Graduate Research Plan Statement

Introduction

Climate change can be a strong selective pressure for thermal tolerance in plants and animals. Environmental change can cause genome shifts on a short evolutionary timescale, termed rapid evolution.[1] Animals have increased thermal tolerance on rapid time scales by reducing their body size, which is correlated with metabolic demands and survival probabilities.[1] Macroalgae may also be experiencing rapid evolution in response to climate change, but it is less clear which life history traits are responding to thermal stress. Environmental change can cause genome shifts on a short evolutionary timescale, termed rapid evolution.[1] In several studies, rapid evolution has led animal populations to decrease body size and fecundity, presumably because large-bodied animals have higher metabolic demands and/or mortality.[1] While decreasing body size may be a mechanism for "evolutionary rescue" in animal populations experiencing strong selective pressures, it is less clear how rapid evolution impacts life history traits in macroalgae.[1] Here, I propose to investigate the rapid evolution of a macroalgae that serves as a critical ecosystem engineer in marine ecosystems: kelp.

Bull kelp (*Nereocystis luetkeana*) serves as an ecosystem engineer with a vast spatial range on the United States West Coast. Indigenous people rely on kelp forests for food, ceremonies, and medicine. Kelp forests hold a 16.5 billion global algal aquaculture market, which boosts local economies.[2] Additionally, kelp forests support ecotourism and mitigate local impacts from storm surges and ocean acidification.[2] Kelp require cold, nutrient-dense water and are vulnerable to rising ocean temperatures.[3] Marine heat waves have pronounced impacts on kelp forests, contributing to the ecosystem's decline.[4] Although culturally and economically relevant, kelp forests have consistently declined; from 2014 to 2016, bull kelp experienced a ~90% canopy loss without canopy recovery,[5] and from 2016 to 2019, this increased to a 95% canopy loss.[2] Kelp are fast-growing with short generation timescales, making them ideal for studying rapid evolution. Some kelp forests still cover large portions of their original habitat, suggesting that these populations may have undergone rapid evolution in response to differing external conditions.[4,6] If heat-tolerant alleles can be identified, we could use them to propagate and restore populations to maintain or increase global harvests.[2]

Proposed Research

Temporal genomics incorporates genomic data from time series, museum collections, and direct field sampling to detect evolutionary changes.[7] Inland seas like the Salish Sea may emulate future ocean warming conditions, creating a unique opportunity for temporal genomic techniques.[3] The southern Strait of Georgia, located in the Canadian portion of the Salish Sea, has warmer water temperatures and contains an example of kelp populations exhibiting higher thermal optimums, which is ideal for the proposed research.[8] By using temporal genomics to compare bull kelp from the southern Strait of Georgia to the population in Santa Cruz, as well as the Santa Barbara Long Term Ecological Research (LTER), I will (1) identify changes in levels of genetic diversity over time (and habitat resilience) in Santa Babara bull kelp, (2) identify genes associated in evolution for increased thermal optimum from the Strait of Georgia, and (3) assess the potential for future conservation through evolutionary rescue.

Experimental Design

(1) To determine genetic variability, I will use low-coverage whole genome sequencing (WGS) for bull kelp populations off the coast of Santa Cruz, California. I will conduct additional low-coverage WGS with time series data collected by the Santa Barbara LTER. Using low-coverage WGS will serve as a cost-effective, comprehensive mechanism to compare the population genome across time.[9] Using the Analysis of Next Generation Sequencing Data (ANGSD), I will estimate allele frequencies over time to identify relative genetic variation,[9] which is indicative of ecosystem resilience. This will estimate how resilience has changed in ocean warming conditions. Additionally, it will assess which populations are eligible for evolutionary rescue. (2) I will utilize low-coverage WGS with populations of bull kelp in the Strait of Georgia. ANGSD will find allelic frequencies of populations with higher thermal optimums. I will sample bull kelp throughout the Strait of Georgia, conduct growth experiments in controlled laboratory conditions, and determine thermal optimum by growth rate. I will compare their respective allele frequencies to determine which alleles are heat-adapted. (3) Evolutionary rescue requires genetic

