

Assessment of Bull Kelp at Squaxin Island in 2013, 2014 and 2016.

December 29, 2017



WASHINGTON STATE DEPT OF
**NATURAL
RESOURCES**

The Nearshore Habitat Program is funded by the Washington State Department of Natural Resources as part of the agency's work as steward of public lands to ensure environmental protection (<http://www.dnr.wa.gov/>). It is a component of the Puget Sound Ecosystem Monitoring Program (PSEMP) (<http://sites.google.com/site/pugetsoundmonitoring/>).

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Nearshore Habitat Program
Aquatic Resources Division



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Executive Summary

The Washington State Department of Natural Resources (DNR) manages 2.6 million acres of state-owned aquatic land for the benefit of current and future citizens of Washington State. DNR's stewardship responsibilities include monitoring nearshore vegetation and other indicators of nearshore habitat health.

Bull kelp (*Nereocystis luetkeana*) provides critical biogenic habitat to a wide range of species and other ecosystem functions, including primary production and cycling of nitrogen and carbon. Bull kelp is known to respond to a variety of environmental conditions. There is concern that it has declined in Central and South Puget Sound in recent decades. The bull kelp bed at Tucksel Point on the southern tip of Squaxin Island has been recognized for more than a century as a notably large bed in South Puget Sound. It has persisted in recent decades amidst reports of losses in other areas.

We surveyed the extent of the surface canopy of the bull kelp bed at Tucksel Point in 2013, 2014 and 2016 using a variety of surface-based methods. Key findings include:

1. The total canopy extent decreased in 2014 and in 2016, relative to 2013. In 2016, it was one third of the total area surveyed in 2013.
2. Maximum depth decreased significantly. In 2016, average maximum depth was -2.5 m (-8 ft) MLLW, compared to -4.4 m (-14.4 ft) MLLW in 2013.
3. Density of kelp stipes at the surface in 2016 was relatively low. Mean density was estimated using two different methods to be 0.28 stipes/m² and 0.32 stipes/m². No density measurements exist from 2013-2014 for comparison.
4. Plants appeared to be in poor condition in 2016. Many bulbs lacked blades. Endophytes and epiphytes were common, and kelp crabs were abundant. While the degree to which these characteristics affect kelp persistence or reproduction is not well understood, they are generally not associated with healthy beds.

These results raise concerns about the trend over time and the recent condition of the Tucksel Point kelp bed. Comparison to older datasets suggests that the alongshore extent and density of the bed has decreased. Methodological differences among datasets make more detailed comparisons difficult to interpret with certainty.

Some priorities are identified for future work to understand bed condition:

1. Survey canopy extent, depth distribution and density in future years to assess recovery or decline.
2. Analyze data on environmental conditions to provide additional insight into factors driving bed size and health.
3. Consider how populations of herbivores and predators are interacting and potentially influencing bull kelp abundance.



1 Introduction

The Washington State Department of Natural Resources (DNR) is the state steward of 2.6 million acres of state-owned aquatic land. DNR manages these aquatic lands for the benefit of current and future citizens of Washington State. As part of this responsibility, DNR's Nearshore Habitat Program monitors the health of nearshore vegetation and other indicators of habitat health.

Kelp refers to large brown seaweeds in the order Laminariales. More than 20 species of kelp occur in Washington State (Gabrielson et al. 2012). Kelp is known to provide critical biogenic habitat to a wide range of species (Thom 1987) and other ecosystem functions, including primary production (Duggins et al. 1989) and cycling of nitrogen and carbon. Kelp also responds to a variety of environmental conditions (Dayton 1985).

Kelp species that form floating surface canopies are the easiest type to observe because the floating canopies are visible at the surface at low tide. Kelp canopies have been mapped since European contact for navigation, resource utilization and habitat management. In greater Puget Sound, bull kelp (*Nereocystis luetkeana*) is the primary canopy-forming species that occurs east of Tongue Point on the Strait of Juan de Fuca (Mumford 2007).

A 1990 synthesis of historical maps concluded that bull kelp likely increased in Puget Sound between the early 1900's and early 1980's, with some of the greatest increases documented in the Main Basin and South Puget Sound (Thom and Hallum 1990). However, the authors acknowledged that the measured increase could be attributed to greater resolution in the second comprehensive dataset that was used for change analysis. The first time period, 1911-1912, was based on identification of beds with harvest potential by local biologist George B. Rigg (Rigg 1912, Cameron 1915). The second time period, 1977-1978, was based on charts annotated during aerial surveys to provide ground-truth data for aerial imagery interpretation (Albright et al. 1980).

More recent analyses and anecdotal reports suggest that bull kelp is declining in South Puget Sound. Data compiled from diverse historical sources shows a decrease in the amount of shoreline in South Puget Sound with bull kelp in recent years (Figure 1-1, Appendix 1). This pattern of loss in recent decades agrees with observations of long-standing researchers in South Puget Sound who remember the gradual disappearance of multiple beds that were common in the late-1970's (Tom Mumford, personal communication, October 1, 2016).

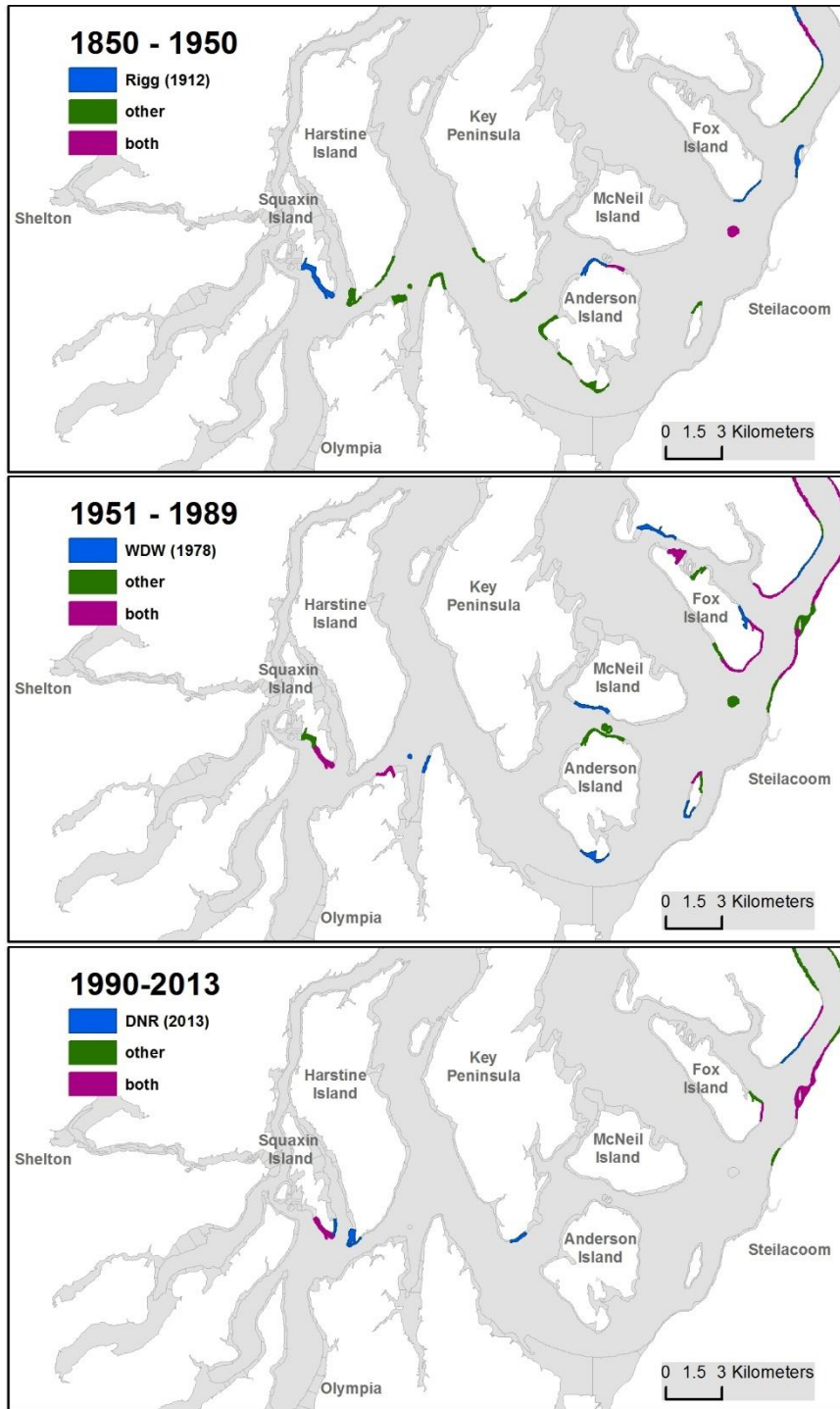


Figure 1-1. Presence of bull kelp during three time periods. Data shown in blue reflects a single comprehensive survey during the time period. The comprehensive surveys shown in the first two time periods are the same as those analyzed by Thom and Hallum (1990). Areas shown in green were identified in other surveys that did not cover the entire study area. Data in purple were noted by both the comprehensive survey and at least one other survey. The polygons summarize bull kelp presence in 1000 m alongshore segments. The waterward extent represents the -20 ft (MLLW) bathymetry line, not the extent of the bull kelp bed. Appendix A lists all datasets included. Compiled from data in the Washington Marine Vegetation Atlas (<http://www.dnr.wa.gov/programs-and-services/aquatics/aquatic-science/washington-marine-vegetation-atlas>).

