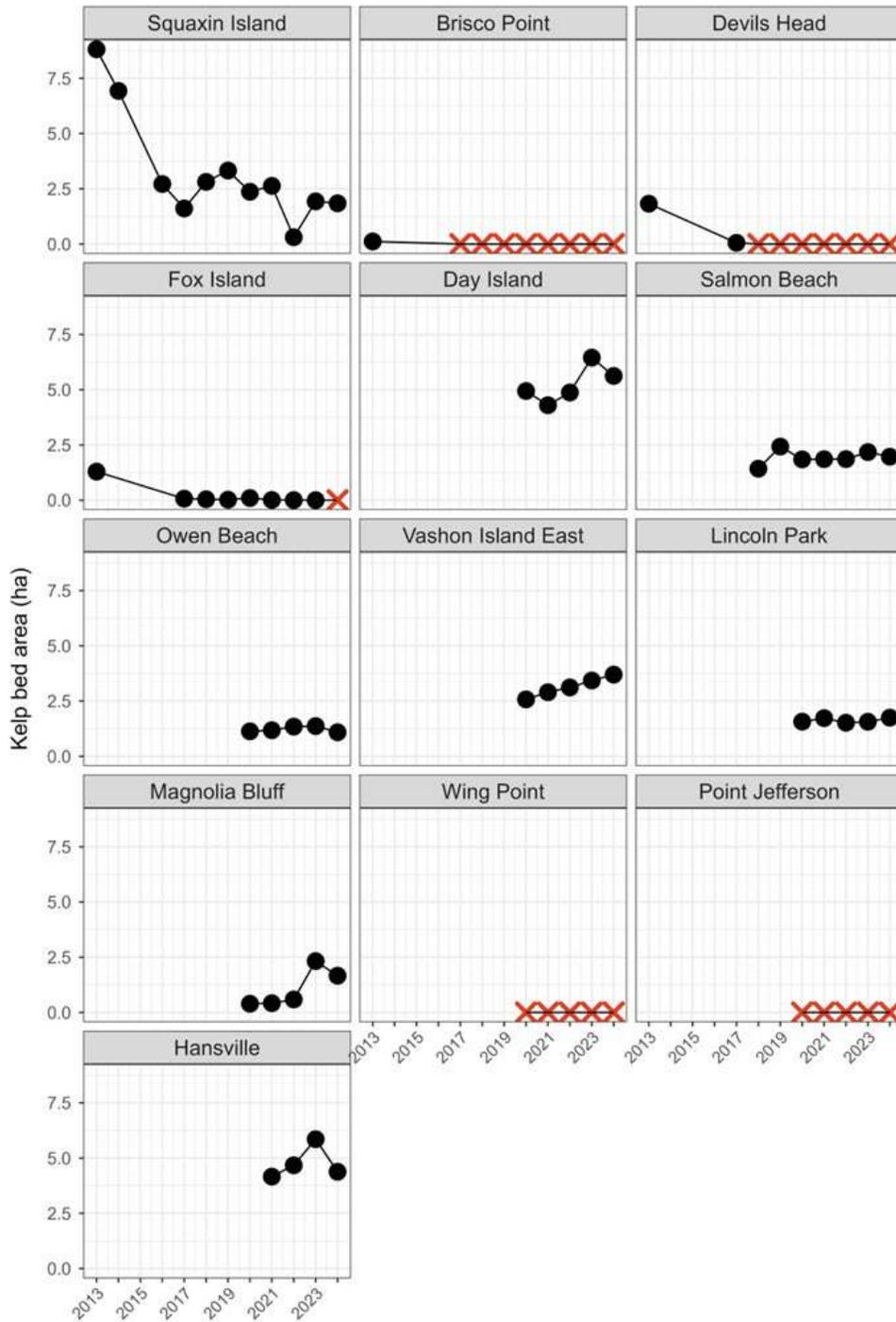


Figure 3-52. Floating kelp bed area at the 13 core DNR Nearshore Habitat Program kayak monitoring sites through 2023. Sites are arranged from innermost site in Puget Sound (Squaxin Island) to outermost site (Hansville). Black points represent floating kelp present, and red x's denote no floating kelp. Figure from Ledbetter and Berry, 2024.

The thirteen DNR Nearshore Habitat Program core kayak survey sites show variable trends, with stability (no trend – Salmon Beach), decreases (Squaxin and Fox Islands), and total loss (Brisco Point, Devil’s Head, Wing Point and Point Jefferson) through the entire data record (Figure 3-53A; Ledbetter and Berry 2024). Trends were also assessed for 5-year and 3-year time periods (Figure 3-53B, C; Ledbetter and Berry 2024).

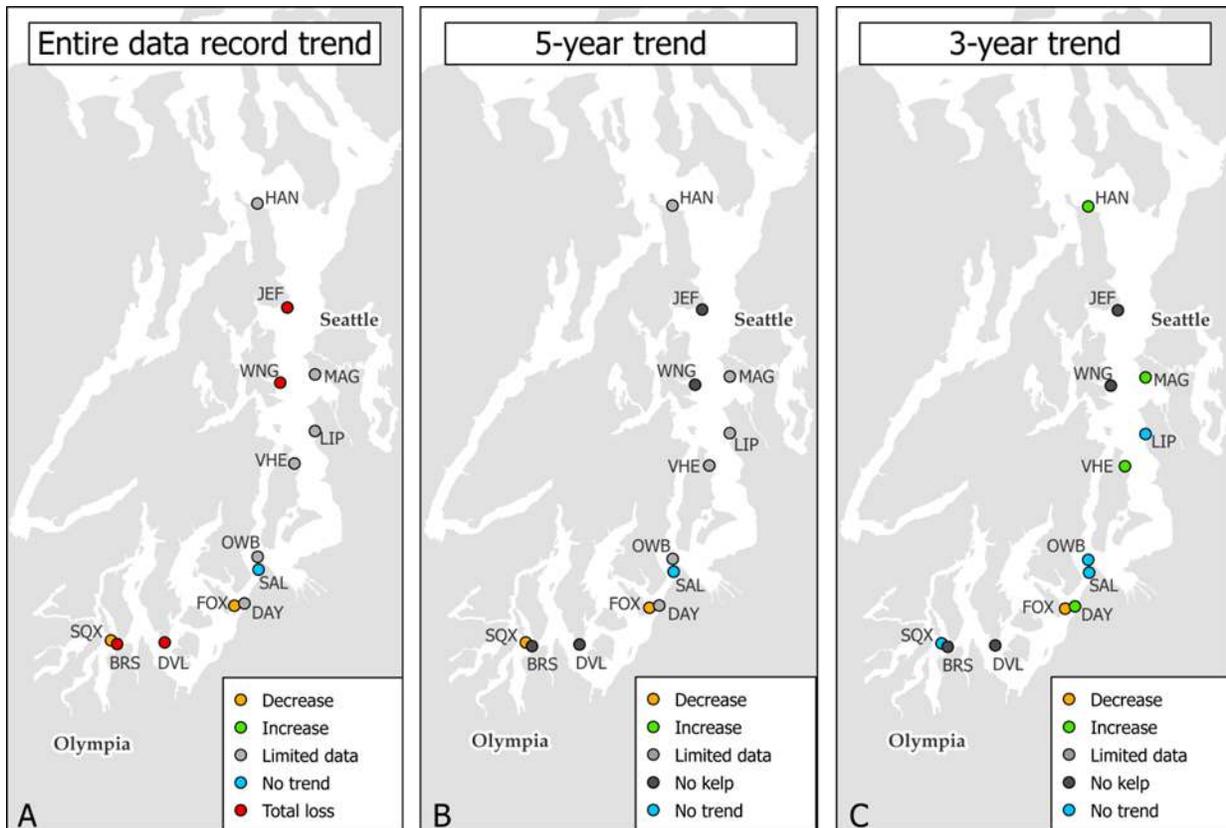


Figure 3-53. Trends in floating kelp bed area across three time periods for the 13 core DNR Nearshore Habitat Program kayak monitoring sites through 2023. Figure from Ledbetter and Berry, 2024.

DNR kayak surveys have also documented the minimum and maximum depths of each surveyed bed (Ledbetter and Berry 2024). In 2023, the depth distribution of floating kelp across all sites ranged from -0.2 m to -13.7 m MLLW (Figure 3-54). Mean maximum depth ranged from -2.3 m to -10.7 m MLLW. Overall, the bed footprints were shallow; in 2023 at 10 out of 16 sites more than 85% of the bed footprint occurred shallower than -6 m MLLW (Ledbetter and Berry 2024). Analysis of kelp bed depth distribution and change can provide insight into causes of change over time. For more comprehensive information on depth distributions collected as part of this dataset, see Ledbetter and Berry 2024.

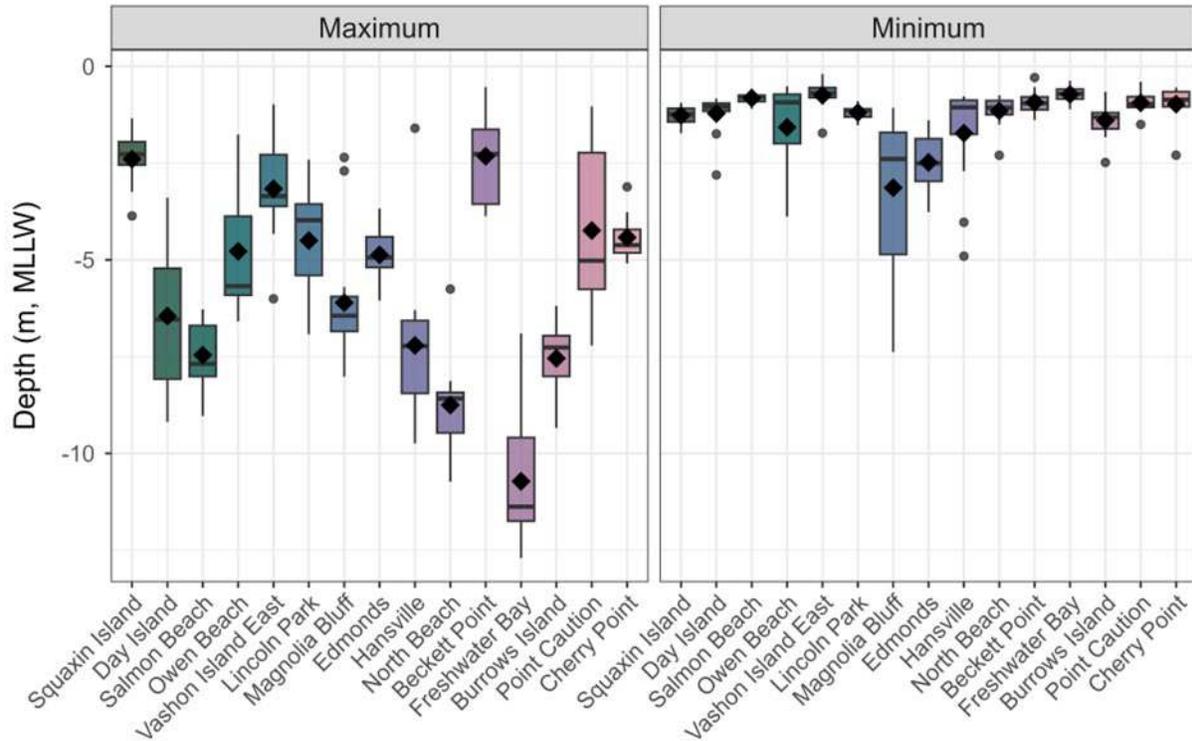
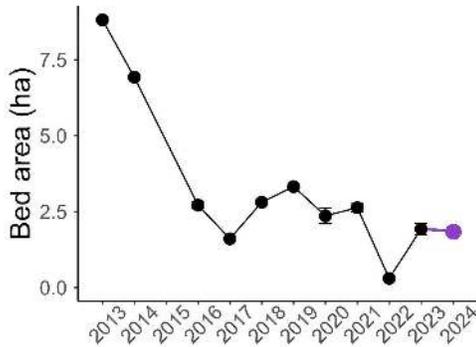


Figure 3-54. Minimum and maximum bed depth in 2023 at DNR floating kelp monitoring sites. Circular points represent outliers and diamond points represent the mean. Sites are arranged from south (Squaxin Island) to north (Cherry Point) and colored to be easily distinguishable. Figure from Ledbetter and Berry, 2024.

