SUMMARY OF FINDINGS

INVESTIGATING SEAWEED CULTIVATION AS A STRATEGY FOR MITIGATING OCEAN ACIDIFICATION IN HOOD CANAL, WA

FOR ACTIVITIES PERFORMED MAY 2015 – DECEMBER 2019

FUNDED BY THE PAUL G. ALLEN FAMILY FOUNDATION AND US NAVY

EXECUTIVE SUMMARY

In Puget Sound, where the effects of ocean acidification threaten important marine resources, there is a heightened need for investigating mitigation actions. Corrosive conditions associated with acidification are already impacting some calcifiers such as pteropods, crab, and foraminifera[1], and laboratory studies further suggest that oysters, crabs, krill, and salmon are also sensitive to the effects of acidification.[2] These species are not only important to the health of the marine ecosystem, but some are highly valued culturally and economically as well. According to the Governor's Office,[3] in the coming decades, as seawater absorbs increasing amounts of dissolved carbon dioxide, conditions in Washington waters are expected to worsen, with changes occurring "more rapidly in Puget Sound waters than along our coast." In the face of these deteriorating conditions, we are confronted with many questions, one of which is: what can we do locally - in the water - to ameliorate the effects of acidification? The investigation described in this report sought an answer to that question.

In 2012, following several years of detrimental impacts to the Washington State shellfish industry resulting from acidification, former Governor Christine Gregoire convened the Washington State Blue Ribbon Panel on Ocean Acidification. The Panel recommended 42 actions in a 2012 report entitled "Ocean Acidification: From Knowledge to Action." A key early action recommended by the Panel was to develop phytoremediation techniques as a potential strategy for mitigating effects of acidification in local waterways. As a concept, phytoremediation is an approach to environmental remediation that uses plants or algae to take up and remove potentially harmful compounds from the environment to improve surrounding conditions. It is widely applied on land for a variety of purposes, including the reduction of carbon dioxide accumulation. For example, large-scale tree planting removes carbon dioxide from the atmosphere. In marine waters, seaweed cultivation could potentially provide a similar strategy for removing carbon dioxide from seawater to improve local conditions by offsetting the effects from ocean acidification.

Serendipitously, soon after the Panel's recommendations were finalized, the Paul G. Allen Family Foundation issued a research competition, *The Paul G. Allen Challenge to Mitigate the Effect of Ocean Acidification,* calling on scientists from around the world to propose adaptation and mitigation strategies to address acidification. Seizing on this opportunity, a team from the Blue Ribbon Panel submitted a concept proposal and succeeded in securing support through the *Challenge*. Core members of the project team included Puget Sound Restoration Fund (PSRF), Hood Canal Mariculture (HCM), a Washington State based commercial shellfish farm, the U.S. National Oceanic and Atmospheric Administration (Pacific Marine Environmental Laboratory and Manchester Research Station), University of Washington Applied Physics Lab, Washington Sea Grant, System Science Applications, Washington Department of Natural Resources, and other advisory partners. During the team's negotiations with the Paul G. Allen Family Foundation on the final project, the U.S. Navy directed additional funding towards the project.

Thus began an investigation into whether seaweed cultivation could draw down CO_2 within the kelp farm and improve conditions for calcifying species. The field study was conducted at a five-acre seaweed and shellfish farm operated by HCM, located off Hood Head, just north of the Hood Canal Bridge in Jefferson County, Washington. After acquiring the necessary permits, propagating kelp seed, and outplanting sugar kelp (*Saccharina latissima*), the team measured the effect of kelp on several metrics of seawater chemistry and on a small suite of calcifying organisms within the kelp farm. Additionally, the team developed a computer model that simulates environmental variables and kelp growth, and then integrates the sampling data into an interface that graphically depicts the effect of kelp cultivation on seawater chemistry.

Combined funding from the Paul G. Allen Family Foundation and the U.S. Navy enabled two years of field investigation at the Hood Head demonstration site. Overall, the project was conducted 2015–2019 to test key early actions identified by the Washington State Blue Ribbon Panel on Ocean Acidification.

