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Bull Kelp (Nereocystic lutkeana) Restoration and Management in Northern California

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This Master's Project

Bull Kelp (*Nereocystic lutkeana*) Restoration and Management in Northern California

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List of Acronyms and Abbreviations

GFNMS…………Greater Farallones National Marine Sanctuary

GFA…………Greater Farallones Association

CDFW…………California Department of Fish and Wildlife

OPC…………Ocean Protection Council

BML…………Bodega Marine Labs

ENSO …………El Niño Southern Oscillation

SSWD…………Sea Star Wasting Disease

TBF…………The Bay Foundation

TCF…………The Climate Foundation

KELPRR………… Kelp Ecosystem Landscape Partnership for Research Resiliency

UAV…………Unmanned Aerial Vehicle

MARINe ……….Multi-Agency Rocky Intertidal Monitoring Network's

CCKA……………California Coastkeeper Alliance

IMAS…………The Institute for Marina and Antarctic Studies

MPA…………Marine Protected Area

EAC……………East Australian Current

FRDC……….. Fisheries Research and Development Corporation

Abstract

Northern California's coastal marine ecosystems support one of the most productive and biodiverse habitats on the planet. Bull kelp forests (*Nereocystic lutkeana*) form habitats for an abundance of marine mammals, sea bird, fish, and invertebrates. In recent years, compounding ecological and climatic factors have disrupted the balance of the bull kelp forests and led to an unprecedented loss of bull kelp biomass and canopy cover. These areas that are typically teeming with marine life have shifted into a stable state of sea urchin barrens due to over grazing of bull kelp by purple sea urchins (*Strongylocentrotus pupuratus*). These sea urchin barrens provide very little habitat diversity and do not support the variety of life that rely on habitat forming bull kelp for nourishment, shelter, and breeding grounds. Marine heatwaves and warming ocean trends have exacerbated the detrimental effects of the sea urchins by leaving bull kelp more susceptible to grazing pressures. Estimates have shown a 93% loss of bull kelp canopy cover along the Mendocino and Sonoma counties coastline. This devastation has far reaching repercussions, from multi-million-dollar economic impacts on recreational and commercial fisheries that rely on bull kelp to provide habitat and food to their target species, to the loss of carbon sequestration services. This paper examines kelp restoration case studies to determine which restoration techniques and management practices have been successful. Based on this synthesis, I provide recommendations to the Greater Farallones National Marine Sanctuary (GFNMS) to restore and manage these areas that have been heavily affected by bull kelp loss. My bull kelp restoration and management recommendations for GFNMS are three pronged. 1) Mobilize stakeholders to participate in mass urchin culling events in urchin barren areas that are in close proximity with remaining bull kelp forests. 2) At sites where sea urchins are successfully thinned to a manageable density, employ kelp enhancement techniques of outplanting thermally tolerant juvenile bull kelp and transplanting adult bull kelp from neighboring bull kelp forests. 3) Implement a citizen science and education program to increase awareness and visibility of the collapse of bull kelp forests on the Northern California coast.

1. Introduction

The planet and the oceans are experiencing increased damages to ecosystems in the wake of anthropogenic sources of degradation, including climate change from carbon input to the atmosphere (Intergovernmental Panel on Climate Change 2014). Humans are increasingly being faced with the challenge of protecting and restoring the degraded ecosystems that we have altered, while also managing the effects of ongoing climate change. Scientists and environmental managers are exploring a multitude of mechanisms to both combat this ecosystem degradation and lower carbon emissions (Roberts et al. 2017a). These mechanisms range from sophisticated carbon capture technology to the use of naturally occurring ecosystem engineers (Shelamoff et al. 2019, Roberts et al. 2017b). Ecosystem engineering, such as oyster farming, tree planting, or building living shorelines, gives us the ability to utilize naturally occurring carbon sequestration processes through biological functions that have the ability to mitigate carbon emissions (Shachak et al. 1994). Kelp (*Laminariales* spp.) forests in particular serve as an important ecosystem engineer for temperate coastlines around the world and are a powerful player in the carbon cycle (Shelamoff et al. 2019). Although kelp forests have been degraded around the world (Vergés et al. 2014), restoration of these underwater forests can provide managers with a potential tool to slow down anthropogenic climate change through mitigating carbon emissions. Restoring the carbon sequestration of these kelp forest systems would rely on ecosystem-based management. Ecosystem-based management occurs when environmental management practices focus on restoring and managing all of the interactions within an ecosystem rather than a single service or species (Robinson et al. 2019).

Expanses of bull kelp (*Nereocytis luetkeana*) typically extend along the coastal waters of Northern California, creating one of the most diverse and productive ecosystems on the planet (Steneck et al. 2002). Kelp forests are highly efficient in their natural ability to sequester carbon through the uptake of carbon dioxide (CO_2) from the water column, effectively removing CO_2 from the ocean (Pfister et al. 2018a, Teagle et al. 2017). This carbon sequestration mechanism makes kelp forests around the world a highly valuable resource to protect and restore in order to offset carbon emissions and slow climate change. Bull kelp is facing a devastating decrease in abundance along the coastal waters of Mendocino and Sonoma counties in Northern California. A combination of ecological and climatic stressors has led to estimated 93% reduction in bull

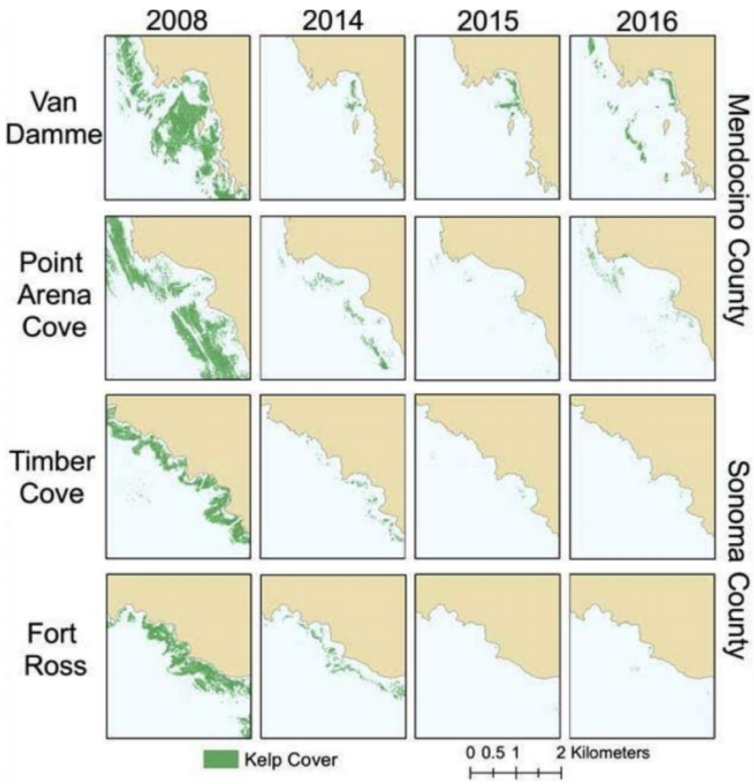

Figure 1. Demonstrates reduction in kelp canopy cover in Northern California sites from 2008-2016. Source: CDFW

kelp biomass and unprecedented decreases in kelp forest canopy cover (Figure 1) (Catton et al. 2019).

The coastal waters adjacent to Mendocino and Sonoma Counties are a part of the Greater Farallones National Marine Sanctuary (GFNMS) under the National Oceanic and Atmospheric Administration (NOAA). GFNMS and their non-profit partner, Greater Farallones Association (GFA), aim to protect, conserve, and manage a myriad of marine ecosystems that lie within the 3,295 square mile boundary of federally protected waters (Figure 2) (ONMS et al. 2014). The waters within GFNMS makeup one of the most productive habitats in the world, including the coastal bull kelp forests. In this area, sea birds, sharks (*Selachimorpha* spp.), sea turtles (*Chelonioidae* spp.) and some of the largest marine mammals are known to migrate thousands of miles for nourishment or mating in the nutrient rich waters that persist there (ONMS et al. 2014). The duty to preserve biodiversity and marine resources from the coastline to 30 miles of open ocean offshore (Duncan et al. 2019) poses many challenges for restoration efforts for GFNMS and GFA managers and researchers with increased ocean degradation, sea level rise, and warming ocean temperatures.

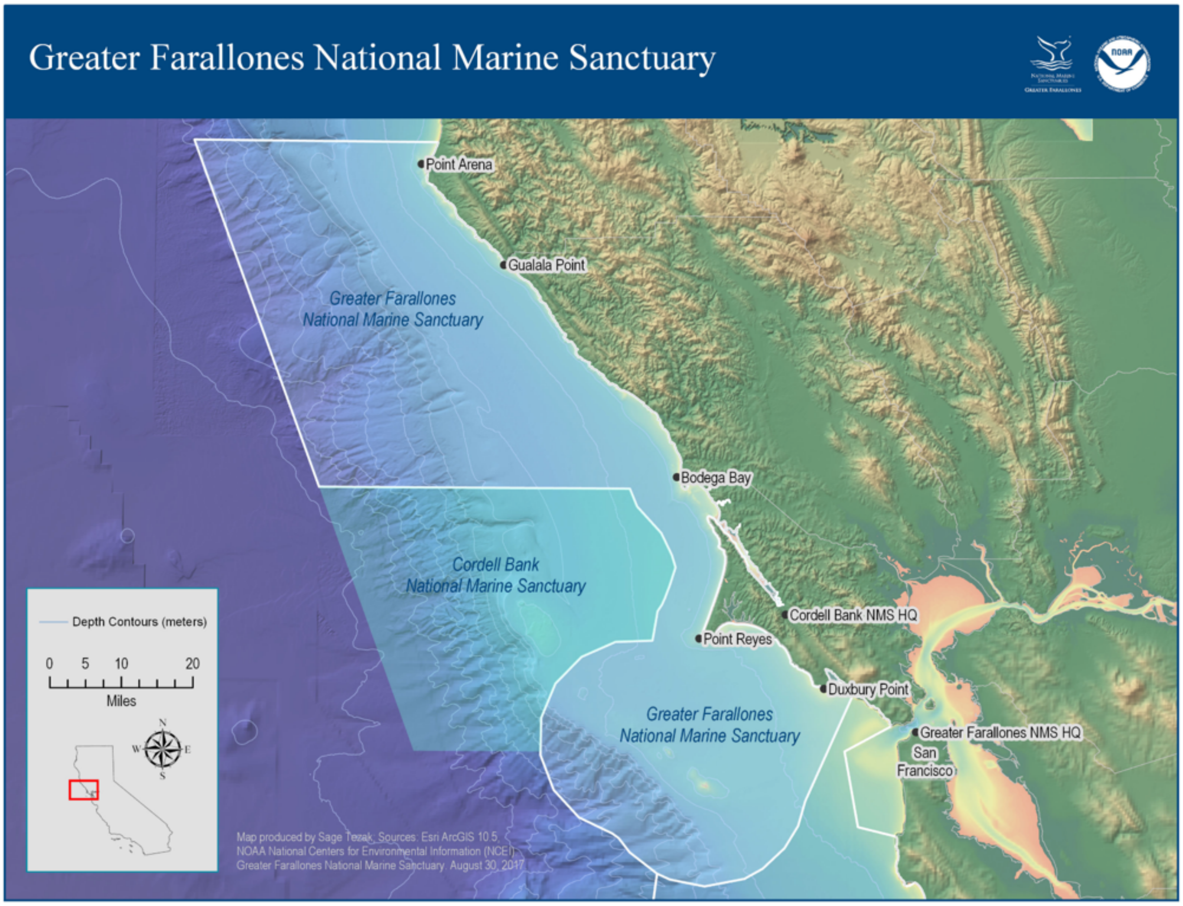

Figure 2. Map of the Greater Farallones National Marine Sanctuary Boundary. Source: NOAA/GFMNS

GFNMS and GFA have recently focused management efforts on mitigating the current loss of critical bull kelp habitat. GFA has developed and published the Bull Kelp Recovery Plan in 2019 in collaboration with a multitude of agencies and stakeholders are exploring methods of restoration in hopes of recovering this vital and historically persistent habitat (Hohman et al. 2019). Interagency efforts to address bull kelp loss are underway with key players such as California Department of Fish and Wildlife (CDFW), Ocean Protection Council (OPC), Bodega Marine Laboratories (BML), Noyo Center for Marine Science, and various other organizations (Hohman et al. 2019). So far efforts have been focused on site selection of recovery areas and monitoring protocols (Hohman et al. 2019), but there lacks a comprehensive study on kelp restoration and management practices that could be implemented.

1.1 Objectives

The Kelp Recovery Plan that GFA and GFNMS have taken a lead on has provided extensive framework for recovery site selection, monitoring protocol, and stakeholder engagement needs (Hohman et al. 2019). I will expand on the existing Kelp Recovery Plan by establishing tangible and definitive actions to take in order to control sources of damage to bull kelp forests and reestablish bull kelp biomass. This project provides management recommendations based on best available science and previously successful restoration and management programs. Recommendations presented here are based on the results of kelp management conducted in similar ecosystems in other areas of the world.

1.2 Background

1.2.1 Ecology and Geographic Distribution of Global Kelp Forests

Kelp forests occurs worldwide, often dominating the shallow waters along subtidal rocky coastlines in temperate regions of the globe (Dayton 1985). Kelp species are a form of brown macroalgae that typically grows in large stands to form dense kelp forests and sprawling canopy cover (Steneck et al. 2002). Various regions of the world possess kelp species that are unique to that particular area, with distinct morphological features but similar life cycles (Dayton 1985). Although kelp species can appear individual from each other, they provide common services and benefits to their overall ecosystems (Teagle et al. 2017). Kelp forests provide nourishment, structural complexity, and shelter for many species across trophic levels (Steneck et al. 2002, Campbell et al. 2014). The ability for kelp to support high primary productivity rates, fuel coastal food webs, and support nutrient cycling allows these underwater forests to serve as host to hotspots of marine biodiversity (Teagle et al. 2017).

Kelp forests often occur in areas of ocean upwelling, which provide a stable input of cold, nutrient rich waters (Steneck et al. 2002). These nutrient loads are a contributing physical factor that allow some kelp species to reach growth rates as high as one meter per day (Dayton 1985). Light availability has implications on the photosynthetic abilities of macroalgae, irradiance in high amounts can increase the nutrient uptake of kelp (Drobnitch et al. 2017).

Levels of irradiance can diminish from 10% at 12 m to 75% at bottom depth, allowing for higher carbon and nutrient uptake from kelp leaves at the surface than in the under story (Drobnitch et al. 2017).