For sites with at least 5 years of data, the entire data record trend is used to inform the WA Floating Kelp Bed Area Vital Sign Indicator. The Indicator also reports recent (5-year) trends, although these are supplementary to entire-data-record-trend classifications. Information about the DNR kayak surveys is included as part of the Indicator Summary Report (Claar et al. 2025), and as pop-ups on the Floating Kelp Indicator interactive webmap (Figure 3-55).

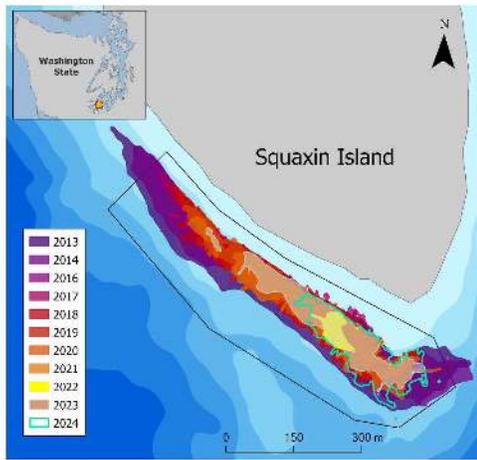
Location: Squaxin Island (SQX)
 Sub-basin: South Puget Sound

More information:
[DNR Nearshore Habitat Program](#)



Recent (5 yr) bed trend: **Decreasing**
 Entire data record: **Decreasing**
 The indicator considers data through 2023,
 2024 is included in graph

The DNR Nearshore Habitat Program has monitored Squaxin Island since 2013. Bed area decreased from 2013 to 2016 before stabilizing. Following a massive decline in 2022, the bed had a partial recovery in 2023. This bed is a priority for research and restoration.



We have a broad understanding of changes in bull kelp extent in South Puget Sound based on [synthesis](#) of diverse historical data sources (see map). In the last 145 years, bull kelp forests have disappeared from 80% of these shorelines. Bull kelp is now concentrated around the Tacoma Narrows in the east and Squaxin Island in the west.

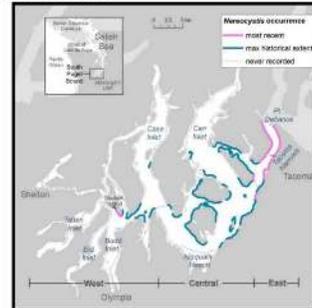


Figure 3-55. Example of a Location (Squaxin Island) pop-up from the WA Floating Kelp Bed Area Vital Sign Indicator interactive webmap. The pop-ups include a plot of bed area over time (top left), a map of bed area footprint over time (bottom left), trend information and summary (top right) and supporting information (bottom right).

3.3.2.7 WA DNR UAS monitoring surveys

WA DNR has been surveying floating kelp beds using multispectral UAS (uncrewed aircraft systems; “drones”) at multiple sites since 2020 (Table 3-17). WA DNR primarily uses 5-band multispectral drones, which include red, green, blue, near-infrared, and red-edge bands (Table 3-18, Figure 3-56). UAS imagery can be analyzed to classify floating kelp canopy area and bed area at very high resolutions (<6-inches), providing the ability to map and track changes in kelp canopies at sites of interest.

Table 3-17. DNR Nearshore Habitat Program UAS monitoring surveys at core sites, showing which sites were surveyed during each year between 2020 and 2024.

Site	2020	2021	2022	2023	2024
Lincoln Park	x	x	x	x	x
North Beach	x	x	x	x	x
Owen Beach	x	x	x	x	x
Squaxin Island	x	x	x	x	x
Vashon Island	x	x	x	x	x
Hansville	x		x	x	x
Magnolia	x		x	x	x
Cherry Point			x	x	x
Edmonds		x		x	x
Salmon Beach			x	x	x
Ebeys Landing		x			
Hat Island			x		
Pillar Point		x			
Possession Point	x				
Pt Caution					x
Tatoosh Island			x		
Years of data:	5 yrs	4 yrs	3 yrs	2 yrs	1 yr

Table 3-18. List of multispectral band combinations found to be useful in creating contrast between floating kelp canopy and the surrounding environment. Table & caption from Cowdrey & Claar 2024.

Name	Visualization channel		
	Red	Green	Blue
RGB (reference)	Red	Green	Blue
False-color NIR	Near-infrared	Green	Blue
Color infrared (CIR)	Near-infrared	Red	Green
False-color NEG	Near-infrared	Red edge	Green
NEG inverted	Red edge	Green	Near-infrared
High-contrast NEE	Near-infrared	Red edge	Red edge

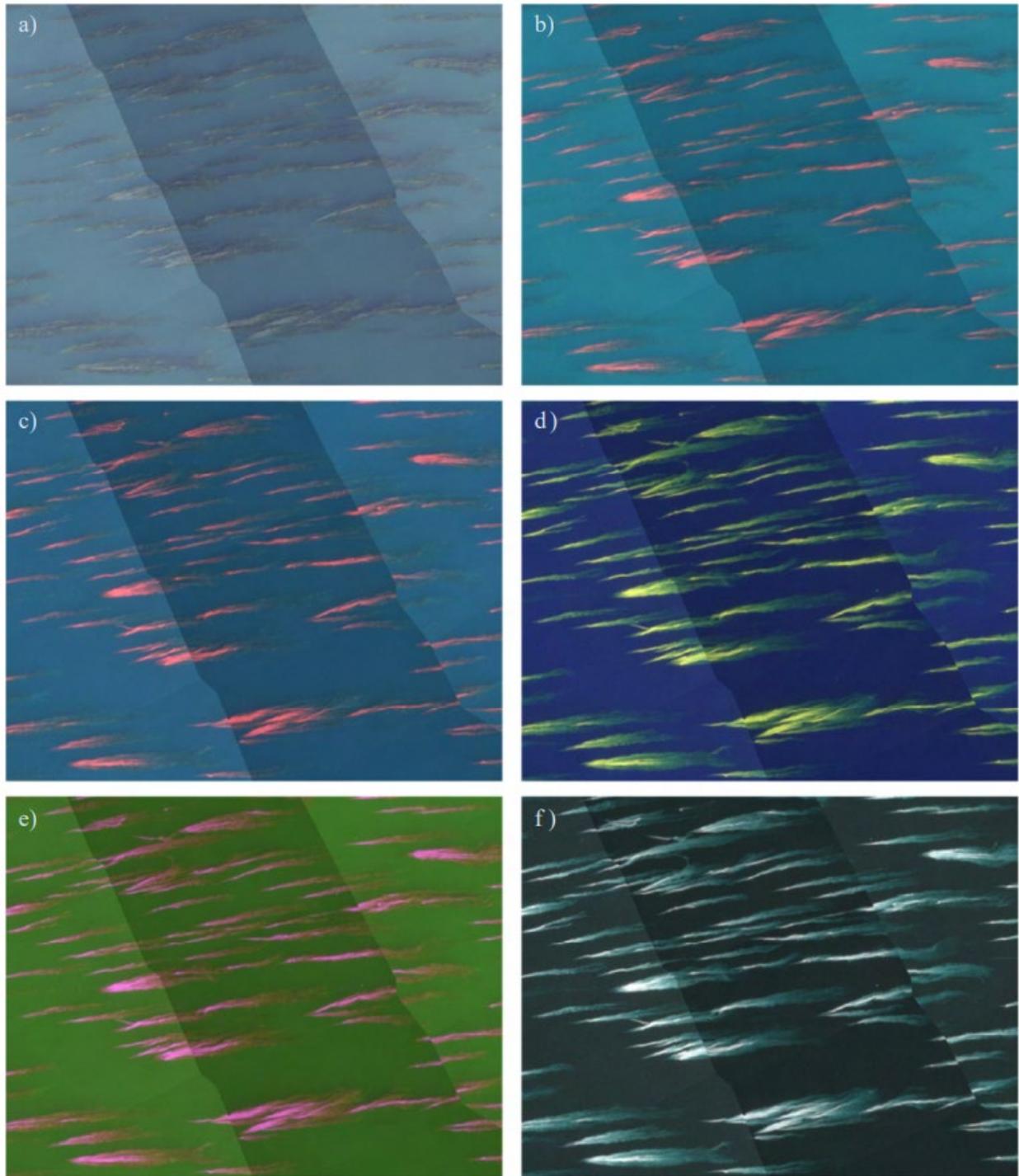


Figure 3-56. Panels showing the appearance of kelp canopy using different multispectral band combinations for display including: RGB (a), false-color NIR (b), CIR (c), NEG (d), NEG inverted (e), and high-contrast NEE (f). Note: the dark band running down the middle of each frame is an artifact of the mosaicking process. Figure and caption from Cowdrey & Claar, 2024. See Table 3-18 for definitions of band combinations.

Table 3-19. List of surveys used in interannual change assessment, with selected surveys in green. “S1” and “S2” correspond to the first and second paired survey. Notes on why each selection was made are included with each comparison set. Table and caption from Cowdrey and Claar 2024

Site	Year	Paired survey selected		Selection notes
		S1	S2	
Lincoln Park	2021	S1		Some floating wrack/detritus present in all surveys. S1 in 2022 has shadows from trees on the bluff behind the site impacting canopy visibility in the southern portion.
	2022	S1	S2	
Vashon Island	2021	S1	S2	All four surveys appeared suitable for comparison. In 2022, S2 had somewhat more uniform blade orientation throughout the site so the second survey for both years was chosen for consistency.
	2022	S1	S2	
Owen Beach	2021	S1	S2	S2 in both years shows impacts from currents in that plants at the deep edge of the site are pulled under and no longer visible. Other conditions similar.
	2022	S1	S2	
North Beach	2021	S1		S2 was selected in 2022 because the orientation of the blades was more similar to that seen in 2021. Blades in S1 were visibly drooping, rather than trailing out.
	2022	S1	S2	

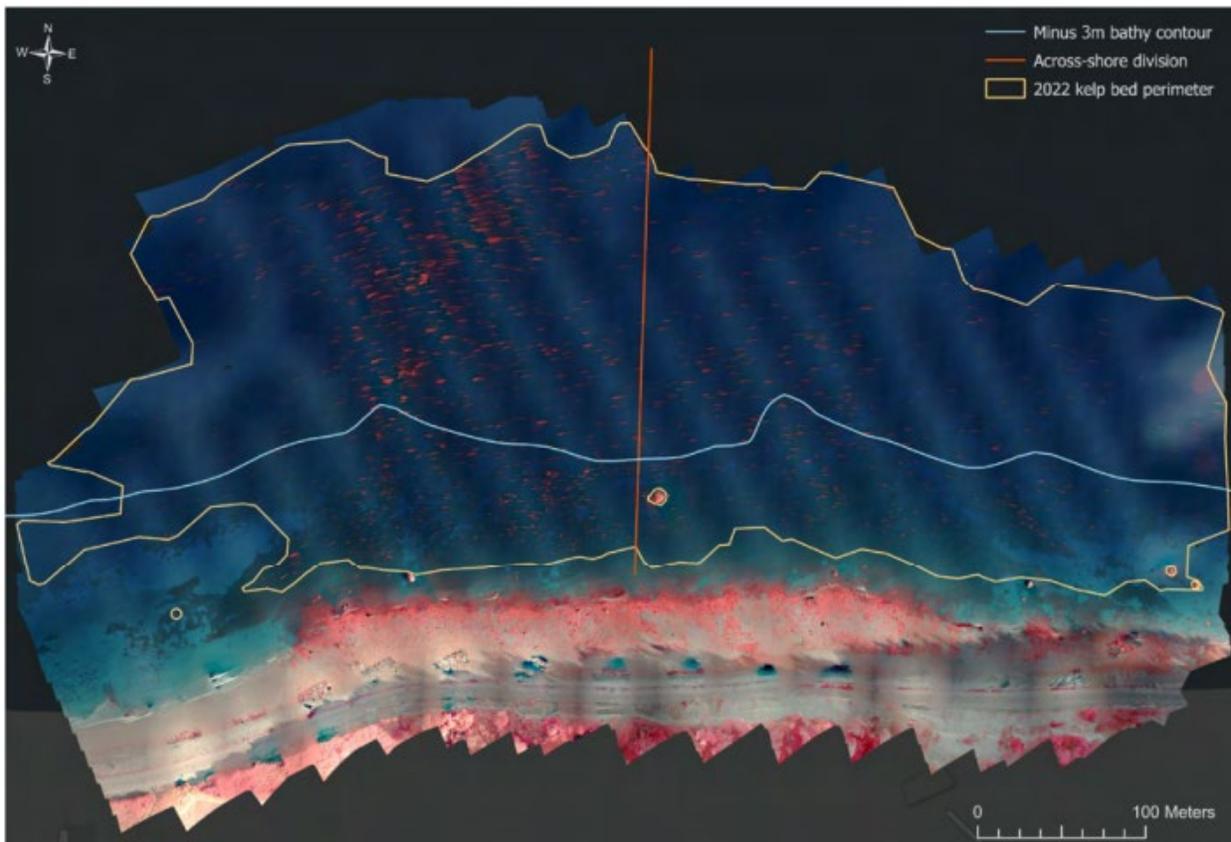


Figure 3-57. Survey conducted at North Beach in 2022 visualized in a CIR color band combination, showing the bed extent perimeter (yellow), across-shore divider (red), and -3 m bathymetric contour (light blue) used to divide the site into quadrants. Canopy area metrics were summarized in each of the four areas. Figure and caption from Cowdrey & Claar, 2024.

