Growth and morphology of *Saccharina latissima* in response to varying exposure to hydrodynamic conditions: A ripple effect

Emily Chapman[1,2], Isaiah Freedman[1,3], Kat O'Brien[1,4]

FHL 446 Marine Botany
Summer A 2023

[1] Friday Harbor Laboratories, University of Washington, Friday Harbor, WA 98250
[2] Department of Biology, San Francisco State University, San Francisco, CA 94132
[3] Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA 92093
[4] Department of Biology and Environmental Studies, Oberlin College and Conservatory, Oberlin, OH 44074

Contact Information:
Emily Chapman
Biology Department
San Francisco State University
1600 Holloway Ave
San Francisco, CA 94132
echapman1@mail.sfsu.edu

Keywords: bullation, growth, kelp, morphology, wave action, wave exposure

Abstract

Kelps (Order Laminariales) exhibit high morphological plasticity across the range of habitats in which they are found. *Saccharina latissima*, or sugar kelp, found commonly in the Pacific Northwest's rocky intertidal and subtidal, exhibits this variation. Prior studies have linked *Saccharina latissima*'s morphological variability to the surrounding physical environment. In order to better understand this relationship, we gathered morphological, growth, and environmental data from three different field sites on San Juan Island, Washington at Friday Harbor Labs, Cattle Point, and Deadman Bay. We found significant differences in variation between our sites in growth rate ($p < 0.01$), bullation pattern and prevalence ($p < 0.05$), and wave exposure ($p < 0.01$). However, we were unable to conclusively link the kelp's growth and morphology to wave exposure. Our results appear to conflict with the outcomes of previous studies. Despite its drawbacks, this experiment still has implications for *S. latissima*'s climate resilience and further understanding of coastal ecology. As climate change is expected to increase the frequency and severity of extreme weather events, documenting *S. latissima*'s morphology and reaction to increased wave action and disturbance is critical to detecting and understanding changing patterns.

Introduction

The marine intertidal and subtidal zones of Washington State are diverse and dynamic. The surrounding Pacific Northwest coast is host to numerous ecosystems including tidal flats, eelgrass beds, marshes, and kelp forests. These habitats are present in the marine reaches of the Salish Sea, which encompasses Puget Sound and the Strait of Juan de Fuca (Khangaonkar et al., 2019). San Juan Island (Figure 1), our study location, is home to a myriad of these ecosystems that support a smorgasbord of biodiversity. The hydrodynamic conditions resulting from close proximity to the Sound and Strait are ecosystem regulators. Such hydrodynamic conditions consist of wave action and current, upwelling and downwelling, tidal cycling, and anthropogenic turbulence (Mumford, pers. comm. 2023). Here, we focus on kelp morphology and its relationship to hydrodynamic conditions.

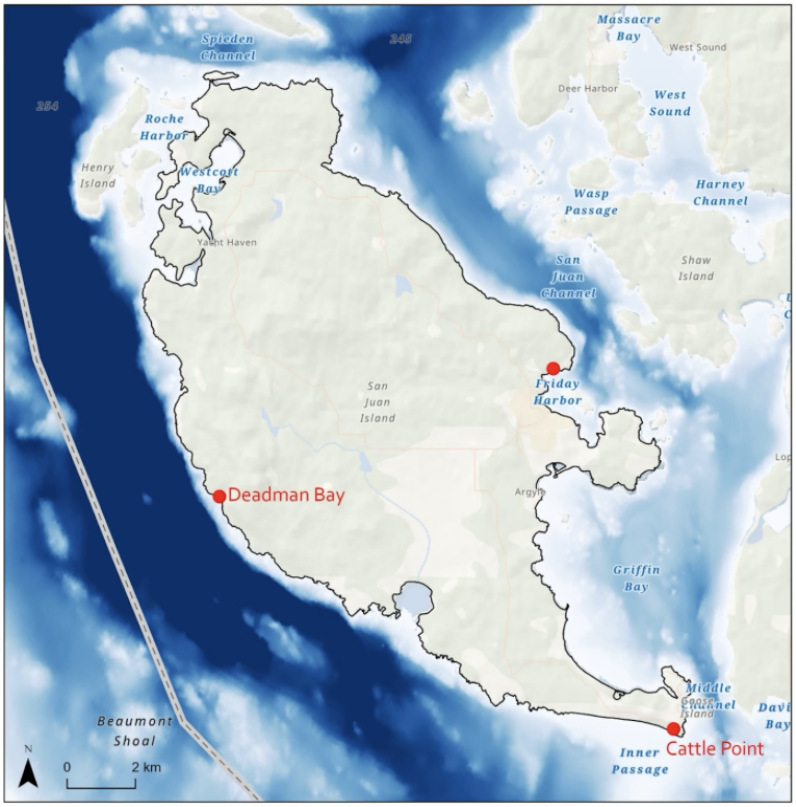

Figure 1. Map of San Juan Island in the Salish Sea. Marked field collection sites: Deadman Bay (DB), Cattle Point (CP), and Friday Harbor Labs (FHL)

At the land-sea interface, macroalgae are ecological and cultural foundation species which sustain a substantial abundance of marine populations (Zhu et al., 2021). Kelp beds in particular provide critical ecosystem services related to carbon sequestration, primary productivity, erosion control, and habitat for important life stages of fishes, invertebrates, and marine mammals (Hollarsmith et al., 2022). Organismal reliance on macroalgae extends from primary consumers and epibionts, such as bryozoans and urchins, to secondary and tertiary consumers, namely endangered rockfish and sea otters (WDFW, 1981). Likewise, during the mixed semi-diurnal tidal cycling in the Salish Sea, kelp found in the lower rocky intertidal zone provide sun protection and thermoregulation for crustaceans and other ecologically and commercially critical invertebrates (White & Marshall, 2006).

Saccharina latissima, a kelp within the class Phaeophyceae and order Laminariales, is commonly found in sheltered sublittoral fringe and lower intertidal habitats that are subject to moderate-to-high wave exposure (Merzouk et al., 2011). As a euryoecious and plastic species, *S. latissima* tolerates temperatures from 0 to 23ºC, with optimal growth at 10 to 15ºC, allowing wide distribution in the Pacific Northwest and Salish Sea temperate waters (Diehl et al., 2023). These neritic zones and shores are influenced by both oceanic and atmospheric dynamics and experience a steep stress gradient associated with tidal cycles. A driving factor for our examination of productivity and morphology in *S. latissima* is location-based exposure to differing wave action and currents.