Figure ES1. Project Chronology in Photos. A. Seeded line cultured in kelp lab Dec ‘16; B. Scientific buoy installation Jan ‘17; C. Joth Davis preparing for sampling Feb ‘17; D. Brian Allen lifting seeded line to show abundant growth Mar ’17; E. Ryan Cox and Josh Bouma harvesting kelp Aug ‘17; F. Lesley Stahl with CBS 60 Minutes interviewing Betsy Peabody Dec ‘17; G. Richard Feeley collecting water samples; H. Brian Allen and Nina Bednarsek collecting bioassays Jun ‘18; I. Meg Chadsey inspecting SkyRoot Farm's kelp pile (Oct ’17), 4 months after delivery to the Whidbey Island farm; J. SkyRoot Farm owner Eli Wheat incorporated seaweed grown at Hood Head demonstration site into his pasture (pictured Oct ‘17); K. Olympia oysters, one of the species used in bioassays at Hood Head.

PROJECT OUTCOMES & KEY FINDINGS

The establishment of a kelp farm in Puget Sound enabled project scientists to measure, evaluate, and model the physical, chemical, and biological effects of cultivated kelp in a natural environment on a local scale. Project highlights are shown in Figure ES-1. The following is a summary of project outcomes and key findings.

PROJECT OUTCOMES

1. Permitted and installed a commercial-scale kelp farm in Hood Canal, Puget Sound.
2. Established a kelp propagation facility to produce sporophytes on twine for both sugar and bull kelp (*Nereocystis luetkeana*) for outplant at the Hood Head investigation site and for use in bull kelp enhancement trials.
3. Cultivated over 20 metric tons (live weight) of sugar kelp in 2017 and 2018.
4. Monitored standing biomass of sugar kelp over two growing seasons.
5. Conducted seasonal estimates of net production (as amount of carbon fixed per day in tissues) and estimated potential removal of carbon and nitrogen in standing biomass at harvest.
6. Transported sugar kelp grown at Hood Head to Whidbey Island and Quilcene organic farms with the intent of enriching soil in 2017 and 2018.
7. Assessed seawater chemistry conditions at Hood Head in 2017 and 2018 with seasonally-deployed instruments and small boat surveys.
8. Conducted bioassay experiments to evaluate both growth and shell dissolution of Pacific and Olympia oysters, mussels, pteropods, and other pelagic gastropods using mesocosms deployed inside, outside, and at the edge of the kelp farm.
9. Developed a new model to assess the effect of kelp on seawater chemistry that integrates kelp production metrics, seawater chemistry, and comprehensive water property observations to generate fine-scale, 3-dimensional simulations over time.
10. Initiated development of a companion model, called "Puget Sound SeaweedSiteEvaluator," to assess the potential for candidate kelp farm sites to exert a positive effect on seawater chemistry locally.
11. Engaged the public through high-visibility media outlets and a suite of other outreach activities, generating widespread interest in kelp farming, the development of locally grown seaweed products, and the potential for cultivation of seaweed for restoration purposes. Engagement activities helped leverage well over $500K in new funding to guide the development of seaweed farms and markets in Washington.
12. Conducted extensive laboratory experiments in 2019 to further assess biological effects in Pacific and Olympia oysters and the biological responses observed in the field.

KEY FINDINGS

<u>Key Finding 1. Farmed kelp offers some potential for removing carbon and nitrogen from seawater at harvest.</u>