variability to occur.[10] The populations off the coast of Santa Cruz with the greatest genetic variability will be grown in-lab. In-lab, bull kelp native to the coast of Santa Cruz will receive a dispersal of bull kelp gametophytes from the Strait of Georgia, with the aim of introducing heat-adapted alleles into the Santa Cruz population genome. The lab will emulate conditions unique to the coast of Santa Cruz (e.g., water temperature, daytime length, nutrient availability). This will determine the potential for evolutionary rescue to occur by introducing adapted alleles. This research assumes that selective sweeps in bull kelp occur through the introduction of new alleles and could set a foundation for a new direction in ecosystem conservation. Success will be measured by repeating growth experiments to identify changes in thermal optimum as new kelp is grown in-lab.

Resources

I am applying to be advised by Dr. Malin Pinsky, a leading researcher on temporal genomics and ecosystem change at the University of California in Santa Cruz (UCSC). UCSC has a strong reputation for advancing research in marine biology and genomics, which will be combined in this project. The Global Change Research Group (PI: Dr. Pinsky) consists of a large laboratory where I have a variety of senior students to assist me in genomic techniques. The group often collaborates with the Santa Barbara LTER, and this proposal relies on the long-term ecological research provided by Santa Barbara.

Intellectual Merit

The completion of this study will determine the ability for evolutionary rescue by finding genetic variability and success of introduced alleles. It will additionally inform management by determining which areas are the most impactful to protect. This research aims to identify past evolutionary trends in bull kelp to understand future mechanisms of adaptation and the likelihood of evolutionary rescue, which could be replicated to study other species. Therefore, this work may also inform conservation efforts for other species that are declining due to climate change and heat stress. Additionally, I will publish my findings in open-access journals so additional studies may build upon my work. Lastly, I aim to present my research at various academic conferences to expand the geographic relevancy of kelp forests.

Broader Impacts

This research will provide insight into critical conservation and management strategies for struggling populations of bull kelp. Although recent research plans have suggested a framework to begin the conservation of kelp forests,[2] bull kelp populations are experiencing rapid canopy loss,[5] and immediate, novel conservation research is vital to prevent local extinction. Areas with high genetic variability, as determined by step 1 of the proposal, are the most likely to undergo rapid evolution independently and would, therefore, be the most efficient to protect.[10] A strong understanding of evolutionary processes is necessary to optimize protection and restoration. This innovative genomic restoration strategy will help work towards habitat restoration and a sustainable kelp harvest and provide stronger mitigation for future extreme climatic events. Kelp forests hold great value to indigenous culture in California.[2] I intend to incorporate engagement with Indigenous tribes into this research, as outlined in the State of California's Interim Action Plan for Protecting and Restoring California's Kelp Forests,[2] with the Tribal Marine Stewards Network. The Tribal Marine Stewards Network generates educational opportunities and internships among Indigenous individuals. A partnership with this network will engage a new generation of Indigenous groups with hands-on kelp research. I aim to inspire young scientists to conduct similar research to help protect our at-risk ecosystems.

References

[1] Grainger, T. N., & Levine, J. M. *Ecology letters* (2022). [2] California Ocean Protection Council. Interim Action Plan for Protecting and Restoring California's Kelp Forests (2021). [3] Fales, R. J. Doctoral dissertation, University of Washington (2023). [4] Beas-Luna, R., *et al. Global Change Biology* (2020). [5] Arafeh-Dalmau, N., *et al*. *Biological Conservation* (2023). [6] Bell, T. W., & Siegel, D. A. *Proceedings of the National Academy of Sciences* (2022). [7] Clark, R. D., *et al*. *Molecular Ecology Resources* (2023). [8] Mora-Soto, A., *et al*. *Frontiers in Marine Science* (2024). [9] Lou, R. N., *et al*. *Molecular Ecology* (2021). [10] Bell, G. *Annual Review of Ecology, Evolution, and Systematics* (2017).