In general, surface wave action we observe in the ocean is produced by wind (Denny, 1988). Wind events are the main propagator of upwelling– the degree to which winds push surface water away from shore and subsurface water rises. The water rising to the surface is colder and richer in nutrients, which fosters high biological productivity (NOAA, 2023; Harley et al., 2006). Marine systems are expected to drastically respond to changes in wind patterns with higher frequency of extreme wind events expected. Accordingly, as wind events are predicted to increase in frequency, upwelling is due to increase. This strong correlation with upwelling intensity is seen in weather events such as El Niño and La Niña climate cycles (NOAA, 2023).

In tandem with high productivity rates, upwelling and alongshore advection patterns are strong determinants of dispersal and recruitment in marine systems (Gaylord & Gaines, 2000). In the midst of a changing climate, increasing frequency of extreme winds and associated storm waves has severe implications for intertidal and shallow subtidal systems that are vulnerable to hydrodynamic disturbance (Harley et al., 2006). It is expected that sublittoral and intertidal zones will exhibit a pronounced response to climate change impacts that may differ significantly from those seen in deep benthic habitats (Hawkins et al., 2009; Helmuth et al., 2006). In addition, warming ocean temperature is a confounding factor in the changing system (IPCC, 2015). Kelp may be particularly vulnerable to climate change due to their cold-water affinities and limited dispersal ability as well as their large thallus size may make them more susceptible to being destroyed by storm wave action (Merzouk et al., 2011). Due to the necessity for light, macroalgae cannot effectively hide in cracks and crevices to avoid flow forces (Denny, 1988).

Figure 2. A typical *Saccharina latissima* (Wuitner, 1921)

A typical *S. latissima* (Figure 2) consists of a holdfast and haptera that permanently attach to stable coastline bedrock or unstable substrata such as boulders and cobbles, a stipe, and a singular foliose blade lacking a midrib (White & Marshall, 2006). Bullations, the corrugated patterns that appear laterally down the blade, typically take the form of two rows of bubbles with a smooth strip in between. However, this pattern can vary significantly from individual to individual, often taking other forms (Zhu et al., 2021). This variability of bullation pattern has been observed in many other kelp species as well (Koehl et al., 2008). The variation in morphology is believed to be an adaptation to maximize photosynthetic potential while also resisting dislodgement. A study examining mechanical stress on bull kelp (*Nereocystis luetkeana*) found that blades grew longer, narrower, and less ruffled than normal when exposed to strong currents (Coleman & Martone, 2020). Our study aimed to see if the same holds true for *Saccharina latissima*. With high variability in their morphologies *S. latissima* could compensate for differing flow forces with more or less bullations.

Our examination focuses on a combination of differing flow forces: wave action and currents. Although we focus on these forces acting simultaneously, there is a stark distinction between the two. On a baseline level, currents are long term unidirectional forces that can be temporary or long lasting as well as on the surface or in deep water driven by wind, temperature, gravity, and the spin of Earth on its axis. Wave action, on the other hand, is short term orbital forces primarily influenced by wind speed and duration. Both of these forces create drag that act on kelp blades.

We revisited the hypotheses of Zhu et al. (2021) in which they demonstrated that growth, general morphology, physiology, and frond surface shape of *S. latissima* will vary with different levels of hydrodynamic exposure and nutrient availability. With that, they present a general hypothesis that there is no “standard” *Saccharina latissima* morphology. As wave action decreases, *Saccharina* blades compensate for low nutrient concentrations by forming more complex and rougher frond surfaces.

Conversely, Diehl et al. (2023) examined *Saccharina latissima* in the Baltic Sea and found results that conflicted with Zhu et al. They concluded that variability in *S. latissima* morphology did not necessarily correlate with abiotic conditions. Our research expands upon Zhu et al. and Diehl et al. with a localized *in situ* examination on San Juan Island, Washington, surrounded by the Salish Sea.

We hypothesize that *S. latissima* growing in more protected conditions will grow thinner and slower with more bullations, while those growing in more exposed areas will grow thicker, faster, and with less bullations. Our study attempts to reconcile the results from these two prior studies and determine if a correlation exists between *S. latissima*’s biological parameters and physical environment (in the form of wave and current action).

Materials & Methods

Research Sites

For our study, we selected three sites on San Juan Island: Cattle Point (CP) (Figure 3), Deadman Bay (DB) (Figure 4), and the Friday Harbor Laboratories (FHL) dock (Figure 5). Three *S. latissima* individuals were selected and tagged at both Cattle Point and Deadman Bay, and four were selected at the FHL dock. These three sites were chosen due to their varying exposure to currents and wave action. The Cattle Point field site is the southernmost point of San Juan Island, and is exposed directly to the Strait of Juan de Fuca, which extends west to the Pacific Ocean.

Figure 3. 6/28/ 2023 7:28am Tide: 1ft Cattle Point Lighthouse

Figure 4. 6/25/2023 3:15pm Tide: 1.6ft Pictured: D.W. Freshwater (left) and Isaiah Freedman (right) observing intertidal kelp at Deadman Bay

Figure 5. 6/30/2023 1:17pm Tide: 2.3ft Friday Harbor Labs Dock

Deadman Bay is a more sheltered alcove, facing southeast, with deeper tidepools. Friday Harbor dock is a sublittoral habitat that experiences less wave action due to its protected location within the harbor. The *S. latissima* thalli chosen on the FHL dock are all attached to the inside of a floating dock, facing the labs. This site is subtidal, as the dock rises and falls with the tides, and it is largely protected from waves and wake since it faces the shore rather than the open harbor. In order to ensure consistent data, and for easier site revisiting within the two weeks study period, we tagged individuals with a zip tie secured around the stipe. We visited sites every two to three days to measure growth rates, photograph the blades, and ensure clod cards (Figure 6) remained secure.

