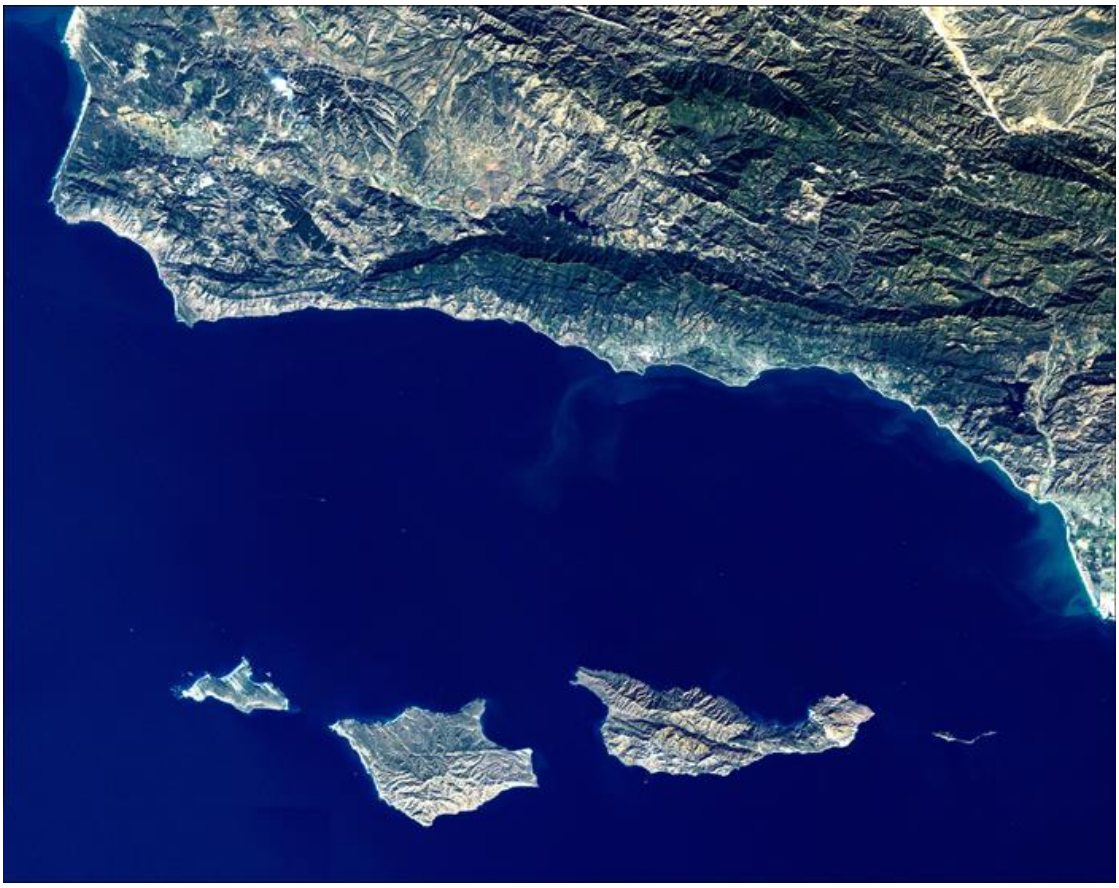
SANTA BARBARA COASTAL LONG TERM ECOLOGICAL RESEARCH PROGRAM



MIDTERM REVIEW BRIEFING DOCUMENT

PREPARED FOR THE NATIONAL SCIENCE FOUNDATION SITE REVIEW TEAM

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I. PROJECT OVERVIEW

The Santa Barbara Coastal LTER (SBC) is an interdisciplinary research and education program established in April 2000 to investigate the relative importance of land and ocean processes in structuring coastal ecosystems. Its principal study domain is a 10,000 km^2 area that includes the Santa Barbara Channel (located in the northern portion of the Southern California Bight) and the steep coastal watersheds, small estuaries and sandy beaches that drain into it (Fig. 1). The focal ecosystem of SBC is giant kelp (*Macrocystis pyrifera*) forests, a diverse and highly productive marine ecosystem that occurs on shallow rocky reefs at the interface of the land-sea margin in the Santa Barbara Channel and other temperate regions throughout the world. Not only are giant kelp forests ecologically important to the areas in which they occur, but they also provide highly valued provisioning, cultural and regulating services.

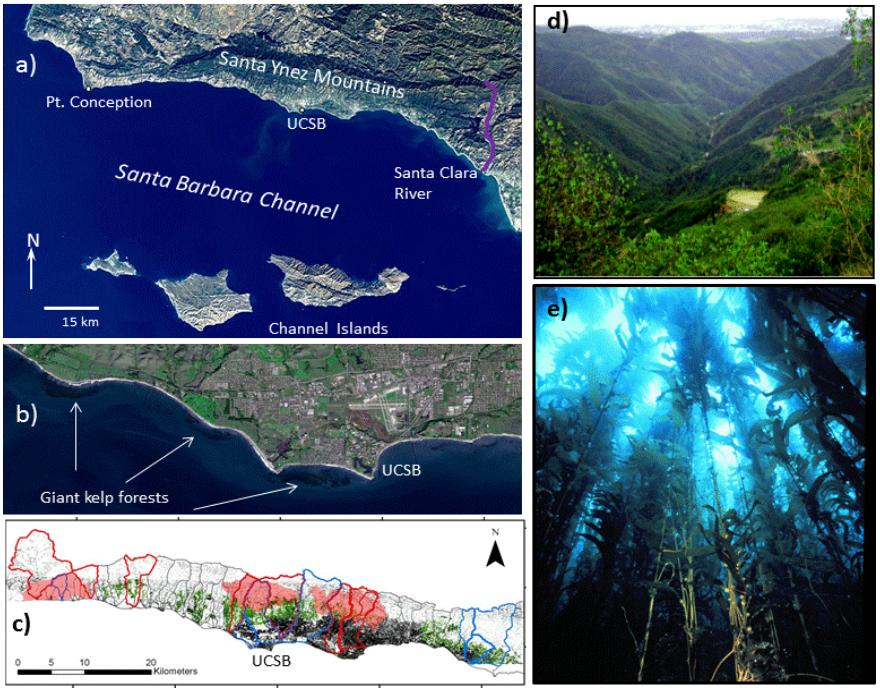

Fig 1. (a) Map of the SBC study domain, (b) Satellite image showing the close proximity of giant kelp forests to the land-sea interface, (c) Land cover of SBC watersheds: green = agriculture, black = urban/suburban, white = undeveloped, pink = recently burned in 2004, 2008 and 2009. Catchments with red borders are currently sampled; catchments with blue borders were previously sampled. (d) Typical SBC watershed with steep slopes and narrow canyons, (e) Submarine view of a giant kelp forest.

The primary focus during our first 6-year funding cycle (SBC I) was identifying and quantifying inputs to giant kelp forest communities from land and the ocean and documenting patterns and sources of spatial and temporal variation in key elements of kelp forest structure and function. We established a core group of long-term integrated measurements aimed at quantifying inorganic and organic subsidies to giant kelp forests in the Santa Barbara Channel and their effects on kelp forest community structure, productivity and dynamics. During SBC II we sought to determine how environmental drivers acting over different spatial and temporal scales interact to influence the community structure and ecological functions of giant kelp forests. Our research approach to this overarching topic focused on three general themes: (1) the influence of environmental drivers on exchange rates of nitrogen and carbon between giant kelp forests and adjacent land and ocean habitats, (2) the direct effects of key environmental drivers on kelp forest community structure and function, and (3) the indirect effects of environmental drivers on kelp forest community structure and function and the feedbacks between structure and function.

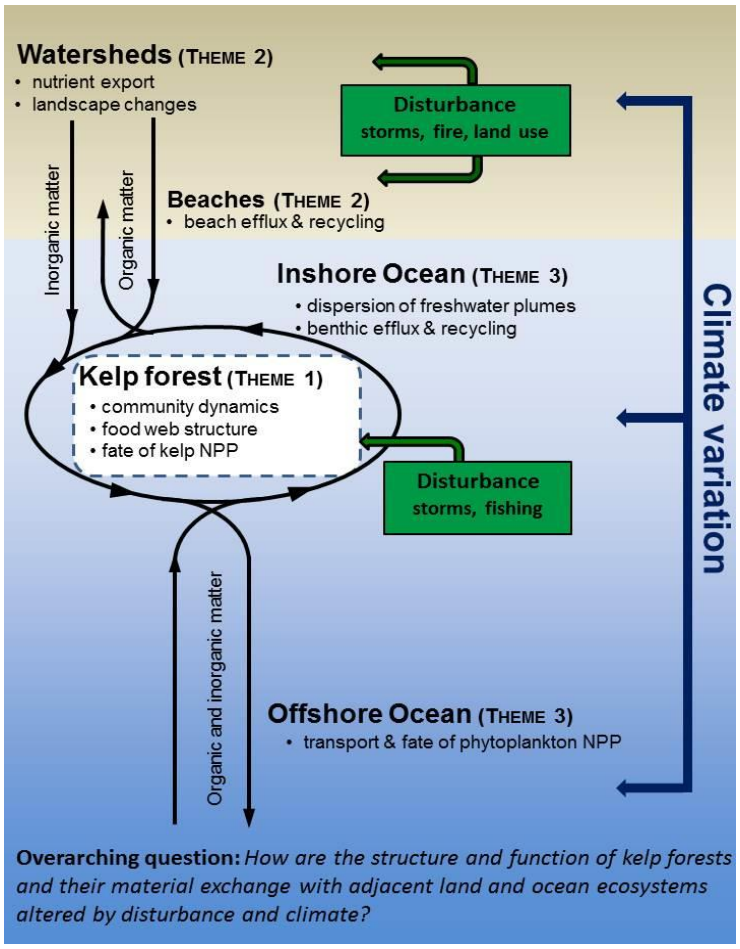

Fig. 2. Conceptual framework for SBC III illustrating how the three research themes are integrated to address the overarching question. Black arrows indicate the movement of organic and inorganic materials within and between land and ocean ecosystems.

Results obtained during our first two awards highlighted the importance of understanding the nature and dynamics of the processes that connect the various coastal ecosystems in the SBC study domain. Hence the overarching question motivating our research in SBC III is: *How are the structure and function of kelp forests and their material exchange with adjacent land and ocean ecosystems altered by disturbance and climate?* We have organized our research around three general themes to address this question: (1) Biotic and abiotic drivers of kelp forest structure and function, (2) Material exchange at the land-ocean margin, and (3) Movement and fluxes of inorganic and organic matter in the coastal ocean (Fig. 2).

The research of SBC III encompasses all five core areas common to LTER sites. and takes advantage of a variety of approaches that include: (1) coordinated long-term measurements of key environmental drivers and ecological response variables, (2) manipulative field experiments designed to isolate the causal mechanisms underlying the patterns observed in our long-term measurements, (3) shorter-term, measurement-intensive studies aimed at obtaining a mechanistic understanding of processes that cannot be isolated using manipulative experiments, and (4) integrated synthesis using models and analyses that allow for predictions beyond the spatial and temporal scope of our measurements, and help guide future directions of our research. Because SBC is the only temperate reef site in the US LTER Network, and the only kelp forest site in the International LTER Network, broader scale long-term synthesis is achieved by partnering with other entities to extend the spatial scale of our data sets and analyses and by collaborations with non-LTER scientists.

During the three-year period of this review, 37 Investigators, 10 postdoctoral fellows, 41 graduate students, 11 REU students and 213 undergraduate students participated in SBC sponsored research resulting in 93 peer-reviewed publications, 10 dissertations/theses and $11.5 million in collaborative research funding from 15 different sources. A multifaceted outreach program serves to deliver SBC research findings to K-12 education, resource managers, policy makers and the general public to enhance broader benefits to society.

