

Productivity assessment of two kelps, *Saccharina latissima* and *Alaria marginata*, at varying seawater depths

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Abstract

Climate change now affects virtually all forms of life, disrupting the foundations existence on Earth. Major reductions in greenhouse gases are vital, but mitigation strategies to reduce extreme impacts must be implemented now. Importantly, the healthy functioning of the ocean is the ultimate reservoir of stability for living beings. Anthropogenic emissions are raising ocean temperatures and acidification beyond its immense buffering capacity. Mitigation efforts must include kelp forest restoration and ocean aquaculture. This in situ experiment examined *Saccharina latissima* and *Alaria marginata* kelps to assess their productivity in assimilating carbon relative to growing depth. Light played an important role, due to attenuation with depth. Future research should work to optimize species mix and spatial configurations, over longer durations.

Introduction

Carbon dioxide steadily rises in the atmosphere and ocean (Fig. 1). Fossil fuel production and industrial uses remain the largest, still increasing, global greenhouse gas emissions (IPCC 2023, see Fig. 2). In our atmosphere, these gases have long altered relatively stable biosphere diversity, but now result in extreme weather events, ice melt, flooding, drought, food insecurity, disease, species extinctions, and numerous other shifts in biological viability.

Ancient photosynthetic organisms, such as cyanobacteria and their descendants, reduced atmospheric carbon dioxide levels by incorporating carbon into microbial-resistant compounds. Algal and plant cell walls and structures, along with carbonate mineral production, formed the basis for carbon sequestration, where carbon in sediments became unavailable for respiration. (This step is essential for maintaining modern atmospheric oxygen levels required by aerobic organisms. Aquatic algae also had to adapt to low CO₂ levels due to the success of terrestrial plants, often with the enzyme rubisco (RuBisCO) and carbon concentrating mechanisms, or CCMs).

The Biological Carbon Pump describes this sedimentation as dissolved and particulate organic carbon and carbonates which drift and eventually settle on the floor of a water body. This removes atmospheric CO₂ and over long time periods has created hydrocarbon fossil fuels.

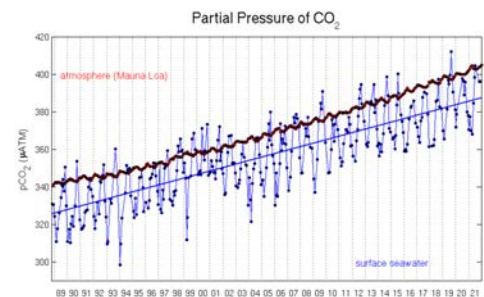


Fig. 1 ALOHA time series

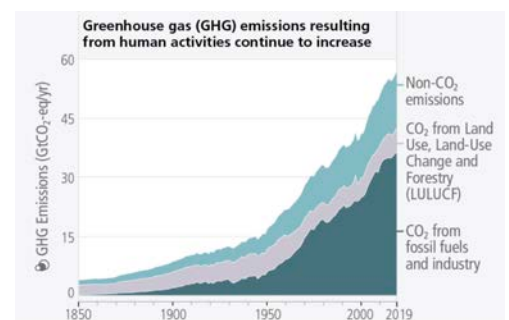


Fig. 2 IPCC 2023

(Algae 3e 2016). Humans have reversed and destabilized these sequestration processes by combusting fossil fuels (coal, petroleum, natural gas, etc.). A third of CO₂ emissions from over two centuries have been absorbed by the ocean, causing a significant 0.1 unit decrease in pH, with much more expected in the future (Hurd 2014). Fig. 3 shows how increasing acidity shifts ocean production from calcium carbonate precipitation (buffer) toward carbonic acid, increasing atmospheric CO₂ and heat, 90% of which the ocean continues to absorb (Algae 2016, NOAA).