The bull kelp bed at Tucksel Point on the southern tip of Squaxin Island has been characterized since the late 1800's as a notably large and persistent bed in South Puget Sound (Figure 1-1). Its persistence in recent years, amidst the disappearance of other beds, makes it a strong candidate for ongoing assessment. Understanding long-term trends in bull kelp could provide insight into habitat condition for a wide range of species. Because the bed is situated in a geographic extreme in Puget Sound in relation to oceanic influence, it could provide information on the effects of climate change or anthropogenic impacts.

On a more basic methodological level, analyzing changes in bull kelp in Puget Sound over time requires synthesizing data collected with diverse methodologies. The Northwest Straits Commission (NWSC) recently developed a volunteer-based kelp bed mapping protocol (Bishop 2014) that could produce monitoring data from individual beds at many sites in northern Puget Sound. Applying and comparing the NWSC methods could provide context for future comparisons that synthesize volunteer-based mapping results and other datasets.

The objectives of this study are to:

- Map the total extent of the Tucksel Point bull kelp canopy in 2013, 2014 and 2016. Assess changes in total canopy extent and depth distribution over time. Compare 2013-2016 results to other surveys.
- Collect information on bed density to facilitate more detailed assessments of bed condition.
- Implement the NWSC volunteer-based kelp bed mapping protocol and compare it to other results.

2 Methods

2.1 Study Area

The data used in this study were collected in the nearshore area off Tucksel Point, near the southern tip of Squaxin Island (Figure 2-1). Historical data and surveys spanning decades determined that bull kelp occurs in a single discrete bed along this relatively exposed, high current, southwest-facing stretch of shoreline.

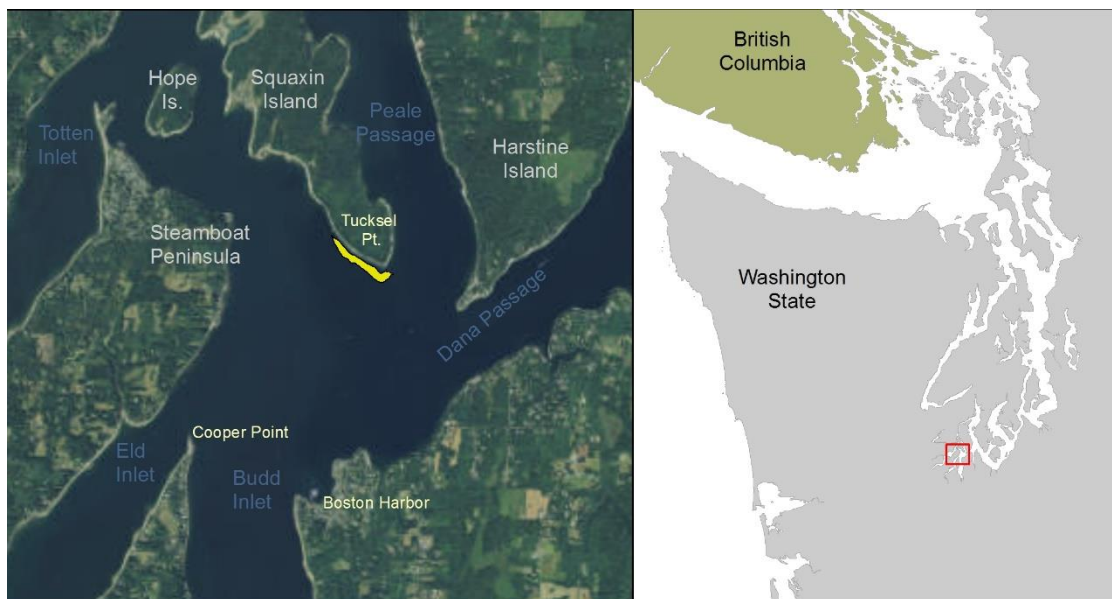


Figure 2-1. A. Study area location, showing the location of bull kelp bed in yellow waterward of Tucksel Point on Squaxin Island. B. Regional context, red box denotes location of A.

2.2 2013 and 2014 Survey of Canopy Extent and Depth

We mapped the spatial extent of the bull kelp canopy by motoring around the perimeter of the bed in a 17' Boston Whaler during low tide (<0 m MLLW) on August 5, 2013 and August 8, 2014. A Trimble ProXT Receiver and Nomad Data Logger recorded the location of boat during the circumnavigation.

The boat navigated along the deep extent of all bull kelp that occurred along the shoreline and the across-shore edges. The shallow, shoreward boundary of the bed was not navigable by boat at low tide. So, the shallow boundary line was photo-interpreted in the office using DNR 3-ft color orthophotographs.

A single maximum bed depth value was approximated in 2013 as the typical depth reading of the Boston Whaler's depth sounder while navigating the outer edge of the bed and correcting for tidal stage. This general estimate was further developed on August 17, 2016 by measuring depth at regularly spaced points along the outer boundary of the 2013 perimeter polygon with the Boston Whaler's depth sounder.

2.3 2016 Survey

We mapped canopy extent and a series of other measures of bed depth and density during low tides on July 18-22, 2016. Work was conducted from 2 single, sit-in Eddyline Equinox kayaks (4.3 m length). Garmin GPSMap 78sc units recorded the location of the kayaks during navigation. The spatial accuracy during surveys was $\pm 2.1 - 2.7$ m (reported by instruments based on satellite coverage at the time).

We returned to the site on August 17, 2016, collected samples for identification of endophytes and observed the condition of the bed in a Boston Whaler.

Surface temperature and salinity at the shallow and deep boundaries of the west and center beds were measured on July 21 between 12:00 and 12:30 Pacific Daylight Time (PDT).

2.3.1 2016 Full Canopy Extent

We mapped the full spatial extent of the bull kelp canopy by kayaking around the perimeter of the bed while recording the location with a GPS. This method generally used a 'connect-the-dots' approach of kayaking from the outermost bulb to outermost bulb of the bed. It included spatially isolated single bulbs. Both the deep and the shallow boundaries were delineated. We mapped the full extent 3 times to assess differences among observers and repeated surveys.

2.3.2 2016 NWSC Bed Mapping

We applied the protocol designed by the Northwest Straits Initiative Commission for volunteers to delineate the perimeter of kelp beds (Bishop 2014, updated in 2016). The protocol defines a bed to be a cluster of stipes and blades greater than 5 meters wide. Gaps greater than 8 meters in size in the kelp canopy constitute a separate bed. These thresholds lead to a different demarcation of bed location and extent (as compared to the full extent). We mapped the beds multiple times to assess differences among observers and repeated surveys.

2.3.3 Density

Density of individual kelp plants was measured using two techniques. First, it was measured at points along a 40 meter systematic grid (Figure 2-2). A relatively large grid of points was defined in the office, then culled to include plausible kelp locations using on-the-ground field information.

In order to capture non-zero density measurements in this low density bed, a relatively large circular quadrat with a diameter of 4.3 meters was used. The quadrat's diameter was demarcated by the ends of a kayak of the same length. The circle's perimeter was located by swinging the paddle from bow to the stern of the kayak, just above the

water surface. The length of paddle used to define the circle was equal to the circle's radius (2.15 meters). Density was calculated at each point, then averaged to estimate mean bed density.

