Title

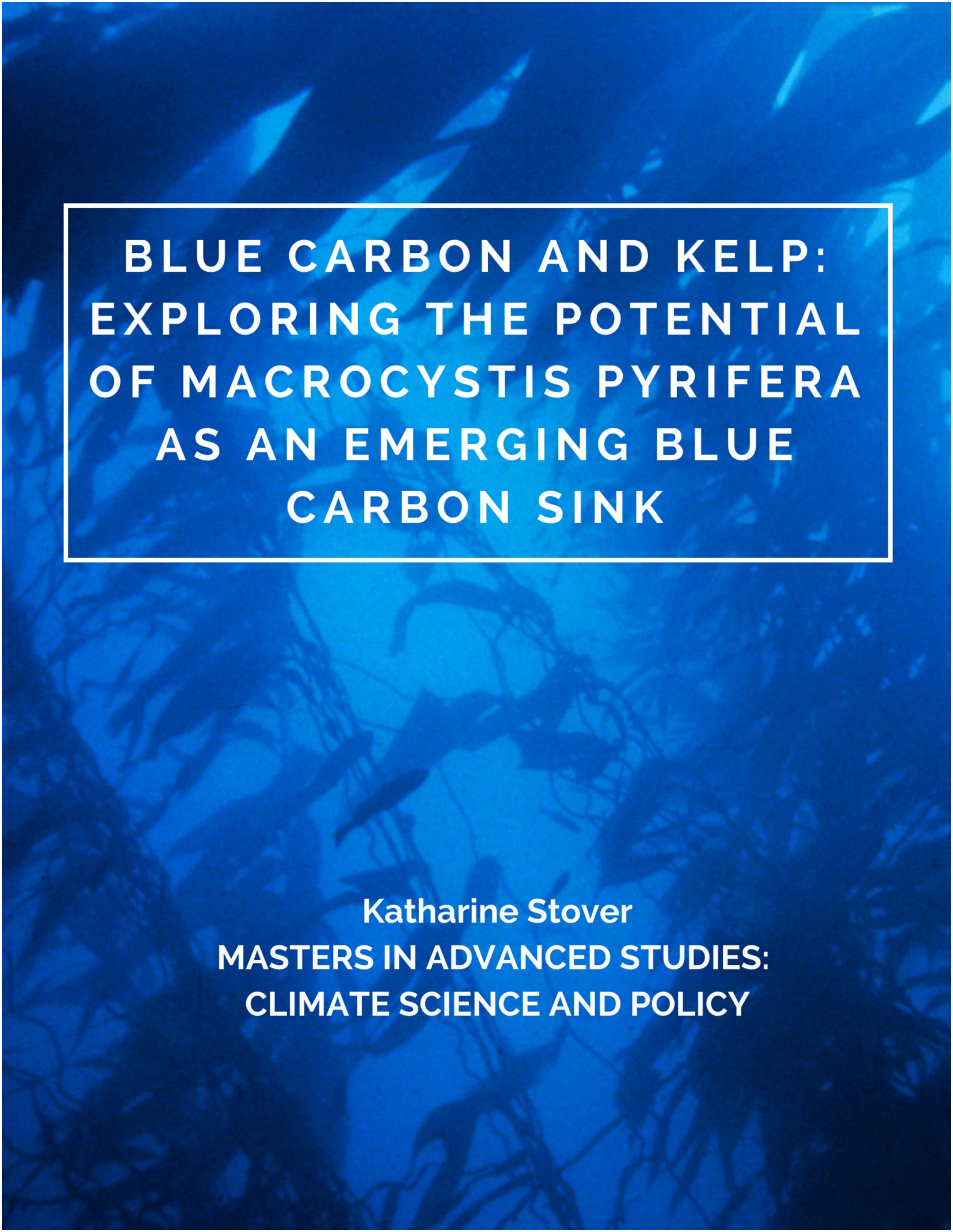
Blue Carbon and Kelp: Exploring the Potential of Macrocystis Pyrifera as an Emerging Blue Carbon Sink

Author

Stover, Katharine

Publication Date

2018-06-01



BLUE CARBON AND KELP: EXPLORING THE POTENTIAL OF MACROCYSTIS PYRIFERA AS AN EMERGING BLUE CARBON SINK

Katharine Stover
MASTERS IN ADVANCED STUDIES: CLIMATE SCIENCE AND POLICY

In completing this project, I gained valuable support from my capstone advisor, Dr. Brian Von Herzen, and other members of my capstone committee. Dr. Von Herzen has been instrumental in increasing the understanding of the potential of kelp and other macroalgae to improve the health of our oceans and reduce the impacts of climate change. Dr. Corey Gabriel has been a wonderful support and resource this year and Dr. Mark Merrifield has provided additional guidance.

In addition, I am extremely grateful to my family and friends for their support in my second foray into grad school. In particular, my parents Charles and Katharine Stover and my sisters, Emily and Rebecca Stover, have been my confidants and cheerleaders. My cohort has been an amazing source of support and we have taught each other a lot. Lastly, I want to thank Justin Kita for his insight and constant support.

Brian Von Herzen

SCRIPPS INSTITUTION OF OCEANOGRAPHY
UC San Diego

CLIMATE SCIENCE AND POLICY

Contents

Table of Figures

Abstract

This project examines the potential emergence and recognition of kelp forests as blue carbon sinks. A carbon sink is the long-term sequestration of carbon in a natural environment. This can refer to carbon storage in soil, forests, and deep sea sediments among other sources. Blue carbon is the term used to define the carbon sequestered by marine ecosystems. This project designs the research processes to assess the scientific and economic impacts of kelp as a potential blue carbon sink. To this end, this project includes a dynamic geodatabase and an app to connect with divers in a citizen science project. This project incorporates scientific, policy and economic research.

Scope of Work and Project Motivation

This project was inspired by the work of the Climate Foundation, a Woods Hole, Massachusetts, based nonprofit that focuses on regenerating collapsing ocean ecosystems, providing international food security and measuring associated CO2 export from the atmosphere and oceanic mixed layer into the middle and deep ocean. This project is at the nexus of climate science, ecosystem conservation, and new business development. It provides an opportunity to work with blue carbon certification models. My education and previous professional experience are in conservation and business. I am interested in this project for several reasons. There appears to be an opportunity to scale kelp production more quickly than other blue carbon ecosystems due to the rapid growth rate of the macroalgae and the development of offshore mariculture of kelp.

The main deliverable of this project is a research design for presentation to practitioners for the study of kelp as a source of blue carbon. This includes an organizational plan to aggregate existing information, the design of a common data infrastructure, and the major questions to be addressed in the study. This project is designed to bring stakeholders together and to create a platform for data sharing that will help to facilitate blue carbon research into many species of macroalgae.

The second deliverable is a geodatabase to assist in prioritizing project sites for carbon sequestration research. This includes data that will influence site selection and prioritization of study sites on the California coast. The third deliverable is an app that promotes partnerships, is a platform for data collection from divers, and has a chat feature for practitioners.

There is already a great deal of data on kelp ecosystems globally and several long-term ecosystem studies being conducted along the California coast. While specific study is needed to determine carbon sequestration, some of the data can be assembled from ongoing and past research. This project also explores the frameworks for blue carbon policy and economic valuation and how kelp might fit into a compatible framework. It makes sense to create a framework that builds upon the existing blue carbon frameworks.

While this research is well beyond the scope of a one-year master's program, I intend to keep working in this field after my graduation.

This work was conducted as a Capstone Project for the Masters of Advanced Studies in Climate Science and Policy at Scripps Institution of Oceanography (SIO) in San Diego, California.

Introduction

This project identifies a process to help address uncertainty in the mechanisms of carbon export from kelp forests. Science does not have a clear understanding of the local and remote carbon export from kelp beds (coastal and deep sea combined). Parts of the carbon sequestration mechanisms in kelp are well understood.

The proposed research design includes mechanisms to aggregate and evaluate sediment core data, kelp biomass data, anecdotal data from scuba-site surveys, and data from ROV video/still images. As part of this project, I built a geodatabase. This geodatabase comprises biomass data, kelp range data, sediment core locations, locations of hypoxic events, among other data indicators.

The proposed model includes both the wild populations and potential aquaculture operations. Initially, the focus of the project will be on southern California due to the high density of sediment cores and academic research on the kelp forests of the region. The next step of this project is to build the case for certification and set up monitoring networks for dynamic reporting of carbon export on an annual basis.

I reviewed the existing science on carbon export in kelp, especially in reference to blue carbon certifications. I reviewed existing technologies for studying kelp ecosystems and ways that they could be used as part of a large-scale, cooperative research program. Given the long-term ecological research that is currently being conducted along the California coast, it makes sense to partner with existing studies and investigate areas where we can work from existing data sets. In order to aggregate data from existing studies, it makes sense to develop common databases for this project. To accomplish this integration, I have built an app for data collection from both scientists and recreational divers to populate a robust data set and encourage community involvement in the form of citizen science.