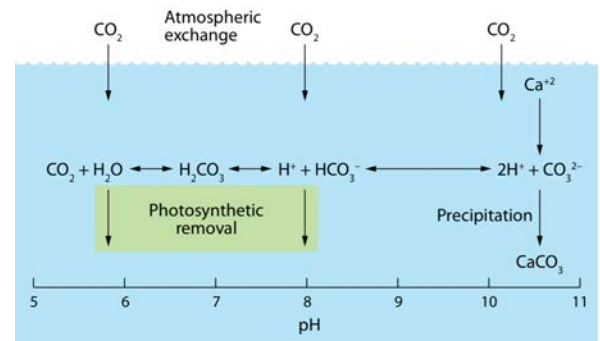


Fig. 3 Algae 3e

Macroalgae provide habitat for innumerable organisms along coastal intertidal zones and permanently submerged waters. Their ability to incorporate carbon into their tissues is also well known. Many are in decline, while some, such as *Sargassum* are thriving in the Atlantic, likely due to excess nutrients from human activity (C. Hurd in GSC 2023). Studies show kelps are more directly vulnerable to warming waters than to acidification, but indirectly suffer from trophic phase-shifts, increasing herbivory by urchins and other herbivores, compounded by overfishing, as well. (Provost et al. 2017, Ling et al. 2020). Public awareness of kelp importance has begun to rise, even as our anthropogenic impacts on air, land, and sea are unrelenting. Typical estimations of carbon capture are based on ocean thermal or salinity density gradients (pycnocline), or ocean turnover time. Some research indicates remineralization of carbon via the natural biological carbon pump varies greatly throughout the ocean and is underestimated by perhaps 2-3 times (Guidi et al. 2015). Thorough economic and ecological accounting is essential prior to scaling-up projects which may have vast impacts (Hurd et al. 2022). Unpredicted or negative outcomes are likely without careful prior study and prototype testing to determine actual net benefits to the ecosystem and all its inhabitants, including benthic communities. Due to the emergency imperatives inherent in our present complex global climate crises, more attention is being focused on the ocean and its possible benefits. Researchers, entrepreneurs, non-profits, and conferences are now laying out both methodologies and associated pitfalls of deep ocean seaweed carbon sequestration technologies (Boyd et al. 2022, Ross et al. 2023).

Prior ocean aquacultural research has focused mainly upon raising fish, oysters, macroalgae, and other organisms in mariculture systems modeled on terrestrial farming methods. These have typically been conceived as two-dimensional monocultural designs, substituting water for soils and petroleum inputs. More recently this has been enhanced through three-dimensional, Integrated Multi-Trophic Aquaculture (IMTA) techniques. These combine complementary

species in the water column as rough analogs to natural trophic webs. The goal is to derive efficiency and ecosystem coherence from this approach. Little research has been done, however, in creating these more complex associations and food-webs. Sizing, species mix, markets or mitigation, and other parameters are needed for large-scale economies. Open ocean projects must be much more robust than typical projects near shores and protected areas (Buck et al. 2018). As efforts continue in this direction, multiple issues arise. One is the need to optimize any open ocean cultivation of kelps as a three-dimensional array, intentionally designed to be as benign as possible, even when scaled to have significant impact. Another issue is the inexorable heating and acidification of the ocean, suggesting that techniques to locate kelp “refugia” (Graham et al. 2007) may be applicable for growing of carbon-sequestering kelps. Global simulations of deep ocean conveyors and processes will become ever more important to locate any viable carbon sequestration effort, if at all (Baker 2022).

Techniques to test possible viable configurations of kelps in three dimensional arrays require beginning with horizontal and vertical propagation methods. Many people and organizations employ horizontal long lines and buoys at or below the surface to propagate seaweeds for food and other product uses. In order to learn more about the effect of depth on possible 3-dimensional arrays, vertical testing is needed. The experimental configuration described below is a preliminary step toward a viable, robust kelp mariculture on the horizon.

I designed an experiment to measure differences in the productivity of two locally established kelps at varying depths in the seawater column, in the semi-protected inlet of Friday Harbor Bay. This extends previous work tracking growth of *Saccharina* (Nigam et al. 2014). One aspect of this effort is to optimize growth factors for each specie, such as light. This study looks at two common brown algae species, *Saccharina latissima* and *Alaria marginata*, to understand how depth affects growth and erosion of these widely distributed macroalgae. I expected to see some attenuated growth at the lowest depth, due mainly to light limitation, and evidence of erosion where wind-blown surface currents are stronger. While the study period was brief, it is a microcosm of ocean processes which may inform further research and application of carbon sequestration concepts to OA (ocean acidification) realities.