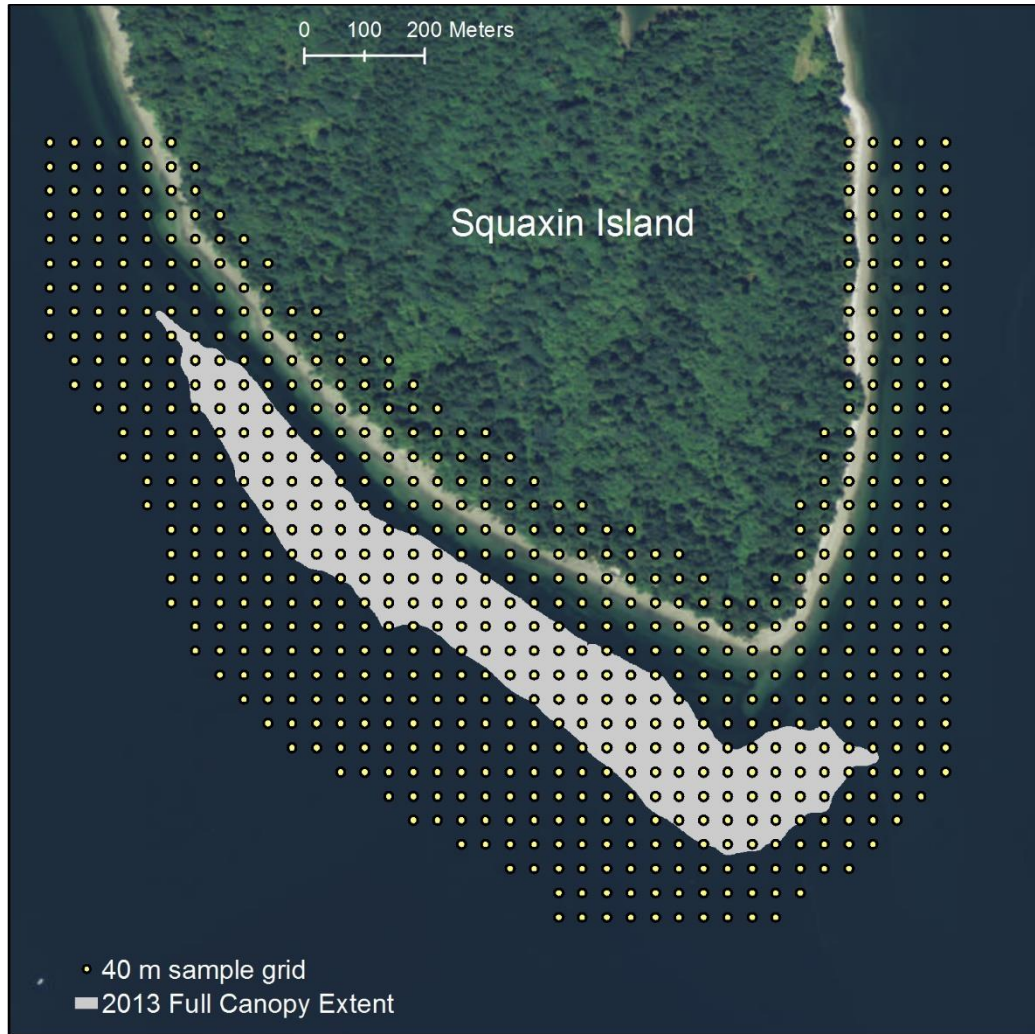


Figure 2-2. A 40-meter grid of points was defined in potential floating kelp habitat prior to field work for density surveys and for starting points of regularly placed across-shore transects through the bed. Points were also used to estimate maximum bed depth of the 2013 (data collected in 2016). The 2013 kelp canopy extent is included for reference in grey.

A total of 154 points were assessed for density. Mean density calculations were based on estimates from:

- 48 points inside the bed, as delineated by the 2016 full extent polygon.
- 8 points had kelp present but were located slightly outside the delineated 2016 full extent polygon. These points were also included in the average density calculation. Points located outside the 2016 full extent polygon without kelp were excluded from the calculation.

Density was also measured along across-shore transects that were also used for depth estimation (described below and shown in Figure 2-3). Along each transect, we counted the total number of kelp individuals (stipe or blade) that the hull of the boat passed over at the cockpit. The total count of individuals within the transect was extrapolated to an areal estimate by multiplying the GPS-derived transect length by the hull width at the cockpit (0.6 m).

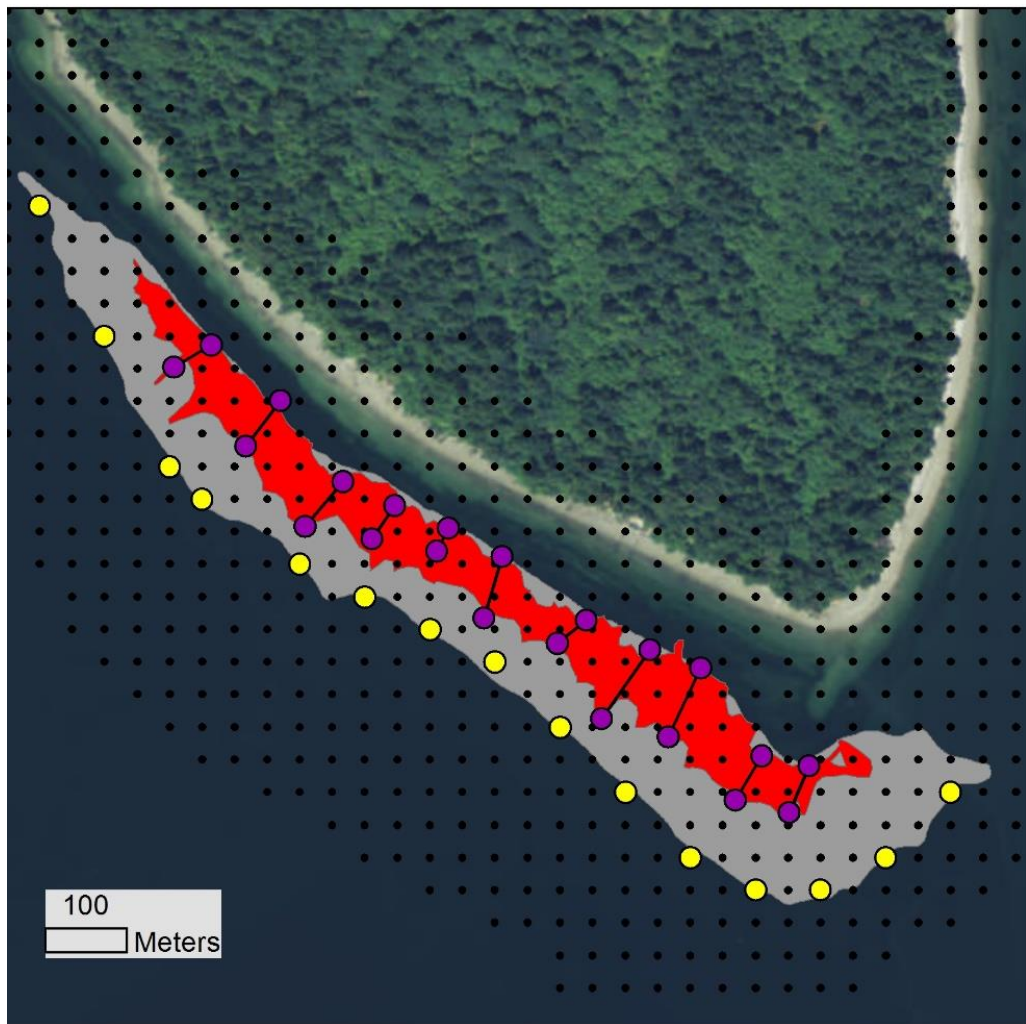


Figure 2-3. Locations of minimum and maximum depth measurements. Yellow dots denote locations where maximum bed depth in 2013 was assessed. Purple dots correspond to 2016 minimum and maximum depth measurement locations. The connecting black line shows the transects used for density estimation. The 2013

canopy extent is shown in grey and the 2016 extent is shown in red. Black dots denote density measurement stations, dots above +1 m MLLW and greater than 200 meters from the delineated bed were assumed to be 0.

2.3.4 Depth Distribution

Minimum and maximum bed depth were measured at 11 regularly placed across-shore transects through the bed by lowering a weighted tape measure. Transect boundaries began and ended where kelp occurred within 5 m in either alongshore direction. Measured depths were subsequently corrected to predicted tides in the office.

Minimum and maximum depth measurements were collected at regularly spaced intervals along the 2013 and 2016 bed perimeters (Figure 3-4).

2.3.5 Data Analysis

Geospatial data was processed using ArcMap version 10.3.1 (ESRI 2011). Numerical analysis was performed using R version 3.2.3 (R Development Core Team (2008)).

2.4 2016 Drone-based Aerial Photography Survey

We collected natural color digital photography with a resolution of 23 mm from a drone flying at 80 m altitude on July 20, 2016 during low tides (Table 2-1). Three flight lines were delineated to capture the extent of bull kelp. Flight line 2 was not collected due to a malfunction in the gimbel that positions the camera.

Drone photography was georeferenced and retained for future analysis.

Flight line	location	Time	Water level (MLLW)	Tidal stage	Sun angle (above horizon)	Image quality
1	northwest	1245-1251	-2.0 ft	low slack	65°	Water more 'milky', tide lower. Oblique imagery.
3	center	1410-1415	-0.2 ft	incoming	60°	Greater kelp discrimination due to contrast, tide slightly higher

Table 2-1. Conditions during 2016 drone-based aerial photography

3 Results

3.1 Full Canopy Extent

In 2013, bull kelp canopy extent was estimated to be 9.5 ha (Figure 3-1). In 2014, canopy extent estimate decreased to 6.9 ha. The bed contracted slightly along the deep edge of the bed and the margins.



Figure 3-1. Bull kelp canopy extent in 2013 and 2014.

In 2016, canopy extent was delineated three times (Figure 3-2). The mean area estimate was 2.7 ha (sd = 0.18), and ranged from 2.5 to 2.9 ha (Table 3-1). Discrepancies between the three surveys were most often associated with:

- Whether individual kelp plants that were distant from the rest of the bed were included. This difference is visible along the deep edge in the northwest section of the bed, where some polygons extend in narrow rays to include a single plant. Differences among observers are primarily attributed to visibility; single plants can be hard to see from a kayak.
- Whether the boundary of the bed was generalized in areas where the bed width contracted substantially into an hourglass shape. This difference is visible in the southeast portion of the bed.

