Title Page

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ABSTRACT

Project Title: *Kelp forests: their dynamics, services, and fate in a changing climate*
Competition: NOAA-COCA, NOAA-OAR-CPO-2016-2004413

Kelp forests are key natural features worldwide that have significant ecosystem effects on the chemistry, biology and physical features of the coastal zone. Though carbon and nitrogen uptake by kelp forests could ameliorate increasing anthropogenic levels of both, we know little about climate drivers of kelp abundance and the function of kelp *in situ*. Our research plan has three objectives:

I. Characterize the dynamics of kelp forests in coastal Washington State, including correlates with key ocean climate drivers such as the Pacific Decadal Oscillation, North Pacific Gyre Oscillation, sea surface temperature, and upwelling,
II. Describe the ecosystem services that kelp forests provide including habitat for living marine resources, users of blue carbon, sites of nutrient uptake and recycling, and producers at the base of the food web
III. Use our understanding from I. and II. to make predictions about the future fate of kelp forests, recognizing that kelp fitness is a generally a positive function of upwelled nutrients, and a negative function of seawater temperature.

Our proposed research will leverage long-term aerial surveys of canopy kelp abundance over hundreds of kilometers with multiple climate indicators. We will couple this large-scale investigation of dynamics to *in situ* fieldwork to determine key *functional* aspects of kelp forests. We will target 2 regions of the Washington state coastline to query function using methodologies that indicate carbon and nitrogen dynamics. Our sampling will test the extent to which kelp forests remove CO_2, increase pH, and potentially serve as an ocean acidification refuge for calcifying species. We will further quantify nitrogen uptake and recycling within the kelp bed.

Relevance to NOAA's Climate Goals. Although we have an understanding of the role that marine macrophytes play in habitat provisioning for multiple taxa in coastal marine areas, the role of these natural features on the carbon and nitrogen cycle remains little understood, even as these ocean cycles are increasingly anthropogenically impacted. Our proposed work plan will target kelp forest effects on carbon and nitrogen, while determining how the dynamics of these iconic species are tied to climate. Our multi-scaled research project will:

1. Directly inform the vegetation-based remediation systems for ocean acidification that the Washington Department of Natural Resources is testing.
2. Indicate the environmental data that provide explanatory power for kelp forest dynamics.
3. Further, the NOAA Marine Sanctuary Program's mission to maintain the ecological integrity of coastal systems and anticipate climate-related changes within its waters will be supported directly by the results of our findings.

Our partnership will result in a number of communication-related activities targeted to local, state, tribal, and federal agencies in Washington State, and addressing the linkage between kelp dynamics and function and ocean climate.

STATEMENT OF WORK

Identification of the Problem

Kelp forests are key natural features worldwide that have significant ecosystem effects on the chemistry, biology and physical features of the coastal zone. Kelp growth rates can exceed that of crop plants (Mann 1973), making them critical primary producers in the coastal ocean. In the northeast Pacific Ocean, canopy kelp show metabolic activities that result in the fixation of 1.3 kg of carbon and incorporation of up to 65 g of nitrogen annually per m^2 of ocean bottom (Wheeler & Druehl 1986). The multilayered use of the water column results in a leaf area index (for a single species) that matches that of multispecies plant assemblages in rain forests (Wheeler & Druehl 1986). Kelp forests also modify the physical environment, ameliorating wave energy and providing refugia from waves and currents for the hundreds of mobile species that live within them. Kelp forests provide critical habitat for a taxonomically diverse array of species. They host unique microbes (Michelou et al. 2013), invertebrates (Harvell 1984) and fish eggs on their fronds, while providing critical coastal habitat for myriad species (Estes & Palmisano 1974, Leaman 1980, Bodkin 1988). Indigenous Americans have utilized kelp for food and tools for millennia (Croes 1995), and the 'kelp highway', with its rich diversity of species likely facilitated colonization of the Americas by maritime hunter-gatherers (Erlandson et al. 2007). It is thus imperative that we *understand the dynamics, services and fate of kelp forests in a changing climate*.

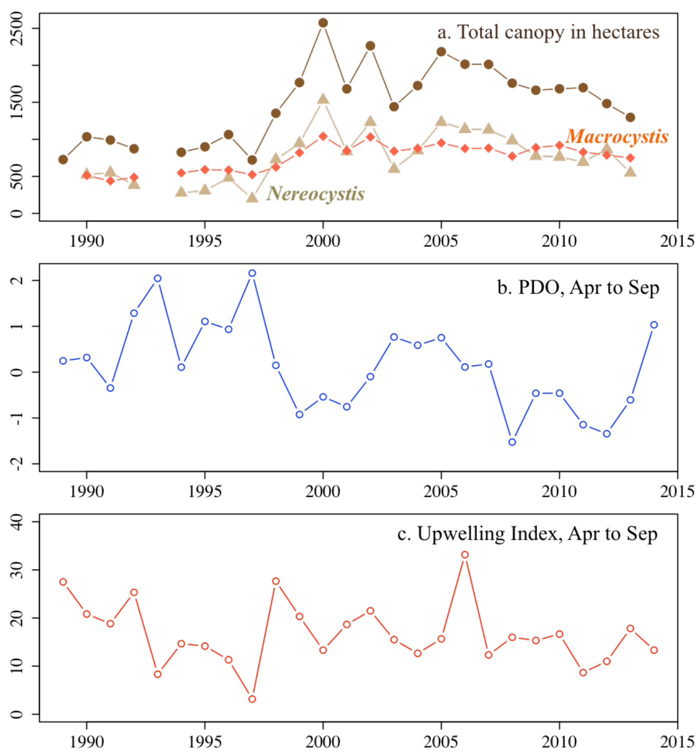

Figure 1. Kelp abundance and climate variables. The abundance (in hectares, a.) of the kelp canopy in Washington state since 1989. The PDO (b.) averaged over Apr to Sep in each year, a climate variable that negatively correlates with kelp abundance (r=-0.445, p=0.029), while the averaged Upwelling index (c) shows no correlation.

As coastal environments change globally, the macrophyte assemblages within them may play an increasingly important role for the viability of marine populations. Ocean acidification, the change to the seawater carbonate system that occurs with increased atmospheric carbon dioxide, is a threat to calcifying species globally (Orr et al. 2005), with demonstrated low pH and saturation states for calcifiers throughout the North Pacific (Wootton et al. 2008, Feely et al. 2008). Through diel cycles of carbon uptake, kelp forests can elevate pH locally during daylight hours (Hofmann et al 2011, Wootton & Pfister 2012, Frieder et al. 2012, Krause-Jensen et al. 2015) and thus may provide refugia for calcifiers from ocean acidification as has been shown with seagrass (Semesi et al. 2009). Indeed, estimates of kelp forest metabolism in Alaska with sea otters present result in Teragram quantities of carbon storage annually, an economic valuation in 100's of millions of dollars (Wilmers et al. 2012). Similarly, the large quantities of nitrogen that are utilized by kelp forests may make them a component of coastal resilience to anthropogenic nitrogen inputs. *Though a natural feature of shoreline ecosystems worldwide, there is relatively little known about the diverse aspects of ecosystem function provided by kelp.*

A critical concern is how the abundance and function of kelp forests will be altered by global change. There are many aspects of kelp biology that suggest they may be increasingly vulnerable to anthropogenic changes in the coastal ocean (Schiel & Foster 2015). Though kelp forests utilize large amounts of nitrogen, nitrogen pollution could be detrimental if they favor phytoplankton blooms that shade kelp. Warmer seawater temperatures are known to be harmful to kelp forests, as are periods of reduced upwelling and greater storm activity associated with ENSO events (Dayton 1985, Tegner & Dayton 1987, 1991). Further, any anthropogenic activities that increase water column turbidity, including sewage runoff and coastal erosion, threaten the viability of kelp forests.

In Washington State, the conspicuous algae along the shores are composed of two species *Nereocystis luetkeana* and *Macrocystis pyrifera* (henceforth *Nereocystis* and *Macrocystis*) which currently cover a ribbon of approximately 850 hectares along Washington's shores (Figure 1a). The two species sometimes co-occur or form monospecific stands. We use *Macrocystis pyrifera* synonymously with *M. integrifolia*, based on work that suggests the two 'species' represent a monospecific genus due to plasticity (Demes et al 2009). *Macrocystis* and *Nereocystis* differ in their life history with *Macrocystis* outliving the usually annual *Nereocystis*. In British Columbia, *Macrocystis* can live 4-8 years (Lobban 1978), and typically live 2-3 years (Druehl & Wheeler 1986). *Nereocystis* is also thought to better tolerate high wave action sites, while the positioning of its reproductive tissue (sporophylls) on the surface may increase vulnerability to oil spill pollution (Antrim et al. 1995). Both species of canopy kelp are the base of a well-characterized food chain where sea otters prey on the herbivorous sea urchins, thus allowing kelp to thrive (Estes & Palmisano 1974).

The large-scale patterns of the kelp canopy in Washington state has been followed through aerial surveys conducted annually by the Department of Natural Resources (DNR) since 1989 (Fig 1a), and the two species have demonstrated variability in both space and time. Kelp abundance in the past has been as much as 3 times the current aerial extent (Fig 1a). Tracking the aerial extent of the kelp has revealed dynamic behavior with relationships to climate drivers. Low kelp abundance corresponded with the 1997-1998 ENSO event, while relatively high abundances during negative periods of the Pacific Decadal Oscillation (PDO), a pattern echoed in other benthic kelp populations (Pfister & Wang 2005). NOAA is predicting strong El Nino conditions in 2015-2016 that could surpass the 1997-1998 event representing an important opportunity to determine influence on kelp distributions.

