NATURAL RESOURCES

Mapping floating kelp presence along Seattle shorelines in 1984 using historical aerial imagery

March 2025

WASHINGTON STATE DEPT OF NATURAL RESOURCES

The Nearshore Habitat Program is part of the Washington State Department of Natural Resources and supports the agency's mandate to ensure environmental protection of state-owned aquatic lands.
https://www.dnr.wa.gov/programs-and-services/aquatics/aquatic-science/nearshore-habitat-program

The Nearshore Habitat Program is also a component of the Puget Sound Ecosystem Monitoring Program (PSEMP). https://www.psp.wa.gov/PSEMP-overview.php

Cover photo: Scanned aerial photograph slide of Magnolia kelp bed captured September 7, 1984, by Ron Thom (University of Washington).

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The Nearshore Habitat Program is part of the Aquatic Resources Division within the Washington State Department of Natural Resources (DNR), the steward for state-owned aquatic lands. The Nearshore Habitat Program monitors and evaluates the status and trends of marine vegetation for DNR, in association with the Puget Sound Partnership as a component of the Puget Sound Ecosystem Monitoring Program (PSEMP).

The Nearshore Habitat Program is grateful to the WA State Legislature for providing funding for DNR to map current and historical floating kelp distributions throughout the state using archival imagery to fill critical knowledge gaps.

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EXECUTIVE SUMMARY

Floating kelp forests are declining in some parts of Washington State. In response, multiple large-scale collaborative initiatives to improve the understanding and protection of these critical habitats have begun. These include the Puget Sound Kelp Conservation and Recovery Plan, the Puget Sound Partnership Floating Kelp Vital Sign Indicator, the statewide Kelp Forest and Eelgrass Meadow Health and Conservation Plan, and the Habitat Strategic Initiative Lead Marine Vegetation Implementation Strategy. The Washington State Department of Natural Resources (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.

Despite the many efforts that DNR and collaborators have initiated to monitor and protect floating kelp, large knowledge gaps remain about kelp persistence and loss across the State. To inform effective conservation and recovery, historical analysis is a useful tool to fill these gaps and identify the timing and location of kelp losses so that causes of decline can be investigated.

This report summarizes an analysis of floating kelp distribution along the Seattle shoreline based on historical aerial imagery collected by Ron Thom in 1984. The results of that analysis are compared to a boat-based linear extent survey of kelp presence in Central Puget Sound in 2019 to evaluate change between these two points in time. Since this study documents a decline in floating kelp associated with the placement of a marina, this work is also informative to DNR's Habitat Stewardship Measures applied to aquatic leases.

KEY FINDINGS

- Analysis of historical aerial imagery found previously undocumented declines in floating kelp in Seattle shoreline areas between 1984 and 2019.
    - A wide bull kelp forest along Magnolia Bluff in Seattle contracted to one fifth of its historical linear extent, primarily in the area where Elliott Bay Marina was constructed in 1989.
    - Total loss of floating kelp presence occurred along the southern shoreline of Lincoln Park and along the West Seattle shoreline between Alki Point and Point Wilson.
- Historical imagery is a valuable resource for filling critical data gaps in floating kelp distribution, even when metadata is lacking, or image quality has degraded. Furthermore, historical imagery can be integrated with other survey methodologies to assess loss and persistence of floating kelp beds over time.
- The results of this study will be integral to a wider analysis of kelp canopy change over time in Central Puget Sound, a sub-basin where the WA Floating Kelp Bed Area Vital Sign Indicator classifies floating kelps as declining but where more data are needed.

1 Introduction

Floating kelp forests are a critical nearshore habitat in Washington waters. They support 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, Chittaro et al. 2023). In Puget Sound, the primary canopy-forming floating kelp species is bull kelp (*Nereocystis luetkeana*). Historical analysis of floating kelp distribution has documented substantial declines in South Puget Sound (Berry et al. 2021), and losses have been observed in other locations around the State. Additional historical analyses are needed to fully understand where and when kelp losses have occurred to inform effective kelp conservation and recovery.

The Washington Department of Natural Resources (DNR) and collaborators monitor floating kelp beds throughout the state using a variety of methods, including fixed-wing aerial imagery, uncrewed aircraft systems (UAS) imagery, and boat- and kayak-based surveys. These monitoring programs inform the Washington State Floating Kelp Vital Sign Indicator (Berry et al. 2023) – one of many metrics developed to track outcomes of the Puget Sound Action Agenda (Puget Sound Partnership 2022). The Vital Sign Indicator has identified substantial declines in floating kelp in some sub-basins of Puget Sound and concern for decline in others (Figure 1) and has also revealed many spatial and temporal data gaps that limit our understanding of floating kelp losses and persistence. Filling these data gaps and expanding understanding of historical floating kelp distributions is a strategic action identified in the Puget Sound Kelp Conservation and Recovery Plan (Calloway et al. 2020). This knowledge is critical in supporting effective conservation and recovery of kelp forests in Washington and serves to inform efforts like the Kelp and Eelgrass Health and Conservation Plan (RCW 179.134.440).

The value of reconstructing historical kelp distribution for filling data gaps has already been demonstrated in the work completed in South Puget Sound (Berry et al. 2021). The study found a 63% loss of floating kelp relative to the earliest historical baseline and showed that losses primarily occurred in areas with higher temperatures, lower nutrient concentrations, and relatively slow currents. This research provided key insights into kelp decline in South Puget Sound and laid the foundation for subsequent manipulative experiments evaluating temperature and nutrient stressor impacts to kelp in laboratory settings (Weigel et al. 2023, Fales et al. 2023), advancing knowledge of the drivers of floating kelp decline.

Central Puget Sound is the only sub-basin other than South Puget Sound currently classified as declining in the Floating Kelp Vital Sign Indicator (Figure 1), although the timing and location of kelp losses is not fully documented. Central Puget Sound encompasses the marine waterways north of Tacoma Narrows and south of Possession Point. It contains increasingly urbanized and developed shorelines (Simenstad et al. 2011) including the Seattle waterfront. DNR monitors floating kelp at sites in Central Puget Sound via kayak- and UAS-based surveys (Ledbetter & Berry 2024, Cowdrey & Claar 2024), but programmatic monitoring only began in recent years.

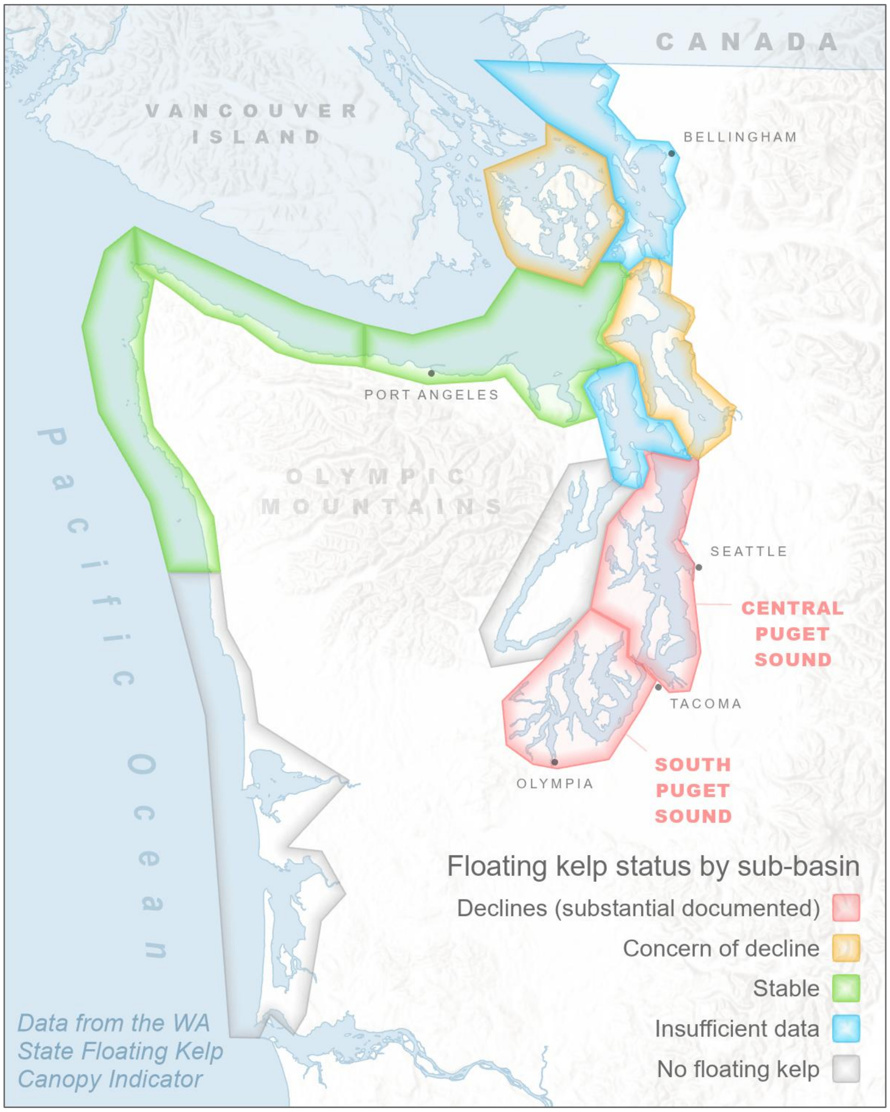

Figure 1. Floating kelp status of each sub-basin in Washington State, as described in the WA State Floating Kelp Bed Area Vital Sign Indicator.