II. SITE BASED RESEARCH

Below we summarize our core data collection and major research activities and accomplishments in the three general thematic areas upon which our current award is structured. We note that much additional research not reported below has been and continues to be done with support from the Santa Barbara Coastal LTER. A full list of SBC's publications can be found at: http://sbc.lternet.edu/cgi-bin/publications.cgi.

CORE DATA COLLECTION

We collect data on a core group of long-term integrated measurements on land and in the ocean aimed at quantifying climate, disturbance and inorganic and organic subsidies to and from giant kelp forests and their effects on kelp forest community structure, productivity and dynamics. These data and accompanying metadata are easily accessed from the SBC data catalog (http://sbc.lternet.edu//data/dataCollectionsPortal.html), which facilitates browsing by (1) Habitat, (2) Measurement type, and (3) LTER Core research area. A web link to our research sites (http://sbc.lternet.edu/sites/sampling/) provides an interactive map that allows the viewer to easily obtain information on the locations and frequency of data collection and the year data sets were initiated. We will soon be adding data on trends in the nearshore carbonate system including measurements of pH, oxygen, chlorophyll fluorescence, total alkalinity and dissolved inorganic carbon. These measurements were made possible by supplemental funding from NSF in 2014 and 2015, which allowed us to upgrade our oceanographic moorings and laboratory instrumentation.

THEMED RESEARCH

THEME 1. Biotic and abiotic drivers of kelp forest structure and function

We have previously shown that wave disturbance from storms preferentially removes giant kelp, which in turn affects the kelp forest community by altering the physical structure provided by the forest's foundation species (Arkema et al. 2009, Byrnes et al. 2011; Miller et al. in press). Wave disturbance also acts to reduce kelp NPP (Reed et al. 2008, 2011) and alter the structure of the forest community by reducing the amount of organic matter available to kelp forest consumers and decomposers. Unlike wave disturbance, fishing preferentially targets higher trophic levels (Kay et al. 2012a, 2012b) and thus has the potential to exert strong top-down control on the kelp forest food web. All of these interactions are affected by variations in climate that alter the supply and export of organic and inorganic matter to kelp forests. Research associated with Theme 1 uses data from long-term monitoring, experiments and directed process studies to examine the general question: *How do variations in climate, wave disturbance and fishing influence the structure and dynamics of kelp forest communities and the fate of kelp NPP?*

THEME 1A. Effects of wave disturbance on kelp forest structure and function

Results of structural equation modeling and simulation analyses of our times series data predicted that an increase in frequency of severe wave disturbance will cause a decrease in the diversity and complexity of the kelp forest food web (Byrnes et al. 2011). We are testing this prediction in a long-term experiment established in 2008 in which *Macrocystis* is removed from 2000 m^2 plots once per year in winter to simulate the effects of severe wave disturbance occurring on an annual basis. Adjacent plots serve as controls. Results to date underscore the value and need for multi-site, multi-year experiments as a combination of natural processes acting indiscriminately have reduced kelp in both kelp removal and kelp control plots leading to predicted patterns of community structure at only 1 of 4 sites (Reed et al. 2015). Understory algae at this one site (Mohawk) have increased in abundance over time in the kelp-removal plot relative to the kelp control with an associated decline in sessile invertebrate abundance, which is consistent with the predictions of Arkema et al. (2009). However, unlike in the simulations performed by Byrnes et al. (2011) where species richness declined in all functional groups when

subjected to winter storms that removed kelp on an annual basis, sessile invertebrates have been the only group to show a decline in species richness after eight successive years of experimental kelp removal.

We are also assessing the effects of wave disturbance on kelp forest structure and function via correlative analyses of long-term data collected in situ by divers, moored sensors and small boat sampling and remotely by satellites. Previous analysis of plot-scale data found that wave disturbance typically overwhelms bottom-up and top-down forcing to control regional patterns of giant kelp biomass and NPP (Reed et al. 2011). These conclusions were reaffirmed with analyses of more spatially and temporally comprehensive data on kelp biomass derived from 30-m resolution Landsat satellite imagery spanning the entire coast of California since 1984 (Cavanaugh et al. 2013, Bell et al. 2015, Young et al. *in press*). Wave disturbance explained more variability in giant kelp biomass in central California compared to southern California, where primary drivers also included nitrate availability and sea urchin density.

Wave disturbance leads to frequent local extinctions and recolonizations of giant kelp stands that occur asynchronously throughout its distribution in California. This phenomenon led us to propose that local patches of *Macrocystis* existed as a metapopulation in southern California (Reed et al. 2006). We have been using our Landsat time series of *Macrocystis* canopy biomass (which we calibrated to our long-term study plots sampled monthly by divers) to test predictions of metapopulation theory. Our ability to delimit kelp patches based on population asynchrony using a graph theory community detection approach (Cavanaugh et al. 2014) coupled with dynamic estimates of demographic connectivity obtained from a high-resolution (1 km horizontal), three-dimensional ocean circulation model (Mitarai et al. 2009, Simons et al. 2013) and estimates of patch fecundity (Castorani et al. *in press*) enabled us to overcome the major constraints that have limited empirical tests of this theory. We found that demographic connectivity strongly predicted local population dynamics as highly connected patches had lower probabilities of extinction and higher probabilities of colonization, leading to greater likelihoods of occupancy, but this relationship was mediated by patch size (Fig. 3; Castorani et al. *in press*). Estimates of demographic connectivity coupled with data on population genetics obtained from microsatellite analyses indicated the presence of multiple metapopulation systems in southern California (Johansson et al. *in press*). Collectively, our results provide the first comprehensive evidence that southern California giant kelp populations function as a metapopulation system, challenging the view that populations of this important foundation species are predominantly governed by self-replenishment.

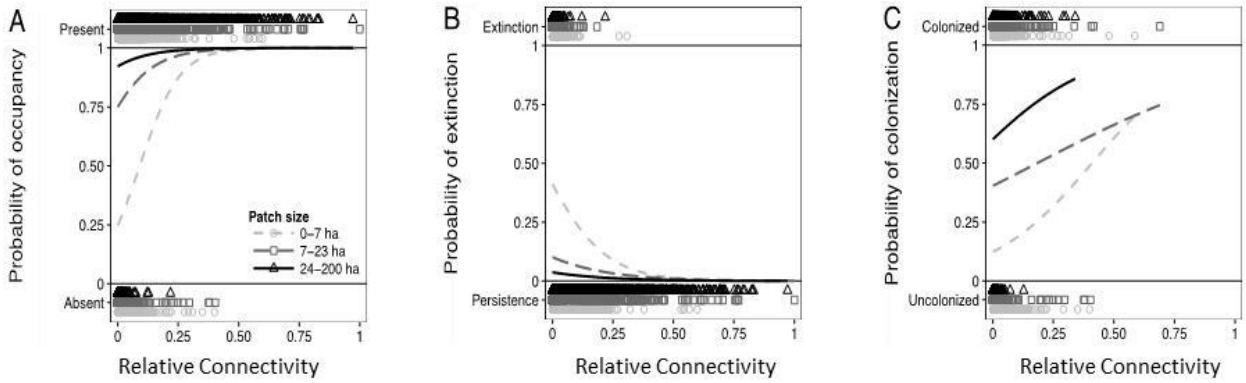

Fig. 3. Probabilities of local giant kelp (A) occupancy, (B) extinction, and (C) colonization as a function of connectivity and patch size (see Castorani et al. *in press* for details).

THEME 1B. Determining the fate of kelp NPP

We continue to measure losses of entire *Macrocystis* plants and fronds on surviving plants monthly at our three long-term kelp NPP sites. These data provide independent estimates of

biomass loss for our modeled estimates of kelp NPP. We are expanding our mathematical model to include other forms of kelp NPP that are lost. Of particular interest to us are dissolved losses, because results from our prior research (Halewood et al. 2012) suggest that *Macrocystis* may be an important source of the dissolved organic carbon (DOC) that supports bacterial carbon demand in the nearshore ocean. We estimated dissolved losses by giant kelp using short-term in situ incubations of entire blades and portions of stipes and found that blades produced on average 2-3 times more DOC than stipes, and stipes and blades produced on average 30% and 80% more DOC respectively, during the day compared to the night (Reed et al. *in press*). The growth stage, C/N ratio, and epiphyte load of the blades and the temperature of the ocean during the incubations had no discernable effect on rates of DOC release. We incorporated these results and time series data on surface and bottom irradiance into our empirical model of reef-scale NPP and found that the production of kelp DOC was on average highest in summer and spring (~0.5 g C m^{-2} d^{-1}) and lowest in winter and autumn (~0.31 g C m^{-2} d^{-1}), but it varied greatly among years for any given season as large oscillations in standing biomass led to corresponding fluctuations

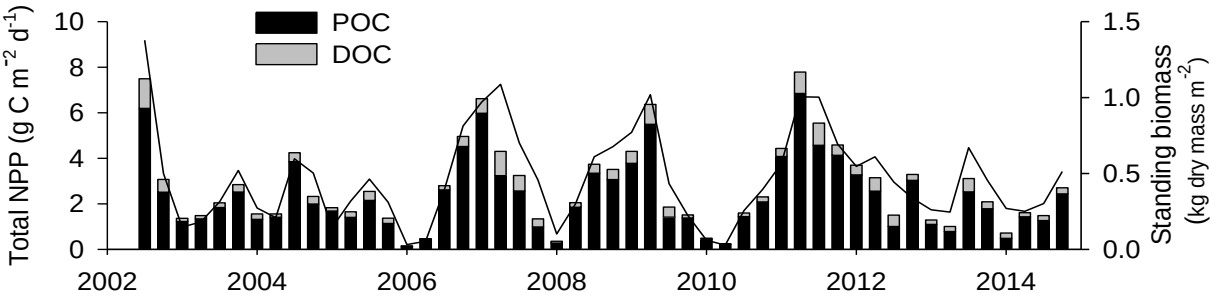

Fig. 4 Modeled estimates of the amount of NPP partitioned into Particulate Organic Carbon (POC) and Dissolved Organic Carbon (DOC). Solid line is monthly measurements of kelp standing biomass.

in reef-scale NPP of DOC (Fig. 4). Importantly, the fraction of NPP released as DOC averaged ~14% of total NPP, which is sufficient to account for the elevated levels of DOC that we previously observed in coastal waters adjacent to giant kelp forests.

Results from laboratory and field incubation experiments specifically designed to study the loss of small detrital particles from kelp blades revealed that unlike DOC, kelp derived POC represents a very small fraction of the particulate carbon suspended in the nearshore water column (Yorke et al. 2013). Moreover, feeding experiments showed that growth of kelp forest suspension feeders was unaffected by suspended kelp detritus (Yorke et al. *in prep*) and stable isotope analyses showed that that positive associations between kelp and sessile invertebrates observed in our long-term data result from the physical structure of kelp rather than its role as a food source (Miller et al. *in press*). Diet studies and stable isotope analyses of kelp forest consumers confirmed, however, that *Macrocystis* is an important source of dietary carbon and nitrogen for invertebrate grazers in the kelp forest and the fish predators that feed on them (Koenigs et al. *in press*). Collectively, these results reaffirm the conclusion from our prior research that small kelp detrital particles do not represent a significant food source to coastal suspension feeders (Page et al. 2008, Miller and Page 2012).