The importance of kelp as a natural resource is the motivation behind the Washington DNR's characterization of the patterns of kelp abundance. Kelp dynamics, their drivers (particularly climate), and the prognosis for kelp populations into the future are key goals for the DNR. For these reasons, the DNR is committed to continued canopy kelp quantification over the entire shoreline. As the state steward for 2.6 million acres of aquatic lands, DNR manages the majority of Washington State's intertidal and subtidal areas and their attached resources, including kelp, eelgrass and shellfish (http://www.dnr.wa.gov/programs-and-services/aquatics). Due to the profound threat that ocean acidification poses to the resources that DNR manages, The Commissioner of Public Lands Peter Goldmark has directed DNR to play an instrumental role in efforts to understand and respond to rising ocean acidity; a Letter of Support from DNR is attached. In 2012, a Blue Ribbon Panel of scientists and decision-makers, including DNR's Commissioner, defined Washington State's strategic response to ocean acidification (https://fortress.wa.gov/ecy/publications/publications/1201015.pdf). DNR is leading actions to develop vegetation-based remediation systems (Action 6.1.1), preserve and restore kelp and seagrass in order to naturally buffer against acidification (Action 6.3.1), and identify refugia (Action 6.3.2). DNR's field research efforts to date have focused on the role of *Zostera marina* on carbonate chemistry, as potential refugia for commercial shellfish, which commonly occur in soft sediment environments. Work proposed here would provide foundational input to DNR on the role of kelp in the identified strategic actions. In addition to DNR's strategic actions, DNR manages uses on state-owned lands. Protection of native vegetation is a primary concern, and is a centerpiece of a draft Habitat Conservation Plan that the agency is considering to guide management (http://www.dnr.wa.gov/programs-and-services/aquatics/aquatic-lands-habitat-conservation-plan).

Similarly, NOAA's Olympic Coast National Marine Sanctuary (OCNMS) has a broad mission to understand and protect the area's ecological integrity in their Management Plan and to anticipate climate-related changes within the OCNMS (e.g. Miller 2013) and see attached Letter of Support from Kevin Grant, Deputy Superintendent of OCNMS. Due to the dominance of exposed rocky coastline, the critical importance of kelp habitat to OCNMS further derives from a lack of functional estuarine habitat, meaning that fishes such as salmon rely on kelp canopy as nursery habitat. Furthermore, both the DNR and OCNMS Management Plan calls for assessment of natural and human-caused threats to kelp habitats and function, identifying indicator stressors, and developing management measures to conserve these habitats and functions. Interest in kelp is also widespread among the general public; citizen-science efforts have been initiated to monitor kelp canopies by kayak and plant kelp for restoration through a grass roots effort in Washington and British Columbia known as the Salish Sea International Kelp Alliance (http://www.nwstraits.org/our-work/kelp-recovery/). Global inventories of giant kelp from satellite data, with citizen science help are also underway (www.floatingforests.org).

Our goal is to understand how kelp forests provide ecosystem services, particularly those that ameliorate climate change impacts, and how kelp respond to climate drivers. We have thus forged a collaboration between biogeochemists and ecologists from academia, and state (Washington State DNR), and federal managers (NOAA National Marine Sanctuaries).

__Scientific Objectives__

I. Characterize the dynamics of kelp forests in coastal Washington State, including correlates with key ocean climate drivers such as the Pacific Decadal Oscillation, North Pacific Gyre Oscillation, Oceanic Niño Index, sea surface temperature, and upwelling.
II. Describe the ecosystem services that kelp forests provide including habitat for living marine resources, users of blue carbon, sites of nutrient uptake and recycling, and producers at the base of the food web.

III. Use our understanding from I. and II. above to make predictions about the future fate of kelp forests, recognizing that kelp fitness is a generally a positive function of upwelled nutrients, a negative function of seawater temperature, and possibly stimulated by ocean acidification.

PROPOSED METHODOLOGY

I. What are the links between the dynamics of kelp forests and climate drivers in coastal Washington State?

Analysis of aerial surveys so far has focused on determining changes in kelp abundance and distribution. While fluctuating overall areal cover, as well as both stasis and flux of the two species individually are evident (Figure 1a), their causes remain an open and important question that seek to address: Are there key factors that underlie these dynamics? For example, the annual kelp *Nereocystis luetkeana* may recover more quickly following high wave events, while *Macrocystis pyrifera* lives longer – up to 2 to 3 years compared to *Nereocystis*. We will utilize the DNR data to understand if the abundance of each species correlates with indicators of local conditions and broader oceanographic climate drivers. Next, we review the methodology for the aerial surveys and how we intend to examine environmental correlates over multiple scales.

Ongoing methodology for aerial kelp surveys.
The Washington Dept. of Natural Resources has monitored floating kelp canopies using aerial photography since 1989 along the Strait of Juan de Fuca and Pacific Ocean coast. Floating canopies of *Nereocystis* and *Macrocystis* have been mapped annually between 1989 and 2014 (except 1993) using standardized aerial photography collection and geoprocessing methods. For greatest comparability across years, methods were generally held consistent, except for upgraded computer processing tools and replacement of film-based imagery with digital technology in 2009 when color-infrared film became unavailable. Canopies are hand-delineated onto 1:12,000 base maps based on low-tide, near-vertical aerial photography collected in late summer during optimum environmental conditions. Species composition is determined using additional low-altitude flights; monotypic beds are identified and the composition of mixed beds are estimated in 10% increments. Delineated paper maps are scanned at 100 dots/inch using a Microtek 9600 XL flat-bed image scanner. Area values are calculated from the scanned images using Global Lab Image (v3.1). For comparison to historical kelp bed maps, which delineated a planimeter encompassing nearby plants, canopies are joined into beds using a 25-meter radius of association between plants within each species class.

Proposed methodology for linking aerial abundance estimates with environmental variables.
Kelp abundance can be influenced locally by waves (Reed et al. 2011, Cavanaugh et al. 2011), grazers (Estes & Palmisano 1974, Dayton 1985, Pérez-Matus & Shima 2010), as well as by larger-scale ocean climate including sea surface temperature and nutrient-provisioning via upwelling (Dayton 1985, Cavanaugh et al. 2011). We will test whether the abundance of *Nereocystis*, *Macrocystis*, or both correlate with:

a. Sea surface temperature. We will obtain sea surface temperature (SST) records from 3 NOAA shore sources as well as 2 NOAA buoys (http://www.ndbc.noaa.gov/), including:
   (1). Port Angeles, WA; Neah Bay, WA; La Push, WA (tidesandcurrents.noaa.gov)
   (2). The Cape Elizabeth buoy (#46041)

(3). The Neah Bay buoy (#46087, since 2004)

b. Wave height data from Cape Elizabeth buoy and Neah Bay buoy

c. Upwelling Index for 48 deg N latitude (http://www.pfeg.noaa.gov/)

d. The Pacific Decadal Oscillation (PDO)(http://research.jisao.washington.edu/pdo/)

e. The North Pacific Gyre (NPGO) (http://www.o3d.org/npgo/)

f. The Oceanic Nino Index (ONI) (http://www.cpc.ncep.noaa.gov/)

The above variables are those related to local conditions and general ocean climate that are particularly relevant; the location of some of these is shown in Figure 2. Sea surface temperature and wave height are obvious local data that have had explanatory power in previous studies of macrophytes. Larger scale ocean condition indices include the Upwelling Index, estimated from atmospheric pressure fields for particular latitudes and an index of whether there is net upwelling or downwelling. The PDO was suggested initially by patterns in biological data (Mantua et al. 1997, Francis et al. 1998) and is a composite of sea surface temperature variability with a cycle that may be 15-25 years. Positive PDOs are associated with warmer water in the northeast Pacific; negative PDOs with cooler water. The NPGO is nearly anticorrelated with the PDO and is based on variability in sea surface height. Finally, the Oceanic Nino Index (ONI) is a 3 month average of sea surface temperature anomalies.

We will correlate these variables as predictor variables – e.g. is the SST in the fall/winter preceding the kelp abundance metric a significant predictor versus the contemporaneous measure? We will also ask if there are cycles in kelp data that have explanations via temperature or climate records. Although there are no nutrient databases that extend back to 1989, Pfister and colleagues, working at Tatoosh Island, WA, have macronutrient data (nitrate, nitrite, ammonium, phosphate, silica) from 1999 onward (Wootton & Pfister 2012), and we will use those data to examine nutrient correlates.