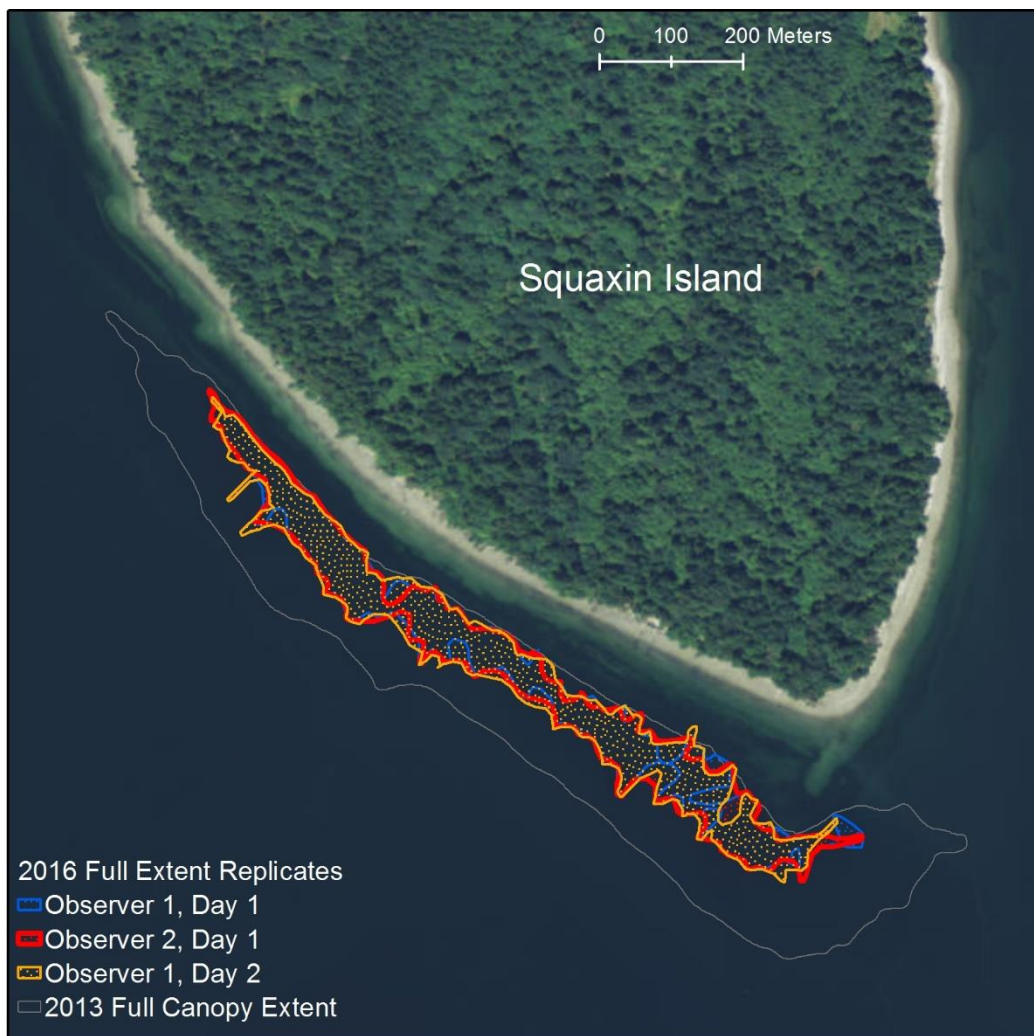


Figure 3-2. Three surveys of bull kelp canopy extent in 2016, collected by 2 observers over 2 days.

feature	area_ha	observer	day	tidal height
full extent	2.53	1	18 July	-0.4
full extent	2.74	2	18 July	-0.4
full extent	2.89	1	19 July	-0.5
center bed	0.31	1	18 July	-0.4
center bed	0.32	2	18 July	-0.4
west bed	0.5	1	19 July	-0.3
west bed	0.61	2	18 July	-0.3
west bed	0.63	1	18 July	-0.3

Table 3-1. 2016 features mapped, including area, observer, date and tidal height at time of survey.

3.2 Comparison of Full Canopy Extent (2013-2016)

Between 2013 and 2016, canopy extent decreased substantially to approximately one-third of its original size (Table 3-2). No survey was completed by DNR in 2015, however the Squaxin tribe observed that the bed was approximately 30% larger in 2015 than it had been in 2014 (Scott Steltzner, Personal Communication, September 17, 2016).

year	area (ha) ± sd	% of 2013 area
2013	9.5	100%
2014	6.9	73%
2016	2.7 ± 0.18	28%

Table 3-2. Annual kelp canopy area 2013-2016

The three 2016 full extent surveys were merged for visual comparison to the 2013 and 2014 surveys. The canopy extent of the merged 2016 bed was 3.3 ha, approximately one-third of the full canopy extent in 2013 (Figure 3-3). The deep edge of the bed contracted considerably. The alongshore extent of the bed also contracted slightly.

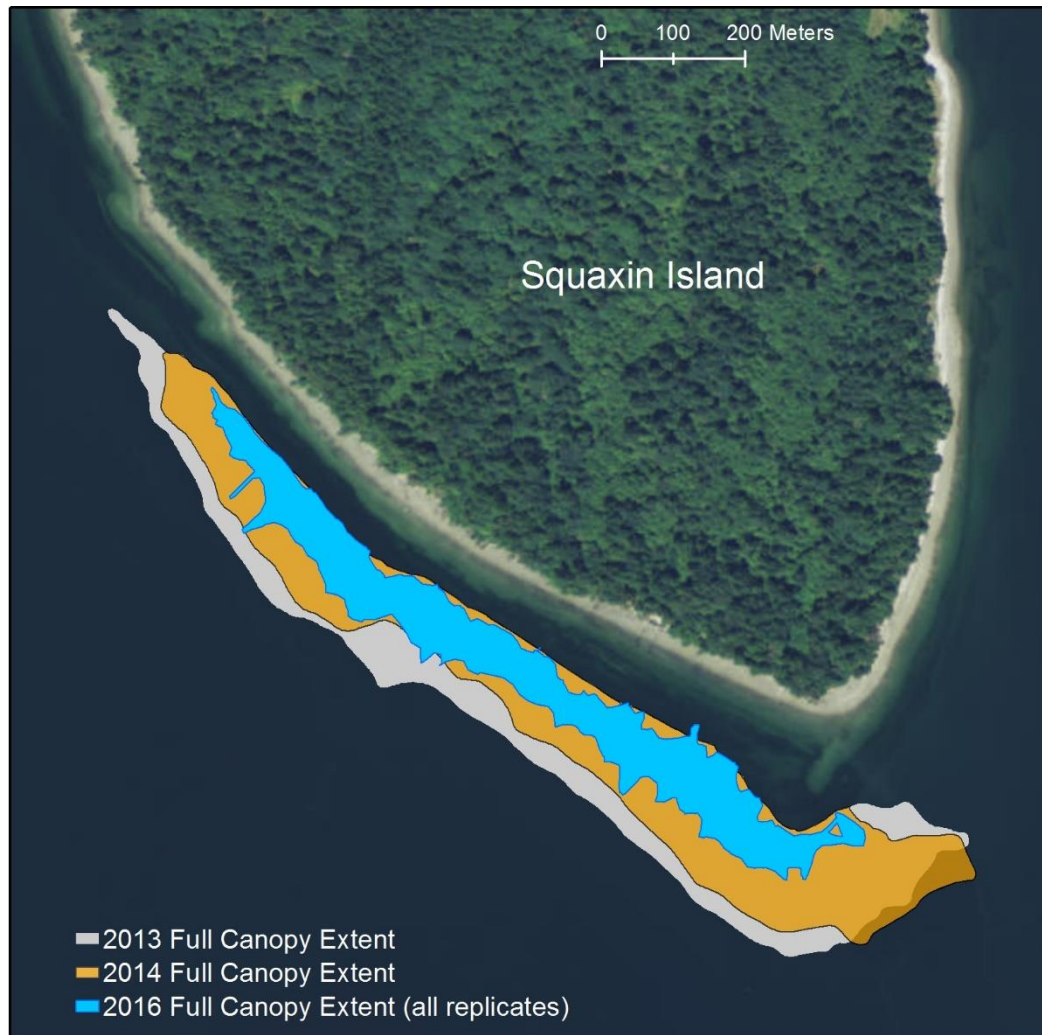


Figure 3-3. Bull kelp canopy extent in 2013, 2014 and 2016.

3.3 NWSC Volunteer-based Survey Protocol Results

Two beds were delineated using the NWSC protocol, named the ‘west’ and ‘center’ beds (Figure 3-4 and Table 3-1). No other areas met the minimum NWSC size and density thresholds. Mean area of the west bed was 0.6 ha, estimates ranged from 0.50 to 0.6 ha. The center bed was approximately 0.3 ha. The bed perimeters mapped by different observers who were working together on the same day were relatively similar, and area estimates differed by 3%. The survey of the west bed on a different day was substantially smaller and differed by 20-23% in total area from previous estimates. The observers reported that during surveys on the first day, consultations between surveyors before and during the navigation led to the similar results.

The beds delineated using NWSC protocol were approximately one-third of the area of the full canopy extent due to the minimum thresholds for plant density and bed width (Table 3-1).