The Hood Head investigation demonstrated the capacity to grow two species of kelp successfully in Puget Sound, and to produce a variety of kelp products of interest to local markets. Hood Head is an excellent site for cultivating sugar and bull kelp, as evidenced by successful kelp cultivation in 2017 and 2018, and represents, at one hectare, the first commercial-scale demonstration of the viability of open-water kelp farming in Washington State. In 2017, 6,364 kilograms (kg) of sugar kelp (wet weight) was harvested and delivered to an organic farm on Whidbey Island, which resulted in the reconveyance of 130 kg of carbon (representing 20.36% of kelp biomass dry weight) and 18 kg of nitrogen (representing 2.85% of kelp biomass dry weight) from sea to land. Had we harvested kelp at peak biomass* in 2017, with 19,417 kg sugar kelp produced, we would have removed approximately 395 kg of carbon and 55 kg of nitrogen. In 2018, estimates for carbon and nitrogen contained in kelp blades grown at Hood Head averaged 21.54% for carbon and 1.99% for nitrogen. If kelp had been removed in 2018 at peak biomass, over 22,000 kg would have been removed from this small farm in Hood Canal, representing 474 kg of carbon and 44 kg of nitrogen. We note that this removal of carbon at peak biomass would be equivalent to the CO_2 emitted by 31–37% of **one** typical passenger vehicle in a year (per EPA web site). Similarly, the amount of nitrogen removed from the marine system at peak biomass would be equivalent to ten 43-lb bags of typical lawn fertilizer. Estimates for carbon removed from Puget Sound only reflect net production, that is, they do not reflect the significant amounts of carbon fixed by kelp and subsequently released back into the water during respiration, the dissolved organic material leaked from fronds, and eroded kelp blades. Nor do they reflect the amount of carbon used to produce the kelp. *Note: Kelp was not harvested at peak biomass in 2017 and 2018 in order to maintain kelp biomass at the project site throughout the monthly sampling cruises April-June.

<u>Key Finding 2. The effect of kelp growth on seawater chemistry was not detected by state-of-the-art sensors and analyses used for assessment.</u>

Differences in seawater chemistry inside compared to outside the kelp farm were below the range of detection by the best available oceanographic instruments and integrated biogeochemical analyses. We attribute this result, in part, to high average current velocities at the Hood Head site that resulted in low average residence time of seawater within the kelp farm. The kelp signal was also likely overwhelmed by the larger signal from springtime phytoplankton blooms in north Hood Canal during the same timeframe that kelp was growing.

<u>Key Finding 3. Kelp may help reduce cumulative adverse effects on calcifying organisms growing within the kelp farm.</u>

Results from a small field study indicated improved conditions for various calcifying organisms (including Pacific and Olympia oysters, bay mussels, and pteropods) that were deployed in mesocosms inside and outside the kelp farm. Inside the kelp farm, we found reduced shell dissolution in all of the examined species. Two oyster species (Pacific and Olympia oysters) showed faster growth inside the kelp farm. It is important to note that the improved benefits are likely due to multiple factors; i.e. more favorable carbonate chemistry conditions, food availability, and energy trade-offs.

We investigated possible drivers of the field results with subsequent laboratory experiments with juvenile Pacific and Olympia oysters. Our laboratory results demonstrated that both oyster species can grow faster and have significantly less dissolution under experimental conditions of higher pH mean and frequency of variability. The amplitude of pH variation in the treatment was 0.2, equating to around 0.7 aragonite saturation state. These results are consistent with the findings of previous investigations. The difference between the laboratory treatments was much greater than observed or predicted effects of the kelp farm. The laboratory results indicated that benefits to oysters are observed after two to four weeks of exposure in the experimental conditions, indicating the beneficial effect of cumulative exposure over time.

Our field results suggest that association with kelp may locally benefit shellfish and other calcifiers, while our laboratory results confirm that Pacific and Olympia oysters benefit from improved pH conditions.

Key Finding 4. Model simulations of the Hood Head kelp farm indicated slightly reduced concentrations of dissolved inorganic carbon.

A key component of this project was the creation of a kelp model to explore phytoremediation effects under varied carbonate chemistry and nutrient (nitrogen) conditions. Field data collected during the two-year field investigation (flow conditions, temperature, salinity, stratification, chemistry, biology, kelp production) were used to drive model calculations. In simulations of farm dynamics during the spring and summer of 2017 and 2018, the largest decreases in dissolved inorganic carbon (DIC) and increases in aragonite saturation were found in the middle of the farm during periods of weak currents.

Although changes to seawater were too small to be measured *in situ*, model simulations showed a very small increase in aragonite saturation (maximum increase was 0.025). Laboratory studies have not demonstrated that changes at this scale have biological effects.

Key Finding 5. The simulated effect of kelp farms on local acidification conditions depends on current velocity, kelp density, and farm size.