Another potentially important form of NPP that is lost prior to the death of a *Macrocystis* frond is the production by individual blades lost to senescence and grazing. To gain a better understanding of the factors controlling this process, we measured the life span, size, thickness, nitrogen content, pigment content, and maximum photosynthetic rate (P_{max}) of *Macrocystis* blades along a strong light gradient in the kelp forest. We found that shorter blade life spans and larger blade areas were associated with increased light availability, and that nitrogen content and P_{max} decreased with blade age (Rodriguez et al. Oecologia *in review*). These findings are consistent with the predictions of leaf life span theory developed for land plants and represent the

first application of this theory to marine macroalgae. We are in the process of incorporating these results into our model of kelp NPP to account for the proportion of frond biomass lost to blade senescence and grazing prior to the death of the frond.

THEME 1C. Effects of fishing on kelp forest structure and function

Fishing can trigger trophic cascades that alter community structure and dynamics and thus modify ecosystem attributes. We combined our time series data of sea urchin and macroalgal abundance with fishery data on landings of spiny lobster to evaluate whether: (1) patterns in the abundance and biomass of lobster (a key kelp forest predator), sea urchins (the major kelp forest grazer and an important prey of lobster), and macroalgae in giant kelp forest communities indicated the presence of top-down control on urchins and macroalgae, and (2) harvesting lobster triggers a trophic cascade leading to increased sea urchin densities and decreased macroalgal biomass (Guenther et al. 2012). We found a trend towards decreasing urchin density with increasing lobster abundance, but little evidence that urchins control the biomass of macroalgae. With one exception, sea urchins remained more abundant at heavily fished sites, supporting the idea that fishing for lobsters releases top-down control on urchin grazers. Macroalgae, however, were positively correlated with lobster fishing intensity, which contradicts the trophic cascade model. The recent establishment of marine protected areas (MPAs) by the State of California at two of our study sites provided us with an unique opportunity to experimentally test the effects of fishing on kelp forest structure and function. The effects of fishing are becoming apparent after only four years of protection as the biomass of lobster and macroalgae have shown proportionally larger increases at the two protected sites compared to three fished sites and proportionally larger decreases in the biomass of sea urchins (Fig. 5). These preliminary patterns are consistent with a trophic cascade model. We plan to follow the changes in the kelp forest communities at these sites over the long term as the effects of protection from fishing typically take a decade or more to fully develop.

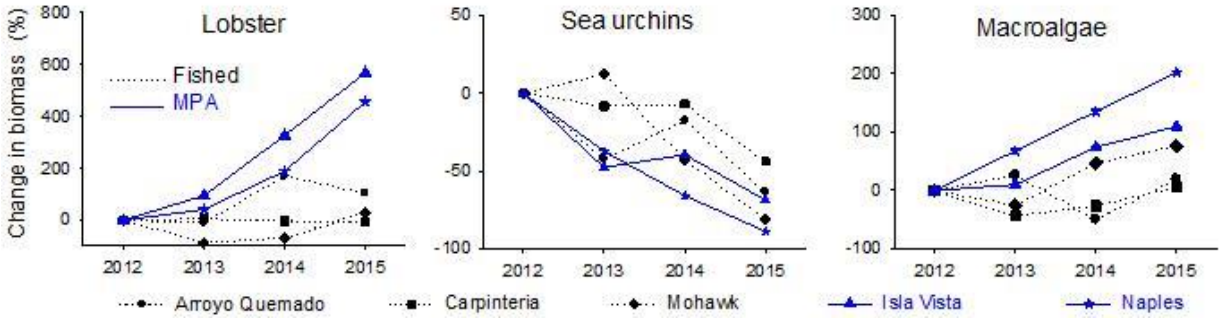

Fig. 5. Percent change in the biomass of spiny lobster (predator), sea urchins (herbivore) and macroalgae (primary producer) at three sites open to fishing and two sites recently protected from fishing.

The effects of protection from fishing in MPAs may also be manifested as behavioral responses of predators as well as numerical responses. With support from an NSF Research Opportunity Award we collaborated with colleagues from Chapman University to test whether prey reductions in MPAs caused lobsters to broaden their diet to include less palatable prey that are ignored outside reserves. We found that lobsters attacked unpalatable sea hares exclusively inside old (> 20 years) MPAs, where lobster density was high and prey density was low; no attacks were observed in fished areas, or in a more recently established (9 year old) MPA (Berriman et al. 2015). Palatable market squid were attacked equally inside and outside reserves. Such trait-mediated effects on predators are likely to amplify the ecological effects of MPAs.

We also initiated studies inside and outside of MPAs to determine whether fishing increased susceptibility to invasion by the introduced seaweed *Sargassum horneri,* which is an aggressive invader that is rapidly spreading throughout California and Baja Mexico (Marks et al. *in press*).

Data collected to date show higher densities of this aggressive invader outside reserves compared to inside reserves. Research aimed at determining the factors facilitating and inhibiting the spread of this species and the ecological consequences of its invasion is ongoing.

THEME 2. Material exchanges at the land-ocean margin

Coastal watersheds, estuaries and beaches in southern California are subject to highly episodic environmental drivers that operate over scales of seasons, years, decades and millennia, including the warm and cool phases of ENSO and the PDO. The resulting large temporal and spatial variability in the fluxes of materials from land to the coastal ocean requires a multi-tiered research approach to capture the full range in the magnitude of fluxes and their responses to changes in climate, land cover, fires and sediment dynamics. We are using long-term measurements, remote sensing, experiments, stratigraphic analyses and modeling to understand how watersheds and coastal margins interact with nearshore waters and kelp forest ecosystems, the processes that cause these interactions to fluctuate in time, and to address the general question: *How do the inputs of dissolved and particulate nutrients from watersheds and coastal margins to nearshore waters vary as a function of land use, disturbance by fire and storms, seasonality and longer-term climatic variations?*

THEME 2A Export of nutrients from watersheds

The export of nutrients and sediments from watersheds via streams is one component of material exchange between the land and the coastal ocean. To measure these fluxes, streams are sampled hourly during storms, and weekly or biweekly throughout the year. Samples are analyzed for dissolved inorganic and organic nitrogen and phosphorus and particulates. In situ data loggers measure stream stages which are converted to discharge; rainfall is measured with a distributed network of tipping bucket gauges.

Streams in eight watersheds representing different land uses and fire histories result in variable fluxes of nitrate to the coastal ocean (Fig. 6). Annual nitrate fluxes (moles nitrate ha^{-1} y^{-1}) from these watersheds varied 2 to 5 orders of magnitude during the period from 2002 to 2014. The greatest variation occurred in watersheds that experienced fires. Highest median fluxes occurred in watersheds with agricultural activity. During water years (WYs) 2012 to 2015 California has experienced drought with few rainstorms and reduced runoff (annual rainfall in Mission Creek watershed was 344, 273 and 191 mm for WYs 2012, 2013 and 2014; mean from 1970 to 2010, 561 mm). As a result, fluxes of nitrate and other constituents have been low (e.g., 31 moles nitrate ha^{-1} y^{-1} in WY 2014 versus 232 moles nitrate ha^{-1} y^{-1} in WY 2011).

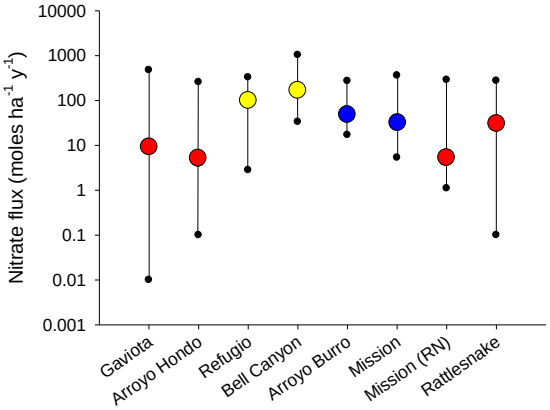

Fig. 6. Annual nitrate fluxes for eight coastal watersheds (arranged west to east from left to right) for 2002 to 2014. Values are the median (red = burned, yellow = agriculture, blue= urban) and range (black) calculated for all years.

Concentration versus runoff relationships in six coastal watersheds revealed how land use and watershed hydrology interact to regulate solute inputs to streams and downstream aquatic ecosystems. We found consistent hyperbolic relationships between stream nitrate concentrations and runoff patterns within three broad land use classes: dilution in agricultural watersheds, invariance in urban watersheds, and enrichment in an undeveloped watershed (Goodridge and Melack 2012). These analyses indicate that undeveloped, upland regions of the watersheds play an important role in determining stream nitrate concentrations and nitrate flux to the Santa Barbara Channel.

Particulates suspended in coastal streams can cause turbid conditions in nearshore waters and contain considerable amounts of nitrogen, phosphorus and carbon that can be mineralized in coastal sediments. We found that suspended-sediment concentrations in SBC watersheds vary over five orders of magnitude (1 to > 100,000 mg L^{-1}; Warrick et al. 2015). Sediment concentrations were weakly correlated with discharge, and several hysteresis patterns were observed during high flow events. Annual sediment yields varied 400-fold across the four watersheds investigated, and sediment discharge was elevated in one watershed that was partially burned by a late summer wildfire. Dozens of high flow events provided evidence that suspended-sediment yields were generally related to peak stream discharge and that watersheds smaller than 100 km^2 can provide large fluxes of sediment to the coast.

Mineralization and nitrification rates in chaparral ecosystems at varying stages of recovery from fire were measured and laboratory experiments were conducted to understand the influence of pH, charcoal from fires, and ammonium supply on N cycling in soils (Hanan et al, *in review*). Nitrate production was highest in the most recently burned sites, but was limited by the availability of ammonium. When ammonium concentrations were sufficiently high, pH determined the relative proportion of inorganic N that was nitrified. Charcoal slightly augmented the effects of elevated pH and ammonium on nitrate production during the early stages of incubation in the 1 and 4-year post-fire sites, while it slightly dampened their effects by week 8. In 20 and 40-year old chaparral, charcoal had no effect. In summary, nitrification is constrained by ammonium supply, though increases in pH that occur after a fire can enhance nitrification rates when substrate is available. Charcoal may enhance N cycling immediately after fire, but impacts are short-lived.

Our modeling framework combines and revises two models that we previously have applied to the study area. The first is a rainfall-runoff model (Beighley et al. 2005, 2008) and the second is RHESSys, a hydroecological model (Shields and Tague 2012). After implementing an hourly time step to the runoff algorithm in the RHESSys model and adding a subsurface water table threshold, the revised model was calibrated and validated with observed data from LTER sites (Chen et al. *in preparation*). This version of RHESSys is now being used to model the nitrate versus concentration patterns described by Goodridge and Melack (2012). In addition, we incorporated results from our field and laboratory studies of fire influences on nitrogen cycling in soils into the RHESSys framework. We modeled mineralization, nitrification, N leaching, NPP, and plant uptake under a range of climate and fire timing scenarios. Modeling results suggest that chaparral systems are vulnerable to rapid nitrification and leaching immediately after fire, however recovering plants rapidly immobilize soluble N under most climate scenarios. Notably, following drier years, NPP and plant N-uptake recovered more slowly. In cases where drought and fire were followed by heavy rain, nitrate losses were more severe, which can further slow plant recovery and promote a positive feedback on N export.

The Hillslope River Routing (HRR) model developed for other regions of the world by SBC Investigator Beighley and colleagues includes terms for surface, soil and groundwater storage, infiltration, soil drainage to groundwater, surface runoff, shallow soil flow, groundwater flow, and channel discharge. We applied the HRR model to all the catchments in the SBC study domain to extend our earlier work (Beighley et al. 2003, 2005 and 2008). We are combining downscaled climate data with outputs from ten climate models provided by colleagues at Scripps Institute of Oceanography to examine how climate change may influence runoff. These analyses, still in progress, indicate that downscaled rainfall forecasts cannot generate high streamflow and tend to overestimate low flows; most models suggest potential changes in streamflow from -40% to +50%).

