SBC LTER Annual Report:
September 1, 2010- August 31, 2011

RESEARCH ACTIVITIES

Background

The Santa Barbara Coastal Long Term Ecological Research (SBC LTER) program (http://sbc.lternet.edu/index.html) was established in April 2000 and is housed at the University of California Santa Barbara. Its overarching mission is to understand the linkages among ecosystems at the land-ocean margin through interdisciplinary research, education and outreach with a focus on developing a predictive understanding of the structural and functional responses of giant kelp forest ecosystems to environmental forcing from the land and the sea. Giant kelp forests occur on shallow rocky reefs that fringe temperate coastlines throughout the world and are extremely important to the ecology and economy of the regions in which they occur. Our principal study site is the semi-arid Santa Barbara coastal region, which includes steep watersheds, small estuaries, sandy beaches, and the neritic and pelagic waters of the Santa Barbara Channel and the habitats encompassed within it.

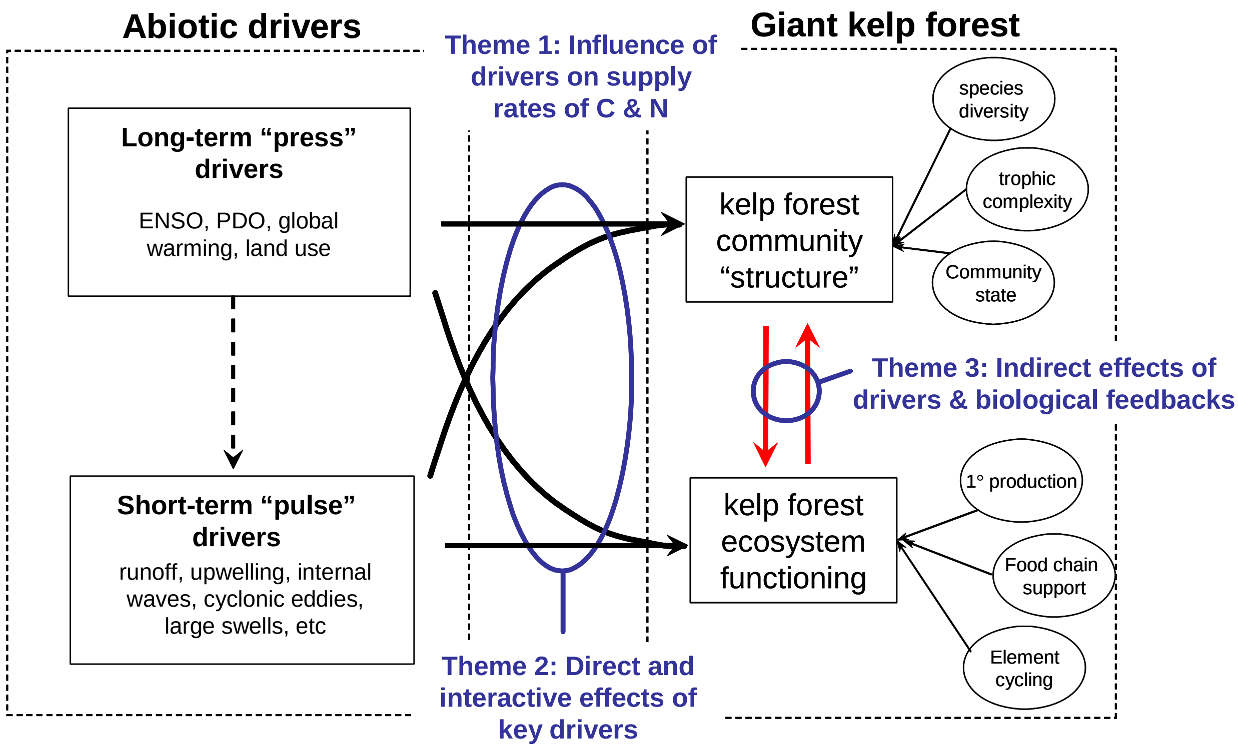
During our first six-year funding cycle our research focused on testing hypotheses and addressing questions relating to the role of terrestrial, oceanic and atmospheric forcing in accounting for the dynamics that we observed in kelp forest structure and function. Much of this work centered on; (1) determining the dynamics of production and food web structure in kelp forests, (2) identifying the important processes on land and in the coastal ocean that drive changes in the nature and quantity of subsidies delivered to kelp forests, and (3) establishing sampling programs to generate long-term data sets that could address questions and hypotheses relating to the core areas of LTER research. This research led to substantial increases in our knowledge of our study system. Armed with this increased knowledge we followed the advice of our first mid-term review and reduced our sampling effort in a number of these areas in our second cycle of funding in order to more intently pursue linkages among ocean, reef and land components and their propensity to change under different environmental conditions.

Our ability to predict how coastal ecosystems will respond to environmental change requires a recognition that the drivers of change (e.g., climate, disease, human actions) typically act over different temporal and spatial time scales. This inevitably results in a complex set of interactions among the biotic responses that these forcings elicit. The LTER Network has long been interested in environmental drivers that span a range of temporal and spatial scales and have recently formalized this interest into a pulse/press framework in which abiotic drivers act in a chronic long-term (i.e., "press") or periodic short-term (i.e., "pulse") fashion to influence biotic structure and ecosystem function (LTER Decadal Plan 2007). We adopted this framework for our current funding cycle which seeks to obtain a more predictive understanding of the importance of land and ocean processes in determining the structure and function of giant kelp (*Macrocystis pyrifera)* forest ecosystems. The overarching question motivating our current research is:

> *How do abiotic drivers acting over different spatial and temporal scales interact to influence kelp forest structure and function?*

To address this question we have focused our research around three general themes (Figure 1): (1) The influence of abiotic press and pulse drivers on exchange rates of N and C between giant kelp forests and adjacent land and ocean habitats, (2) The direct and interactive effects of key press and pulse drivers on kelp forest community structure and function through the modification of nutrient supply and wave disturbance, and (3) The indirect effects of pulse and press drivers on kelp forest community structure and function and the feedbacks between structure and function.

Figure 1. Conceptual framework of SBC LTER research. Specific research questions and hypotheses are organized under one of three central themes. The solid black arrows represent the influx of physical disturbance and chemical subsidies as influenced by abiotic press and pulse drivers. The ecological consequences of interactions between press and pulse drivers (dashed arrow) are manifested over a time period that is greater than the current six-year funding cycle, which necessitates the need for long-term research



THEME 1**:** The influence of abiotic press and pulse drivers on the rates of delivery of N and C to giant kelp forests

- *QUESTION 1a. How are the rates of delivery of N and organic C to giant kelp forests from terrestrial and oceanic environments altered by press and pulse drivers?*
- *QUESTION 1b. What are the sources and fate of dissolved and particulate organic matter in the nearshore zone?*

THEME 2: The direct and interactive effects of key press and pulse drivers on kelp forest community structure and function through the modification of nutrient supply and wave disturbance

- *QUESTION 2. How do wave disturbance and N loading act and interact to influence the structure, function, and resilience of the kelp forest ecosystem?*

THEME 3: Indirect effects of pulse and press drivers on kelp forest community structure and function and the feedbacks between them.

- *QUESTION 3a. How does the negative effects of giant kelp on understory algae and phytoplankton interact with wave disturbance and N loading to affect the magnitude and interannual variability of NPP of the kelp forest ecosystem?*
- *QUESTION 3b. How does the forest interact with its flow environment to modify the delivery of N and C and influence the species composition and performance of kelp forest biota?*

Short-term (hours to weeks) abiotic drivers that affect the delivery of nutrients and organic matter to kelp forests (e.g., upwelling, runoff) are embedded within a climatic regime (i.e., press driver) that fluctuates over much longer time scales (years, decades or more). The rate at which nutrients and organic matter are exchanged between kelp forests and adjacent habitats will depend not only on the direct effects of the pulse and press drivers, but also on the interactions among them (Theme 1, Figure 1). Abiotic drivers not only influence supply rates of N and C to kelp forests, but also the frequency and intensity of physical disturbance. Because the return interval of some of the key press drivers occurs on decadal and longer time scales, long-term research is needed to evaluate the ecological consequences of the direct and interactive effects of pulse and press drivers on the structure and function of giant kelp forests (Theme 2, Figure 1). Like most natural systems, the structure and function of a giant kelp forest are inextricably linked. Thus, abiotic pulse and press drivers that directly affect the abundance and species composition of a kelp forest community will indirectly influence the system's capacity to fix carbon and take up nutrients used to support the complex kelp forest food web (Theme 3, Figure 1). Similarly, the amount and form of organic matter produced by the forest and made available to kelp forest consumers will in turn influence the abundance and species composition of organisms inhabiting the forest. Positive and negative feedbacks between kelp forest structure and function may arise from these indirect effects.