An important finding of this investigation was determining more precisely the conditions under which seaweed farming *could* significantly affect seawater chemistry locally. *The Hood Head seaweed farm did not measurably change the seawater chemistry at the site.* However, modeling results suggest that under the right conditions, including current speed, nutrient availability, kelp density, and farm size, seaweed farms could measurably affect seawater chemistry locally. As we populate our toolkit for adapting to or mitigating acidified conditions, it is critical to understand the limits, potential, and correct application of each tool. Our experience also underscores that assessment and modeling are important in designing future kelp farming operations, if one of the intended purposes is nutrient and carbon uptake in the environment.

Key Finding 6. There may be benefits to growing kelp in Puget Sound.

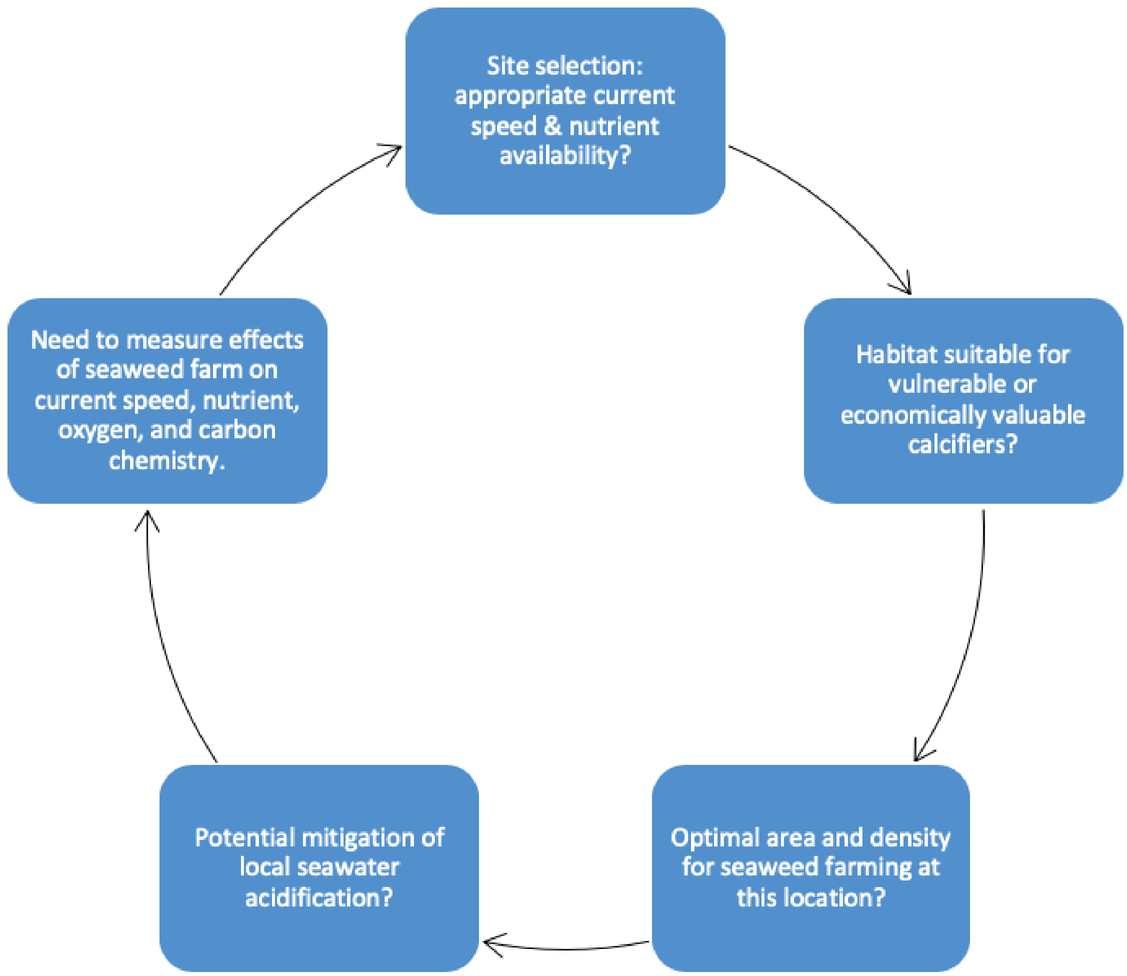
Based on our investigation at Hood Head, we demonstrated that seaweeds can be cultured in Puget Sound at a commercial scale, and that there is strong interest among growers and others for producing food-grade kelp. There is also growing interest among organic farmers in late season kelp biomass for soil enrichment. While limited, biological assessments suggest that growing seaweed in proximity to shellfish may make a positive difference for calcifiers, including oysters. To be clear, seaweed farming will not solve basin-wide acidification problems. Additional research needs to be conducted to determine whether seaweed farming in Puget Sound could improve local conditions at shellfish farms and provide an adaptation strategy that would assist in growing shellfish under increasingly acidifying conditions. (See Future Research section.)