Figure 6. Clod cards drying before dispersal

Growth

Saccharina latissima, like all kelps, has basal meristematic growth in the blade near its stipe (Zhu et al., 2021). To measure the growth rates of our individuals of study, we cut small square holes (~ 1 cm^2) 15 centimeters from the base of the blade. After 10 days, we measured the distance from the hole to the start of the stipe and used the difference to determine how much the blade had grown to the nearest 0.5 cm. We calculated a daily growth rate using this difference.

In addition to growth rate, we used the cutout portions of each blade to measure blade thickness. After removal, we cross-sectioned the cutouts and examined them under a microscope magnified 20x. We used the eyepiece's reticle scale to measure each cutout's thickness. We ran a single-factor ANOVA ($\alpha = 0.05$) to determine whether there was a significant difference in thickness between the Cattle Point ($n = 3$), Deadman Bay ($n = 3$), and FHL ($n = 4$) samples.

Morphology

We analyzed blade morphology by examining bullations, the corrugated patterns that run along the length of the blade, using two methods. For the first method, we adapted the protocol outlined by Zhu et al. (2021), which categorized bullations into seven morphological types: bubble, thready, spring, net, bowl, smooth, and scattered (Figure 7).

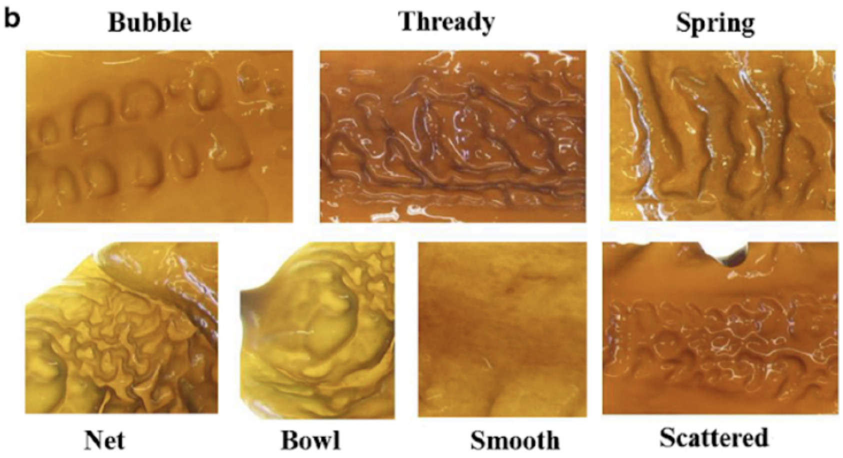

Figure 7. The seven morphological patterns of *S. latissima* (Zhu et al., 2021)

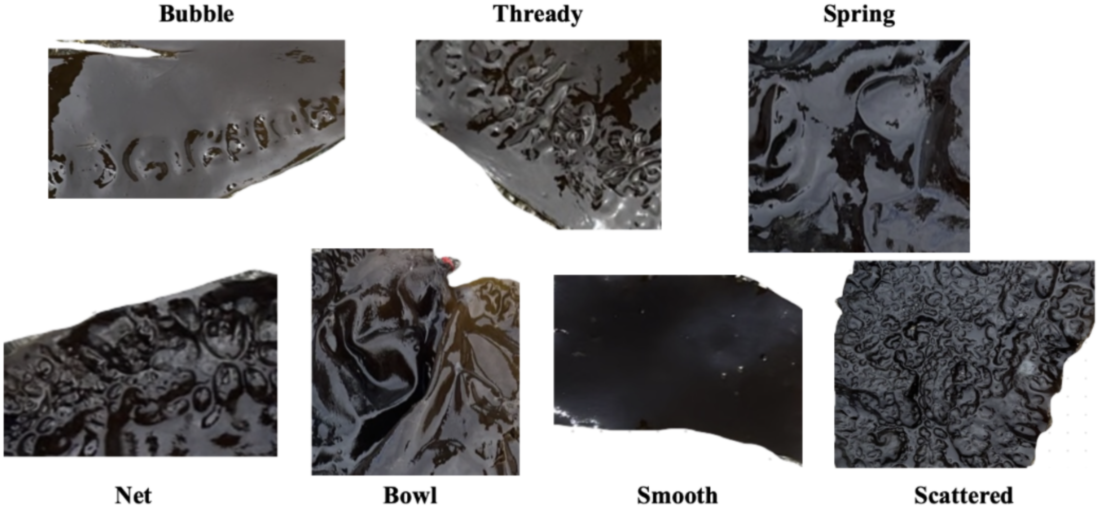

Figure 8. Seven morphological pattern types of *S. latissima* (San Juan Island 2023)

We photographed the blades *in situ* and analyzed the images to categorize the bullation patterns along the blade. Using the Zhu et al. (2021) protocol, we split sections of each blade into seven morphological patterns, which consisted of six bullation types (bubble, thready, spring, net, bowl, & scattered) and smooth (Figure 8). After categorization, we reported bullation patterns as a proportion of the entire blade. To categorize each thalli bullation pattern, a grid was placed over an image of each blade (Figure 9) , and the percent bullation was calculated from that image.