The global distribution of kelp forests demonstrates the species ability to persist in extreme environments. While most kelp resides in temperate areas at latitudes between the tropics and the arctic, populations of kelp beds can also be found in polar and equatorial regions (Bolton 2010). Kelp forests in total are present along 25% of global coastlines (Smale 2020). In the Atlantic Ocean, along the coast of China and Japan, *Laminaria* spp. dominate, whereas along Australian, New Zealand and South African coasts, *Ecklonia* spp. are most commonly found (Bolton 2010). Along the coast of North and South America in the Eastern Pacific basin, and certain areas of South Africa and Australia, *Macrocystis* sp., or Giant Kelp, dominate (Dayton 1985). The coastal waters north of Central California experience some of the highest diversity of kelp, but bull kelp is the most predominate (Steneck et al. 2002). The regions of the globe that support kelp forests have particular ocean conditions that allow those kelp species to grow at an extremely fast rate (Springer, Yuri et al. 2006). The high productivity of kelp forests can be attributed to the dynamic physical and chemical conditions where they grow (Dayton 1985). Light availability, temperature, nutrient loads, substrata, and salinity are all controlling factors of kelp proliferation (Steneck et al. 2002), and each kelp species has different tolerances for these controlling factors. Some species have wider tolerances of these abiotic and biotic factors than others, allowing them to grow in a larger geographical range (Drobnitch et al. 2017).

1.2.2 Climatic stressors

An overarching physical force that controls the biological and physiological processes of kelp is thermal tolerance and optimal temperature range for growth rates (Smale 2020). Most species of kelp thrive in cold water (Teagle et al. 2018) and are sensitive to temperature changes and thermal stress (Springer, Yuri P. et al. 2010), therefore kelp species are heavily influenced by climatic stressors like ocean warming trends and marine heatwaves (Steneck et al. 2002). Even a few degrees of warming can inhibit growth rates by a significant amount (Tegner et al. 1996). While there are species that have a tolerance to higher temperatures, ones that lack that tolerance experience higher risks of degradation with the increased occurrence of warmer waters

(Dayton and Tegner 1999). Heatwaves and warming trends have the potential to exacerbate ecological interactions (Kordas et al. 2011). Grazing pressures on kelp by herbivorous fish and sea urchins can intensify as abundance increases, resulting in stable states where urchin barrens persist and prevent the reestablishment of canopy-forming kelp (Bennett et al. 2015). This ecological phenomenon, compounded with the inhibition of kelp's primary productivity when temperature increases, has raised alarms globally for the fate of kelp forests as a marine resource (Smale 2020).

There are many reported cases of marine species, including kelp, experiencing range shifts in response to ocean warming (Smale 2020). Spatial range shifts and the disappearance of kelp can be directly corelated to anthropogenic carbon input resulting in warming oceans (Campbell et al. 2014). Geographic redistribution of kelp can lead to decreased ecosystem functioning and alterations in community composition from historical conditions (Vergés et al. 2019). Increased ocean temperatures also have adverse effects on kelp forests such as decreased photosynthesis, low reproduction, and loss of carbon uptake. These adverse effects that result from increased frequency of marine heatwaves cause massive declines in kelp biomass along coastlines worldwide (Wernberg et al. 2016).

Kelp is highly susceptible to degradation from abiotic changes because of their sessile nature and sensitivity to temperature changes (Smale and Wernberg 2013).Genetic variation has been identified as a possible factor that can ameliorate devastating loss from thermal stress and warming seas, but not enough is understood about specific species genetics and their ability to cope with climatic changes (Wernberg et al. 2018). Die offs of kelp have lasting ecosystem wide consequences including a decrease in habitat diversity, structural complexity and productivity (Campbell et al. 2014). In the wake of these consequences, entire ecosystem phase shifts result in a loss of biodiversity and ecosystem services (Filbee-Dexter, K. and Scheibling 2014). Kelp bed loss creates major disruptions in food web dynamics, which has a disproportionate impact on lower trophic levels that rely on kelp for refuge and food (Campbell et al. 2014). The loss of this dominant coastal species leaves kelp ecosystems in a completely degraded state. Marine ecosystems are susceptible to remain in a degraded state for long periods of time following rapid ecological changes (Nyström et al. 2012). In many cases, this ecological shift is that from kelp forest to sea urchin barren. This shift occurs when there is a predatory release of urchin and they experience population explosions, effectively devouring kelp forests until there is little to nothing left (Rogers-Bennett and Catton 2019).

1.2.3 Northern California and Bull Kelp

1.2.3.1 Upwelling, "the Blob" and El Niño

Along the Northern California Coast and within GFNMS, the California Current System (CCS) supports the occurrence of upwelling (McCabe et al. 2015) as a driving force of primary production and intense biodiversity along coastal ecosystems (Ikawa et al. 2012). This phenomenon happens due to the gravitational pull in the Northern Hemisphere which moves water southwards, while winds drive warmer shallow waters offshore, creating the movement of surface waters away from shore at a 90° angle, where after cold, nutrient rich waters are driven up from the ocean depths to provide nourishment and conditions for high productivity (McCabe et al. 2015). Bull kelp forests within GFNMS rely on this upwelling for nutrients, and these nutrients further support trophic dynamics within bull kelp forests (Hohman et al. 2019). The coastal winds that drive upwelling are subject to changes in frequency and intensity in the wake of climate change, altering the availability of chemical and physical conditions that bull kelp relies on (Springer et al. 2010).

El Niño Southern Oscillation weather patterns are characterized by warm and nutrient deficient water conditions. When warm waters invade the CCS, the CCS carries lower nutrient levels, causing food availability to shift dramatically and leaving populations that depend upon that high supply of nutrients vulnerable to mass die offs (Leising et al. 2015). This pattern brings changes to coastal community compositions, including increased abundance of species that are not characteristic of the region. With large-scale climate patterns changing, increased frequencies and intensity of marine heatwaves and El Niño events have severely affected the success of bull kelp growth. Around 2014-2015 in the northeast Pacific a decrease in upwelling events led to unusually warm sea surface temperatures, exhibiting an increase of 4° C above long-term trends in some areas (Leising et al. 2015). This event came to be known as the "Warm Water Blob," ("the Blob") with effects mimicking that of warm El Niño years (Leising et al. 2015). The warm water intrusion resulting from the Blob has had lasting devastations to many marine populations of invertebrates, seabirds, plants, and mammals.

The Blob was followed by an El Niño year in 2015, which heavily compounded on the already nutrient poor, warm water conditions (Catton et al. 2019). Sensitivity to warm waters left bull kelp individuals vulnerable to overgrazing and slowed growth rates during, which was compounded with ecological stressors that led to the decimation of bull kelp forests.

1.2.3.2 Bull Kelp Morphology, Life Cycle, and Distribution

Bull kelp is a brown algae that is a part of the Laminariales order of kelp that are associated with cold water coastal habitats (Dayton 1985). Bull kelp morphology consists of a holdfast, stipe, pneumatocyst, and blades (Steneck et al. 2002) (Figure 3). The holdfast is the lower portion of bull kelp that adheres the whole plant to the rocky substrate, anchoring it to the bottom during storms and wave surges. The next portion is the stipe, resembling a long thin stalk about 1/3-inch-thick that grows towards the surface (Abbott and Hollenberg 1976). The stipe comes to an end at pneumatocyst, a gas filled bulb that forms near the surface of the water as a floatation device which the blades grow from. The blades sit close to or at the surface and serve as the point where photosynthesis, respiration, and nutrient uptake take place (Springer et al. 2010).

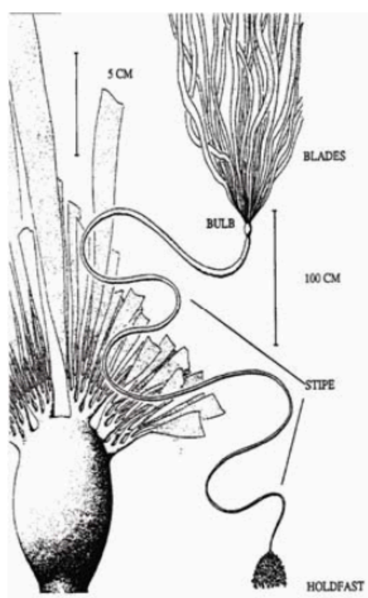

Figure 3. Kelp morphology, including holdfast, stipe, pneumatocyst (bulb), and blades (Abbott and Hollenberg 1976)

Typical to all kelp species, bull kelp exhibits alternation or generations in its life cycle, alternating between the adult sporophyte phase and the microscopic gametophyte phase (Springer et al. 2010). Spores, the reproductive unit of kelp, are produced through reduction division in patches on the kelp's blades called sori (Amsler and Neushul 1989). Male and female spores are released from the blades by in extremely high densities during the summer and fall months, after which they are fertilized in the water column and settle upon rocky substrate to grow into microscopic male or female plants (Amsler and Neushul 1989). There are narrow temperature ranges that bull kelp spores can successfully germinate within (Springer et al. 2010). While spores can travel long distances through water columns if they are released from an intact blade to drift through the water column, more often they settle in larger concentrations near parent plants as a result of still being attached to the sori when they settle at depth (Dobkowski et al. 2019). This occurrence has implications on kelp genetics, due to this method of reproduction, increased spatial dispersal can increase genetic variation among kelp populations and be evolutionarily beneficial for the species (Wernberg et al. 2018).

Once kelp gametophytes have settled on substrata and begin to grow into mature sporophytes sometime during spring (Springer et al. 2006). Average growth rates of *Nereocystis* reach up to 10 cm per day, and the heights of mature individuals range from 3 to 20 m deep (Dayton 1985). The photosynthetic abilities and growth rates are highest in summer and fall months due to increased light availability (Dobkowski et al. 2019).

The spatial distribution of *Nereocystis* ranges from Point Conception, California to the Aleutian Islands in Alaska (Abbott and Hollenberg 1976). Within these areas lies the optimal temperature tolerance of Bull Kelp which ranges from 5 - 20° C (Springer et al. 2006). They occupy rocky reefs and subtidal bedrock year-round but experience higher mortality rates during the winter months when strong storms can dislodge holdfasts and wash out kelp beds. During this time of year bull kelp biomass is lower than usually resulting in an increased sensitivity to grazing pressure by herbivorous fish and sea urchin (Dayton et al. 1992).

1.2.3.3 Ecosystem Services and Economic Significance

The cultural, economic, and environmental services that bull kelp forests provide through habitat provisioning, carbon sequestration, and fisheries support make them a desirable resource to protect and restore (Steneck et al. 2002). The cycling of nutrients through coastal food webs is directly and indirectly due to bull kelp which harnesses the resources from upwelling events into high growth rates, providing food and habitat structure, and nursery grounds for other trophic levels (Field et al. 2006). This transport of nutrients supports massive amounts of primary production by phytoplankton and algae, which then attracts higher trophic levels of consumers, creating a hotspot of biodiversity (Teagle et al. 2017). A large abundance of marine mammals, invertebrates, seabirds, and fish depend on bull kelp in various life stages for these direct services (Steneck et al. 2002).

Kelp all over the world act as carbon sinks, effectively removing CO2 from the water column as it grows, after which it is can be transported to the deep sea when large storms events and ocean swells dislodge holdfasts and wash them out to sea, where it permanently remains (Pfister et al. 2018b). Studies show that globally, kelp forests sequester roughly 200 million tons of atmospheric CO2 per year (Filbee-Dexter, Karen and Wernberg 2018). We have ability to utilize them as bioengineers to mitigate anthropogenic climate change, increasing their value as a marine resource. They protect adjacent terrestrial areas from erosion by absorbing wave energy, dampening the impacts of large storms during winter months.

Bull kelp is a critical asset to California's economy, stimulating millions of dollars in revenue per year from commercial and recreational fisheries and ecotourism (Springer et al. 2010). Areas along the coast of Mendocino and Sonoma are extremely popular for outdoor recreational activities directly dependent on bull kelp forests like diving, kayaking, whale watching, and many other coastal activities that bring a surplus of visitors each year (Hohman et al. 2019). Commercial and recreational fisheries rely on kelp to provide habitat for target species like abalone, finned fish, and sea urchin. Estimates show that recreational abalone fisheries alone are valued somewhere between $24-$44 million (Reid et al. 2016) They have historic cultural importance to native coastal tribes (Hohman et al. 2019), and all types of coastal communities find value in their aesthetic services.

1.2.3.4 Bull Kelp Forest Trophic Structure and Disturbances

Food web dynamics associated with Northern California bull kelp forests have experienced severe ecological disturbances in the past decade, contributing to the loss of bull kelp biomass and habitat complexity (Catton et al. 2019). Kelp forests exist in a state of equilibrium, with various species of invertebrates, plants, and mammals keeping each other's populations in check (Figure 4). Kelp forests are heavily regulated by trophic cascades and top-down control within the ecosystem (Estes et al. 2004) Sea otters (*Enhydra* lutris) serve as the keystone species for kelp forests that exert this top-down control, meaning their presence or absence has a disproportional effect on species composition within the kelp ecosystem (Stewart and Konar 2012). Sea otters feed on various invertebrates in the rocky subtidal areas including sea urchin (*Echinoidea*) and abalone (*Haliotidea*) (Nicholson et al. 2018). Generally, the presence of sea otter's is associated with increased kelp abundance and low sea urchin abundance (Estes et al. 2004). The removal of sea otters from the system causes these subtidal areas to shift form one stable state of kelp forest, to another stable state of urchin barren (Stewart and Konar 2012). In the 18th and 19th centuries, sea otters were hunted to near extinction (Dunn and Hovel 2019), and have only been able to successfully reestablish in approximately 13% of

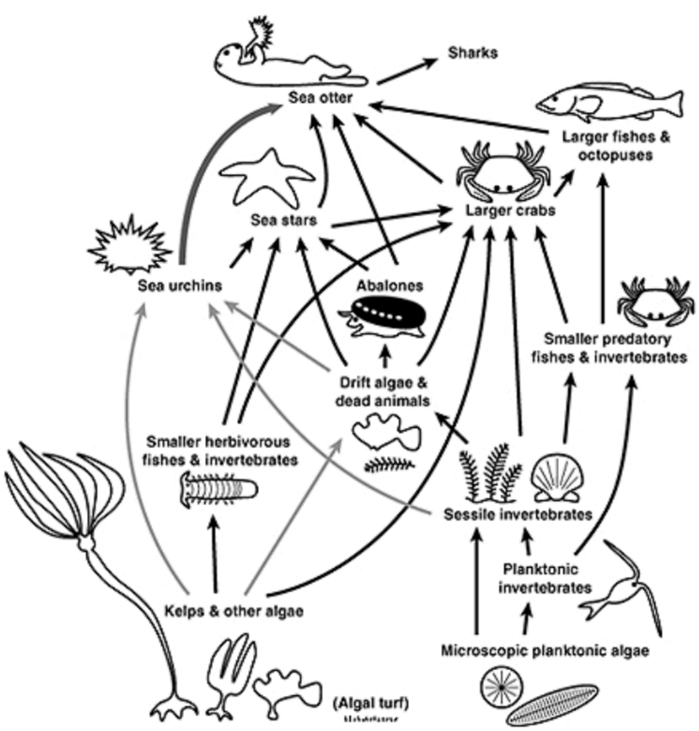

Figure 4. Typical Bull Kelp food web with the presence of sea otters (Brumbaugh AMNH-CBC)

their historic persistence and range from San Mateo County to Santa Barbara County (Figure 5) (U.S. Fish and Wildlife Service 2015). It is not clear what is preventing sea otter distribution from reestablishing further north, but their absence has had long-lasting affects.