In 2021 and 2022, multiple surveys were conducted in order to assess variability due to tides, currents, and other environmental conditions (Table 3-19). Cowdrey and Claar 2024 provides an in-depth analysis of these comparisons, as well as analysis of classification indices and thresholds.

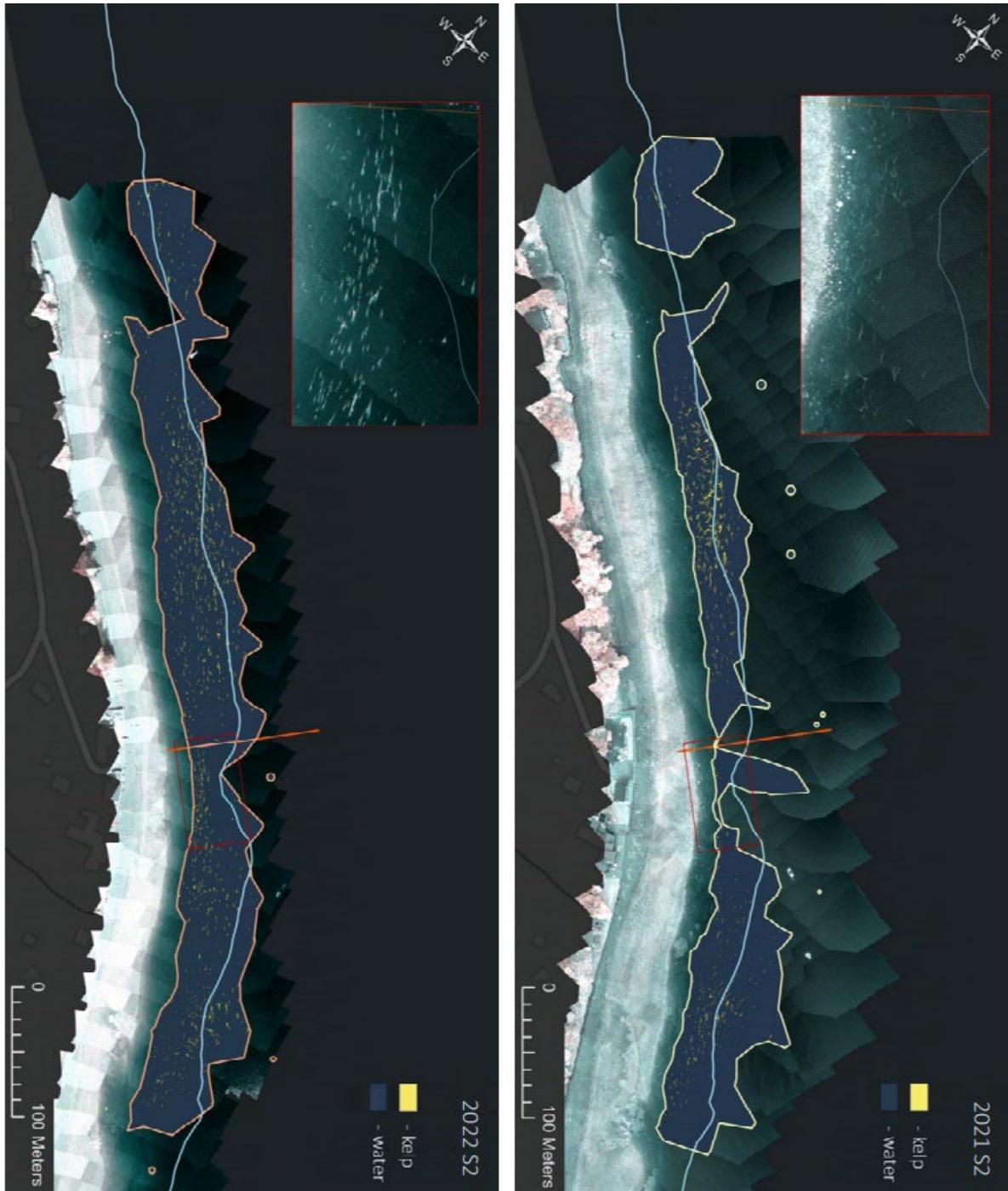


Figure 3-58. Surveys at Vashon Island from 2021 (right) and 2022 (left) displayed in “NEE” band combination showing their respective bed extent perimeters, and classified canopy results shown in yellow. The -3 m bathymetric contour and shoreline midpoint quadrant dividers are shown in blue and red respectively. Figure and caption from Cowdrey & Claar, 2024.

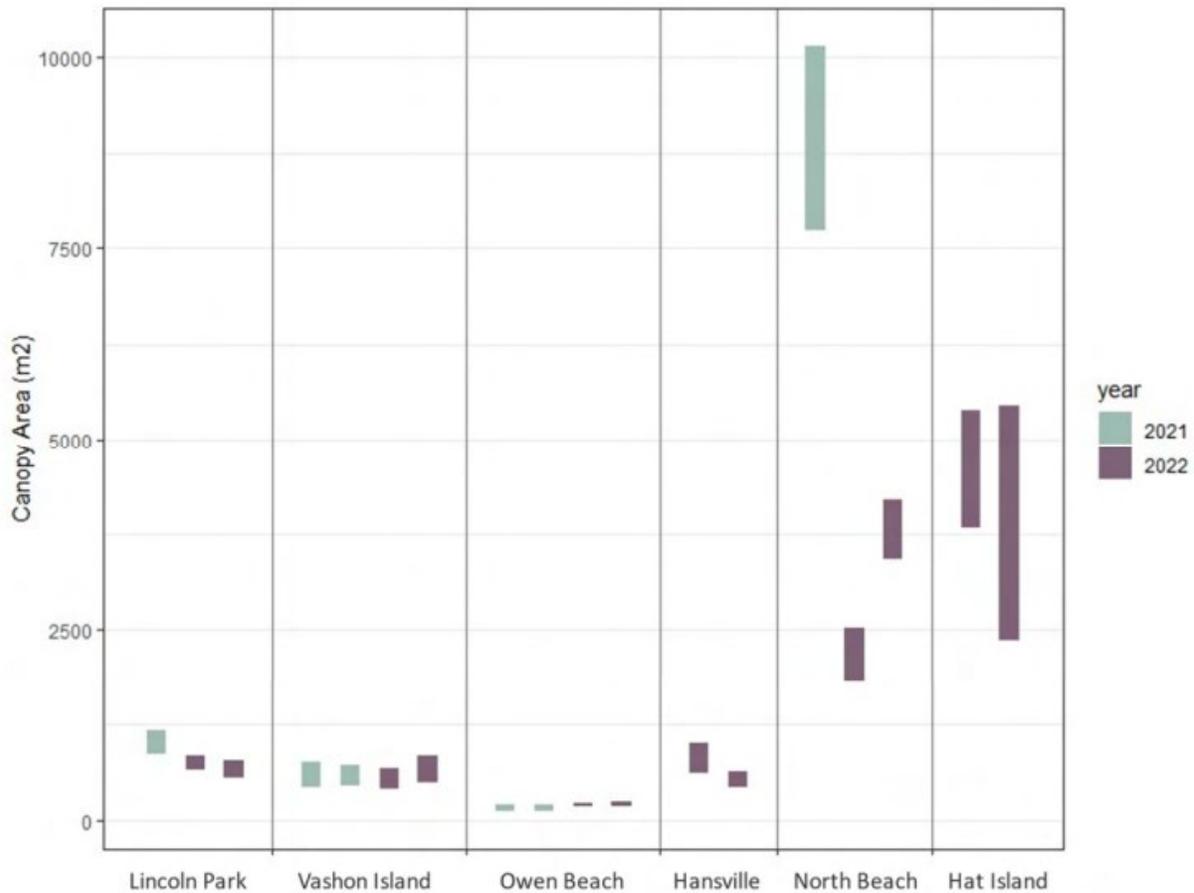


Figure 3-59. Canopy area estimate ranges within revised bed extents for each survey based on low and high BNDVI thresholds selections. Surveys are grouped by site and symbolized by year. Figure and caption from Cowdrey & Claar, 2024.

For visualization and analysis, imagery for each site can be divided (e.g., by bathymetry) which allows for fine spatial scale mapping of floating kelp canopies (e.g., depth) (Figure 3-57). These maps can then be compared across years to assess how kelp canopies change over both time and space (Figure 3-58; Figure 3-59). For example, North Beach experienced a loss in kelp canopy area (Figure 3-59), with the most substantial losses occurring in the shallow portion of the bed (Figure 3-60). On the other hand, Vashon Island did not have a detectable change in site-level canopy area between 2021 and 2022 (Figure 3-59), but had a likely increase in canopy area in the shallow-East portion of the bed (Figure 3-58). At North Beach, the most substantial changes in kelp canopy between 2021 and 2022 occurred shallower than -3m depth below MLLW.

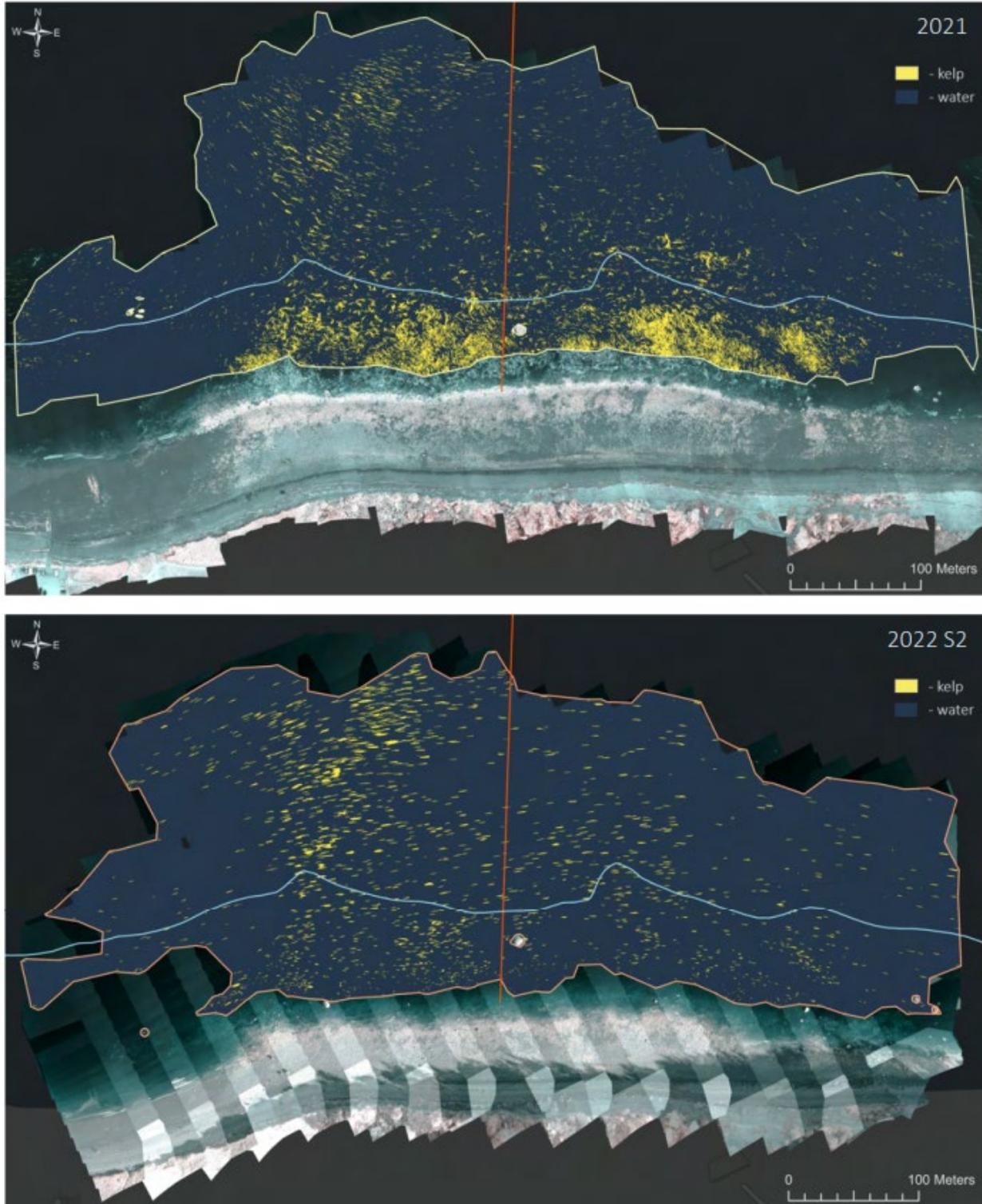


Figure 3-60. Surveys at North Beach from 2021 (top) and 2022 (bottom) displayed in “NEE” band combination showing their respective bed extent perimeters, and classified canopy results for both shown in yellow. The -3 meter bathymetric contour and shoreline midpoint quadrant dividers are shown in blue and red respectively.