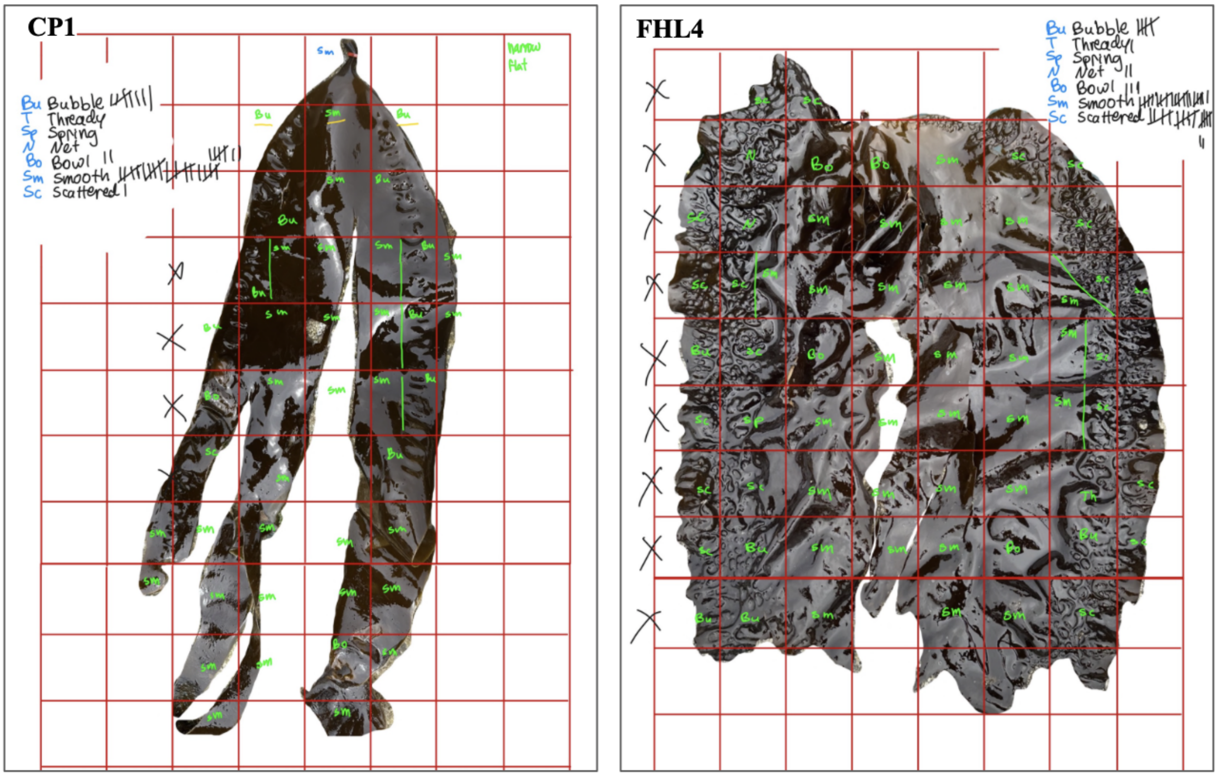

Figure 9. *S. latissima* morphology variability in CP1 versus FHL4

Figure 10. FHL3 Rugosity Measurement Example

For the second method, we measured the rugosity of each blade. Using a piece of string, we first laid it over the bullations while keeping the string taut, following the curve of the blade but not moving up and down with the bullations themselves, calling this the "how the crow flies" calculation (Figure 10). We made these measurements by tracing a path parallel to the edge, approximately 4 cm medially. If the blade was shredded or torn, we followed the longer side. After the measurement was recorded, we laid the string down again, this time directly on the surface of the blade following the pattern of the bullations, classified as "how the wolf wanders". We calculated a ratio between the "crow flies" length over the "wolf wanders" measurement, which described the blade's rugosity. A larger difference (high rugosity) between these two measurements describes a blade that is highly bullated and a smaller difference (low rugosity) between these measurements indicates a smooth blade.

Wave Exposure

Clod cards, as described by Doty (1971), are small plaster of Paris blocks that can be used to measure wave action. When secured underwater, they slowly dissolve away, eroding more quickly in areas with more exposure to waves and tidal currents. We constructed clod cards from plaster of Paris molded using an egg tray that produced cards approximately the shape and size of half a chicken's egg. They varied slightly in weight, ranging from 20-25 grams. After the plaster pieces air dried (Figure 6), we secured them to metal jar lids and measured the combined weight. Then, we adhered them to a heavy concrete block with rubber cement for intertidal placement in our intertidal sites (Figure 11 and 12).

Figure 11. 6/30/2023 Clod cards before dispersal at FHL Lab 3

Figure 12. 7/5/2023 Clod cards after retrieval at DB

For the FHL site, we attached the metal plates to the dock tires using zip ties, making sure to place these as close to our specimen as possible. We used three clod cards per site. As a control, we placed a clod card in a container filled with sea water. This container was placed in a large seawater tank to keep the temperature similar with that of our deployed clod cards. The control card allowed us to measure clod card weight loss when no wave action was present. The water was changed every two days to ensure dissolution matter remained relatively constant. The clod cards at our study sites were left in place for five days, after which we retrieved the clod cards, rinsed them in freshwater, and dried them in a 55℃ drying oven for 26 hours. We then measured their dry-weight in grams and determined the weight lost for each clod card. We used a basic calibration equation ($m_c/t = k$), which incorporates the dry weight of the control clod card (m_c) and the amount of time elapsed (t) to determine the calibration loss rate (k) (Doty 1971).

Similar calculations on the *in situ* clod cards, dividing the loss rate by the calibration loss rate, results in a "diffusion index factor" (DF), a value that relates to the overall wave exposure of the site. The diffusion factor is the rate at which the clod card dissolves relative to the rate of the control card.

Results

Growth

Ten days after cutting small square holes in the blades 15 cm from the base of the blade at our three study sites, we were able to determine their growth rates by measuring how far the holes had traveled because of new basal growth (Table 1). A single-factor ANOVA found that there was a significant difference in the growth in the meristem of the identified blades ($F_{2,7} = 10.81$, $p < 0.01$).

Table 1. Blade growth over a ten-day period of the ten studied *S. latissima* individuals

Sites	Cattle Point			Deadman Bay			FHL Dock			
Individual	CP1	CP2	CP3	DB1	DB2	DB3	FHL1	FHL2	FHL3	FHL4
Growth (cm)	8.5	6.0	8.0	6.5	6.0	2.5	0.0	2.5	3.0	2.0
Average growth		7.5			5.0			1.9		
Daily growth (cm/day)		0.75			0.5			0.19		

Thickness

Using the cutout pieces of blade from each specimen, analysis showed some slight differences in thickness between the blades at each of the three sites (Table 2). While the FHL dock had the thinnest individuals of the three sites, as we expected, analysis of the cutouts via single-factor ANOVA failed to find a significant difference in blade width ($F_{2,7} = 3.68$, $p > 0.05$).

Table 2. Blade thickness of *S. latissima* individuals and the site averages

Sites	Cattle Point			Deadman Bay			FHL Dock			
Individual	CP1	CP2	CP3	DB1	DB2	DB3	FHL1	FHL2	FHL3	FHL4
Blade Thickness (mm)	1.282	0.968	0.924	1.298	1.122	1.254	1.100	0.935	0.803	0.902
Average thickness (mm)		1.058			1.225			0.935		

Morphology - Rugosity

Analysis of rugosity measurements of the *S. latissima* blades found differences in bullations between all three sites (Table 3). A single-factor ANOVA ($F_{2,7} = 6.70$, $p < 0.05$) revealed these differences to be statistically significant.