THEME 2B. Trajectories of landscape changes in coastal watersheds

An important aspect of material input to nearshore waters is how disturbances, such as fire, urbanization and agriculture, alter the landscape to modify these inputs. Recent changes, in response to wildfires that occurred in 2008 and 2009, were examined using Airborne Visible Infrared Imaging Spectrometry (AVIRIS) data acquired prior to the fires and on multiple dates following the 2008 Gap and Tea fires and the 2009 Jesusita fire (Fig. 7). Our analyses of AVIRIS data includes quantifying pre-fire fuel conditions, fire severity and monitoring post-fire recovery of biomass and plant nitrogen and water content. Species composition and land cover were mapped using Multiple Endmember Spectral Mixture Analysis, and post-fire canopy biochemistry mapped using spectral fitting and partial least squares regression.

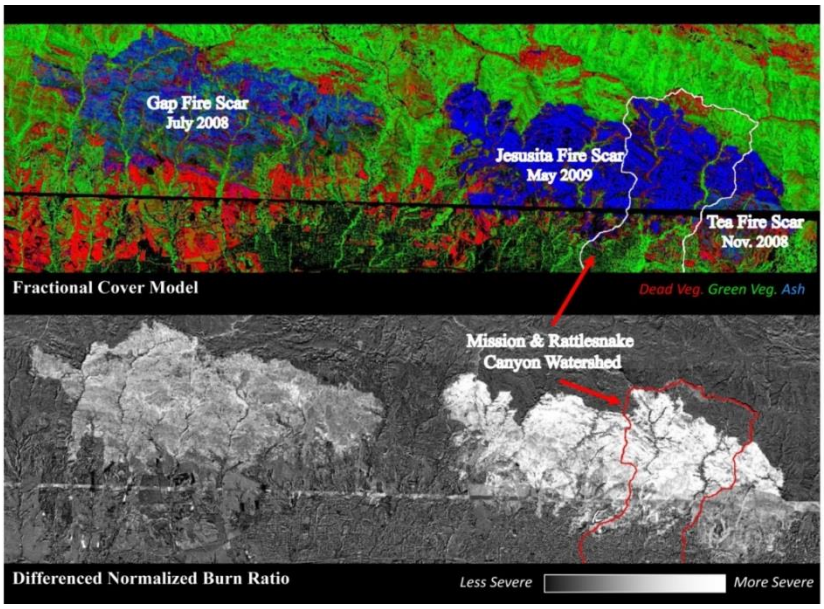

Fig.7. Fire scars on the Santa Barbara front range. The upper frame shows a mixing model of non-green vegetation (NPV, red) green vegetation (GV, green), and ash (blue). The 2007 Gap, 2008 Tea and 2009 Jesusita fires appear as areas with high ash content (blue) with high levels of NPV due to one year of post-fire regrowth by forbs and grasses. The lower frame shows a Difference Normalized Burn Ratio (dNBR), a measure of fire severity. The Jesusita fire consisted almost entirely of a high severity fire. Lower dNBR in the Gap and Tea fire scars are a product of some regrowth leading to apparent lower levels of severity. However, variation in dNBR in the Gap fire indicates variability in fire severity.

Initial results reveal changes that occurred as a result of the fires and post-fire landscape recovery are related to interannual variation in precipitation. All fire scars had a spike in ash and exposed soil cover, and a decrease in green vegetation. The two 2008 scars showed little recovery in 2009. Following the rainy season in 2010, green vegetation increased from less than 10% to over 50%, and exposed soil decreased to less than 10%, within both the 2008 scars and the more severely burned 2009 scar. The apparent dependency of landscape recovery on interannual climatic variation, rather than fire severity, has important implications for coastal water quality given the higher erosion potential for exposed soils and the potential for future climatic variability.

We extended the time scale of our examination of landscape changes by analyzing sediment cores collected from accumulated deposits in two estuaries (Goleta and Carpinteria) and a coastal pond (Dune Pond) that border the Santa Barbara Channel. The redistribution of sediment is largely controlled by low frequency, high magnitude events. These events are controlled by tectonic processes such as earthquakes and associated tsunamis, climatic or weather related events such as flooding and changes in precipitation patterns, and land-use changes associated with European colonization. Historical accounts of a possible tsunami in 1812 have remained untested, but cores from Carpinteria Slough and Dune Pond contain a sand layer with the characteristics of a tsunami (single graded bed), which with the available chronological constraints appears to have been deposited at about this time. At its thickest, the sand deposit within Carpinteria Slough is up to 50 cm thick.

Historical accounts suggest that low-frequency but very high magnitude floods have occurred. We found evidence of three periods of rapid infilling in Carpinteria Slough over the

middle to late Holocene (last 6,000 year). In addition, pollen profiles from Dune Pond reveal shifts in pollen and sedimentary character that record climate change over the last 4,000 years. Furthermore, pollen profiles collected from Dune Pond record an order of magnitude increase in sedimentation rates since European colonization and a change in plant assemblages and fire frequency brought about by land-use changes.

THEME 2C. Exchanges of nutrients on beaches

Sandy beaches that line the Santa Barbara coast are recipients of large amounts of kelp wrack exported from shallow rocky reefs (>500 kg m^{-1} yr^{-1}; Dugan et al. 2011) with peak inputs of wrack typically in the autumn (Revell et al. 2011). These kelp inputs provide a major subsidy to intertidal food webs (Dugan et al. 2003). In this award we are investigating the role of beaches in the exchange of nutrients by examining kelp wrack inputs to beaches, wrack shredding by intertidal consumers such as talitrid amphipods and the biogeochemical processing and fate of macroalgal wrack and other sources of coastal particulate organic matter (POM) in intertidal beach porewater. We are studying how the dynamics of talitrid amphipods (which exhibit strong temporal variability in zonation, abundance and biomass; Dugan et al. 2013) affect the fate and processing of kelp wrack subsidies (Fig. 8) and subsequent nutrient cycling. Episodic events, like ENSOs, that erode beaches can strongly modify seasonal patterns of sand accretion, wrack inputs and consumer abundance (Revell et al. 2011). Our ongoing measurements spanning a 2014 storm-induced erosion event show slow recovery of beach sand, and talitrid populations, which affected rates of wrack consumption and processing.

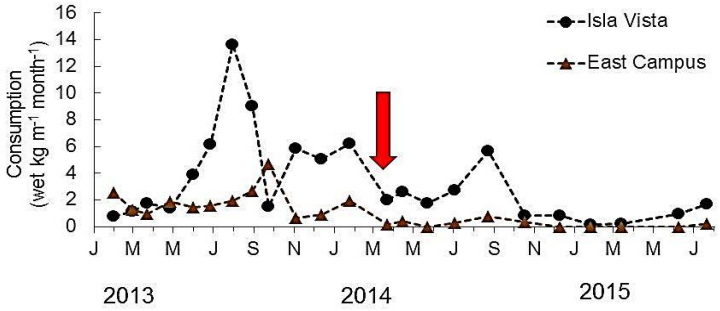

Fig.8. Estimated monthly consumption of *Macrocystis* by talitrid amphipods per meter of shore at two beaches during 2013-2015.

Concentrations of dissolved inorganic nitrogen (DIN) and dissolved organic nitrogen (DON) in intertidal pore water of sandy beaches can vary 1000 fold among SBC beaches and are positively related to the biomass of macroalgal wrack (Dugan et al. 2011). Stable carbon isotope analyses indicated a greater influence of kelp wrack inputs in pore water POM and in consumers at sites with wider upper beach zones compared to those at sites with narrow or absent upper zones. Using piezometers we found ammonium was the dominant form of dissolved nitrogen in beach pore water (Goodridge and Melack 2014**)**. Using the naturally generated radioisotope ^{222}Rn, we determined that the residence times of pore water was positively correlated with tidal amplitudes and ranged from 4.4 to 6.4 days (Goodridge and Melack 2014**)**. Concentrations of DOC and DON and the proportion of DIN to DON in pore water increased with residence time due to enrichment of dissolved nitrogen by microbial processing. The ratio of DOC to total dissolved N in pore water was correlated with residence time and DIN concentration. Based on calculations of the flux of DIN to nearshore waters we estimated that beaches can supply DIN at levels similar to other routes (streams, upwelling and internal waves) to a zone within 50 to 100 m from shore, a region occupied by abundant macroalgae and sea grasses. Our results suggest that spatial and temporal variability in the residence time and DIN concentration of pore water and in the abundance and composition of wrack consumers can influence delivery of DIN from intertidal beaches to the coastal ocean.

THEME 3. Movement and fluxes of inorganic and organic matter in the coastal ocean

We are using existing long-term data, new data collected from focused sampling, and modeling of coastal ocean circulation to investigate the general question: *How do oceanographic processes act to influence: (a) the dilution and dispersal of freshwater runoff plumes, (b) nitrogen recycling and efflux from benthic sediments within and adjacent to kelp forests, and (c)*

the fate of net primary production by phytoplankton? Our activities and accomplishments in this area of research during the past three years are summarized below.

THEME 3A. Dilution and dispersal of freshwater runoff plumes

The dispersion and dilution of creek runoff has important applications for ecological processes and pollution management. In southern California creek runoff events are both episodic and short-lived and the plumes are buoyant, making it challenging to measure their spatial/temporal evolution. We use ultra-high spatial resolution (100 m) Regional Ocean Modeling System (ROMS) circulation modeling to study the structure and evolution of freshwater runoff and associated passive tracer dispersal from Mission Creek (MC) and Arroyo Burro (AB) into the Santa Barbara Channel (Romero et al. *in review*). Plume evolution is tightly coupled to freshwater discharge, wind forcing and submesoscale flow structures. During flooding, winds are typically onshore causing downwelling and retention of freshwater plumes close to shore (Fig. 9a). Following the peak in discharge, the winds slacken and shift towards upwelling favorable conditions. Consequently the plumes are advected offshore and the tracer field is diluted by the ambient circulation (Fig. 9b-d). This pattern held for all seven of the storms simulated. Tracer concentrations dilute rapidly from values of ~1 near the creek mouths to concentrations many orders of magnitude lower offshore. Plumes reach the bottom in the inner 1 km, but form thin layers at the surface offshore that are a few meters thick.

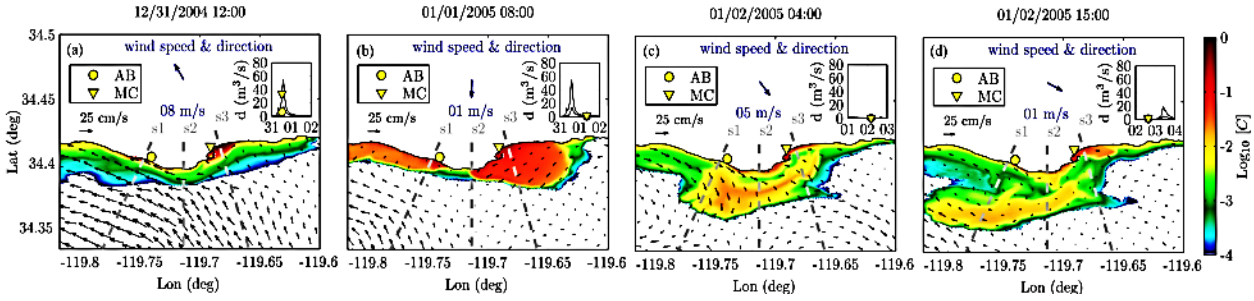

Fig. 9: Evolution of surface tracer concentrations (log base 10) during the first storm of W04-05. The black vectors show surface currents. AB and MC are shown with yellow circle and triangle, respectively. The in set shows the hydrographs and corresponding instantaneous discharge rates from AB (circle) and MC (triangle). Wind speed and direction are shown in blue. Movie for this event is available for QuickTime or Windows.