Methods

Water column depths were measured on 18 and 22 June 2023 using a weighted rope, tagged incrementally to locate an area approximately 25 meters deep. Depth soundings were made near Friday Harbor Labs dock and later in deeper areas around the bay. Depth varies constantly with changing tides but is small relative to the 10 meter vertical separations between kelp stations.



Fig. 4 Depth soundings

The photo shows the site near the Northeast point of the bay. It is semi-protected but subject to strong currents and frequent boat traffic.

The experiment was deployed on 25 June 2023 off the cove near the Eastern point of FHL (48.5455597,

-123.0088181). Three weighted and buoyed rope assemblies were constructed linearly on ground from 1/4" and 3/8" polypropylene ropes. A central high visibility measuring and marker-buoy was assembled to establish the fixed experiment location. The main buoy was anchored with a concrete block, holding rope vertically at 25 meters. Each buoyed rope received a tag line and small buoy attached, to

locate and manipulate underwater sections. Two outer rope assemblies were created with a heavy shackle anchor and main float at 22 meters up. Tags to identify individual kelp blades were zip-tied at three stations measured from the bottom. Three tags each (spaced approximately 20 cm apart) were stationed at 1 meter, 11 meters, and

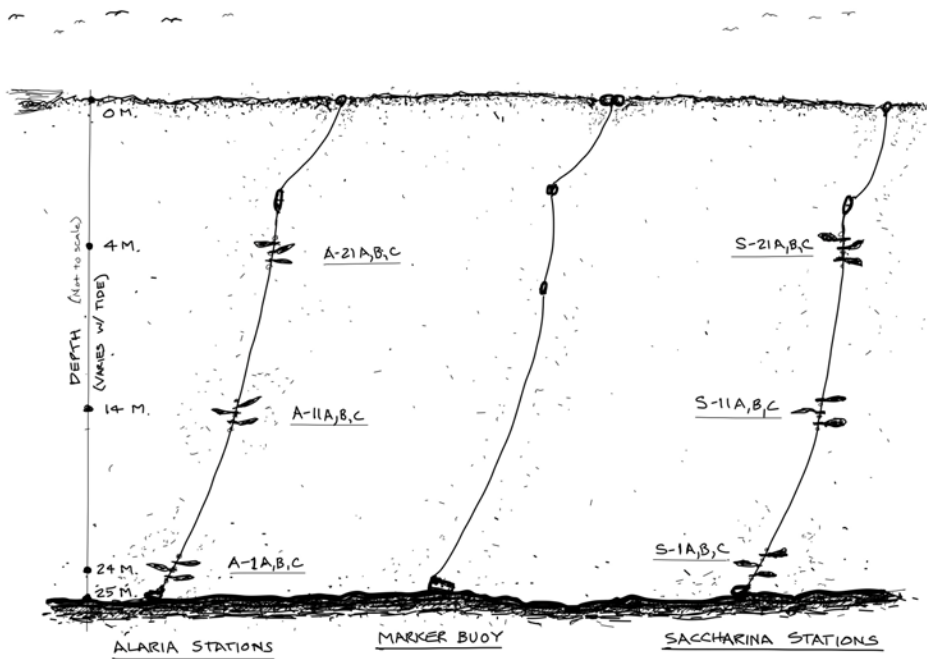




Fig. 6 Kelp Array deployment

21 meters from the bottom. (This corresponds to an approximate depths of 24 m., 14 m., and 4 m. from the surface.) Blades of *S. latissima* and *A. marginata* were obtained from FHL dock, retaining the holdfast portion for attachment through the rope weave at each tagged location. Some were later zip-tied at the holdfast for strength. For each species, 9 blades were collected. Blades were highly variable in size and shape, and ranged from 30-60cm in length. Each blade was punched down the middle (6 holes) at 5 cm on center, from the basal end at the stipe attachment point. Each blade was photographed next to a meter scale for later processing of areas with Image J (ImageJ.org, ImageJ.net, NIH.gov) and 1/8" holes were used to track blade growth over the course of the experiment. Ropes and kelp blades were deployed to avoid

damage, but fragile blades created difficulty in maintaining complete data. *A. marginata* maintained rope attachment throughout the experimental run, but *S. latissima* lost blades in the first week but were completely gone from the rope by the second week (except for one much reduced blade and two stipe fragments).