Table 3. Rugosity of the ten studied *S. latissima* individuals and the site averages

Sites	Cattle Point			Deadman Bay			FHL Dock			
Individual	CP1	CP2	CP3	DB1	DB2	DB3	FHL1	FHL2	FHL3	FHL4
Rugosity	1.091	1.035	1.124	1.013	1.042	1.024	1.153	1.081	1.104	1.156
Average rugosity		1.076			1.026			1.123		

Morphology - Bullations

Analysis using the Zhu et al. (2021) protocol revealed similar differences between the blades at each site. Bullations on individuals at the FHL dock were most pronounced, the blades almost entirely covered in patterned corrugations, resulting in a range of bullation coverage, from 57% to 100% (Table 4). The blades at Cattle Point and Deadman Bay were less bullated, but the patterns were still present on all but one individual (Figure 13 and 14). The blades sampled from Cattle Point had a bullation coverage ranging from 21% to 31%, whereas Deadman Bay's coverage was more conservative, ranging from 0% to 26% (Table 4). It should be noted that many of the blades at both Cattle Point and Deadman Bay were heavily shredded, which made analysis of their morphology difficult. In addition, the blades at the FHL dock, while very large, were fragile and tore easily when moved and lifted out of the water (Figure 15).

Figure 13. *S. latissima* at Cattle Point: Morphology

Figure 14. *S. latissima* at Deadman Bay: Morphology

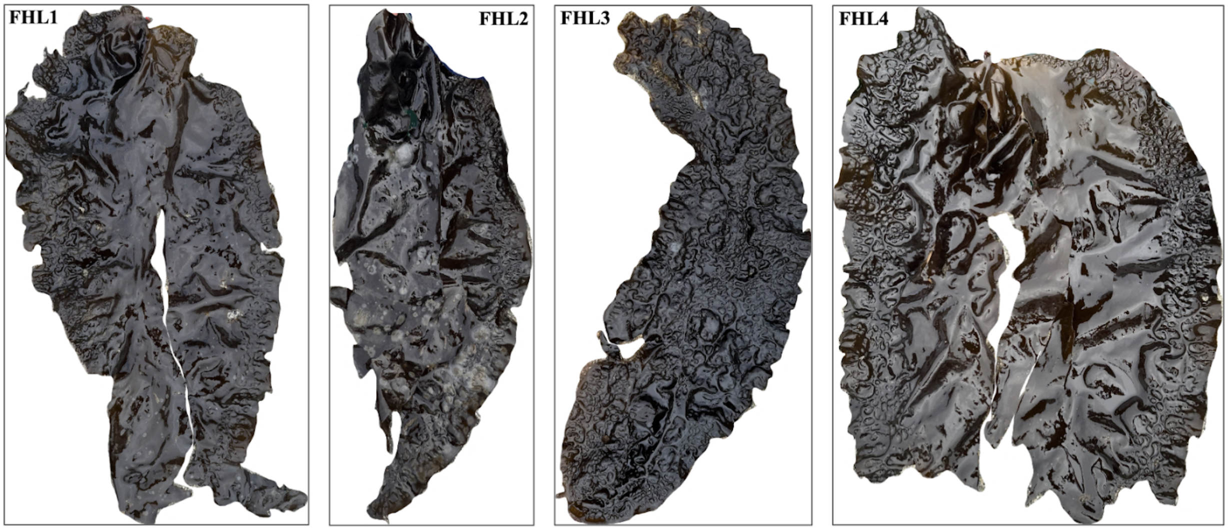

Figure 15. *S. latissima* at Friday Harbor Labs Dock: Morphology

Table 4. Proportion of blade with bullations (bubble, thready, spring, net, bowl, and scattered, as described by Zhu et al. 2021), as opposed to smooth

Proportion of bullation (%)										
Sites	CP1	CP2	CP3	DB1	DB2	DB3	FHL1	FHL2	FHL3	FHL4
Bullation type										
Smooth	69	78	74	93	74	100	40	39	0	43
Bubble	23	0	2	7	9	0	4	11	3	10
Thready	0	22	0	0	0	0	2	0	3	2
Spring	0	0	0	0	6	0	8	0	0	0
Net	0	0	19	0	0	0	4	11	7	4
Bowl	5	0	0	0	0	0	13	21	13	6
Scattered	2	0	5	0	11	0	30	18	73	35
Percent Smooth	69	78	74	93	74	100	40	39	0	43
Percent Bullated	31	22	26	7	26	0	60	61	100	57

Wave Exposure

Weights of the clod cards after retrieval revealed significant differences between our three sites. Calculations from the clod cards revealed that Cattle Point, our most exposed site, had the greatest DF (5.97), followed by the FHL Dock (4.36) and Deadman Bay (3.92) (Table 5). A single-factor ANOVA found the difference between sites to be statistically significant ($F_{2,5} = 14.95$, $p < 0.01$).

Table 5. Diffusion index factor (DF) for Cattle Point, Deadman Bay, and the FHL dock, obtained from clod cards

	Cattle Point			Deadman Bay			FHL Dock		
Individual	CP1	CP2	CP3	DB1	DB2	DB3	FHL1	FHL2	FHL3
DF	6.36	5.57	6.00	-	-	3.92	3.94	4.96	4.30
Average DF		5.97			3.92			4.36	

_

Correlation of Factors

After analyzing growth rate, blade thickness, rugosity, and wave exposure, we attempted to find correlations between factors using simple linear regression. However, no clear trend could be found between the biological parameters (growth rate and rugosity) and exposure (DF) when plotting the three data points (Cattle Point, Deadman Bay, and FHL Dock). When two factors were plotted against one another (e.g. growth rate and DF), we were unable to plot a trendline with any significant correlation coefficient (R^2 = 0.49 and 0.09 for growth rate and rugosity, respectively; since there was no significant difference in blade thickness between sites, we did not plot that comparison) (Figure 16 and 17).