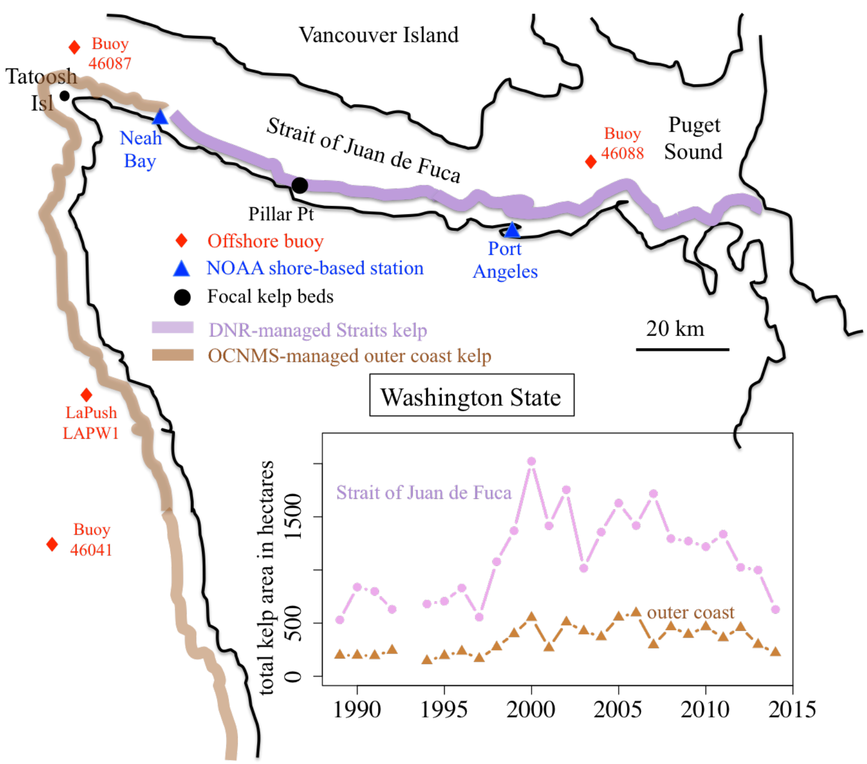

Figure 2. The long-term kelp monitoring study area in Washington State, the principal managers, the location of environmental data sources, and the proposed focal study sites. Inset: Kelp canopy dynamics along the outer coasts versus in the Strait of Juan de Fuca.

Because increasing nitrate concentrations are correlated with lower SST at Tatoosh Island (Pfister et al. 2007) and other locales (Parnell et al. 2010), we can also use SST as a proxy for oceanic nutrient supply. We note that kelp abundance differs regionally in the state (Figure 2, inset) and will also probe these spatial differences.

Statistical approaches for these queries will recognize the correlated nature of the data. We will use regressive and autoregressive models (see Pfister et al. 2007, Wootton & Pfister 2012), and ARMA (autoregressive moving average) models in Ives et al. (2010), including those with lagged responses (ACF) to ask if kelp responses to climate are delayed by a year or more. We propose to test the following hypotheses:

H1. Canopy kelp cover in aerial surveys is correlated with ocean condition indices such as the PDO.

H2. The relationship between canopy kelp cover and ocean indices is stronger toward the open coastal areas where landward and anthropogenic influences decrease.

H3. Both species respond similarly to climate and ocean parameters.

Interpretation and Significance

Though we recognize that this section of the proposed research is highly correlative, it will leverage a significant database curated by the Washington DNR and will lay the groundwork for understanding climate linkages to kelp forests. From these analyses among kelp extent local variables and regional variables, we will provide insight into 1. the scale of influence on kelp dynamics, and 2. predictions about kelp forests into the future. Both are key objectives for the DNR and OCNMS. Ocean climate indices have varied greatly since kelp surveys began in 1989 and include periods of a positive and negative PDO and an ENSO event. We thus expect that our statistical queries will be informative. Because there are predictions of changing ocean conditions for the northeast Pacific, including increased wave intensity (Seymour 2011), and increased frequency of ENSO events (Timmerman et al. 1999, Cai et al. 2014), our understanding of linkages can give us predictive power. We recognize both the constraints and the benefits of using climate indices (Stenseth et al. 2003), but note the evidence for a key role for climate in driving *Macrocystis* populations in California (Parnell et al. 2010, Cavanaugh et al. 2011), including competitive interactions among kelp species (Dayton et al. 1999).

We also recognize that kelp forests are linked to the abundance of top predators, particularly sea otters (*Enhydra lutra*) in the northeast Pacific (Estes & Palmisano 1974) and the role of sea otters in Washington state are that of a keystone predator (Kvitek et al. 1988, 1989). Sea otters in Washington State have been censused for the entire duration spanning aerial kelp surveys allowing us to explore the role sea otters have in kelp dynamics. Sea otter numbers have been increasing steadily at a rate 7.6% since 1989 (Jeffries & Jameson 2014), though different regions of the state show different growth rates in recent years, with southern outer coast populations growing as much as 11% and those in the northern segment and into the Strait of Juan de Fuca growing at 3.5%. Although kelp areal coverage initially increased with sea otter abundance, as would be expected with a keystone predator (Laidre & Jameson 2006), kelp have fluctuated since. Importantly, east of Pillar Point in areas where sea otters are relatively rare, kelp still increased over the same interval and kelp populations continue to show some variability that may be unrelated to sea otters, and perhaps related to sea urchin harvest (Pfister & Bradbury 1996). Further, the 2 species of kelp have different patterns of variability. We can treat these underlying sea otter trends as a covariate in our exploration of climate trends, first factoring out the positive role of a sea otter trend on kelp dynamics, then testing for an effect of climate (e.g. Parmesan et al. 2013). Alternatively, we can incorporate climate effects directly into model parameterization (e.g. Stenseth et al. 2015). Both approaches have merit and will provide insight into climate versus species interactions.

The independent fluctuations seen between *Macrocystis* and *Nereocystis* (Figure 1) suggest the species respond differently to environmental variables or that they interact negatively. We will test these hypotheses using the available data. *Macrocystis* productivity declines and mortality increases with increasing wave action in California (Reed et al. 2011, Cavanaugh et al. 2011) and we can test whether *Nereocystis* benefits from higher wave energy by testing for correlations with maximum wave height buoy data and kelp abundance. Fluctuations between the 2 kelp species and climate can be modeled by considering density-dependent versus density-independent interactions, as has been done for bird time series data in Europe (Stenseth et al. 2015). We recognize that interactions may be non-stationary (e.g. change through time) and may intensify when nutrients are abundant (Dayton et al. 1999).

II. What are the ecosystem services associated with kelp forests?

A. What are the effects of the kelp forest on the carbon cycle?

Based on the estimates of current plant coverage and the carbon uptake of *Macrocystis* (Wheeler & Druehl 1986), kelp forests may account for in excess of 1 million Kg of C every year, thus contributing to 'blue carbon' (Duarte et al. 2005, McLeod et al. 2011). Marine macrophytes, including seagrasses and kelp, are increasingly recognized as an important determinant of surrounding seawater chemistry (Krause-Jensen et al. 2015). For example, calcifying species can benefit in proximity to seagrasses (Beer et al. 2014). Due to strong diel cycles in productivity and respiration, pH fluctuations in coastal areas can be great over the scale of hours (Wootton et al. 2008); algae have carbon concentrating mechanisms to utilize bicarbonate and elevate pH (Stepien et al. in review). In *Macrocystis* beds in other locales, diurnal pCO_2 differences were 270 µatm (DeLille 2009), and diurnal pH differences were as much as 0.36 pH units (Frieder et al. 2012). While we recognize that much kelp carbon enters the detrital food web, participates in respiration, and thus may not be a net sink for carbon (Duggins et al. 1989, Krumhansl et al. 2014), we are interested in quantifying the local carbonate environment that kelp modify for calcifying species. The DNR aerial data indicate abundance and dynamics. We propose to augment this existing science by testing the hypothesis:

> *H4.* During daylight hours, kelp forests serve as pH refugia for calcifiers by locally raising the pH.

Research Plan.

Kelp canopies span a large geographic area and encompass great environmental variation. We propose to test how kelp beds interact with the seawater carbonate system at locales inside and outside the kelp bed at 2 different sites. The 2 sites will include: 1. A site within the Strait of Juan de Fuca characterized by a persistent kelp bed (Pillar Point) and 2. A site in the outer coastal waters and within the OCNMS. The OCNMS site will be in the vicinity of Tatoosh Island, where Pfister and colleagues have maintained a long-term ecological research program. These 2 sites allow us to look at a higher energy outer coast site (Tatoosh Island) and a site representative of the ~250 km of shoreline along the Strait of Juan de Fuca since monitoring began, areas where kelp abundance dynamics have differed (Figure 2, inset). At each site, we will sample a number of carbon chemistry parameters via boat and within the middle of the kelp forest and 20 m outside of the kelp forest. Our sampling will include:

(1). pH, DO, temperature, salinity via instrumentation (SeapHOx™).

(2). Total alkalinity (TA), spectrophotometric pH, DIC, $\delta^{13}C_{DIC}$ and chl *a* via single, bottled-collected samples replicated 4 times in both inside and outside locales, at both sites, during midday when photosynthesis is at a maximum.

(3) Macronutrients, Dissolved organic carbon (DOC), Particulate organic matter (POM) via single, bottled-collected samples replicated 4 times inside and outside locales, during midday when photosynthesis is a maximum.

(4) $\delta^{13}C$ of kelp tissue, collected among 6 plants at each site. The meristematic region of the blade containing the youngest tissue will be targeted.

The combination of instrumental and bottle collected samples will allow us to do frequent measurements for some variables, while more expensive seawater sample collections will be less frequent (those in (2) and (4)). The seawater carbonate system is described by 4 key variables: pH, TA, pCO_2, and DIC. Generally, when 2 are measured the remaining 2 can be estimated because of the known relationships among these variables in seawater (Emerson & Hedges 2008). However, our specific interest in kelp effects on TA and pH, and the recognition that upwelling systems are recognized to have variable carbonate dynamics that are poorly understood (Reum et al 2015), motivates us to 'overparameterize' the carbonate system. Simultaneously, we recognize that some of these measurements are expensive and will pair occasional sampling of DIC to check our instrumental measures. More specific methodology follows.