Statistical analysis of the dilution of passive tracers shows strong anisotropic spatial dependency. Tracer concentrations above 10% dilution are found against the coast and near the discharge locations. Strong cross-shelf gradients are still observed for a dilution of 0.01%; however, the probability of finding tracer concentrations > 0.01% of the discharged value is no longer tightly constrained to the coast. Further, scale dependent diffusivities from measurements and subsequent plume dispersion analyses are qualitatively consistent with our simulations of nearshore particle-pair dispersion (Romero et al. 2013) providing a path for modeling their impacts on nearshore ecosystems (see Theme 3C summary).

THEME 3B. Nitrogen recycling and efflux from sediments

Unlike many plants on land giant kelp has a limited capacity for internal nitrogen storage, and the rocky substrata upon which it grows offers little potential as a source for nitrogen uptake. Consequently, the high net primary production of kelp forests is maintained primarily by a continuous, but variable, supply of nitrogen (N) from the surrounding ocean and adjacent landscape. Analyses of our monthly time series data on kelp growth, elemental composition and nutrient concentrations in seawater revealed a large number of instances when relatively high growth rates and kelp nitrogen coincided with ambient seawater nitrate concentrations that were < 1 µmol L^{-1}, which is lower than that needed to sustain kelp growth (Brzezinski et al. 2013). To help resolve this apparent discrepancy between nitrate concentration and the growth and N

content of giant kelp in the Santa Barbara Channel, we investigated several routes of nitrate supply to the kelp forest (e.g., upwelling, internal waves, terrestrial runoff and "other" oceanographic processes to determine whether they are collectively of sufficient magnitude and have enough complementarity over time to sustain the levels of kelp growth that we measured across seasons (Fig.10). Our analyses show that while upwelling and internal waves occur throughout most of the year they deliver little nitrate except in spring and early summer. Other

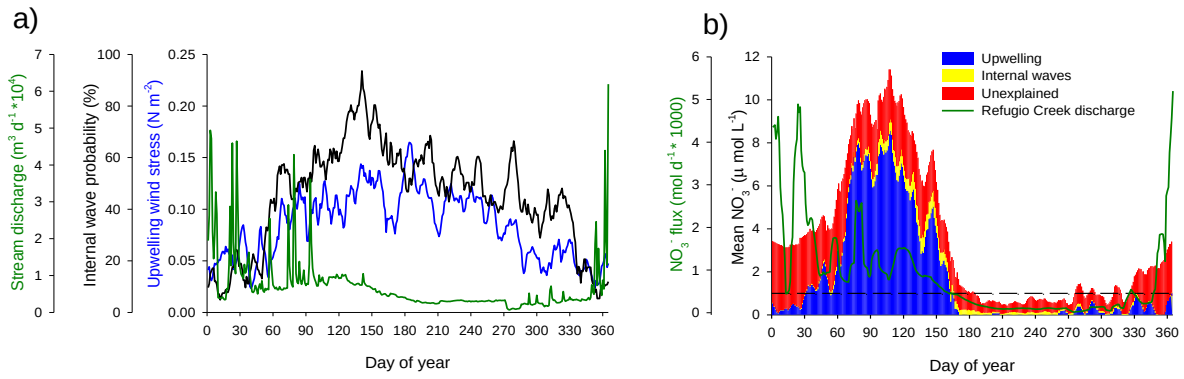

Fig. 10. (A) Seasonality in the mechanisms delivering nitrate to the Arroyo Quemado kelp forest. (B) Concentrations seawater nitrate at Arroyo Quemado kelp forest delivered from upwelling, internal waves and unexplained marine sources and the discharge of nitrate from nearby Refugio Creek. Dashed horizontal line represents the lower limit of nitrate below which kelp growth is not sustained. See Brzezinski et al. 2013.

oceanographic processes (e.g., coastal trapped waves and coastal eddies; Washburn and McPhee-Shaw 2013) appear to supply sufficient nitrate in winter to sustain kelp growth even in the absence of storm runoff from land. As a result the supply of nitrate to kelp forests in the SB Channel during mid-summer through autumn is generally inadequate to support kelp growth, suggesting other forms of recycled nitrogen fill this deficit (Fram et al. 2008). Our 14-year nutrient time series obtained from monthly water samples suggests that benthic sources of ammonium may fill this deficit. We have begun testing prototype chambers for measuring efflux of ammonium from sediments, have recruited a PhD student interested in biogeochemistry of sediment water exchange and we are recruiting a PhD student to examine excretion rates by kelp forest consumers. A 2-3 year research campaign on nitrogen recycling and the rates and sources of ammonium efflux from sediments is planned for 2016.

THEME 3C. Transport and fate of phytoplankton NPP

Our prior research has shown that high phytoplankton primary productivity in the Santa Barbara Channel is mainly localized to the shelf along the mainland coast, the western channel along the northern coasts of the Channel Islands, and a region of counter-clockwise flow over the Santa Barbara Basin (Brzezinski and Washburn 2011, Goodman et al. 2012). Phytoplankton also enter the Channel from the strong coastal upwelling system north of Pt. Conception, which serves as an important subsidy for kelp forest suspension feeders in the region (Miller et al. 2013). Results from SBC I and II showed that cross-shore processes such as internal waves, internal tides, freshwater plumes, and coastal eddies can rapidly transport phytoplankton, nutrients, and other subsidies to kelp forests (Bassin et al. 2005, McPhee-Shaw et al. 2007 and Fram et al. 2008. More recent results by Goodman et al. (2012) and Halewood et al. (2012) suggest that cross-shelf processes extend across the inner shelf in spring, but dissipate in summer and fall when stratification is high causing the inner shelf to become more isolated. There are remaining uncertainties about how cross-shore processes control delivery of subsidies to nearshore habitats. In our current research we are using an autonomous ocean glider with bio-optical sensors to examine cross-shelf exchanges of phytoplankton and suspended sediments on time scales of hours to weeks near the Mohawk kelp forest (Fig. 11). We observed events of rapid evolution and onshore transport of a phytoplankton plankton bloom across the mid-shelf

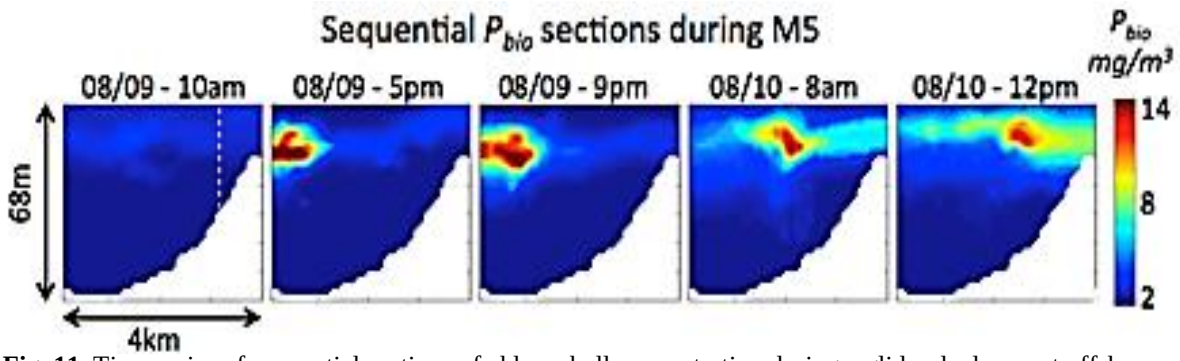

Fig. 11. Time series of sequential sections of chlorophyll concentration during a glider deployment offshore of the Mohawk kelp forest. The mean time and date of each section is shown above each section.

and inner-shelf and strong correspondence with sediment loads and surface wave forcings (Henderikx Freitas et al. *in review*). We are also working to understand the dynamics of these events with the goal of quantifying factors such as the cross-shore fluxes of nutrients, dissolved oxygen and particulate and dissolved organic carbon.

There are uncertainties about other pathways of phytoplankton transport that do not result in their delivery to near-shore habitats. To address these uncertainties we have been examining the removal of phytoplankton from the euphotic zone by water mass subduction at convergent density fronts (Washburn et al. *in review*). Vertical chlorophyll and density sections across the Santa Barbara Channel from four oceanographic cruises show extensive areas of chlorophyll below the euphotic zone (Fig. 12). The similar chlorophyll and density patterns indicate subduction at density fronts where water masses collide. Vertical velocities > 30 m day^{-1} occur at these fronts. Two pathways for the subducted phytoplankton were identified: (1) transport to depth out the eastern channel entrance, and (2) upward transport back into the euphotic zone and recirculation in the channel. Study results indicate that subduction rates of particulate organic carbon greatly exceed rates due to gravitational sinking in the channel.

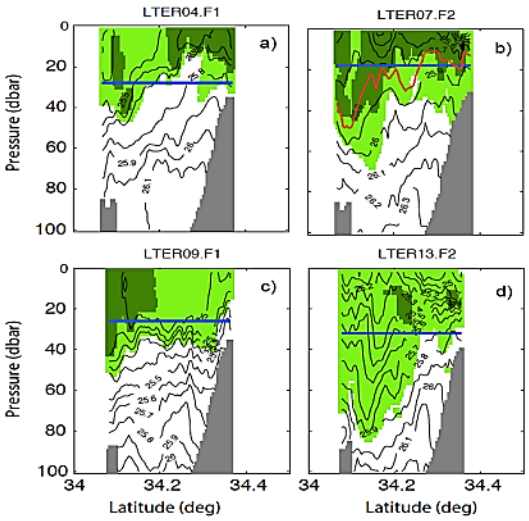

Fig. 12. Sections across the SBC of potential density anomaly σ_θ in kg m^{-3} (black lines) and chlorophyll concentrations (> 1 mg m^{-3} light green; > 5 mg m^{-3} dark green) from 4 cruises. Horizontal blue lines show 1% light depths.

We have used high resolution (250 m and 100 m) ROMS simulations to understand and parameterize nearshore particle dispersion for different sites across the Southern California Bight (Romero et al. 2013). We found that eddy kinetic energy levels were much lower in embayments compared with headlands and these differences were also found in directional eddy diffusivities determined from two-particle statistics (Fig 13). Particle diffusivities were strong functions of distance offshore and alongshore diffusivities were much larger than cross-shore diffusivities with this difference decreasing offshore. Directional particle dispersion was successfully parameterized in a power-law model as a function of coastal geometry, distance from the shore, energy of the flow, including that due to submesoscale straining rates. These results provide us with valuable tools for addressing cross-shelf exchanges in complex topographic environments.

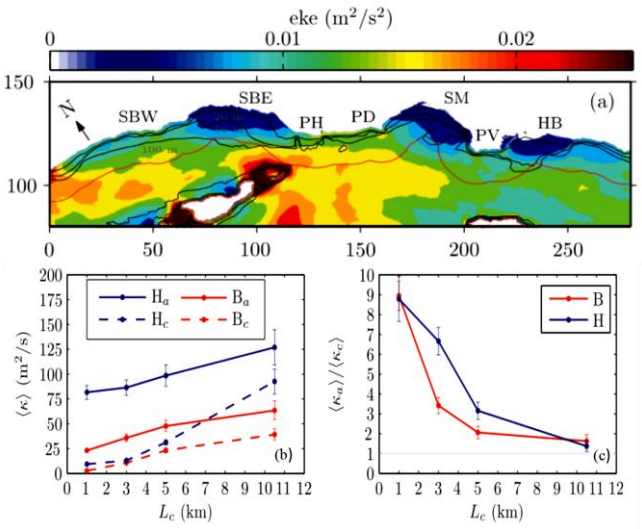

Fig. 13. A) Eddy kinetic levels for 250 m resolution ROMS simulation of the Southern California Bight. Particle release sites are shown starting from Santa Barbara West (SBW) and continuing to Huntington Beach (HB). B) Composite directional relative diffusivity values increase as a function of distance offshore (L_c) and are greater for headlands (blue; SBW, PH, PD & PV) than embayment (red; SBE, SM & HB) sites. C) Along-shelf diffusivity values (*a* subscript) are also greater than cross-shelf diffusivities values (*c* subscript) and this difference decreases as a function of L_c.