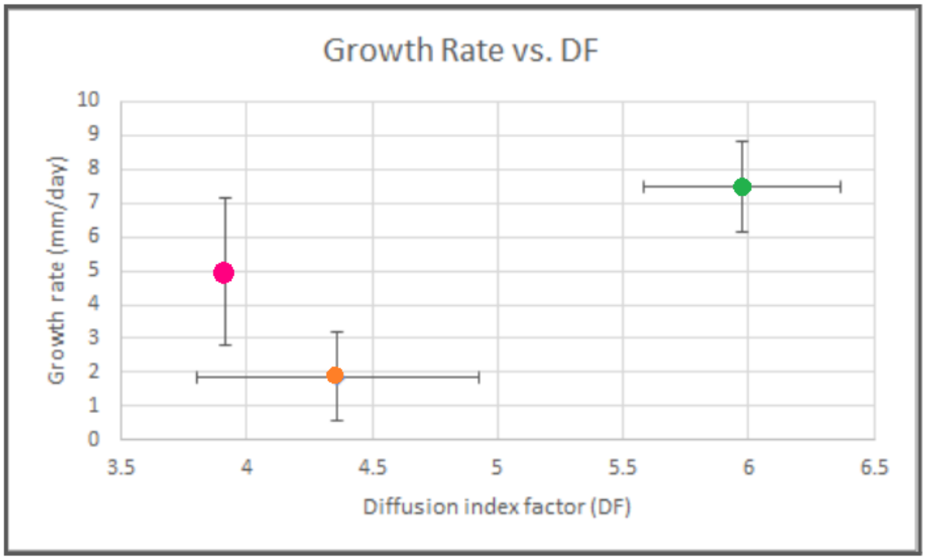

Figure 16. Growth rate and DF at Cattle Point (green), Deadman Bay (magenta), and the FHL dock (orange); error bars represent standard deviation.

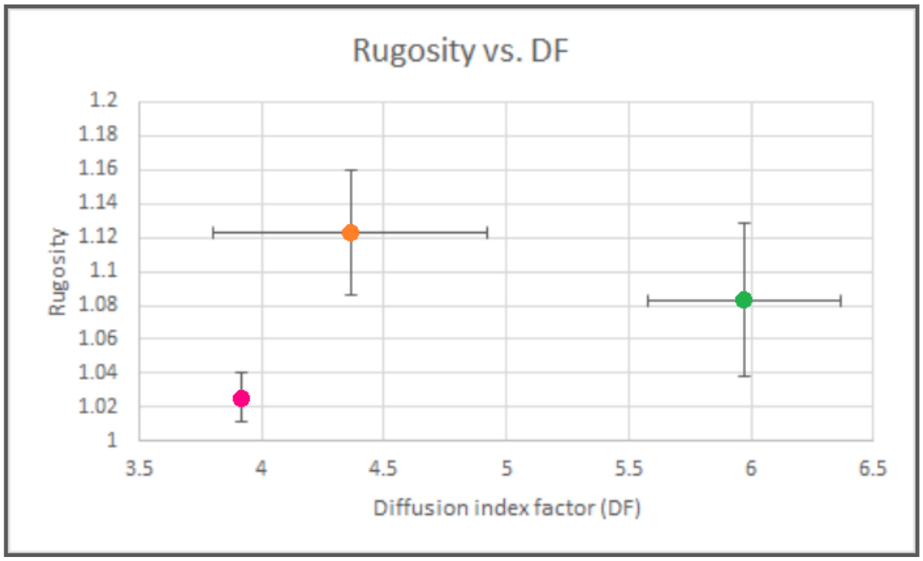

Figure 17. Rugosity and DF at Cattle Point (green), Deadman Bay (magenta), and the FHL dock (orange); error bars represent standard deviation.

Discussion

Interpretation of Results

While no obvious correlations were found between our multiple study parameters, we can still draw certain conclusions on the morphological plasticity of *S. latissima*. The growth rates of our ten individuals supported our hypotheses that individuals exposed to higher wave action have greater growth rates. Cattle Point, our most exposed site, had the highest DF as well as the highest growth rates. In addition, the FHL dock had the slowest growth, highest rugosity, and highest percent bullation of the three sites.

There was a significant difference between our sites within three of the four metrics assessed - DF, rugosity, and growth. Thus, we in part accept our hypotheses that *S. latissima* growing in more protected conditions grows at a slower rate than those exposed to more forceful wave action and is more bullated. At the Friday Harbor dock, the vast majority of the blades were heavily bullated, whereas our samples from both Cattle Point and Deadman Bay were smoother, lacking prevalent bullations.

We can confidently state that variation between sites is present and tied to morphological differences. However, we cannot fully accept nor reject our overarching hypothesis due to inconclusive evidence. Further study with a higher sample size and control of other factors, such as blade size, would likely lead to a more definitive result and conclusion.

Morphology

It is widely known that several different species of macroalgae have smooth, strap-like narrow blades in rapidly flowing water, but wide, ruffled “bullated” blades in sheltered sites (Koehl et al., 2008). In all of our sites, the size and proximity of individuals in the tidepool could potentially play a strong role in determining the thallus shapes. These blades were all torn to some degree and possibly missing sections, which could in turn skew our bullation and rugosity assessments. Bullations, as well as greater ruffled and corrugated edges, create drag potential. The intense currents during ebb and flood tides are likely responsible for this morphological distinction. Having shredded blades could possibly be advantageous at very exposed points with relation to drag by dispersing wave force and reducing the risk of tearing blades from their holdfasts, lowering their fitness (Coleman & Martone, 2020).

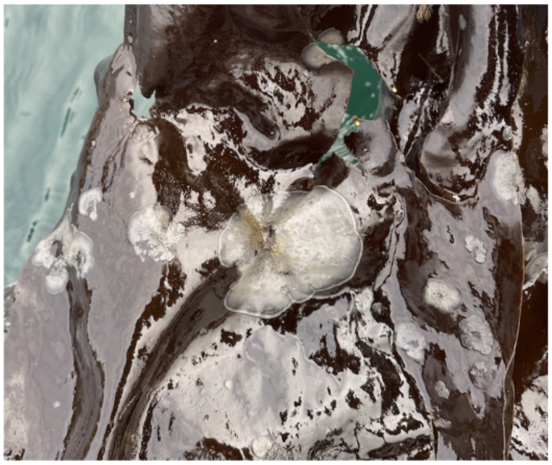

Figure 18. Bryozoans (Membranipora membranacea) on FHL1 thallus

While not quantitatively measured, it is interesting to note that some of the FHL dock blades were covered in encrusting bryozoans (mostly *Membranipora membranacea*) (Figure 18). As mentioned earlier, the blades at the FHL dock were fragile and tore easily when pulled out of the water. It is likely that the bryozoan's presence, and lack thereof at Cattle Point and Deadman Bay, is an indicator of their overall health and relates to this fragility (Førde et al., 2016). Furthermore, other studies seem to indicate that this reduced tensile strength relates to the wider growth pattern observed at the docks at the relatively low water flow (Diehl et al., 2023). We initially wanted to measure the tension strength of the blades with a tensiometer. However, due to limited time, we were unable to examine this metric. We hypothesize, however, that there would be a statistically significant difference in tensile strength between the three sites.