I took growth measurements and photo documentation on day 6 and day 11 to track growth over time. Direct numerical data was entered in a spreadsheet, while photographic data was processed using Image J to determine surface area. Biomass and blade erosion were determined through a combination of measurements. Resulting calculations graphed for area blade growth, to determine significance of growth variations due to depth. Light levels were taken on day 11, in air and in water at incremental depths to 15 meters below the surface. These measurements helped to determine the significance of light attenuation with depth upon growth.



Fig. 7 Kelp documentation

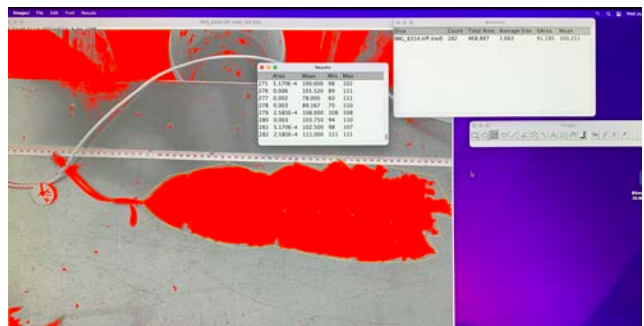


Fig. 8 ImageJ

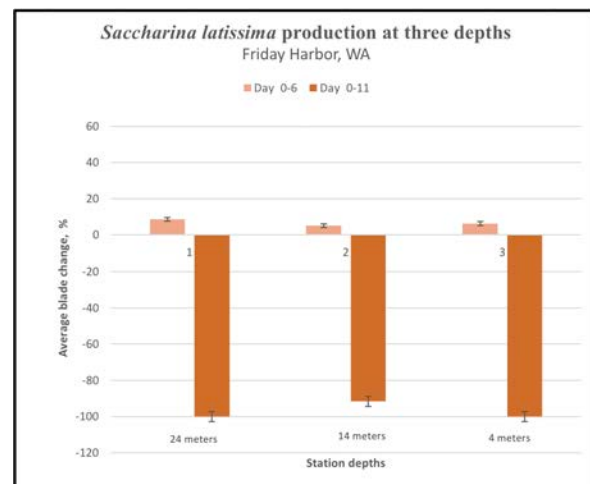
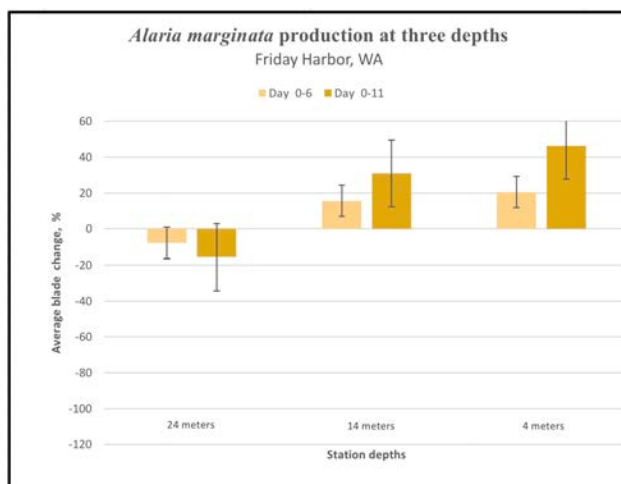
Results

This short experiment was a valuable prelude to further mariculture projects involving kelp production. Problem areas were especially useful in providing future directions forward. Even within the simplified format and brief time period--growth, erosion, and differentiation by depth were quantified in this ocean-based exercise.

While the main goal is to optimize carbon incorporation or product biomass, net blade area growth can be considered equivalent to creation of biomass. This experiment employs simplified and expedient methods to approximate true productivity. For example, blade areas are calculated at each stage analyzing photographs with ImageJ, while blades actually grow and fold in 3-dimensions. New growth, largely at the basal meristematic area, was calculated by: Net linear change in holes (initially spaced 5 cm apart) x Average width of the blade in that region. Blade erosion is accounted for by changes in surface area, less the calculated basal growth. Due to variability in original blade sizes, each growth pattern was converted to relative growth, or percentage change in original blade. Precise measurements will not eliminate errors, but trends can be read from the given data.