RESPONSES TO PERCEIVED WEAKNESSES RAISED IN PANEL SUMMARY OF SBC III PROPOSAL

Weakness: *This study has not yet provided sound justification that land-based inputs of nutrients play a significant role in any aspect of kelp dynamics*
Response: We agree that we have yet to demonstrate that land-based inputs of nutrients play a significant role in kelp dynamics, although particulate load appears to moderate reef food webs. Although the severe drought in California the past four years has hampered our research in this area, our results to date indicate that dissolved nitrogen delivered by streams is typically not needed to sustain kelp growth throughout the year (Brzezinski et al. 2013). Our results from hydrogen isotope analyses, however, show that terrestrially derived particulate organic matter is broadly distributed in nearshore sediments, and our finding of ^{15}N enrichment in kelp forest invertebrates with increasing influence of runoff suggests that terrestrially derived N enters the kelp forest food web indirectly through a trophic intermediary, such as microbes or benthic algae (Page et al. 2008). SBC III is continuing this line of research through: (1) determining landscape and climate effects (as modified by fire and rain) on fluxes of dissolved and particulate matter to the coastal ocean by a combination of modeling, experiments and measurements (see Theme 2a in **THEME RESEARCH**), (2) evaluation of very large, episodic inputs of particulates determined from sediment cores in coastal sloughs (see Theme 2b in **THEME RESEARCH**, and (3) determining the extent to which the efflux of ammonium from nearshore sediments is of terrestrial origin (see Theme 3b in **THEME RESEARCH**).

Weakness: *The effect of runoff plumes from the land was not developed*
Response: The dispersion and fate of runoff plumes in the coastal ocean is an active area of SBC research that is being investigated primarily through the use of Regional Ocean Modeling System (ROMS) simulations of creek runoff with a horizontal resolution of 100 m which predict substantial concentrations of runoff materials at SBC kelp forests (see Theme 3a **THEME RESEARCH**). Their potential effects on the kelp forest community is an active area of investigation (see Theme 3b **THEME RESEARCH**)

Weakness: *The plan for measuring long-shore transport of phytoplankton is not adequate as presented (one glider will not be sufficient for assessing both long- and cross-shelf transport)*
Response: Our approach to measuring the transport of phytoplankton is multifaceted and includes sophisticated modeling of ocean circulation using high resolution ROMS solutions as well as data from synoptic shipboard cruises, ocean color satellite data, HF radar current

observations, our moored sensor array and autonomous glider (see Theme 3c in **THEME RESEARCH**).

Weakness: *The objectives of the kelp removal experiment to mimic wave disturbance were not clear*
Response: The rationale for and results from the kelp removal experiment are described in Theme 1a in *Summary of activities and accomplishments in of programmatic research.*

Weakness: *The importance of acidification as an ecosystem level climate change driver should be considered and monitoring of pH, pCO2, total alkalinity and/or total DIC should be included*
Response: We agree that ocean acidification (OA) is an emerging and potentially important climate driver in our system. However, incorporating detailed investigations of the effects of OA into the conceptual framework of SBC III was beyond the scope of our budget. Generous supplemental funding from NSF in 2014 and 2015 is enabling us to enhance our capacity to measure important parameters of the carbonate system, and SBC investigators are actively seeking collaborative funding to pursue research on the myriad effects of OA and hypoxia in the SBC study domain.

Weakness: *Temporal and spatial variation in land use, as opposed to land cover, could be incorporated to better model watershed effects*
Response: Land use varies among the watersheds included in our study and include agriculture (primarily orchards, some grazing plus greenhouses and plant nurseries in a few watersheds), suburban housing and urban developments as well as largely undeveloped uplands. A detailed analysis in the Carpinteria area examined nutrient export associated with specific land uses (Robinson et al. 2005; Robinson and Melack 2013). A recent review paper with contributions from Melack examined effects of land use changes on Mediterranean stream ecosystems (Cooper et al. 2013). Ongoing remote sensing and modeling is focused on improved characterization of land use/covers and incorporating this information into hydrological and biogeochemical models.

Weakness: *Collaboration with other LTERs was not described. Recommend pursuing collaborative work with similar systems outside of the LTER*
Response: We describe our collaborations with other LTERs in the section *Cross-site and broader-scale syntheses* of this document, and we also detail our efforts in pursuing collaborations with ecologists working in kelp forest systems outside the LTER.

III. CROSS-SITE AND BROADER SCALE SYNTHETIC RESEARCH

SBC has been very active in cross-site and broader scale synthetic research, in part because our efforts in this area were perceived as a weakness by the NSF panel that reviewed the proposal for SBC III, but also because cross-site and broader scale synthesis is a natural direction for our ongoing research. Below we list progress made in this area during the first three years of our current award.

LTER NETWORK CROSS SITE PROJECTS

Investigator Dugan is leading a cross-site LTER working group that is synthesizing the ecological responses of soft sediment ecosystems to shoreline armoring and sea level rise. Investigators, postdocs and students from GCE, VCR, SBC, FCE and PIE were involved in the two meetings which have resulted in poster presentations and a draft manuscript for publication.

Investigator Page led a cross-site LTER study between SBC and MCR that showed the use of stable nitrogen isotope analysis to assess the trophic position in of reef consumers in kelp forests of California and coral reefs of Polynesia compared favorably to published observations of diet. Their findings published in a special issue of *Oceanography* (Page et al. 2013) revealed that higher level fish consumers in both systems feed lower on the food than previously thought.

Investigator Brzezinski and former SBC post doc Krause participated in a cross-site three-week oceanographic process cruise with CCE to investigate how physical and chemical dynamics in frontal regions influence diatom productivity and abundance. This work produced two manuscripts, each with authors from both SBC and CCE. Brzezinski et al. (2015) explores the influence of iron stress on diatom silicification and resulting impact on the vertical export of diatom carbon. Krause et al. (2015) quantified the importance of diatoms versus other phytoplankton to phytoplankton biomass, organic matter production and carbon export.

As a follow up to an international effort that examined the changing role of history in restoration ecology (Higgs et al. 2014), Investigator Guerrini organized and led a special session on the use of history in the LTER network at the 2015 ESA meeting in Baltimore that included contributions from SBC, AND, CWT, BES, HFR, and MCM. She then led a product-oriented working group at the recent 2015 LTER All Scientists Meeting to develop options for publishing LTER cross-site historical studies. As a result of these workshops, Guerrini is preparing a prospectus for a synthesis volume of history papers, memoirs, and photo essays on the various uses of history and the different kinds of historical evidence at LTER and other long-term research sites for the LTER book series with Oxford Press.

Post doc Castorani, IM O'Brien and graduate student Yorke led cross-site working groups at the recent triannual LTER All Scientists meeting. In addition, SBC scientists are actively participating in ongoing or recently completed LTER cross-site projects on the structure of variability in NPP, the use of the metacommunity concept to synthesize biodiversity, a meta-analysis of nutrient enrichment effects on stream ecosystems and insights from long-term experiments (Smith et al. 2015). PI Reed co-edited a special issue in *Oceanography* highlighting research from the eight coastal LTER sites. SBC contributed five papers to this special issue. Co-PI Holbrook and IM O'Brien contributed chapters to the Oxford LTER Book Series cross-site volume *Long-Term Ecological Research: Changing the Nature of Scientists (in press).*

SBC is one of four LTER sites funded by NSF on a cross site Math Science Partnership (MSP) project that focuses on environmental literacy in K-12 education via the LTER schoolyard program. In collaboration with BES, KBS, SGS, SBC is working with middle school teachers in professional development workshops and in their classrooms to improve student understanding of key environmental concepts, including the water cycle, carbon cycle, and biodiversity. Collectively, the project involves 142 K-12 schools and districts that directly impact over 355 science and mathematics teachers and up to 70,000 students from diverse backgrounds. The project is unique as a LTER cross-site K-12 program.

NON-LTER CROSS-SITE AND BROADER SCALE RESEARCH

Former SBC post doc Byrnes led an NCEAS working group on the global impacts of climate change in kelp forest ecosystems. The working group consisted of recognized experts in kelp forest ecology from around the globe and included SBC investigators Rassweiler and Cavanaugh and graduate student Okamoto. An outgrowth of this effort is the recently formed Kelp Ecosystem Ecology Network (KEEN) spearheaded by Byrnes to assess the impacts of environmental change on kelp forests globally. KEEN includes members from 24 bioregions and six continents who use standardized sampling methods and experimental protocols developed by SBC to create unified open access datasets for assessing past and predicting future changes in kelp forests worldwide. SBC investigators are actively collaborating with KEEN members on a number of synthetic projects including global changes in kelp abundance (Krumhansl et al. *in prep*) and regime shift dynamics of sea urchin grazing (Ling et al. 2015).

Our development of a spatially and temporally comprehensive data set of giant kelp biomass derived from Landsat satellite imagery (calibrated to measurements by SBC divers in long-term study plots) has allowed us to examine environmental drivers of kelp biomass dynamics, population genetics and demographic connectivity at large (> 1000 km) spatial scales with high spatial and temporal resolution (see Theme 1a in **THEME RESEARCH**). Cavanaugh and Byrnes are expanding the capabilities of this dataset to the entire globe by partnering with Zooniverse to develop a web-based citizen science project (Floating Forests) that uses the efforts of volunteers to analyze Landsat imagery of giant kelp from across the world. More than 2 million classifications of > 500,000 images by nearly 6,000 volunteers have been completed to date.

With supplemental NSF funding Investigators Miller and Page and graduate student Yorke are conducting cross-site research with colleagues at the University of Auckland on sources of particulate organic matter in kelp forests and their use by suspension feeders. Their research involves comparisons between New Zealand and California kelp forests, which differ substantially with respect to the physical stature and ecology of the dominant kelp species. Assessing the roles of physical and anthropogenic disturbance and climate are integral to their research as both systems include marine protected areas and are expected to be influenced by climate change.

Additional partnership programs that advantage SBC data and opportunities are listed in VII. COLLABORATIONS WITH FORMAL AND INFORMAL PARTNERS.

CONTRIBUTIONS TO THE LTER NETWORK

SBC actively contributes to the governance, research mission and information management of the LTER Network by serving on a variety of Network wide committees. PI Reed is a member of the LTER Executive Board, the Science Council and the Publications Committee. Investigator Washburn recently completed a 3 year term on the Network Information System Advisory Committee. IM O'Brien recently completed a 3 year term as Chair of the Information Management Committee and currently serves as the Information Management representative on the LTER Executive Board. She also is taking a lead role in working with the IM Committee, the Executive Board and NSF in developing the operational structure for a new LTER Network Data Center.