Site characteristics

SBC LTER is ideally suited to explore issues of connectivity between terrestrial and marine ecosystems and the actions and interactions of pulse and press drivers on kelp forest structure and function. Our site is bounded by the Transverse Ranges of central and southern California to the north, the Channel Islands to the south, Pt. Conception to the west, and the Santa Clara River to the east (Figure 2). The catchments draining into the Santa Barbara Channel offer a rich diversity of watersheds that are characterized by a wide variety of land covers and uses. Giant kelp forms expansive forests on shallow rocky reefs, which dominate the nearshore in this region. Because of their close proximity to shore, kelp forests are influenced by physical and biological processes that occur on the land as well as in the open ocean. Streams and rivers transport nutrients, dissolved and particulate organic matter (DOM and POM), sediments, and pollutants from coastal watersheds to kelp forests, while ocean currents, internal waves, and other oceanographic processes supply nutrients, DOM, POM, larvae and plankton from adjacent offshore waters. In return, kelp forests export large amounts of DOM and POM to inshore intertidal habitats, as well as to offshore deep-water habitats. The transport of nitrate into the euphotic zone and disturbance from storm-generated waves are arguably the two most important factors regulating the standing crop and production of macroalgae (including giant kelp) in the coastal waters of southern California, and our research themes emphasize these two aspects. Short-term (i.e., pulse) and long-term (i.e., press)

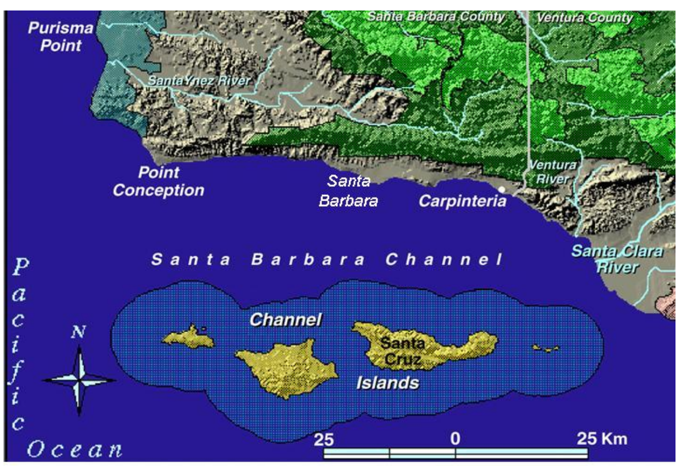


Figure 2. Regional map of SBC LTER. The site boundaries extend from Pt.Conception in the west to the Santa Clara River in the east, from the top of the Santa Ynez Mountains in the north out to the Channel Islands.

changes in climate, oceanography and land use that directly or indirectly alter the disturbance regime and/or the supply of nutrients can have a profound influence on the structure of kelp forest communities and on the flow of materials to and from them.

The Santa Barbara region has a Mediterranean climate characterized by relatively calm, dry conditions in summer and autumn, prevailing winds in the spring, and episodic rain storms in the winter. This environmental setting creates strong seasonality in bottom-up forcing (via variation in the supply of nitrogen) and top-down control (via physical disturbance from storm generated waves). A number of "pulse" drivers operating on seasonal time scales influence these bottom-up and top-down forces including terrestrial runoff, large oceanic swells, wind-driven upwelling, internal waves, and other less understood oceanographic processes that supply nitrogen to otherwise depleted surface waters in summer and fall, and are thought to be important in enabling giant kelp to persist and grow year round in most years.

Aside from the seasonal cycle, the El Niño Southern Oscillation (ENSO) is the dominant climatic signal over most of the Pacific Ocean. The two phases of ENSO are generally termed El Niño (the warm, nutrient-poor phase) and La Niña (the cool nutrient-rich phase). The strengths of the various pulse drivers are El Niño dependent causing the relative contributions of land- and ocean-derived nitrogen and carbon to kelp forests in southern California to vary between El Niño and La Niña years, while the strength and intensity of El Niños vary with longer-term climatic cycles that have return frequencies of decades (e.g. the Pacific Decadal Oscillation).

General Research Approach

Certain abiotic drivers of kelp forest ecosystems are easily manipulated (e.g., physical disturbance that removes kelp), while others are difficult or practically impossible to manipulate on a meaningful scale (e.g., sea surface temperature, water column productivity, elevated runoff, land use change). Because of this, our research relies on a variety of approaches that include: (1) Coordinated long-term measurements of key abiotic drivers and ecological response variables. The purpose of our long-term measurements is to unveil spatial and temporal patterns in the structure and function of giant kelp forests in the Santa Barbara Channel and in the physical and chemical forcing variables that influence them. Because kelp forests occur at the land-ocean margin, we collect long-term measurements on land and intertidal beaches, in the offshore ocean, and in the shallow coastal zone where kelp forests occur (Table 1), (2) Manipulative field experiments designed to isolate the causal mechanisms underlying the patterns observed in long-term measurements, (3) Measurement-intensive process studies aimed at obtaining a mechanistic understanding of processes that cannot be isolated using manipulative experiments, and (4) Integrated synthesis using modeling and analyses that allow for predictions beyond the spatial and temporal scope of our data, and that help guide the direction of our future research. Collectively, these elements provide a powerful basis for building a greater understanding of the direct and indirect effects of pulse and press drivers on kelp forest ecosystems, which is essential for predicting how giant kelp forests will respond to ongoing changes in the environment.

Table 1. Long-term core monitoring performed by Santa Barbara Coastal LTER (data available via the SBC LTER website http://sbc.lternet.edu/data/.)

Title	Summary of measurements	Year initiated
Watershed Hydrology and Stream Chemistry:		
Precipitation	Rainfall at 12 stations	2003
Stream Discharge	Stream stage and discharge at 16 stations	2002
Stream Chemistry	Storm-flow and base-flow sampling of nutrients, major anions and cations at 8 stations	2001
Ocean Physics & Biogeochemistry:		
Nearshore Ocean Water Chemistry Profiles	Profiled CTD and seawater nutrients, organic matter, & chlorophyll collected monthly at 5 reefs	2001
Moored Hydrography and Currents	Near continuous measurements of conductivity, temperature, & currents (ADCP) at 4 reefs	2001
Temperatures	Bottom temperature every 15 min at 11 reefs	2001
Irradiance	Bottom and surface irradiance every minute at 4 reefs	
Kelp Forest Ecology		
Kelp forest Community Structure	Annual data on the abundance (density or % cover), species composition and size structure of fishes, macroinvertebrates, giant kelp and understory algae at 11 reef sites	2000
Long-term Kelp Removal Experiment	Twice per season sampling (every 6 weeks) in kelp-removal and kelp-control plots at 4 reef sites. Sampled variables include: the abundance, species composition and size structure of fish, macroinvertebrates, and macroalgae, standing and detrital biomass of macroalgae.	2008
Kelp Net Primary Production	Monthly data on standing biomass, stoichiometry and biomass loss rates of giant kelp. Seasonal data on giant kelp NPP.	2002
Kelp Canopy Area and Biomass	SBC developed methods for processing satellite images from Landsat 5 Thematic Mapper to create a long-term, high frequency (~ every 6 weeks), spatially extensive (Southern California Bight) dataset on surface canopy area and biomass for giant kelp	1984
Sandy Beach Ecology		
Macroalgal Wrack	Composition, cover and biomass of macroalgal wrack at 5 beaches	2008
Shorebirds	Shorebird density and species composition at 5 beaches	2008

*Other long-term data available from third parties include meteorology, ocean swell height and period, surface currents, satellite imagery (color, SST), and hydrology.

Research Presentations

SBC Investigators, students and postdocs gave more than 68 presentations or posters at scientific meetings, workshops and seminars during the period 9/1/10 to 8/30/11. A list of presentations on SBC research can be viewed at: http://sbc.lternet.edu/catalog/presentations.jsp

Information Management

The primary objective of the SBC LTER IM system is to facilitate research and outreach efforts by focusing on data organization and integrity, ease of access, and long-term preservation. We maintain an open, cross-platform system that is based on Internet standards, leveraging existing systems where possible, and building new tools geared toward collaboration and integration between data collection and publication. The SBC LTER IM system is integrated with other research groups at MSI, particularly the Moorea Coral Reef LTER (MCR LTER). SBC was closely involved with the installation of an information management system for the MCR LTER (also at MSI/UCSB), and in development of scripted processing methods which are of use to several groups of local researchers.

Since SBC has adopted community-vetted components for its IM system, its products are well suited to deployment elsewhere in the ecological informatics community. SBC's proximity to the NCEAS ecoinformatics programming group has facilitated its early adoption of several programming tools, and in the process SBC has provided valuable feedback for further development of products such as Metacat, Morpho and the EML data manager library. Most recently, SBC has been involved in two network-wide IM activities: a) to develop an LTER Controlled Vocabulary (http://vocab.lternet.edu), and b) network-wide use of EML specification through the EML Best Practices recommendations and EML Metrics and Congruence Checker tools.

SBC is also well-represented in information the management activities of the LTER Network. SBC information manager O'Brien currently serves as co-chair of the Executive Committee of the LTER Network's IM committee. She is currently involved in several network working groups charged with: (1) developing standards for data quality control, (2) establishing a collection of vetted measurement units, and (3) evaluating the usefulness of keyword thesauri for browsing and querying metadata. She is editor of the metadata section of the IMC website, which facilitates content, recommendations and discussions regarding metadata standards and implementation. With another information manager (Corinna Gries, CAP) she led an IMC group in developing a database for managing project descriptions using the EML schema with content delivered via web services.

LTER Network and Synergistic Activities

As a lead PI Reed serves on the LTER Science Council. He is also a member of the Publications Committee, and served on the LTER Executive Board (2006-2009) and the writing team that produced the LTER Integrated Research Plan (2006-2007). Reed along with investigators John Melack and Brad Cardinale were members of the LTER Network Planning Committee and active in the LTER Network's Planning Grant process (2004-2007) of which SBC Education Director Ali Whitmer was a co-Principal Investigator. Libe Washburn serves on the LTER Network Information Systems Advisory Committee (NISAC). SBC Information Manager Margaret O'Brien is extremely active in the LTER Network 's information management arena as noted above and recently we began collaborating on a common relational data model with three other LTER sites (MCR, CWT, GCE), Whitmer has played a prominent role in the LTER Network's education and outreach activities. She is a CoPI of a Math-Science-Partnership (MSP) Project (Pathways to Environmental Literacy), the LTER Network's first large cross-site education and outreach project, which is a collaboration among 4 LTER sites (SBC, SGS, BES, KBS) and the LTER Network Office.

SBC LTER researchers have served on LTER midterm review panels for NSF and have actively participated in LTER cross-site working groups that have spanned a range of topics including NPP and diversity, community state changes, and regional oceanographic modeling. In 2011, Investigator Guerrini represented SBC LTER at a workshop sponsored by the Andrews Forest LTER on humanities and arts at the LTERs. The workshop at Andrews LTER involved invited participants from a dozen LTER sites, including the four originally funded for “LTEaRts” programs (Andrews, Harvard Forest, Bonanza Creek, North Temperate Lakes) as well as two non-LTER arts/science outreach programs. The purpose of the workshop was to share activities, ideas, and strategies with the aim of developing programs with collaborative engagement of the sciences, humanities, and arts in sustained, place-based work to understand ecosystems and our place within them. She is directly involved in the further development of arts and humanities in the LTER network including a “manifesto” to be submitted to Frontiers in Ecology and the Environment and session proposals for the 2012 ESA and ASM meetings.