3.3.2.8 WA DNR/Suquamish UAS surveys

Kelp canopies were generally smaller with increasing distance into central Puget Sound (correlation test, $P = 0.08$). Notably large beds are present in Admiralty Inlet at Double Bluff (16.3 ha), Foulweather Bluff (17.1 ha), and Scatchet Head/Possession Point (152.7 ha; Table 3-20).

Table 3-20. Bed Extents for surveys completed in the WA DNR/Suquamish Central Sound UAS baseline mapping project.

Sub-Region	Site	Area (ha)	Latitude
Admiralty Inlet	Double Bluff	16.34	47.968718 °N
Admiralty Inlet	Useless Bay	1.01	47.967085 °N
Admiralty Inlet	Foulweather Bluff	17.11	47.937716 °N
Admiralty Inlet	Hansville	6.15	47.920392 °N
Admiralty Inlet	Scatchet Head/Possession Point	152.68	47.907245 °N
Central	Edmonds	3.25	47.821911 °N
Central	Discovery Park	5.92	47.669219 °N
Elliott Bay	Magnolia	1.80	47.631223 °N
Elliott Bay	Elliott Bay Marina Breakwater	0.32	47.627300 °N
Elliott Bay	Centennial/Myrtle Edwards Parks	2.28	47.622365 °N
Elliott Bay	Pier 70-69	0.06	47.614399 °N
Elliott Bay	Pier 69-68	0.15	47.613287 °N
Elliott Bay	Pier 62 North	0.28	47.608902 °N
Elliott Bay	Pier 62 South/Seattle Aquarium	0.11	47.608170 °N
Elliott Bay	Jack Block Park	0.29	47.585171 °N
Central	Lowman Beach Park	0.41	47.545328 °N
Central	Lincoln Park	1.39	47.535551 °N
Central	Blake Island	0.10	47.531041 °N
Central	North Vashon	7.39	47.512289 °N
Central	Glenacres	3.69	47.484973 °N
South Central	Sunrise Beach	0.36	47.343321 °N
South Central	Pt. Dalco	0.81	47.334446 °N
South Central	Gig Harbor	1.35	47.323624 °N
South Central	Owen Beach	1.09	47.316074 °N
South Central	Pt. Ruston/Dune	2.49	47.301685 °N
<i>South Sound</i>	<i>Day Island</i>	<i>7.63</i>	<i>47.242631 °N</i>

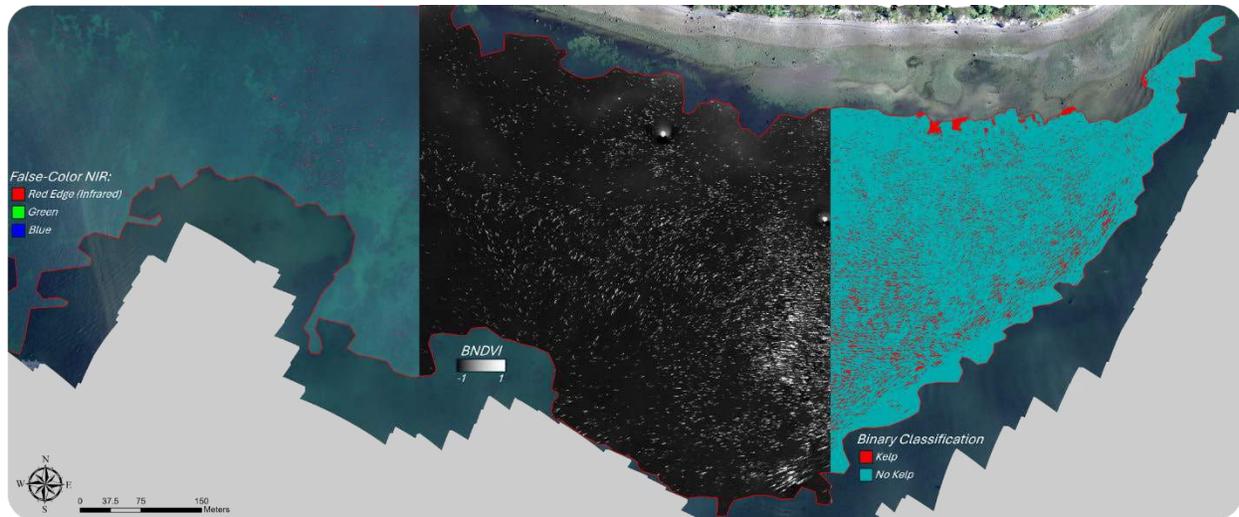


Figure 3-61. Possession Point survey orthomosaic visualized by steps in the imagery classification process: the full orthomosaic in true color (background), manually delineating bed extent while viewing in false-color NIR (left), calculating the BNDVI index for the orthomosaic within the bed extent (center), and producing binary classifications based on threshold values in the BNDVI index (right).

Kelp canopies also persist along urbanized waterfront in Elliott Bay, with examples of overwater structure removal such as the Pier 62 renovation project followed by floating kelp canopy establishment (Figure 3-62). These canopies in Elliott Bay are smaller (0.7 ± 0.3 ha) but are important contributors to habitat connectivity in the region.

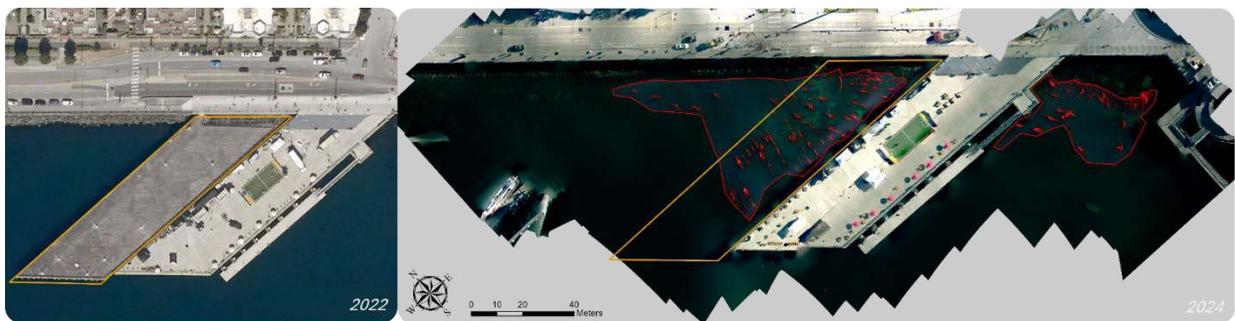


Figure 3-62. The Pier 62 area in downtown Seattle shown prior to removal of the degrading northern structure in 2022 (left), and the survey orthomosaic from 2024 (right) visualized in true color at the full extent, false-color NIR within the bed extent, and with the previous pier extent indicated in yellow, highlighting the kelp canopy present in the now-unshaded area.

Kelp was also observed growing in seagrass beds at several sites, highlighting the varied habitat composition (e.g., small rocks in soft-bottom substrates) upon which kelp canopies can persist. Analyses associated with this work are ongoing, with a final report to be produced by September 2025. This project expanded WA DNR's multispectral UAS mapping capacity through a partnership with the Suquamish Tribe with the goal of collaboratively improving the monitoring and management of critical nearshore habitats.

3.3.2.9 ShoreZone survey

The Nearshore Habitat Program at DNR completed a state-wide inventory of saltwater shorelines using the ShoreZone Mapping System between 1994 and 2000 (Figure 3-63). The ShoreZone Mapping System uses helicopter-based aerial videography to classify physical and biological characteristics of the shoreline. The Washington State ShoreZone Inventory characterizes approximately 3,000 miles of saltwater shorelines in the State. Results have been analyzed at multiple spatial scales, including a summary of the percent of shoreline with marine vegetation (including floating kelp) (Table 3-21; Figure 3-64).

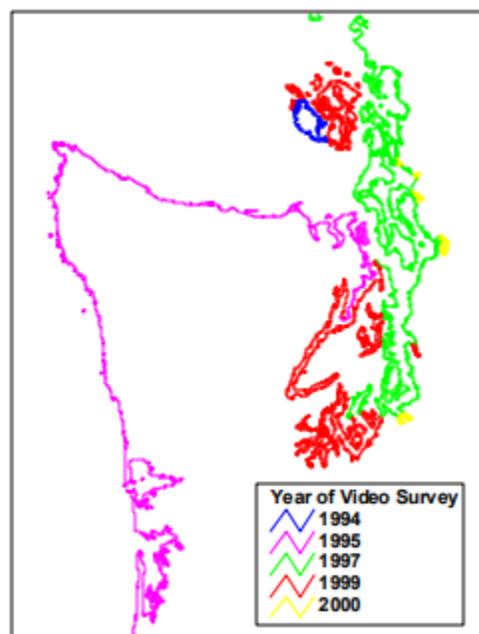


Figure 3-63. ShoreZone video acquisition by year. Figure and caption from Berry et al. 2001.

Table 3-21. Percentage of aquatic vegetation along coastal shorelines in Washington State (By county) Source: Department of Natural Resources. Table and caption from ShoreZone Inventory Summary of Key Findings.

County Name	Total Miles	Percent of Shoreline with Aquatic Vegetation			
		Elgrass	Floating Kelp	Non-floating kelp	Sargassum
Clallum	254	20%	40%	80%	1%
Grays Harbor	187	5%	> 1%	6%	> 1%
Island	214	63%	10%	18%	8%
Jefferson	254	58%	7%	33%	18%
King	123	62%	13%	27%	25%
Kitsap	254	48%	> 1%	21%	21%
Mason	232	28%	> 1%	24%	33%
Pacific	276	22%	> 1%	1%	> 1%
Pierce	239	26%	7%	44%	19%
San Juan	408	41%	31%	63%	47%
Skagit	229	51%	12%	26%	15%
Snohomish	133	22%	1%	1%	3%
Thurston	118	4%	> 1%	24%	4%
Whatcom	147	55%	7%	18%	34%
Total	3067	37%	11%	31%	18%

Table 1. Percentage of Aquatic Vegetation Along Coastal Shorelines in Washington State (By county). Source: Department of Natural Resources.



Figure 3-64. Screenshot from ShoreZone layer as visualized on the Floating Kelp Indicator map, colored by floating kelp presence (dark brown=continuous, yellow=patchy, grey=absent).

3.3.2.10 KelpWatch (Landsat satellite data)

KelpWatch provides quarterly floating kelp canopy area maps, using 30-m resolution Landsat satellite data (Figure 3-65; Figure 3-66; Figure 3-67). Data spans from 1984 to present. Maximum floating kelp canopy occurs in Washington State during either Q3 or Q4 each year.