In 2011 harmful algal blooms (HAB) had extreme repercussions for many invertebrate species, most notable in the kelp scenario was the death of thousands of red abalone (*Haliotis rufescens*) in Sonoma and Mendocino County (Reid et al. 2016). Abalone are a significant competitor for space and food with sea urchin, and this release of competition was yet another factor that allowed for sea urchin populations to boom (Rogers-Bennett and Catton 2019). This also caused an estimated $12 million decline in fisheries value after regulations were imposed as a result of the HAB that decimated abalone populations (Reid et al. 2016). As kelp continued to disappear due to sea urchin grazing, the surviving abalone starved and experienced further

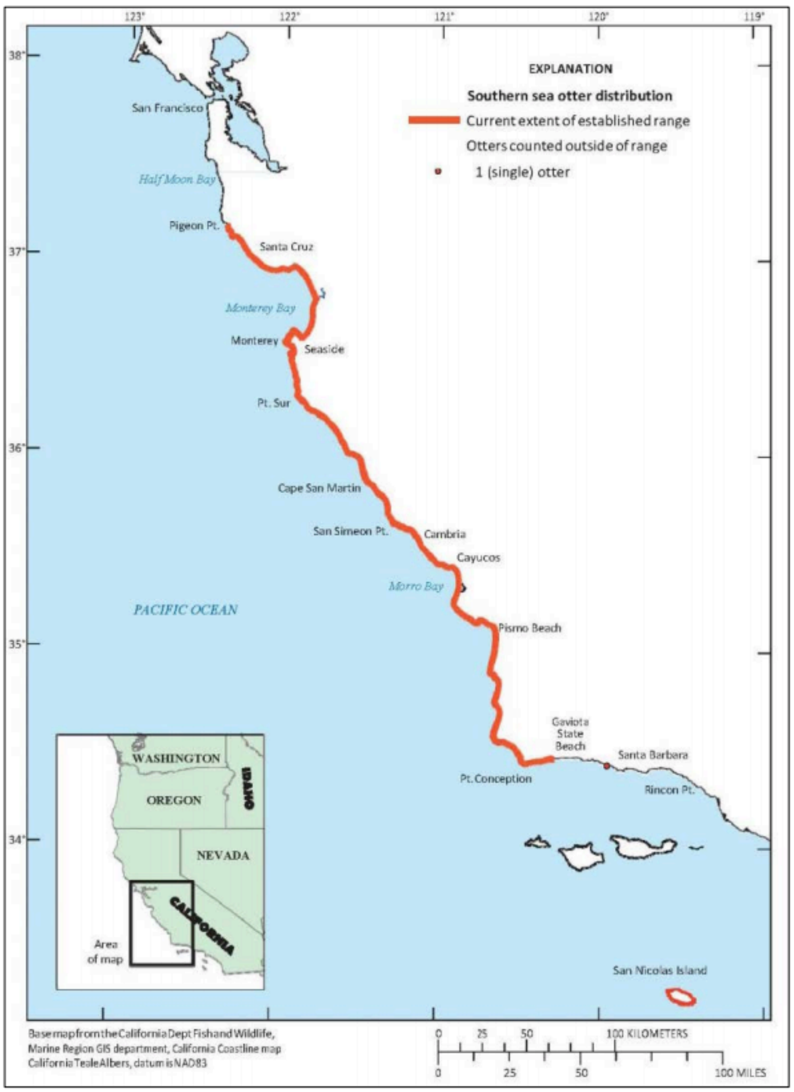

Figure 5. Southern Sea Otter range from 2016 census (Source: USFWS, Tinker et al. 2016, Kreuder et al. 2003)

mortality events while fisheries continued to feel the economic repercussions of this (Rogers-Bennett and Catton 2019).

The next devastation occurred in 2013, when a densovirus (*Parvoviridae*) hit the Pacific West Coast and caused the death of millions of sea stars (*Asteroidea*), affecting over 20 different species, from Alaska to Baja due to the Sea Star Wasting Disease (SSWD) (Hewson et al. 2014). Because sea stars serve as a crucial predator to sea urchin, this predation release would allow sea urchins to proliferate even further (Catton et al. 2019). The sunflower star fish (*Pycnopodia helianthoides*) are one of the sea urchins' dominant predators and means of population control in Northern California, and sunflower starfish were so heavily affected by the SSWD to the point that no individuals were found during 2016-2019 surveys (Rogers-Bennett and Catton 2019).

All of these species, which would normally relieve kelp from the grazing pressures of purple sea urchin (*Strongylocentrotus purpuratus*) (Nichols et al. 2015), experienced their own population decline (Figure 6) and resulted in chain reaction leading to kelp forest demise and regime shifts to urchin barrens (Rogers-Bennett and Catton 2019). The loss of urchin predators and decline in bull kelp has created a complex scenario, where there is an absence of bull kelp as

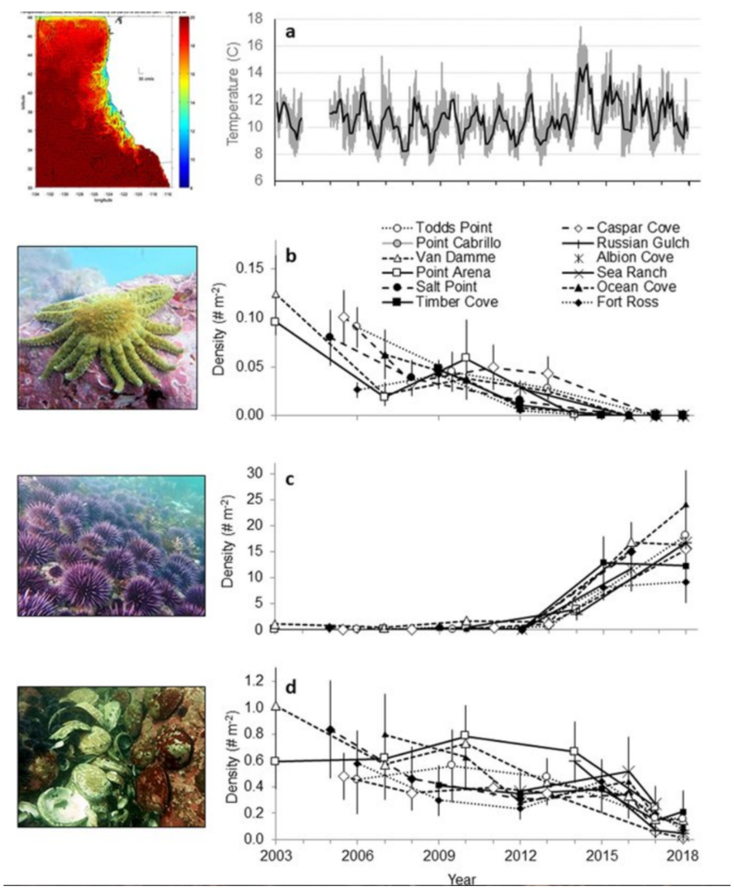

Figure 6. Increased ocean temperatures in California, decreased sunflower starfish density, increased purple sea urchin density, and decreased abalone density.

a food source for sea urchin, urchin's gonad production is negatively impacted and reduced, leading to a decrease in the sea urchins' value to fisheries (Claisse et al. 2013). The purple sea urchin population explosion that decimated the kelp forest has also contributed to starvation of the red sea urchin (*Strongylocentrotus franciscanus*), impacting yet another multi-million-dollar fishery (Rogers-Bennett and Catton 2019, Reid et al. 2016). These starving urchins have the ability to conserve energy by decreasing their gonad production which is why they are able to stay live for long periods of time with no nourishment (Reid et al. 2016), but with no gonads these sea urchins have little marketable value, leaving commercial harvesters with no motivation to collect sea urchins and keep the population under control.

1.3 Importance of Restoring the Structure and Function of Bull Kelp Forests

Increasingly, environmental agencies, managers, and scientists are utilizing ecosystem-based management approaches, which focus on restoring the interactions within an entire ecosystem, to reverse ecosystem degradation(Robinson et al. 2019). Ecosystem-based management can serve as an important tool for kelp forest restoration strategies. Using kelp as an umbrella species to protect and restore has implications on the conservation of all the trophic levels and species that use habitat-forming kelp forests (Claisse et al. 2013). Implementing ecosystem-based management practices and policies to preserve marine resources is a critical in the case of bull kelp restoration. Restoring bull kelp forests can serve as an important tool for preserving the underwater coastal community composition and ecosystem services that are supported by kelp forests (Claisse et al. 2013).

1.4 Bull Kelp Recovery Plan

The Bull Kelp Recovery Plan was created in 2018-2019 by the Kelp Recovery Working Group. The working group was comprised of GFA staff, GFNMS Advisory Council members, and CDFW staff in order to provide guidance to GFNMS and CDFW managers (Hohman et al. 2019). The goal was to supply managers with recommendations to respond to the widespread bull kelp loss. The Bull Kelp Recovery Plan focuses on 206 miles of subtidal rocky area along Mendocino and Sonoma County(Hohman et al. 2019). The extensive efforts of the working group were very successful at establishing recovery site selection criteria and identifying areas for restoration focus and monitoring protocols. On top of that, the working group established a Kelp Recovery Network that has facilitated communication and outreach between stakeholders, interest groups, and members of the public.

The Bull Kelp Recovery Plan outlines the criteria that they used to identify and apply site selection for recovery efforts analysis. Categories were used for weighting each criterion (Hohman et al. 2019):

1) Ecological Significance
2) Areas in Need of Further Assessment
3) Positive Additional Aspects

Sites were assigned numbers for each of these categories from individual scales, added up and ranked into four tiers; primary, secondary, tertiary, and areas to be avoided. From this process the working group was able to provide recommendations to managers on where to focus restoration efforts that would have the highest impact physically, culturally, and economically.

Standardized monitoring protocols were identified by the working group in the Bull Kelp Recovery Plan. The framework for unmanned aerial vehicle (UAV) data collection was laid out in order to obtain fine scale, high resolution imagery to assess bull kelp canopy cover. The plan includes the use of satellite imagery for large scale monitoring to track broad regional patterns (Hohman et al. 2019). Long-term ecological monitoring efforts are identified as important efforts to track ecosystem responses of restoration implementation.

The Kelp Recovery Network built on the existing efforts by CDFW's Kelp Ecosystem Landscape Partnership for Research Resiliency (KELPRR). KELPRR was formed in 2018 and successfully brought together leading scientists, agencies, fisheries managers, and more to find science-based solutions to bull kelp recovery (Hohman et al. 2019). The Kelp Recovery Network seeks to broaden and expand the efforts of KELPRR to promote engagement and increase collaboration across various sectors.

Restoration and management actions for bull kelp recovery in Northern California are ongoing and widespread, but far from complete. Funding and implementation for sea urchin removal and bull kelp regeneration are critical next steps for scientists and managers to focus on. The Bull Kelp Recovery Plan provides critical next steps to create a network and increase engagement. I propose here, tangible and physical actions for active bull kelp recovery that build on the existing framework.

1.5 Research Questions

Due to ocean dynamics and variable coastal conditions, creating a lasting framework for kelp restoration has proven to be a difficult task with many physical and ecological challenges. My project provides a plan for ecosystem-based management of kelp forests that can fit the Northern California coast. While efforts towards kelp restoration have been initiated, many suggestions have concluded that further need for research is necessary before implementation can occur. However, the disappearance of bull kelp has disrupted entire ecosystems and severely threatens the integrity of bull kelp forests for the future (Teagle et al. 2017). GFNMS needs to be advised on actions that can be taken immediately to thwart further ecosystem degradation. The use of scientific literature, case studies, and existing restoration plans serves to inform coastal managers at GFNMS on efficient strategies to re-establish resilient kelp ecosystems.

This study has three main goals:

1. Establish a plan for sea urchin population control and removal. The analysis takes into consideration physical removal techniques and the use of urchin competitor and predator control tactics.
    a. What type of physical removal of urchins is viable at the current magnitude of urchin take over?
    b. Are efforts towards the re-introduction of *Pycnopodia* be feasible or successful?
    c. Can the reintroduction of abalone as a competitor of the sea urchin be accomplished?
2. Successful bull kelp propagation strategies.
    a. There are challenges to planting or transplanting flora into marine ecosystems that are not usually limiting factors to planting terrestrial species. Because the ocean and coastal areas are extremely dynamic and constantly changing systems, the success of growing kelp has faced many challenges.

3. Review of the best available science on kelp genetics and the potential to create resilient bull kelp populations that can withstand a higher range of thermal stress.
    a. In the wake of climate change, it is critical to anticipate that the situation is not getting better, we have not found any instant fixes that can reverse warming oceans and increased levels of carbon dioxide. Creating populations that can withstand higher temperatures could be a key component for restoring native bull kelp forests.

2. Methods

In order to provide recommendations for bull kelp restoration and management practices to GFNMS and GFA I have done a literature review and in-depth comparison of two case studies on kelp restoration programs. I used various academic and professional resources to compile my literature and reports. My primary source for academic and peer-reviewed literature was the University of San Francisco library database, Environment Complete. Using key search words such as '*Nereocystis,*' 'bull kelp,' 'sea urchin,' 'abalone,' and the names of prominent coastal marine ecologists and scientists, I procured the literature included in this review.

The two case studies I have presented are from areas that have undergone a similar phase shift from kelp forest to urchin barren like that of the Northern California; Southern California and the Southern Australia Eastern Tasmania region. While sea urchin removal and kelp forest restoration efforts have occurred and are currently occurring in other parts of the world, there are limitations that helped narrow my focus to these two areas. The case study selection criteria I established was: 1) ecological and physical relevance to Northern California, and 2) English language publications. My decision to focus on Southern California and Tasmania was based on the similar ecological interactions and physical ocean conditions that comprise these areas, the availability of detailed literature. Kelp restoration in Japan and Norway were initially considered, but the language barrier for available literature and the limited timeline of my project resulted in me eliminating the further consideration of those regions.

I review and synthesize Southern California, Southern Australia, and Tasmania's efforts for urchin removal and kelp enhancement and use my literature review from Northern California to determine the best practices derived from these case studies. Although the two case studies are conducted on a different species of kelp, giant kelp (*Macrocystis pyrifera*), than that of Northern

California's bull kelp, the mechanism for restoration and management can be interchangeable. The similar physiological characteristics of kelp species (Bolton 2010) and the universal mechanisms involved in sea urchin removal (Nyström et al. 2012) allow for relevant comparisons. I obtained access to annual reports for the Southern California case studies through publicly available information on their websites and contacting the individual leading organization. Literature for the second case study on Southern Australia and Eastern Tasmania was compiled from communications with the leading researcher, Dr. Cayne Layton, on giant kelp restoration at University of Tasmania. Additional information was obtained from reports for Australia's National Environmental Science Programme for the Marine Biodiversity Hub detailing the role of restoration in marine and costal environments.

3. Synthesis and Results of Southern California and Eastern Tasmania Giant Kelp Restoration

Southern California and Southern Australia's giant kelp forest restoration efforts were chosen for my two case studies because of the relevant criteria that they both met for my synthesis. Similar ecological and climatic stressors that have contributed to the loss of giant kelp forests in both areas, to Northern California's bull kelp loss allows for an applicable comparison of restoration and management practices. The increased encroachment of urchin barrens from over grazing sea urchins, and infiltration of warm water to each area has significantly contributed to widespread loss of kelp in all cases. In the following case studies, I present a summary of each region's sea urchin removal and kelp enhancement practices, and synthesize which applications are transferrable to restoration and management of Northern California's bull kelp forests.