Instrumental measures. At each locale, we will collect continuous data on water temperature, pH, dissolved oxygen, salinity, using a submersible SeapHOx™ (www.seabird.com/seaphox) for a period of 3 hours at a time. The SeapHOx™ is a relatively new instrument designed to provide greater accuracy in pH measurements and has become adopted by ocean acidification research. Although we would like to have a sufficient number of instruments to have a network of temporary moorings, it is outside the financial scope of this grant, and the company does not lease instrumentation. We thus propose to buy a single instrument and use it opportunistically among all sampling sites. A further advantage of the SeapHOx instrument is that we can directly compare with other monitoring programs in the California Current system which use SeapHet and SeapHOx instrumentation (Hoffman et al. 2011, Bresnahan et al. 2014). We will augment this SeapHOx sampling with some equipment we already have (Hydrolab MS5 (www.ott.com*)* and a CTD plus O_2 data logger (YSI 600 OMS; https://www.ysi.com/600OMS-V2). We will also opportunistically use temporary moorings to deploy the SeapHOx for several days. Frequent calibration will be done using NBS pH standards, and the saturated air method for DO. The net result will be a number of paired samplings to compare and contrast environmental variables inside and outside the kelp forest.

Seawater collection. We will supplement the automated data collection with water sampling analysis on 4 samples with an hourly sampling interval. These water samples will be analyzed in the lab for pH using spectrophotometric methods with water-soluble m-Cresol Purple indicator dye (Spectrum Chemicals), total alkalinity (Apollo SciTech AS-Alk2 SeaWATER gran titration with 0.1 N HCl at 25ºC), DIC carbon and seawater oxygen isotope compositions ($\delta^{13}C_{DIC}$ and $\delta^{18}0_W$, and exploratory ($\delta^{13}C_{DOC}$ in Colman Lab), nutrient content ([PO_4], [$Si(OH)_4$], [NH_4^+],

[NO_2^-], [NO_3^{2-}], and DOC; University of Washington Marine Chemistry Lab). Analysis of spectrophotometric pH and TA will be checked with standards made by the A. Dickson CDQC Laboratory at Scripps Institute of Oceanography. These samples will be used both to check field measurements of pH, and to provide information on the dynamics of potential drivers of variation in Total Alkalinity. We also collect 8 samples every year, fix them with mercuric chloride, and send them to the CDQC lab for analysis of TA, salinity, and DIC. These analyses serve as a further check on field probes for salinity and pH, and on our lab analyses of pH and TA. These fixed samples are infrequent because they are expensive ($125.00 each at CDQC).

Interpretation and Significance
The importance of 'blue carbon' necessitates improving our understanding of the role that marine macrophytes play in the coastal carbonate cycle (Harley et al. 2012). Coastal Washington waters have demonstrated a decline in pH (Wootton et al. 2008, Wootton & Pfister 2012) and pH and aragonite saturation states have been shown to already reach levels that were not expected for decades into the future (Feely et al. 2010). Oyster growers and the aquaculture industry has been negatively affected and the Washington State Blue Ribbon Task Force was a response to these problematic trends (https://fortress.wa.gov/ecy/publications/SummaryPages/1201015.html).

Our proposed research will establish the nature of pH fluctuations in association with kelp forests, and the likelihood that kelp forests can ameliorate the future pH environment for associated calcifying species. Our goal is an integrated understanding of how kelp forests will affect the seawater chemistry and if these areas serve as refugia for calcifiers.

(B) What are the effects of the kelp forest on nitrogen cycling and retention?

In addition to likely strong feedbacks in the carbon cycle, kelp also utilize great quantities of nitrogen with estimates of 65 g for each m^2 of *Macrocystis* in British Columbia (Wheeler & Druehl 1986). Thus, not only are kelp forests a key player in the coastal nitrogen cycle, but they likely ameliorate anthropogenic nitrogen inputs. Given the known area of kelp forests in 2014, and assuming a nitrogen content for both species in accord with Wheeler & Druehl (1986), 552,500 kg of nitrogen are contained within kelp tissue every year. This is likely an underestimate given the fluxes of nitrogen through algae. Also, as its carbon to nitrogen ratio varies narrowly, kelp nitrogen utilization is an important control of the carbon dynamics discussed above. Thus, macrophytes such as kelp forests likely serve as natural features that ameliorate nitrogen pulses.

We propose comparative sampling in and outside of kelp forests (as described above) to test specific hypotheses about the role of kelp forests in the coastal nitrogen cycle. Kelp utilize both ammonium and nitrate. Most nitrate is sourced from upwelling, while ammonium comes from the excretory processes of animals. Microbes too can provide these nitrogen resources via dissimilatory metabolism. Stable isotopes of nitrogen in nitrate, nitrite and ammonium can reveal information about the source of the nitrogen. For example, the $\delta^{15}N_{NO3}$ of 'new' upwelled seawater in the study region is ~6.0‰ (Pfister et al. 2014a). Values greater than this indicate assimilation and recycling of nitrate through photosynthetic and microbial organisms (Wankel et al. 2006, Wawrik et al. 2012, Pfister et al. 2014), as these processes result in fractionation, where the lighter isotope is preferentially taken up by microbes and seaweeds and the surrounding water becomes enriched. Similarly, the $\delta^{15}N_{NH4}$ increases with assimilation and microbial transformation. Thus, we expect $\delta^{15}N_{NH4}$ and $\delta^{15}N_{NO3}$ to be elevated inside of kelp beds as opposed to outside, consistent with a hypothesis of regeneration and recycling in kelp forests. Further, as nitrate is depleted in seawater, it is enriched at a constant rate, such that $\delta^{15}N_{NO3}$ shows a constant negative relationship with the nitrate concentration at time t $[NO_3]_t$ normalized to the maximum nitrate $[NO_3]_{max}$ arriving from deep, upwelled water (Altabet 2005).

The dual isotopic composition of nitrate ($\delta^{15}N_{NO3}$ and $\delta^{18}O_{NO3}$) in particular is diagnostic of the relative roles of assimilatory (uptake) versus regenerative processes. If the only effect that kelp presence has on nitrate concentrations in the water column is through uptake, the two isotopes fractionate approximately equally and we expect a slope of 1:1 (Granger et al. 2010). However, if there is associated microbial activity and regeneration, the $\delta^{15}N_{NO3}$ and $\delta^{18}O_{NO3}$ relationship deviates from a 1:1 relationship. Specifically, microbial nitrification results in greater enrichment of $\delta^{18}O_{NO3}$ relative to $\delta^{15}N_{NO3}$, decoupling the two and leading to a slope in excess of 1 (Wankel et al. 2006, Pfister et al. 2014a). We will thus test whether there is increased nitrogen processing within the kelp bed versus outside of it with this diagnostic tool.

Though kelp preferentially take up the lighter isotope of carbon, kelp tissue $\delta^{13}C$ should also be relatively elevated in areas where flow is dampened while carbon uptake continues to be high. Isotopes of carbon (described above) will further reveal information on biological processing. Because upwelled water is depleted in ^{13}C, the $\delta^{13}C$ of kelp can provide an indicator of upwelling. For areas where wave action is reduced, we expect to see a greater indication of the drawdown of carbon without replenishment. We thus hypothesize:

> *H5.* Seawater within kelp forests has greater $\delta^{15}N_{NO3}$ and $\delta^{15}N_{NH4}$ compared with areas lacking canopy kelp.
> *H6.* Kelp tissue and phytoplankton $\delta^{15}N$ and $\delta^{13}C$ should increase in areas where flow is dampened, including calmer waters.

Research Plan.
Using the same template for the sampling plan described above for the carbon cycle, we will sample seawater and kelp at the 2 sites, one within the Strait of Juan de Fuca and the other in the outer coastal waters and within the OCNMS. The sampling will be done concordant with our carbon cycle sampling.

Seawater for nitrogen isotopic analysis will be hand-pumped through a Pall 47 mm filter holder, with a combusted 47 mm gf/f filter (0.7 µm pore size). The stable nitrogen isotope compositions ($\delta^{15}N$ values) of the POM in the water column will be measured on these filters (along with ($\delta^{15}C$) a standard elemental analyzer interface to an isotope ratio mass spectrometer. Dried and powdered kelp tissue will be analyzed similarly. The nitrogen isotopes of ammonium in seawater will be measured in the Altabet lab according to a modified version of the NH_4^+ oxidation method described in Pather et al (2014). The dual isotopes of nitrate ($\delta^{15}N_{N03}$ and $\delta^{18}O_{N03}$) will be measured with Cd reduction to NO_2^-, followed by reaction with azide to N_2O (e.g. Pfister et al. 2014a).

The effects that kelp have on both carbon and nitrogen uptake and dynamics will be dependent on water flow through the kelp bed and relative amount of replenishment. In order to better quantify these flow rates, we will deploy inexpensive current meters (SeaHorse™) to determine how the presence of kelp ameliorates flow. We can use temporary moorings to get data over several days during our water sampling campaigns. We favor these temporary moorings over permanent ones because they are cheaper, can be moved around, and will not need to withstand high physical energy. The OCNMS has extensive experience with moorings and will provide expertise and logistical support.