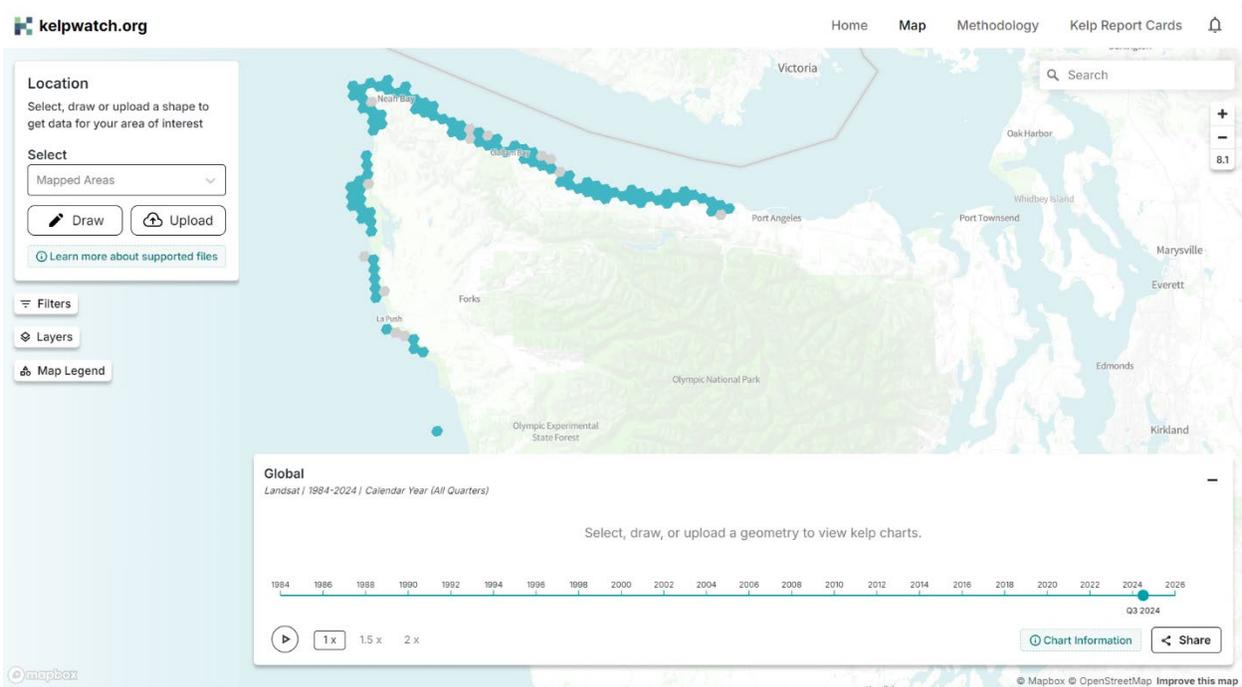


Figure 3-65. Screen capture of kelpwatch.org during Q3 of 2024, showing all areas of Washington State currently included in this product.

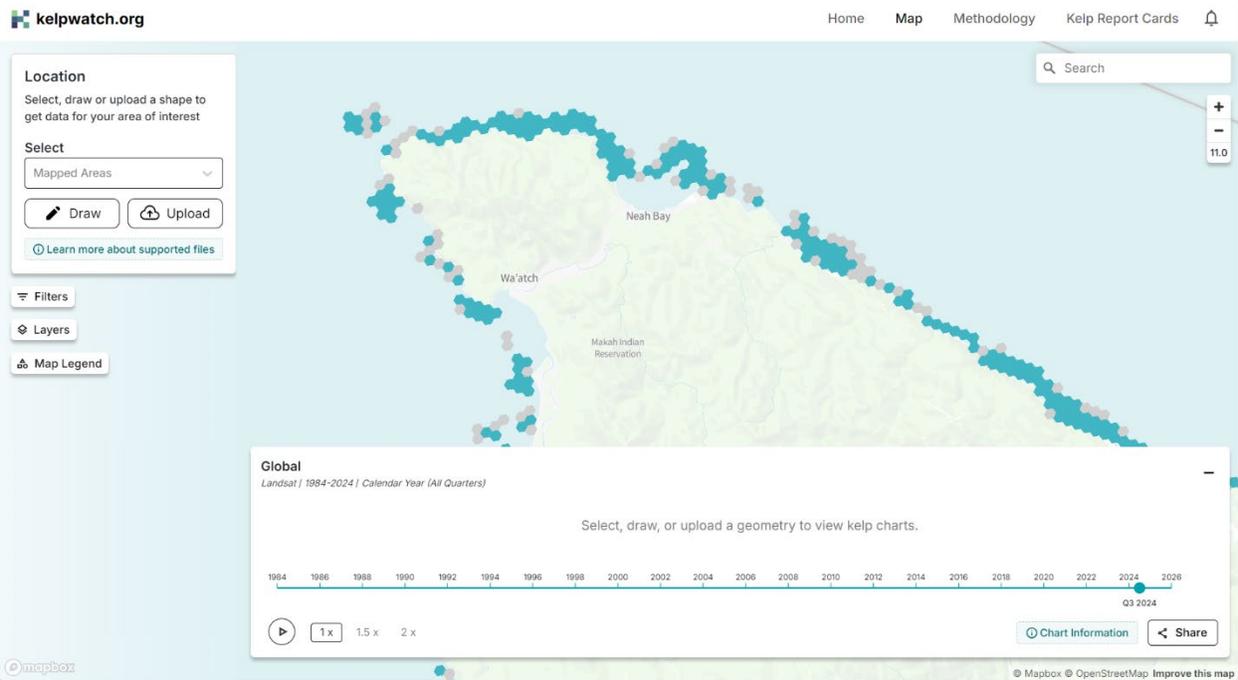


Figure 3-66. Screen capture of kelpwatch.org during Q3 of 2024, showing the Cape Flattery/Neah Bay area of Washington State.

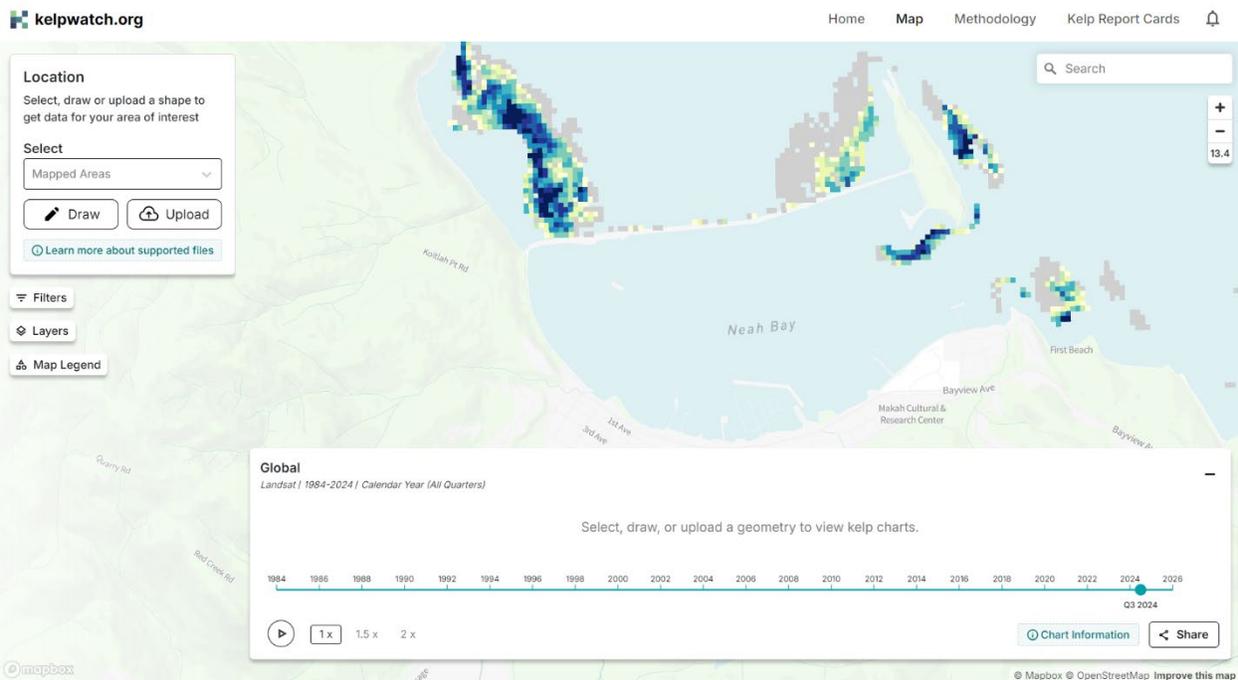


Figure 3-67. Screen capture of kelpwatch.org during Q3 of 2024 showing a close-up of Neah Bay, Washington. Each pixel is 30x30 m.

3.3.2.11 WA DNR SPS and CPS linear extent surveys

Linear extent surveys were conducted by WA DNR in 2017 for the South Puget Sound (SPS). This survey found that bull kelp beds occurred along 2% of the SPS shoreline, with a vast majority of shorelines with bull kelp located along the Tacoma Narrows and its approaches at Day Island and Fox Island (Berry et al. 2019) (Figure 3-68).

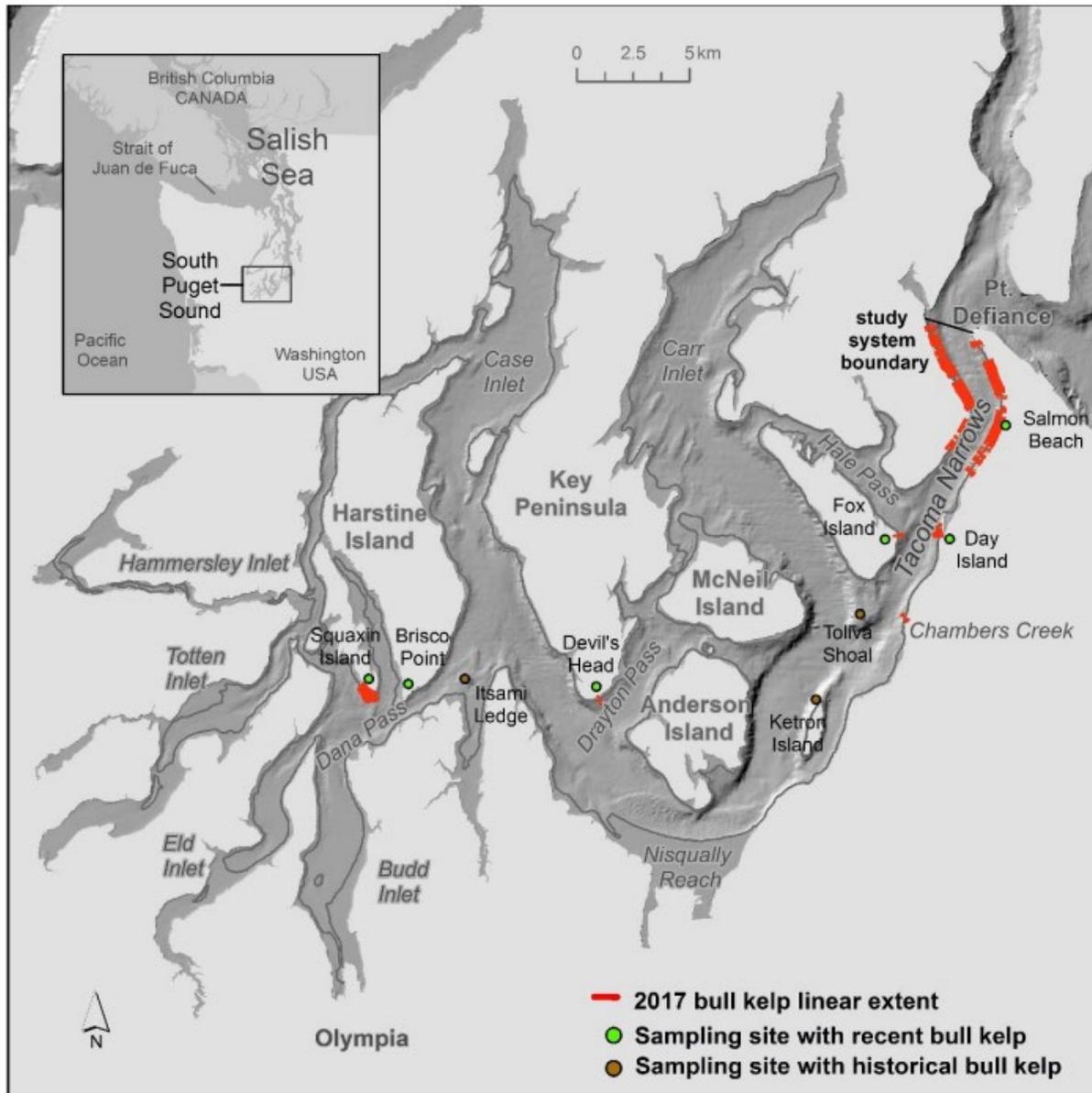


Figure 3-68. Linear extent of bull kelp in 2017, visualized along the -6 m bathymetry line (MLLW). Red lines denote presence (buffered to be visible at map scale), grey lines denote absence. Shorelines north of the study system boundary were not surveyed. Figure and caption from Berry et al. 2019.