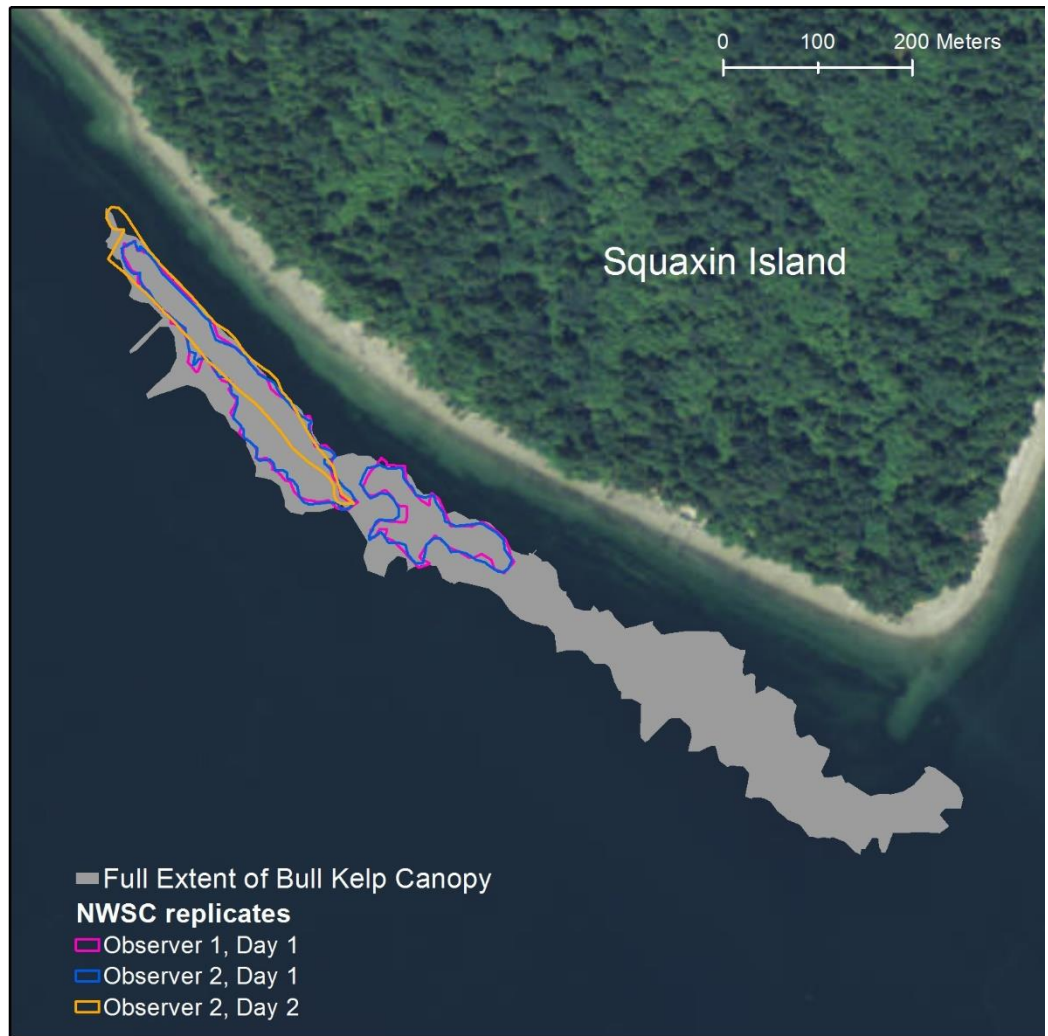


Figure 3-4. The perimeters of the west and center kelp beds delineated using the NWSC protocol. Colors represent repeated surveys by two observers over two days. Pink polygons were mapped by observer 1 and blue polygons were mapped by observer 2, working in tandem to define the bed boundaries on day 1. The tan polygon was mapped solely by observer 2 on the subsequent day. The 2016 enhanced full extent polygon is shown in grey.

Surface temperature and salinity at the shallow and deep boundaries of the west and center beds were measured on July 21 between 12:00 and 12:30 Pacific Daylight Time (PDT). All temperatures were 16° C or greater, temperatures in shallow areas were higher than in deep areas, salinity measurements were similar at all locations (Table 3.3).

Bed	Location	Temperature (°C)	Salinity (psu)	Depth (m MLLW)
west	shallow edge	16.4	28.1	-1.2
west	deep edge	16.0	28.2	-2.4
center	shallow edge	16.9	28.1	-1.3
center	deep edge	16.1	28.3	-2.4

Table 3-3. Salinity and temperature observations

3.4 Bed Depth

In 2013, average maximum depth was -4.4 m MLLW (sd = 0.9), and ranged from -2.7 to -6.0 m. In 2016, maximum depth was significantly shallower (Welch’s two sample t-test, $t = -8.91$, $df = 23.6$, $p\text{-value} < 0.0001$). The average maximum depth was -2.5 m (sd = 0.2), and ranged from -2.1 m to -2.8 m (Figure 3-5).

In 2016, the average minimum depth was -1.2 m (sd=0.3), and ranged from -0.7 m to -1.6 m. No minimum depth estimates exist from 2013 or 2014 for comparison because the line was imprecisely mapped in those years. The mapped location of the shallow edge of the bed was generally similar in all three years, along the low tide line.

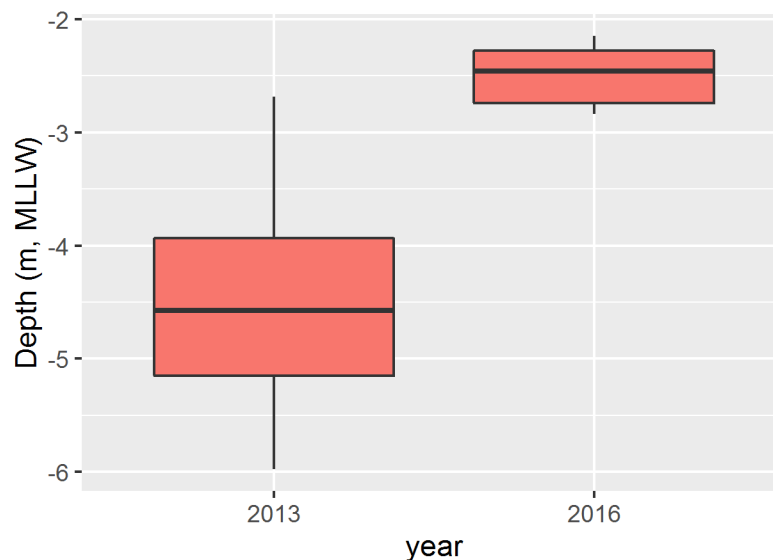


Figure 3-5. Annual maximum bed depth.

3.5 Density

No density measurements exist from 2013 or 2014. In 2016, density of kelp measured in across-shore transects through the bed averaged 0.32 m^{-2} and ranged from 0.02 to 1.09 m^{-2} . (Figure 3-6). Results based on grid point measurements were similar: average density was 0.28 m^{-2} , it ranged from 0 to 2.5 m^{-2} .

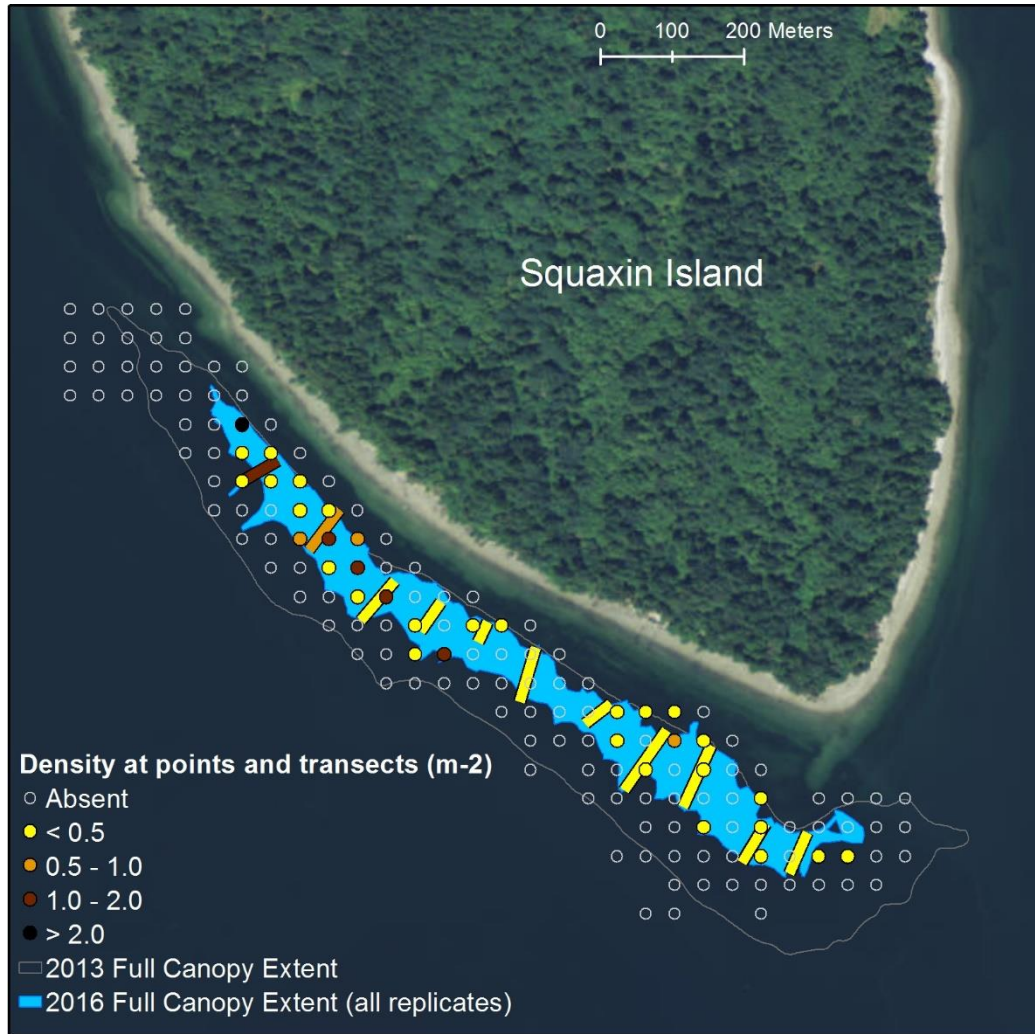


Figure 3-6. Kelp density measured at points and along transects through the bed. The 2013 and 2016 full extent polygons are included for context.