Key Finding 7. Model simulations suggest that kelp farms could be engineered and sited to achieve larger effects on local acidification conditions.

The model proved to be the best vehicle for defining the conditions under which seaweed cultivation could exert a detectable effect on seawater chemistry. In the model, inputs included the seeding density of the kelp, water temperature, solar irradiance, current velocity, ambient nutrient concentrations, and carbonate chemistry variables. The model simulation calculated growth, photosynthetic and respiration rates of the kelp, and the impacts of kelp growth and metabolism on nutrient, oxygen, and DIC concentrations in seawater flowing through the farm. Modeling results indicate that the Hood Head site – an area of relatively fast-flowing currents with average speed of ~10-15 centimeters/second (cm/sec) at a depth of 3 meters – is a suboptimal location for siting kelp farms if a major objective is to locally reduce dissolved inorganic carbon and counter acidification. However, model simulations indicated that sites with lower current speeds, higher kelp density, and a larger growing area may have a greater local effect on seawater chemistry. In model simulations, the sweet spot that yielded the largest kelp effect occurred when flow rates were 10% of ambient flow observed at the Hood Head site. However, these optimal flow conditions may not exist in Puget Sound, and other complexities (e.g., respiration of detritus, self-shading, flow blocking) require further investigation. The sweet spot will also depend upon having sufficient light intensity and nutrient availability, which are both high at Hood Head. Sensitivity analyses with the model clearly showed that much larger decreases in DIC occurred in simulations where farm size or kelp density were significantly increased. For example, the maximum drawdown of DIC increased from approximately 1 µmol/kg to 35 µmol/kg when kelp densities increased tenfold. For context, the area at the Hood Head farm devoted to kelp cultivation was about 2.5 acres (1 hectare), which was composed of eighteen 500 foot growlines, with ten feet of separation between adjacent lines. The density of kelp grown at Hood Head in 2017 and 2018 was relatively low compared to commercial densities elsewhere in the world, especially in Asia. Therefore, increasing densities at kelp farms in Puget Sound should be feasible.

<u>Key Finding 8. Outreach and publicity associated with this project stimulated new interest in kelp farming in Washington State.</u>

The Hood Head investigation garnered significant publicity and attention. The coupling of multiple project elements – including kelp cultivation, chemical and biological assessment, and modeling – created a unique platform for building interest in actions that can potentially deliver multiple benefits. Seaweed farming workshops hosted by Washington Sea Grant and other partners in 2019 and 2020 attest to this growing interest.



Conceptual diagram of a decision tree for determining whether seaweed farming may have beneficial effects on seawater chemistry for calcifiers at a local scale.

FUTURE RESEARCH

Future Research 1. Adaptation and mitigation strategies associated with moving carbon from sea to land must consider a full carbon analysis.