Similar linear extent surveys were also conducted in Central Puget Sound in 2019. The report summarizing the Central Puget Sound dataset is currently in progress.

3.3.2.12 Historical CPS and SPS data

An analysis of historical data sources in South Puget Sound found a loss of 63% of bull kelp (*Nereocystis*) extent between 1878 and 2017 (Berry et al. 2021 PLoS One) (Figure 3-69).

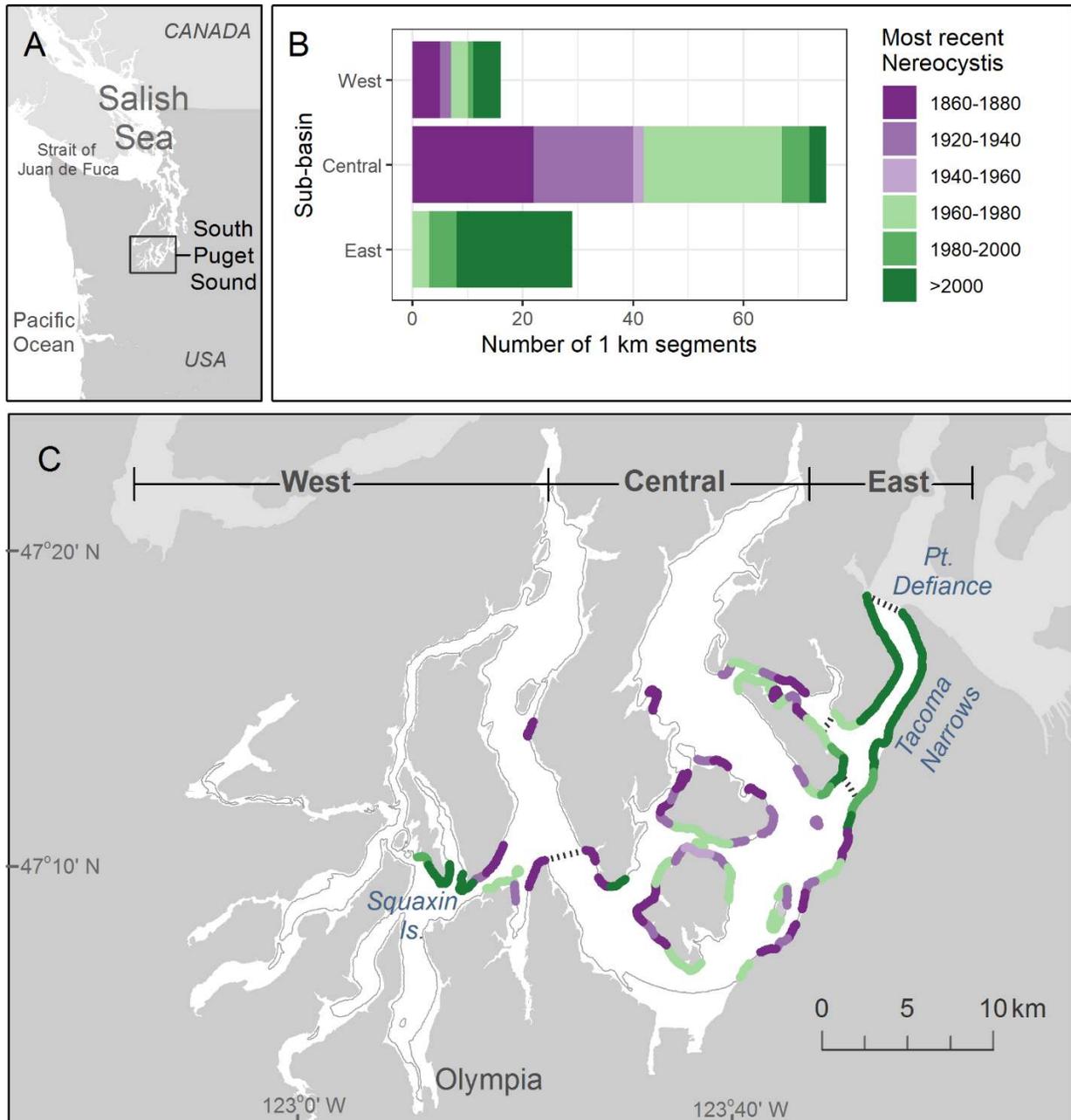


Figure 3-69. Most recent observation of *Nereocystis* presence along shorelines in South Puget Sound (SPS) between 1873 and 2018. (A) The location of SPS, the southern terminus of the Salish Sea. (B) Bar charts show the most recent year *Nereocystis* was present in 1-km segments within each sub-basin. Years were binned into 20-year increments, with two bins excluded due to lack of data. (C) The -6.1 m bathymetric contour line denotes all shorelines where *Nereocystis* occurrence was assessed, classified by the most recent observation of presence (same legend as in B). The gray line denotes absence throughout the time period. The general location of three sub-basins (West, Central and East) is defined at the top of the map, and dotted gray lines on the map identify precise boundaries. Map image based on

publicly available data from the Washington State Department of Natural Resources. Figure and caption from Berry et al. 2021.

Multiple time periods were included in this study, based on available maps and data. This allowed for a comparison of proportion of SPS shoreline with *Nereocystis* before 1980 and after 1980 (Figure 3-70). This comparison shows substantial losses in both the West and Central sub-basins of SPS, where there was a median of 25-50% of shorelines with *Nereocystis* present before 1980 compared to nearly 0% of shorelines with *Nereocystis* present after 1980.

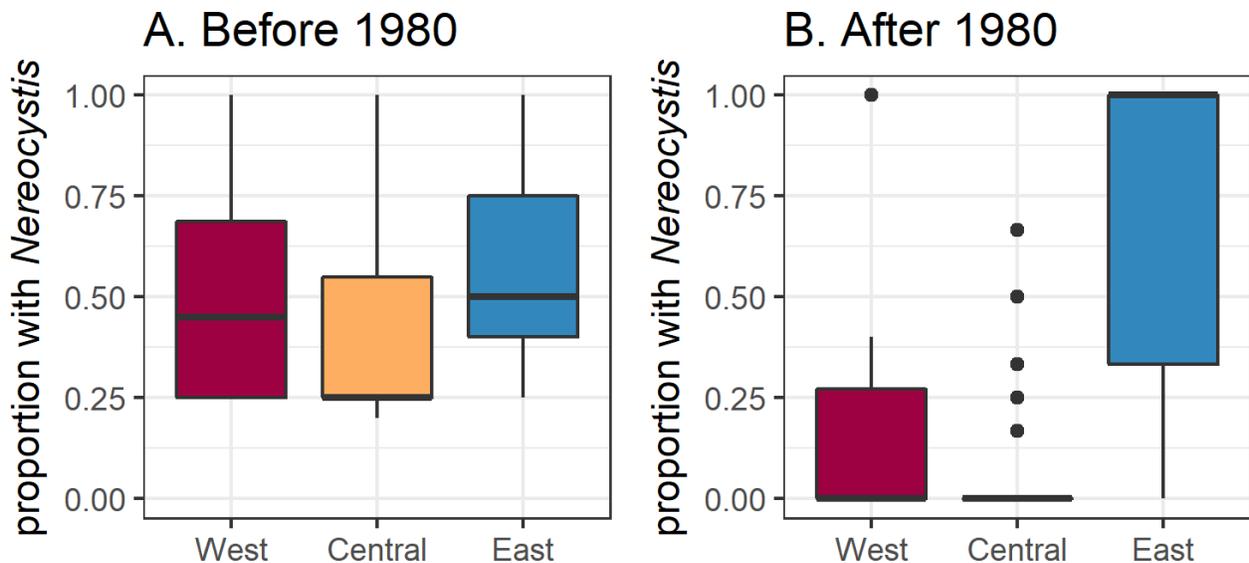


Figure 3-70. Distribution of *Nereocystis* persistence at 1-km segments (A) before 1980 and (B) after 1980. Persistence was calculated as the proportion of all observations in each segment with *Nereocystis* present within each time period. All 1-km segments where *Nereocystis* occurred at least once in either time period were included ($n = 120$). Figure and caption from Berry et al. 2021.

The long time span of this data set also allowed for comparisons of most recent bull kelp observation (decade) and oceanographic characteristics such as waves and currents (Figure 3-71).

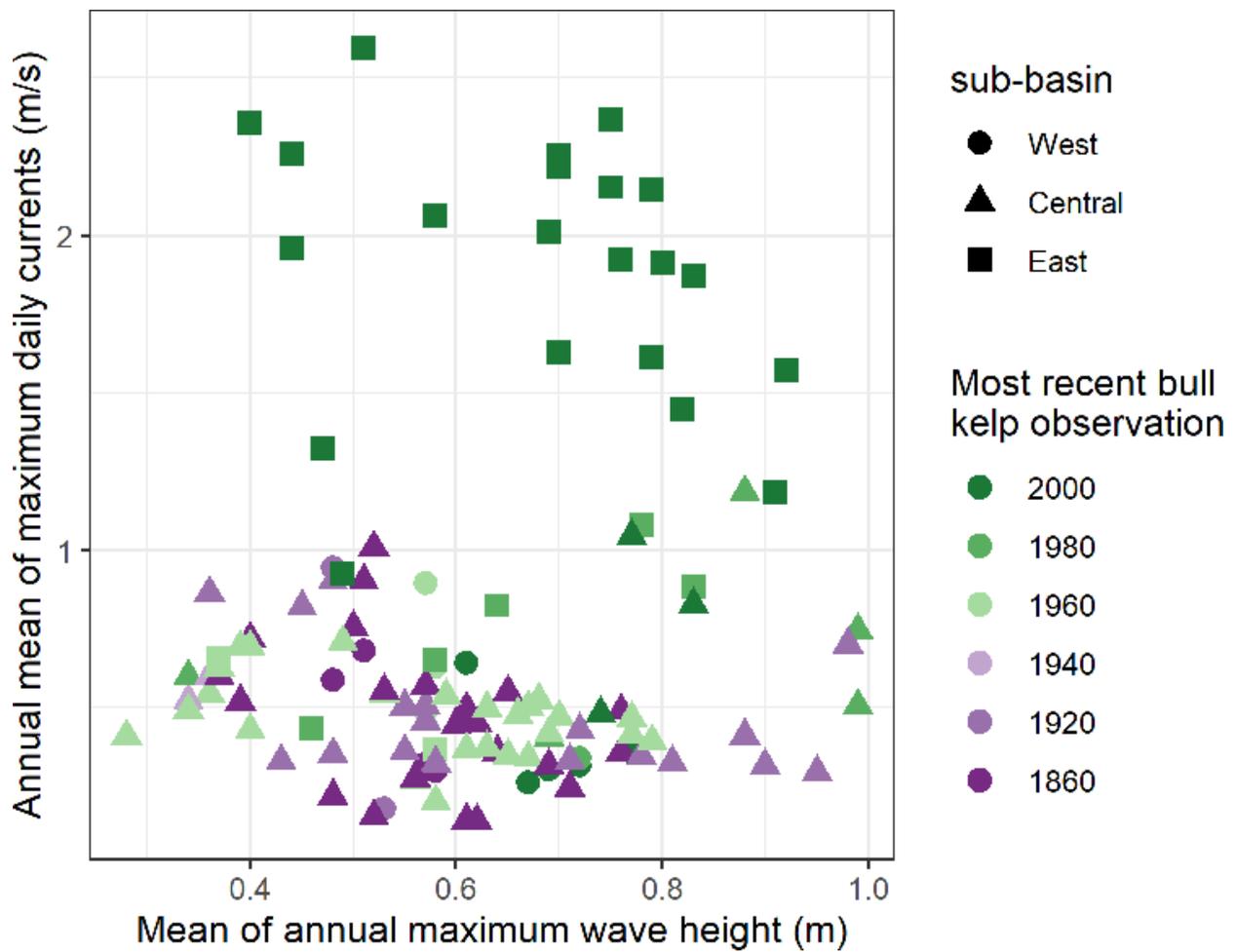


Figure 3-71. Current and wave exposure at 1-km segments with *Nereocystis*. The annual mean of maximum daily current velocity (y-axis) was derived from a 2014 model run of the Salish Sea Model [Youngmann 1978; Ensemble Oceanic Nino Index 2019]. Average annual maximum wave height (x-axis) was modeled between 1950 to 2010 by the Washington Coastal Resilience Project [Bos et al 2015]. 1-km kelp segments are coded by sub-basin and the most recent year that *Nereocystis* was observed ($n = 120$). Figure and caption from Berry et al. 2021.