Kelp was present at 8 grid points outside the 2016 full extent polygon, near the perimeter boundary and, in many cases, within the uncertainty of the spatial data (Figure 3-6). These points were included in the calculation of average density, along with all points that fell within the 2016 full extent polygon.

The points located outside the bed where kelp was noted to be present provide information on the accuracy and precision of the bed survey. The mean distance of

points from the edge of the surveyed bed was 8 meters, and it ranged from 1 to 28 m. This discrepancy is attributed to:

- 1) Mapping error in low density kelp areas, the majority of the points had only 1 kelp stipe present;
- 2) Positional error associated with the GPS units;
- 3) Movement of the kayaks due to currents.

3.6 Plant Condition

Many of the bull kelp individuals appeared to be in poor condition. Although no plant measurements were collected, they generally appeared small relative to bull kelp observed elsewhere in WA. Many had irregularities on the surface of the bulb and stipe, either surface irregularities that appeared to be endophytes (Figure 3-7, 3-8) or that appeared to be mechanical damage (Figure 3-9). Some had mis-shapen growth (Figure 3-10), and high epiphyte cover (Figure 3-11). Many lacked blades (Figure 3-9), Majid crabs were commonly found on the stipes and bulbs (Figure 3-11), and sometimes appeared to be submerging the plants (Figure 3-12).



Figure 3-7. Example of bull kelp individuals that appeared to be in relatively good condition. Surface irregularities are visible on stipe and bulb.



Figure 3-8. Stipe and bulb with rounded surface irregularities that appear to be associated with endophytes.



Figure 3-9. Stipe with linear surface irregularities that appear to be associated with mechanical damage.

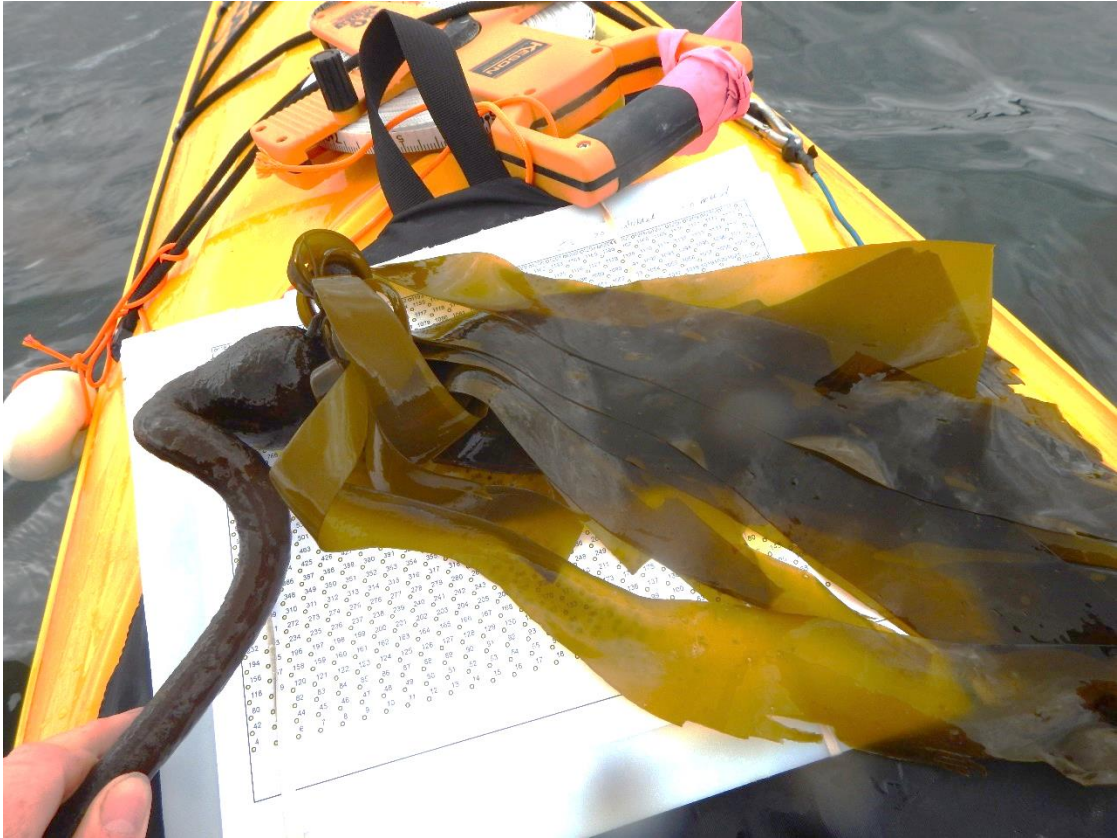


Figure 3-10. Bull kelp with mis-shapen stipe.



Figure 3-11. Majid crab on submerged, epiphytized bull kelp.



Figure 3-12. Bull kelp cluster which appeared to be submerged by abundant majid crabs.

We examined the surface irregularities (Figure 3-8) from samples collected on August 17, 2016 under a microscope (Figure 3-13). They appear to be associated with an endophyte that is characterized by flat basal cells with a central cluster of upright uniseriate filaments. The larger circular patches on the host could be damaged kelp tissue. The sample did not key out to one of the common endophytes in the region, in part because the basal cells were not clearly visible and in part because no reproductive structures were visible. One candidate endophyte is the brown alga *Streblonema* sp., which is known to form galls and produce misshapen stipes in bull kelp (Apt 1988). No galls were observed at Tucksel Point, and misshapen stipes were present but not common (Figure 3-10). Bull kelp beds within Puget Sound have been documented with a high proportion of *Streblonema* infestation (Andrews 1977). However, pathogenic rates are unknown. Another candidate species is the brown alga *Myrionema* sp., for which little information could be found.

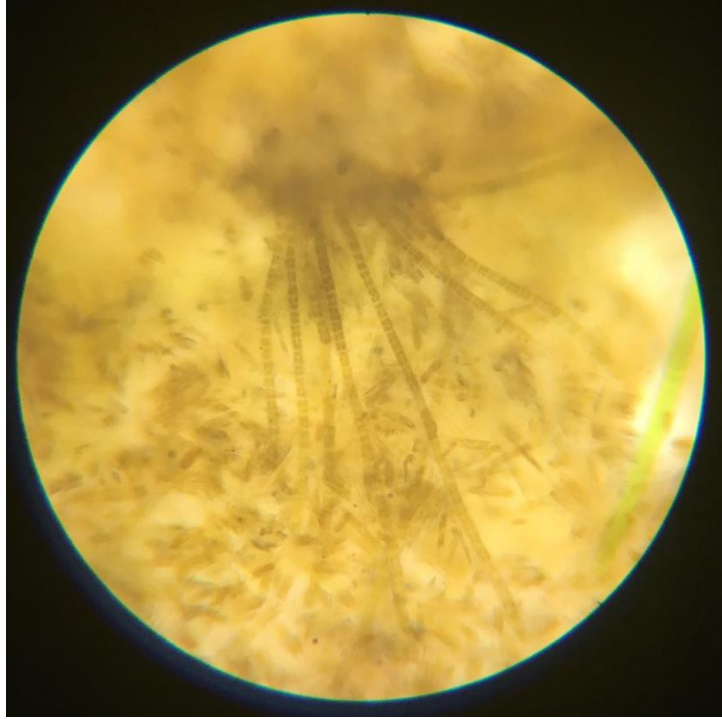


Figure 3-13. Magnified view of endophyte showing upright filaments projecting from surface of kelp tissue. Diatoms and green algae are also visible on kelp tissue.

3.7 Comparison to Historical Datasets

Historical datasets between 1873 and 2004 suggest that the Tucksel Point bull kelp bed has persisted throughout the time period (Figure 1-1, Figure 3-14, Table 3-6). The only map that did not show bull kelp to be present was the US Coast Survey map from 1873. However, it was noted to be present in the 1878 survey within the same series.