In order to ensure that a mitigation or adaptation strategy has the intended net effect, all aspects of the carbon cycle manipulation must be considered, including the added emissions required to implement the effort (which were *not* taken into account for this project). Due to the complexity of such a holistic project, we encourage the research community to conduct studies that fully assess carbon cycle implications of, for instance, amending terrestrial soils with seaweeds. Monitoring the long-term fate of kelp-borne carbon and other nutrients in organic soils is an important aspect of a more comprehensive evaluation to assess whether net sequestration has occurred or decomposition of organic material has released carbon and nutrients to the atmosphere and water, respectively. In this example, a thorough accounting of this strategy would weigh the external carbon costs incurred through the harvest, delivery, and utilization of kelp against the avoided costs associated with conventional agricultural fertilizers, soil management, and water use, all of which require substantial resource inputs. Unless sequestered, respiration and breakdown of the organic material will release carbon dioxide to the atmosphere.

Development of best practices for carbon cycle manipulations intended for adaptation and mitigation strategies is critically needed to ensure implementation will have the desired net effects on carbon (and nutrients). It is clear that the most effective way to address ocean acidification is through rapid decarbonization of society. Thus, we need to reduce CO_2 emissions as quickly as possible, while simultaneously exploring methods for protecting, restoring, or expanding ecosystems that may store large amounts of carbon, and pursuing other approaches that can help remove CO_2 from the atmosphere and seawater.

Future Research 2. Develop co-culture system designs for seaweed and shellfish to optimize culture conditions.

The work supported by this investigation did not assess or quantify the potential importance of cultivating seaweed and shellfish in close physical proximity. Though bioassays were deployed within the kelp farm to assess biological effects, shellfish were not actually cultivated simultaneously with seaweed at the Hood Head kelp farm. Future research should therefore assess the specific biogeochemical conditions in seawater associated with cultivating seaweeds and shellfish together in order to investigate potential beneficial effects.[4] Because acidification problems are expected to worsen in the coming decades, it is important for seaweed and shellfish farmers to continue to work with researchers to design and assess co-culture systems. Understanding how to co-culture seaweed and shellfish in very close proximity could help the shellfish industry adapt to changing ocean conditions, similar to the way shellfish hatcheries have adapted to acidification by buffering incoming seawater to increase aragonite saturation and the viability of larval oysters.

SEAWEED FARMING AS A POTENTIAL TOOL TO AID IN GROWING MARINE FOODS UNDER CHANGING OCEAN CONDITIONS

Dissolved inorganic carbon (DIC) in the global ocean is increasing at an average rate of 1 µmol per kg seawater per year. Against this backdrop, the Hood Canal kelp farm may have reduced DIC by as much as 1 µmol/kg seawater within the center of the farm during the high growth period. This effect would fall below the limits of detection for laboratory and field methods, but would also counteract a small amount of anthropogenic acidification. Within the farm, preliminary results suggest that oysters and other calcifying species deployed in mesocosms showed less dissolution, and two oyster species also showed increased growth. This suggests that kelp may benefit CO_2-sensitive organisms and underscores the need for more research on the potential of co-culture. It should be added that no amount of kelp grown in Puget Sound will mitigate anthropogenic CO_2 inputs.

For kelp cultivation to potentially improve carbonate conditions for shellfish locally, farms would need to be designed, sited, and sized carefully to realize specific benefits. The model suggests that kelp farms could potentially have a larger effect under different conditions than those observed at Hood Head. In modeling scenarios, reducing current speed by 90% roughly quadruples the decrease of DIC. Increasing the farm size by ~600% or doubling kelp density roughly doubles the effect on DIC. Again, an important caveat here is that these model predictions do not include nonlinear relationships or thresholds such as flow disturbance/blocking by the kelp, nutrient limitation, and shelf-shading. **It is also important to note that even in these scenarios, the maximum predicted kelp farm effects on DIC are small compared to observed natural variation on daily and monthly time scales.** In sum, questions remain about how best to deploy farming as a tool to combat the effects of acidification and whether the magnitude of farm effects on carbonate chemistry matters for calcifying organisms.

In places where shellfish are already affected by acidification, or where high seawater CO_2 is already occurring or predicted, seaweed farming could be further evaluated as a specific strategy for co-cultivating seaweed and shellfish. Further, if kelp farms can be sited to achieve multiple benefits, the production of marketable seaweed products can help fund these co-culture operations and provide a mechanism for removing some carbon and nitrogen from the marine system at harvest. As an added note, would-be seaweed farmers will need to carefully assess water quality conditions at proposed sites. Ultimately, it may be that seaweed is grown for different reasons in different places.