In the absence of long-term monitoring datasets, historical photography can be a valuable tool for reconstructing ecological baselines and informing modern stewardship and management practices. Historical aerial photographs have been used in numerous terrestrial applications, such as analyzing tree invasion in grasslands in New Mexico (Swetnam et al. 1999) and assessing land use and land cover change in the Klamath River Basin (Eitzel et al. 2024). The use of historical photographs to reconstruct marine vegetation baselines is less common given the challenges in detecting marine vegetation in aerial imagery. Time of year, surface conditions, tide height, and current speed all factor into detection of marine vegetation in aerial photography (Schroeder 2019, Reshitnyk et al. 2023, Timmer et al. 2024, Cowdry & Claar 2024), and it is rare that historical photographs collected for another purpose meet the necessary conditions. However, sometimes by happenstance and sometimes by intent, a dataset meets the necessary collection conditions and can be used to extract marine vegetation distribution data.

The goal of this project was to leverage a small collection of aerial images of the Seattle shoreline taken in 1984 to fill a data gap in the historical distribution of floating kelp in Central Puget Sound. To achieve this, the 1984 imagery was spatially referenced and reviewed by a group of experts to generate an estimate of the linear extent of floating kelp in 1984. We conducted 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 along these shorelines over the last four decades.

2 Methods

2.1 1984 Imagery Dataset

The imagery evaluated in this project was a collection of approximately three dozen aerial photographs captured on 35mm color infrared slide film stored in a box labeled, “Subject: Kelp Beds. Date: 7 Sept 84. Infrared. From 700’ Magnolia Bluff + West Seattle.” It was originally collected by Ron Thom (University of Washington) for part of a baseline study to identify optimal placement of the King County wastewater treatment outfall (Thom, personal communication). Figure 2 shows the location of Magnolia and West Seattle in Central Puget Sound, near Seattle, WA.

As the box denotes, the imagery was originally captured on Color Infrared slides, but inspection revealed that the infrared signal – which normally appears as red - had faded to a dull orange/yellow/white in many of the images. The slides were numbered sequentially, and some contained hand-written notes about the location shown. Measurement of floating kelp from above is dependent on tide and current conditions (Cavanaugh et al. 2021, Timmer et al. 2024, Cowdrey & Claar 2024). While we do not have exact time of photography from which to calculate tidal height and current speed, shadow angles in the photographs suggest the images were captured around low tide, which was a -0.16ft tide at 0952 on September 7th, 1984, at the Seattle tide station (NOAA). Historical current speed data was not available.

Figure 2. Maps showing the location of Magnolia and West Seattle, the general area where the 1984 images were captured, in Central Puget Sound near Seattle, WA.

The imagery was captured at highly oblique and possibly varying angles, rather than from the direct overhead position typical of most satellite and aerial imagery used in remote sensing analyses (Figure 3, Wang et al. 2016). The camera was likely checked out from University of Washington for the flight (Thom, personal communications), but there is no additional metadata available about the camera or images.

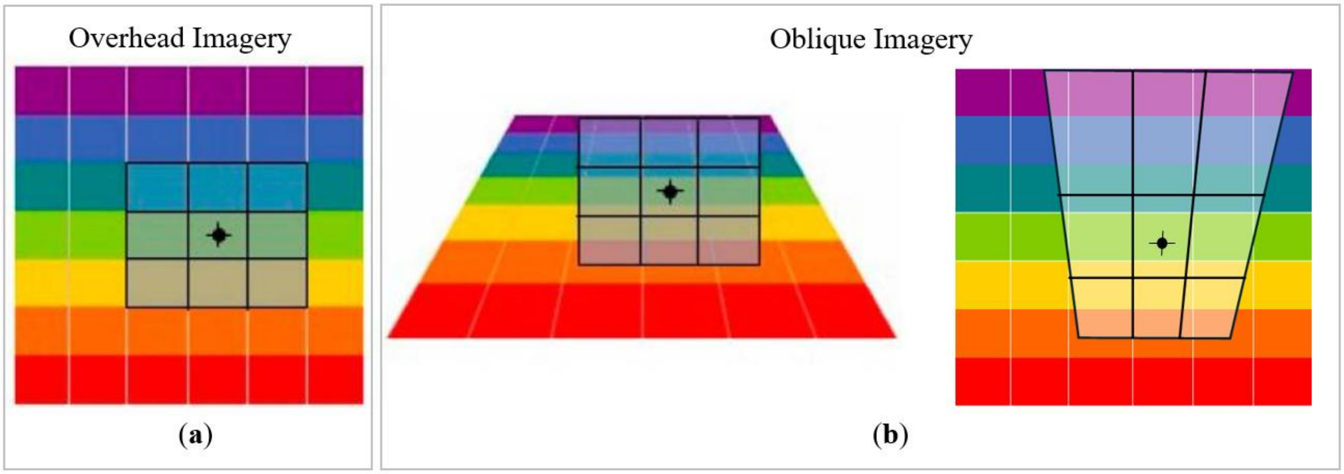

Figure 3. The changes of ground area captured by neighborhood pixels in (a) the reference image; (b) the oblique angle image. The 1984 imagery was captured at angles similar to (b), although the exact angles are uncertain and likely vary across images. Modified from Wang et al. 2016

2.1.1 Supporting Data

A hand-drawn map in Lincoln Park from a 1985 report (Thom 1985), based in part on this 1984 image collection (Thom, personal communication), shows the approximate location of kelp in this cove (Figure 4). The hand-drawn map was georeferenced in ArcGIS Pro 2.9.1 (Esri, Redlands California, USA) using prominent features such as the ferry terminal, Lincoln Park pool, and shoreline contour as reference features. This georeferenced map was then used to support and validate mapping of linear extent.

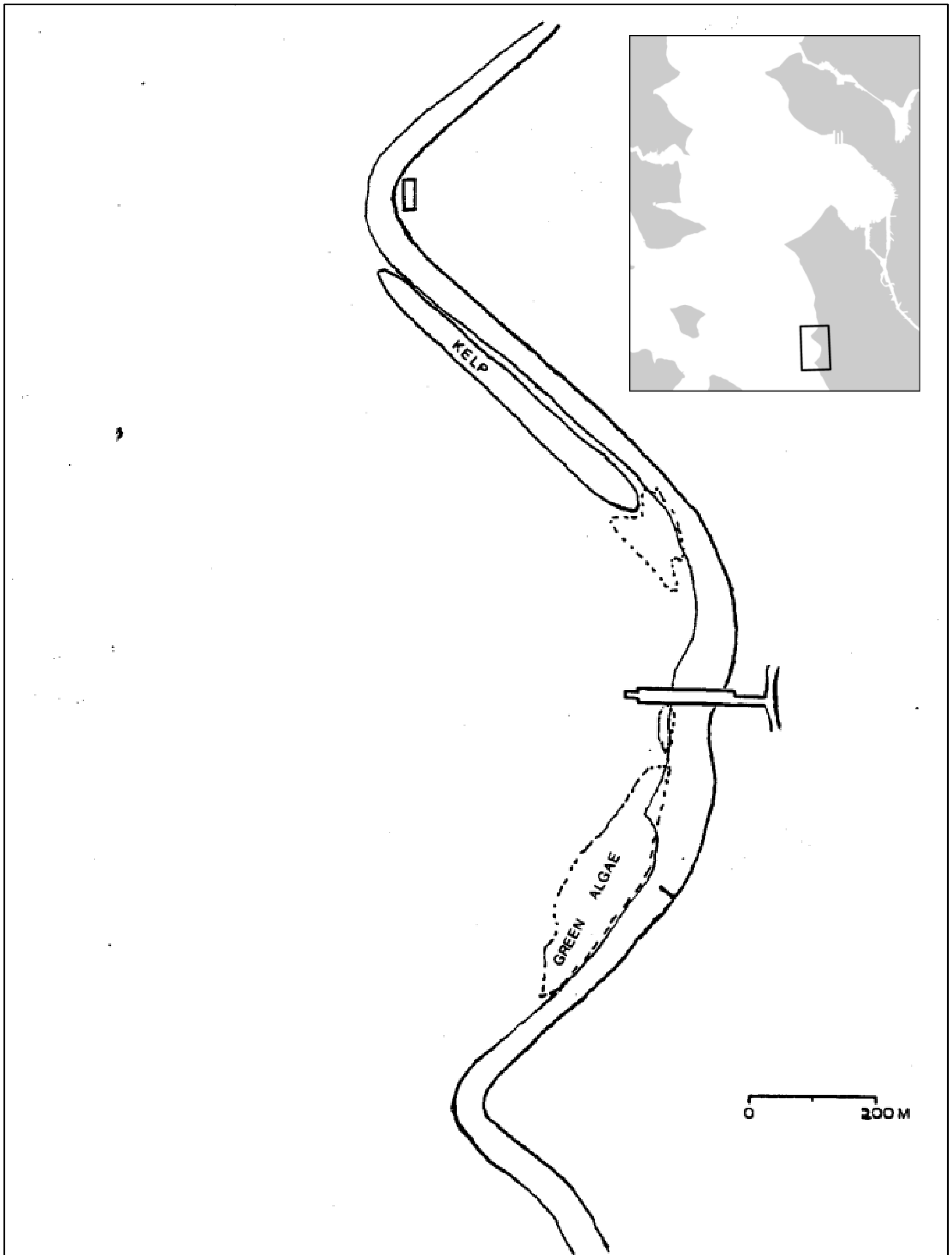

Figure 15. Location of the main algal beds in Fauntleroy Cove. Note that intertidal algae is also abundant inshore from the kelp bed.

Figure 4. Hand-drawn map of Lincoln Park area in Fauntleroy Cove from Thom 1985. Inset map top right was added for this report. Original figure legend reads: *Location of the main algal beds in Fauntleroy Cove. Note that intertidal algae is also abundant inshore from the kelp bed.*

2.2 Scanning Slides

The 35mm slides were scanned at 6800 dpi and saved as TIFs by Archive Washington (Olympia, WA, USA). Scans were provided in raw and color-corrected format (Figure 5). Color-corrections were performed by the vendor to improve contrast and tone in the faded imagery. Both sets of images were utilized in analysis. Given that the primary data extraction methods were visual assessment and review of the photographs rather than spectral analysis, the color-corrected versions of the imagery were often preferable for evaluating kelp presence. After scanning, the slides were stored in their original box at the Natural Resources Building, 1111 Washington St, Olympia, WA.