All maps except 1873 portray kelp near the Tucksel Point, but the alongshore extent varies. The surveys in 1912 and 1954 show the bed extending farther to the northwest, approximately double the alongshore length of other surveys. The remaining surveys portray the bed to be limited to the southwest-facing portion of the shoreline. The 1978 survey portrays the bed to be substantially wider than later years. However, this delineation is not precise, it is based on rough field notes drawn in pencil on a 1:100,000 NOAA chart.

The 1994 and 2004 surveys include the most methodological information for consideration. The 1994 survey was completed in a 17' Boston Whaler on July 6, 1994 by Allison Bailey, Betty Bookheim and Tom Mumford. The tide was estimated to be +0.3 m (MLLW), based on the notes and the fact that they successfully navigated the Whaler along the shallow edge of the bed. The field notes describe the bed as dense along the deep edge, and less dense along the south portion of the bed. One observer noted that the bed was smaller in 1994 than it had been in undocumented

observations from 1992. Overall, the 1994 canopy extent appears similar to the 2013-2016 extent, with two important caveats:

- The footprint of the 1994 bed would have been smaller due to the higher tidal height at the time of mapping, relative to the 2013-2016 perimeter. Interestingly, a substantial bed remained visible at +0.3 m (MLLW) tidal height in 1994. In 2013-2016, the bed was completely submerged at 0.45 m (MLLW).
- The bed was described as ‘dense’ in 1994, especially along the outer edge. In 2016, the bed had low density.

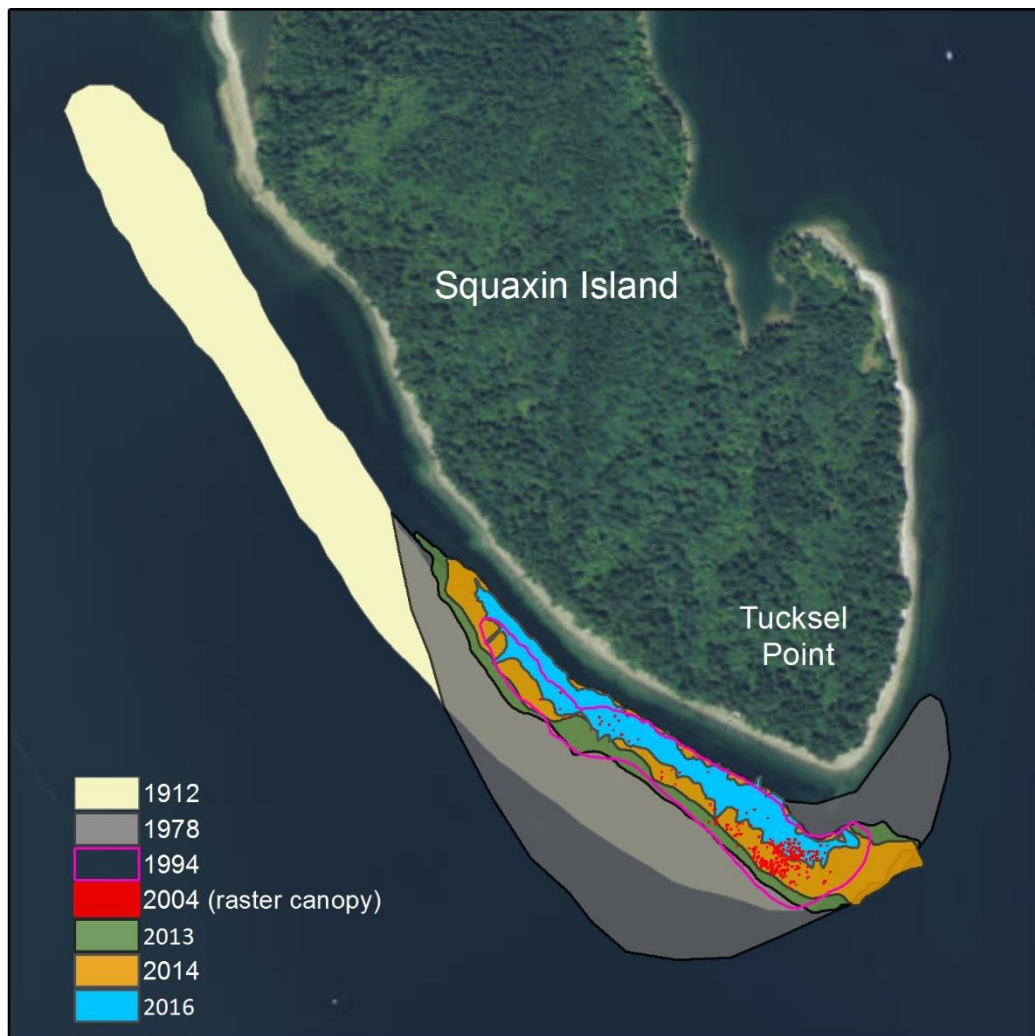


Figure 3-14. Bull kelp extent from various surveys between 1912 and 2016. Differences between the survey results reflect methodological differences as well as changes in the kelp canopy. (US Coast Survey and WSU survey not included).

The 2004 data were derived from digital classification of low-tide aerial photography on August 30, 2004 at 13:49 PDT. Tidal height was -0.05 m (MLLW). Color-infrared imagery was collected at 1:12,000 using a large format survey grade camera (methods are described in Berry 2007). The classification identified pixels with a floating canopy rather than bed perimeter, which includes both the canopy and gaps between individual kelp fronds. Despite this difference, survey results suggest that the bed was substantially smaller in 2004 than all other years. This result could be attributed to seasonal differences; perhaps the kelp died off relatively early in 2004 as it did in 2016. It could also be attributed to methodological differences, especially the detection capability of aerial photography.

Year	Source	Comparison to 2013-2016	Methodological Considerations
1873	US Coast Survey (T-sheet #1327)	No bull kelp noted at Tucksel Point	Tidal height unknown. Bull kelp noted on Briscoe Point, which confirms that it was delineated during this work.
1878	US Coast Survey (T-sheet #1672)	Wide bed noted. Alongshore extent similar to 2013-2016.	Tidal height unknown. Presence noted with symbols, not a precise polygon.
1912	Rigg (1912), Cameron (1915)	Alongshore extent greater to northwest. Bed density much higher (3/4-5/4 per sq. ft.).	Tidal height unknown. Bed width delineation not reliable due to map scale (1:100K).
1954	Washington State University	Alongshore extent greater to northwest, similar to 1912 survey.	Unknown – data drawn from summary in Thom and Hallum (1990).
1978	Washington Dept. of Wildlife	Similar alongshore extent. Bed wider, but based on imprecise mapping.	Imprecise field notes, drawn on 1:100K map.
1994	Washington Dept of Natural Resources	Similar in alongshore extent. More dense along deep edge (based on field notes).	Tidal height unknown, assumed to be positive tide because Boston Whaler navigated along shallow edge. This would likely have led to a smaller bed delineation.
2004	Washington Dept of Natural Resources	Canopy extremely limited in extent and density.	Detection could be lower with color-infrared aerial photography. High quality imagery: 1:12000 scale collected at 0 ft (MLLW).

Table 3-6. Bull kelp characterization from surveys between 1873 and 2004, compared to results in 2013-2016.



4 Discussion

This study implemented a series of bull kelp surface canopy survey techniques in order to characterize bed extent and condition in recent years. It also compared recent results to historical data in an effort to extend the time span of consideration.

Results show that total canopy area and maximum depth decreased significantly between 2013 and 2016. Additionally, the plants were low in density and in poor physical condition in 2016. These results raise concern about the current condition and the future viability of the bed.

Comparison of datasets over longer time periods is much more uncertain. Studies in 1911 and 1954 suggest that alongshore bed length was more than twice the current length, while other studies suggest alongshore length has not changed. Stipe density appears to be considerably lower, based on comparison to two existing characterizations in 1911 and 1994.

4.1 Preliminary Observations of Bull Kelp Abundance in 2016 in greater Puget Sound

Given the large interannual variability of bull kelp (e.g. Van Wagenen 2015), it is important to consider the results at Squaxin Island in a larger spatial and temporal context. Preliminary observations by regional researchers suggest distinct regional patterns in bull kelp abundance in 2016. In comparison the long-term monitoring record, abundance appears to have been stable or high along the Strait of Juan de Fuca and low in Central and South Puget Sound in 2016.

Low bull kelp abundance was observed in areas with large and persistent beds in Central Puget Sound:

- In early August, Brian Allen and Tom Mumford observed low abundance of bull kelp in Central Puget Sound at sites with historically persistent beds (Tom Mumford, personal communication, August 17, 2016). The Wing Point bull kelp bed at the entrance to Eagle Harbor on Bainbridge Island was reduced to a few stipes, the majority lacked blades and harbored kelp crabs. Along the eastern Seattle shoreline, the Elliott Bay Marina breakwater was devoid of bull kelp where it had previously been observed. The known bull kelp beds to the west of the Elliott Bay Marina and adjacent to Myrtle Edwards Park were both present. To the north, there were small beds at the Shilshole Marine breakwater and near the Richmond oil pier.
- On July 3, in Admiralty Inlet along the southern shoreline of Scatchet Head on Whidbey Island, the bull kelp bed was observed to be substantially reduced in bed width and density relative to recent years (Jeff Gaeckle and Helen Berry).