3.1 Southern California

Along the coast of Southern California, giant kelp typically covers the rocky subtidal coast of Palos Verdes in extensive stands of dense kelp forest. Various ecological, anthropogenic, and climatic factors led to the widespread loss of giant kelp and transformation to urchin barrens (Nichols et al. 2015, Tegner et al. 1996, Michael H. Graham 2004). Historical data from Ventura and Los Angeles Counties demonstrated a 76% loss of giant kelp from 1911-

2009 off the Palos Verdes coast (The Bay Foundation et al. 2018) (Figure 7). In 2013 the leading organization, The Bay Foundation (TBF) identified and began restoration efforts on 150 acres of urchin barren to decrease the density of purple sea urchins.

3.1.1 Palos Verdes Kelp Forest Restoration Project – Urchin Control

The Palos Verdes Kelp Forest Restoration Project was a collaborative effort between The Bay Foundation and Los Angeles Waterkeeper. The Bay Foundation has published multiple annual reports detailing restoration results of their Palos Verdes Kelp Forest Restoration Project. These reports date from 2013 to 2018, are available to the public, and detail the methodology and success of their restorative efforts. I have based my analysis of best practices and recommendations on the metrics from these reports in regard to sea urchin removal and subsequent kelp planting. The goal was to reduce purple sea urchin density to 2 individuals per

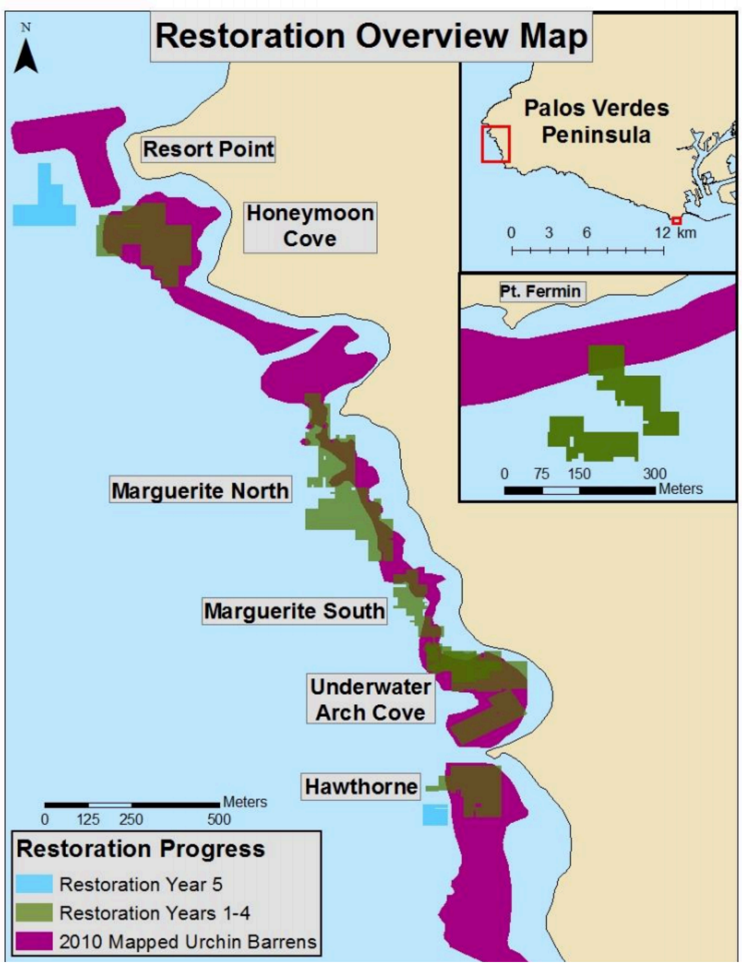

Figure 7. Restoration Overview for the Palos Verdes Kelp Forest Restoration Project showing restoration years 1-4, year 5, and mapped urchin barrens in 2010.

m^2 (The Bay Foundation et al. 2018). That goal was based on research from previous restoration efforts in Malibu and Santa Monica Bay, called the "Kelp Project," that took place in 1997. The Kelp Project demonstrated that reducing urchin density to the target level of 2 sea urchin per square meter allows the natural recruitment and development of giant kelp and other macroalgae species (The Bay Foundation et al. 2018). After the Kelp Project's target for urchin density and restoration goal of >1 giant kelp holdfast per 10 m^2 was reached, efforts ceased in 2004. Six years later, surveys demonstrated that the Kelp Project and been a success through the persistence of giant kelp in high densities in the area and ability to withstand disturbances.

The Bay Foundation utilized the Kelp Project as a model for the Palos Verdes Kelp Forest Restoration Project due to the resiliency demonstrated by the restored giant kelp forests. Large storm events and simultaneous red tide harmful algal blooms occurred in 2005 and 2006. The restored giant kelp forests in the area were able to survive through these compounding disturbances. This was an indication to The Bay Foundation managers that those levels and metrics of restorative efforts are substantial enough to recreate healthy, self-sustaining populations of giant kelp.

At the start of the Palos Verdes Kelp Forest Restoration Project, The Bay Foundation established protocols for pre-restoration monitoring, post-restoration monitoring, and response monitoring to keep restoration efforts uniform from year to year.

Pre-restoration Monitoring Protocol:

- monitoring was done in 30m x 30m sites for restoration at each site
- Split into 2m x 30m transects for urchin thinning
- Each transect divided into 10m segments for estimating urchin density
- Reasoning for this methodology is for "greater resolution of inter-block variability" and allows for adaptive management

Post-restoration Monitoring Protocol:

- 1-2 weeks after urchin removal
- The Bay Foundation does monitoring in the same transects to ensure uniformed performance standards
- Restoration sites re-surveyed every 1-3 months to make sure sea urchin density stays below 2 individuals per m^2.

Response Monitoring

- Vantuna Research Group leads monitoring efforts to measure the ecosystem and community response to restoration efforts.
- They measure species richness, biomass, and productivity.
- Intertidal and shallow subtidal monitoring occurs in accordance to Multi-Agency Rocky Intertidal Monitoring Network's (MARINe) Core and Biodiversity protocols used throughout the west coast.
- Red and purple sea urchin gonadosomatic index (ratio of gonad weight to body size) used to asses secondary production and importance to economically significant sea urchin fisheries

The Bay Foundation made considerable progress at restoring giant kelp forests along the Palos Verdes Peninsula. Over the five years of recorded urchin removal efforts, they were able to successfully cull approximately 45 acres (19 hectares) of urchin barren and effectively bring their density down to 1.35 urchins/m^2 on average across all six restoration sites (Table1). Post-restoration surveys at the end of the fifth restoration year demonstrated that every site that sea urchins were culled at was below the targeted 2 urchins/m^2, and fish assemblages and giant kelp density were responding positively to the removal efforts. The response of the natural recruitment and enhancement of giant kelp to this magnitude of urchin removal reveal that their targeted metrics are sufficient and could be applied to particular areas along the Northern California coast to promote bull kelp restoration. The goal to thin urchin densities to <2 urchins/m^2 is a goal that should be adopted by restoration managers for the Bull Kelp Recovery Program.

One large contrast in the kelp restoration efforts between that of Southern California and Northern California is the scalability of restoration. The scale of the Palos Verdes project in comparison to the scale of bull kelp loss that Greater Farallones National Marine Sanctuary is facing are quite different. While The Bay Foundation identified 150 acres (61 hectares) of urchin barren to restore, coastal areas of Mendocino and Sonoma County are looking at 331 km of coastline as the area of interest for bull kelp restoration efforts (Hohman et al. 2019). This difference in area means restoration managers will need to explore adaptative management strategies to scale up sea urchin removal efforts in Northern California.

For the duration of the Palos Verdes project, dive efforts for the removal of sea urchins were conducted in partnership by The Bay Foundation, LA Waterkeepers, commercial urchin divers, and volunteer divers. This combined effort is critical to the efficiency and efficacy of sea urchin removal. The partnership encompasses stakeholders that have aligned goals for giant kelp restoration and ensures that physical removal efforts by groups of divers are spread over multiple resources. Collaborative efforts across multiple agencies in tandem with the promotion to volunteer divers is a model that needs to be used for bull kelp restoration if sea urchin removal goals can be met to the degree needed.

The Bay Foundation analyzed each year of post-restoration monitoring data they had collected to demonstrate trends in ecosystem responses to the purple sea urchin removal. Overall researchers saw positive responses to giant kelp restoration actions through a variety of metrics. Sea urchin gonad production had increased in both purple sea urchins and red sea urchins in restoration sites where purple sea urchin density had been thinned to less than 2 urchins/m^2, compared to urchin barren and control sites. Indicator species are species that the scientists can survey to use as an indication of a healthy kelp forest ecosystem, such as kelp bass (*Paralabrax clathratus*) and California sheephead (*Semicossyphus pulcher*) (The Bay Foundation et al. 2018). Kelp bass surveys showed trends of increased density, while California sheephead showed no significant trends (Table 1). The species richness for invertebrates and fin fish overall increased across all restoration sites from pre-restoration conditions, although it was variable year to year (Table 1). Similar survey methods of indicator species could be used in the bull kelp forests of Northern California to measure the success of restoration efforts.

Quarterly aerial surveys of Southern California kelp forests have been conducted since 2003, supported by the Central Region and Region Nine Kelp Survey Consortium. The Bay Foundation was able to utilize these surveys to create base maps of kelp canopy cover to analyze progress of their restoration efforts. In the 2015 monitoring year, aerial surveys showed an increase from 2010 in kelp bed canopy cover at the two completed restoration sites, with canopy cover percentage reaching 52% at one and 83% at the other (Table 1, Figure 8). Researchers and restoration managers noted that these results are preliminary, but data revealed that the density of giant kelp increased by 2 to 3-fold, suggesting that the ecosystem was responding positively to their restorative efforts. Aerial surveys can be a costly monitoring technique and The Bay Foundation resourcefully acted on an opportune moment to partner with an already

Table 1. Palos Verdes Kelp Forest Restoration Project progress by year across 6 sites, Underwater Arch Cover (UAC), Honeymoon Cove (HoC), Hawthorne Cover (HaC), Marguerite Cove (MC), Point Fermin (PF), and Resort Point (RP). The Bay Foundation

Restoration Year	*Urchins Culled*	*Area cleared (acres)*	*Sites Targeted*	*Urchin Density Post-restoration (#/m²)*	*Kelp % cover*	*Kelp Density (#/100m²)*	*Kelp Bass Density (#/100m²)*	*Sheepshead Density (#/100m²)*	*Spiny Lobster Density (#/100m²)*	*Species Richness*
2014 Year 1	1,989,779	12.68	UAC HoC	1.81	-	UAC - 25 HoC - 7.5	UAC - 6.7 HoC - 1.2	UAC - 0.4 HoC - n/a	-	Increase from pre-restoration
2015 Year 2	1,188,995	15.06	UAC HoC HaC MC	1.18	UAC - 52% HoC - 82%	UAC - 45.8 HoC - 222.5	UAC - 4.5 HoC - 1.1	UAC - n/a HoC - 0.3	-	Decrease from previous year, increase from pre-restoration
2016 Year 3	234,863	5.97	MC PF	1.10	UAC - 0% HoC - 68%	UAC - n/a HoC - 290	UAC - 4.1 HoC - 1.3	UAC - 1.9 HoC - 0.6	-	Increase from previous year
2017 Year 4	118,566	6.45	UAC MC PF	1.37	UAC - 15% HoC - 98% PF - 99%	UAC - 190 HoC - 480	UAC - 17.5 HoC - 4.3	UAC - 1.7 HoC - n/a	-	Same as previous year
2018 Year 5	69,848	4	HaC RP	1.35	-	UAC - 270 HoC - 700	UAC - 5.2 HoC - 2	UAC - 2.1 HoC - 0.8	UAC - 2 HoC - 1	Slight decrease from previous year
Total	3,602,051	45.05	6	1.35	-	-	-	-	-	Variable year to year, increase at all restoration sites from pre-restoration

well-established program. Because there is a long history of giant kelp loss in Southern California compared to the recent bull kelp loss in Northern California, aerial survey protocols have just recently been established within the Greater Farallones National Marine Sanctuary. Unmanned aerial vehicles (UAVs) and drones have emerged as an efficient tool for spatial monitoring of percent cover. These emerging technologies are less expensive than using overhead LiDAR from a manned airplane and can be utilized by agencies in Northern California to develop a long-term monitoring program like that of Southern California.

The 2015 season posed many challenges for monitoring and restoration efforts for divers in the Palos Verdes restoration project. Large ocean swells, low visibility, and warmer sea surface temperatures due to El Niño events were limiting factors for pre-monitoring, purple sea urchin removal, and post-monitoring. These difficult conditions contributed to limited diver access to restoration sites and species surveys which could have skewed data. On top of physical limitations, elevated sea surface temperatures had adverse effects on species presence and composition, and giant kelp biomass. Giant kelp density decreased in 2016 due to warm El Niño waters, surveys revealed declines from previous restoration years across all sites except Point Fermin (Figure 8). Kelp biomass was still higher than the densities prior to the start of restoration efforts, but of all five targeted restoration sites for that year, only one saw an increase in kelp canopy cover while the other four saw decreases. These physical and climatic setbacks are likely to occur in Northern California, where diving conditions can be more difficult than in Southern California and marine heatwaves and nutrient deficient waters occur more frequently as extreme weather patterns increase. Because of these uncontrollable changes in water quality, it is likely that restoration managers will have to adapt to years of unsuccessful restoration efforts.