While assessing various adaptation and mitigation strategies, there are other ocean challenges that also need to be considered. In the years since the Blue Ribbon Panel Report was published, scientists have developed a better understanding of the threat posed by multiple stressors. The process of CO_2 absorption from the atmosphere and the resulting acidification is not the sole factor affecting ocean health. Warming seawater temperatures, hypoxia, harmful algal blooms, emerging diseases, and other changes have created compounding, increasingly stressful conditions for marine organisms beyond ocean acidification alone. This both heightens and complicates the search for remediative actions. In 2012, when the Blue Ribbon Panel identified phytoremediation strategies as a key early action*,* seaweeds were thought to be potential winners in the CO_2-rich oceans predicted for our future. After all, seaweeds absorb CO_2 from the surrounding seawater and convert it into biomass. Unfortunately, from our vantage point in 2019, we have since witnessed a 90% decline of kelp beds off the Northern California coast due in part to a marine heatwave that reduced kelp populations. We know now that kelps are vulnerable to warming seawater temperatures. It is also broadly understood that increasing atmospheric CO_2 concentrations are contributing to rapid warming of the ocean as well as the atmosphere.[5] In consideration of all of these factors, seaweed-based phytoremediation strategies will need to be carefully assessed and properly sited when considering acidification. **However, kelp farms will NOT be able to effectively combat the triple threat of acidification, warming, and hypoxia.**

Moving forward, as coastal communities and governments continue to evaluate potential actions to remediate acidification and combat the effects of multiple stressors, we need to focus on actions that can make a difference for the organisms that live and grow in the marine environment. Evidence shows that some species are already negatively affected under increasingly corrosive seawater conditions. The scale and extent of the problem is not yet known, since biological monitoring in the field has been limited. Additionally, corrosivity will increase, heightening the impetus to act now to investigate potential mitigation actions. For shellfish production, this likely means that growing oysters and other shellfish amid changing ocean conditions is going to be increasingly challenging as impacts from acidification worsen, particularly as the shell-building process itself pushes the system toward higher carbon dioxide levels in the immediate environment of the calcifying shellfish.

While kelp cultivation does not pose a fix for acidification or the acceleration of its effects via carbon and nutrient pollution from watersheds, our findings show that kelp farming may produce benefits in the marine environment within the farm. Additionally, kelp farming can help showcase Puget Sound as a living system that produces marine products, which could help motivate and sustain clean water efforts moving forward. We have shown in our study that under the right conditions kelp farming may offer promise for co-culturing sensitive marine organisms. Future research can help refine the uses of this tool.

Finally, while Washington State is particularly susceptible to acidification impacts, due to a unique combination of oceanographic and climate factors, coupled with high freshwater inputs from rain and snowmelt, we are also equipped with a strong social and cultural legacy in which marine resources are highly valued. Our region is also a known incubator for innovative public/private partnerships that advance cutting-edge, forward-thinking solutions to large-scale collective challenges. Ocean acidification is one of the major challenges of our day, demanding urgent and collective solutions. It is a testament to both the Paul G. Allen Family Foundation and the U.S. Navy that they invested generously in scoping out early-stage potential in-water solutions.

FOOTNOTES

1 Bednaršek, N., R.A. Feely, M.W. Beck, S.R. Alin, S.A. Siedlecki, P. Calosi, E.L. Norton, C. Saenger, J. Štrus, D. Greeley, N.P. Nezlin, and J.I. Spicer (2020): Exoskeleton dissolution with mechanoreceptor damage in larval Dungeness crab related to severity of present-day ocean acidification vertical gradients. Sci. Total Environ., doi: 10.1016/j.scitotenv.2020.136610.

Bednaršek, N., R.A. Feely, N. Tolimieri, A.J. Hermann, S.A. Siedlecki, G.G. Waldbusser, P. McElhany, S.R. Alin, T. Klinger, B. Moore-Maley, and H.O. Pörtner (2017): Exposure history determines pteropod vulnerability to ocean acidification along the US West Coast. Sci. Rep., 7, 4526, doi: 10.1038/s41598-017-03934-z.