Project Methodology

I used Geographic Information Systems (GIS) analysis to interpret data sets of sediment core locations, oxygen-minimum zones, kelp range and other relevant data. I used ArcMap, QGIS, and Carto for mapping software and data visualization. The maps created from this analysis highlight the best sites for studying carbon export in kelp with the express purpose of facilitating site selection along the California coast and identifying existing data for study. Site selection is based upon the density of sediment cores in that location (an existing data set), the presence of active projects in the area (in order to work with existing ongoing research wherever possible), the use by recreational scuba divers (to facilitate data collection through citizen science), and the presence of low-oxygen conditions in some areas.

Kelp forests are one of the most important ecosystems of the California coast and are heavily researched in the area. This region is ideal for my study and the existing data sets will help to reduce the time needed for this process.

Kelp forests

This project focused on Giant Kelp, *macrocystis pyrifera*, (subsequently referred to as kelp) and its impacts of kelp along the southern California coast. Kelp is a type of photosynthetic (and chemosynthetic for some deep water species) macroalgae that has a global range. It is found in the photic zone of the ocean which is approximately the first 30 meters down from the surface in California waters. (Schiel & Foster, 2015) Some undersea kelp forests have been found as deep as 100 meters in clear waters west of the Galapagos Islands. (Graham *et al*., 2007) The species can grow to 50 meters in height, with the top fronds floating stretching across the surface. Kelp has an estimated lifespan of 7 years. It affixes itself to rocky substrate with a holdfast which is structurally similar to a plant's root system but does not transport nutrients. (Schiel & Foster, 2015) It is one of the fastest-growing organisms on the planet, growing up to two feet per day. (Schiel & Foster, 2015)

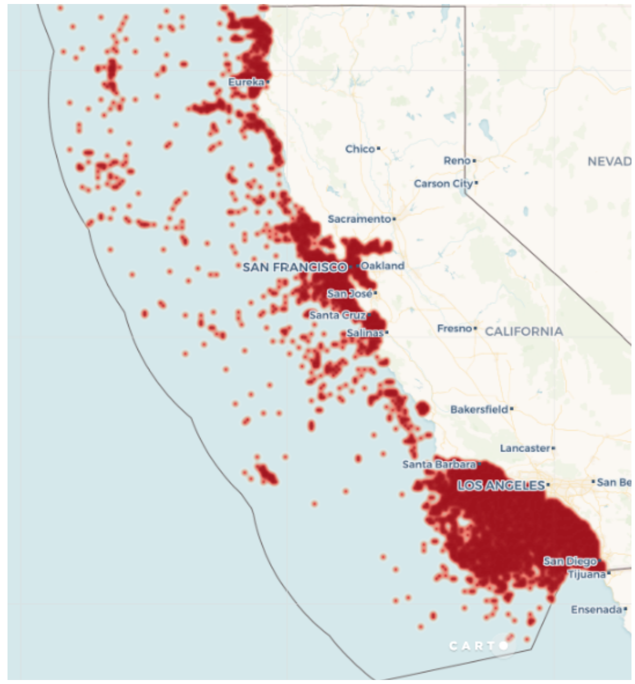


Figure 1. Sediment core density off of the California coast within the United States EEZ.

Kelp is abundant along the coast of California and its iconic forests provide the base habitat for much of its marine fauna. Its forests nurture the development of everything from sea stars to, indirectly, great white sharks through providing a food source in marine mammals This great aggregation of biodiversity is dependent upon Kelp's net primary production and the habitat that the species provides. Kelp forest ecosystems are crucial nurseries and provide shelter for species from predators and storms.(Schiel & Foster, 2015)

Kelp is predated upon by sea urchins and species of fish and invertebrates that graze upon it. Sea urchins are one of the main kelp predators and are particularly destructive because they eat the holdfast that keeps the kelp attached to the rocky substrate. Sea stars and sea otters are both predators of sea urchins and thus maintain healthy kelp ecosystems. (Steneck *et al*., 2002) However, when the ecosystem goes out of balance, these urchins can get out of control, resulting in urchin barrens as are seen in Tasmania and northern California today. These urchin barrens have contributed to loss of kelp forest (mostly bull kelp in northern California) cover exceeding 90% in these regions. (Renshaw *et al*., 2017)(Krumhansl *et al*., 2016)

While aggregations of kelp are called forests, it is not a vascular plant. Its cells lack lignin (a compound which gives plant cells structure and rigidity) which gives kelp greater flexibility for movement in ocean currents. (Trevathan-Tackett *et al*., 2015) This lack of lignin can mean that some kelp species may break down more quickly than woody biomass. However, the complexity of the hemicellulose and other molecules of some kelp species means that it is not quickly broken down in sediment or as a food source. (Trevathan-Tackett *et al*., 2015)

Net primary production is the net chemical energy that is taken up by an ecosystem or a species. Kelp's net primary production fluctuates more with biomass than seasonality and is used as a measurement of carbon export from the surrounding water. (Reed *et al.*, 2008) Here in southern California, kelp's biomass reaches a high in late winter/early spring. (Bell *et al* ., 2015) Warmer waters are less nutrient-rich, correlating to the seasonal lows in biomass in the summer months in southern California. Ideal temperature for maximum growth of kelp is between five and twenty degrees Celsius. (Rodgers & Shears, 2016)

Additional factors that affect kelp mortality are wave height and intensity. (Seymour *et al.*, 1989) Changes in currents and water temperature related to El Nino Southern Oscillation (ENSO) fluctuations can cause loss of biomass in kelp. (Ramírez-Valdez *et al.*, 2017) These factors are modeled to become more unpredictable in a changing ocean, which may lead to further loss of kelp forest biomass in the future.

The Ocean Carbon Cycle

The ocean provides innumerable functions for our planet's inhabitants. Indeed, they make the planet habitable. Over half of the oxygen we depend upon (70 percent) comes from plankton in the ocean, and the majority of carbon is also sequestered in the world's oceans currently. (NASA, 2010) The ocean is a crucial part of the global carbon cycle, which is the global flow of carbon through physical, chemical, and biological mechanisms. The ocean's carbon cycle is crucial for the understanding of net primary production and carbon sequestration in kelp. The ocean and atmosphere are constantly exchanging gases and water vapor, and currents and weather patterns are closely linked. Carbon enters the upper ocean in the mixed layer through interchange of biological organisms, chemical reactions, precipitations, or the mechanical mixing of wave action. Carbon is taken up by microscopic organisms, both plant and animal, and larger photosynthetic macrophytes.

Kelp pulls the carbon dioxide from the water in the photosynthesis process and incorporates it into its tissues. This carbon is then exported from the kelp in the form of particulate organic carbon (POC) or dissolved organic carbon. The carbon may be eaten, dissolve further (or be otherwise broken down by other animals or microbes), or become sequestered at this point. Sequestration is the state where the carbon is effectively kept out of the atmosphere for a period of time. This can mean burial in nearshore or deep ocean sediment or movement in deep ocean currents. The standard for blue carbon certification is 100 years. In particular, deep ocean circulation is crucial for the long-term removal of dissolved organic carbon (DOC) and particulate organic

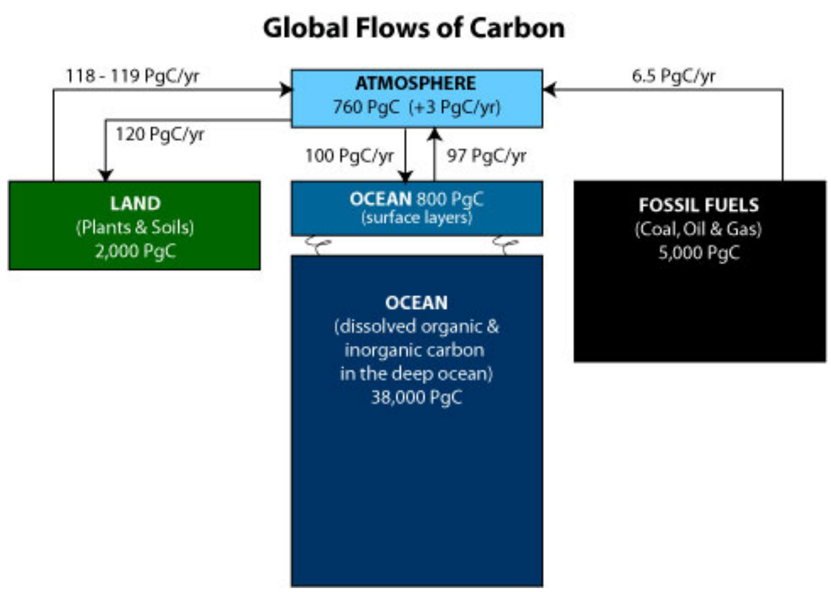


Figure 2. The Global Carbon Cycle. Image from NASA's webpage on the global carbon cycle. (NASA, 2010)

carbon (POC) from the atmosphere. This circulation is measured in terms of residence time, the time a substance is in a particular environment, for carbon dioxide. In the case of deep ocean circulation, this is on an approximate timescale over 500 years. (Pickard & Emery, 2013)