The difficult physical ocean conditions that persisted for the duration of the 2015-2016 restoration year due to El Niño events slowed overall progress of the project. During this time period there were five restoration sites total, the two sites from the first year's efforts were considered completed, and three sites were still in progress. The two completed sites were continually monitored to ensure that sea urchin densities stayed below the target threshold of 2 urchin/m^2, and that sea urchins in shallow subtidal areas and offshore areas were not infringing on the restoration site. The continued monitoring of completed sites is a critical step to restoration, and something that should be factored into any ongoing bull kelp restoration projects. Because sea urchins can hide in crevices between rocks and migrate from deeper

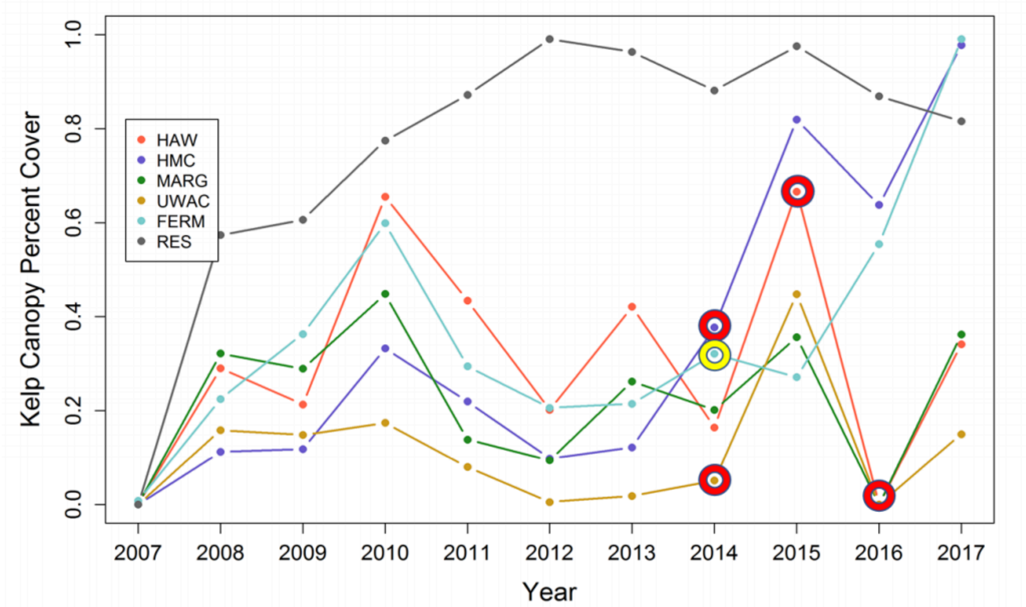

Figure 8. Annual kelp canopy percent cover from 2007 – 2017 by restoration site. Rec circles indicate completed restoration sites Underwater Arch (brown), Honeymoon Cove (purple), Marguerite (MARG – green), and Hawthorne (HAW – orange) one year after restoration finished. Restoration efforts began at Point Fermin (FERM – light blue) in 2014 (yellow circle). Data provided by MBC Applied Environmental.

offshore areas, it is important to continually suppress their populations and prevent a resurgence of grazing pressure.

Fish assemblages in both restoration and control sites were progressing to resemble reference sites throughout most of the project timeline. The control site changes could be attributed to spillover of restoration effects for sites in proximity to restoration areas. Results for the 2015-2016 restoration year were heavily impacted by a mass wasting event of sea urchin and sea stars (SSWD) that occurred in the Fall of 2015. Researchers believe that the abnormally high sea surface temperatures that limited giant kelp productivity due to thermal stress could have also exacerbated the wasting diseases on sea urchins and sea stars. Not only were the targeted purple sea urchin densities down, but the non-target red sea urchins also experienced decline in numbers most likely due to the wasting disease and commercial urchin fishery harvesting. Overall, researchers found that sea urchin loss, whether due to human suppression or disease, was still beneficial for the transformation from urchin barren to kelp forest community structure.

Once El Niño conditions subsided and project efforts were able to continue, results showed positive responses within the subtidal communities. The overall results from the 2016-

2017 restoration and monitoring year showed that decreased sea urchin densities allowed other species to be free of grazing and competition pressures. This loss of sea urchins resulted in the development of other subtidal organisms, growth of kelp, and the overall community assemblage of reference, restoration, and control sites to begin to look like each other. After the difficult El Niño conditions caused loss of kelp canopy cover in 2016, surveys taken during the 2017 restoration year showed that biomass was beginning to recover (Table 1, Figure 8). The return of cold, nutrient rich waters was beneficial to the giant kelp growth rate and boosted the community composition. While both reference and restoration sites lost kelp biomass in those warm years, giant kelp densities increased in all three restoration sites in 2017 and 2018 (Table 1). These results suggesting that purple sea urchin suppression is beneficial for kelp restoration even in the events of climatic disturbances and thermal stress to kelp growth. This demonstrates the degree of importance that sea urchin culling efforts have to kelp restoration, and in Northern California bull kelp forests they should be undertaken as a first step in the restoration process. As mentioned previously, the increased frequency of marine heatwaves poses challenges to kelp growth, but removal of sea urchins is not a wasted effort.

Gonadosomatic indices were measured for red sea urchins and purple sea urchins at kelp reference sites and restoration sites for comparison of gonad production by site type. The purpose is to measure the response of sea urchins to restoration efforts and assess if gonad production has increased. Increased gonad production demonstrates healthier sea urchin individuals which is important for recreational and commercial fisheries. Red sea urchins showed no significant difference of gonadosomatic index between the two site types, while purple sea urchins demonstrated a significant difference between each site type. Different gonadosomatic values among restoration sites suggest that gonad production by purple sea urchins is increasing to match reference sites in some areas, but not all. This variation could be attributed to a loss of kelp at certain restoration sites, or potentially increased competition between sea urchins following a period of increased juvenile sea urchin recruitment. Involvement from fisheries stakeholders is critical to restoration efforts and reestablishing the value of sea urchins will promote that involvement. Being able to demonstrate that kelp restoration also restores sea urchin value to commercial and recreational divers in Northern California is critical for support from that community which is why the gonadosomatic measurements are important to include.

Notable differences in fish assemblages were found between sites within Marine Protected Areas (MPA) and sites that lie outside of MPAs. The highest density of kelp bass was found at a reference site which lies within the nearby Marine Protected Area. The MPA restricts from fishing activities which is likely why abundance and size of individuals was greater there. No restoration sites lie within the MPA, so fishing pressure could be a contributing factor as to why kelp bass biomass is lower there. Along the Sonoma and Mendocino coastlines there are 21 MPAs with various levels of protection on living and physical marine resources that are present (ONMS et al. 2014). The three types of MPAs include; State Marine Reserves (SMR) that prohibit the take or damage of all marine resources, State Marine Conservation Areas (SMCA) which allow a limited amount of commercial and recreational take, and Special Closure Areas that restrict all human access. Fishing restrictions within MPAs likely have positive impacts on fish assemblages and abundance as demonstrated by the Palos Verdes surveys, which places importance on the proximity of restoration sites to MPA sites. If bull kelp restoration sites along the Northern California coast are strategically placed near MPAs with fishing restrictions, positive impacts on species abundance and biodiversity from spillover could aid in restoring ecosystem function.

Overall species richness across all sites had increased from pre-restoration efforts in 2013. In particular, increases in California spiny lobster (*Panulirus interruptus*) density were observed in 2018 with high variability, which had been absent in all restoration sites prior to purple sea urchin removal efforts (Table 1). California spiny lobsters serve as an important fishery species and are mobile in nature so this could be contributing to variability among sites. Because spiny lobsters are sea urchin predators, there are implications on potential sea urchin population control with increased spiny lobster density. The distribution of the California spiny lobster only reaches as far north as Santa Barbara County (Barsky 2019) so that potential to control sea urchin population does not currently apply to Northern California sea urchin suppression. With further research on the effects of spiny lobster on sea urchin suppression there could be potential benefits in establishing a spiny lobster translocation program to the Northern California coast.

3.1.2 The Southern California Regional Kelp Restoration Project - Giant Kelp Enhancement

From 2001 to 2007, multi-agency efforts by the California Coastkeeper Alliance (CCKA), in partnership with NOAA and CDFW, were focused on restoring sustainable giant kelp forests along 300 miles of Southern California's coastline (Wisniewski et al. unpublished). CCKA is a part of a large international network of non-profit organizations called The Waterkeeper Alliance, and is comprised of local Waterkeeper organizations from around California. Waterkeepers from Santa Barbara, Los Angeles, Orange County, and San Diego came together and were coordinated by CCKA to carry out The Southern California Regional Kelp Restoration Project. Giant kelp forests along these four counties' coastlines have seen fluctuations in abundance since the 1960's due to natural and anthropogenic causes such as El Niño, large storms, warm waters, water quality from development and sewage, effects of commercial and recreational fishing, and the spread of urchin barrens (Wisniewski et al. unpublished). Though efforts to restore kelp forests had been attempted across large regions of California, none had proven long-term success and as the 2000's came around, trends of giant kelp biomass were still in decline.

While the Regional Kelp Restoration Project had many goals, my focus in this synthesis is on their giant kelp enhancement techniques and the approach to fostering community engagement. The urchin removal protocol for the Regional Kelp Restoration Project was collection and transportation of sea urchins to offshore sandy areas, which is not feasible in Northern California due to the need for more immediate and less time-consuming urchin thinning methods. Their kelp enhancement efforts included several reforestation techniques; outplanting kelp grown in the lab, transplanting drift kelp, and implementation of sporophyll bags to restoration sites. The project goal to foster community engagement included many channels of contact with the public through community events, media and news outlets, classroom education, and community presentations.

Kelp reforestation efforts were facilitated by a kelp mariculture lab that CCKA established at the Southern California Marine Institute located in Terminal Island, CA. The Los Angeles lab served as a central location for the four county's Waterkeeper organizations involved in the project to receive their supply of juvenile kelp from as well as a meeting place and site for general operations and coordination. The restoration and mariculture techniques that were employed in the lab and the field were detailed in a Kelp Cultivation Manual so there was uniformity to restoration methodology carried out by each regional Waterkeeper organization. In the manual there are detailed methods to outplanting lab cultivated juvenile kelp, transplanting drift kelp, and placing sporophyll bags at restoration sites.

To outplant kelp, sporophylls are taken from neighboring kelp forests of the restoration site and brought into the mariculture lab to be cultivated. In lab, sporophylls can be stressed to release spores that can then be cultured on either ceramic tiles or fiber rope, both of which are suitable substrate for spores to adhere to and grow on. Once these juvenile plants reach 2-3 cm they are brought to restoration sites and outplanted to the same region the sporophylls came from onto suitable rocky reefs and secured by rubber band. The next restoration technique involved collecting drift kelp and attaching the holdfast to rocky reef substrate with natural rope and rubber bands. This method allows for the kelp plant's holdfast to attach to the rock that it was transplanted onto, and rather than harvesting kelp from neighboring kelp forests, using drift kelps allows for the preservation of existing kelp forests. The last technique the project utilized for kelp reforestation was the input of mesh bags filled with reproductively active sporophylls in order to provide a sustainable and continuous source of spore release to restoration sites. This was done by tying the sporophyll filled mesh bags to buoys so that spores were suspended above restoration sites and able to settle out of the water column onto rocky reef below in dense numbers that mimic natural giant kelp spore dispersal.

The Regional Kelp Restoration Project utilizes many techniques that are transferrable as best practices for bull kelp restoration in Northern California. The use of multiple kelp enhancement applications together is essential for any type of success to combat the compounding ecological and climatic impacts. The setup of the CCKA is a good model for the distribution of physical labor and restoration efforts among counties and cities. While the Northern California coastal communities in Sonoma and Mendocino Counties are not nearly as high in population as Southern California, there are established marine laboratories and universities along the Northern California coast that could serve are hubs for the project. The following three laboratories span my study area: Humboldt State University Marine Laboratory, University of California Davis Bodega Marine Laboratory, and the College of Marin Bolinas Field Laboratory. These are just three examples of many that could serve as leaders in kelp enhancement practices and research. It would be strategic to split the area of interest for bull kelp restoration into regions that could implement a uniform strategic plan across along the coast under the guidance of one leading organization.

Success rates of kelp reforestation for the Regional Kelp Restoration Project were variable by site and by technique. While the first three years of the project were successful with outplanting kelp, the last three proved to more difficult due to various complications with equipment, personnel, and physical ocean conditions. In 2003 it was recorded that outplanted juvenile kelp from tiles and rope had about a 10% survival rate which is in the same range as typical kelp planting experiments that have occurred around the world. In 2006 it was recorded that there was only a 1% survival rate. Reasons for this ranged from large ocean swells and grazing pressures, to poor attachment techniques by divers. In 2006 due to low success of outplanting and limited funding for the mariculture lab, all techniques switched to solely transplantation which demonstrated higher survival rates, and sea urchin removal. Efforts in Orange County had proved to be successful, with the 2014 restoration year consisting of 1,141 outplanted giant kelp units and 233 transplants, three large areas of kelp canopy were formed and persisted for approximately one year.

While kelp reforestation techniques are extremely variable in their success, it is possible to develop standardized protocol that could dampen some negative impacts. For the case of bull kelp restoration, it is important to take on multiple tactics, and proper training of divers and strategic timing of kelp outplanting can make a difference in the survivability of juvenile kelp.

The greatest success from the Regional Kelp Restoration Project was their response from community engagement and ability to involve the public. Through classroom education, volunteer opportunities, dive shop partnerships, and community events, the project was able to reach an audience of over 48,000 people and have 8,417 students participating in classroom elements of the project. Education within the classroom consisted of students growing their own kelp in classroom aquaria called ‘eco-karts,’ that were then used in the outplanting process. All of their outreach and education material is transferrable to communities and schools within Mendocino, Sonoma, Marin, and San Francisco Counties. The Greater Farallones Association has already established K-12 education programs in each of these counties such as classroom programs, after school programs, and camps throughout the year that could easily incorporate bull kelp restoration elements into them.

3.2 Eastern Tasmania

In the waters of Southern Australia and Tasmania, increasing inputs of warm water from the East Australian Current have contributed to the widespread collapse of kelp forests (Ridgway 2007). It is not fully understood why this infiltration has occurred, but the waters that the East Australia Current input into the region are nutrient deficient and carry large quantities of aggressive long-spined sea urchin (*Centrostephanus rodgersii*), leading to an expansion of their normal distribution (Ling et al. 2009a). Many efforts are under way to tackle the problem including numerous sea urchin culling programs, reforestation efforts, and research on expanding the thermal tolerance of giant kelp (Ling and Johnson 2012, Ling et al. 2010, Tracey, Sean et al. 2015).

The Institute for Marine and Antarctic Studies (IMAS) at the University of Tasmania have various researchers who have published extensive peer reviewed literature on kelp restoration advancements. In one giant kelp restoration project that I synthesize here, researchers from the University of Tasmania have worked to restore kelp forests from urchin barren states through trial experiments of systematic discrete sea urchin eradication in Eastern Tasmania. Other researchers at IMAS are currently experimenting with cultivating thermally tolerant kelp species and the process of outplanting the lab bred specimens that demonstrate increased thermal plasticity. The many experiments conducted by researchers at University of Tasmania and IMAS contribute significant advancements to kelp restoration efforts around the globe. Here I synthesize the successes and failures of some projects that I further use to build my recommendations for bull kelp restoration projects in Northern California.

3.2.1 Eastern Tasmania Sea Urchin Eradication and Control Trials

In 2011 and 2012, IMAS and commercial abalone diver industries of Tasmania collaborated on sea urchin culling experiments to minimize the impacts of destructive over grazing on local beds of kelp (Tracey, S. et al. 2014). The focus area of this project was one particular rocky reef on the east coast of Tasmania called Wineglass Bay. Sea urchin barrens in Wineglass Bay were considered incipient and patchy and had not yet reached an extensive barren phase. Extensive urchin barrens are much more difficult to reverse than incipient barrens, so efforts to decrease urchin abundance before densities trigger that shift to extensive barren are critical (Tracey et al. 2014). The goal was to test culling efficiency to prevent the transformation of early barrens into extensive barrens. This project was a small-scale trial over twelve plots, each encompassing 1,500 m^2. Among the twelve plots, there were two culling treatments at eight plots that were performed by Tasmanian Abalone and commercial dive industries members, and four control plots. The first treatment was performing discrete systematic culling to all eight treatment plots. The second treatment which was applied to four of those eight previously culled plots, was a second culling event that took place two weeks after the initial. Baseline surveys were taken by IMAS staff before the first culling, before the second culling, and one year post all culling events.