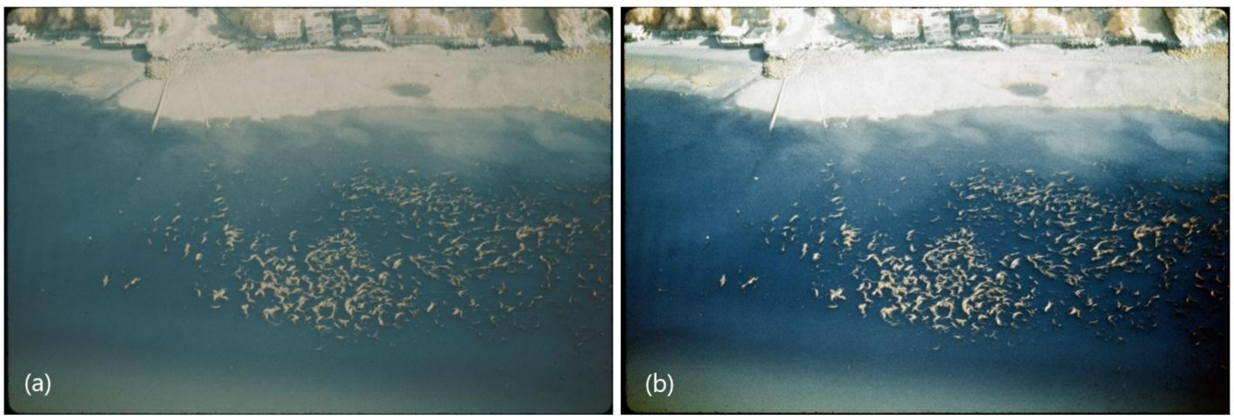

Figure 5. Example of (a) raw scanned image and (b) color-corrected image provided by Archive Washington. Images shows 32nd Ave beach in Magnolia.

2.3 Mapping Images

The highly oblique angle of the photographs precluded traditional photogrammetric rectification methods. However, many of the images overlapped with one another and showed notable shoreline features, such as large boulders, seawalls, and buildings that are still present in modern satellite and aerial imagery (Figure 6). The shoreline features were distributed through a limited area of each image frame (typically 20% or less of the image), and so could be used roughly align images with each other and with the shoreline, distortion notwithstanding. This enabled each image to be evaluated with regard to its spatial context.

Images were brought into ArcGIS Pro 2.9.1. Those with identifiable shoreline features (e.g., building structure, large boulder) were moved, scaled, and rotated to approximately align those features where they appeared in other reference images (Figure 7). Reference orthoimagery datasets included:

a. King County West 2010 6-inch 4-band (WA Technology Solutions)
b. NAIP 2019 Natural Color Imagery Basemap (Esri, USDA Farm Service Agency)
c. Google Earth Pro 3D Basemap (Google Earth, Image Landsat/Copernicus)

Google Earth Pro, which presents high resolution imagery in a 3D interactive viewer, was particularly useful in confirming that shoreline features in the oblique aerial imagery matched those in the reference imagery. We explored historical orthoimagery sources closer in time to 1984 as potential references, but none were high enough resolution to be of use.

Images without identifiable shoreline features were aligned with neighboring images and the shoreline. The result (Figure 7) was a series of rasters where each image has 1-2 points within it that were accurately georeferenced, with surrounding pixels varyingly offset from their true location. Each image could then be evaluated with respect to its neighboring images and in its approximate location along the shoreline.

Figure 6. Examples of shoreline features used for image scaling, rotating, and placement on the map. Circle around (A) shows end of 32nd Ave, (B) shows a building structure; both features are visible in 2010 King County/WA Tech 6" imagery (left) and the 1984 imagery (right).

Figure 7. 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 have not been transformed or rectified relative to the ground. Underlying imagery is 2019 NAIP Natural Color Imagery Basemap (Esri, USDA Farm Service Agency).

2.4 Vegetation Characterization

Ten DNR Nearshore scientists with expertise in marine vegetation mapping and monitoring reviewed the images for floating kelp presence, enabling us to more definitively describe kelp presence and identify areas where image quality impacted classification certainty. If floating kelp was present, reviewers further classified the presence by type and then subtype (Table 1). Reviewers evaluated each individual image along the shoreline. They had the option to select multiple types and subtypes for each photo, and to provide further comment on the location of these types and subtypes in each photo. The type and subtype classification schema used in this project was developed by DNR for use in boat-based floating kelp linear extent surveys in Central Puget Sound, conducted in 2019 (Berry et al. *in prep*). It was used here to 1) provide additional context for the area and abundance of kelp present in 1984 and 2) facilitate a more detailed comparison between kelp presence in 1984 and 2019. The image quality made it challenging to determine whether incidental kelp was a single individual or a small cluster of individuals, so these two subtypes were grouped together and only reported at the type level (incidental) in the results.

Reviewers also provided a likelihood (low, moderate, or high) for each level of characterization to help capture their uncertainty in describing particularly faded images. Several of the images in the original collection did not show nearshore vegetation (e.g., a photo of Boeing Field, a photo of Pier 91) and therefore those were not subject to review. The kelp presence characterization agreed upon by the majority of reviews was selected for the final linear extent mapping.

Table 1. 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.

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-plant 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.

2.5 Analysis of Floating Kelp Linear Extent

Kelp presence, type, and subtype were spatially characterized using a linear model for kelp presence. This method represents an appropriate way to extract spatial data from the imagery without going beyond the limitations posed by the oblique capture angle. DNR has used a -6.1 m MLLW isobath derived from gridded bathymetric data (Nysewander et al. 2005) to describe linear extent of floating kelp from a variety of data sources in South Puget Sound (Berry et al. 2021), and in recent boat-based surveys of floating kelp in Central Puget Sound. This isobath represents a common maximum depth of bull kelp beds in Central Puget Sound, observed in the field (Berry et al. 2019). Kayak monitoring at 16 sites across Puget Sound found that 85% of the kelp bed footprint occurs shallower than -6 m MLLW at a majority of sites (Ledbetter & Berry 2024). The -6.1 m MLLW isobath was used for this mapping project to facilitate comparison between 1984 and 2019.

The -6.1 m isobath was split into segments at points of change in kelp presence, type, and subtype in the 1984 imagery, as determined by expert review. These points of change were located by referencing the shoreline features visible in each photo. For example, if a kelp forest appeared to start directly offshore from a particular building, we drew a perpendicular line directly offshore of that building in the reference imagery and split the line segment at that location, then assigned the resulting segments the appropriate type and subtype classification (Table 1) as determined by reviewers. Following methods used for the 2019 boat-based linear extent surveys, we used a minimum segment length of 4 m for kelp presence. The minimum segment length was implemented for describing the presence of incidental kelp. There was some subjectivity involved evaluating the exact angle of the 1984 photographs and translating that to appropriate splitting location. However, most of the photographs capture overlapping areas of shoreline, so in many cases, multiple viewing angles were used to evaluate the relationship between the kelp location and the shoreline features. Length in meters was calculated for each segment. Given the uncertainty associated with exact vertex placement, length of presence is reported here rounded to the nearest 10 m (0.01 km).

2.6 Change Analysis

To evaluate floating kelp distribution change over time, we compared the results of this 1984 imagery analysis with data from a boat-based linear extent survey of floating kelp presence, type, and subtype conducted by DNR throughout Central Puget Sound in July of 2019 (Berry et al. *in prep*). The 2019 surveys were conducted within one hour of a low tide (< 0 m MLLW) in calm weather conditions between late June and early September to capture peak kelp presence and optimize canopy visibility; methods for a very similar survey conducted in South Puget Sound are described in Berry et al. 2019.

The 2019 survey represents the most recent synoptic survey of floating kelp in the study area at the time of this report. We clipped the 2019 survey data to areas within the estimated footprints of the 1984 photographs and calculated the length in meters for each segment for each category of kelp presence, type, and subtype. We reported change in linear extent in meters of each kelp type and subtype between 1984 and 2019.

3 Results

3.1 Imagery Coverage

The imagery was found to cover four disjunct areas of shoreline (Figure 8). Slides 2 through 19 captured approximately 4 km of shoreline around Magnolia Bluff, beginning at Pier 91 in Smith Cove and heading northwest until Four Mile Rock; this area is referred to as Magnolia throughout this report. Slides 20 through 24 show the southern shoreline of Lincoln Park, beginning at the Fauntleroy Ferry Terminal and heading northwest for approximately 0.5 km, ending just before the Lincoln Park pool; this area is referred to as Lincoln Park throughout this report. Slides 25 and 26 show the 63rd Ave outfall pipe just south of Alki Point and slides 27 through 35 cover an approximately 6-km stretch of shoreline in West Seattle between Point Williams and Alki Point; these two areas (slides 25- 35) are reported on together and referred to as West Seattle throughout.