Kelp forests are among the most productive ecosystems on the planet, with an estimated net primary production of between 1020-1960 Tera grams/year (1Tg=10^{12} g). (Krause-Jensen and Duarte 2016), and the highest specific productivity of any ecosystem on the planet, fixing more than 2500 g/C/m2/year.(Cummings, 2005) They also reduce ocean acidification on a local scale, which can help shellfish with more effective shell formation. (Chan *et al*.,2016) Kelp and other macroalgae are also grown in aquaculture (also referred to as mariculture), either alone or in conjunction with fish or shellfish species. Aquaculture is an industry that is growing rapidly and an area of extensive research. The FAO estimates that macroalgal (seaweed) aquaculture makes up approximately 20% of global aquaculture production, with a value of $6.7 billion in 2014.(FAO, 2016) The United Nations Food and Agricultural Organization stated that in 2014, more than 8 million tons of kelp were harvested, valued at approximately $1.4 billion. (FAO, 2016.) In addition, the products derived from macroalgae have the potential to make positive environmental impacts on many fronts: methane emissions from cows, production of biofuel and pressure on some wild fisheries for components for animal feed. (FAO, 2016)

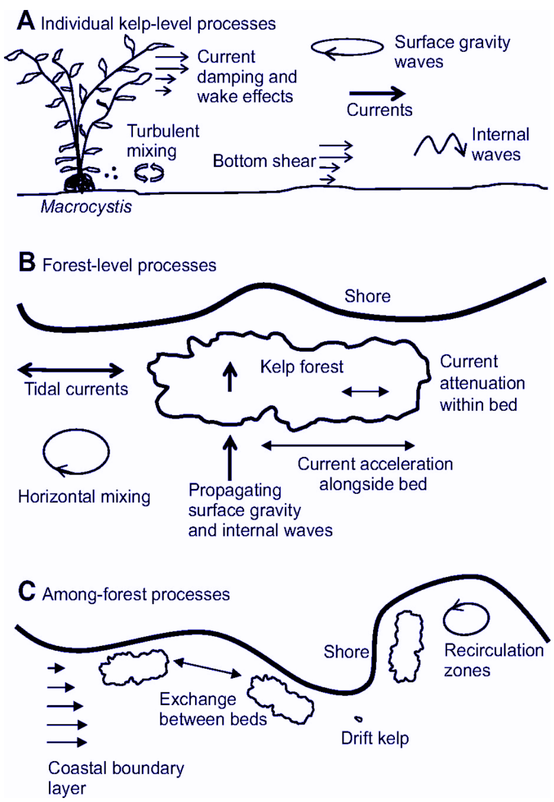


Figure 3. Movement processes in a kelp forest. Image Source: Gaylord et al. (2012)

The figure on the right from Gaylord *et al.* (2012), illustrates some of the ocean circulation and localized movements that affect kelp. These forests grow in coastal areas which can have powerful wave activity, in addition to upwelling, downwelling, and coastal currents. This movement, combined with predation activity such as that of sea urchins, can remove kelp plants from their holdfasts or pieces of the plants into the water column. Kelp has gas-filled floats called pneumatocysts which are filled with carbon monoxide or carbon dioxide, depending upon the species. These floats will allow kelp plants that have lost their connection to the substrate to form rafts (and thus potentially drift further away from the coast) and other pieces to float until they burst.

These pieces of kelp have several fates. Many of them are consumed by fish and other species, some sink and are buried in sediment, and others move down marine canyons to the deeper ocean. Marine canyons can be more turbulent due to dynamic currents, the movement of longshore currents and upwelling events. (Sumner & Paull, 2014) (De Leo, *et al.* 010) Storms

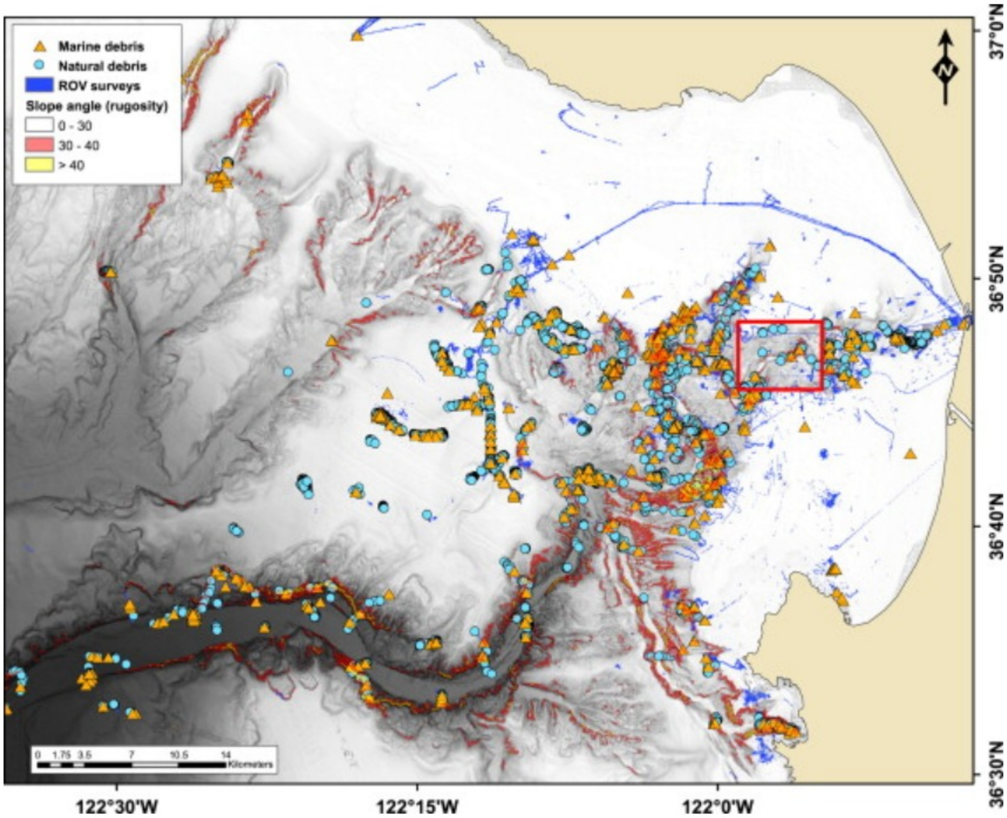


Figure 4. Location of marine and natural debris in the Monterey Canyon (

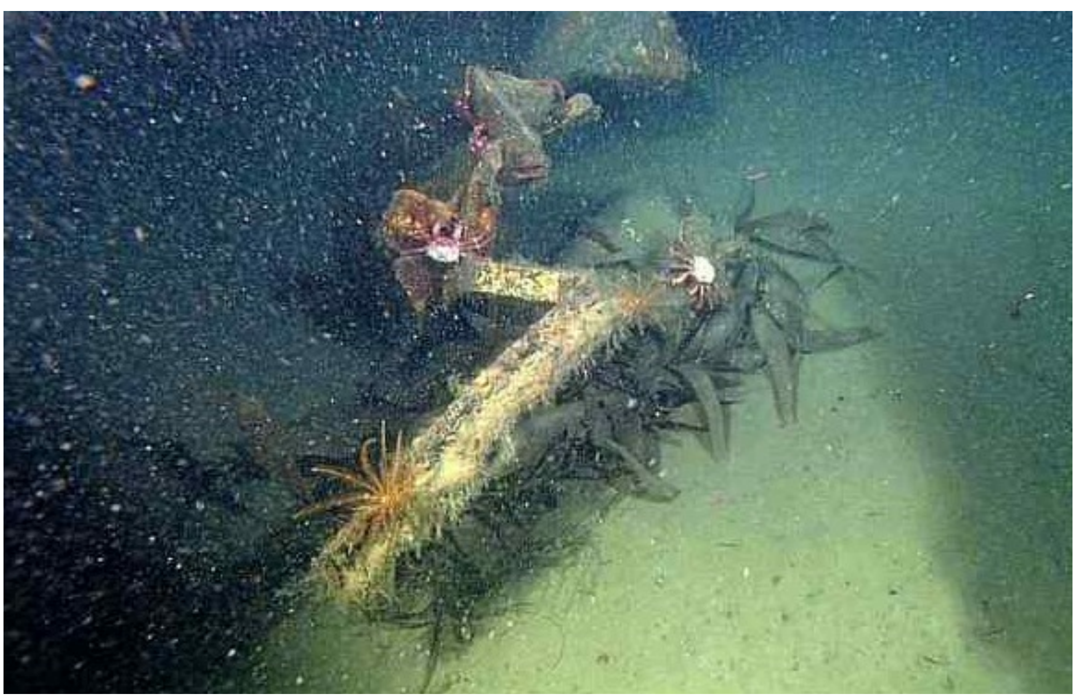


Figure 5. Drift Kelp on a ship wreck on the sea floor off of the California coast.