Interpretation and Significance
Although we are working in a coastal area that has comparatively lower amounts of anthropogenic nitrogen inputs, these kelp forests give us an opportunity to understand how nitrogen cycles in these coastal environments. Areas to the east of the proposed study area in Puget Sound are experiencing increasing water column concentrations of dissolved inorganic nitrogen (DIN, http://www.ecy.wa.gov/programs/eap/Nitrogen/Index.html) and it is likely that export through the Strait of Juan de Fuca will increasingly elevate DIN levels where canopy kelp thrive. The contributions that kelp make to nitrogen uptake and oxygen production may counteract the nitrogen inputs from anthropogenic inputs and our aim is to quantify this contribution. Further, we will quantify the extent to which the kelp canopy serves as a locus for nitrogen recycling (H5 and H6) helping us predict how kelp would respond to potentially increasing nitrogen loads in the future. Finally, our measurements will reveal how kelp forests change the flow environment. Though the scope of this funding opportunity allows us to measure these variables in only a few locales in Washington, the work is an essential start and the results are likely general to canopy kelp across its geographic range.

Timeline of Research and Analysis Activities and the PI or Partner responsible.

Activity	Year 1, 1 Jul 2016 – 30 Jun 2017			Year 2, 1 Jul 2017 – 30 Jun 2018		
	Summer	Fall/Winter	Spring	Summer	Fall/Winter	Spring
Kelp Aerial Data Analysis (CP, HB)						
Kelp Forest Field Sampling (CP, HB, LA)						
Seawater Chemistry Analysis (MA, AC)						
Field Data Analysis (CP, HB)						
Manuscript Preparation (CP, MA, AC)						
Disseminating Results (All)						

III. Relevance To NOAA- COCA Goals: Climate Change And Decision Makers

In the past, resource managers were usually tasked with understanding a particular type of habitat loss or change to exploitation. Climate change effects on natural resources, in contrast, may be more difficult to predict due to direct effects on a species in a multitude of ways (elevated temperature, decreased pH, etc.), but also indirect species effects via interactions (McCoy & Pfister 2014), non-additivities (Stenseth et al. 2004, de Sassi et al. 2012) and ecological surprises (Doak et al. 2008). The prognosis for kelp in the future will involve factors that managers cannot control (sea surface temperature, degree of upwelling, and ocean pH, Steneck et al. 2002, Boehm 2015) but also factors that can be regulated: the protection of apex predators, anthropogenic nitrogen loading, kelp harvest, reduced sediment run-off, and invasive species control such as *Sargassum muticum*. Our proposed research will give managers the tools to determine which of these factors have an impact on kelp forest function.

A further key to management goals is an understanding of local versus regional influences on kelp abundance and what data sources provide the best guidance for species dynamics. Thus a key contribution of the proposed research will be the determination of whether local data sources (e.g. local temperature data) versus regional data (e.g. upwelling or the PDO) are better explanatory variables for kelp dynamics, indicating the extent to which new local data sources are necessary to co-locate with kelp forests.

We are also providing the information for valuation of impacts on kelp forests (e.g. Vasquez et al. 2013). Carbon uptake by blue carbon entities has a known value in carbon markets (e.g. Wilmers et al. 2012). Similarly, the uptake of nitrogen by kelp forests likely contributes to shunting nitrogen from other pathways that have negative economic consequences such as Harmful Algal Blooms (HABs). Further, if kelp and other macrophytes (e.g. Saderne et al. 2015, Hendriks et al. 2014) are providing pH refugia for calcifiers by raising pH, this is an essential contribution of macrophytes that necessitates protective measures for kelp given the known climate driven trends in pH.

Washington State prohibits commercial harvest of kelp. Recreational harvest levels are unknown, but are considered to be relatively low in many areas. Sites of intensive harvest in state parks near population centers have been closed to recreational harvest, while other sites are being monitored to understand harvest levels and impacts (Helen Berry personal communication). Apex predators (sea otters) have had stable populations. Both of these factors likely contribute to a persistent kelp population across most of the Washington shores. Other locales where apex predators have been overexploited (S California) provide the cautionary evidence that protective measures are needed for kelp and the species they support as demonstrated by predator removal and subsequent reduced kelp resilience in Tasmania (Ling et al. 2009).

DISSEMINATING RESULTS TO THE BROAD COMMUNITY

We will communicate our findings not only in academic outlets, but beyond in order to reach and benefit a broad community. We propose the following specific activities to communicate our findings: 1. Publish in top-tier journals, using our State, Federal, and Academic publicity offices to reach news outlets for this work, 2. Maintain on each of our websites an updated description of this interdisciplinary collaboration among academic scientists and State and Federal biologists to highlight how collaborative science is done to inform decision-making, 3. Host 2 public talks highlighting the work we are doing, the methodology we use, and its importance to state resources. We propose one talk in Port Angeles, WA in affiliation with the Fiero Marine Center, and one talk at the state capitol campus in Olympia, WA hosted by DNR to communicate findings to state scientists and managers. 4. Disseminate findings to local scientists through a presentation at a symposium organized by the University of Washington's Ocean Acidification Center. 5. Strategic attendance at National Meetings, particularly those that highlight the application of ocean climate analysis to decision makers. For example, ASLO 2015 hosted a session entitled "The role of natural ecosystems in coastal protection: mechanisms, quantification and application", attended by a diversity of science practitioners. Further, Pfister is a member of several entities that utilize this information: California Current Acidification Network (CCAN) and Ocean Carbon and Biogeochemistry (Ocean Acidification subcommittee). Finally, The PIs and Partners will brief the Commissioner of Public Lands and other DNR decision makers on how research results inform DNR's strategic objectives to understand the role of marine vegetation in biogeochemical processes related to ocean acidification, to identify areas to be managed for future use, and to identify habitat refuges.

DATA/INFORMATION SHARING PLAN

We will make our ecological and environmental data accessible within 2 years of collection primarily through well-established, web-accessible data archives, as well as through use of our own University and Government affiliations. We recognize that our data types will be diverse and we will use the appropriate archive.

1. **Types of data**
   a. This project will collect a variety of information including: physical environmental characteristics (pH, temperature, salinity, nutrients, flow) and kelp nutrient status.
   b. We will collect this data with observational methodology.
   c. We will use of a variety of computer software packages to analyze the data, including basic analysis in R, as well as GIS based data
   d. All the data will be stored locally at the different institutions on duplicate hard drives and uploaded to the databases available to the public.
   e. Data will be handled in a variety of ways tailored to the analysis approach and use, from already built database programs for mixing the results from the nitrogen isotope addition to straightforward spreadsheets for less complex information.

2. **Data and Metadata Standards**
   a. Data will be made available through a variety of sites appropriate to the type of data. Metadata for all collections will follow the established guidelines for environmental data (E.g., LTER).
   b. All data will be made available as soon as it is quality checked and mounted to the public web site.
   c. No datasets will be covered by copyright.
   d. If necessary, all IRB policies will be followed.

3. **Policies for access and sharing and provisions for appropriate protection/privacy**
   a. We expect to share with other researchers, the primary data, and any samples or physical collections as appropriate.
   b. PI's will share the data as it becomes available and is posted to the web sites. Data will be available within 2 years of the end of the project.
   c. We anticipate that these data will be used by coastal scientists and resource managers.

4. **Plans for archiving and Preservation of access**
   a. Environmental Information: At the University of Chicago, we are guaranteed server space via the Biological Sciences Division Information Services (BSDIS). The BSDIS is the primary technology provider for biological and medical sciences at the U of Chicago and is committed to providing this service in perpetuity. Established archival programs we will use for the ecological and environmental data are: the Knowledge Network for Biocomplexity (KNB), the Ecological Archives of the Ecological Society of America, National Oceanographic Data Center (NODC). We will upload our data and data descriptions (metadata) to the KNB (http://knb.ecoinformatics.org/index.jsp), an NSF-funded program for sharing ecological and environmental data, used by the LTER program and NCEAS. Links to these data storage programs will be available on our websites. Our third archival resource will be the Biological and Chemical Oceanography Data Management Office (BCO-DMO) based at WHOI and dedicated to data generated from NSF Oceanography funding. All isotope data and environmental data will be deposited

here. We have archived data on both NODC and BCO-DMO numerous times and will continue to make use of this public resource.

b. The original data as well as any published papers will be archived. All archival facilities have fully redundant off site back up of computer files. (See the Facilities Document).

5. **Prior Experience Publishing Data**

All PIs and Partners have had experience publishing data for open use. Repositories used to date include the KNB, NODC, BCO-DMO, and Washington DNR website.

Specific Personnel Responsibilities

I. Responsibilities of each PI or Partner with respect to Data Repositories:

Pfister - Washington coast seawater environmental data will continue to be deposited to BCO-DMO.

Altabet – All stable isotope data will be deposited to BCO-DMO.

Colman –Collaboratively with Altabet, will insure all stable isotope data will be deposited to BCO-DMO. Further, the Carbon Dioxide Information Analysis Center (CDIAC) is a specific repository for ocean carbon data, and the $\delta^{13}C_{DIC}$ will go here.

Berry – All kelp aerial survey data will continue to be publically posted to the DNR Natural Habitat Program website (http://www.dnr.wa.gov/programs-and-services/aquatics/aquatic-science). Links from Washington DNR websites to these data repositories will be established to aid managers and the public in finding them.

Antrim – Links from NOAA Marine Sanctuary websites to these data repositories will be established to aid managers and the public in finding them.