The purpose of this experiment was to test the long-term effectiveness of the physical removal of sea urchins from discrete aggregations. From the surveys taken, researchers were able to quantify densities of sea urchins before any culling efforts, after a single culling effort, and after two culling efforts (Table 2). Results led researchers to a few conclusions:

- The amount of sea urchins culled decreased significantly as the density decreased (Table 3)
- Systematic culling events taken place in incipient barrens successfully prevented the transformation of sea urchin densities to reach extensive barrens
- Culling reduced the mean density of sea urchins even on year post culling effort (Table 3)
- Surveys from the following year showed that there was no significant difference between one culling event and two culling events.

Table 2. Sea urchin culling efforts by commercial abalone divers in 2011 and 2013 in Wineglass Bay. (Tracey et al. 2014)

Survey	*Urchin Density (#/m²)*	*# of urchins culled*
Baseline	1.51	-
Post initial cull	0.12	15,166
1 year post secondary cull	0.13	930

This research is useful in adopting management protocols for Northern California bull kelp restoration plans because of its implications on culling effects on early stage urchin barrens. While there is a difference in the severity of urchin barrens from this particular location of Tasmania compared to many bull kelp forests, it is still critical to prevent the further loss of the remaining bull kelp that persists in Northern California. The results showing that multiple culling events do not have any more effect than one single culling event are notable in that physical and monetary resources can be spent more efficiently. Rather than spending time and money to do multiple culling sessions, divers can cull sea urchins on a larger scale.

The application of this study is on a much smaller spatial scale than what bull kelp restoration managers are facing, and the notable high costs of the program with commercial urchin divers that they used are potentially prohibitive for instating across a large area. Although the methods used in Wineglass Bay sufficiently lowered sea urchin densities, these efforts would need to be used in conjunction with a larger range of restoration practices. This has potential to be utilized on the remaining bull kelp forests as preventative measures to keep from collapsing to further urchin barrens. Because extensive urchin barrens prove to be difficult to reverse to their original productive kelp forest state, it is important to protect what remains.

Another study published in 2013 by researchers at IMAS, in partnership with Fisheries Research and Development Corporation (FRDC), that addressed management options to minimize long-spined sea urchin barrens and building up the resilience of giant kelp forest ecosystems took a different approach. While sea urchin culling was an aspect of their project, the translocation of urchin predators and investment in fisheries management of those predators was analyzed as a potential for large scale sea urchin density control (Johnson et al. 2013). The southern rock lobster (*Jasus edwardsii*) is an important predator of the long-spined sea urchin in the waters of Tasmania and Australia (Ling et al. 2009b). Previous research has demonstrated that southern rock lobsters are effective at controlling the population of sea urchins to prevent overgrazing (Ling et al. 2009). Increased threats of extensive urchin barrens forming in the rocky reef area of Eastern Tasmania had the potential to impact black-lipped abalone (*Haliotis rubra*) and rock lobster fisheries value by a $25 million loss, which is nearly a 15% decrease (Johnson et al. 2013). These projected negative economic impacts to fisheries value prompted a variety of stakeholder's interest in restoration efforts. Commercial and recreational fisheries both supported conservationists' interest in forming urgent responses to the management of fisheries species and the limitation of long-spined sea urchin recruitment to incipient barrens.

The situation that fisheries are facing in Eastern Tasmania has some parallels to that of Northern California fishers. The red sea urchin and abalone fisheries that bull kelp forests support have been hit hard from the loss of habitat. While the demise of fisheries targeted species of abalone in Northern California were prompted by harmful algal blooms, the disappearance of their bull kelp habitat at the same time left them unable to recover. Sea urchin's impact as habitat modifiers leaves rocky reef areas devoid of biodiversity which abalone cannot survive or reestablish their populations in. Their inability to persist in barren habitats highlights the importance of removing the habitat modifying sea urchin to support the reemergence of abalone and other various invertebrate species. In Northern California, similar to Eastern Tasmania, the inclusion of important fisheries representatives is critical in the bull kelp restoration work. The magnitude of removal work that needs to be done on the existing expanses of urchin barrens requires resources and efforts from as many interest groups as possible, without the support of fisheries this large-scale project could not be completed.

On a small-scale urchin removal effort, the researchers tested the efficiency of abalone divers culling sea urchins passively while they were primarily fishing for abalone. The results demonstrated that this method was not effective and is not likely to have an impact on controlling sea urchin densities. A part of their findings was that the culling rate significantly declined as abalone catch rate increased. Where there was a high yield of abalone catch, dives were longer, but divers paid little attention to culling urchins as their economic prerogative would be to increase their abalone catch. At sites where abalone yield was low, divers would not spend much time due to poor fishing conditions, resulting in truncated periods of urchin culling that only effectively decreased sea urchin densities on a scale of small individual patches. These results demonstrate that this would not be a sufficient method for sea urchin population control, unless the financial return of culling urchins matched that of fishing for abalone. In Northern California, with abalone fisheries being closed due to decimated populations, this option would obviously not be able to apply, although subsidies on urchin collection or smashing could promote divers to participate in sea urchin population control efforts.

Findings from the same project by IMAS and FRDC on managing urchin barrens and increasing kelp forest resilience demonstrated that on a larger scale, the management of the rock lobster fishery could have a more positive influence on controlling sea urchin population than the physical removal by fisheries divers. Experiments were run to measure the effectiveness of sea urchin population control from the translocation of rock lobsters to urchin barrens, the closure of rock lobster fishing on particular reefs, and to assess predation rates by the rock lobsters on sea urchins. What researchers found was that while rock lobster abundance is negatively correlated to sea urchin abundance, the likely reason for that relationship is the intensive fishing that occurs on these rocky reefs rather than lack of suitable habitat. The significant factor in their findings is the persistence of rock lobsters on urchin barrens was highly size dependent. During the translocation experiments, some of the rocky reef sites, kelp forest and urchin barren, were closed to fishing activities. From the application of these treatment, researchers deduced that large rock lobsters (140+ mm carapace length (CL)) occupied urchin barren sites in higher abundance than in adjacent kelp forests, while small rock lobsters (<110mm CL) were more abundant within kelp beds (Johnson et al. 2013, Ling et al. 2009). The large rock lobsters were considered capable of predation on sea urchins and persisted in the urchin barren areas that completely lacked any type of canopy forming algae. The important factor for the large predatory rock lobsters was not in fact the habitat, but the vulnerability to fishing pressures. Areas of both kelp forest and urchin barren that were closed off for these trials demonstrated a 'reserve effect' on the abundance of large and small rock lobsters through increased growth to a predatory capable size class. Not only was the growth of rock lobsters able to expand under reserve conditions, but this resulted in increased spill-over to adjacent fished areas. The implications of these findings highlight the importance of establishing no-take marine reserves in order to restore ecological function. While the discovery that lobster populations can sustain themselves in urchin barrens where fishing is closed off is important to managing the fishery that could reduce sea urchin populations, it is also important to understand the role that kelp forest habitat play in the recruitment and development of rock lobsters. The settlement of rock lobster larvae and their growth to significant size-class are dependent on the availability of kelp forests and the protection for juveniles that they provide. It is clear form their results that marine reserves need to encompass barren habitat and kelp forest habitat to rebuild and protect the stock of rock lobster at all life stages. Overfishing of rock lobsters in rocky reef areas of Eastern

Tasmania will only increase the resilience of urchin barrens by taking the large, sea urchin predatory capable individuals out of the scenario. These findings left researchers and managers faced with the task of determining target densities of rock lobsters to maintain the balance between fisheries needs and conservation needs in a sustainable manner.

All of these results demonstrating that proper management of the rock lobster fishery has positive impacts on suppressing urchin barrens show that efforts to increase sea urchin predator densities can aid in the overall kelp restoration process. Although lobsters are not present in Northern California as a sea urchin predator, the demonstrated success of large lobsters as a sea urchin population control mechanism means the translocation of California spiny lobsters from central California to Northern California rocky reefs could prove to be beneficial. In Northern California one of the most critical sea urchin predators is the sunflower starfish which has not had much success reestablishing populations since the sea star wasting disease. In 2018 the Sea Star Wasting Syndrome Task Force was established as a multi-agency effort to develop response research and management implementations to the widespread sea star decimation which includes sunflower star fish (SSWSTF 2018). The task force developed a Strategic Action Plan (SSWSTF 2018) that outlines the coordinated efforts for disease diagnostics, surveillance of sea star populations and the disease, management and conservation plans, and communication and citizen science networks (SSWSTF 2018). The recovery of sea stars and sunflower star fish in particular would contribute to the balance of kelp forest community structure overall and the task force should be a part of the bull kelp recovery process as well.

3.2.2 Cultivation of Thermally Tolerant Giant Kelp

In an ongoing study at IMAS, researchers have set out to increase the potential success of giant kelp restoration efforts and marine permaculture by focusing on giant kelp individuals that appear to have higher thermal tolerance than average (Layton, C. pers comm). The research began in May of 2019 in partnership with The Climate Foundation as a means to support active restoration techniques in Tasmania's lost giant kelp forests. The hopes of researchers are to facilitate the growth of thermally tolerant giant kelp to develop permaculture for commercial kelp harvest, habitat for fisheries through integrated multi-trophic aquaculture, and overall restoration of the once dense giant kelp forests of Tasmania.

In Eastern Tasmania there are giant kelp forests that persist even with influent warm water from the EAC that IMAS researchers believe to be better adapted to warmer ocean temperatures. Their experiment began with collecting giant kelp sporophylls from various areas where giant kelp forests remained and cultivating them in lab. Through isolated cultures, researchers were able to produce giant kelp gametophytes whose performance could then be tested in various thermal and nutrient levels to measure thermal plasticity. The experiment setup involved sporophylls from six separate remnant giant kelp populations with seven crosses to create 42 isolated giant kelp family lines. Each family line was tested at four temperature treatments in a closed system apparatus where gametophyte fertilization could occur. From the lab testing of the remnant giant kelp families, researchers found that about 10% of tested individuals demonstrated above average thermal tolerance, with no observable relation to where the parent kelp was collected from (Layton, C. pers comm).

Three restoration sites were established where divers were able to install hardware onto rocky substrate to secure the lab-bred giant kelp. Bolts were drilled into rocks that were used to secure ropes to the rocky reef in a grid pattern. Twine that was seeded with microscopic giant kelp individuals was wound around the secured ropes so that eventually as the giant kelp grew, the holdfasts could secure to the rocky reef themselves. It is important to note that kelp was outplanted on 12 x 12 m transects that were culled of all long-spined sea urchin. The giant kelp seeds they used on the twine to outplant were from the families of kelp that researchers found to be successfully tolerant of warmer waters in lab, and overall 45 m if the kelp-seeded twine was outplanted at each of the restoration sites. This experiment is ongoing, and results are still preliminary, but in February of 2020 divers found over 300 juvenile giant kelp individuals growing on experimental arrays at one of the restoration sites, with sizes ranging from 25 – 65 cm.

The implications of this study are extremely valuable and applicable to bull kelp restoration work in Northern California. If giant kelp can be bred to have a higher fitness and survival rate in warmer ocean temperatures, than there is potential for bull kelp to have the same reaction. This could ameliorate the effects of marine heatwaves and prevent any further contraction in the range of bull kelp along the Northern California coast. This study is expected to will be published in the near future, and if results remain positive, the research done here could inform marine scientists on the best methods to create a population of bull kelp that can withstand warm, nutrient deficient waters that could persist through El Niño years, marine heatwaves, and warming ocean trends.

3.3 Comparison of Case Studies

Both urchin culling case studies demonstrated unique results that are each useful for the application of restoration practices to bull kelp forests in Northern California. The Palos Verdes Kelp Forest Restoration Project and the Eastern Tasmania sea urchin eradication and control trials had very different designs to sea urchin removal. While both projects used culling as the mechanism rather than harvesting, the spatial scale of efforts in Southern California took place over nearly 38 times larger of an area than in Eastern Tasmania, and 130 times longer on a temporal scale (Table 4). The scale of each project can inform management decisions for different types of restoration for bull kelp forests. In remnant bull kelp forests in Northern California where sea urchins have not taken over yet, the methods performed in Tasmania for culling incipient barrens are applicable to prevent the further development to extensive barrens. In the Tasmania study, researchers explored the potential benefits of multiple sea urchin culling events, rather than a straightforward design of reference, control, and restoration treatments (Table 3). This testing of multiple culls proved valuable as it revealed that culling incipient barrens once was enough to prevent the formation of extensive barrens and promote kelp recruitment and increase biodiversity, but there is no significant difference between multiple cull events and single cull events so physical effort and time should not be wasted (Table 3).

The Palos Verdes project is more applicable to large scale extensive urchin barrens than the Eastern Tasmania project. The density of sea urchins in urchin barren restoration sites on the Palos Verdes Peninsula matches the sea urchin densities in many parts of Northern California urchin barrens. The project results indicate that assisted recovery techniques of thinning extensive urchin barrens to less than 2 urchins/m^2 allows for variable degree of natural kelp recruitment and return to kelp forest species composition (Table 3).

Researchers and restoration managers from IMAS and The Bay Foundation have each created projects of value to the field of kelp forest restoration in different ways. In the case of Northern California, modeling urchin culling efforts after the Palos Verdes project is more efficient and transferable than that of Tasmania's project based on the extent of urchin barrens than persist in the area.

Table 3. Results of urchin culling efforts by location for the Palos Verdes Kelp Restoration Project and IMAS urchin culling trials (Tracey et al. 2014, The Bay Foundation et al. 2018).

Location	*Southern California*	*Eastern Tasmania (Southern Australia)*
Area targeted for urchin culling	0.45 km^2	.012 km^2
Urchins cleared	3,602,051	16,096
Timeline	5 years	14 days
Culling Rate	541 urchins/hour	431 urchins/hour
Treatments	1. Reference 2. Control 3. Restoration	1. Control 2. One cull 3. Two culls
Results	Density was reduced from 17.74 urchins/m^2 to 1.35 urchins/m^2. Increase in giant kelp and fish assemblages when urchin density is cleared to <2 urchins/m^2	Decreased urchin density from 1.51 urchins/m^2 to 0.13 urchins/m^2. One cull is just as effective as two culls, suggests no need for repetition of culls Observed macroalgae return 2 years post cull. Effective on a smaller localized scale. Systematic culling of urchins in a spatial discrete pattern effectively reduces urchin density in early stage (insipient) urchin barrens. Abalone fishers culling urchins while they dive for abalone helps prevent extensive formation, but likely has no significant effect at controlling large -scale sea urchin density.