Top figure from (Brothers, ten Brink, Andrews, Chaytor, & Twichell, 2013) and bottom image from MBARI.(Schlining, 2006) are also crucial in moving kelp into deeper waters as these high-energy events may remove it from its holdfast or damage the macroalgae so that stalks and fronds sink. (Krause-Jensen & Duarte, 2016)

In contrast to other blue carbon sources, carbon export in a kelp forest is not necessarily local and can be up to as many as hundreds of km away. It is achieved through burial in local sediment, remineralization in substrate, dissolution in water (which then must sink to the deep ocean) or burial in deep ocean sediments. Krause-Jensen and Duarte (2016) explore the role of macroalgae in carbon sequestration and the ocean currents that drive that movement. Wind plays a significant role in driving kelp movement at the surface, but also in the currents that move the kelp downwards in the water column until the pneumatocysts burst. (Krause-Jensen & Duarte, 2016) The pneumatocysts can also degrade with age and grazing behavior and burst on their own. (Steneck *et al.*, 2002)(Filbee-Dexter, 2016) I created the figure below from information from the Krause-Jensen and Duarte (2016) article to map out the carbon sequestration process in kelp beds. This figure does not incorporate the carbon that is lost to feeding as that carbon is not sequestered. It is useful to consider the role of kelp detritus (small pieces of kelp plants) that precipitate down the water column. Also, the goal ultimate goal of carbon export from kelp for blue carbon certification would be export to the deep sea sediments and sequestration there. The time horizon for deep ocean circulation is the longest of all of the currents, averaging about 1000 years until that carbon would outcrop again – and thus interact with the atmosphere. The current UN standard for blue carbon certification is 100 years. Deep-ocean sequestration exceeds that time interval significantly. (Takahashi *et al.*, 2009)

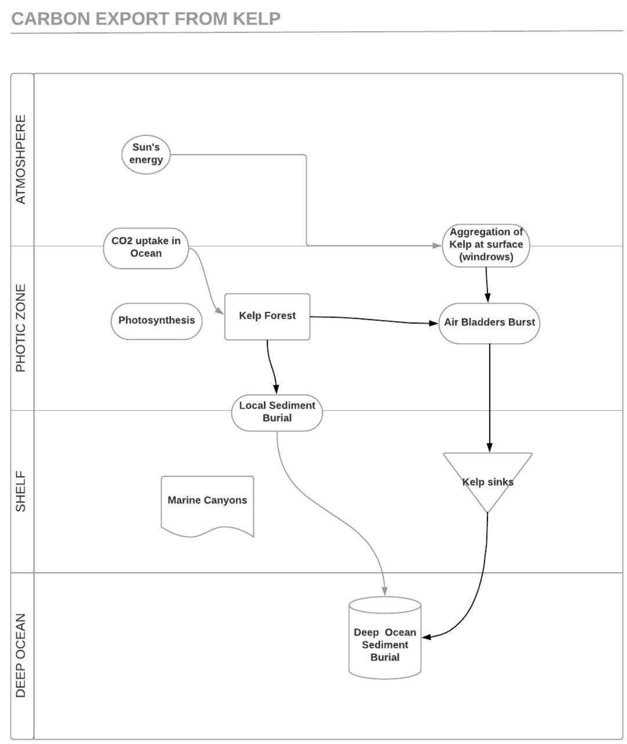


Figure 6. Carbon export and sequestration from Kelp forests. Data from Krause-Jensen and Duarte (2016)

Kelp is not included in the current blue carbon standards for several reasons. There are high levels of uncertainty about the amount of carbon sequestered by kelp forests and what portions are sequestered in near-shore or offshore environments. In addition, standardized monitoring methodologies have yet to be developed.

The Role of Climate Change

This project is closely connected to the impacts of and exploring potential mitigation options for climate change. It explores the roles of natural systems and their impacts on reducing the amount of carbon dioxide in the atmosphere. It also explores the role of ecosystem services, and by extension, that of blue carbon sequestration.

Our planet receives over two thirds of its oxygen from the oceans, and the oceans are a crucial sink for carbon dioxide. The oceans have trapped much of the heat from climate change thus far, due to the high heat capacity of water. Our oceans are changing dramatically as our climate and ocean chemistry changes. This affects biological processes and the ability of the oceans to act as a heat sink. Kelp can reduce ocean acidification on a localized basis and this help to maintain the health of shellfish and small invertebrates that live in its ecosystem. (Weatherdon, *et al.,* 2016)

Some regions have suffered a great loss of kelp biomass in response to warming ocean. Warmer waters tend to have lower nutrient levels, which is crucial for kelp growth. (Krumhansl *et al*., 2016) In Tasmania, the water temperature has risen dramatically, resulting in a 95 percent loss of kelp in coastal waters.(NOAA & NASA, 2013) (Marzinelli *et al*., 2015) In addition, Kelp germination rates are reduced and spore mortality and dormancy increased with warmer waters and higher carbon dioxide levels in ocean waters. (Gaitán-Espitia et al., 2014) Kelp biomass is reduced and urchin growth rates are increased with warming temperatures, this increasing pressures on the forests, especially in low-latitude regions. (Provost *et al.*, 2017)

Policy Frameworks

To understand blue carbon, one must first delve into biological economics. A key element of ecological economics is the concept of ecosystem services. It is defined as "t*he ecological characteristics, functions, or processes that directly or indirectly contribute to human wellbeing: that is, the benefits that people derive from functioning ecosystems"*. (Costanza *et al*., 1997) Ecosystem services are a way to identify and model these benefits as players in the economy and as a part of the larger system. It also recognizes our indisputable connection to the natural world.

The primary differentiation in types of ecosystem services is between use values and non-use values. Use values can be described as direct and indirect. For example, a forest can provide direct benefits such as water or air filtration services. These ecosystem services can save humans the investment in the infrastructure for water treatment and also provide timber for construction. Direct value is the recreation value provided by many ecosystems and associated expenditures. In a local example, according to a 2016 National Park Service Report, visitors to the Channel Islands National Park spent over $22 million that year. (Cathy & Lynne, n.d.)

Use and non-use values can be interwoven with cultural identity as in cases where a community has traditions connected to a specific species. In the case of southern California, our cold waters, surfing culture, and kelp forests are part of the collective identity of the state. This is shown in the high level of support for the marine protected areas in the state - the majority of which include kelp ecosystems. (Baldassare, Bonner, Kordus, & Lopes, 2017) These non-use values influence consumer and conservation decisions.

Another core concept of ecosystem services is consumer willingness to pay. While the mechanisms for each of the values mentioned are different, all are ultimately dependent upon consumer demand and willingness to invest in those services. For carbon credits, this can mean customers must buy credits to offset their own emissions or can voluntarily invest in projects that reduce the amount of greenhouse gases in the atmosphere.

Ecosystem services valuations are dependent upon accurate and consistent measurement techniques and the ability to compare values across ecosystems. The advent of big data analytics and improve computing power have greatly increased our ability to assess the changes in ecosystems in a near real-time basis. Cooperation between monitoring organizations and data sharing agreements have also facilitated the integration of ecosystem services into mainstream economics. Remote sensing is integral in assisting accurate valuations in a way that helps to reduce uncertainty on the part of the consumer. These improvements in valuation techniques an ecosystem monitoring have also assisted policy makers in making more accurate damage assessments and understanding potential harms based upon decisions.

One challenge presented by ecosystem services (and kelp as an emerging blue carbon sink) is that of reducing uncertainty. In payments for ecosystem services, the consumer or governance agency wants to be able to know what benefits they will receive from their investment. As in any long-term investment, an accurate assessment of the risk involved is crucial to proper pricing and valuation of that financial instrument. The most common valuation has been to use the social cost of carbon - a formula developed by the United States Environmental Protection Agency. Another aspect of uncertainty is reasonable predictability that an investment will continue to yield predictable results over time. In this case, it applies to whether blue carbon ecosystems will continue to sequester the same amount of carbon over time. The global change precipitated by our changing climate and acidifying ocean adds a greater degree of uncertainty to this sequestration amount.

Blue Carbon: Further Exploration

Blue carbon is the carbon sequestered through aquatic ecosystems. It is currently certified under the United Nations for three ecosystems: saltwater marshes, mangrove forests, and seagrass meadows. Blue carbon policy has two parts: the biological mechanisms to capture and sequester carbon, and the export into the ecosystem.