Osborne, E.B., R.C. Thunell, N. Gruber, R.A. Feely, and C.R. Benitez-Nelson (2019): Decadal variability in twentieth-century ocean acidification in the California Current Ecosystem. Nature Geosci., doi: 10.1038/s41561-019-0499-z.

2 Barton, A., B. Hales, G. Waldbusser, C. Langdon, and R.A. Feely (2012): The Pacific oyster, *Crassostrea gigas*, shows negative correlation to naturally elevated carbon dioxide levels: Implications for near-term ocean acidification impacts. Limnol. Oceanogr., 57, 698–710, doi: 10.4319/lo.2012.57.3.0698.

Barton, A., G.G. Waldbusser, R.A. Feely, S.B. Weisberg, J.A. Newton, B. Hales, S. Cudd, B. Eudeline, C.J. Langdon, I. Jefferds, T. King, A. Suhrbier, and K. McLaughlin (2015): Impacts of coastal acidification on the Pacific Northwest shellfish industry and adaptation strategies implemented in response. Oceanography, 28(2), 146–159, doi: 10.5670/oceanog.2015.38.

McLaskey, A. K., Keister, J. E., McElhany, P., Olson, M. B., Busch, D. S., Maher, M., & Winans, A. K. (2016). Development of *Euphausia pacifica* (krill) larvae is impaired under pCO2 levels currently observed in the Northeast Pacific. Marine Ecology Progress Series, 555, 65-78. doi: 10.3354/meps11839.

Miller, J. J., Maher, M., Bohaboy, E., Friedman, C. S., & McElhany, P. (2016). Exposure to low pH reduces survival and delays development in early life stages of Dungeness crab (*Cancer magister*). Marine Biology, 163(5), 118. doi: 10.1007/s00227-016-2883-1.

Trigg, S. A., McElhany, P., Maher, M., Perez, D., Busch, D. S., & Nichols, K. M. (2019). Uncovering mechanisms of global ocean change effects on the Dungeness crab (*Cancer magister*) through metabolomics analysis. Scientific Reports, 9(1), 10717. doi: 10.1038/s41598-019-46947-6.

Waldbusser, G. G., Hales, B., Langdon, C. J., Haley, B. A., Schrader, P., Brunner, E. L., Hutchinson, G. (2015). Ocean acidification has multiple modes of action on bivalve larvae. PLoS ONE, 10(6), e0128376. doi: 10.1371/journal.pone.0128376.

Williams, C. R., Dittman, A. H., McElhany, P., Busch, D. S., Maher, M. T., Bammler, T. K., Gallagher, E. P. (2019). Elevated CO_2 impairs olfactory-mediated neural and behavioral responses and gene expression in ocean-phase coho salmon (*Oncorhynchus kisutch*). Global Change Biology, 25(3), 963-977. doi: 10.1111/gcb.

3 Office of the Governor: Final Policy Brief Changing Ocean Conditions. September 2019. www.governor.wa.gov.

4 Fernández, P.A., P.P. Leal and Henríquez, L.A. (2019). Co-culture in marine farms: macroalgae can act as chemical refuge for shell-forming molluscs under an ocean acidification scenario, Phycologia, 58:5, 542-551. doi: 10.1080/00318884.2019.1628576

5 Durack, P.J., P.J. Gleckler, S.G. Purkey, G.C. Johnson, and J.M. Lyman. (2018). Ocean warming: From the surface to the deep in observations and models. Oceanography, 31(2), 41–51, doi: 10.5670/oceanog.2018.227. Available online: https://tos.org/oceanography/article/ocean-warming-from-the-surface-to-the-deep-in-observations-and-models

Jackson, J.M., G.C. Johnson, H.V. Dosser, and T. Ross (2018): Warming from recent marine heat wave lingers deep in British Columbia fjord. Geophys. Res. Lett., 45(18), 9757–9764, doi: 10.1029/2018GL078971. Available online: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2018GL078971