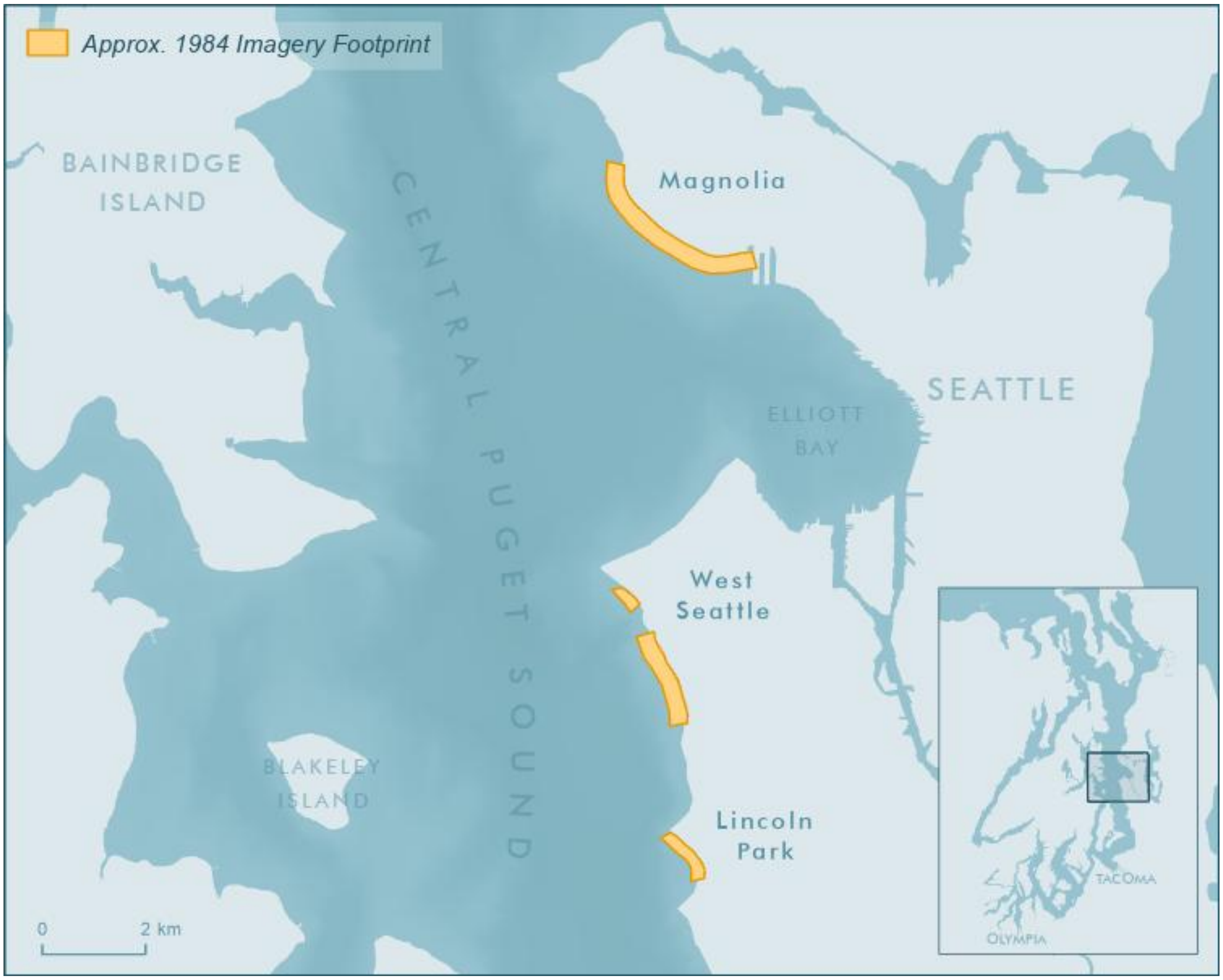

Figure 8. Generalized footprint of 1984 aerial imagery (orange) of floating kelp beds in the vicinity of Seattle, WA, as determined by matching notable shoreline features present in historical imagery (1984) with modern reference orthoimagery datasets (2010 & 2019).

3.2 Linear Extent of Floating Kelp in 1984

3.2.1 Magnolia

The 1984 images clearly capture a kelp forest wrapping from Smith Cove out to 32nd Ave (Figure 9a). The rest of the photographs in this group are more faded and kelp is less clearly visible (Figure 9b). Total linear extent results for each category in each area are presented in Table 2 (Section 3.3). Our analysis of the 1984 photography resulted in kelp forest presence stretching from Smith Cove around to the 32nd Ave West beach for 1.13 km along the -6.1 m MLLW isobath. 100% of reviews of the seven images that covered this forest area agreed that kelp was present with high (91%) or moderate (9%) likelihood, and 98% agreed that type was forest with high (73%) or moderate (24%) likelihood. The forest is narrower to the east but appears to extend deeper as it wraps west around the shoreline. There was less agreement as to forest subtype (wide vs. fringing) for the eastern portion of the forest, given the challenge of assessing distance in the oblique imagery, but the majority of reviews (71%) categorized it as fringing. Every reviewer characterized the western portion of the forest as wide. The result was 0.71 km of wide forest and 0.42 km of fringing forest.

To the northwest of the major forest, incidental floating kelp was present along smaller segments of shoreline. Given the degraded image quality and the difficulty of detecting single or sparse kelp, agreement was lower overall for this section of shoreline. Several of the photographs showed shallow, feathery vegetation which about half of respondents deemed likely to be eelgrass. By summarizing observations of incidental kelp where at least 50% of reviewers agreed, a total of 0.46 km of incidental floating kelp was present. Kelp was absent for the remaining 2.01 km of shoreline.

3.2.2 West Seattle

Two slides show an area just south of Alki Point, near the 63rd Ave outfall pipe with no floating kelp present for approximately 0.5 km. Then, for an approximately 6-km stretch of shoreline in West Seattle between Point Williams and Alki Point, kelp is patchily present in most images (Figure 10a). The photographs in this section are particularly poor in quality, with some large, faded areas and significant sun glint. As a result, uncertainty in our kelp classification for this area is higher than for Magnolia or Lincoln Park. Every review of the nine photographs in this span of shoreline agreed that kelp was present in every slide, with high (55%) or moderate (30%) likelihood. This overall presence likelihood is lower than reviewers reported for Magnolia or Lincoln Park, and agreement for types and subtypes was also generally lower. For most of this shoreline section, a majority of reviewers characterized kelp presence as wide or fringing forest, except a small section of kelp presence that most reviewers agreed was incidental. Mapping the results onto the isobath yielded 0.85 km of wide forest, 0.44 km of fringing forest, and 0.08 km of incidental presence. The lower likelihoods for kelp presence and the disagreement on the type and subtype classification level are indicative of the uncertainty introduced by the poor image quality for this section of shoreline; however, reviewers agreed that kelp was present in the photographs with majority agreement for types and subtypes.

3.2.3 Lincoln Park

The five photographs of the southern shoreline of Lincoln Park from 1984 show a kelp forest present along 0.51 km of the isobath (Figure 10b). For this section of shoreline, we have supporting information in the form of a hand-drawn map showing kelp presence based partially on the 1984 imagery (Figure 3). We used this map to validate our linear extent assessment of kelp forest presence in Lincoln Park, providing supporting evidence of kelp presence in this area. The shape of the kelp forest in the hand-drawn map seems to be generalized, so its use in assessing forest width was limited, but 91% of reviews across the four kelp-containing photographs agreed that the visible kelp fit the forest category with high (56%) or moderate (31%) likelihood. The northwestern portion of the forest appears to be wider; 63% of reviews agree it is wide, and 63% agree the southeastern section constitutes fringing forest. Mapping the results yielded 0.44 km of wide forest and 0.07 km of fringing forest.

A summary of expert reviews for individual slides is presented in Table S1.