Blue carbon policy has evolved with the development of international standards, governing working groups, and improved monitoring mechanisms for carbon export. Other aspects of blue carbon policy are the development of markets to trade carbon credits and the ability to use the ecosystem services provided. The concept of carbon credits came out of the discipline of ecological economics.

Blue carbon is a crucial resource in the fight against climate change. Seagrass meadows, mangroves, and tidal marshes provide a myriad of ecosystem and carbon sequestration benefits. These ecosystems capture and store more carbon than terrestrial forests. (Howard *et al*., 2017) In addition to the benefits that healthy blue carbon ecosystems provide, these ecosystems can become net carbon sources when they are degraded. For the three certified blue carbon sink ecosystem types, carbon is locally exported into surrounding. This local export means that when the sediment is disturbed and loses its natural components (i.e. mangroves are cut down and bulldozed) there is a net off gassing of greenhouse gases. Thus, destroying blue carbon ecosystems for development not only removes a carbon sink but creates a greenhouse gas source at the same time. (Howard *et al*., 2017) Kelp forests may not react the same way because the mechanisms of carbon sequestration in kelp are different and non-local.

The key factors in developing blue carbon certifications are the ability to establish standardized measurements and quantify carbon exports from the ecosystems in question. The three existing blue carbon sinks have these measures established and monitoring protocols are applied. Once the quantity of carbon sequestered is established and tracked annually, then credits can be sold which can be used to protect and improve that ecosystem. The carbon price is determined by the market or the social cost of carbon is used. The social cost of carbon was developed by the United States Environmental Protection Agency. (EPA, 2016)

In order to integrate kelp into the blue carbon certification framework, it is necessary to create its own model of sequestration and mechanisms for assessment. (Krause-Jensen et al., 2018) Given that it has different ecosystem functions than the other blue carbon sinks, it makes sense to design a model that can work in tandem with other blue carbon valuation systems but that addresses the unique aspects of macroalgal ecosystems. This model will incorporate wild and aquaculture carbon sequestration and explicitly acknowledge where human interventions can play a part.

Blue carbon policy was developed out of a partnership between economics and biology. Much of its advocacy and policy formulation has been from non-governmental organizations. Many of these organizations have a vested interest in creating financing mechanisms for conservation. Blue carbon serves as an effective vessel for protecting the myriad of other ecosystem services that these macrophytes provide. Each of the current certified blue carbon sinks composes an ecosystem in itself. Kelp forest ecosystems are no different. Mangroves are the best studied blue carbon ecosystem and currently face large threats from aquaculture and development. Studying the carbon sequestration benefits, especially in the context of aiding countries in meeting their nationally determined contributions to international agreements, adds additional value to ecosystems under threat. There is also a general trend in conservation to move from conserving species to landscapes – as they are umbrellas for biodiversity conservation

To frame the project, it is important to consider its three elements. First, it is assessing the carbon export from kelp in its native habitat along the California coast. Second are the economic formulas and carbon trading that help to set the value of sequestered carbon. Thirdly, the policy elements include directing countries to invest in their own natural infrastructure protection as part of their mitigation strategies and creating policies to promote information-sharing and investment in monitoring mechanisms. Specialized funding opportunities would also be extremely useful to this project.

Research Design Overview

The main deliverable of this project is a research design, included as the second half of this report. This design is organized to collect existing data into a common data framework. It will also facilitate the cooperation of researchers to evaluate the amount of carbon that is sequestered by kelp in the local sediment and deep ocean currents. The current mechanisms of export are known, but there is a high level of uncertainty on the quantities of carbon sequestered. In addition, it is unknown whether there is regional or forest-level variation based upon local factors such as topography.

Given this high level of uncertainty, it is useful to consider tools that may help with its reduction. Citizen science, satellite imagery analysis, sediment core analysis, the Argo floats and RFID tracking technologies could be useful in a larger research design. The use of the Hyperspectral Infrared Imager mission (HyspIRI) has been correlated with in-situ biomass measurements and may be a particularly useful tool for monitoring kelp forest changes over time, including seasonal variability. This project has also been used as part of a citizen science effort to identify satellite imagery of kelp forests. (Bell *et al*., 2015)

As part of this project, I designed an app that can be used by scuba divers and scientists to upload their data into a geodatabase. This data will provide evidence of sediment cores, locations of sediment falls, and continue to populate the database for further analysis as described in the research design. In addition, scientist participation will be encouraged by the opportunity to win equipment from their labs, sponsored by companies. A citizen science project will document kelp burial in sediment on dive sites, providing location data and photographic evidence that can guide scientists' inquiries. Satellite imagery analysis is already being used to assess biomass and track kelp forests extent from space. This research design plans to use RFID chips to track kelp rafts drifting offshore to get a better idea of where it might be sinking into deep ocean sediments. Finally, analysis of ROV footage can show kelp burial at depth and that process can begin by analyzing existing footage.

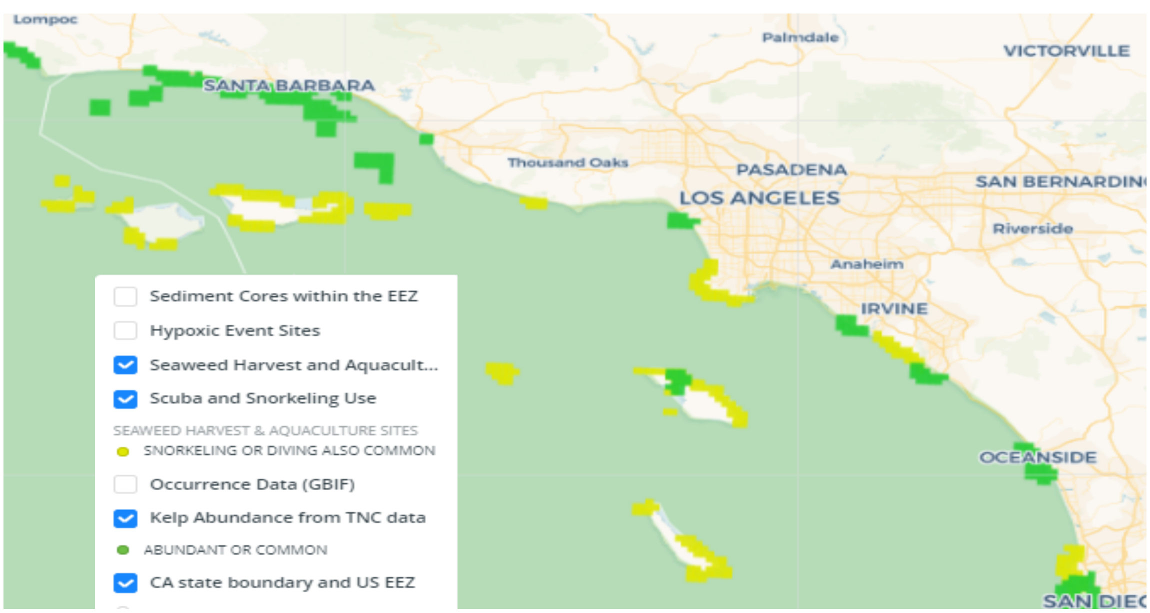


Figure 7. Snorkeling/Scuba primary use sites, aquaculture lease sites, and seaweed harvest sites. Data Source: NOAA California Ocean Uses Database

Hamel and Bryant (2017) advocate for the integration of uncertainty analyses into models of ecosystem services. This is due to ongoing issues with data quality and the challenges of communicating spatial model results with stakeholders.(Hamel & Bryant, 2015) The author's recommendations are crucial in the context of assessing kelp's role as a potential blue carbon sink. They conclude that "*ultimately it is the responsibility of leaders of ES assessments to build in resources for consideration of uncertainty, recognizing that where resources cannot be expanded, resources should perhaps be reallocated to allow for uncertainty assessment of less intricate modeling efforts.*" (Hamel & Bryant, 2015)

The model that I have created is a step to couple the certification system (policy and economic framework) with that of the natural system. For this purpose, I am considering aquaculture a part of the natural system, even though it is driven by human activity. The photosynthesis and carbon fixation are the natural mechanisms that I am interested in. Given that the natural system has two components for the purpose of carbon sequestration I designed them in parallel and indicated the areas of greatest uncertainty. These areas are shown in red in the figure above. I also included a need for further research as a part of the system as I intend for the final model to be one that can evolve with new scientific and policy information.