3.3.3 Data Access

For more information or to access these datasets, see the following links, reports, and webmaps.

3.3.3.1 WA DNR COSTR/AQRES

Example technical report:

Van Wageningen, R.F. (2015). *Washington Coastal Kelp Resources: Port Townsend to the Columbia River. Summer 2014*. Nearshore Habitat Program, Washington State Department of Natural Resources.

https://www.dnr.wa.gov/publications/aqr_nrsh_vanwagenen_2015_kelp_tables.pdf

Web App including data from 1989-2021:

<https://wadnr.maps.arcgis.com/apps/webappviewer3d/index.html?id=bf65099e13d14dbfa386bf54790eea01>

Data download:

COSTR

https://fortress.wa.gov/dnr/adminsa/gisdata/datadownload/kelp_canopy_strait_coast.zip

AQRES

https://fortress.wa.gov/dnr/adminsa/gisdata/datadownload/kelp_canopy_aquatic_reserves.zip

Nearshore Habitat Program. (2022). WA DNR COSTR/AQRES Aerial Imagery (v2021.0) [Data set]. Washington Department of Natural Resources.

<https://doi.org/10.5281/zenodo.11068629>

Data layers:

<https://experience.arcgis.com/experience/028ded90c96c46eab38ecf72bd8ec847/>

Scroll down to Web Services, then Floating Kelp Monitoring

Manuscript:

Claar, D. C., Berry, H., & Christiaen, B. (2025). Geographic variability of floating kelp recovery after a marine heatwave event in the Salish Sea and adjacent open coast. *PLoS one*, 20(12), e0336574.

3.3.3.2 Kelp Aerial Monitoring (KAM): High-resolution aerial imagery

Technical reports:

NV5 Corvallis, (2023). Kelp and Seagrass 4-band Orthophotography. Technical Report, 22 pg. Prepared for WA State Department of Natural Resources, Nearshore Habitat Program. https://www.dnr.wa.gov/publications/aqr_acquisition_report.pdf

NV5 Corvallis (2022) Kelp and Seagrass 4-band Orthophotography. Technical Report, 24 pg. Prepared for WA Department of Natural Resources, Nearshore

Habitat Program.

https://www.dnr.wa.gov/publications/aqr_nrsh_2022_nv5_kelp_ortho_acquisition_report.pdf

StoryMap with interactive map and data links:

<https://storymaps.arcgis.com/stories/b501ab57cc5749f8861202b7ad22a681>

Image Service URLs:

2022

https://gis.dnr.wa.gov/image/rest/services/Aquatics/Nearshore_img_OpenCoast_2022/ImageServer
https://gis.dnr.wa.gov/image/rest/services/Aquatics/Nearshore_img_StraitJdF_2022/ImageServer
https://gis.dnr.wa.gov/image/rest/services/Aquatics/Nearshore_img_SanJuanIs_2022/ImageServer
https://gis.dnr.wa.gov/image/rest/services/Aquatics/Nearshore_img_AquaticRes_2022/ImageServer
https://gis.dnr.wa.gov/image/rest/services/Aquatics/Nearshore_img_NPugetSound_2022/ImageServer
https://gis.dnr.wa.gov/image/rest/services/Aquatics/Nearshore_img_Saratoga_2022/ImageServer
https://gis.dnr.wa.gov/image/rest/services/Aquatics/Nearshore_img_AdmiraltyIn_2022/ImageServer
https://gis.dnr.wa.gov/image/rest/services/Aquatics/Nearshore_img_Tacoma_2022/ImageServer
https://gis.dnr.wa.gov/image/rest/services/Aquatics/Nearshore_img_SquaxinIs_2022/ImageServer

2023

https://gis.dnr.wa.gov/image/rest/services/Aquatics/Nearshore_img_AquaticRes_2023/ImageServer
https://gis.dnr.wa.gov/image/rest/services/Aquatics/Nearshore_img_NPugetSound_2023/ImageServer
https://gis.dnr.wa.gov/image/rest/services/Aquatics/Nearshore_img_SanJuanIs_2023/ImageServer
https://gis.dnr.wa.gov/image/rest/services/Aquatics/Nearshore_img_Saratoga_2023/ImageServer
https://gis.dnr.wa.gov/image/rest/services/Aquatics/Nearshore_img_EastStraitJdF_2023/ImageServer
https://gis.dnr.wa.gov/image/rest/services/Aquatics/Nearshore_img_WestStraitJdF_2023/ImageServer
https://gis.dnr.wa.gov/image/rest/services/Aquatics/Nearshore_img_Tacoma_2023/ImageServer

2024

https://gis.dnr.wa.gov/image/rest/services/Aquatics/Nearshore_img_AdmiraltyIn_2024/ImageServer
https://gis.dnr.wa.gov/image/rest/services/Aquatics/Nearshore_img_AquaticRes_2024/ImageServer
https://gis.dnr.wa.gov/image/rest/services/Aquatics/Nearshore_img_NPugetSound_2024/ImageServer
https://gis.dnr.wa.gov/image/rest/services/Aquatics/Nearshore_img_NorthCoast_2024/ImageServer
https://gis.dnr.wa.gov/image/rest/services/Aquatics/Nearshore_img_SanJuanIs_2024/ImageServer
https://gis.dnr.wa.gov/image/rest/services/Aquatics/Nearshore_img_Saratoga_2024/ImageServer
https://gis.dnr.wa.gov/image/rest/services/Aquatics/Nearshore_img_EastStraitJdF_2024/ImageServer
https://gis.dnr.wa.gov/image/rest/services/Aquatics/Nearshore_img_WestStraitJdF_2024/ImageServer
https://gis.dnr.wa.gov/image/rest/services/Aquatics/Nearshore_img_Tacoma_2024/ImageServer

3.3.3.3 Samish Aerial data

Samish Indian Nation kelp Story Map:

[Palmer-McGee 2021](#)

Samish Indian Nation Department of Natural Resources website:

<https://www.samishtribe.nsn.us/departments/environment>

Image Service & StoryMap:

The 2022 2023 and 2024 aerial imagery was generated by WA DNR in partnership with NV5 Geospatial, and can be accessed at these ArcGIS Online Image Service links:

[2022](#), [2023](#), [2024](#).

Imagery can also be viewed on this StoryMap: [Claar 2024](#)

3.3.3.4 Linear extent from 1984 imagery in Central Puget Sound

Report:

McKenna, G., Berry, H., Claar, D., Cowdrey, T. 2025. Mapping floating kelp presence along Seattle shorelines in 1984 using historical aerial imagery. Nearshore Habitat Program, Washington State Department of Natural Resources.

https://dnr.wa.gov/sites/default/files/2025-05/aqr_nrsh_mckenna_2025.pdf

StoryMap:

<https://storymaps.arcgis.com/stories/c13a62f9930a4f2481e3ba1fb620f8e0>

3.3.3.5 MRC Kayak surveys

ArcGIS Online feature service:

<https://www.arcgis.com/home/item.html?id=762bb0b250a64b519d67f0f6b123dba6>

Sound IQ website:

<https://www.nwstraits.org/our-work/soundiq/>

<https://maps.cob.org/geviewer/Html5Viewer/Index.html?viewer=SoundIQ>

Contacts:

NWSC GIS Specialist: Suzanne Shull, sshull@padillabay.gov

NWSC GIS Specialist: Leah Skar, Skare@nwstraits.org

NWSC Kelp Program Manager: Jeff Whitty, whitty@nwstraits.org

Marine Program Manager: Dana Oster, oster@nwstraits.org

Datasets are available through the NWSC and individual MRCs:

- [NWSC Kelp Monitoring](#)
- [Clallam County](#)
- [Island County](#)
- [Jefferson County](#)
- [San Juan County](#)
- [Skagit County](#)
- [Snohomish County](#)
- [Whatcom County](#)

MRC kayak protocol document:

<https://www.nwstraits.org/media/3380/mrc-kelpkayaksurveyprotocol-2023update.pdf>

3.3.3.6 WA DNR Kayak surveys

Report: Long-term kayak monitoring of floating kelp in Puget Sound: Results through 2024: https://dnr.wa.gov/sites/default/files/2025-07/aqr_ledbetter_2025.pdf

Report: Long-term kayak monitoring of floating kelp in Puget Sound (through 2023): https://www.dnr.wa.gov/publications/aqr_ledbetter_berry24.pdf

2019 StoryMap:

<https://storymaps.arcgis.com/stories/96fc7e27353c4cc3872a0610881331dd>

Monitoring report (2017 & 2018):

https://www.dnr.wa.gov/publications/aqr_nrsh_bullkelp_sps_2019.pdf

Monitoring report (2013, 2014, & 2016):

https://www.dnr.wa.gov/publications/aqr_nrsh_squaxin_bullkelp_1217.pdf

3.3.3.7 WA DNR UAS monitoring surveys

Report: Monitoring Puget Sound Bull Kelp Forests with Multispectral UAS (2024)
https://www.dnr.wa.gov/publications/aqr_nrsh_monitoring_bull_kelp_multispectral_uas.pdf

StoryMap: Mapping bull kelp forest canopies with aerial imagery

<https://storymaps.arcgis.com/stories/9daebbe14134440290e87bb77d2feb75>

Report: Kelp Forest Canopy Surveys with Unmanned Aerial Vehicles (UAVs) and Fixed-Wing Aircraft (2021)

https://www.dnr.wa.gov/publications/aqr_nrsh_kelp_canopy_survey_report.pdf

3.3.3.8 WA DNR/Suquamish UAS surveys

Final Report in progress at the time of this publication.

3.3.3.9 ShoreZone survey

Nearshore Habitat Inventory landing page:

<https://www.dnr.wa.gov/programs-and-services/aquatics/aquatic-science/nearshore-habitat-inventory>

Report: Washington State ShoreZone Inventory: Summary of Key Findings

https://www.dnr.wa.gov/publications/aqr_nrsh_shrzne_sum_find.pdf

ShoreZone Inventory Users Manual

https://www.dnr.wa.gov/publications/aqr_nrsh_szusermanual.pdf

ShoreZone Inventory Data Dictionary

https://www.dnr.wa.gov/publications/aqr_nrsh_szdatadict.pdf

Shoreline Biology from ShoreZone in the Washington Coastal Atlas Interactive Map

<https://www.dnr.wa.gov/programs-and-services/aquatics/aquatic-science/washington-marine-vegetation-atlas>

3.3.3.10 KelpWatch (Landsat satellite data)

KelpWatch landing page:

<https://kelpwatch.org/>

Data download:

<https://doi.org/10.6073/pasta/a9071a2ce1b78242c2ad1dda5854ec78>

Manuscripts:

Bell, T. W., Cavanaugh, K. C., Saccomanno, V. R., Cavanaugh, K. C., Houskeeper, H. F., Eddy, N., ... & Gleason, M. (2023). KelpWatch: A new visualization and analysis tool to explore kelp canopy dynamics reveals variable response to and recovery from marine heatwaves. *Plos one*, 18(3), e0271477.

<https://doi.org/10.1371/journal.pone.0271477>

Bell, T.W., Allen, J.G., Cavanaugh, K.C., & Siegel, D.A. (2020). Three decades of variability in California's giant kelp forests from the Landsat satellites. *Remote Sensing of Environment*, 238, 110811. <https://doi.org/10.1016/j.rse.2018.06.039>

Houskeeper, H.F., Rosenthal, I.S., Cavanaugh, Ka.C., Pawlak, C., Trouille, L., Byrnes, J.E.K., Bell, T.W., and Cavanaugh, Ky.C. (2022). Automated satellite remote sensing of giant kelp at the Falkland Islands (Islas Malvinas). *PLoS ONE*, 17(1): e0257933.