4. Discussion and Recommendations

Giant kelp and bull kelp are both cold water species that rely on the upwelling of cold, nutrient rich waters to produce in high densities (Steneck et al. 2002). Because of the specific thermal tolerance of bull kelp and giant kelp, their ability to maintain high growth rates is negatively impacted by infiltration of low nutrient warm water and marine heatwaves in both California and Tasmania (Rogers-Bennett and Catton 2019, Ridgway 2007). In conjunction with similar thermal stressors, giant kelp and bull kelp forests maintain a state of equilibrium between the trophic dynamics that each type of kelp forest supports. One of the most critical balances within both kelp forest community structures is the presence of sea urchin predators in order to keep sea urchin populations under control (Teagle et al. 2018, Wernberg et al. 2016, Ling et al. 2009, Stewart and Konar 2012, Nichols et al. 2015). Keeping sea urchin populations to a maintainable level helps to suppress the damages that over grazing can do to kelp forest biomass (Nichols et al. 2015). The loss of sea urchin predators and competitors in both case studies, as well as thermal stressors, allows for a comparison of restoration and management implementation that can be applied to Northern California and demonstrates the need for an ecosystem-based management approach as a response to the multiple stressors that have triggered the loss of kelp.

Both Northern California and Southern California coastal waters are heavily influenced by the California Current System (CCS) and upwelling events which enable high productivity and biodiversity in these kelp forests (McCabe et al. 2015, Pfister et al. 2018, Ikawa et al. 2012). Loss of primary productivity in both regions has been directly influenced by El Nino events as well as the warm water ‘Blob.’ These warm water events have directly contributed to the degradation of kelp forests and loss of ecosystem function in both Northern and Southern California. In Southern Australia and Eastern Tasmania, the Great South Australian Coastal Upwelling System serves as the driving physical forces for high rates of productivity in the region. Australia’s upwelling system supports Eastern Tasmania’s giant kelp forests in equivalence to the CCS and California’s upwelling system that supports California’s kelp forests. Similar to the CCS and California’s upwelling being impacted by marine heatwaves, Southern Australia and Eastern Tasmania are experiencing increased inputs of warm, nutrient deficient water brought by the East Australian Current from the Coral Sea (Ridgway 2007). This infiltration of non-preferential physical conditions contributes to Eastern Tasmania's giant kelp forest degradation and subsequent shift to sea urchin barrens. The EAC brings waters that inhibit giant kelp growth and reproduction, and transport long-spined sea urchins (*Centrostephanus rodgersii*) that proliferate in these warmer conditions (Ling et al. 2009).

My synthesis of techniques from urchin culling, to enhancement of natural predation through fisheries management, has revealed just how complicated this ecological predicament is, and shaped my conclusion on restoration and management strategies. Although it is ideal to provide a set of tangible and definitive guidelines to restore the bull kelp forests of Northern California, the existing literature indicates that the solution is much more complex. There is no one perfect formula to address the widespread degradation of kelp forests, and an effective program will be one that encompasses a suite of various restoration and management implementations. Ecosystem-based management is necessary in this process to reestablish the complex interactions and services that kelp forests support.

An extremely important distinction in kelp restoration is understanding the difference between assisted recovery and active restoration (Layton et al. 2020). In the case of kelp forests, assisted recovery means removing the element that is causing decline or building substrate for kelp to grow on. This involves sea urchin removal or input or rocky substrate. While decreasing the density of over grazing sea urchins is a critical step in the restoration process, this cannot be a standalone action. This is where active restoration comes in, meaning on top of removing the grazing pressure, restoration strategies must also promote and induce the natural growth and reproduction of kelp in efforts to make self-sustaining kelp forests. There has been wide variability of success among the kelp restoration case studies, projects, and research that I have examined. While some projects demonstrate short term success and rejuvenation of kelp density, the long-term results have been limited. The most important take away from my synthesis has been that many efforts for urchin removal and kelp enhancement must be implemented in conjunction with one another to have any lasting results for restoring bull kelp (Layton et al. 2020).

4.1 Sea Urchin Control Recommendations

There are certain areas of the Greater Farallones National Marine Sanctuary that are not open to sea urchin crushing efforts due to unintended ecosystem consequences and cultural sensitivity to tribal partners. Both of these aspects are very important to the integrity of the restoration progress, and tribal stakeholders should be involved in the process for restoration planning. CDFW has jurisdiction over fishing regulations in California and currently they prohibit wonton waste which includes smashing of urchins. It is important to understand that while smashing urchins may be seen as not favorable methods by agencies and tribal partners, the dire situation that kelp forests are in requires efficient and large-scale actions that urchin harvesting cannot accommodate as a standalone action. Kelp forest ecosystems are of traditional significance to many tribes in coastal Northern California and restoring the balance to create a sustainable kelp forest that sea urchins are a part of, but not controlling, is paramount. To prevent overfishing of the red sea urchin and purple sea urchin fisheries in Northern California were once healthy, like most fisheries in Northern California, there are limits on the amount of sea urchins that can be taken per person. While all of these are barriers to urchin culling projects, there are ways around it. Areas can be designated as exceptions by CDFW, effectively opening areas to smashing and increasing take limits. Conditions are not ideal and there are chances that not all stakeholders will agree on methods, the critical part is that everyone has the same interest in restoring a productive, culturally and economically important ecosystem.

From the case study of Southern California, there were multiple aspects that were successful, and those practices could be implemented by the Greater Farallones Association and partner agencies project coordinators within Northern California urchin barrens. Of particular importance was the specific target metrics for sea urchin removal. The Bay Foundation established their goals to thin sea urchin densities to less than 2 sea urchins/m^2 which proved effective for giant kelp recruitment and recovery as well as increased species diversity in the restoration areas. With sea urchin density reduced to this threshold, juvenile kelp and other understory algae are able to recruit to the rocky reefs and recolonize. The densities of sea urchins in the Palos Verdes peninsula, where the Bay Foundation focused their restoration efforts on, are comparable to sea urchin densities found along urchin barrens along Mendocino and Sonoma County coastlines. Because of this similarity and the positive results from The Bay Foundation's sea urchin removal efforts, the goal to decrease the density of sea urchins to less than 2 sea urchins/m^2 should be adopted in Northern California by bull kelp restoration managers.

The vast area that urchin barrens have taken over along rocky reefs in Northern California will require extensive physical labor and time to manage. In both Southern California and Tasmania, the partnership with fisheries divers to assist in culling efforts was critical in each kelp restoration project. It is highly recommended that the Greater Farallones Association, in partnership with other agencies, commercial fisheries, and non-profits employ tactics to get as many people physically removing urchins as possible. Education, outreach, and encouragement of volunteer divers to join in on sea urchin culling efforts would significantly help in the physical task of urchin crushing. The development of a multi-county citizen science project that teaches people the importance of kelp forests ecosystems and methods to culling urchins has many potential benefits.

Results from IMAS research on predatory control of sea urchins in Eastern Tasmania show that there is potential to develop a translocation program for sea urchin predators that is effective at reducing sea urchin population naturally. The introduction of species to ecosystems has been proven to be detrimental to many ecosystems around the world, making it critical to translocate only species that are native to California waters and contribute to the balance of kelp forest ecosystems. While sea otter translocation projects can prove to very expensive and unsuccessful, they should not be considered as an immediate action, but a potential effort down the line. More immediately, consideration should be given to the development of a program to translocate California sheephead and California spiny lobster, both of which are sea urchin predators in Southern California, and important fisheries species.

4.2 Kelp Enhancement Recommendations

The removal of sea urchins is a critical first step to bull kelp restoration and must be followed up by active restoration techniques in order for widescale restoration efforts to have a significant impact and long-term successful outcomes. From each case study and research that I have synthesized, it is clear that a variety of kelp enhancement techniques must be applied in tandem and continuously. Research on kelp resilience is ever expanding, and scientists are continuously working to expand on the set of tools for restoration managers to explore to recover the bountiful kelp forests that once existed worldwide.

Immediate actions that I recommend as best practices for kelp enhancement post sea urchin removal would be a combination of transplanting healthy juvenile and adult kelp along with methodical spore dispersal at these sites. Spore dispersal can be accomplished as described by the Southern California Regional Kelp Restoration Project, where divers attached mesh bags filled with kelp spores to buoys over rocky reef areas to settle out onto the substrate. Choosing restoration sites to focus on can be done in a strategic way, the mechanism that bull kelp spores are released in the water column make it critical to choose sites that are in proximity to neighboring remnant bull kelp forests. The closer a restoration site is to an existing bull kelp forest, the easier it is to transplant bull kelp individuals as well, so focusing on expanding the existing kelp forests is an efficient way to increase bull kelp forest range.

Cultivating kelp in lab and outplanting is an extremely tedious, delicate, and expensive process, and before significant investments have been made towards that a few critical steps must be made. One of these critical steps is ensuring that the population of kelp that you are outplanting will have a decent chance at survival and will not be wiped out in the event of a marine heatwave. To combat this possibility and increase resilience, lab trials of cultivating thermally and nutrient depleted tolerant kelp, like that of IMAS researchers in Tasmania, would be worth investing time and resources into. While the physiology of bull kelp is important to research, the delicacy in the physical process of outplanting kelp is a risk. There is a need for skilled divers and refined protocols to decrease the chance of juvenile bull kelp mortality. Reef Check is a reputable dive organization that develops and trains skilled scientific and volunteer divers and would be a great organization to work with on developing outplanting protocols. Bull kelp transplanting and outplanting will be very delicate and most trials around the world have faced low success and high mortality. Trials that have succeeded often were lucky to get favorable ocean conditions that promoted growth rather than inhibited. In order to successfully establish a self-sustaining population of bull kelp, there must be a continuous effort to outplant and transplant microscopic, juvenile, and adult bull kelp to mitigate negative impacts of grazing pressures and difficult ocean conditions (Layton et al. 2020, Hernández-Carmona et al. 2000).

4.3 Citizen Science and Education Program Recommendations

Researchers from all parts of the world are working to develop the most efficient and successful way to restore kelp forests to the state that they once were in. Each kelp degradation situation has some unique aspect to it, and the application of restoration techniques can be adapted to fit different scenarios, but it does not translate to a sure answer to reforesting kelp forests. A critical step in the bull kelp restoration is public awareness and understanding of the issue, and that a citizen science and education program directly focused on bull kelp will be highly valuable.

In the Southern California Regional Kelp Restoration Project, one of the most successful efforts was exposing the issue of giant kelp deforestation to the public through classroom settings, public events, and media exposure. These are all things that should be ramped up by the agencies and stakeholders that are working on bull kelp recovery. The use of classrooms to breed juvenile kelp is a source of education and emotional enrichment for K-12 students that has the ability to impact them for years to come. The Greater Farallones Association already has relationships with schools from Mendocino, Sonoma, Marin, San Francisco, and San Mateo counties that could be expanded on to educate the younger generation on the problem at hand.

One very important population of people to include in the bull kelp citizen science program are the divers of California. Thousands of people per year take to the Northern California coast for recreational activities like scuba diving, free diving, fishing, and much more. Many of these people are aware of the extensive kelp loss yet have no way to get involved in the restoration of them. Setting up a widespread network of citizen science divers to participate in urchin removal efforts will be the only way to address the current magnitude of urchin barrens that exist. Outreach in coastal communities, dive shop partners, and widespread social media campaigns are all ways that members of the public can make impacts to save bull kelp forests and restore the natural underwater beauty to Northern California.

5. Conclusion

Kelp forests exist as a regulating, provisioning, and supporting ecosystem to both humans and marine species alike. This species is a prolific icon of the Northern California coast, providing aesthetic beauty and supporting the subtidal marine community composition. The reemergence of bull kelp is of paramount importance if we wish to sustain recreational and commercial fisheries, biodiversity, and climate mitigation. The potential for kelp species to sequester carbon in large amounts via photosynthetic growth demonstrates how critical it is to establish a resilient bull kelp population.

Following extensive sea urchin removal efforts, a push for warm water tolerant populations of bull kelp will be essential for their future success. The increased frequency of marine heatwaves and ocean warming suggests that this trend will not cease anytime soon, making the re-establishment of bull kelp with the existing genetic thermal thresholds futile. The spread of tropical and sub-tropical marine species poleward demonstrates that warm water species are increasing their range into cold-water boundaries that they could not previously thrive in (Filbee-Dexter and Wernberg 2018). If there is to be time and money dedicated to restoring kelp, it is extremely important to ensure their ability to survive warm water and nutrient deficient conditions.

New and innovative solutions are constantly appearing in the kelp restoration world, and the effort put forth by scientists, environmental managers, and the public is inspirational. Recent publications have demonstrated novel findings that could have huge implications on the kelp restoration communities. One recent study from IMAS was published which has demonstrated that the thermal tolerance of giant kelp can be enhanced by increased nitrogen availability (Fernández et al. 2020). With further research this could prove to be true to other kelp species including bull kelp. In March of 2020, a new publication from researchers in Norway and Australia demonstrated a high survival rate of outplanted kelp from a very simple technique called 'green gravel,' which are the placement of small rocks seeded with kelp onto rocky reefs (Fredriksen et al. 2020). These innovative strategies are just the tip of the iceberg for where the status of kelp restoration can go.

In March 2020 the State of California allocated $500,000 towards a pilot project for urchin removal at one location in Mendocino County. CDFW has opened up Caspar Cover, a well know dive site that once had extensive bull kelp, to public urchin removal efforts. This is the first project of its kind, and dependent on the results this could expand to other locations along the coast. Now more than ever, it is imperative to get the public involved and informed on the status of Northern California's bull kelp forests.

There is a global crisis occurring that requires a high caliber of ecological, biological, and sustainable intervention. It is the responsibility of all humans to lessen their carbon footprint and impact on the planet, but there must be actions taken by leaders and managers for restoration and protection of vulnerable ecosystems. The trajectory of today's climate problem has a grim outcome, lowering carbon emissions is not enough at this point, projections show that we must actively take carbon out of the atmosphere. There is an overwhelming need for scientists and managers to work together on carbon capture efforts. Natural processes of carbon sequestration are a useful mechanism in this scenario, this is where kelp forests come into play. Kelp forest's ability to capture massive amounts of carbon from the ocean demonstrates the urgent nature of recovering and protecting these species worldwide.

Dedicated to my family, my parents, Rosa Maria and Keith, my friends who supported me throughout, Gabriella and Kevin, and my classmates Claire, Alisa, and Marina

LITERATURE CITED

Abbott I A, Hollenberg G J (1976) Marine Algae of California. Stanford University Press, Stanford, CA

Amsler, C. D., and M. Neushul. 1989. Diel periodicity of spore release from the kelp nereocystis luetkeana (mertens) postels et ruprecht. Journal of Experimental Marine Biology and Ecology **134**:117-127.

Barsky, K. 2019. Annual status of the fisheries report - california spiny lobster.

Bennett, S., T. Wernberg, E. S. Harvey, J. Santana-Garcon, B. J. Saunders, and D. Bellwood. 2015. Tropical herbivores provide resilience to a climate-mediated phase shift on temperate reefs. Ecology Letters **18**:714-723.

Bolton, J. J. 2010. The biogeography of kelps (Laminariales, Phaeophyceae): a global analysis with new insights from recent advances in molecular phylogenetics. *Helgoland Marine Research* **64**:263-279.

Campbell, A. H., E. M. Marzinelli, A. Vergés, M. A. Coleman, and P. D. Steinberg. 2014. Towards Restoration of Missing Underwater Forests. *PloS one* **9**:e84106.

Catton, C., L. Rogers-Bennett, and A. Amrhein. 2019. “Perfect storm” decimates northern California kelp forests.