Along the Strait of Juan de Fuca, beds were observed in 2016 to be stable or increasing compared to previous 1-3 years:

- Along the outer coast and the Strait of Juan de Fuca, relatively large beds were observed in comparison to previous years during aerial photography collection for long-term kelp canopy monitoring (Bob Van Wagenen).
- In the Neah Bay area in July and August, bull kelp and giant kelp beds were extensive (Kathy Pfister and Helen Berry). This observation was quantified in long-term monitoring surveys.
- In the Elwha area, bull kelp beds were substantially larger than in the last 5 years (Helen Berry). Changes in these beds could constitute local recovery following massive sediment outflows associated with Elwha River dam removal that peaked between fall 2011 and fall 2013.
- In the Port Townsend area, the North Beach bed was observed to be relatively large relative to recent years (Ian Fraser).
- Near Ebey's Landing on the eastern Strait of Juan de Fuca, bed area was measured to be similar in 2015 and 2016 in August (Island County Marine Resource Committee 2016).

Given these observations from other areas of PS, the decline seen at Tucksel Pt is consistent with other observations from central/south PS. This raises concern about the viability of kelp generally in the central/south PS region but given the Tucksel Pt bed is at the most distant edge of the range for kelp, concern is especially high for the Tucksel Pt bed.

4.2 Candidate Stressors

The cause of the observed decrease in canopy extent between 2013 and 2016 at Tucksel Point is unknown. A variety of biological and physical factors are considered to be candidates, based on field observations and on studies predominately completed in other regions with other species of kelp.

Environmental conditions likely play an important role. Bull kelp is known to respond to irradiance, substrata, sedimentation, nutrient levels, temperature, water motion and salinity. However, since these factors seldom act in isolation, their effects are often difficult to understand (Dayton 1985). Bull kelp is believed to have low tolerance to elevated temperatures. In response to a 3.5°C rise in temperatures induced by a power-generating station in central California, bull kelp decreased by 97% over 10 years and did not recover. It was replaced by giant kelp (Schiel et al. 2004), a species more tolerant of warm water which does not occur within Puget Sound proper.

Kelp growth and abundance can be limited by nutrient levels, especially nitrate. Because temperature has been shown to be inversely related to nitrate concentration, temperature has been used as a proxy for nitrate availability in California (Dayton et al. 1999). Kelp climate research has used a threshold of 16°C, above which there are insufficient nutrient levels in the water column (while also acknowledging variability in the nitrate-temperature relationship in areas with high abundance of animals and water mixing.) All of the temperature measurements in the Tucksel Point bed were above the 16°C threshold on the single day that temperature was measured in 2016.

Analysis of a longer term temperature time series near Tucksel Point could provide more information on the relationship between temperature and kelp abundance. Additionally, research in this region could provide insight into whether the relationship between temperature and nitrate in Washington is similar to that developed in California.

Climate change is expected to alter environmental conditions in complex ways. Bull kelp is generally expected to respond negatively to increased temperatures and positively to decreases in calcified herbivores (Harley et al. 2011). Because Tucksel Point experiences elevated temperatures relative to other regions in Puget Sound that are closer to oceanic influence, changes in this bed may foreshadow changes in other regions of Puget Sound.

A variety of invertebrates live on, and graze on, kelp plants. Kelp crabs in the Family Majidae were abundant in the Tucksel Point kelp bed and have been observed in other beds of concern in South and Central Puget Sound. *Pugettia producta*, the species observed at Tucksel Point, is the most common majid crab found in Puget Sound kelp beds (Kozloff 1993). Kelp crabs are known to feed primarily – and sometimes exclusively – on kelp forest seaweeds (Hines 1982). A recent local study documented that kelp crabs consume bull kelp in the San Juan Archipelago along with other species, including snails (K. Dubkowski, personal communication, October 12, 2016). In lab studies, crabs eat bull kelp stipes and blades, generally choosing the blade first and then moving on to the stipe. When given small bull kelp (<40 cm), they sometimes sever the stipe first with their claws (and sometimes consume the bulb before it floats away). Local research suggests that juvenile mortality is very high among small bull kelp and physical damage and/or consumption likely plays a role. When exposed to large consumers, young bull kelp generally fails to thrive, while it tends to grow well when protected by exclusion cages.

Kelp crabs are generally not observed to have a major effect on giant kelp (*Macrocystis pyrifera*) abundance in California (Shiel and Foster 2015). However, increased kelp herbivory by kelp crabs at Tucksel Point could be related to lower crab predation rates. In central California, Hines (1982) noted that kelp crabs were rarely seen with epiphytes on their shells because the life span of crabs was short following their terminal molt at adulthood. In contrast, the kelp crabs at Tucksel Point were epiphytized, which suggests they have a longer life span. They also appeared to be abundant. Kelp crabs have a wide range of predators in California including octopuses, sea otters (*Enhydra lutris*) and a wide variety of fishes, especially bottomfish (Hines 1982). While sea otters are not known to have been present in South Puget Sound historically, other species were present historically which consume kelp crabs, including river otters. Populations of many bottomfish species in Puget Sound are currently substantially lower than historical levels (Palsson et al. 1998, WDFW 2011). These could have led to changes in food web interactions in the region, including decreased kelp crab predation.

4.3 Survey Protocols for Detecting Change over Time

Many factors are known to limit the precision of bull kelp canopy area estimates, including tidal height, currents, water roughness, season, and confusion among

vegetation species (Van Wagenen 2015, Britton-Simmons et al. 2008). In spite of these limitations to precision, canopy surveys are substantially less expensive and resource-intensive than subtidal assessments based on SCUBA, and they cover larger areas. For these reasons, bull kelp canopy assessments potentially complement subtidal SCUBA surveys, which provide more rich and detailed information, but are generally limited to smaller areas. Other more rapid subtidal assessment techniques such as towed video or ROVs are difficult, or impossible, to deploy in bull kelp beds due to entanglement.

The boat-based methods employed in 2016 at Squaxin Island provided greater confidence in kelp abundance estimates than previous surveys:

- Surveying the full extent multiple times provides an estimate of uncertainty, and makes more robust testing of results possible.
- Maximum and minimum depth measurements allow for comparison of depth distribution, a metric that is known to respond to water column characteristics.
- Density measurements on a systematic grid and across-bed transects provide two repeatable estimates of bed density. These locations could be re-surveyed to assess change over time with more precision than a new random draw of locations. Density measurements also provide a quality check on the degree to which all individual plants were included in a canopy extent survey.

Comparison of kelp canopy extent among historical datasets had high uncertainty due to differences among survey methods, especially survey resolution and intensity. Scales ranged from 1:12,000 to 1:100,000 and survey intensity ranged from rapid, general-purpose mapping to multi-day kelp surveys that optimized tide and weather conditions. In addition to methodological considerations, environmental conditions at the time of the survey are known to play an important role in kelp detection. We have noted in the past 4 years that all plants in the Tucksel Point bed and other beds south of the Tacoma Narrows, were completely submerged at tidal stages above +0.5 m. This leaves a very small window for effective surveying, and reinforces that observed bed area is strongly dependent on tidal stage. Water surface roughness also affects plant visibility. These factors make the most reliable comparison of historical datasets to be presence vs absence. The Tucksel Point bed has been highly persistent, unlike other beds in South Puget Sound (figure 1-1). Additionally, the consistent presence of the bed in early general-purpose surveys suggests that the bed was visible over a greater tidal range in the past, perhaps because the bed or the individual stipes were larger. In contrast, recent mapping efforts have targeted narrow tidal windows and ideal conditions in order to effectively delineate the bed.

4.4 Priorities for Future Work

Annual surveys of the Tucksel Point kelp bed using the 2016 methods will provide ongoing information on the bed condition. Related studies to better understand environmental conditions could include:

- Analysis of existing long-term temperature data to understand temperature patterns near Tucksel Point and other bull kelp beds.

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- Analysis of total tissue nitrogen to analyze whether nitrogen is limiting. While anthropogenic nitrogen input into Puget Sound has increased over time, nitrogen availability to kelp may have decreased due to uptake by plankton and water stratification.
 - Assessment of predator and herbivore populations at the site, especially kelp crabs.



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Appendix A Datasets Included in Historical Analysis

Source	Year surveyed	Portion of South Puget Sound Surveyed
US Coast Survey	1873	subarea
US Geological Survey	1875	subarea
US Coast Survey	1878	subarea
US Geological Survey	1886	subarea
Coast Pilot	1889	subarea
Fertilizer Resources of the United States (Rigg 1912, Cameron 1915)	1911-1912	comprehensive
Coast Pilot	1926	subarea
Coast Pilot	1951	subarea
Washington State University	1954	comprehensive
Phillips	1962-1963	subarea
Washington Department of Fisheries	1975-1989	subarea
Washington Department of Wildlife	1977-1978	comprehensive
WA State ShoreZone Inventory	1997-1999	comprehensive
WA Department of Natural Resources	2004	subarea
WA Department of Natural Resources	2013	comprehensive
WA Department of Natural Resources	2014-2016	subarea