Implications of Varied Bullation and Wave Action

Until recently, it was believed that angiosperm-based coastal ecosystems, such as seagrass meadows, salt marshes and mangroves were the largest carbon sinks. In emerging research, however, macroalgae have been identified as major carbon donors to sediment burial reservoirs in the deep sea and other depositional areas where the carbon is removed from exchange with the atmosphere (Krause & Jessen, 2016). Kelp, as autotrophic macrophytes, primarily export carbon through particulate organic matter (POM) and dissolved organic matter (DOM). POM includes debris and detritus that is negatively buoyant while DOM includes mucilage and polysaccharides, or "slime", that are continuously exuded from kelp blades (Mumford, 2023). Both exports of carbon in kelp depend upon the photosynthetic capability of the alga. In measuring growth rate, we examined a proxy for productivity of our specific *S. latissima* blades. It could be advantageous for *S. latissima* to exhibit more bullations to increase nutrient and gas exchange (i.e. photosynthesis), meaning that they are more of a carbon sink than those that have less bullations. Further examinations of *Saccharina* would be necessary to determine whether this holds true or not.

Future research of the bullation patterns of kelp in exposed landscapes could indicate resilience to drastic change in hydrodynamic conditions in future meteorological predictions (Khangoankar, 2019). It is anticipated that climate change will be a forceful driver of large and local scale atmospheric forcing, increasing sea surface temperatures which minimize abundance and distribution of kelps like *S. latissima* (IPCC, 2015). The Intergovernmental Panel on Climate Change (IPCC) predicts amplified El Niño and La Niña events that will increase the severity of upwelling and downwelling effects on kelp ecosystems (IPCC, 2015). *S. latissima*, a proven morphologically plastic species, exhibits potential for acclimation to such events solely with regard to wave force tolerance due to varied bullation pattern. If *S. latissima*'s ability to adapt to environmental conditions holds true, this plasticity would allow for further resilience in the face of climate change.

Starting Points for Future Studies

When comparing our blade morphologies to those of Zhu et al. (2021), we identified two main setbacks. First, the bullation types we found did not directly match those identified in Zhu's protocol. We made our best attempt at matching our kelps to the images and descriptions given, but it is likely that we deviated to some degree. Second, our gridding of the images to categorize morphological patterns could have likely been done in a more efficient manner, such as through an image processing software (e.g. ImageJ). The limited time allocated to this analysis prevented us from being thorough and confident in our assessment.

Another potential drawback of our study can be found in the identity of the individual kelps we chose to examine. After the completion of data collection, we noted many similarities between *Saccharina latissima* and *Hedophyllum nigripes*, a related kelp species. *Hedophyllum nigripes* was previously considered a member of *Saccharina*, but the Laminariales (kelp) family tree has gone through significant change in recent years (Lane et al., 2006). The main morphological difference between the two species is the presence of mucilage ducts in the stipes of *H. nigripes* and their absence in *S. latissima*. While three of our individuals at the FHL dock examined under a microscope did not appear to have mucilage ducts, we cannot rule out the possibility that some of our other individuals may have not actually been *Saccharina latissima*, as we originally believed. We were unable to check the individuals at Cattle Point and Deadman Bay for mucilage ducts after making this discovery. While we do not have any strong evidence indicating that our individuals were *H. nigripes*, this possibility weakens our ability to draw meaningful conclusions.

We took pictures for bullation type assessment in the intertidal zone. Photography of our samples was difficult due to the uneven surfaces, submersion of most of the blades, and ever-changing sunlight. The “wolf wanders” rugosity measurement is by no means the most accurate execution of a complex measurement. Each specimen was unique, and although we tried to perform the rugosity measurements in roughly the same area along the blades, there was still room for error.

We also had difficulty finding our samples. At Cattle Point, at a tide of 1ft, we only found a handful of *S. latissima*, all of which were within the same tide pool and not directly exposed to the harsh waves of the Strait of Juan de Fuca. At Deadman Bay, the specimens that we were able to find and relatively easily revisit were all within the same tidepool, this time with a more direct outlet to the bay. Our low sample size limited our ability to draw conclusions. We originally included a fourth site, Reuben Tarte County Park, located on the north side of the island. However, during our initial site scouting, we arrived at Reuben Tarte (during a tide of 1.7 feet) to find all the *S. latissima* to be submerged in approximately 4-5 feet of water. Its inaccessibility made it difficult to study, so we disregarded it from our list of sites.

Complications with the clod cards may have skewed our wave exposure results. Due to issues with the adhesive used, we adhered the clod cards to a concrete block at Cattle Point and Deadman Bay and left them near the respective sites rather than attaching the clod cards directly to the rocks. As such, the clod cards at these sites did not match up one-to-one with the individuals of study. At the FHL dock, on the other hand, the clod cards were attached directly to the individuals of study by cutting a small hole in the metal plates and feeding through a zip tie, which were secured directly to the stipe of three of the kelps. Unfortunately, this left the clod cards vulnerable to abrasion with the blades and the dock. We believe this abrasion led to more weight loss than would have otherwise occurred for FHL's clod cards. We originally hypothesized that this site would have the lowest DF, since it is in a harbor and protected by a dock, as opposed to Cattle Point and Deadman Bay, which face west and southwest towards the Strait of Juan de Fuca and Haro Strait, respectively. Had the attachment issues not occurred, we believe that Deadman Bay would have had a higher DF than the FHL dock. This is a starting methodological point for future study.