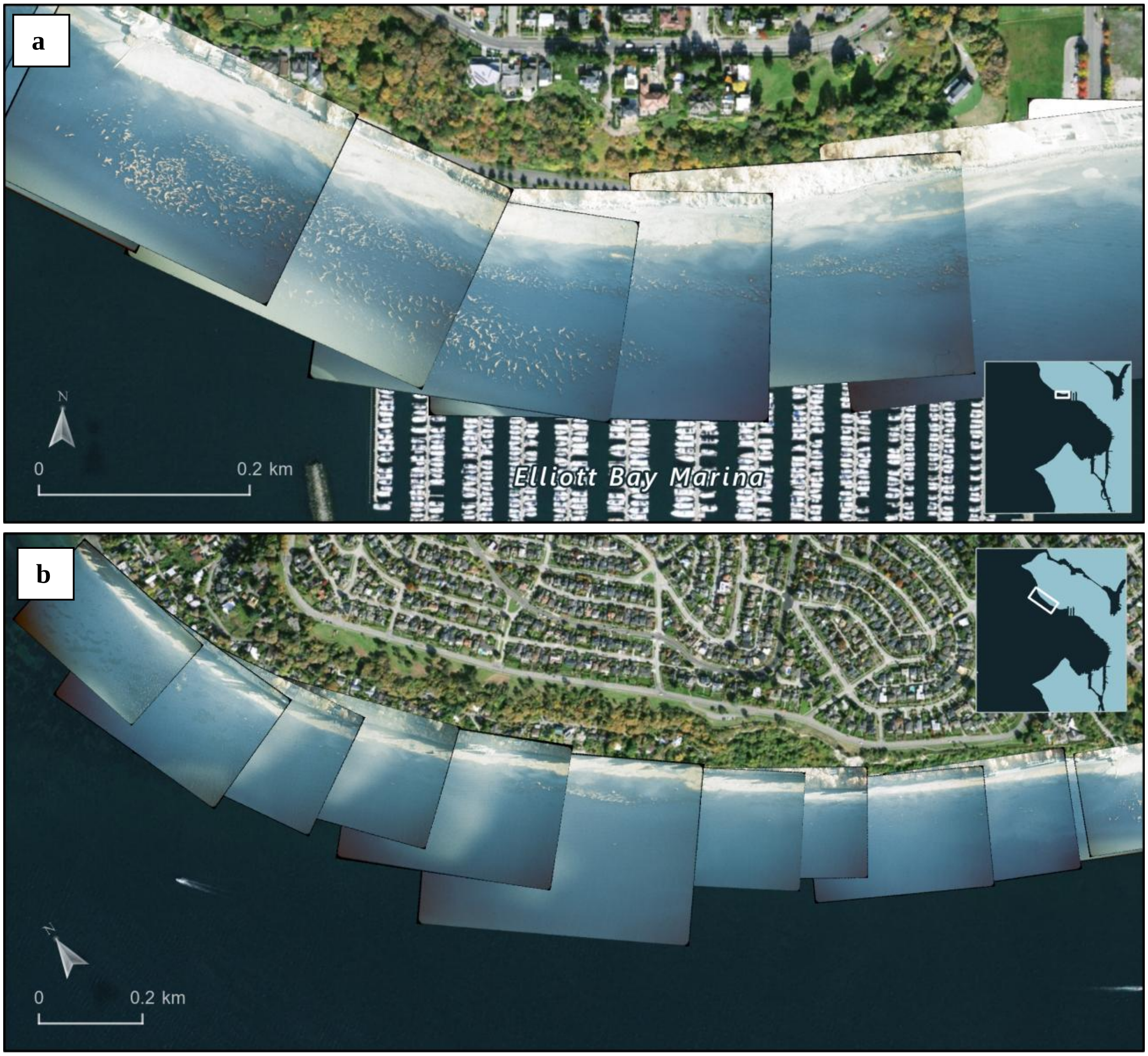

Figure 9. Images (1984) of Magnolia Bluff from (a) Smith Cove to 32nd Ave and (b) 32nd Ave to Four Mile Rock. Images have been rotated, scaled, and placed to align approximately with the shoreline, but have not been transformed or rectified. Underlying imagery is 2019 NAIP Natural Color Imagery Basemap (Esri, USDA Farm Service Agency).

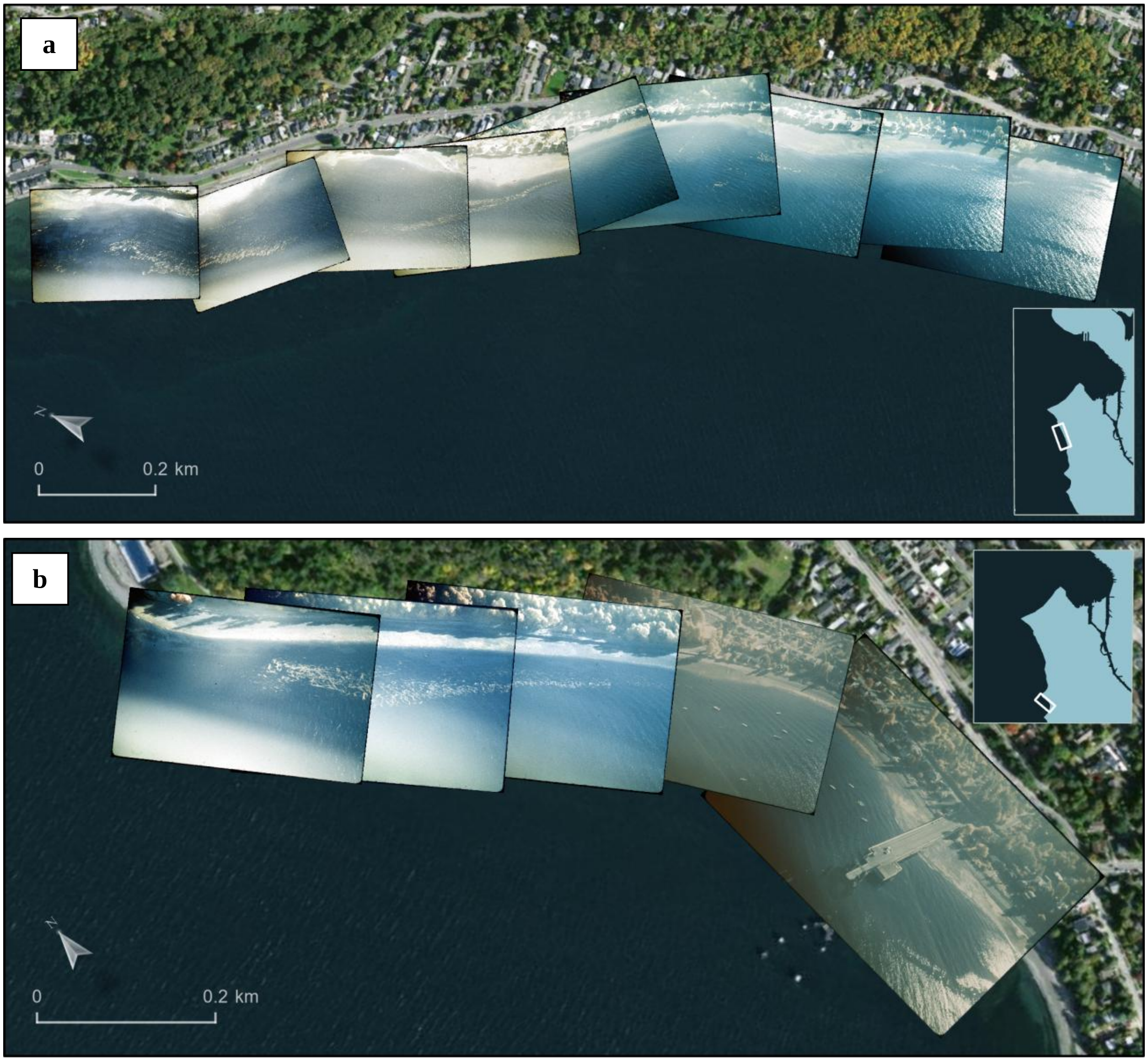

Figure 10. Photographs of (a) West Seattle shoreline between Alki Point and Pt Wilson and (b) Lincoln Park, in Fauntleroy Cove. Images are approximately aligned with their location on shore but are not transformed/orthorectified relative to the ground. Underlying imagery is 2019 NAIP Natural Color Imagery Basemap (Esri, USDA Farm Service Agency).

3.3 Change in Linear Extent between 1984 and 2019

3.3.1 Magnolia

We compared the results of our 1984 floating kelp linear extent mapping to boat-based linear extent mapping surveys of floating kelp conducted throughout Central Puget Sound in 2019 (Table 2, Figure 11, Figure 12). Kelp was estimated to be present along 1.58 km of the -6.1 m isobath in 1984, but only along 0.70 km in 2019, representing an estimated decline of 57% in linear extent of kelp presence. Wide forest was only present in 2019 west of the Elliott Bay marina for 0.15 km. This constitutes a decrease in the linear extent of wide forest presence between 1984 and 2019 of 0.56 km (79%). Fringing forest presence was similar between the two surveys (0.42 km in 1984 and 0.47 km in 2019) but the location varied between datasets. In 1984, the eastern fringing kelp forest extended into Smith Cove, while in 2019, fringing kelp presence occurred along the Elliott Bay Marina Breakwater. Incidental kelp was present for only 0.08 km in 2019, which equates to an 0.38 km (82%) decrease in incidental kelp linear extent relative to 2019. However, detection of incidental kelp was difficult in the 1984 images so the reported decline in incidental presence is less certain than the decline in forest extent.

3.3.2 West Seattle

Our comparison of 1984 imagery analysis results and 2019 boat-based linear extent survey found a total loss (100%) of the linear extent of floating kelp between 1984 and 2019 (Table 2, Figure 11, Figure 13). This represents a loss of 1.37 km of floating kelp extent since 1984, the majority of which was forest habitat, although assessment of this area is less certain due to poor image quality. Note that kelp is present in 2019 along some nearby segments of the shoreline not surveyed in the 1984 imagery but was totally absent from areas of presence surveyed in 1984. Since we cannot comment on kelp presence or absence in 1984 outside of the area in the imagery, we represent only those areas in common between the two datasets here.

3.3.3 Lincoln Park

In 1984, a kelp forest wrapped along the southern portion of Lincoln Park in Fauntleroy Cove for 0.51 km. The 2019 boat-based survey found no kelp present along this extent of shoreline, which represents a total loss (100%) of this bed relative to 1984 (Table 2, Figure 11, Figure 13).

Table 2. Total length (km) of kelp presence grouped by type and subtype at each site in 1984 based on the 1984 photographs and in 2019 from boat-based linear extent survey and the change between years.

		Total Length (km)			
Site	**Year**	**Forest - Wide**	**Forest - Fringing**	**Incidental**	**Total Kelp Presence**
Magnolia	1984	0.71	0.42	0.46	1.59
	2019	0.15	0.47	0.08	0.70
	change	-0.56	+0.05	-0.38	-0.89
West Seattle	1984	0.44	0.85	0.08	1.37
	2019	0.00	0.00	0.00	0.00
	change	-0.44	-0.85	-0.08	-1.37
Lincoln Park	1984	0.44	0.07	0.00	0.51
	2019	0.00	0.00	0.00	0.00
	change	-0.44	-0.07	0.00	-0.51

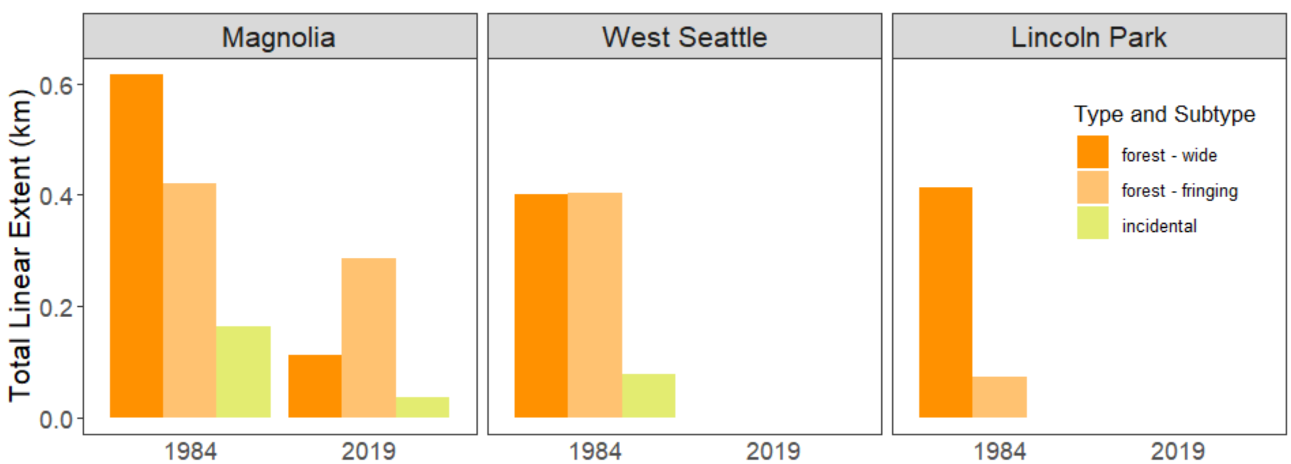

Figure 11. Linear extent (km) of floating kelp at each site in 1984 (left) and 2019 (right) grouped by type and subtype; dark orange = forest wide, light orange = forest fringing, yellow = incidental (single and multiple). See Table 1 for category definitions.