II. Each PI/Partner will be responsible for ensuring that peer-reviewed manuscripts are published in journals readily accessed and labeled with DOIs, though this responsibility will fall most on the academic PIs who are experienced in this area (see CVs).

BIOGRAPHICAL SKETCH

Catherine A. Pfister – Lead PI
Department of Ecology & Evolution, University of Chicago
http://pfisterlab.uchicago.edu/

Professional Preparation

University of Illinois, Champaign-Urbana	Biology	B. S.	1984
University of North Carolina at Chapel Hill	Marine Sciences	M.S.	1987
University of Washington, Seattle	Zoology	Ph.D.	1993
University of California at Berkeley	Integrative Biology	Postdoc	1993-1995

Appointments

2013 – present	Professor, Department of Ecology & Evolution, Committee on Evolutionary Biology, and The College, University of Chicago
1995 – 2013	Assistant, then Associate Professor, Department of Ecology & Evolution, Committee on Evolutionary Biology, and The College, University of Chicago
1993 – 1995	Miller Institute for Basic Science Postdoctoral Research Fellow, Dept. of Integrative Biology, University of California, Berkeley

Publications in the last 3 years (2013-2015)

accepted. Pfister, C. A., R. T. Paine, J. T. Wootton. The iconic keystone predator has a pathogen. Frontiers in Ecology and the Environment.

accepted. Wootton, J. T. and C. A. Pfister. Processes affecting extinction risk in the laboratory and in nature. Proceedings of the National Academy of Sciences

In press. McCoy, S. J., C. A. Pfister, G. Olack, A. Colman. Diurnal and tidal patterns of carbon uptake and calcification in geniculate intertidal coralline algae. Marine Ecology

2014. Pather, S., C. A. Pfister, M. Altabet, D. M. Post. Ammonium cycling in the rocky intertidal: remineralization, removal and retention. Limnology and Oceanography 59:361-372.

2014. Pfister CA, Gilbert JA, Gibbons SM. The role of macrobiota in structuring microbial communities along rocky shores. PeerJ 2:e631; DOI 10.7717/peerj.631

2014. McCoy, S. J. and C. A. Pfister. Historical comparisons reveal altered competitive interactions in a guild of crustose coralline algae. Ecology Letters 17:475-483.

2014. Pfister, C. A., M. Altabet, D. Post. Animal Regeneration and microbial retention of nitrogen along coastal rocky shores. Ecology 95:2803–2814

2014. Pfister, C. A., A. J. Esbaugh, C. A. Frieder, H. Baumann, E. E. Bockmon, M. M. White, B. R. Carter, H. M. Benway, C.A. Blanchette, E. Carrington, J. B. McClintock, D. C. McCorkle, W. R. McGillis, T. A. Mooney, P. Ziveri. Detecting the Unexpected: A Research Framework for Ocean Acidification. *Environmental Science and Technology*. 10.1021/es501936p

2013. Wootton, J. T. & C. A. Pfister. Experimental Separation of Genetic and Demographic Factors on Extinction Risk in Wild Populations. Ecology 94:2117-2123. doi: 10.1890/12-1828.1

Five Other Relevant Publications

2012. Wootton JT, Pfister CA. Carbon system measurements and potential climatic drivers at a site of rapidly declining ocean pH. *PLoS ONE* 7(12):e53396. PMCID: PMC3532172.

2011. Pfister CA, McCoy SJ, Wootton J T, Martin PA, Colman AS, Archer D. Rapid environmental change over the past decade revealed by isotopic analysis of the California mussel in the northeast Pacific. *PLoS ONE* 6(10):e25766. PMCID: PMC3185010.

2008. Wootton JT, Pfister CA, Forester JD. Dynamical patterns and ecological impacts of changing ocean pH in a high-resolution multi-year dataset. *Proceedings of the National Academy of Sciences* 105(48):18848-18853. PMCID: PMC2596240.

2008. Morris WF, Pfister CA, Tuljapurkar S, Haridas CV, Boggs CL, Boyce MS, Bruna EM, Church DR, Coulson T, Doak DF, Forsyth S, Gaillard JM, Horvitz CC, Kalisz S, Kendall BE, Knight TM, Lee CT, Menges ES. Longevity can buffer plant and animal populations against changing climatic variability. *Ecology* 89(1):19-25.

1998. Pfister CA. Patterns of variance in stage-structured populations: evolutionary predictions and ecological implications. *Proceedings of the National Academy of Sciences*. 95(1):213-218.

Synergistic Activities
Principal Investigator, Department of Education Graduate Training Program, Graduate Assistance in Areas of National Need (GAANN), *A Graduate Training Program in Ecology*, Awarded to the University of Chicago, 2004-2007, 2007-2010, 2011-2014, 2015-2018

Associate Editor, *The American Naturalist,* 2003 to 2008, *Proc of the Royal Acad of Sci*, B, 2010-present; Board of Editors, The University of Chicago Press, 2008-2011,

Workshop Leader, Marine Biological Lab, Woods Hole, "Coastal Nitrogen Synthesis Charette", Sep 2014; Scientific Advisory Board, 2007-10; Working Group Leader, "Demographic Variation and Climate Change", NCEAS, Santa Barbara, 2004-2006

Participant: NSF Workshop, Evolution and Global Change, May 2010; California Current Acidfication Network, Dec 2011; NOAA OA Program Reviewer, 2014; NSF Postdoctoral Fellow Panelist, 2015

Board Member, Ocean Carbon & Biogeochemistry (OCB; a joint committee formed by NSF, NASA & NOAA), Ocean Acidification Subcommittee, 2012-present

Collaborators and Other Affiliations
Collaborators and Co-Editors
Mark Altabet, Dan Doak, Bruce Kendall, Bill Morris, Robert Paine, Nicole Phillips, David Post, Kaustuv Roy, Alan Shanks, Mei Wang

Graduate Advisors and Postdoctoral Sponsors
Mark Hay (MS), Robert Paine (PhD), Wayne Sousa (Postdoctoral)

Thesis Advisor and Postgraduate-Scholar Sponsor
Dissertations Directed: Satie Airame, PhD 1999 (UCSB); Karl Polivka, PhD 2002 (US Forest Service); Doug Nutter, PhD 2005 (University of Maryland); Julie Collens, PhD 2009 (Illumina Co); Ole Shelton, PhD 2009 (NOAA/NMFS); Erin Grey, PhD 2009 (Governors State University); Sophie McCoy, PhD 2013 (Plymouth Marine Lab). Current: Orissa Moulton, Courtney Stepien, Simon Lax, Katherine Silliman, Mark Bitter. Postdoctoral Fellows: Scott Peacor, 2000-2001 (Assoc Prof, Michigan State University, Dept. of Fisheries and Wildlife and GLERL); Handojo Kusumo, 1999-2003 (Univ of Ill -Chicago); Bret Elderd, 2002-2005 (Louisiana State University)

BIOGRAPHICAL SKETCH
MARK A. ALTABET – co-PI

PROFESSIONAL PREPARATION

BSc in Biology	1979	S.U.N.Y at Stony Brook
PhD in Organismal and Evolutionary Biology	1984	Harvard University
Postdoctoral Fellow, Chemical Oceanography	1984-1986	Woods Hole Oceanographic Institute

APPOINTMENTS

2012-present	Chair, Dept. of Ocean and Estuarine Science, School for Marine Science and Technology, University of Massachusetts Dartmouth
2001-present	Professor, School for Marine Science and Technology, University of Massachusetts Dartmouth
2001-present	Adjunct Professor, Brown University, Department of Geological Sciences
1995-2001	Associate Professor, School for Marine Science and Technology, University of Massachusetts Dartmouth
1990-1996	Associate Scientist, Woods Hole Oceanographic Institution
1993-1993	Fulbright Scholar and Visiting Professor, Institute for Earth Sciences, The Hebrew University in Jerusalem
1986-1990	Assistant Scientist, Woods Hole Oceanographic Institution

PUBLICATIONS Last 3 Years (career h-index of 45 according to Google Scholar https://scholar.google.com/citations?user=1Jj7uyYAAAAJ&hl=en)

Montes, E., M. A. Altabet, F. Muller-Karger, M. I. Scranton, R. Thunell, Cl. Benitez-Nelson, L. Lorenzoni, Y. Astor (2013) Biogenic nitrogen gas production at the oxic-anoxic interface in the Cariaco Basin, Venezuela. *Bigeosciences,* 10, 267–279, doi:10.5194/bg-10-267-2013

Bryant Mason, A., Y. J. Xu, and M.A. Altabet. (2013) Limited capacity of river corridor wetlands to remove nitrate - A case study on the Atchafalaya River Basin during the 2011 Mississippi River Flooding. *Water Resour. Res.*, 49, doi:10.1029/ 2012WR012185.