Inability to make linear correlations highlights the fact that more factors are likely at play than just wave exposure. Despite all being locations around San Juan Island, our three sites were drastically different. The clod cards only measured the total amount of wave action the sites were exposed to over the course of the five day study period. Other factors, such as maximum wave exposure and time of submersion, have potential to factor in as well. Incorporating much of this into future studies would allow for more accurate data collection, analysis, and drawing of conclusions. Further studies that control for the specific area an individual grows (protected by a rock, in a tidepool, etc.) and size class would also allow for more accurate and insightful results.

Overall, while we were unable to confirm our hypotheses, we see this study as a great starting point for future research on kelp plasticity and response to environmental change. In addition to simply uncovering more about kelp biology, understanding this relationship has significant implications for conservation and restoration efforts.

Acknowledgments and Attribution

This research study would not have been possible without the support of our Marine Botany instructors, Dr. Thomas Mumford and Dr. Wilson Freshwater. Their extensive knowledge of phycology, observational techniques, and the coastline of San Juan Island greatly facilitated our ability to conduct this project. In addition, Sarah Tanja, the teaching assistant for Marine Botany, was an integral resource, and her enthusiasm for algae helped propel our work forward. We would also like to thank Jessie Bell, another student taking Marine Botany, for her help creating the GIS map of our sites. We would like to thank Friday Harbor Laboratories and the University of Washington for the use of their facilities, docks, and the stockroom’s many resources. For the funding, we would like to additionally thank Deb and Glen Bruels and the CSU COAST Grant. Finally, we would like to thank our many musical influences who kept us motivated through our work - Elsie Gawler, Oshima Brothers, Destroy Boys, Hozier, Tame Impala, and Steely Dan, among many others.

References

Coleman, L. J., & Martone, P. T. (2020). Morphological plasticity in the kelp *Nereocystis luetkeana* (Phaeophyceae) is sensitive to the magnitude, direction, and location of mechanical loading. *Journal of Phycology*, *56*(6), 1414-1427.

Diehl, N., Steiner, N., Bischof, K., Karsten, U., & Heesch, S. (2023). *Frontiers in Marine Science*, *10*, 995982.

Doty, M. S. (1971). Measurement of water movement in reference to benthic algal growth. *Botanica Marina*, *14*(1), 32-35.

Førde, H., Forbord, S., Handå, A., Fossberg, J., Arff, J., Johnsen, G., & Reitan, K. I. (2016). Development of bryozoan fouling on cultivated kelp (Saccharina latissima) in Norway. *Journal of Applied Phycology*, *28*, 1225-1234.

Gaylord, B. & Gaines, S. D. (2000). Temperature or transport? Range limits in marine species mediated solely by flow. *The American Naturalist, 155*(6), 769-789.

Gilson, A. R., White, L. J., Burrows, M. T., Smale, D. A., & O'Connor, N. E. (2023). Seasonal and spatial variability in rates of primary production and detritus release by intertidal stands of *Laminaria digitata* and *Saccharina latissima* on wave‐exposed shores in the northeast Atlantic. *Ecology and Evolution*, *13*(6), e10146.

Harley, C. D., Randall Hughes, A., Hultgren, K. M., Miner, B. G., Sorte, C. J., Thornber, C. S., Rodriguez, L. F., Tomanek, L., & Williams, S. L. (2006). The impacts of climate change in coastal marine systems. *Ecology letters*, *9*(2), 228-241.

Hollarsmith, J. A., Andrews, K., Naar, N., Starko, S., Calloway, M., Obaza, A., Buckner, E., Tonnes, D., Selleck, J., & Therriault, T. W. (2022). Toward a conceptual framework for managing and conserving marine habitats: A case study of kelp forests in the Salish Sea. *Ecology and Evolution*, *12*(1), e8510.

Khangaonkar, T., Nugraha, A., Xu, W., & Balaguru, K. (2019). Salish Sea response to global climate change, sea level rise, and future nutrient loads. *Journal of Geophysical Research: Oceans*, *124*(6), 3876-3904.

Koehl, M. A. R., Silk, W. K., Liang, H., & Mahadevan, L. (2008). How kelp produce blade shapes suited to different flow regimes: a new wrinkle. *Integrative and Comparative Biology*, *48*(6), 834-851.

Krause-Jensen, D., & Duarte, C. M. (2016). Substantial role of macroalgae in marine carbon sequestration. *Nature Geoscience*, *9*(10), 737-742.

Lane, C. E., Mayes, C., Druehl, L. D., & Saunders, G. W. (2006). A multi‐gene molecular investigation of the kelp (Laminariales, Phaeophyceae) supports substantial taxonomic re‐organization 1. *Journal of Phycology*, *42*(2), 493-512.

Merzouk, A., & Johnson, L. E. (2011). Kelp distribution in the northwest Atlantic Ocean under a changing climate. *Journal of Experimental Marine Biology and Ecology*, *400*(1-2), 90-98.

Mumford, T. (2023, Jun. 30). *Macroalgal Primary Productivity, Macrophyte Contributions to Coastal Food Webs, Trophic Cascades, & Carbon Sequestration* [Lecture]. FHL 446A - Marine Botany, Friday Harbor Laboratories, Friday Harbor, WA, United States.

NOAA (2023, Jan. 23). *What is upwelling?* National Ocean Service. https://oceanservice.noaa.gov/facts/upwelling.html

NOAA (2023, Feb. 2). *What are El Nino and La Nina?* National Ocean Service. https://oceanservice.noaa.gov/facts/ninonina.html

White, N. & Marshall, C. (2006). *Sugar kelp (*Saccharina latissima*)*. MarLIN - The Marine Life Information Network. https://www.marlin.ac.uk/species/detail/1375

Wuitner, É. (1921). Pheophyceees (Algues brunes) Laminariees, Laminaria saccharina (Lamour) [Image]. Freshwater and Marine Image Bank, University of Washington, Seattle, WA, United States. https://digitalcollections.lib.washington.edu/digital/collection/fishimages/id/53666/rec/1

Zhu, G., Ebbing, A., Bouma, T. J., & Timmermans, K. R. (2021). Morphological and physiological plasticity of Saccharina latissima (Phaeophyceae) in response to different hydrodynamic conditions and nutrient availability. *Journal of Applied Phycology*, *33*, 2471-2483.