Claisse, J. T., J. P. Williams, T. Ford, D. J. Pondella, B. Meux, and L. Protopapadakis. 2013. Kelp forest habitat restoration has the potential to increase sea urchin gonad biomass. *Ecosphere* **4**:art38-19.

Dayton, P. K. 1985. Ecology of kelp communities. Annual Review of Ecology & Systematics **16**:215-245.

Dayton, P. K., and M. J. Tegner. 1999. Temporal and spatial scales of kelp demography: The role of oceanographic climate. Ecological Monographs **69**:219.

Dayton, P. K., M. J. Tegner, P. B. E. Edwards, and P. E. Parnell. 1992. Temporal and spatial patterns of disturbance and recovery in a kelp forest community. Ecological Monographs **62**:421.

Dobkowski, K. A., K. D. Flanagan, J. R. Nordstrom, and A. Buschmann. 2019. Factors influencing recruitment and appearance of bull kelp, nereocystis luetkeana (phylum ochrophyta). Journal of Phycology **55**:236-244.

Drobnitch, S. T., K. Nickols, M. Edwards, and C. Amsler. 2017. Abiotic influences on bicarbonate use in the giant kelp, macrocystis pyrifera, in the monterey bay. Journal of Phycology **53**:85-94.

Duncan, B., K. D. Johnson, T. H. Suchanek, M. Brown, and J. L. Largier. 2019. Developing ocean climate change indicators for the north-central california coast and ocean. Journal of environmental management **252**:N.PAG.

Dunn, R. P., and K. A. Hovel. 2019. Experiments reveal limited top-down control of key herbivores in southern California kelp forests. *Ecology* **100**:N.PAG.

Estes, J. A., E. M. Danner, D. F. Doak, B. Konar, A. M. Springer, P. D. Steinberg, M. T. Tinker, and T. M. Williams. 2004. Complex Trophic Interactions in Kelp Forest Ecosystems. *Bulletin of Marine Science* **74**:621-638.

Fernández, P. A., J. D. Gaitán-Espitia, P. P. Leal, M. Schmid, A. T. Revill, and C. L. Hurd. 2020. Nitrogen sufficiency enhances thermal tolerance in habitat-forming kelp: implications for acclimation under thermal stress. *Scientific Reports* **10**:3186.

Field, J. C., R. C. Francis, and K. Aydin. 2006. Top-down modeling and bottom-up dynamics: Linking a fisheries-based ecosystem model with climate hypotheses in the northern california current. Progress in Oceanography **68**:238-270.

Filbee-Dexter, K., and R. Scheibling. 2014. Sea urchin barrens as alternative stable states of collapsed kelp ecosystems. *Marine Ecology Progress Series* **495**:1-25.

Filbee-Dexter, K., and T. Wernberg. 2018. Rise of Turfs: A New Battlefront for Globally Declining Kelp Forests. *Bioscience* **68**:64-76.

Fredriksen, S., K. Filbee-Dexter, K. M. Norderhaug, H. Steen, T. Bodvin, M. A. Coleman, F. Moy, and T. Wernberg. 2020. Green gravel: a novel restoration tool to combat kelp forest decline. *Scientific reports* **10**:3983.

Hernández-Carmona, G., O. García, D. Robledo, and M. Foster. 2000. Restoration Techniques for Macrocystis pyrifera (Phaeophyceae) Populations at the Southern Limit of Their Distribution in México. *Botanica Marina* **43**:.

Hewson, I., J. Button, B. Gudenkauf, B. Miner, A. Newton, M. Breitbart, E. Fahsbender, and K. Lafferty. 2014. Densovirus associated with sea-star wasting disease and mass mortality. :.

Hohman, R., S. Hutto, C. Catton, and F. Koe. 2019. Sonoma-mendocino bull kelp recovery plan. plan for the greater farallones national marine sanctuary and the california department of fish and wildlife. Federal Information & News Dispatch, LLC. San Francisco.

Ikawa, H., I. Faloona, J. Kochendorfer, K. T. Paw U., and W. C. Oechel. 2012. Air-sea exchange of CO2 at a northern california coastal site along the california current upwelling system. Biogeosciences Discussions **9**:17707-17741.

Intergovernmental Panel on Climate Change. 2014. Climate change 2013 – the physical science basis. Cambridge Univ. Press, New York, NY.

Johnson, C. R., S. Ling, C. Sanderson, G. Dominguez, E. Flukes, S. Frusher, C. Gardener, K. Hartmann, S. Jarman, R. Little, M. Marzloff, J. Soulie, J. Melbourne-Thomas, and K. Redd. 2013. Rebuilding ecosystem resilience: Assessment of management options to minimize formation of 'barrens' habitat by the long-spined sea urchin (centrostephanus rodgersii) in tasmania. Institute for Marine and Antarctic Studies, University of Tasmania.

Kordas, R. L., C. D. G. Harley, and M. I. O'Connor. 2011. Community ecology in a warming world: The influence of temperature on interspecific interactions in marine systems. *Journal of Experimental Marine Biology and Ecology* **400**:218-226.

Layton, C., M. A. Coleman, E. M. Marzinelli, P. D. Steinberg, S. E. Swearer, A. Vergés, T. Wernberg, and C. R. Johnson. 2020. Kelp Forest Restoration in Australia. *Frontiers in Marine Science* **7**:.

Leising, A., I. Schroeder, S. Bograd, J. Abell, R. Durazo, G. Gaxiola-Castro, E. Bjorkstedt, J. Field, K. Sakuma, R. Robertson, R. Goericke, W. Peterson, R. Brodeur, C. Barceló, T. Auth, E. Daly, R. Suryan, A. Gladics, and P. Warzybok. 2015. State of the California Current 2014-15: Impacts of the Warm-Water "Blob". :.

Ling, S. D., C. R. Johnson, K. Ridgway, A. J. Hobday, and M. Haddon. 2009a. Climate-driven range extension of a sea urchin: inferring future trends by analysis of recent population dynamics. *Global Change Biology* **15**:719-731.

Ling, S. D., and C. R. Johnson. 2012. Marine reserves reduce risk of climate-driven phase shift by reinstating size- and habitat-specific trophic interactions. Ecological Applications **22**:1232-1245.

Ling, S. D., S. Ibbott, and J. C. Sanderson. 2010. Recovery of canopy-forming macroalgae following removal of the enigmatic grazing sea urchin Heliocidaris erythrogramma. *Journal of Experimental Marine Biology & Ecology* **395**:135-146.

Ling, S. D., C. R. Johnson, S. D. Frusher, K. R. Ridgway, and J. C. Castilla. 2009b. Overfishing Reduces Resilience of Kelp Beds to Climate-Driven Catastrophic Phase Shift. *Proceedings of the National Academy of Sciences of the United States of America* **106**:22341-22345.

McCabe, R. M., B. M. Hickey, E. P. Dever, and P. MacCready. 2015. Seasonal cross-shelf flow structure, upwelling relaxation, and the alongshelf pressure gradient in the northern california current system*. Journal of Physical Oceanography **45**:209-227.

Michael H. Graham. 2004. Effects of Local Deforestation on the Diversity and Structure of Southern California Giant Kelp Forest Food Webs. *Ecosystems* **7**:341-357.

Nichols, K., L. Segui, and K. Hovel. 2015. Effects of predators on sea urchin density and habitat use in a southern California kelp forest. *Marine Biology* **162**:1227-1237.

Nicholson, T. E., K. A. Mayer, M. M. Staedler, J. A. Fujii, M. J. Murray, A. B. Johnson, M. T. Tinker, and K. S. Van Houtan. 2018. Gaps in kelp cover may threaten the recovery of california sea otters. Ecography **41**:1751-1762.

Nyström, M., A. Norström, T. Blenckner, M. la Torre-Castro, J. Eklöf, C. Folke, H. Österblom, R. Steneck, M. Thyresson, and M. Troell. 2012. Confronting feedbacks of degraded marine ecosystems. Ecosystems **15**:695-710.

ONMS, NOS, NOAA, and DOC. 2014. Gulf of the farallones national marine sanctuary management plan. National Oceanic and Atmospheric Administration. Alexandria, Va.

Pfister, C. A., H. D. Berry, and T. Mumford. 2018a. The dynamics of kelp forests in the northeast pacific ocean and the relationship with environmental drivers. Journal of Ecology **106**:1520-1533.

Pfister, C. A., H. D. Berry, and T. Mumford. 2018b. The dynamics of kelp forests in the northeast pacific ocean and the relationship with environmental drivers. Journal of Ecology **106**:1520-1533.

Reid, J., L. Rogers-Bennett, F. Vasquez, M. Pace, C. A. Catton, J. V. Kashiwada, and I. K. Taniguchi. 2016. The economic value of the recreational red abalone fishery in northern california. California Fish & Game **102**:119-130.

Ridgway, K. R. 2007. Long-term trend and decadal variability of the southward penetration of the East Australian Current. *Geophysical Research Letters* **34**:L13613-n/a.

Roberts, C. M., B. C. O'Leary, D. McCauley, P. Cury, C. Duarte, J. Lubchenco, D. Pauly, A. Sáenz-Arroyo, U. R. Sumaila, R. Wilson, B. Worm, and J. C. Castilla. 2017a. Marine reserves can mitigate and promote adaptation to climate change. :.

Roberts, C. M., B. C. O'Leary, D. McCauley, P. Cury, C. Duarte, J. Lubchenco, D. Pauly, A. Sáenz-Arroyo, U. R. Sumaila, R. Wilson, B. Worm, and J. C. Castilla. 2017b. Marine reserves can mitigate and promote adaptation to climate change. :.

Robinson, L. M., M. P. Marzloff, I. van Putten, G. Pecl, S. Jennings, S. Nicol, A. J. Hobday, S. Tracey, K. Hartmann, M. Haward, and S. Frusher. 2019. Structured decision-making identifies effective strategies and potential barriers for ecosystem-based management of a range-extending species in a global marine hotspot. Ecosystems **22**:1573-1591.

Rogers-Bennett, L., and C. A. Catton. 2019. Marine heat wave and multiple stressors tip bull kelp forest to sea urchin barrens. *Scientific Reports* **9**:1-9.

Sea Star Wasting Syndrome Task Force. 2018. Research and management priorities to address sea star wasting syndrome: A collaborative strategic action plan.

Shachak, M., J. H. Lawton, and C. G. Jones. 1994. Organisms as ecosystem engineers. Oikos **69**:373-386.

Shelamoff, V., C. Layton, M. Tatsumi, M. J. Cameron, J. T. Wright, and C. R. Johnson. 2019. Ecosystem engineering by a canopy-forming kelp facilitates the recruitment of native oysters. *Restoration Ecology* **27**:1442-1451.

Smale, D. A., and T. Wernberg. 2013. Extreme climatic event drives range contraction of a habitat-forming species. *Proceedings. Biological sciences* **280**:20122829.

Smale, D. A. 2020. Impacts of ocean warming on kelp forest ecosystems. New Phytologist **225**:1447-1454.

Springer, Y., C. Hays, Carr, Mackey, and J. Bloeser. 2006. Ecology and management of the bull kelp, nereocystis luetkeana: A synthesis with recommendations for future research. :.

Springer, Y. P., C. G. Hays, M. H. Carr, and M. R. Mackey. 2010. Toward ecosystem-based management of marine Macroalgae—The bull kelp, nereocystis luetkeana. Pages 1-42 *In* Anonymous Oceanography and marine biology, CRC Press.

Steneck, R. S., M. H. Graham, B. J. Bourque, D. Corbett, J. M. Erlandson, J. A. Estes, and M. J. Tegner. 2002. Kelp forest ecosystems: biodiversity, stability, resilience and future. *Environmental Conservation* **29**:436-459.

Stewart, N. L., and B. Konar. 2012. Kelp forests versus urchin barrens: Alternate stable states and their effect on sea otter prey quality in the aleutian islands. Journal of Marine Biology :1-12.

Teagle, H., D. A. Smale, and D. Schoeman. 2018. Climate-driven substitution of habitat-forming species leads to reduced biodiversity within a temperate marine community. Diversity & Distributions **24**:1367-1380.

Teagle, H., S. J. Hawkins, P. J. Moore, and D. A. Smale. 2017. The role of kelp species as biogenic habitat formers in coastal marine ecosystems. Journal of Experimental Marine Biology & Ecology **492**:81-98.

Tegner, M. J., P. K. Dayton, P. B. Edwards, and K. L. Riser. 1996. Is There Evidence for Long-Term Climatic Change in Southern California Kelp Forests? *CalCOFI* **37**:3.

The Bay Foundation, Vantuna Research Group, P. House, A. Barilotti, H. Burdick, T. Ford, J. Williams, C. Williams, and D. Pondella. 2018. Palos verdes kelp forest restoration project.

Tracey, S., C. Mundy, T. Baulch, M. Marzloff, K. Hartmann, S. Ling, and J. Tisdell. 2014. Trial of an industry implemented, spatially discrete eradication/control program for centrostephanus rodgersii in tasmania. Institute for Marine and Antarctic Studies, Tasmania, December. :.

Tracey, S., T. Baulch, K. Hartmann, S. Ling, V. Lucieer, M. Marzloff, and C. Mundy. 2015. Systematic culling controls a climate driven, habitat modifying invader. Biological Invasions **17**:1885-1896.

U.S. Fish and Wildlife Service. 2015. Southern sea otter (enhydra lutris nereis): 5-year review: Summary.

Vergés, A., E. McCosker, M. Mayer-Pinto, M. A. Coleman, T. Wernberg, T. Ainsworth, P. D. Steinberg, and G. Williams. 2019. Tropicalisation of temperate reefs: Implications for ecosystem functions and management actions. Functional Ecology **33**:1000-1013.

Vergés, A., P. D. Steinberg, M. E. Hay, A. G. B. Poore, A. H. Campbell, E. Ballesteros, K. L. Heck, D. J. Booth, M. A. Coleman, D. A. Feary, W. Figueira, T. Langlois, E. M. Marzinelli, T. Mizerek, P. J. Mumby, Y. Nakamura, M. Roughan, E. Sebille, A. S. Gupta, D. A. Smale, F. Tomas, T. Wernberg, and S. K. Wilson. 2014. The tropicalization of temperate marine ecosystems: Climate-mediated changes in herbivory and community phase shifts.

Wernberg, T., M. A. Coleman, S. Bennett, M. S. Thomsen, F. Tuya, and B. P. Kelaher. 2018. Genetic diversity and kelp forest vulnerability to climatic stress. *Scientific reports* **8**:1851-8.

Wernberg, T., S. Bennett, R. C. Babcock, T. de Bettignies, K. Cure, M. Depczynski, F. Dufois, J. Fromont, C. J. Fulton, R. K. Hovey, E. S. Harvey, T. H. Holmes, G. A. Kendrick, B. Radford, J. Santana-Garcon, B. J. Saunders, D. A. Smale, M. S. Thomsen, C. A. Tuckett, and F. Tuya. 2016. Climate-driven regime shift of a temperate marine ecosystem. Science **353**:169-172.

Wisniewski, C., P. Owens, T. Ford, N. Caruso, L. Bodensteiner, J. Altstatt, and D. Burcham. Southern california regional kelp restoration project; Fifth progress report. unpublished.