Figure 12. 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.

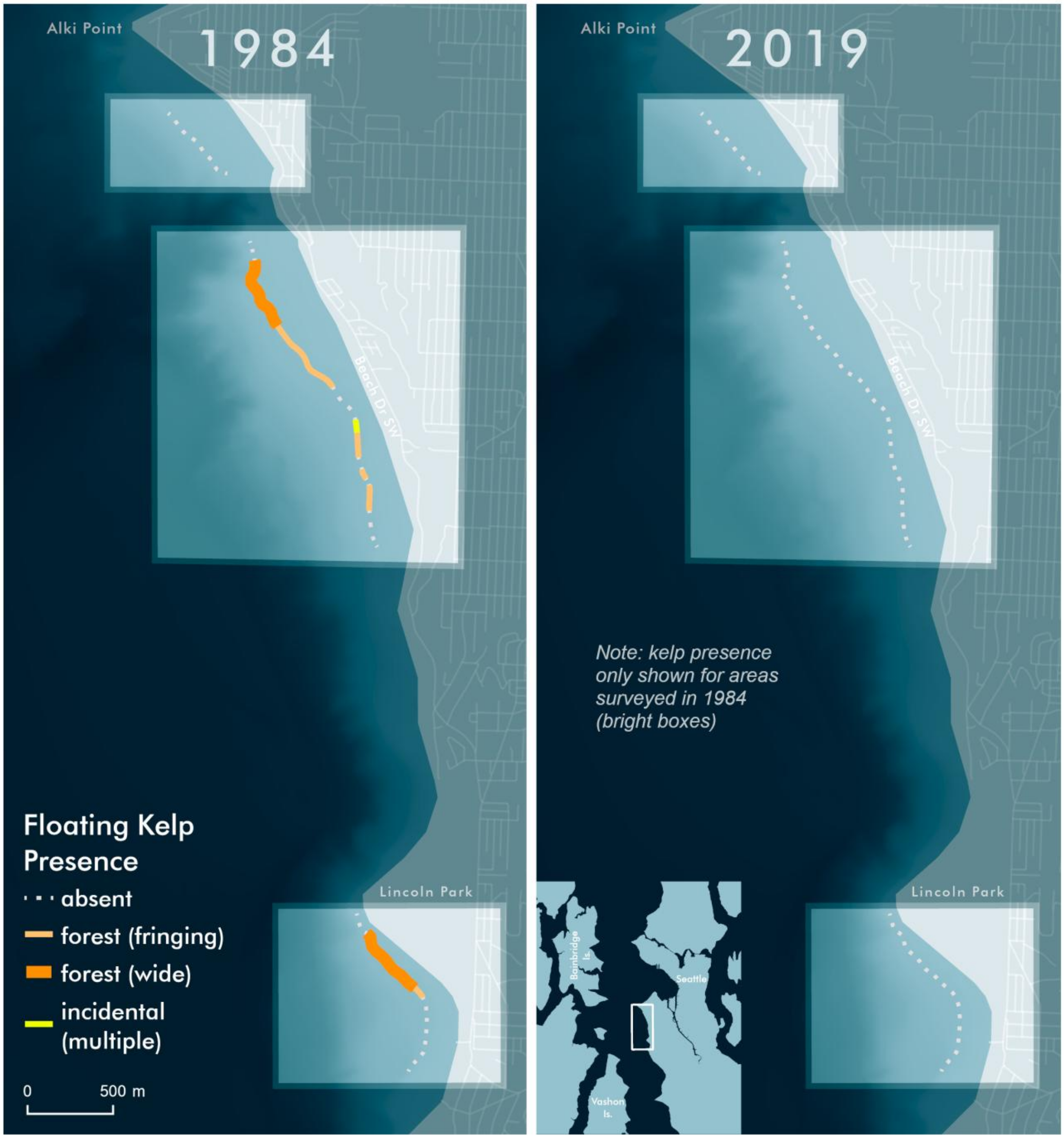

Figure 13. Floating kelp presence in West Seattle and Lincoln Park in 1984 derived from aerial imagery (left) and 2019 derived from boat-based linear extent mapping (right). Floating kelp presence is symbolized by type/subtype: dotted grey = absent, wide orange line = forest (wide), narrow orange line = 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.

4 Discussion

This unique historical dataset of oblique aerial imagery was processed to generate floating kelp linear extent data along areas of the Seattle shoreline in 1984. Comparison of these results to a 2019 boat-based kelp presence survey showed an overall decline in linear extent of floating kelp since 1984 within the surveyed areas.

4.1 Use of Imagery in Historical Kelp Analysis

Historical photographs offer an opportunity to go back into the past and create new datasets for environmental conditions from decades ago. The photos used here enabled an analysis of change in bull kelp presence along several areas of the Seattle shoreline between 2019 and 35 years earlier. However, using historical data sources comes with many challenges, and the 1984 photographs were no exception.

Data extraction from the 1984 aerial photographs was challenging for several reasons. Very little metadata was available for this dataset. We knew the date but not the time of the flight, although it was likely around low tide. We had an approximate altitude for the flight (700') but no other positional information, including camera angle or image centroid. We knew that the photographs were collected on color infrared film but had no other information about the camera. To complicate the lack of metadata, most of the photographs were grainy and/or had large light leaks obscuring portions of the shore.

Typically, the first step of converting imagery into spatial data involves transforming, or rectifying, the image so that each pixel can be reshaped and associated with its actual x,y location in space. With highly oblique imagery, area, distance, and direction are all severely distorted relative to nadir (direct overhead) imagery, so more significant transformations are required. Rectifying highly oblique photos is also referred to as inverse perspective mapping, the methodologies for which are rapidly evolving primarily in association with self-driving car technology (Kim 2019, Shi et al. 2023). Some conservation applications of inverse perspective mapping are also in development. ReScape is a one such application that was investigated for this project, which takes oblique/large angle images of coral reefs captured by recreational divers and transforms them so coral area and percent cover can be accurately assessed (Ferris et al., 2024). However, ReScape and other currently available inverse perspective mapping programs and algorithms require camera metadata (angle, height, focal length, etc.) or camera calibration files, where the user supplies calibration images captured with the same camera that was used to capture the original oblique imagery. Neither of these were a possibility for this dataset.

Given the challenges described above, we proceeded with an alternate method of extracting spatial data by relying on notable shoreline features to approximately georeference some points within each image. Expert reviewers described floating kelp presence qualified with type and subtype descriptors. This method enabled us to map the linear extent of kelp distribution along the -6.1 m isobath, extracting meaningful spatial data while remaining within the limitations of the imagery. Except for Lincoln Park where we have hand-drawn maps, we did not evaluate the accuracy of the kelp distribution results against other data sources from the same time period, which may or may not exist.

This is a unique dataset in that the photographs were collected specifically for marine vegetation mapping, and so it met seasonal conditions and appears to have met the tidal window necessary for assessing kelp. There are several other historical imagery datasets that, while not specifically collected for marine vegetation mapping, have the potential to expand our understanding of the timeline of kelp change in Washington waters. These include USDA's National Agriculture Imagery Program (NAIP), Washington State Department of Ecology's Coastal Atlas Shoreline Photos, DNR's own historical aerial film collections that have yet to be analyzed for kelp forest mapping, and likely others. Each dataset will have unique characteristics (time, tide height, camera angle, image quality, metadata availability, etc.) that will shape what type and quality of floating kelp data can be extracted. This report provides an example of how some of those challenges can be mitigated using creative spatial analyses.

4.2 Kelp Forest Change Over Time

Central Puget Sound is estimated to have lost approximately 80% of its maximum historical floating kelp extent over the past century and a half (Berry *in prep*). Work is still in progress to identify precisely where and when these declines have occurred, and our results provide some insight into the location and timing of losses for the Seattle shorelines surveyed.

The drivers of floating kelp decline in Central Puget Sound remain uncertain, but many factors including temperature, nutrient availability, and shoreline development may play a role. Increasing temperatures associated with climate change are a threat to kelp forests globally (Wernberg et al. 2019, Smale 2020). Floating kelp loss in South Puget Sound has primarily occurred in areas with high temperatures and low nutrients (Berry et al. 2021), and laboratory experiments have demonstrated deleterious effects of high temperatures to both gametophytes and juvenile sporophytes from Puget Sound *Nereocystis* populations (Weigel et al. 2023, Fales et al. 2023). Another potential stressor, shoreline development, is linked with changes in water movement and depth that can alter nutrients, turbidity, sedimentation, and substrate availability, all of which impact bull kelp populations (Airoldi 2003, Hollarsmith et al. 2022). We did not evaluate current or historical temperature or other environmental conditions for this report but present a brief discussion of shoreline development here as a one possible factor contributing to kelp loss in the study area.