The participants of SBC LTER also engage in a wide variety of synergistic activities, which are listed in the Contributions section of this report.

RESEARCH FINDINGS

Below we summarize our major research findings 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 LTER's publications and products can be found at: http://sbc.lternet.edu/catalog/publications.jsp

THEME 1: The influence of abiotic press and pulse drivers on rates of delivery of N and C to giant kelp forests

Oceanic transport of offshore shelf C and N to the inner shelf

To understand the effects of the important abiotic processes of ocean circulation and transport on the delivery of C and N to kelp forests, a broad range of oceanographic sampling has been conducted since the beginning of the SBC-LTER. The main elements of the sampling are monthly small boat surveys, an array of moorings along the inner shelf in the Santa Barbara Channel, high frequency (HF) radars for measuring surface currents (Beckenbach and Washburn 2004), and a series of oceanographic cruises onboard UNOLS vessels during 2001-2006. Results from the analysis of the oceanographic data bear directly on the Questions 1a and 1b of Theme 1.

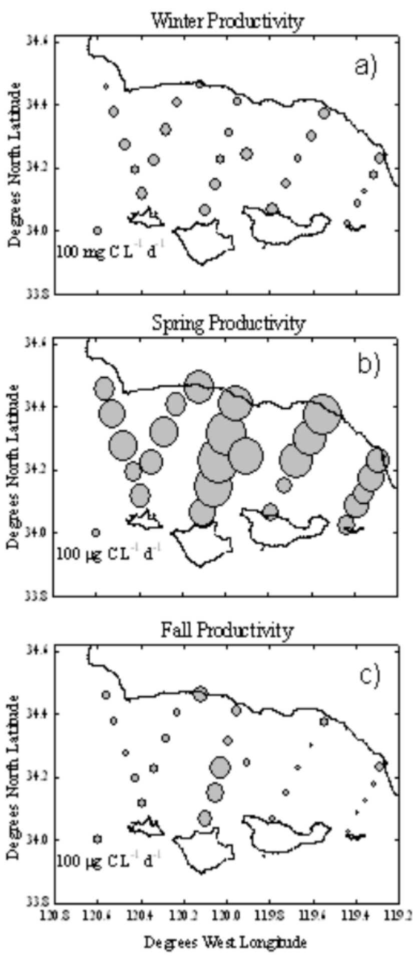


Figure 3. Phytoplankton primary productivity averaged by season. Dot size indicates productivity according to scale at lower left.

A major research focus of our current award has been the analysis and synthesis of the extensive data set from the oceanographic cruises. To date, our analyses of these cruise data have concentrated on issues related to Question 2 of Theme 1 by examining offshore oceanic sources of dissolved and particulate organic matter. In particular, we are studying the relationship between chlorophyll biomass and phytoplankton primary productivity (PPP) and the pulse drivers of wind-driven upwelling, seasonal river runoff, eddy circulation, and water mass variability. Satellite remote sensing imagery (e.g. Otero and Siegel, 2004) suggests that two areas of the Santa Barbara Channel exhibit consistently high levels of chlorophyll biomass, the western channel over the Santa Barbara Basin and the eastern channel along the mainland coast near the mouths of the Ventura and Santa Clara Rivers (Figure 2). Prevailing coastal circulation patterns place these regions of high chlorophyll biomass upstream from extensive kelp forests along the mainland coast because: (a) offshore currents are counter-clockwise and tend to transport materials from the western channel toward the mainland shore in the central portion of the channel, and (b) nearshore currents along the mainland coast are predominantly westward. Therefore we hypothesize that these areas are important sources of organic particles for kelp forests along the mainland coast where core SBC-LTER monitoring sites are located. An important goal of our cruise analyses has been to quantify patterns of PPP and chlorophyll biomass measured in situ with patterns inferred from remote sensing.

Patterns of PPP during 15 UNOLS cruises show a seasonal cycle in the Santa Barbara Channel much as is observed in terrestrial systems with high productivity in spring and lower productivity in fall and winter (Figure 3). The first empirical orthogonal function (EOF) mode derived from the PPP measurements was nearly spatially uniform and accounted for 67% of total variance. Correlation of this mode with nitrate concentrations indicates it describes wind-driven upwelling effects. The second EOF mode accounting for 17% of variance exhibited a productivity maximum in the center of the channel. The signature of this mode is evident along the central lines during spring and fall (Figures 3a and 3b). Comparison with current patterns observed by shipboard current profilers and shore-based HF radar indicates this mode is large when organized cyclonic circulation prevails in the western channel and small when it does not. It also is consistent with previous remote sensing observations of a chlorophyll maximum in the western portion of the channel. We are currently exploring which aspects of the cyclonic circulation enhance PPP; two leading contenders are increased residence time and local supply of nutrients by uplift of density surfaces.

Analysis of our UNOLS cruise data during the second half of our current award will continue to focus on Theme 1 as we will examine ocean transport processes that deliver N and C from the regions of high PPP identified in our current analysis to kelp forests near shore. This research will involve all SBC LTER oceanographic data sets including the UNOLS cruises, and nearshore monthly water sampling and moorings. Another direction that we are planning is a study of the effects of the important press driver El Niño. As of this writing an El Niño is developing in the western Pacific which, if it continues to build, will give us the opportunity to measure its effects throughout the SBC LTER study area, including the coastal ocean. In preparation, we are discussing with NSF program managers and ship operations personnel the possibility of an oceanographic cruise for late summer or fall 2010. A third research direction that we are planning involves continuous oceanographic sampling using the new technology of gliders. We currently have NSF supplemental funding to purchase one glider and are working on proposals (e.g. NOAA) to purchase a second and to fund the required technical support personnel. Data from gliders will allow continuous observation of evolving ocean conditions that will enhance our previous research on the formation of algal blooms (Anderson et al, 2006, 2008) and coastal eddies (Bassin et al. 2005) as well as facilitate our future planned research on storm driven runoff effects. Partnerships are also being explored to understand consequences of newly identified press drivers such as ocean acidification and declining oxygen levels in the northeastern Pacific. Some of this work has already begun: For example, key measurements of the coastal ocean carbonate cycle been added to the monthly cross-channel sampling of co-PI Siegel's long-term NASA funded Plumes and Blooms project.

<u>Inner shelf transport and the sources and fates of DOM</u>

The continental shelf in the Santa Barbara Channel is extremely narrow being only a few kilometers wide in many areas. Cross shelf processes have a dramatic effect on the supply and export of key resources to and from the kelp forest ecosystem. The nutrients sequestered in organic matter (OM) are of particular interest because of their ecological and biogeochemical significance. Organic matter (OM) is partitioned into particulate (POM) and dissolved (DOM) phases and is produced by photoautotrophic processes (phytoplankton and macroalgae). The portion partitioned into DOM serves as a substrate for heterotrophic microbial processes, and factors that control the production and remineralization of DOM can have a profound influence on the distribution of nutrients within marine systems. Despite its proximity to the coast and relatively high levels of phytoplankton productivity (> 2 g C m^{-2} d^{-1}) we observed DOM concentrations in the center of the Santa Barbara Channel to be less than or equal to concentrations measured in the subtropical oligotrophic gyre at the same latitude. This relatively low background concentration of DOM allows us to resolve relatively small changes in this important organic pool.

Our preliminary observations of a cross-shelf survey of the Santa Barbara Channel revealed a significant onshore to off shore gradient in the concentration of DOM indicating the build up of a pool of organic nutrients that could potentially be available for export away from the near shore system. Significant heterogeneity in DOM concentrations was observed throughout the Channel (Figure 4). DOC sources, sinks and dilution processes of this upwelling system control much of this variability in DOC concentrations.

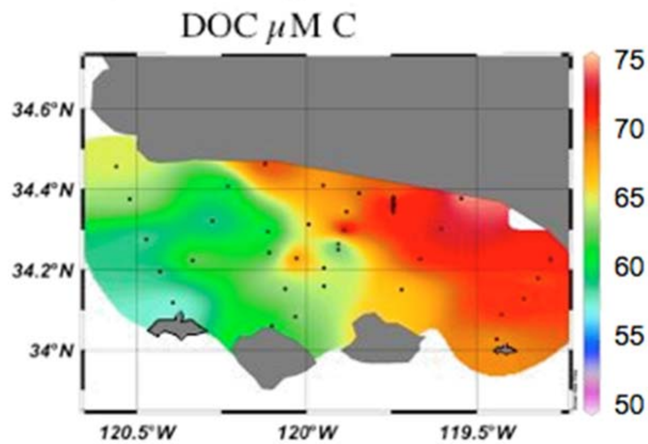


Figure 4. Surface contour of DOC in the Santa Barbara Channel October 2005. Note DOC gradient that develops from onshore to off shore in the western portion of the SB Channel.

Biogeochemically, the portion of newly produced DOM that is resistant to rapid microbial degradation is potentially available for export away from the shallow near shore environment. However, in order for DOM to be important in cross shelf transport a gradient must develop between the near shore and offshore environments. Knowledge of the sources and fate of the DOC produced in these upwelled water masses is needed to gain insight into the bioavailability of this important organic pool. However, prior to our investigations little was known about the temporal evolution of this gradient, its persistence or how it developed in the context of primary productivity and potential availability to heterotrophic microbes.