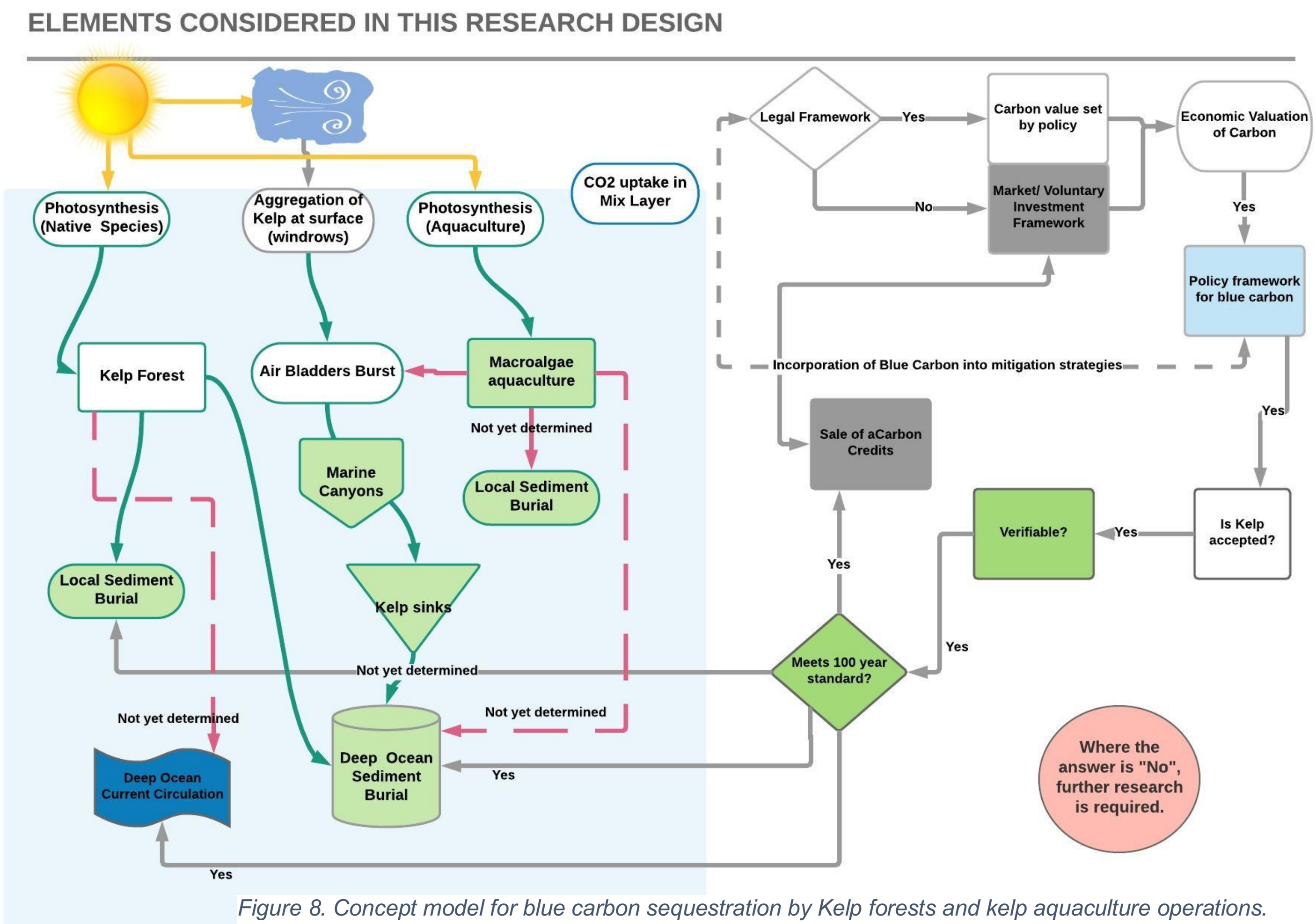


Figure 8. Concept model for blue carbon sequestration by Kelp forests and kelp aquaculture operations.

Another, more complex aspect of the model is that it may only be possible to account for carbon sequestration by macroalgae under certain conditions. Any certification mechanism relies on replicable measurements and the ability to scale criteria reliably across different ecosystem units of the same type. It may only be possible to track biomass changes and extrapolate carbon sequestration locally or through marine canyons once that relationship is better quantified. (Krause-Jensen *et al*., 2018) It is my opinion that this would still comprise a valid carbon sink worthy of a certification mechanism. Even if it is a more limited amount of carbon than the total amount sequestered by kelp, it would still provide a mechanism for conservation financing. In addition, the blue carbon credits that might be obtained through modified kelp aquaculture could be used as financing mechanisms for new companies and an incentive for small island developing states to utilize their exclusive economic zones for climate change mitigation actions.

Research Design

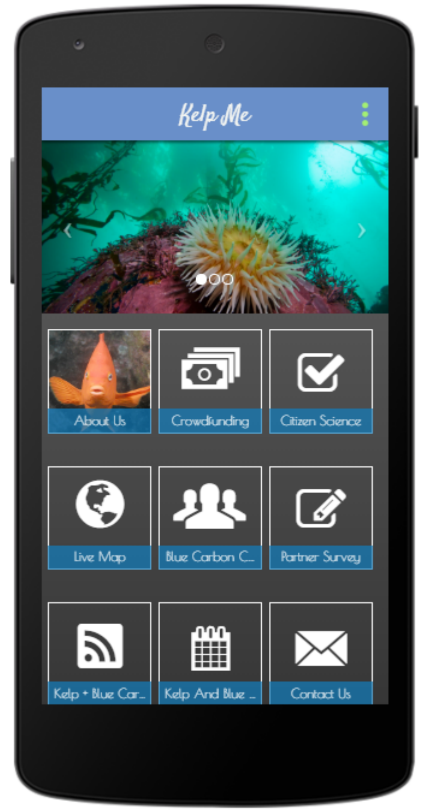
A key research question for this project is how much carbon is sequestered by *Macrocystis pyrifera*. This question is complex. There are existing estimates as referenced previously in this paper. The issue is that these estimates are paired with high levels of uncertainty. In order to understand the amounts in question, (and any potential variation between ecosystem conditions), it is necessary to gather a larger pool of data and analyze collectively. To achieve this, it will be helpful to aggregate data from all along the California coast.

This study will take six months for organizational development, building the information architecture and stakeholder meetings; two years for data collection; and a third year for data analysis and development of a certification framework for kelp-derived carbon stocks. The greatest portion of time for this study will be spent on working with stakeholders and making sure that data can be aggregated in a useable fashion in a manner that is convenient for participants. Building a common data format can be accomplished with several existing platforms. The most important factor is the ease of uploading data or the ability of the platform to interface with common data platforms used by researchers.

For this study, I conducted geospatial research to identify the most appropriate locations for research. The California coast is within the natural range of *Macrocystis pyrifera*, has a high density of sediment cores, and is the home to several ocean research institutions. This makes this coastline a great site for studying carbon export in kelp. There are high-quality data sets in existence and a large array of monitoring technologies already in use. In addition, there are several marine canyons and anoxic zones along the coastline, which each may play crucial roles in carbon sequestration from kelp forest ecosystems.

In order to understand the magnitude of potential contributions to carbon sequestration from kelp ecosystems, there are several additional questions that must be answered.

- How much carbon is sequestered in local sediments?
- How much carbon is sequestered in the deep ocean?
- What is the length of time that the carbon is sequestered for in each ecosystem?
- What carbon can potentially be sequestered in kelp mariculture?



The data for many of these analyses exists or can be collected through ongoing research on ecosystem health. For near-shore analyses, this study can build off of existing sediment cores and aggregate new data over time.

The overall challenge of this study is how to build frameworks to collect the data from a dispersed group of researchers along the coast of California. The goals of this project are to understand if kelp sequesters carbon on a time scale relevant to the blue carbon certification framework (100 years), and if so, how much is sequestered. There are several technological innovations that can help with answering this question, along with aiding in the establishment of monitoring protocols for kelp's carbon export.

Site selection for this project has been facilitated by geospatial analysis, visualized in Carto, QGIS, and ArcGis. This database shows high densities of sediment cores in southern California, with other clusters of high densities in the San Francisco bay area and around Monterey. In addition, this geodatabase includes data sets for bottom substrate type, kelp range, and ocean acidification. The study area is coastal California, within the Federal exclusive economic zone (EEZ). While the vast majority of study sites will be in near-shore coastal areas, the EEZ parameter is included in case there are offshore aquaculture projects included in the future. In addition, there may be deep-sea carbon sequestration that occurs a greater distance from shore.

It is necessary to gain concrete understanding of the mechanisms of carbon sequestration in kelp forests, and whether these effects are uniform. For this, we can draw upon existing research and build a common data infrastructure to gather sediment and ocean chemistry data. The goal is to combine existing databases with new measurements taken by researchers. In order to accomplish this for ocean sediment information, data will be pulled into a database (built off of the data sets in the existing geodatabase), and supplemented by periodic uploads and from the app, Kelp Me. The data that is sought for sediment cores is the following: the location of the sediment core, presence/absence of kelp, the chemical composition of the sediment (if available), depth of the core, the age of the sample, and any characteristics of the surrounding sediments. This information is requested in the Kelp Me app, and researchers are incentivized to participate through competition for the number of uploads attributed to their institution. These data sets will address questions around the local sediment burial portion.