The Seattle shorelines surveyed in this report have been highly modified over the last 150+ years. We found losses in kelp forest extent between 1984 and 2019 at all shorelines surveyed, and at both Magnolia and Lincoln Park, major shoreline modifications have occurred between the survey dates.

4.2.1 *Magnolia*

Along Magnolia Bluff, we estimate that floating kelp linear extent declined by 57% overall. This decline was driven by the loss of 79% of the wide forest extent primarily in the section of shoreline now occupied by Elliott Bay Marina. Construction of Elliott Bay Marina began in 1989, a few years after the historical photographs were collected. The construction process took three years, and involved backfilling the shore side of the bulkhead, breakwater, and marina itself, majorly modifying the available substrate in the construction area and likely in the adjacent areas of the nearshore.

Mitigation for the loss of fish-rearing habitat was required under the construction permit for Elliott Bay Marina and included the creation of rocky reef habitat via substrate amendments both east and west of the marina (Cheney et al. 1994, Figure S6). The mitigation goal was to replace “in-kind” food resource production, and post-project surveys in 1991 indicated this was feasible (Cheney et al. 1994). These surveys found dense *Nereocystis* presence in the small mitigation area west of the marina shortly after construction was completed but none in the eastern mitigation area.

A small kelp forest west of Elliott Bay Marina persists to this day (2025), and it has been monitored annually by the NHP via kayak since 2020. These surveys indicate that the bed footprint at this site has increased in recent years, with the kelp forest extending deeper in 2023 than in previous years, although density is variable (Ledbetter & Berry 2024). Despite the loss of kelp within the footprint of the marina, the apparent stability of the diminished kelp forest adjacent to the marina suggests that kelp forests may exhibit resilience to nearby development-related stressors under some conditions.

However, while bull kelp has occurred on marina floats and pilings in recent years, floating kelp forests continue to remain absent on the substrate east of the marina within Smith Cove (McKenna, personal observation) where they once extended. Subsequent substrate amendments, *Nereocystis* sporophyte transfers, and seeding efforts conducted by Puget Sound Restoration Fund and the Port of Seattle in Smith Cove in recent years have not succeeded in restoring a bull kelp forest to this area (Puget Sound Restoration Fund 2024). This suggests that the area east of the marina remains unsuitable for bull kelp forests forty years after construction.

Floating kelp was still present along the marina breakwater in 2019 as a fringing forest. However, the linear presence of wide kelp forest along this shoreline is only a small fraction of its historical extent. While the limiting factors for kelp recovery and persistence in Smith Cove are uncertain, changes in hydrodynamics, sedimentation, nutrient availability, and turbidity resulting from Elliott Bay Marina’s presence along this shoreline could all play a role. More research is needed to identify causes of loss and resilience in these urbanized nearshore environments, and what stewardship and mitigation efforts, if any, can reduce the impacts to floating kelp forests.

4.2.2 West Seattle

In West Seattle, there appears to have been a total loss of floating kelp presence in 2019 since 1984 in the areas covered by the photographs. Given the poor image quality, agreement between reviewers was lower for kelp type and subtype, and overall likelihood of presence estimates were lower than for Magnolia or Lincoln Park. It may be possible to increase the certainty in linear extent data for this area by evaluating other data sources from a similar time period.

Floating kelp is not entirely absent from the West Seattle shoreline. The 2019 survey found kelp presence along this shoreline in an area not covered by the 1984 photographs. Wide and fringing forests were present just north of Lincoln Park, covering 0.78 km of shoreline, incidental presence covered 0.27 km of shoreline, and a single individual was found just south of Alki Point (Figure 14). Since these areas are outside the coverage of the 1984 imagery, we cannot assess how these kelp occurrences have changed over time.

The causes for decline along this shoreline remain unclear. Shoreline modifications may have taken place here over the last four decades, and other environmental changes may be at play, but this report did not identify any major projects like those that occurred in Magnolia and Lincoln Park.

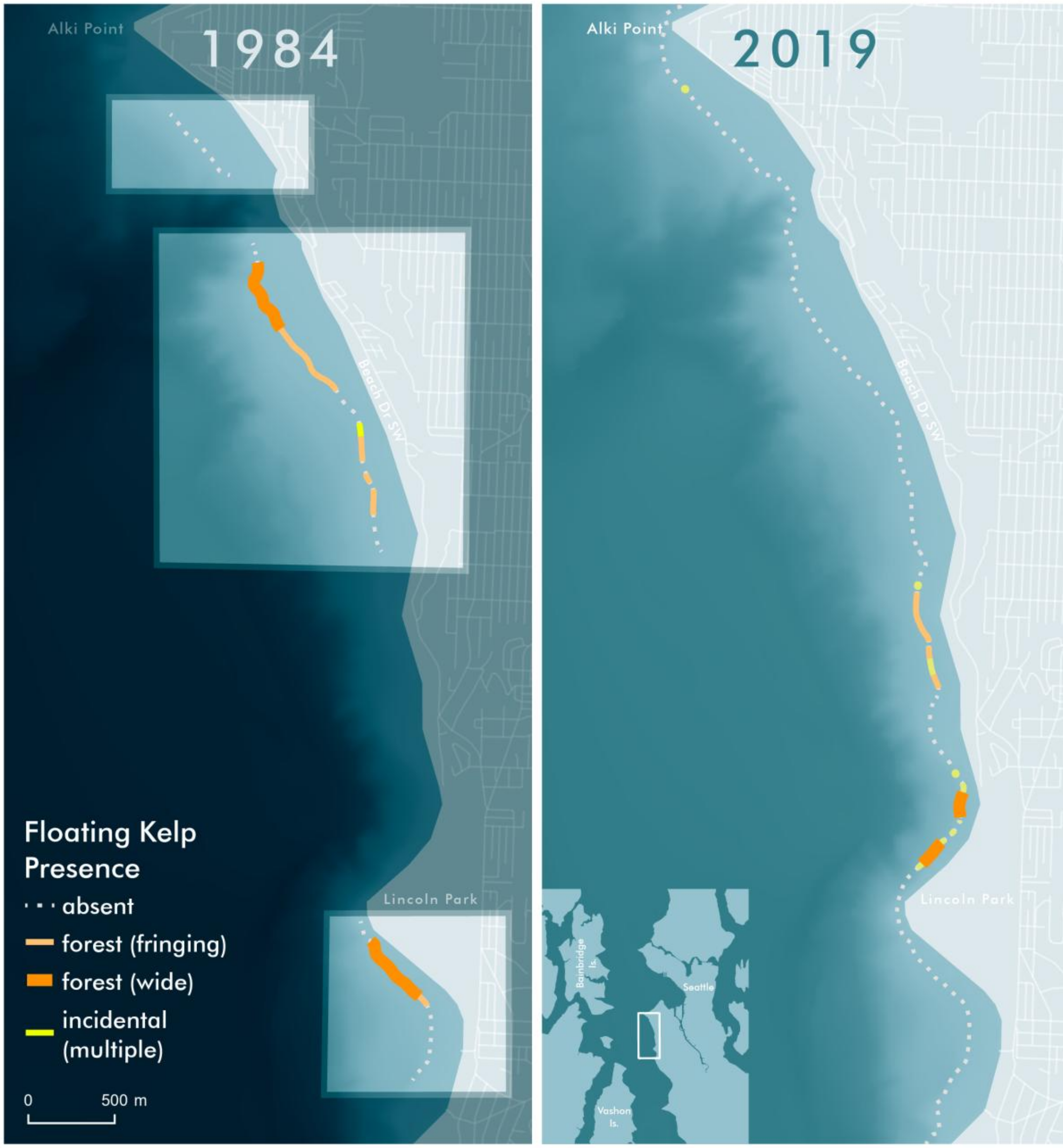

Figure 14. Floating kelp presence in West Seattle and Lincoln Park in 1984 (left) derived from aerial imagery and 2019 (right) derived from boat-based linear extent mapping. Floating kelp presence is symbolized by type/subtype: dotted grey = absent, wide orange line = forest (wide), narrow orange line = forest (fringing). Highlighted areas left show areas surveyed by in 1984 dataset; darkened areas not surveyed in 1984. Data for entire shoreline shown for 2019.

4.2.3 Lincoln Park

The kelp forest that extended along the southern shoreline of Lincoln Park in 1984 disappeared as of 2019 and continues to be absent as of summer 2024 (McKenna, personal observation). The cause of this loss is uncertain, but the history of this shoreline over the last four decades may offer some clues.

The beach along Lincoln Park is a highly modified shoreline. In the 1988, the Army Corps of Engineers conducted shoreline modifications that may have impacted the floating kelp forest here. The modifications included concrete wall reinforcements, rock revetments in front of Colman Pool, and beach nourishments in the upper intertidal zone (+6 to +8 ft MLLW) of the southern shoreline of the Lincoln Park Beach (US Army Corps of Engineers 1990, Thom & Hamilton 1991).

To evaluate the impact of these modifications to benthic infaunal bivalves, macroalgae, and eelgrass, pre- and post-project assessments were completed (Thom 1985, Thom 1988, Thom & Hamilton 1991). According to the post-project study (1991), the fill used for beach nourishment, which was primarily sand, 'slumped' into lower elevations. Sudden sediment deposition has been shown to negatively impact zoospore adhesion rate and gametophyte growth and survival in some species of kelps in laboratory settings (Watanabe et al. 2016, Picard et al. 2022). Research on the impacts of the removal of the Elwha dam supported these findings in the field; floating kelp declined after the major sedimentation event associated with the dam removal, although recovery was observed in areas where the sedimentation flux subsequently declined (Rubin et al. 2022).