In January 2008 we initiated a cross shelf time series study to investigate the temporal and spatial gradients of particulate and dissolved organic matter and their potential sources and sinks in the near shore environment. Monthly measurements of POM, DOM, macro nutrient concentrations, biomass, productivity and community structure of phytoplankton and bacterioplankton communities were collected for 16 consecutive months from 4 depths at 5 stations that spanned from the Mohawk kelp forest to 3 km offshore. Preliminary analysis of these data show significant temporal variability in cross shelf transport that causes the kelp forest ecosystem to be at times highly isolated from offshore influences to it being strongly influenced by offshore waters. The horizontal transect from the Mohawk kelp forest illustrates seasonal gradients of organic and inorganic nutrients between the shallow rocky reef and deeper offshore ocean (Figure 5a). During periods of upwelling large pulses of inorganic nutrients were introduced into the near shore and offshore environments (Figure 5a) resulting in a phytoplankton bloom in early spring across the 3 km transect (Figure 5b). As upwelling relaxed and inorganic nutrients were drawn down temporal gradients in POM and DOM developed, reaching maxima by late spring/early summer (Figure 5ac&d). A pronounced spatial gradient in POM and DOM was observed with maxima developing closest to the kelp forest. In order for DOM and POM to accumulate in the near shore zone biological production and consumption processes must be uncoupled and the rate of physical dispersion must be less than net organic matter (OM) production. Thus, the accumulation of OM in the nearshore environment suggests that the connectivity between kelp forests and the offshore ocean is reduced during periods when upwelling is relaxed and kelp forests become relatively isolated from offshore waters. The source, quality and bioavailability of the resulting OM can have important implications for nutrient cycling within the kelp forest. For example, if the DOM that accumulates nearshore is resistant to rapid microbial degradation, then the nutrients sequestered in DOM and POM are potentially available for export away from the near shore system. These results demonstrate the development of gradients in OM: Additional microbial bioassays were also conducted throughout the study to assess the bioavailability of the accumulated DOM. Analyses of these data are ongoing and should provide further insight into the fate of the accumulated OM and its potential for export from the nearshore environment.

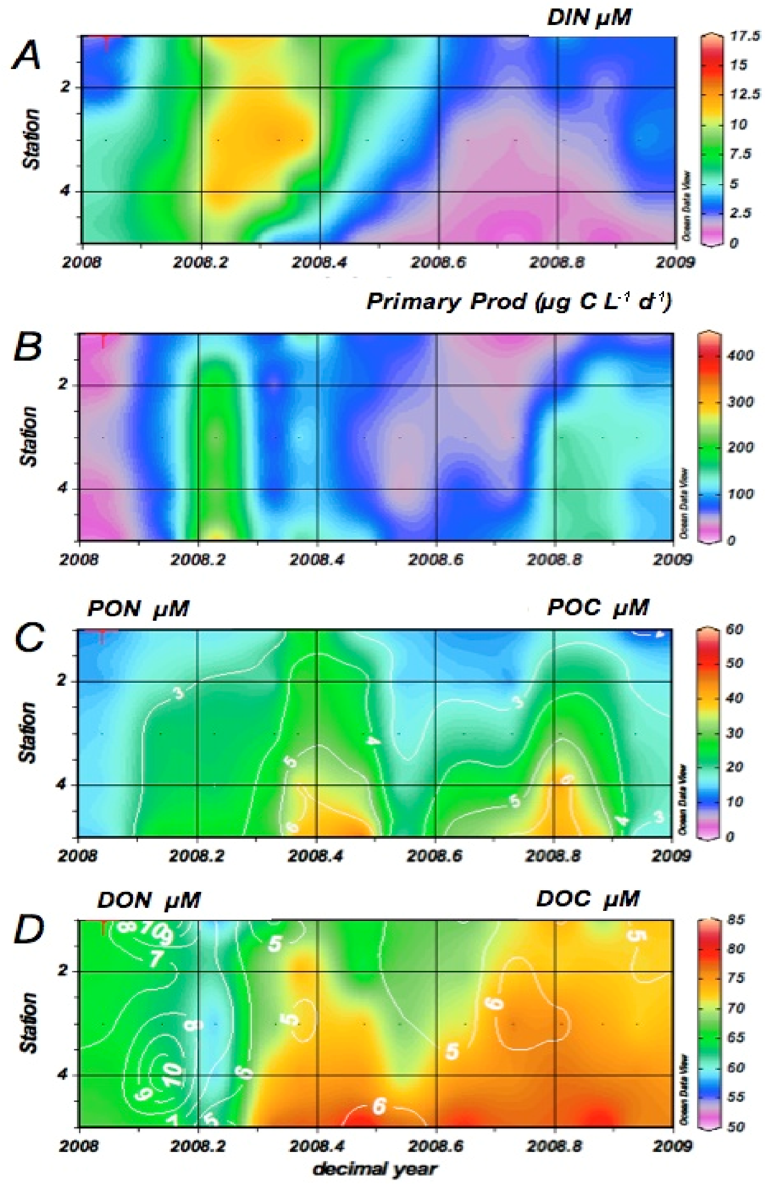


Figure 5. Surface contours of integrated and depth normalized measures of A) inorganic nitrogen; B) phytoplankton primary production, C) POC and PON (overlay contour); D) DOC and DON (overlay contour) collected during 2008 from the rocky reef (station 5) to 3 km into the SBC (station 1).

<u>Watershed processes & land subsidies to kelp forests</u>

Empirical studies: Seventy-four catchments, with a total area of 790 km^2 (ranging from 1 to 50 km^2), drain from the Santa Ynez Mountains along the northern coast of Santa Barbara Channel to coastal waters that support kelp forest ecosystems. These coastal catchments have mountainous headwaters and sloping coastal plains separated by transitional foothills. From west to east, there are both elevational and land use gradients. Headwater elevations increase from approximately 300 to 1400 m, and land uses on the coastal plain and foothills change from mostly rangeland to a combination of urban and agricultural land with chaparral in the mountains.

A network of rain gauges and water level recorders have been installed to permit calculation of rainfall and runoff for a representative set of coastal watersheds (Figure 6). Intensive sampling during rainfall events and weekly to bi-weekly collections during periods with baseflow are routinely performed in the instrumented watersheds. Water samples from streams are analyzed for (a) nitrate, ammonium, total dissolved nitrogen, and particulate nitrogen; (b) soluble reactive phosphorus, total dissolved phosphorus and particulate phosphorus; (c) particulate organic carbon; (d) total suspended sediments; and

(e) conductivity. Subsets of samples are analyzed for silica, major cations and anions, and the natural abundances of ^{15}N and ^{13}C.

Most of the annual precipitation and corresponding runoff occurs in only a few large events resulting in high peak discharges and a rapid return to near baseflow conditions. Consequently, a major proportion of the annual fluxes occurs during a few large storms

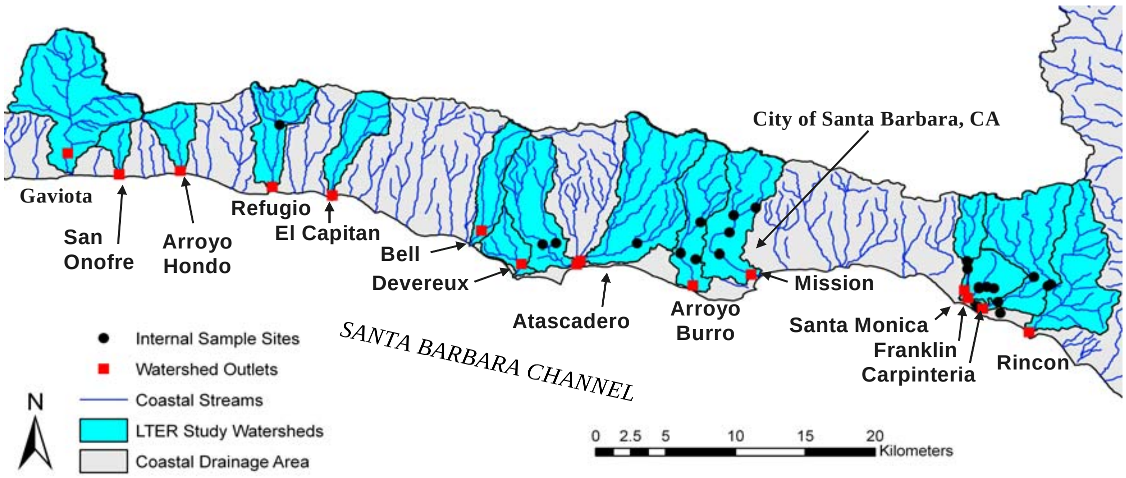


Figure 6. Catchments along Santa Barbara Channel with LTER stream gauging and sampling stations (red squares indicate stations near mouth; black dots indicate stations within catchments).

in each year. For example, in water year (WY) 2003, 46%, 28% and 40% of the respective nitrate, phosphate and dissolved organic nitrogen fluxes were exported during the largest event. We found that land use greatly affected nutrient export from coastal watersheds. Descending order of concentration and flux of nitrate and dissolved organic nitrogen usually followed descending intensity of land use. Volume-weighted mean concentrations of nitrate generally range from 5 to 25 µmol L^{-1} in undeveloped areas, increase to about 100 µmol L^{-1} for urban and most agricultural catchments, and are in excess of 1000 µmol L^{-1} in catchments with greenhouse-based agriculture. Comparative values for dissolved organic nitrogen are 10 to 25 µmol L^{-1} for undeveloped, 60 to 100 µmol L^{-1} for urban and agricultural, and about 200 µmol L^{-1} for greenhouse-based agriculture. Differences in phosphate concentrations were observed between intensive agriculture and urban or less intensive agricultural usage, and between urban and undeveloped catchments. To refine our whole catchment analyses we examined nutrient loading at the landscape-unit scale (Robinson et al. 2002, 2005a, b; Robinson 2006). Two intensive agricultural land uses (greenhouses and nurseries) were, in general, higher than two urban classes (commercial and residential), which were higher than chaparral areas. Using an urban growth model to forecast land uses 50 years into the future and estimates of nutrient export for different land uses, we found that the forecasted reduction in agricultural land use and expansion of urban development leads to a decrease in nitrate export and an increase in phosphate export. Goodman (2008) includes export from the largely suburban catchment of Devereux Slough, which has the added complication that the slough is open to the ocean only occasionally.

The large variation in the concentration of nutrients in runoff during storms requires the sampling of nutrient export at a time step significantly less than one day (Melack and Leydecker 2005). For example, nitrate, soluble reactive phosphate and particulate organic nitrogen varied with the hydrograph: soluble reactive phosphate varied in phase with outflow, nitrate exhibited the opposite pattern, and particulate organic nitrogen concentrations, along with other particulates, reached a maximum on the rising limb of the first storm pulse, implying different mechanisms and/or sources for the various species.