IV. OUTREACH, EDUCATION, TRAINING, BENEFITS TO SOCIETY

OUTREACH AND K-12 EDUCATION

SBC partners with UCSB's Research Experience & Education Facility (REEF), a teaching aquarium that serves as a marine ecology educational facility for UCSB and K-12 schools and colleges in Santa Barbara and Ventura counties. SBC's Schoolyard LTER (sLTER) program is organized around a theme of kelp forest ecology and is developed around and delivered through the REEF and the Marine Science Institute's *Oceans-to-Classrooms* curricula. Our focus is on long-term connections with underserved, low-achieving schools that include year-round on and off campus programs. SBC sLTER curriculum is rich in STEM content, meets California State Science Standards, Common Core Standards and the Next Generation Science Standards and reached 24,000 students in grades 6-12 in the past 3 years. We continue to develop and adapt marine science lesson plans that engage students with learning about the local environment by incorporating ongoing SBC research and working with project data with the goal of building skills in science learning through activities that move from structured or guided investigation to open-ended inquiry and experimentation. The past three years SBC collaborated with three partnership programs to deliver its sLTER content: 1) the American Association of University Women's Tech Trek Program, an on-campus summer residential science and math program designed to develop interest, excitement and self-confidence in young women entering the eighth grade; 2) an NSF funded Math-Science-Partnership "Pathways to Environmental Literacy", a cross-site project involving 4 LTER sites that seeks to connect LTER research with the professional development of middle school science teachers; 3) and Kids In Nature, a curriculum that emphasizes hands-on, placed based activities in the outdoors,

We are broadening our K-12 outreach efforts by developing a bilingual book (English and Spanish) for the LTER Schoolyard Book Series that highlights material connections between giant kelp forests and sandy beaches. The proposal for the book has been approved and a revised draft is in progress. Other programmatic outreach efforts include: (1) developing SBC's Subtidal Field Guide and a local tidepool field guide into free iPhone applications available on iTunes (a similar iPhone application is being developed for sandy beach ecosystems) and (2) regularly hosting a booth at the Santa Barbara Earth Day Festival to raise public awareness about LTER research. The booth features a virtual kelp forest in which SBC students and staff act as 'dive buddies' for children who tour the forest and collect data on kelp forest species using underwater dive slates This festival attracts 25,000 to 30,000 people each year.

TRAINING AND PROFESSIONAL DEVELOPMENT

UCSB undergraduates have a high propensity to get involved in sponsored research. The SBC LTER contributes substantially in this regard as education and training are tightly integrated into all aspects of our research. During the past three years 10 postdoctoral fellows, 41 graduate students, 11 REU students and 213 additional undergraduate students participated in SBC research. Each year 20-30 undergraduate students receive academic credit to participate in an SBC research training program that runs the entire academic year. Students in the program actively participate in the collection, processing and analysis of core data and many develop their own independent research projects. REU students work closely with SBC researchers on a wide range of topics and most choose to pursue an advanced degree following their undergraduate education. Opportunities for training in public education and student mentoring arise from SBC's partnership with the REEF, which is also designed to provide UCSB undergraduates majoring in Aquatic Biology with training in communicating their knowledge of marine ecology in an educational format. SBC graduate students, post-docs and research staff actively participate in this aspect of undergraduate training which engaged 30-40 undergraduate interns annually at the REEF during the past three years.

SBC graduate student and postdoctoral training is coordinated with several graduate programs on the UCSB campus to promote opportunities for interdisciplinary training in ecology, physiology, geology, geography, hydrology, oceanography, and coastal policy. This enables valuable cross-training on environmental issues pertaining to coastal ecosystems, provides a common language for communicating scientific information on these issues, and contributes to the creation of a diverse scientific community of students and postdocs that fosters a respect and appreciation for other disciplines. Annual graduate seminars hosted by SBC faculty, a student organized cross-site LTER graduate student symposium with MCR and CCE, and the triannual LTER Network's All Scientist Meeting serve to expose SBC graduate students to the culture, diverse research and career opportunities offered throughout the LTER Network.

BROADER BENEFITS TO SOCIETY

We are committed to sharing our research results with resource managers, decision makers, stakeholders, and the general public who are interested in applying our findings to policy issues concerning natural resources, coastal management, and land use. To this end, SBC researchers actively use their expertise and SBC data to inform these entities to the betterment of society. Below are some examples of the broader benefits of SBC research during the first three years of our current award.

- In May 2015 a number of SBC investigators and students were first responders to spilled oil gushing from a ruptured pipeline. The coastline and waters affected by the oil spill include a number of SBC's long-term beach and kelp forest research sites and long-term SBC data collected at these sites has been critical in documenting the structure and dynamics of the natural communities at these sites prior to the spill. We are working with state and federal agencies to collect and analyze data to determine the environmental impacts of the spill and the best possible actions for restoration of impacted areas.
- SBC investigators and students are collaborating with the Bureau of Ocean Energy Management, National Marine Fisheries Service and the Channel Islands National Marine Sanctuary to assess factors affecting the spread and ecological consequences of two recent and rapidly spreading invasive species in southern California (the brown seaweed *Sargassum horneri* and the colonial bryozoan *Watersipora subatra*).
- SBC investigators Dugan, Melack, Page and Reed are working with climatologists from Scripps Institution of Oceanography and coastal geomorphologists from the USGS to provide local city and county officials with a vulnerability assessment of the coastal ecosystems of Santa Barbara County to projected climate change.
- SBC data on reef fish biomass were used in analyses conducted for the California Coastal Commission to validate projections for high-relief artificial reefs in mitigation for the loss of fish standing stocks caused by the operations of a coastal nuclear power plant.
- SBC investigators serve as science advisers for public and non-governmental agencies tasked with managing coastal resources, and SBC III sponsored research has resulted in numerous peer-reviewed publications on the design and efficacy of MPAs in enhancing stocks of harvested species and the fisheries that exploit them, and on the impacts of shoreline armoring on sandy beaches and the ecosystems that they support.

V. INFORMATION MANAGEMENT

SCOPE OF DATA AND METADATA

The data managed by the SBC Information Management System (IMS) are diverse, and include contributions from many scientific disciplines in the major ecosystems of our coastal area: watersheds and streams, beaches, subtidal reefs, and oceans (public data catalog; internal inventory, use guest login). We currently incorporate data from several distinct processing and software environments (e.g., SAS, Matlab, MS-Excel), and are planning for several additional types (e.g., model output, raster data). The system supports products from all SBC's research approaches (e.g., long-term time-series, experiments, short-term measurement-intensive process studies, and synthesis/modeling), plus legacy studies and exogenous reference data. About half of SBC's data products are ongoing time series. Additionally, several scientific collaborators take advantage of SBC's well-established data management policies and practices, and publish their data through our system, and SBC provides expertise and consultation for collaborators as they develop data management plans. With increasing frequency, the IMS is asked to post data specifically to accompany a paper, or to meet other publishication requirements. All SBC metadata conform to LTER best practices for content such as keywords, personnel, geo-location, methods and data accessibility.

Policies

SBC has adopted and posted the LTER General Use Agreement and the Network's "Type I-II" designations. Nearly all SBC data are Type I, i.e., publicly available within 1-2 years of collection or laboratory analysis, although some ongoing electronic data are available much sooner. Type II data (e.g., from a student thesis) is generally held back until the paper is published. In addition, we employ a "Type 0 (zero)" designation for data acquired from outside parties that is often already public (e.g. USGS stream flow), and occasionally republished. SBC's and the LTER Network data policies are available at http://sbc.lternet.edu/data.

INTEGRATION WITH SITE RESEARCH

The SBC IMS has well-developed definitions of data types and processes for their maintenance (IM Plan, Table 1). Time-series datasets are formalized via planning and discussion among scientists and IM staff, have established workflows that encompass the entire data life cycle and are compiled into a single multi-year product to facilitate temporal analyses. Changes in methodology are unavoidable, but because updated regularly, changes to methods are recorded and formats adapted. This practice requires extra effort for us as data providers, but capturing this knowledge ensures that interpretations are valid.

OPERATION, INFRASTRUCTURE AND RESOURCES

Details of the SBC IMS infrastructure can be found in our IM Plan. SBC IMS leverages the Marine Science Institute (MSI) and the UC Santa Barbara campus network infrastructure for servers, user accounts and backups. The organization of the file server remains stable so that users are familiar with its structure, and new users are given an orientation. All research groups have dedicated directories for "final" data products that are intended to be shared between disciplines or to be published. All SBC users may view any data file, but write-access is limited to those responsible for collection and maintenance. With this system, data are available to all SBC members immediately, and easily located and monitored by the IMS personnel.

Margaret O'Brien has served as SBC's Information Manager since 2004 and is responsible for directing scientists and technical staff in the planning of all SBC data packages, and in creating or maintaining software for package production. The Moorea Coral Reef LTER (http://MCR.lternet.edu) is co-located at MSI, and the two sites have jointly planned all new IMS projects since 2009. As a result, a priori, IMS improvements are planned with broad input and with leveraging or future redistribution in mind. Additionally, each site's IMS staff is well acquainted with the other system, and capable of acting as back up personnel as needed.

Communication between SBC leadership and the IM group is fostered by the SBC LTER IMS Advisory Committee chaired by co-PI Melack.

SBC's IMS is documented at several levels: (1) as a general Information Management Plan which is updated annually and reviewed internally by the Advisory Committee, (2) as an IM Guide (as Wiki and text), whose intended audience is the IM staff or assistants, and (3) as detailed schematics and descriptions of individual system components (Wiki and text). The IM Plan is available through the SBC LTER website (http://sbc.lternet.edu/info_management); the IM Guide and project documentation is intended for internal use and a guest login is available for reviewers.

RECENT IM ACCOMPLISHMENTS AND PROGRESS ON PROPOSED WORK

The SBC IMS already meets or exceeds all expectations for LTER sites. Below we highlight several recent IMS projects (***Milestones*** refer to those listed in SBC III proposal).

- **2012**: Completed application with map layers for time series sampling sites (***Milestone a***)
- **2012-2013**: Ported and populated the relational model GCE LTER "Metabase2", collaboratively with MCR LTER. Created export code for EML dataset generation (***Milestone b***). We continue to upgrade all SBC data handling protocols for integration with new centralized metadata storage.
- **2013**: Initial contribution of all SBC data the LTER Network Information System (NIS) Provenance-Aware Synthesis Tracking Architecture (PASTA), (***Milestone c***). Contributions are ongoing. As part of the Network's adoption of a new cataloging system, SBC's local catalog was decoupled from older storage, and DOIs integrated into package metadata display in 2014.
- **2013-2014**: Develop new data products related to ocean carbon cycle measurements, including both discrete, manually collected pH samples, and ongoing time series of post-processed data for integration with other SBC data products. SBC has led community efforts to formalize the data handling and publication processes for this data type.
- **2012 - in progress**: Internal standardization of SBC measurements with complete descriptions in anticipation of a potential LTER Network wide requirement (***Milestone e)***. Now that dataset metadata is housed in a relational database, routine comparisons of measurement descriptions (including methods, precision and error) are straightforward, and content can be regularized as appropriate. Work began during initial database population, and continues during regular updates, with ongoing time series measurements of highest priority.
- **2014 - in progress**: Formalize handling procedures for data and metadata for adoption by the Santa Barbara Channel Marine Biodiversity Observation Network led by SBC Investigators Miller, Carlson, Rassweiler, Reed and Siegel.
- **2015 - in progress**: Expand the content of SBC LTER's projectDB with details of specific research projects and sampling activities, to provide website links between sites, publications, datasets and/or related projects (***Milestone d)***. Initial content has been added to provide back-end support for the data catalog; the need for public views of sampling descriptions is under consideration.