Another important piece of the puzzle in nearshore areas is the burial of kelp under sediment through storm, current or other ocean processes. This question will be addressed through two mechanisms. The first piece is a citizen science project working with scuba divers and dive shops in coastal California to document and upload images of kelp buried in sediment falls through the app, Kelp Me. The second is to use the footage from ROV image databases such as the one managed by MBARI to document kelp burial in sediment in nearshore, canyon and deep-sea environments.

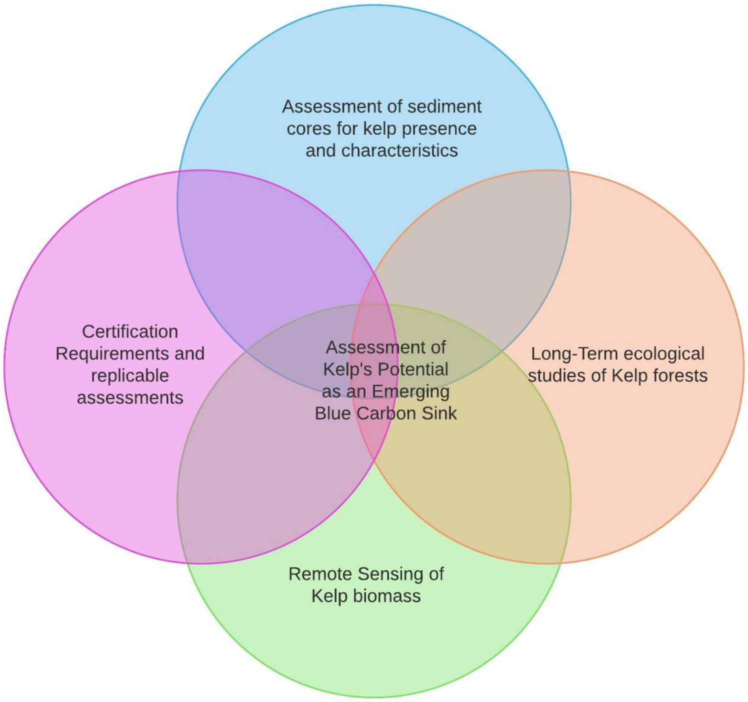


Figure 9. Diagram of data types required for this project.

Marine chemistry data will be pulled from the CalCofi and WOCE databases. This is most important at depth where particulate and dissolved organic carbon can be effectively sequestered in deep ocean currents because the overturning circulation is longer than the 100- year threshold for blue carbon certification.

It is important to conduct this research with a focus on the potential replicability and scalability of any certification processes built into its framework. To this end, this project will engage with practitioners as a working group in the first 6 months of this study while the data infrastructure is being built. It is crucial to build upon the experience of those who evaluate these types of carbon sinks so that the standards we hope to meet can be built into the experiments to evaluate kelp in this context. To this end, working groups will oversee the study throughout its data collection and analysis phases. This project will be managed under one principal investigator and project managers at each participating institution. The majority of the logistical organization can be conducted through appropriate technological apps but will require the participation of three working groups. The first working group is that of scientists working on the carbon export research to local sediment, and then to the deep sea circulation and sediment. The second is a working group with blue carbon credit evaluators to ensure that the data collection mechanisms are consistent with the needs of monitoring protocols. The third is a policy working group that can build out monitoring protocols for kelp as an emerging blue carbon source.

Next steps in this project include the following. First, identifying funding sources for this project. This will begin with posting the project on Kickstarter and crowd science, with funding goals of $150,000 for the first year of the project for salary support and building the data infrastructure. This will occur simultaneously with the search for a home institution and fiscal sponsor, ideally one of the major ocean science research institutions in southern California. This institution would provide meeting space, outreach support, scientific guidance, and collaboration with scientists and graduate students.

Another next step in the project is to formalize the citizen science project through partnerships with research institutions and nonprofits such as Reef Check California. This would provide access to a wider group of participants and enable the project to build upon best practices in citizen science research. A first meeting of partners and stakeholders would be held approximately 2 months into the project. At this meeting, the requirements for a common data infrastructure would be clarified, as well as a deeper discussion of challenges/opportunities of this the project. Upon finalization of the data and technological requirements, a hackathon will be held at 3 months into the project to build a mobile application for data uploads and an RFP would be released for the interactive geodatabase to be completed by 6 months into the project. At 6 months into the project, working groups would be established and meeting monthly, and the research methodologies drafted at 10 months into the project.

During the first year, funds will be raised to support doctoral researchers, travel, meeting expenses, and ongoing support for technological infrastructure. This support is likely to come from foundations, businesses, and academic institutions. It is the goal of this project to complete data synthesis and policy recommendations by the fifth year of the project, a goal that can only be reached through collaborative research and distributed teams working efficiently. That requires institutional support and effective communication practices.

This project presents an opportunity to gain greater understanding of the role of kelp in the global carbon cycle and the regulation of the impacts of anthropogenic emissions on our planet. It can build upon existing research and facilitate increasing cross-sectoral engagement between scientists, policy experts and the global carbon market. It presents an opportunity to merge entrepreneurial growth with innovative conservation financing mechanisms, whilst providing opportunities for coastal communities to invest directly in climate change mitigation in their own backyards.

References:

Agency, E. E. (2010). Marine ecosystems. *The Lancet*, 1–16. Retrieved from http://www.ciesin.columbia.edu/docs/005-390/005-390.html

Baldassare, M., Bonner, D., Kordus, D., & Lopes, L. (2017). PPIC STATEWIDE SURVEY Californians & the Environment. Retrieved from http://www.ppic.org/wp-content/uploads/s_717mbs.pdf

Bell, T. W., Cavanaugh, K. C., & Siegel, D. A. (2015). Remote monitoring of giant kelp biomass and physiological condition: An evaluation of the potential for the Hyperspectral Infrared Imager (HyspIRI) mission. https://doi.org/10.1016/j.rse.2015.05.003

Brothers, D. S., ten Brink, U. S., Andrews, B. D., Chaytor, J. D., & Twichell, D. C. (2013). Geomorphic process fingerprints in submarine canyons. *Marine Geology*, *337*, 53–66. https://doi.org/10.1016/j.margeo.2013.01.005

Cathy, & Lynne. (n.d.). 2016 National Park Visitor Spending Effects: Economic Contributions to Local Communities, States, and the Nation. Retrieved from https://www.nps.gov/nature/customcf/NPS_Data_Visualization/docs/2016_VSE.pdf

Chan, F, Boehm AB, Barth JA, Chornesky, EA, Dickson, AG, Feely, RA, Hales, B, Hill, TM, et al. (2016). The West Coast Ocean Acidification and Hypoxia Science Panel Table of Contents, (April).

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., … van den Belt, M. (1997). The value of the world's ecosystem services and natural capital. *Nature*, *387*(6630), 253–260. https://doi.org/10.1038/387253a0

Cummings, B. (2005). Ecosystems. Retrieved August 15, 2018, from https://slideplayer.com/slide/10753818/37/

De Leo, F. C., Smith, C. R., Rowden, A. A., Bowden, D. A., & Clark, M. R. (2010). Submarine canyons: hotspots of benthic biomass and productivity in the deep sea. *Proceedings. Biological Sciences*, *277*(1695), 2783–2792. https://doi.org/10.1098/rspb.2010.0462

EPA. (2016). Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866. Prepared by the Interagency Working Group on Social Cost of Carbon. Retrieved from https://19january2017snapshot.epa.gov/sites/production/files/2016-12/documents/sc_co2_tsd_august_2016.pdf

Filbee-Dexter, K. (2016). Regime Shifts in a Kelp Bed Ecosystem and Linkages With Deep-Living Sea Urchins, (July), 282. Retrieved from http://dalspace.library.dal.ca/handle/10222/72189

Food and Agriculture Organization of the United Nations. Fisheries and Aquaculture Department. (n.d.). *The state of world fisheries and aquaculture 2016 : contributing to food security and nutrition for all.* Retrieved from http://www.fao.org/documents/card/en/c/2c8bcf47-2214-4aeb-95b0-62ddef8a982a

Gaitán-Espitia, J. D., Hancock, J. R., Padilla-Gamiño, J. L., Rivest, E. B., Blanchette, C. A., Reed, D. C., & Hofmann, G. E. (2014). Interactive effects of elevated temperature and pCO2 on early-life-history stages of the giant kelp Macrocystis pyrifera. *Journal of Experimental Marine Biology and Ecology*, *457*, 51–58. https://doi.org/10.1016/J.JEMBE.2014.03.018

Graham, M. H., Kinlan, B. P., Druehl, L. D., Garske, L. E., & Banks, S. (2007). Deep-water kelp refugia as potential hotspots of tropical marine diversity and productivity. *Proceedings of the National Academy of Sciences of the United States of America*, *104*(42), 16576–16580.