Figure 7 provides a synthesis of the relationship between nitrate exported per storm, expressed as moles ha^{-1}, and runoff per storm, expressed as cm per unit area, for the period from 2001 to 2005. Urban and agricultural land uses generate about the same export when agricultural use is10% or less. An especially interesting feature is the steep slope of nitrate export from undeveloped catchments. As long as storm size remains small, nitrate export from undeveloped areas is small (i.e., 10-100 times lower than from urban catchments). As storm size increases, there is a disproportional increase in export, and flux from these areas exceeds that contributed from urbanized or agricultural zones when storm runoff exceeds 2 to 5 cm per unit area.

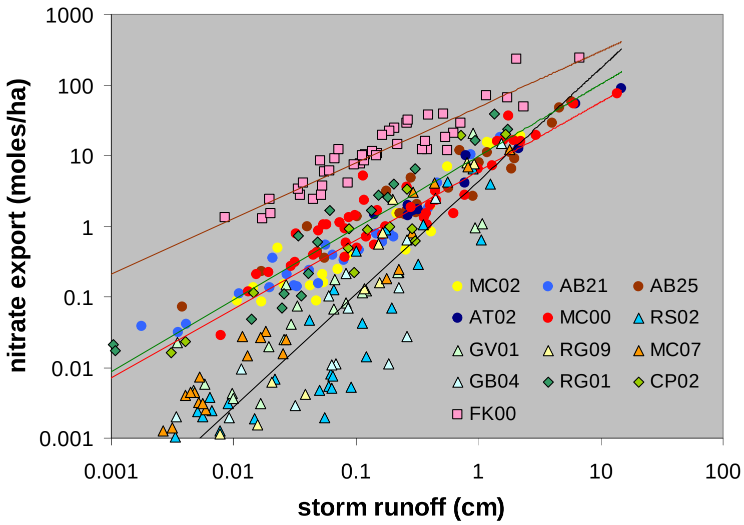


Figure 7. Nitrate exported per storm, expressed as moles ha^{-1}, and runoff per storm, expressed as cm per unit area, for the period from 2001 to 2005. Codes to creek names are as follows: MC, Mission; AB, Arroyo Burro; AT, Atascadero; RS, Rattlesnake; GV, Gaviota; RG, Refugio; CP, Carpinteria; FK, Franklin. Numbers after creek codes refer to position in catchment. Symbols indicate predominant land use in catchment as follows: ▲, undeveloped uplands; ●, suburban/urban; ◊, agriculture; ■, intensive agriculture.

Multi-year, multi-site analyzes of export of nutrients and suspended solids, examination of concentration discharge relations, and impacts of land uses and of fires on solute and particulate export indicate marked impacts of fires, rainfall variations and land uses. Concentration versus runoff relationships revealed how land use and watershed hydrology interactively regulate solute transport. Consistent nitrate-runoff patterns were found within three broad land use classes: dilution in agricultural watersheds, invariance in urban watersheds, and enrichment in an undeveloped watershed. A hyperbolic hydrochemical mixing model fit these nitrate-runoff relationships, generating three parameters that determined the form of nitrate-runoff patterns and inter-watershed variability in nitrate concentrations during baseflow and stormflow. Inter-watershed variations in nitrate concentration were reduced during storms, and undeveloped upland regions play a large role in moderating stream nitrogen concentrations lower in the watersheds.

To investigate the relative importance of marine and terrestrial sources of organic matter to the consumers in nearshore kelp reefs we measured stable isotopes of C and N in suspended organic matter and different types of consumers over a 4 year period in 4 nearshore areas with varying exposure to terrestrial runoff (Page et al. 2008). $\delta^{13}C$ values of suspended particulate organic matter on reefs tended to decrease following periods of significant rainfall at reefs most influenced by runoff. A pattern of ^{15}N-enrichment in 2 common benthic feeding species, the sea urchin *Strongylocentrotus purpuratus* and the annelid *Diopatra ornaata*, with increasing influence of runoff indicated that terrestrially-derived N may enter the food web indirectly through microbes or algae.

Fires impact the hydrology and suspended sediment and nutrient export. Stream gauging and intensive storm runoff and baseflow sampling were used to determine impacts from a fire that burned 3,011 ha in coastal watersheds near Gaviota bordering the Santa Barbara Channel in June 2004 (Coombs 2006). Burned watersheds showed order of magnitude increases in peak discharge, and suspended sediment export from burned watersheds was approximately 10 times greater than from unburned watersheds. Ammonium export from burned watersheds primarily occurred during the first 3 storms of the water year and was 32 times greater than in unburned upland watersheds. Nitrate, dissolved organic nitrogen, and phosphate export from burned watersheds increased by 5.5, 2.8, and 2.2 times, respectively, compared to unburned chaparral watersheds.

From July 2008 to June 2009, three major fires occurred in the foothills and mountains above the greater Santa Barbara area, all within the area being studied by the Santa Barbara Coastal LTER program. Two of these fires burned parts of the same basins, allowing an examination of impacts of fire timing on vegetation, soils, biogeochemistry, and stream communities within the same catchments. The fires afforded an opportunity to integrate multidisciplinary research to examine the effects of fire on terrestrial, riparian, stream, and coastal ecosystems which is being accomplished with supplemental funding from a RAPIDS award. Remote sensing of land cover using (via AVIRIS) and geomorphology (via LIDAR) was done before and after the fires. Land-cover was mapped using multiple endmember spectral mixture analysis applied to the AVIRIS data set to map plant species and plant functional types (Figure 8). Bare-earth digital elevation models have been generated from the December 2009 and August 2010 lidar overflights (Figure 9). On the ground measurements were made of terrestrial vegetation (e.g., peak growing season biomass, percent cover, leaf area index, percent water content, percent nitrogen content, and burn intensity), soil properties (e.g. bulk density, water holding capacity, volumetric water content, total carbon, total organic carbon, total nitrogen, pH and exchangeable nitrate and ammonium), and stream hydrology, biochemistry, and community ecology.

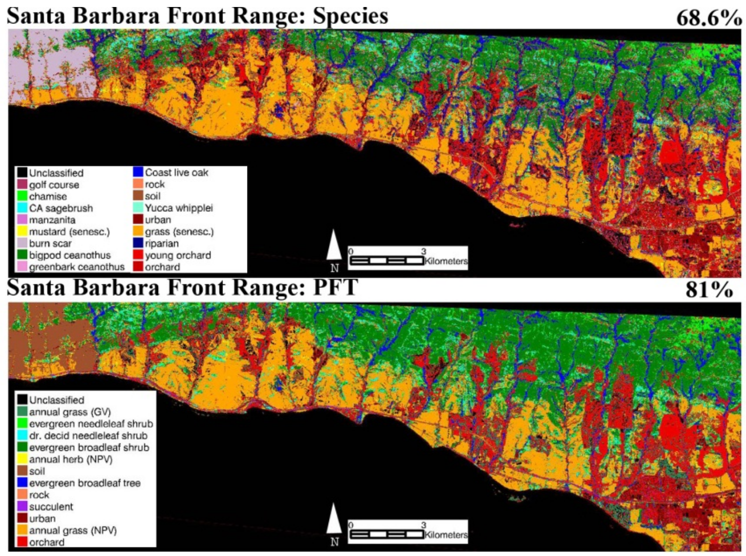


Figure 8. Vegetation mapped to the species and plant functional type. Overall species-level accuracy was 68% while plant functional type (PFT) accuracy was 81%.

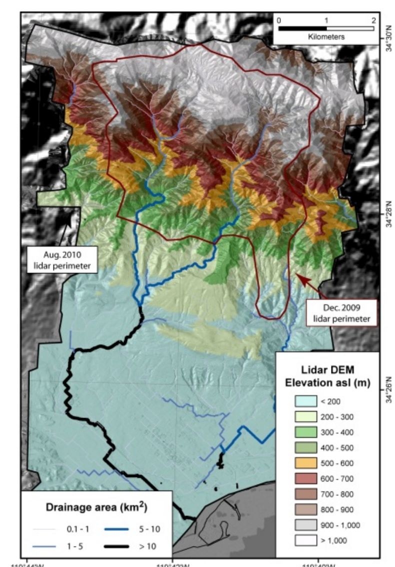


Figure 9. Perimeter of Dec. 2009 and Aug. 2010 lidar data draped over a hillshade image. Resulting digital elevation model (DEM) of lidar data is at 1-m spatial resolution with 8 to 12 lidar returns per m^2.

Remote sensing of land cover showed shrub type (Chamise compared to *Ceanothus*) appeared to have little impact on fire spread, although moist vegetation, such as riparian areas and orchards did restrict fire spread. Spectral Mixture Analysis revealed significant differences between the fires and within fire scars. Currently, we are focusing on evaluating burn intensity to field vegetation and soil sampling. Plant growth within the burn area was vigorous in most sites except those burned twice (fall 2008, spring 2009) and at the highest elevation sites where burn intensity was very high. Bare-earth digital elevation models generated from lidar overflights revealed that the primary areas of erosion after the rainy season in spring 2010 were within the channelized system. Localized sediment transport through arroyo incision was observed rather than widespread erosion on the hillslopes. Soil samples collected prior to the onset of rain were relatively enriched in NH_4, and low in NO_3. Following the season's first rain event, NH_4 concentrations decreased while NO_3 levels simultaneously increased. Fire effects on riparian vegetation were variable, with some stream sites having burned riparian vegetation and others with riparian vegetation remaining intact. Sites within and below burned areas received extensive sediment deposition during the rainy season, with sediment (primarily sand) filling in stream pools, compared to little change in substrata composition and depth at unburned stream sites. Nutrient levels increased at sites in burned basins during the rainy season, but showed little change in unburned basins. Algal biomass at stream sites within or below burned areas decreased during the first major storm of the rainy season after the fires; however, algal biomass recovery after the rainy season ended was greater in streams where the riparian vegetation was burned and the canopy was opened than in burned sites where the riparian vegetation was not burned or in unburned sites. Diatoms dominated benthic algal assemblages at shaded sites, but filamentous green algae dominated sites with open canopies. Invertebrate communities changed radically at the sites in burned basins, but changes were more muted in the unburned sites, with opportunistic, vagile taxa, such as *Baetis* mayflies and *Simulium* larvae, dominating at burned sites. Trout populations in burned basins nearly disappeared, but remained at relatively constant levels in unburned basins. Multi-year, multi-site analyzes of export of nutrients and suspended solids, examination of concentration discharge relations, and impacts of land uses and of fires on solute and particulate export indicate marked increase in export in burn areas.