Galbraith, E.D., M. Kienast and the NICOPP working group (2013) Coherent climate-driven changes in the global marine nitrogen cycle during the past 80,000 years. *Nature Geoscience*, DOI: 10.1038/NGEO1832

Pather, S., C. A. Pfister, D. M. Post and M.A. Altabet (2014) Ammonium cycling in the rocky intertidal: Remineralization, removal, and retention. *Limnology and Oceanography* 59, 361–372 doi:10.4319/lo.2014.59.2.0361

Swart, PK, S. Evans, T. Capo, M.A. Altabet. (2014) The fractionation of nitrogen and oxygen isotopes in macroalgae during the assimilation of nitrate. *Biogeosciences*, 11, 6147–6157, doi:10.5194/bg-11-6147-2014

Dabundo R., M.F. Lehmann, L. Treibergs, C. R. Tobias, M. A. Altabet; P. H. Moisander, J. Granger. (2014) The contamination of commercial $^{15}N2$ gas stocks with ^{15}N-labeled nitrate and ammonium and consequences for nitrogen fixation measurements *PLoS ONE* 9(10): e110335. doi:10.1371/journal.pone.0110335

Charoenpong, C., L.A. Bristow, and M.A. Altabet (2014) A continuous flow isotope ratio mass spectrometry method for high precision determination of dissolved gas ratios and isotopic composition *Limnology and Oceanography Methods* 12, 323-337.

Pfister, C. A., M. A. Altabet, D. M. Post (2014) Animal Regeneration and microbial retention of nitrogen along coastal rocky shores. *Ecology*, 95(10), 2803–2814.

Swart, P.K., W.T. Anderson, M.A. Altabet, C. Drayer,, and S. Bellmund, (2014) Sources of Dissolved Inorganic Nitrogen in a Coastal Lagoon Adjacent to a Major Metropolitan Area, Miami Florida (USA) *Applied Geochemistry* 38, 134-146

Swart, P. K., Evans, S., Capo, T., and Altabet, M. A. (2014) The fractionation of nitrogen and oxygen isotopes in macroalgae during the assimilation of nitrate, *Biogeosciences* 11, 6147-6157, doi:10.5194/bg-11-6147-2014, 2014

Kalansky, J., Y. Rosenthal, T. Herbert, M.A. Altabet (2015) Southern Ocean contributions to the Eastern Equatorial 16 Pacific heat content during the Holocene. *Earth Planetary Science Letters* 424, 158-167

Bourbonnais, A., M. A. Altabet, C.N. Charoenpong, J.Larkum, H. Hu, H. W. Bange, and L. Stramma. N-loss isotope effects in the Peru oxygen minimum zone studied using a mesoscale eddy as a natural experiment" by A. Bourbonnais (2015) *Global Biogeochemical Cycles* 29, 793–811, doi:10.1002/2014GB005001

FIVE OTHER RELEVANT PUBLICATIONS (**** - over 300 citations*)

Altabet, M.A., R. Francois, D.W. Murray, and W.L. Prell, 1995. Climate-related variations in denitrification in the Arabian Sea from sediment $^{15}N/^{14}N$ ratio. *Nature* , **373,* 506-509.

***Francois, R., M. A. Altabet, E.-F. Yu, D. Sigman, M. P. Bacon, M. Frank, G. Barielle and L. Labeyrie. (1997). Contribution of Southern Ocean surface-water stratification to low atmospheric CO_2. during the last glacial period *Nature*., 389, 929-935

***Altabet, M.A., M.J. Higginson, D.M. Murray The effect of millennial-scale changes in Arabian Sea denitrification on atmospheric CO_2.*Nature*, 415, 15-162, 2002

Ryabenko, E., A. Kock, H. W. Bange, M. A. Altabet, and D. W. R. Wallace (2012) Contrasting biogeochemistry of nitrogen in the Atlantic and Pacific oxygen minimum zones. *Biogeosciences* 9, 203-215, doi:10.5194/bg-9-203-2012.

Altabet, M.A., E. Ryabenko, L. Stramma, D. Wallace, M. Frank, P. Grasse, and G. Lavik (2012) An Eddy-Stimulated Hotspot for Fixed Nitrogen-Loss from the Peru Oxygen Minimum Zone *Biogeosciences*, 9, 4897–4908, doi:10.5194/bg-9-4897-2012

SYNERGISTIC ACTIVITIES

(1) Member of curriculum committee for the University of Massachusetts intercampus graduate school for marine science and technology (http://www.umassmarine.net/).
(2) Associate Editor for *Marine Chemistry* (1991 to 2015)
(3) Member of Steering Committee for the Denitrification RCN workshop – "Advancing Methods for Measuring Denitrification in Terrestrial and Aquatic Systems", held May 2008, http://www.denitrification.org/
(4) External scientific advisor to SFB 754," Climate-biogeochemistry interactions in the tropical ocean", a German Research Foundation project based at GEOMAR

THESIS ADVISEES AND POSTDOCTORAL ADVISEES

Post-Docs (5 total): Matthew Higginson (2001 -2003, McKinsey &Co.), David Timothy (2004-2006, Fisheries and Oceans Canada), Rajesh Agnihotri (National Physical Laboratory - India) Laura Bristow (2010-2012, U. Southern Denmark), Annie Bourbonnais (current)

Graduated Students (19 total): Danny M. Sigman (PhD 1997, Princeton), Xinqun Huang (MS 2006, Shanghai Ocean U), Christine Sheehan (MS 2000, Fall River School District), Li-Tao Fu (MS 2001, Xiamen U.), Matt McIlvin (PhD 2008, WHOI), Yishu Song (MS 2006, Indiana U), Christel Flis (MS 2009,unknown) , Lin Zhang (MS 2009, URI), Enrique Montes (PhD 2012, U. S. Carolina), Talya Gulman (MS 2011, U. Maryland), Santhiska Pather (MS 2012, S. Africa), Ben Fertig (PhD 2011, now at Rutgers), Caitlin Chazen (PhD 2010, Northern Virginia Community College), Chawalit Charoenpong (MS 2013 WHOI), April Mason (MS 2012, LSU), Evgeniya Ryabenko (PhD 2012, Helmholtz-Zentrum München, Institute of Groundwater Ecology), Habei Hu, Shuo Chen (current), Sheel Prajapati (current)

Biographical Sketch

Albert S. Colman – co-PI
Department of Geophysical Sciences
University of Chicago
http://biogeolabs.uchicago.edu/asc25/

Professional Preparation

1994	AB	Harvard College	Earth & Planetary Sciences
2002	PhD	Yale University	Dept. Geology & Geophysics
2002-2004	Postdoc	Carnegie Inst. Washington	Geophysical Laboratory
2004-2007	Postdoc	U. Maryland Biotech. Inst.	Center of Marine Biotech.

Appointments

2008 - pres.	Assistant Professor	U. Chicago	Dept. Geophysical Sciences
2004 - 2007	Research Associate	U. Maryland Biotech. Inst.	Center of Marine Biotech.
2002 - 2004	Postdoctoral Fellow	Carnegie Inst. Washington	Geophysical Laboratory
1996	Research Assistant	U. Hawai'i	Dept. Oceanography
1994-1995	Research Assistant	Harvard University	Div. Applied Sciences

Publications in last 3 years

Green, DR, AS Colman, GM Green, FB Bidlack, P Tafforeau, TM Smith (submitted) High-resolution synchrotron and stable isotope analyses reveal tooth mineralization patterns for climate reconstruction. *PNAS.*

Ingalls, M, DB Rowley, B Currie, S Li, G Olack, D Lin, AS Colman (in review) Paleocene-Early Eocene pre-collisional paleoaltimetry of Linzizong Arc of Tibet: implications for India-Asia collision-related crustal mass-balance. *Nature Geoscience.*

Mine, A.H., Hoerner, M.E., Alex, S., Waldeck, A., Olack, G., and Colman, A.S. (in review) Microprecipitation and $\delta^{18}O$ analysis of phosphate for paleoclimate and biogeochemistry research. *Chemical Geology.*

Olack, G, CA Pfister, JT Wootton, AS Colman (for submission) Measuring the stable isotope composition and concentration of DIC. *Limnology & Oceanography Methods.*

McCoy, SJ, Pfister CA, Olack G, Colman AS (2015, in press) Diurnal and tidal patterns of carbon uptake and growth in intertidal coralline algae. *Marine Ecology*.

Colman, AS. (2015) Sponge symbionts and the marine P cycle. *PNAS*, 112, 4191-4192.

Mawji, E., R. Schlitzer and 133 others, incl. AS Colman (2015) The GEOTRACES Intermediate Data Product 2014. *Marine Chemistry, doi:10.1016/j.marchem.2015.04.005.*

Voelker, AHL, AS Colman, G Olack, JJ Waniek, D Hodell (2015) Oxygen and hydrogen isotope signatures of Northeast Atlantic Water Masses. *Deep Sea Res.II doi:10.1016/j.dsr2.2014.11.006.*

He, B, GA Olack, AS Colman (2012) Pressure baseline correction and high-precision CO_2 clumped isotope (Δ_{47}) measurements in bellows and micro-volume modes. *Rapid Comm. Mass Spectr., 26,* 2837-2853.

Five Other Relevant Publications

Pfister, CA, SJ McCoy, JT Wootton, PA Martin, AS Colman, D Archer (2011) Rapid environmental change over the past decade revealed by isotopic analysis of the California mussel in the northeast Pacific. PLoS One, 6, e25766, doi:10.1371/journal.pone.0025766.

Terwilliger, VJ, Z Eshetu, AS Colman, T Bekele, A Gezahgne, and ML Fogel (2008) Reconstructing palaeoclimate and land use from $\delta^{13}C$ and $\delta^{15}N$ values of soil organic matter: a calibration using arid and wetter elevation transects in Ethiopia. *Geoderma, 147,* 197–210.

Mohamed, NM, AS Colman, Y Tal, RT Hill (2008). Diversity and expression of nitrogen fixation genes in bacterial symbionts of marine sponges. *Envir. Microbiology,10,* 2910-2921.