VI. PROJECT MANAGEMENT

GOVERNANCE

SBC is directed by an Executive Committee chaired by lead PI Dan Reed and includes Co-PIs Sally Holbrook, John Melack, and Dave Siegel and three Associate Investigators. The PI and Co-PIs serve on the Executive Committee for the entire six-year funding period. The Associate Investigators on the Executive Committee (currently Bob Miller, Sally MacIntyre and Dar Roberts) are rotating positions that are filled by individuals with lead roles in short-term (i.e., 2-3 year) studies that are ongoing at the time of their appointment. Since its inception SBC has incorporated a philosophy of shared governance in which strategic planning pertaining to the project's research direction, resource allocation, administrative policies and staffing are discussed at scheduled meetings that are open to all investigators, postdoctoral scientists, graduate students, the Information Manager and Outreach Coordinator. Lead PI Reed chairs these meetings and sets their agendas with consultation from the Executive Committee. The meetings serve to keep participants informed of the project's broad range of activities, which aids in coordination and integration of the different project components. This management style has been very effective in instilling a culture of shared ownership, enthusiasm, and pride for the project among its participants.

PROJECT MANAGEMENT AND INSTITUTIONAL SUPPORT

Day to day management of the project is overseen by PI Reed with assistance from a 25% time Project Coordinator (Associate Investigator Dugan). Three full time and several part time research staff are employed to maintain the collection of data associated with SBC's long-term measurements and experiments. Graduate and undergraduate students employed on the project assist in these activities. Information Manager O'Brien and Outreach Coordinator Simon round out the project staff. Coordination between research and information management is facilitated by an Information Management System Advisory Committee (IMSAC) consisting of O'Brien, Siegel, Reed and Melack (chair). The allocation of funds is structured around the primary research themes with a lead investigator assigned to each sub theme. We allocate funds to shorter-term (2-4 year) research campaigns to gain insight into processes underlying the patterns observed in our long-term observations and experiments. A separate allotment of funds is set aside to cover the costs of project management, core long-term measurements, IM and Education/Outreach.

SBC's research and education programs greatly benefit from an off-campus overhead rate of its core NSF funding and generous in-kind support from UCSB's Office of Research, the School of Letters and Science's Division of Mathematical Life and Physical Sciences, Bren School of Environmental Science and Management and the Graduate Division. Administrative support is provided by UCSB's Marine Science Institute (MSI), which offers SBC participants efficient and friendly service in contracts and grants, personnel, budgets, purchasing, and travel and expert chemical analytical services via MSI's Analytical Laboratory. Research facilities on campus that are extensively used by SBC researchers also include a recently renovated seawater system, small boat and diving operations, and computational resources provided by MSI and the Earth Research Institute.

The coordination of research and the exchange of information and ideas among project participants are facilitated because the vast majority of project participants are located at UCSB. Informal and scheduled meetings involving investigators, postdoctoral scientists, students and staff to discuss project related business occur on a daily basis. The sharing of data, documents, and other project related products is made easy through our central data server to which all participants have access. Science meetings designed to update participants on the status of ongoing research are held approximately monthly during the academic year and an annual one-day retreat for all SBC participants and other interested parties helps to insure coordination across the SBC program and to enhance interdisciplinary discussions.

DIVERSITY

Efforts to increase the participation of under-represented groups are achieved through our ongoing Schoolyard program, which targets middle school students in traditionally underserved, low-achieving schools (see Section VII. OUTREACH, EDUCATION, TRAINING AND BENEFITS TO SOCIETY) and our bilingual contribution to the Schoolyard LTER Children's Book Series that is in preparation. We also link with campus programs devoted to increasing educational opportunities for low-income students and groups under-represented in higher education. Since 2001, the number of domestic Under-represented Minority (URM) undergraduate students at UCSB has increased by 89%, and in fall 2014 UCSB was recognized as a Hispanic Serving Institution (HSI) for achieving 25% Latino undergraduate enrollment. UCSB is the first HSI in the prestigious Association of American Universities, which is an association of 62 leading research universities in the United States and Canada. Several campus programs provide women and URM students, post docs and faculty participating in SBC access to professional development training and mentoring in team science leadership, management, and proposal writing.

PLANNING FOR THE FUTURE

Planning for a long-term project like an LTER requires a strategy for replacing expertise in research areas vacated by scientists that have left the project and for adding expertise in areas of new research initiatives. The addition of new Associate Investigators is accomplished either by active recruitment to fill a specific research need, or via invitation to collaborating scientists who are interested in becoming formally associated with the project. In both cases the addition of new investigators is determined by consensus of the Executive Committee with input from Associate Investigators. Eleven of the 21 Associate Investigators listed on the proposal of SBC III were added to our project during SBC II. Most of these additions (7 of 11) are early to mid-career scientists who offer a potential for a long-term commitment to the project.

There are no plans for a leadership transition during this award cycle. In the unanticipated event that PI Reed is no longer able to perform the duties required of a lead PI, this role will be assumed by one of the three Co-PIs as determined by the Executive Committee. All three Co-PIs have considerable lead PI experience and all are willing and capable of leading SBC if needed.

The UCSB campus lies in the center of the physical study domain of SBC LTER and the long-term continuity of our project relies on recruiting UCSB researchers into leadership positions. The structure of our Executive Committee fosters the participation and mentoring of early to mid-career Associate Investigators in project governance and management and is a useful mechanism that aids in leadership transition. Anticipated new faculty positions at UCSB are also aiding plans for SBC's future leadership. Departmental FTE plans include the hiring of several ecologists, oceanographers and geographers over the next several years that would in principle contribute to SBC. Of particular interest to SBC are two interdepartmental FTE planning efforts from both marine and environmental science faculty that are conducted in concert with the departmental plans. Together they have resulted in ongoing and approved searches for Assistant Professor positions in coastal marine ecology, marine microbial ecology, human time-scale climate dynamics, quantitative ecology, marine organic geochemistry and two positions in land surface processes. SBC investigators are actively involved in the planning and recruitment of these positions, and are encouraging the involvement of these new faculty in SBC research.

VII. COLLABORATIONS WITH FORMAL AND INFORMAL PARTNERS

The diverse nature of SBC's study habitats and research themes has attracted a diverse group of scientists (in terms of area of expertise and career level) to work at our site. Unlike several other LTER sites, SBC does not have a formal agreement with a federal agency or non-governmental organization that facilitates collaborations and provides research support. Instead, we rely upon the long-term nature of LTER support and the temporally and spatially comprehensive data that it generates to serve as a platform for attracting collaborations with other extramurally funded projects. We have been very successful in this regard, generating $11.5 million from 15 different funding sources in collaborative research projects during the first three years of SBC III.

Some of SBC's more prominent collaborations with partners the past three years include:

Plumes & Blooms (PnB) is a long-term study of ocean color variability in the Santa Barbara Channel led by SBC Co-PI Siegel. The project was initiated in 1996 and is a joint collaboration among researchers at UCSB and the NOAA Channel Islands National Marine Sanctuary and is now funded primarily by the NASA Ocean Biology and Biogeochemistry program. PnB makes monthly cruises across the Santa Barbara Channel to provide data on water column properties that are combined with satellite imagery to build a time-series of the changing ocean color conditions in the Santa Barbara Channel. SBC LTER and PnB actively share data and expertise in meeting their respective project goals.

The Santa Barbara Channel Marine Biodiversity Observation Network (MBON) is one of three recently established demonstration programs in the US aimed at assessing marine biodiversity and the environmental factors that influence it. The initial 5-year study funded by NASA, BOEM and NOAA is led by SBC investigator Miller and includes 7 other SBC investigators as Co-PIs. The project extensively leverages data on biodiversity and environmental variables collected across a diverse array of habitats by other entities which are integrated over multiple spatial scales using statistical, ecological and oceanographic approaches to construct an integrated picture of biodiversity across the Santa Barbara Channel. SBC is a primary data contributor to the MBON and the active engagement of investigators on both projects makes for a strong partnership.

Santa Barbara Area Coastal Ecosystem Vulnerability Assessment (CEVA) aims to develop a climate change vulnerability assessment of coastal ecosystems (watersheds, wetlands and beaches for Santa Barbara County. The collaborative project funded by NOAA and UC Sea Grant includes investigators from SBC, Scripps Institution of Oceanography (SIO), and the US Geological Survey (USGS) as well as local city (Goleta, Santa Barbara, and Carpinteria) and Santa Barbara County planners. Products are based on ecosystem data and analyses provided by SBC which are coupled with outputs from downscaled models of climate (SIO) and coastal processes (USGS). Active engagement of the California Sea Grant Extension program enhances project coordination and the dissemination of results with local stakeholders.

Department of Interior Cooperative Agreement (DOI) seeks to integrate long-term ecological and physical data collected by various agencies of the DOI and other entities with a goal of developing improved methods for detecting impacts from anthropogenic activities occurring on the continental shelf. SBC investigators are working with DOI scientists and managers to formalize and publish data from DOI monitoring programs in southern California (Kenner et al. 2013, Kushner et al. 2013) and to integrate them with long-term data from SBC and other sources for use in analyses and models aimed at increasing our understanding of the causes and consequences of change in nearshore ecosystems so that State and Federal managers may detect and evaluate possible impacts and develop options to mitigate them.

San Onofre Nuclear Generating Station (SONGS) Mitigation Monitoring program is a cooperative program with the California Coastal Commission aimed at evaluating the success of two large mitigation projects (the restoration of 150 acres of upland to tidal wetland and the construction of an artificial reef large enough to support 150 acres of kelp forest habitat) designed to compensate for the adverse effects of SONGS once-through seawater cooling system on coastal marine resources. The long-term project (established in 1993) is housed at UCSB and led by SBC investigators Page, Reed and Schroeter. Informal exchange of data, expertise and results have been ongoing between SONGS and SBC since SBC's inception in 2000.

Santa Barbara Basin Sediment Trap Time Series was established by researchers at the University of South Carolina (USC) to document the composition and flux of particles sinking to the seafloor, which is informing ongoing investigations of the transport and fate of harmful algal bloom toxins, biological consequences of changes in ocean chemistry and climate change reconstruction. A deep-moored sediment trap (500 m) located in the center of the Santa Barbara Basin has continuously collected data on the flux of sinking particles since 1993 (a second trap was added in 300 m in 2009). Beginning in 2013 SBC and CCE LTER have been contributing to the maintenance of this novel time series, and collaborating with USC investigators on their research.

Southern California Coastal Ocean Observing System (SCOOS) is one of eleven regional observing systems that work to collect, integrate, and deliver coastal and ocean observations in order to improve safety, enhance the economy, and protect the environment. SBC investigators actively participate oversight of the program with Washburn (chair) and McWilliams serving on the SCCOS executive committee, Siegel on the steering committee (along with Washburn and McWilliams). Washburn, McWilliams and Brzezinski are SCOOS principal investigators. SBC partners with SCOOS to maintain an HR radar array in the Santa Barbara Channel and a real-time oceanographic instrument array on Stearns Wharf in the city of Santa Barbara.

Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO) is a large-scale marine science research program established in 1999 by the David and Lucile Packard Foundation to enhance our understanding of the nearshore ecosystems of the U.S. West Coast. Representing a collaboration of scientists from four universities (including UCSB), the interdisciplinary research includes long-term monitoring of ecological and oceanographic processes at dozens of coastal sites to experimental work in the lab and field to explore how individual organisms and populations are affected by environmental change. PISCO and SBC have rich history of collaborating on data collection, processing and analyses, and in the area of informatics.

The HyspIRI Preparatory Project is making quarterly, high-altitude airborne observations over the SBC LTER domain using the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) and the MODIS/ASTER Airborne Simulator (MASTER) instruments to collect precursor datasets in advance for NASA's Hyperspectral Infrared Imager (HyspIRI) mission. Missions started in the spring of 2013 and are planned to conclude this fall. Co-I Dar Roberts is using AVIRIS and MASTER imagery to discriminate chaparral species focusing on broadly distributed species and functional types. Co-PI Siegel is using AVIRIS imagery to assess giant kelp forest photosynthetic condition from spectral reflectance signatures.