Modeling studies: We have developed a hydrological model that predicts runoff from rainfall to extend our measurements of stream discharge and nutrients to all coastal watersheds entering the Santa Barbara Channel within our primary 790 km^2 study area (Beighley et al. 2003, 2005). Furthermore, we have used our rainfall-runoff model to explore the impacts of watershed characteristics, transient weather regimes and land conversion on the frequency distributions of runoff events and their influence on nearshore waters (Beighley et al. 2008). Based on historical evidence and projected urbanization, a 600% increase in runoff during storms from the coastal plain was calculated to occur from 1929 to 2050, which shifts the dominant source of runoff from the mountains to the coastal plain. By combining drainage areas, export relationships, runoff frequencies, nearshore water volume, ambient nitrate and phosphate concentrations in nearshore waters and an assumed mixing volume, we modeled the probability of a runoff event resulting in a particular nearshore nitrate or phosphate concentration. For example, the frequency of a storm event that produces runoff $\geq$ 2.5 cm and a nearshore nitrate concentration greater than 12 µmol L^{-1} ranges from 3% in non-El Nino years to 20% in El Nino years.

Regression models have been developed to estimate the flux (mol ha^{-1}) for a given storm based on the percentage of catchment area used for agriculture or classified as impervious surface, the estimated discharge during the storm and the cumulative water year discharge at the end of the storm. Daily models were also developed to estimate the daily flux (mol ha^{-1} d^{-1}) using daily flow and the cumulative water year discharge at the end of the given day.

To extend our modeling to include mechanistic aspects of the water balance and N and C dynamics, we have begun to apply the Regional HydroEcological Simulation System

(RHESSys). Initial work has focused on the effect of uncertainty in water and climate inputs on streamflow and evapotranspiration (ET) outputs in the Mission Creek catchment. We have tested model sensitivity to three sources of input uncertainty: spatial scaling of precipitation, non-linear variations in temperature caused by a marine fog layer, and outdoor water use. Results indicate that the model is most sensitive to uncertainty in soil parameters and precipitation inputs. Sensitivity to temperature variations resulting from a marine fog layer was negligible in terms of total water flux, but significant variations in ET and streamflow at the seasonal level were observed. Likewise, model sensitivity to outdoor water use was relatively small except potentially during the summer months. Future research in the Mission Creek catchment will be focused on quantifying the effect of fine scale urban spatial complexity and impervious surface connectivity on hydrologic and biogeochemical processes and appropriate modifications of RHESSys model will be developed. The model will then be used in conjunction with land use and climate change forecasts for the region with a goal of quantifying potential catchment responses to different environmental change scenarios.

<u>C inputs to kelp forests identified by stable isotopes.</u>

Understanding trophic connections and how resource variability affects consumers is necessary to predict how food webs might shift in the face of environmental change. Macroalgae and phytoplankton support highly productive marine ecosystems. Research based on stable isotope analyses has supported the idea that macroalgal detritus, especially that of the giant kelp *Macrocystis,* is a major source of dietary carbon to benthic suspension-feeders. However, our recent findings from a four-year stable isotope study (Page et al. 2008) suggest that phytoplankton, not kelp, are the main food resource for benthic suspension-feeders on reefs in the Santa Barbara Channel, and that variation in phytoplankton abundance, combined with feeding selectivity and the scale of consumer tissue turnover times, may drive variability in consumer isotope values.

A common assumption made in 'snapshot' isotope studies of coastal ecosystems over the past 20 years is that the isotopic signature of coastal phytoplankton is similar to that of offshore phytoplankton. Our results suggest that this important supposition may be incorrect. Typically this assumption is made because of the difficulty in separating phytoplankton from detritus to obtain an uncontaminated isotope signature, also a problem encountered in freshwater systems. We are developing methods to overcome these problems and address fundamental questions about the role of POM in coastal food webs. Our objectives are to: 1) determine the contribution of phytoplankton and giant kelp detritus to the pool of suspended reef POM and whether POM composition varies with distance from kelp forests, and 2) evaluate how different components of the POM are used as food by reef suspension feeders.

Associate Investigators Page and Miller are exploring the contribution of phytoplankton and kelp detritus to POM in coastal waters using two complementary approaches: (1) an advanced flow cytometry and cell-sorting system to separate phytoplankton from bulk POM, and (2) analyses of essential polyunsaturated fatty acids (PUFA) in POM and consumers. They have obtained preliminary data that demonstrate the feasibility of both of these methods (Figure 10), and have a recent NSF grant to support expanded work on these issues. Isotope values of isolated inshore phytoplankton and kelp, and compound-specific PUFA, are being used in mixing models to estimate relative contributions of these two major primary producers to suspension feeder diets. They are also testing two hypothesized mechanisms influencing isotopic composition of consumers: (1) selective feeding on particular fractions of the POM, and (2) tissue turnover times.

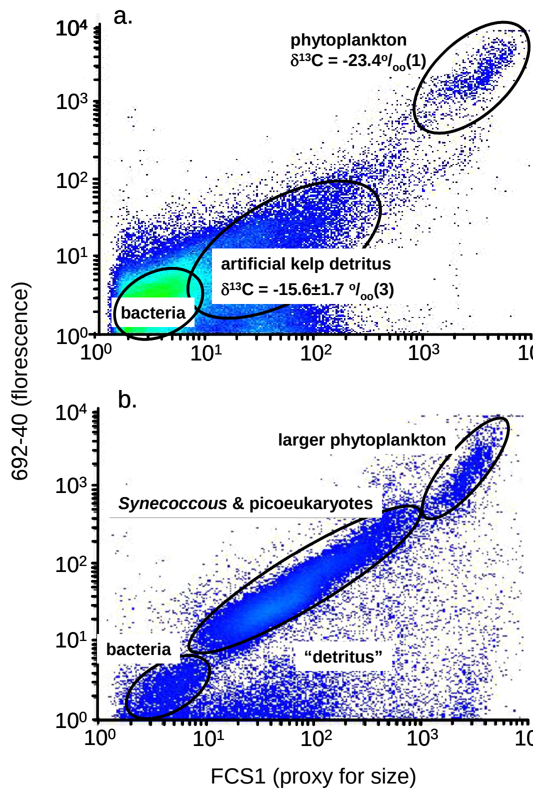


Figure 10. (a) Illustration of the separation of particle classes of natural suspended POM based on size and florescence using the Influx Mariner flow cytometer. Particle classes can be "gated" by optical properties and sorted for isotopic analysis. (b) Separation of laboratory cultured phytoplankton from kelp (*Macrocystis pyrifera*) detritus generated in the laboratory based on optical properties.

Results from this work should provide new insights into the trophic support of benthic suspension feeders, an ecologically and economically important guild in coastal ecosystems. This research will test the general hypothesis that giant kelp detritus is an important source of dietary carbon to suspension feeders, a commonly accepted idea that needs re-evaluation in light of key assumptions that have been made in its support. Stable isotope analyses are an ideal tool for testing this hypothesis given the spatial and temporal scales of variability that exist in the abundance of phytoplankton and giant kelp at our study sites. Our anticipated sampling scheme combined with time-series data on producer biomass collected as part of our long-term core monitoring (Table 1) will enable us to capture this variability, which is generally missed by short-term food web studies involving stable isotope analyses.

Timing and magnitude of nitrogen delivery to giant kelp forests from different sources

We examined sources of nutrients to the kelp forests of the Santa Barbara Channel using time series obtained from an *in situ* nitrate autoanalyzer moored at three of our long-term study sites (Carpinteria, Naples, Arroyo Quemado). The data obtained from this effort provided the first high-resolution (every 30 minutes) time series of nitrate + nitrite (dissolved inorganic nitrogen, DIN) concentrations for this environment. These measurements showed that the major mechanisms that supplied DIN to the inner shelf of the Santa Barbara Channel varied seasonally and consisted of upwelling, diurnal internal tides, and storm runoff (McPhee-Shaw et al. 2007). Upwelling dominated increases of inner-shelf DIN between March and May and accounted for more than half of the annual advective DIN transport to shallow reefs where kelp forests occur (Table 2). In summer, internal waves provided an important source of DIN because they occurred when surface nutrient concentrations were depleted and the other supply mechanisms were inactive.

		Contribution to annual DIN supply			
		With dilution estimates		With hydrologic estimates	
Mechanisms for nutrient delivery	Days	Low end-member stream DIN (%)	High end-member stream DIN (%)	Greater ocean volume (%)	Smaller ocean volume (%)
Year 1: 01 Mar 2001–28 Feb 2002					
Spring upwelling	39	70	68	63	47
Summer internal waves	54	15	15	14	10
Winter upwelling	13	12	12	11	8
Terrestrial storm runoff	6/37*	2	4	12	35
Year 2: 01 Mar 2002–28 Feb 2003					
Spring upwelling	65	81	77	79	70
Summer internal waves	48	9	9	9	8
Winter upwelling	11	7	7	7	6
Terrestrial storm runoff	13/22*	2	7%	4	15

* Days are identified using the moored salinity time series and the hydrographic methods (see text for details).

Table 2. Annual contribution for two sequential years of DIN supplied by four primary mechanisms that advect nitrate into the inner shelf of the Santa Barbara Channel.

Brief episodes of upwelling became important in late autumn and early winter. DIN inputs from storm runoff, detected as salinity dilution at the moorings and estimated from measurements of stream discharge and nutrient concentration were significant during winter runoff events.