<https://doi.org/10.1371/journal.pone.0257933>

Hamilton, S.L., Bell, T.W., Watson, J.R., Grorud-Colvert, K.A., & Menge, B.A. (2020). Remote sensing: generation of long-term kelp bed data sets for evaluation of impacts of climatic variation. *Ecology*, e03031. <https://doi.org/10.1002/ecy.3031>

3.3.3.11 WA DNR CPS and SPS linear extent surveys

Report: SPS Bull Kelp Surveys

https://www.dnr.wa.gov/publications/aqr_nrsh_bullkelp_sps_2019.pdf

Conference Presentation: CPS Bull Kelp Surveys

<https://cedar.wvu.edu/sssec/2020sssec/allsessions/51/>

South Puget Sound Manuscript:

Berry HD, Mumford TF, Christiaen B, Dowty P, Calloway M, Ferrier L, Frossman EE, VanArendonk NR (2021) Long-term changes in kelp forests in an inner basin of the Salish Sea. PLoS ONE 16(2): e0229703.

<https://doi.org/10.1371/journal.pone.0229703>

3.3.3.12 Historical CPS and SPS data

South Puget Sound Manuscript:

Berry HD, Mumford TF, Christiaen B, Dowty P, Calloway M, Ferrier L, Frossman EE, VanArendonk NR (2021) Long-term changes in kelp forests in an inner basin of the Salish Sea. PLoS ONE 16(2): e0229703.

<https://doi.org/10.1371/journal.pone.0229703>

3.4 Discussion

3.4.1 Existing floating kelp data

This report is a compilation of available existing floating kelp canopy distribution and abundance in Washington State. These datasets span a range of collection methods, spatial resolutions, and collection dates, providing a peak into past kelp canopy distribution and how kelp canopies have changed over time.

A difficulty with integrating floating kelp distribution and abundance data at a State-wide scale is that there is no one method that is appropriate to use under every circumstance. Three main considerations should inform methodological choices for kelp canopy monitoring: 1) resolution: is the method likely to accurately detect floating kelp? 2) survey area: is the method feasible across the planned survey area? 3) cost and capacity: is funding available and/or is there staff/volunteer capacity for planning, data collection, processing, and analysis? For example, high-resolution fixed wing imagery can (1) accurately detect floating kelp at the surface across much of Washington, (2) rapidly survey large areas of the State, but (3) tend to be relatively expensive and/or time consuming to process. Alternatively, kayak surveys (1) can accurately detect floating kelp, including submerged individuals, (2) are limited in spatial scope due to tide windows and the amount of time it takes to conduct the surveys, (3) are relatively low-cost compared to some other methods. All of these methods come with tradeoffs, so careful consideration is needed to choose the correct combination of survey methods to most accurately and efficiently map floating kelp at the desired location and scale. Additionally, the presence of these tradeoffs supports a multi-tiered approach for monitoring, that includes both large-scale survey methods as well as local survey methods. By integrating multiple methods, it is possible to build a more complete picture of floating kelp abundance, distribution, and changes over time.

Despite the amount of data that is currently available for kelp canopies, large data gaps remain. These gaps are present both spatially and temporally; of the nine Indicator sub-basins that have floating kelp, approximately half of them have insufficient data for status classification (Figure 3-1). For most of these sub-basins, datasets are available for only a limited subset of sites within a large spatial area, and dataset lengths tend to be relatively short (<5-10 years). The San Juan Islands is an exception since the Samish DNR aerial data spans multiple years between 2004 and the present (longer data record) for all nearshore habitat in the sub-basin. These data are limited by some inconsistencies in survey methodology across years but are bolstered by an Indigenous Scientific Knowledge map that shows previous distributions of kelp canopies in the San Juans. Since Indicator data and assessments are used by managers, researchers, and organizations to identify areas of floating kelp resilience, loss, and change, any data gaps that can be filled represent immediate improvements for science and management.

Given the currently available data, the Indicator identifies Central and South Puget Sound as areas of substantial documented declines. These declines have been documented at a century scale (Berry et al. 2021) across both sub-basins, as well as precipitous declines at some sites over the past decade. As kelp beds shrink and often vanish in these sub-basins, valuable habitat and services are lost from the corresponding nearshore ecosystems. For example, *Nereocystis* forests in the Northeast Pacific (California to Alaska) are estimated to have an economic value of \$142,000 per hectare of kelp forest area per year (Eger et al. 2023). This valuation only included carbon storage, nutrient removal, and fisheries services, so is likely an underestimate of the total economic value provided by *Nereocystis* forests. *Nereocystis* forests also improve the quality of seagrass nursery habitat for young-of-the-year rockfish, providing higher-quality prey and increased recruitment (Olsen et al. 2019). Furthermore, *Nereocystis* forests also have higher abundances of zooplankton, juvenile salmonids, and forage fishes than nearby open water (Schaffer et al. 2020). For these, and many other reasons, substantial kelp declines at a sub-basin scale represent risk and damage to nearshore ecosystems.

Conversely, kelp forests on the open coast of Washington and the Strait of Juan de Fuca have generally been resilient over the past decades to century (Pfister et al. 2018). There are a few exceptions, including near the mouth of the Elwha River which had substantial sediment fluxes following dam removal in 2011-2014 (Rubin et al. 2023), and in the eastern portion of the Eastern Strait of Juan de Fuca. The remainder of the locations (i.e., 5-10 km of coastline each) in these sub-basins are either stable or slightly increasing, although changes are occurring on finer spatial scales (e.g., Clallam Bay MRC site). Despite the general stability of this region, continued monitoring is important to identify new losses and to implement protection, conservations, and restoration efforts as needed.

3.4.2 Current Vital Sign integration and Future Development

Currently, multiple different types of data have been integrated into the Floating Kelp Vital Sign Indicator, either analyzed as part of quantitative trends (at the site/location scale) woven together with other data sources to inform status assessment (at the sub-basin scale). For inclusion in quantitative trend analysis, a dataset must 1) be collected with consistent methods over time, 2) report floating kelp bed area, and 3) include at least 5 survey years.

Datasets used for quantitative trends:

- WA DNR COSTR/AQRES aerial imagery
- Samish DNR aerial imagery
- MRC kayak surveys
- WA DNR kayak surveys

Datasets used for qualitative status assessment:

- All quantitative datasets
- Kelp Aerial Monitoring high-resolution aerial imagery

- Linear extent from 1984 imagery in Central Puget Sound
- WA DNR UAS monitoring surveys
- WA DNR/Suquamish UAS surveys
- ShoreZone survey
- KelpWatch
- WA DNR SPS and CPS linear extent surveys
- Historical CPS and SPS data

Some datasets included in qualitative status assessment may be used for quantitative assessment in the future, depending on data structure, project support, and dataset length. Additionally, while other valuable quantitative datasets of floating kelp exist (e.g., Reef Check surveys), these datasets measure different parameters (e.g., density) which are not currently directly comparable to kelp bed area (i.e., the quantitative measure used in the Indicator).

The WA Floating Kelp Bed Area Vital Sign Indicator will be updated annually, dependent on continued funding and support. Extensive collaborative effort has been put into interpreting and weaving together these multiple data sources and ways of knowing. These efforts are ongoing and are anticipated to continue over the long term. The continuous addition of new data by multiple project partners will allow for continued Indicator improvement with each update.

3.4.3 Conclusions and Next Steps

3.4.3.1 Floating kelp indicator improvement

Floating kelp distribution and abundance varies across the State, and we are only just beginning to be able to assess status and trends in many locations. With the available information, the Indicator has highlighted many areas with substantial data gaps. Filling these knowledge gaps is a top priority to support monitoring, protection, and conservation of Washington’s floating kelp forests. These data gaps can be addressed in two ways: 1) by continuing and expanding existing monitoring programs, and 2) by finding and incorporating already-existing knowledge and data. Already existing information may come in the form of Indigenous Scientific Knowledge, historical maps and imagery, or other data sources that have not yet been accessed or synthesized. In order to find, analyze, and incorporate additional data and knowledge sources, additional funding support will be needed.

3.4.3.2 Research questions arising

As we learn more about spatial patterns in floating kelp abundance and persistence, more questions arise regarding why any particular area is doing better or worse than any other area. Research has identified stressors to floating kelps (e.g., Hollarsmith et al. 2022, Raymond et al. in prep and citations within), but the nearshore environment in the greater Puget Sound area is both spatially and temporally variable, making it difficult to identify which stressor(s) within the constellation of drivers and stressors are affecting kelp abundance and persistence. This is further compounded by the fact that there is fairly

limited in situ data for environmental conditions in and around canopy kelp beds, so the exact conditions that the kelps experience is often unknown. Finally, kelp abundance and persistence are likely linked to health and condition. Unfortunately, limited data are available to describe spatial patterns of canopy kelp morphometrics and condition in the greater Puget Sound area, making it difficult to link environmental conditions and stressors to kelp health, condition, and abundance at a statewide scale.

The HSIL-supported project that funded this report represents an attempt to bridge these knowledge gaps between environmental conditions and canopy kelp health and persistence. The forthcoming data report will represent intensive field sampling and laboratory analyses, with the goal to improve our understanding of questions such as: *Why are canopy kelps thriving in some locations? Why have kelp canopies been lost in some locations? Are canopy kelps healthier in some areas compared to others? What environmental conditions are canopy kelps exposed to throughout the year? Which stressor(s) may be responsible for patterns of resilience and loss?* These questions (and many more) are fundamentally important to our understanding of canopy kelp loss and resilience, and will provide critical data for management, restoration planning, and stressor mitigation efforts into the future.

3.4.3.3 Development of an understory kelp indicator

We acknowledge that, while the WA Floating Kelp Vital Sign Indicator provides a statewide view of kelp canopy species (*Macrocystis pyrifera* and *Nereocystis luetkeana*), it is, by nature, not representative of all kelp in Washington. Washington State is home to 22 species of kelp (including *Macrocystis* and *Nereocystis*) and many other species of marine algae that comprise a broad range of life histories, environmental responses, and ecosystem functions. Momentum is building for the development of an Understory Kelp Indicator, but the process has been hindered by the difficulty of obtaining sufficient data. Monitoring floating kelp lends itself to multiple survey methods: from the surface (kayaks and boats) and from the air (UAS/drones, fixed-wing aircraft, satellites). Conversely, monitoring understory kelp must be conducted underwater, where large-scale surveys are difficult, and species differentiation can sometimes be nearly impossible. However, collection and data processing methods are improving rapidly, opening the possibility of an Understory Kelp Indicator in the near future. More research and method development are needed to realize this potential, and we identify assessment and monitoring of understory kelp as an important next step in building our understanding of kelp forest status and trends in Washington and beyond.

3.4.3.4 Monitoring for management

The Indicator demonstrates the value of monitoring data, and provides direct links to targeted research and management planning, including restoration, protection, mitigation planning:

- In order to identify areas for restoration, it is helpful to know where canopy kelp has existed in the past. If a kelp bed was knocked out by an extreme event, it may follow that there is a higher likelihood of restoration success in that area. This assumption does, however require an understanding of what caused the loss in the first place, and whether that stressor is still present or if it has been alleviated so kelp may again grow in that location.
- In order to identify areas for protection, kelp mapping and monitoring can provide valuable insights: 1) Identify beds with a high chance of protection success, by mapping where kelp has been persistent over time; a kelp bed that is present in an area year after year is more likely to experience conditions conducive to continued persistence over time. 2) Identify beds that are important for canopy kelp connectivity and population stability; an area with persistent canopy kelp may be a seed bank for nearby, more ephemeral beds. 3) Identify priority habitat for protection; knowledge of the location of not only large beds, but also smaller, fringing beds, can be vitally important to identifying habitat and connectivity corridors for other species such as salmonids and forage fish. A kelp bed may look small, but it may provide the only hospitable habitat for some species along their migratory route. It is important not to underestimate these connective, fringing habitats.
- In order to identify areas for stressor mitigation, it is helpful to understand the timeline of previous kelp loss. If the timing of losses can be identified as coincident with purported stressor(s), this information can be used to link the stressor and the loss. If the stressor is known, it is then possible to prioritize areas where it is feasible to mitigate the instigating stressor for that particular location. This could increase the chance of mitigation success, by ensuring that the mitigation effort is consistent with the expected driver of loss.

To realize these benefits, ongoing funding and support for kelp canopy monitoring and assessment is required. Securing investment in monitoring is sometimes difficult, but the returns on investment can be enormous: accurate understanding of kelp distribution and persistence can improve effectiveness of management measures and kelp forest conservation over the long term.

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3.6 Supplementary Material

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