While the sedimentation from shoreline modifications in Lincoln Park was likely far less substantial than that of the Elwha dam removal, it still represents a possible factor in the decline of floating kelp along this shoreline. Thom & Hamilton documented a loss in eelgrass in low intertidal and shallow subtidal zones after the Lincoln Park shoreline modifications (1991). Their study also reports a decline in macroalgae in the upper intertidal where fill was added, although it did not specifically report on subtidal canopy kelp changes in association with the shoreline modifications. Whether this kelp forest loss occurred immediately after the shoreline modifications or varyingly over the last four decades is beyond the scope of this study, and what factors are prohibiting kelp recovery here also remain unknown. Further research may provide additional insight into the impacts of sedimentation from shoreline modifications to kelp forests in this area.

There is a kelp forest on the north shoreline of Lincoln Park that DNR has monitored annually via kayak since 2020 that appears stable (no significant linear trend) across the four years for which bed perimeter data has been collected thus far (Ledbetter & Berry 2024). Since the historical photographs do not cover this section of shoreline, it is impossible to say whether this forest was present in 1984. Historical reports indicate that kelp has been generally present along this shoreline since at least 1914 (Rigg 1915, Berry *in prep*).

4.3 Conclusions and Next Steps

Historical imagery is a valuable resource for recreating ecological baselines. Image quality and metadata shape what results can ultimately be derived from any imagery dataset. For this collection of aerial photographs of kelp forests in Seattle from 1984, we were able to extract linear extent of kelp presence and categorically describe kelp density and bed width in a manner that enabled comparison to a boat-based linear extent survey of kelp in 2019. We recommend using the results from Magnolia and Lincoln Park in a more comprehensive long-term change analysis for Central Puget Sound. Given the poor image quality, results from West Seattle should be used carefully in further analyses. Additional historical datasets for this section of shoreline would strengthen the West Seattle results and increase their utility in future work.

This analysis provides another piece of the puzzle of the historic distribution of kelp in Central Puget Sound. While the causes of floating kelp decline along these shorelines are uncertain, shoreline development may have played a role, particularly at Magnolia where the construction of a large marina coincided with significant and persistent kelp loss, even after mitigation and recovery efforts. More research is needed to understand the impacts of shoreline development and construction on kelp forests and the effectiveness of mitigation or stewardship measures. This study examines just two snapshots in time along a highly urbanized shoreline that has been under development for over a century. Kelp distribution has likely fluctuated significantly both in recent decades and across a much longer time period, and further monitoring and historical analysis will increase our understanding of those changes.

Understanding the historical distribution and identifying areas of loss and resilience are critical to reversing declines in kelp forests in Washington. Assessing the results from this project in conjunction with other current and historical data sources will enable us to more comprehensively describe trends in kelp forest distribution in Central Puget Sound. As a fuller picture of kelp spatiotemporal distribution in Central Puget Sound emerges, further research into potential stressors like shoreline development may help identify priority areas for conservation and restoration and inform more effective stewardship and management of these critical habitats.

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Supplementary Material

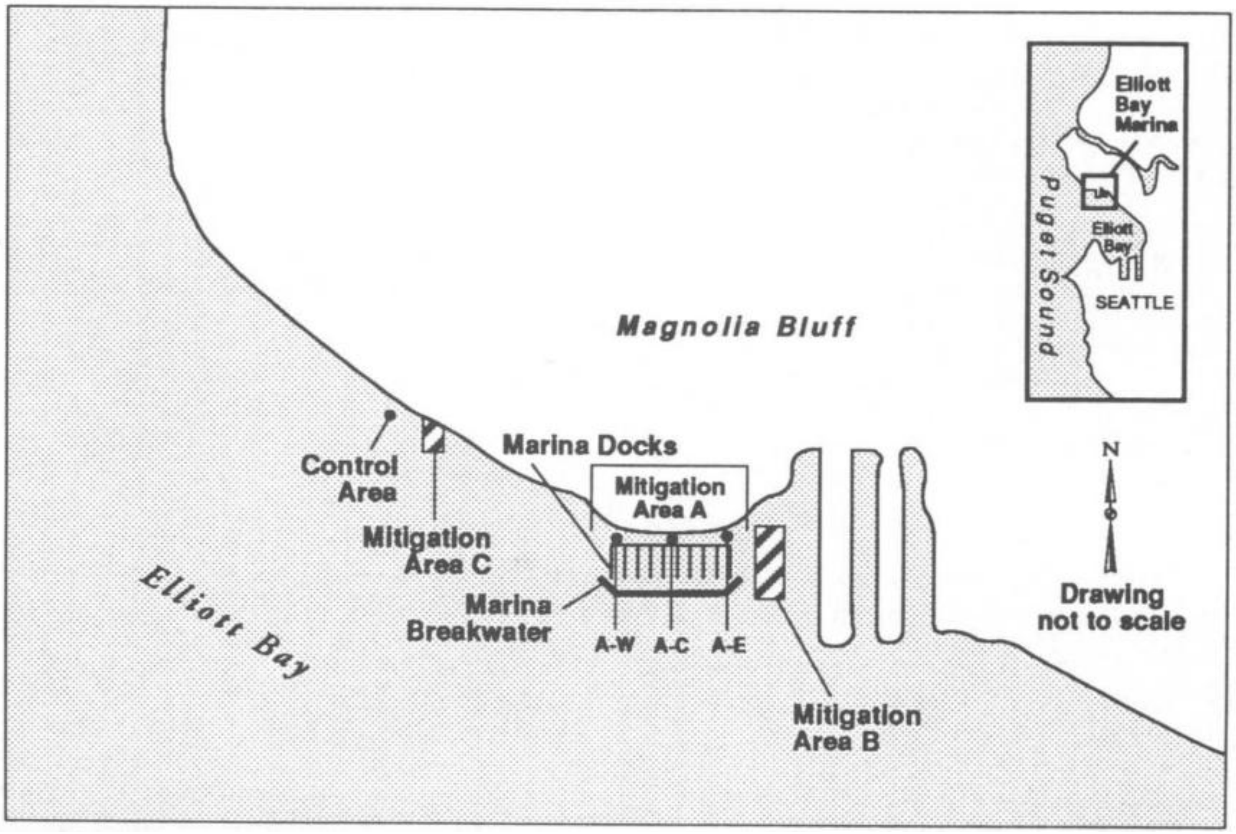

Figure S6. Map of mitigation sites associated with the construction of Elliott Bay Marina from Cheney et al. 1994. Original figure legend reads *Sample Locations for Mitigation and Control Sites, Elliott Bay Marina 1991 Epibenthic Monitoring (not drawn to scale).*

Table S1. Expert reviewer vote percentages for kelp presence, type, and subtype, grouped by likelihood (low, moderate (mod), and high) for each slide in the dataset.

Region	Slide No.	Kelp Presence Votes (%)						Kelp Type Votes (%)						Kelp Subtype Votes (%)					
		absent			present			forest			incidental			forest - wide			forest - fringing		
		low	mod	high	low	mod	high	low	mod	high	low	mod	high	low	mod	high	low	mod	high
Magnolia	03	0	0	0	0	8	92	0	36	50	0	14	0	0	13	13	0	50	13
	04	0	0	0	0	14	86	0	14	71	0	14	0	1	30	20	10	20	20
	05	0	0	0	0	13	88	0	17	83	0	0	0	0	38	23	0	23	15
	06	0	0	0	0	13	88	0	25	75	0	0	0	0	22	67	0	11	0
	07	0	0	0	0	0	100	0	14	86	0	0	0	0	13	88	0	0	0
	08	0	0	0	0	0	100	0	13	88	0	0	0	0	11	78	0	0	0
	09	0	0	0	0	13	88	0	20	40	0	30	10	0	29	14	0	29	0
	10	0	0	0	25	25	50	0	14	14	0	57	0	0	14	0	0	14	0
	11	0	0	0	25	25	50	0	13	13	0	38	25	0	0	0	0	25	25
	12	0	0	0	22	33	44	17	17	0	0	25	17	0	13	0	13	25	0
	13	13	13	0	0	38	38	0	25	25	0	13	38	0	0	0	0	57	14
	14	13	13	0	0	50	25	0	43	29	0	0	29	0	14	0	0	71	0
	15	0	14	0	29	29	29	14	0	14	0	29	29	0	0	0	20	20	0
	16	0	0	0	0	63	38	13	38	0	0	25	25	0	0	0	17	67	0
	17	13	13	0	13	38	25	13	50	13	0	25	0	0	0	0	17	33	33
	18	13	13	0	50	0	25	25	13	0	0	25	13	0	0	0	40	20	0
	19	25	13	13	25	13	13	0	20	0	0	60	0	0	0	0	0	25	0
Lincoln Park	21	0	13	0	13	50	25	13	25	38	0	0	13	0	0	0	25	25	38
	22	0	0	0	0	25	75	0	33	56	0	11	0	0	33	8	0	42	8
	23	0	0	0	0	25	75	0	33	56	0	11	0	0	31	23	0	31	8
	24	0	0	0	0	20	80	0	22	56	0	11	11	0	42	33	0	17	0
West Seattle	27	0	0	0	50	17	33	25	38	13	0	13	0	0	0	0	43	43	0
	28	0	0	0	33	33	33	25	13	38	0	13	0	0	0	0	25	63	0
	29	0	0	0	13	38	50	9	27	27	0	18	9	0	17	0	8	42	0
	30	0	0	0	13	38	50	0	46	8	0	31	8	1	0	0	17	42	8
	31	0	0	0	25	25	50	11	56	11	0	22	0	0	0	0	22	44	22
	32	0	0	0	0	43	57	0	43	43	0	14	0	1	0	22	11	33	22
	33	0	0	0	0	25	75	33	17	33	0	0	0	1	22	0	22	33	22
	34	0	0	0	0	17	83	0	50	25	0	25	0	1	40	20	0	20	0
	35	0	0	0	0	43	57	0	30	30	0	20	20	0	31	15	0	38	0