https://doi.org/10.1073/pnas.0704778104
Hamel, P., & Bryant, B. P. (2015). Uncertainty assessment in ecosystem services analyses: Common challenges and practical responses. *Global Environmental Change*, 1–33. https://doi.org/10.1016/j.ecoser.2016.12.008
Howard, J., Sutton-Grier, A., Herr, D., Kleypas, J., Landis, E., Mcleod, E., … Simpson, S. (2017). Clarifying the role of coastal and marine systems in climate mitigation. *Frontiers in Ecology and the Environment*, *15*(1), 42–50. https://doi.org/10.1002/fee.1451
Krause-Jensen, D., & Duarte, C. M. (2016). Substantial role of macroalgae in marine carbon sequestration. *Nature Geoscience*, *9*(10), 737–742. https://doi.org/10.1038/ngeo2790
Krause-Jensen, D., Lavery, P., Serrano, O., Marbà, N., Masque, P., & Duarte, C. M. (2018). Sequestration of macroalgal carbon: the elephant in the Blue Carbon room. *Biology Letters*, *14*(6), 20180236. https://doi.org/10.1098/rsbl.2018.0236
Krumhansl, K. A., Okamoto, D. K., Rassweiler, A., Novak, M., Bolton, J. J., Cavanaugh, K. C., … Byrnes, J. E. K. (2016). Global patterns of kelp forest change over the past half-century. *Proceedings of the National Academy of Science*, *113*(48), 13785–13790. https://doi.org/10.1073/pnas.1606102113
Marzinelli, E. M., Williams, S. B., Babcock, R. C., Barrett, N. S., Johnson, C. R., Jordan, A., … Steinberg, P. D. (2015). Large-Scale Geographic Variation in Distribution and Abundance of Australian Deep-Water Kelp Forests. *PLOS ONE*, *10*(2), e0118390. https://doi.org/10.1371/journal.pone.0118390
NOAA, & NASA. (2013). *Sensing Our Planet: NASA Earth Science Research Features 2013*. Retrieved from https://cdn.earthdata.nasa.gov/conduit/upload/1046/NASA_Sensing_Our_Planet_2013.pdf
Pickard, G. L., & Emery, W. J. (2013). *Descriptive Physical Oceanography : an Introduction.* Elsevier Science. Retrieved from https://books.google.com/books?hl=en&lr=&id=E0SPDAAAQBAJ&oi=fnd&pg=PP1&dq=physical+oceanography+textbook&ots=TTibFPp1Rn&sig=-I-deU-V_ZReQ3oUDOM8NAjr5zY#v=onepage&q=physical oceanography textbook&f=false
Provost, E. J., Kelaher, B. P., Dworjanyn, S. A., Russell, B. D., Connell, S. D., Ghedini, G., … Coleman, M. A. (2017). Climate-driven disparities among ecological interactions threaten kelp forest persistence. *Global Change Biology*, *23*(1), 353–361. https://doi.org/10.1111/gcb.13414
Ramírez-Valdez, A., Aburto-Oropeza, A., & Arafeh Dalmau, O. (2017). UC Office of the President Working Papers Title Mexico-California Bi-National Initiative of Kelp Forest Ecosystems and Fisheries. Retrieved from https://cloudfront.escholarship.org/dist/prd/content/qt8sp8j4xs/qt8sp8j4xs.pdf
Reed, D. C., Rassweiler, A., & Arkema, K. K. (2008). Biomass rather than growth rate determines variation in net primary production by giant kelp. *Ecology*, *89*(9), 2493–2505. https://doi.org/10.1890/07-1106.1
Renshaw, A., Houskeeper, H. F., & Kudela, R. M. (2017). Landsat satellite evidence of the decline of northern California bull kelp. *American Geophysical Union, Fall Meeting 2017, Abstract #GC23B-1065*. Retrieved from http://adsabs.harvard.edu/abs/2017AGUFMGC23B1065R
Rodgers, K. L., & Shears, N. T. (2016). Modelling kelp forest primary production using in situ photosynthesis, biomass and light measurements. *Marine Ecology Progress Series*, *553*, 67–79. https://doi.org/10.3354/meps11801

Schiel, D. R., & Foster, M. S. (2015). *The Biology and Ecology of Giant Kelp Forests*. https://doi.org/10.1525/california/9780520278868.001.0001
Schlining, B. M. and N. J. S. (2006). No Title. In *MBARI's video annotation and reference system. Proceedings of the Marine Technology Society/Institute of Electrical and Electronics Engineers Oceans Conference, Boston, MA*.
Seymour, R. J., Tegner, M. J., Dayton, P. K., & Parnell, P. E. (1989). Storm wave induced mortality of giant kelp, Macrocystis pyrifera, in Southern California. *Estuarine, Coastal and Shelf Science*, *28*, 277–292. https://doi.org/10.1016/0272-7714(89)90018-8
Steneck, R. S., Graham, M. H., Bourque, B. J., Corbett, D., Erlandson, J. M., Estes, J. A., & Tegner, M. J. (2002, December 19). Kelp forest ecosystems: Biodiversity, stability, resilience and future. *Environmental Conservation*. https://doi.org/10.1017/S0376892902000322
Sumner, E. J., & Paull, C. K. (2014). Swept away by a turbidity current in Mendocino submarine canyon, California. *Geophysical Research Letters*, *41*(21), 7611–7618. https://doi.org/10.1002/2014GL061863
Takahashi, T., Sutherland, S. C., Wanninkhof, R., Sweeney, C., Feely, R. A., Chipman, D. W., … de Baar, H. J. W. (2009). Climatological mean and decadal change in surface ocean pCO2, and net sea-air CO2flux over the global oceans. *Deep-Sea Research Part II: Topical Studies in Oceanography*, *56*(8–10), 554–577. https://doi.org/10.1016/j.dsr2.2008.12.009
Trevathan-Tackett, S. M., Kelleway, J., Macreadie, P. I., Beardall, J., Ralph, P., & Bellgrove, A. (2015). Comparison of marine macrophytes for their contributions to blue carbon sequestration. *Ecology*, *96*(11), 3043–3057. https://doi.org/10.1890/15-0149.1.sm
Weatherdon, L. V., Magnan, A. K., Rogers, A. D., Sumaila, U. R., & Cheung, W. W. L. (2016). Observed and Projected Impacts of Climate Change on Marine Fisheries, Aquaculture, Coastal Tourism, and Human Health: An Update. *Frontiers in Marine Science*, *3*, 48. https://doi.org/10.3389/fmars.2016.00048

Data References:

Bell, T. W.; Cavanaugh, K. C.; Siegel, D. A. 2017. SBC LTER: Time series of quarterly NetCDF files of kelp biomass in the canopy from Landsat 5, 7 and 8, 1984 - 2016 (ongoing). Environmental Data Initiative. http://dx.doi.org/10.6073/pasta/817d2c24ebd78621869e17d94ba0df0c.
Curators of Marine and Lacustrine Geological Samples Consortium: Index to Marine and Lacustrine Geological Samples (IMLGS). NOAA National Centers for Environmental Information. doi:10.7289/V5H41PB8 [March 2, 2018]. Natural Earth download for state political boundaries.
Diaz, R., M. Selman. and C. Chique. 2011. Global Eutrophic and Hypoxic Coastal Systems. World Resources Institute. Eutrophication and Hypoxia: Nutrient Pollution in Coastal Waters. docs.wri.org/wri_eutrophic_hypoxic_dataset_2011-03.xls
GBIF.org (12 June 2018) GBIF Occurrence Download https://doi.org/10.15468/dl.knysyg
Hoekstra, J. M., J. L. Molnar, M. Jennings, C. Revenga, M. D. Spalding, T. M. Boucher, J. C. Robertson, T. J. Heibel, with K. Ellison. 2010. The Atlas of Global Conservation: Changes, Challenges, and Opportunities to Make a Difference. Ed. J. L. Molnar. Berkeley: University of California Press.

National Oceanic and Atmospheric Administration (NOAA). Economics: National Ocean Watch (ENOW) Data. Based on data from the Bureau of Labor Statistics and the Bureau of Economic Analysis. Charleston, SC: NOAA Office for Coastal Management.

National Oceanic and Atmospheric Administration (NOAA) Marine Protected Areas Center (MPA Center), NOAA Office for Coastal Management (OCM). Marine Cadastre/ Ocean Uses California data set. https://coast.noaa.gov/arcgis/rest/services/MarineCadastre/OceanUsesCalifornia/MapServer

Rosenthal, I. S., Byrnes, J. E., Cavanaugh, K. C., Bell, T. W., Harder, B., Haupt, A. J., ... & Boyer, A. (2018). Floating Forests: Quantitative Validation of Citizen Science Data Generated from Consensus Classifications. arXiv preprint arXiv:1801.08522.