Graphs of average blade growth for both species show mostly positive growth during the first week. Each station depth consisted of three blades, averaged for production at that depth. *Alaria* species show a consistent pattern of greater production closer to the surface, where irradiance is higher. It clearly did not grow well at 24 meter depth. *Saccharina* species exhibited growth at each depth initially. Excellent growth near the surface in one blade was obscured by poor growth or erosion in an adjacent blade. Overall, they did not grow as quickly as *Alaria*, as a percentage of initial size, yet were growing well down to 24 meters depth.

In the final week, *A. marginata* continued the same pattern of production, with highest growth near the surface. The deepest blades were unproductive, indicating light-limitation or other factor. Unfortunately, *S. latissima* blades had completely disappeared at the end of experiment--except for a remnant blade and a holdfast segment. The cause is unknown but may have been due either to very strong water speeds or possible herbivory (e.g., *Pugettia producta*, kelp crab).



Discussion

A small experiment can inform in many ways. This one revealed some of the many variables necessary to understand before attempting to create a local ecosystem within the larger ecosystem. This study was necessarily simplified due to constraints of time and logistics. It demonstrated that depth can have a discernible effect on biomass production of kelps or brown macroalgae, but that this may vary between species. Light measurements taken at the site indicate a rapid attenuation of the photosynthetically active radiation (PAR) [see Appendix]. This is a likely factor in the *Alaria* production profile but not conclusive, however. The different pattern of growth in *Saccharina* may be due to variation in pigmentation or other structural features. The heavy loss of blades may be partly due to their acquisition: i.e., removing somewhat mature specimens from around the dock, a more sheltered environment. They may also adapt to higher-force area if acclimated as sporophytes. *S. latissima* is understood to exist primarily in "wave-sheltered areas" as well (Druehl 2016).

The future is already upon us. Humans have accelerated change beyond the ability of most living beings to adapt. Responsible parties plead ignorance, in order to sleep. Can we help the big ocean help put out the fire? We can try.

Acknowledgements

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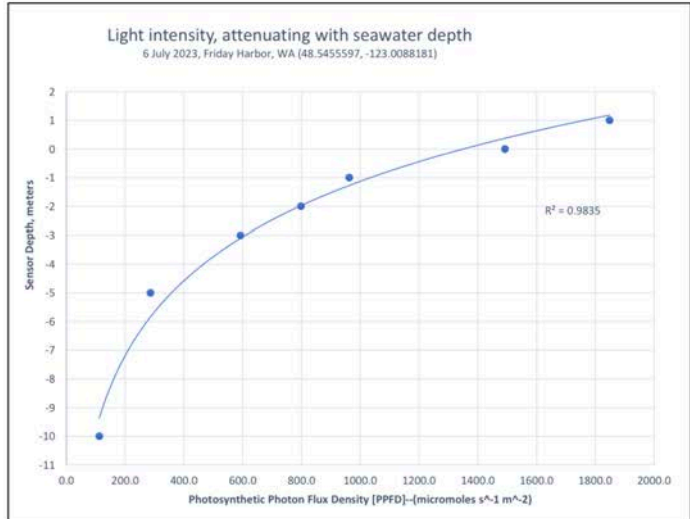
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Appendix

Light measurements

Li-Cor Li-250A Light meter, with Li-192 Underwater Quantum Sensor
 Light is measured in units of Photosynthetic Photon Flux Density (PPFD) or micromoles s⁻¹ m⁻². It detects light energy in the 400-700 nm photosynthetically active range (PAR)

	Depth (m)	Down	Up	Averaged reading
In Air	1	1832.0	1865.0	1848.5
At Surface	-0.1	1496.7	1487.9	1492.3
:	-1	874.8	1049.7	962.3
:	-2	802.7	793.9	798.3
:	-3	652.8	531.7	592.3
:	-5	196.9	374.4	285.7
:	-10	92.2	131.3	111.8