Building on this work we sought to determine the relative importance of different sources of nitrate to the annual nitrogen needs of the giant kelp *Macrocystis pyrifera*. We did this by measuring ambient nitrate concentrations in the kelp forest at the Mohawk Reef kelp for 13 months (using the moored nitrate autoanalyzer described above) and characterizing nitrate delivery using water column thermal structure and flow data collected in the forest interior and at its

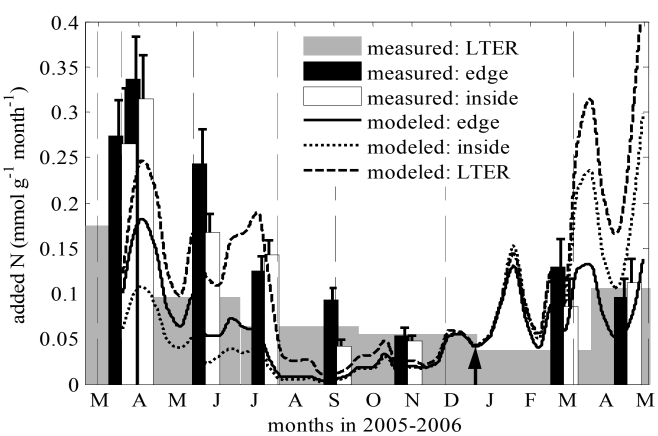


Figure 11. Time series of measured acquisition and modeled uptake of nitrogen in mmol (wet g) $^{-1}$ month^{-1} by growing canopy fronds at the edge and inside the Mohawk kelp forest, and of all fronds in a 40 m x 40 m area of the interior of the forest (LTER) for the period 21 March 2005 through 30 April

offshore edge (Fram et al. 2008). Rates of net nitrogen uptake by kelp were calculated for the entire forest (using data collected from our long-term studies of kelp net primary production; Table 1 and Theme 2 below), and for a select subset of kelp fronds to isolate vertical and cross-shore differences in nitrogen acquisition. The forest's monthly nitrate supply varied by a factor of 50, while measured net nitrogen acquisition varied only fivefold regardless of the method used to measure it. Maximum net nitrogen acquisition rates for fronds in the forest interior were 0.18 mmol N g^{-1} $month^{-1}$ during spring upwelling and declined fourfold during autumn until upwelling resumed the following year. Modeled gross nitrogen uptake with consideration of Michaelis–Menten kinetics for nitrate and mass transfer limitation was higher than observed net acquisition except during the warm stratified summer and autumn months, when net acquisition exceeded modeled gross uptake (Figure 11). This shortfall indicates that the kelp forest received over half its nitrogen from sources other than nitrate (such as ammonium from epibionts) during this period. Most of the nitrate in the forest was delivered as a result of upwelling-favorable winds and convection. Internal waves and local streams contributed, 9% of the nitrate delivered to the forest on an annual basis and 20% during stratified periods. Kelp used less than 5% of the nitrate supplied to the forest. Nitrate delivery to this modest sized kelp forest was roughly equivalent between alongshore (45%) and cross-shore flows (55%), which distinguishes it from large kelp forests in which cross-shore flows dominate exchange.

Carbon and nitrogen linkages between giant kelp forests and sandy beaches

Wave-exposed sandy beaches represent a classic example of a subsidized sedimentary ecosystem where *in situ* primary production is very low and biotic communities are primarily supported by imported organic material from other ecosystems. Subsidies of drift macroalgae or wrack exported from kelp forests to beaches in the Santa Barbara Channel can exceed 500 kg m^{-1} y^{-1} for *Macrocystis pyrifera* alone (Dugan et al. 2011). These inputs from kelp forests to beaches exhibit strong temporal variation in response to pulse and press drivers, such as seasonal variation in wave climate, sediment supply and ENSO events, as well as kelp forest condition (Revell et al 2011).

Our ongoing investigations of the role and fate of kelp wrack subsidies in beach ecosystems indicate that they support a substantial component of the beach food web. Spatial variation in wrack abundance propagates up through invertebrate detritivores (Figure 12) to predatory shorebirds, including the Western snowy plover, a threatened shorebird that breeds on SBC beaches (Dugan et al 2003). Temporal variation in the supply of kelp wrack to beaches in response to press and pulse drivers is expected to have important consequences to the beach food web. For example, we found a doubling of invertebrate consumer richness in 8 weeks following weekly additions of fresh *Macrocystis* to a one of our beach study sites. Consumption of kelp wrack can be rapid as talitrid amphipods alone were estimated to consume kelp wrack at a rate of 18 kg m^{-1} of shoreline in one month, which constituted about ~40% of the measured input (Lastra et al 2008).

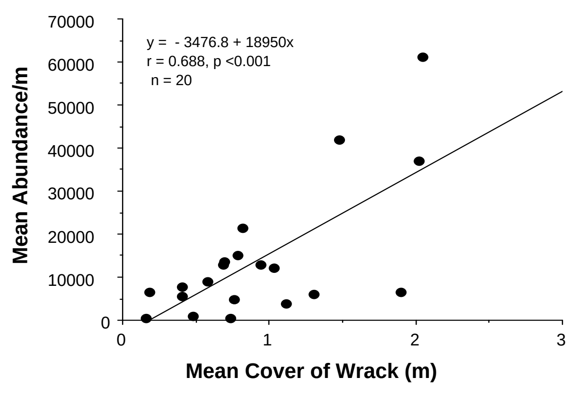


Figure 12. Relationship between the abundance of kelp wrack and the abundance of talitrid amphipods.

This rapid processing of macroalgal wrack by invertebrate detritivores and its decomposition and subsequent nitrogen mineralization by bacteria can lead to high concentrations of dissolved nitrogen in intertidal porewater (>1000 uM, Figure 13), particularly on beaches with heavy wrack accumulation (Dugan et al 2011). Highest DIN concentrations (>200 uM) in intertidal porewater were found in late summer and fall when sand accumulation on Santa Barbara beaches is greatest. Much lower DIN values (<100 uM) occurred in winter and spring when sand levels are typically low. The interaction of press and pulse drivers such as tidal forcing/drainage, erosive events and sediment dynamics are expected to strongly affect release and transport of dissolved nutrients from beach aquifers, as will interactions with terrestrial groundwater sources when present. Planned studies of the decomposition and mineralization of kelp wrack, and the timing and magnitude of the release of intertidal porewater will be used to evaluate the significance of this potential nitrogen source to coastal waters and kelp forests.

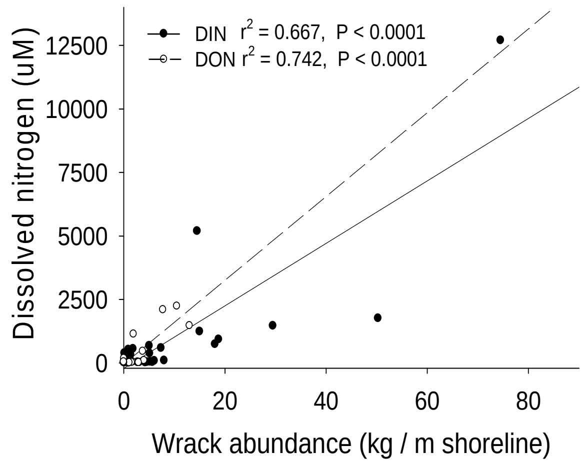


Figure 13. Relationships between the biomass of macroalgal wrack and dissolved inorganic nitrogen and dissolved organic nitrogen in beach pore water

Our ongoing research in this area seeks to understand how beach ecosystems function as both filters and sources of regenerated nutrients to the coastal ocean. Similar to wetlands and estuaries, beaches may act as a filters or buffers for anthropogenic nutrient loads conveyed in groundwater flowing from land to the ocean. As indicated above, the beach ecosystem may also represent a nutrient source to coastal ocean primary producers as wave and tidal activity circulates organic materials, such as wrack and phytoplankton, through beach sand where they are consumed, decomposed and mineralized. The dynamics of release and the transport rates of these dissolved nutrients from the shallow unconfined aquifers of sandy beaches to the nearshore ocean are under study using an array of temporary multi-level sampling wells at beach sites that differ in freshwater influence through spring and neap tide cycles. Wells will be sampled frequently for a selection of water chemistry and biogeochemical parameters over the tidal cycle.

The ability of beach ecosystems to accumulate, process and remineralize wrack material can be affected by abiotic press and pulse drivers that interact with human activities (Schlacher et al 2007). Our finding of a significant relationship between wrack abundance and dry beach width over time (Revell et al 2011), suggests that when dryer upper beach zones are narrow or absent, wrack accumulation and its availability to beach consumers, decomposition and remineralization is decreased. Of particular concern in this regard is climate-induced sea level rise which is expected to increase coastal erosion and reduce beach width and thereby negatively affect beach food webs, wrack and wrack nutrient processing. Coastal armoring, a common societal response to beach erosion is expected to expand with sea level rise. We have found that beaches with coastal armoring were significantly narrower and accumulated 1-3 orders of magnitude less wrack compared to adjacent unarmored beaches (Dugan et al 2008). Shorebird use of armored sections was also significantly lower. Our ongoing studies of the effects of coastal armoring on intertidal beach communities should provide important insights into interactions between humans and climate change and their ecological consequences to linkages between sandy beach and kelp forest ecosystems.