Wiedemann-Bidlack, FB, AS Colman, ML Fogel (2008). Stable isotope analyses of phosphate oxygen from biological apatite: a new technique for microsampling, microprecipitation of Ag_3PO_4, and removal of organic contamination. *Rapid Comm. Mass Spectr., 22*, 1807-1816.

Colman, AS, RE Blake, DM Karl, ML Fogel, KK Turekian (2005). Marine biogeochemistry as revealed through the oxygen isotope composition of phosphate. *PNAS*, *102*, 13023–13028.

SYNERGISTIC ACTIVITIES

Review Panels:

NSF Chemical Oceanography, NSF Oceanography Career Awards, NASA Mars Fundamental Research Program, NASA Exobiology

Conference organization:

Biogeochemistry Theme Coordinator, 2016 Goldschmidt Meeting.
Session Introducer, 2015 Gordon Research Conference on Chemical Oceanography.
Chaired sessions on biogeochem. & chem. oceanography at AGU, GSA, Goldschmidt.

Outreach:

Exploratorium, San Francisco, CA. Served as scientific lead on development of extremophile research multimedia exhibit (www.exploratorium.edu/kamchatka), featured in *Science* and recipient of national award from Amer. Assoc. of Museums.

Futurefarmers (New Media Studio), San Francisco, CA. Collaborations with M. Swaine & A. Franceschini involving perception, art, science, and technology. Installations at Cooper Hewitt National Design Museum (NY), Museum of Science & Industry (Chicago), Notebaert Nature Museum (Chicago), Guggenheim Museum (NY).

Project Exploration (Chicago). Developed and led science exercises to prepare disadvantaged Chicago middle school girls for trip to Yellowstone National Park.

COLLABORATORS (In addition to co-authors in publications listed above)

K. Angielczyk (Field Museum), M. Coleman (U. Chicago), M. Conte (MBL), S. Crosson (U. Chicago), M. Fogel (UC Merced), H. Fricke (Colorado College), E. Hobbie (UNH), C. Jaramillo (Smithsonian), J. Jastrow (Argonne Nat. Lab), D. Karl (U. Hawaii), J. Miller (U. Cincinnati), A. Paytan (UCSC), S. Porter (UCSB), J. Waldbauer (U. Chicago), M. Webster (U. Chicago).

GRADUATE AND POSTDOCTORAL ADVISORS

PhD: Ruth Blake and Karl Turekian, Yale University; *Postdoctoral:* Marilyn Fogel, Geophysical Laboratory, Carnegie Inst. Washington; Frank Robb, U. MD Biotech Inst.

THESIS AND POSTDOCTORAL ADVISEES

Dissertations directed: Nanxi Bian (2013), Bo He (2014); Current: Marie Hoerner, Aric Mine, Samuel Miller. *Postdoctoral fellows:* Sora Kim (joining U. Kentucky faculty 5/2016).

BIOGRAPHICAL SKETCH
Liam D. Antrim- Partner
Acting Research Coordinator, Olympic Coast National Marine Sanctuary
http://olympiccoast.noaa.gov

Professional Preparation

Bates College, Lewiston, Maine	Biology	B.S.	1976
Western Washington University, Bellingham	Biology	M.S.	1985

Appointments/Employment

2000 to present – NOAA/NOS/ONMS/Olympic Coast National Marine Sanctuary, Port Angeles, Washington. Since December 2014, serving as Acting Research Coordinator.

1986 to 2000 (except 1988) – Battelle Marine Sciences Laboratory, Sequim, WA; Senior Research Scientist. Lead author on 58 reports and publications; co-author on 36.

1988 – WA Department of Ecology, Manchester, WA; Aquatic Toxicologist. Completed all phases of acute and chronic toxicity testing with a variety of marine and freshwater organisms, completed reports, maintained marine wet laboratory equipment.

No Publications in the last 3 years (2013-2015)

<u>Five Other Relevant Papers/Publications</u>

NOAA. 2011. Olympic Coast National Marine Sanctuary Final Management Plan and Environmental Assessment. September 2011. 329pp.

Office of National Marine Sanctuaries. 2008. Olympic Coast National Marine Sanctuary Condition Report 2008. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office of National Marine Sanctuaries, Silver Spring, MD. 72pp.

Bowlby, E, C Schoch, C Bernthal, G Galasso, M S Brancato, L Antrim, B Blackie. 2002. Long-Term Science Plan for the Olympic Coast National Marine Sanctuary. *In* Proceedings of the 2001 Puget Sound Research Conference. T. Droscher (ed.). Puget Sound Water Quality Action Team, Olympia, Washington.

Pearson, W.H., R.A. Elston, R.W. Bienert, A.S. Drum, and L.D. Antrim. 1999. Why Did the Prince William Sound, Alaska, Herring Fisheries Collapse in 1993 and 1994? Review of Hypotheses. PNWD-SA-4387. *Canadian Journal of Fisheries and Aquatic Sciences* 56:711-737.

Antrim, L.D., R.M. Thom, W.W. Gardiner, V.I. Cullinan, D.K. Shreffler, R.W. Bienert. 1995. Effects of Petroleum Products on Bull Kelp *Nereocystis luetkeana*. *Marine Biology 122:23-31.*

Synergistic Activities

Regular informal presentations on research and resource protection activities and priorities to local civic groups, regional marine management meetings, OCNMS Advisory Council

Collaborators and Other Affiliations

Responsible for fostering management and scientific collaborations for resource protection and research initiatives on the outer coast of Washington, including with Native American tribes, academic institutions, federal and state agencies, local government, and NGOs

Mentorship (recent)

Advisor, NOAA Nancy Foster Scholar at OCNMS in 2015, Jessie Hale, graduate student at University of Washington. Mentor, two NOAA Hollings Grant summer interns at OCNMS

BIOGRAPHICAL SKETCH
Helen D. Berry - Partner
Nearshore Habitat Program, Washington State Department of Natural Resources
http://www.dnr.wa.gov/programs-and-services/aquatics/aquatic-science

Professional Preparation

Vassar College	Anthropology	B.A.	1986
Oregon State University	Marine Resource Management	M.S.	1995

Positions

2005 – present	Program Manager, Nearshore Habitat Program, Washington Department of Natural Resources (DNR)
1995 – 2005	Marine Ecologist, Nearshore Habitat Program, DNR

Related Reports, Presentations, and Publications

2015. Berry, H.D. Floating kelp trends, *In:* S. Moore, R. Wold, K. Stark, J. Bos, P. Williams, K. Dzinbal, C. Krembs, J. Newton (eds.), *Puget Sound Marine Waters: 2014 Overview.* Seattle, WA: National Oceanic and Atmospheric Administration, Northwest Fisheries Science Center.

2015. Berry, H.D. Nearshore vegetation responses to dam removal in the Elwha drift cell. In: *Proceedings of the 9th Annual Elwha Nearshore Consortium Workshop.* February 20-21, 2015, (Port Angeles, Washington), pp 37-42.

2015. Nearshore Habitat Program. *Puget Sound Submerged Vegetation Monitoring Program: 2010-2013 Report*. Olympia, WA: Washington Department of Natural Resources.

2010. M.N. Dethier, J. Ruesink, H.D. Berry, A.G. Sprenger, B. Reeves. Restricted ranges in physical factors may constitute subtle stressors for estuarine biota. *Marine Environmental Research* 69:240-247.

2001. Berry, H.D., J.R. Harper, T.F. Mumford, B.E. Bookheim, A.T. Sewell, L.J. Tamayo. *The Washington State ShoreZone Inventory: User's Manual and Digital Data.* Olympia, WA: Washington Department of Natural Resources.

Synergistic Activities

Data Steward. *Floating Kelp Inventory of the Strait of Juan de Fuca and Outer Coast.* Washington Department of Natural Resources.1995-present

Technical Advisor, *Citizen science initiative to monitor and protect kelp in northern Puget Sound*. Northwest Straits Marine Conservation Initiative. 2014-present.

Member. Nearshore Habitat Workgroup. Puget Sound Ecosystem Monitoring Program.2012-present.

Partner. Multi-Agency Rocky Intertidal Network (MARINe). Co-manage two long-term monitoring sites in collaboration with University of Washington.

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Antrim LD, Thom RM, Gardiner WW, *et al.* 1995. Effects of petroleum products on bull kelp (*Nereocystis luetkeana*). *Marine Biology* **122**: 23–31.

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Boehm A, Jacobson M, O'Donnell M, *et al.* 2015. Ocean acidification science needs for Natural resource managers of the North American West Coast. *Oceanography* **25**: 170–81.

Bresnahan PJ, Martz TR, Takeshita Y, *et al.* 2014. Best practices for autonomous measurement of seawater pH with the Honeywell Durafet. *Methods in Oceanography* **9**: 44–60.

Cai W, Borlace S, Lengaigne M, *et al.* 2014. Increasing frequency of extreme El Niño events due to greenhouse warming. *Nature Climate Change* **4**: 111–6.

Cavanaugh KC, Siegel DA, Reed DC, and Dennison PE. 2011. Environmental controls of giant-kelp biomass in the Santa Barbara Channel, California. *Mar Ecol Prog Ser* **429**: 1–17.

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Wootton JT, Pfister CA, and Forester JD. 2008. Dynamic patterns and ecological impacts of declining ocean pH in a high-resolution multi-year dataset. *PNAS* **105**: 18848–53.