Data

Date	Time	Range (m)		High growth reading from depth (m)										Linear (Meters)/Growth (cm)	Percent change Day 0-5	Percent change Day 0-11	meters	Aver. Percent Change/Station Depth Day 0-5	Aver. Percent Change/Station Depth Day 0-11	
		Area (cm ²)	Area (cm ²)	Distance A	Distance B	Distance C	Distance D	Distance E	Distance F	Distance G	Distance H	Distance I	Distance J							
05 Jun 21	A-1A	8164	409	75	12	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0						
	A-1B	8355	372	10.5	10	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0						
	A-1C	8356	922	20	22	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0						
	A-11A	8357	689	11.5	14	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0						
	A-11B	8358	582	13	85	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0						
	A-11C	8359	763	16	12	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0						
	A-21A	8360	384	11	10	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0						
	A-21B	8361	764	15.3	12	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0						
	A-21C	8362	692	18	145	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0						
	S-1A	8363	436	11	7	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0						
	S-1B	8363	215	10	4.8	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0						
	S-1C	8363	342	9.4	8	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0						
	S-11A	8364	456	10	8	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0						
	S-11B	8367	462	11	5	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0						
	S-11C	8368	415	12	8	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0						
S-21A	8369	506	12	8.5	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0							
S-21B	8370	211	8	5	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0							
S-21C	8371	8	8	11.4	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0							
1 Jun 21	A-1A	8482	368			5.5	5.4	5.0	5.0	5.0	5.0	5.0	5.0							
	A-1B	8479	362			8	5.2	5.5	5.3	5.1	5.0	5.0	5.0							
	A-1C	8478	848			5.5	5.3	5.0	5.0	5.0	5.0	5.0	5.0							
	A-11A	8475	718			8.2	8	5.5	5.0	5.0	5.0	5.0	5.0							
	A-11B	8476	571			8.2	8	5.5	5.0	5.5	5.2	5.0	5.0							
	A-11C	8477	851			7	7.5	5.8	5.3	5.2	5.0	5.0	5.0							
	A-21A	8471	633			8.5	7	5.6	5.4	5.1	5.0	5.0	5.0							
	A-21B	8473	771			7.8	7.2	5.7	5.3	5.0	5.2	5.0	5.0							
	A-21C	8474	786			10	6.5	5.4	5.0	5.0	5.0	5.0	5.0							
	S-1A	8480	450			8	5.8	5.2	5.0	5.0	5.0	5.0	5.0							
	S-1B	8470	223			6.1	5.2	5	5.1	5.3	5.0	5.0	5.0							
	S-1C	8481																		
	S-11A	8488	508			7.3	6.8	6	5.4	5.1	5.0	5.0	5.0							
	S-11B	8487	363			8	6.7	5.2	5.3	5.0	5.0	5.0	5.0							
	S-11C	8483																		
S-21A	8484	119			7.1	End givve														
S-21B	8485	289			8.5	6.5	5.4	5.2	5.0	broken off										
S-21C	8485	467			8	7.2	6.5	5.4	5.4	5.4	broken off									
6 Jun 21	A-1A	8723	371			6.3	5.7	5.2	5.0	5.0	5.0	5.0	5.0							
	A-1B	8725	260			7	5.5	5.0	5.0	5.0	5.0	5.0	5.0							
	A-1C	8726	822			6.5	5.5	5.0	5.0	5.0	5.0	5.0	5.0							
	A-11A	8727	768			11	6.5	5.7	5.3	5.0	5.0	5.0	5.0							
	A-11B	8729	625			8.7	6.3	5.5	5.0	5.2	5.0	5.0	5.0							
	A-11C	8742	923			11.3	8.5	6.1	5.4	5.2	5.0	5.0	5.0							
	A-21A	8743	777			9.8	6.5	6.0	5.4	5.0	5.0	5.0	5.0							
	A-21B	8744	1032			9.6	6.4	6	5.8	5.2	5.0	5.0	5.0							
	A-21C	8745	848			8.5	6.5	5.5	5.0	5.0	5.0	5.0	5.0							
	S-1A																			
	S-1B																			
	S-1C																			
	S-11A	8718	114																	
	S-11B																			
	S-11C																			
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The Washington Phycology Team and Boating Club