Theme 2: The direct and interactive effects of key press and pulse drivers on kelp forest community structure and function

<u>Role of disturbance and N supply on giant kelp abundance and NPP</u>

Net primary production (NPP) is fundamental to life on earth as it influences nearly all ecosystem processes. As such, NPP constitutes a critically important ecosystem function and determining its patterns and principal environmental drivers is justifiably one of the core research areas shared by all sites in the LTER network. NPP is influenced by disturbance-driven fluctuations in foliar standing crop (FSC) and resource-driven fluctuations in rates of recruitment and growth, yet most studies of NPP have focused primarily on factors influencing growth. We have been measuring NPP, FSC, recruitment, and growth rate of the giant kelp, *Macrocystis pyrifera* at three kelp forests in the Santa Barbara Channel since May 2002 to determine the relative roles of FSC, recruitment and growth rate in contributing to variation in annual NPP (Rassweiler et al. 2008). Our results to date show that the initial FSC present at the beginning of the growth year and the recruitment of new plants during the year explained 63% and 21% of the inter-annual variation observed in NPP, respectively (Reed et al. 2008). The previous year's NPP and disturbance from waves collectively accounted for 80% of the inter-annual variation in initial FSC. No correlation was found between annual growth rate (i.e., the amount of new kelp mass produced per unit of existing kelp mass) and annual NPP (i.e. the amount of new kelp mass produced per unit area of ocean bottom), largely because annual growth rate was relatively constant compared to initial FSC and recruitment, which fluctuated greatly among years and sites. Although growth rate was a poor predictor of variation in annual NPP, it was principally responsible for the high values observed for NPP by *Macrocystis* (up to 4.4 kg dry mass m^{-2} y^{-1}). These high mean values reflected rapid growth (average of ~ 2% $^{-d}$) of a relatively small standing crop (maximum annual average = 444 g dry mass m^{-2}) that replaced itself about seven times per year. Our observations of continuously high nitrogen content in kelp (generally above 1%) coupled with our finding that growth was unrelated to the concentration of DIN in seawater at two of our three sites (Figure 14) suggests that growth has rarely been nitrogen limited since our study began. These findings contrast with those of other investigators who studied kelp growth during prolonged conditions of nutrient stress associated with the 1982-83 El Niño, and they lend support to the contention that the importance of intra-annual variation in nitrogen supply in determining kelp growth and production depends on the state of longer-term climatic regimes.

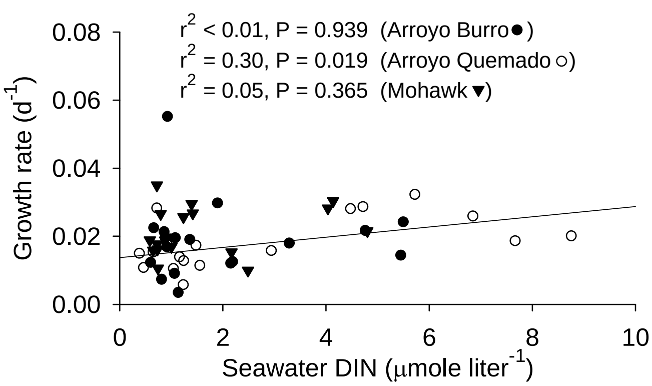


Figure 14. The relationship between specific growth rate and the ambient concentration of dissolved inorganic nitrogen (DIN).

Our time series data on biomass and NPP by giant kelp (Rassweiler et al. 2008) are unique in that we know of no other data for macroalgae that match their temporal and spatial resolution (monthly measurements ongoing since 2002 at three sites). Such resolution is needed to detect directional changes in kelp biomass and NPP associated with long-term press drivers (e.g. global climate change) in the presence of more variable fluctuations associated with short-term pulse drivers (e.g., winter storms). Unfortunately, the large effort associated with collecting data on kelp biomass and NPP limit the number of sites that we can sample, which greatly restricts our ability to place our results into a larger regional context. Motivated by this limitation we analyzed our time series data to evaluate the validity of using a common and easily measured population variable (kelp frond density) to estimate the more difficult to measure variables of standing crop and NPP We found that standing crop was strongly correlated to frond density ($r^2 = 0.79$) and that data on frond density collected in summer were particularly useful for estimating annual NPP, explaining nearly 80% of the variation in the NPP from year to year (Reed et al. 2009). Currently we are applying these relationships to annual time series data on frond density collected at 9 of our long-term monitoring sites as well as to similar data collected by investigators at sites in other regions to test our predictions concerning the role of disturbance in determining the magnitude and variability of annual kelp NPP.

Limits to the spatial extent of data that are routinely collected by divers have led us to search for additional means of investigating regional patterns in kelp biomass and NPP. With additional funding from NASA we have been exploring the use of high-resolution satellite imagery to investigate regional dynamics of giant kelp biomass and production (Figure 15). Our estimates of kelp canopy area using SPOT 5 imagery compared very favorably with near-coincident high-resolution aerial camera surveys ($r^2 = 0.90$;

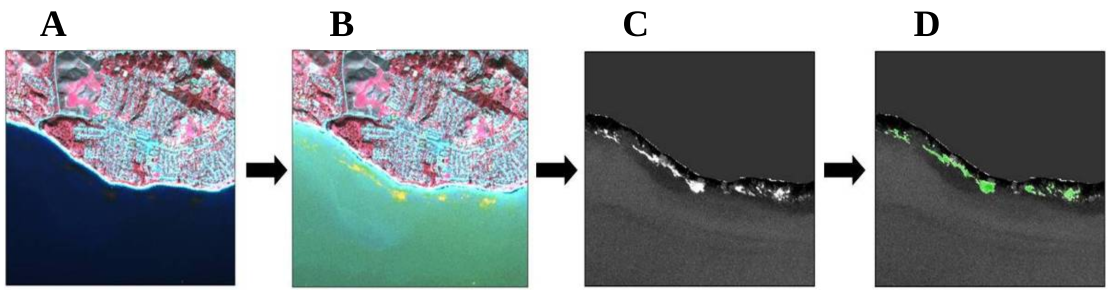


Figure 15. Four steps in the procedure for canopy cover delineation from SPOT 5 imagery. (A) False color SPOT image after geometric and atmospheric corrections have been performed (B) Resampled image after land and cloud areas have been masked out (C) PC band 2 (see Table 1 for band loadings), kelp is easily differentiated in this image because kelp's spectral signature closely matches the second mode of variability of the principal components rotation (D) PC band 2 after the threshold, manual edits, and winnowing filter have been applied. Pixels of kelp canopy are displayed in green.

Cavenaugh et al 2010). Importantly, our monthly measurements of kelp biomass and frond density in fixed plots collected by divers were strongly correlated with satellite determinations of Normalized Difference Vegetation Index (NDVI) signals of those plots ($r^2 = 0.77$). We used this relationship to examine variation in giant kelp biomass across multiple spatial scales (pixel, plot, site, and region). In doing so we found that the relationship between plot scale (40 m) changes in biomass and remote assessments of site scale (~1 km) changes varied among sites and depended on the relative location of the plot and the size of the kelp forest at each site. On a regional scale, changes in biomass among sites were well correlated with each other and with the aggregated regional (~60 km) total. We recently calibrated imagery from Landsat 5 for use in examining regional patterns and drivers of kelp abundance (Cavanaugh et al. 2011). Landsat data have a distint advantage for assessing kelp dynamics because they recently were made available to the public at no cost, and have a much greater temporal (1984-present) and spatial (the Pacific coast of North America) extent. Results of analyses using Landsat data for the entire Santa Barbara Channel during the 25 year period of 1984-2009 depict a high level of regional heterogeneity in the biomass dynamics of giant kelp. The dynamics of kelp biomass in exposed regions were related to wave disturbance, while kelp dynamics in sheltered regions tracked sea surface temperatures more closely.

<u>Interactions between the forest & its flow environment and their consequences on kelp and associated biota</u>

Pulse and press drivers that alter the biomass of giant kelp change the physical structure of the kelp forest, which can have cascading effects on fluid flow, light attenuation and the delivery of waterborne subsidies. These interactions in turn can profoundly influence the biotic structure and ecological functioning of the kelp forest community. To examine the extent to which the forest interacts with impinging currents we measured the flow characteristics inside and surrounding the kelp forest at Mohawk Reef using an array of 13 acoustic Doppler current profilers. We found that velocities were damped by as much as 60% in the interior of the forest and accelerated by as much as 200% along the forest's outer boundary as flow was shunted around the forest (Gaylord et al. 2007). We also found that the shading by the kelp canopy caused as much as a 90% reduction in fraction of surface light reaching the bottom in the interior of the forest relative to the edge of the forest (Figure 16). These physical features bear on the performance of kelp and other forest organisms that rely on light for photosynthesis and/or currents to deliver nutrients and food. For example, we found that kelp fronds on the seaward edge of the forest were longer, bushier (i.e. had larger more numerous blades per unit length) and had higher overall growth rates than fronds growing in the interior of the forest (Stewart et al 2009). Carbon and nitrogen accumulation by edge fronds was also higher, which fueled growth rates of edge fronds that were nearly twice as high as interior fronds when the kelp canopy was densest. Thus, the growth and tissue chemistry of *M. pyrifera* within the kelp forest depended on the extent to which the kelp forest modified the physical conditions within it.

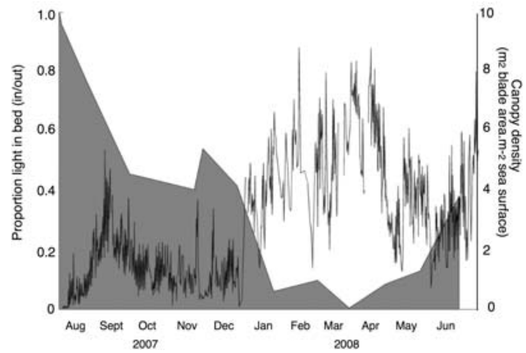


Figure 16. Ratio of bottom irradiance in the interior of the kelp forest to that outside the kelp forest. Shaded area denotes the density of the surface canopy of giant kelp

We have evidence that giant kelp similarly affects the performance of kelp forest consumers. The colonial bryozoan *Membranipora serrilamella* is a ubiquitous filter feeding invertebrate that lives on the blades of giant kelp. We have found that abundance and frequency of occurrence of *Membranipora* were as much as two orders of magnitude higher on the outside edges of forests compared to their interiors (Figure 17), due to higher rates of recruitment and growth at the forest edge (Arkema 2008). Lower rates of recruitment and growth in interiors of forests were attributed to measured reductions in flow and particle flux caused by the presence of giant kelp. Feeding success was highest at intermediate flow speeds and *Membranipora* abundance and growth rate were greatest at sites where water moved at intermediate flow speeds the majority of the time (Arkema 2009). Collectively our results demonstrate how the physical structure of the kelp forests interacts with its surrounding environment to

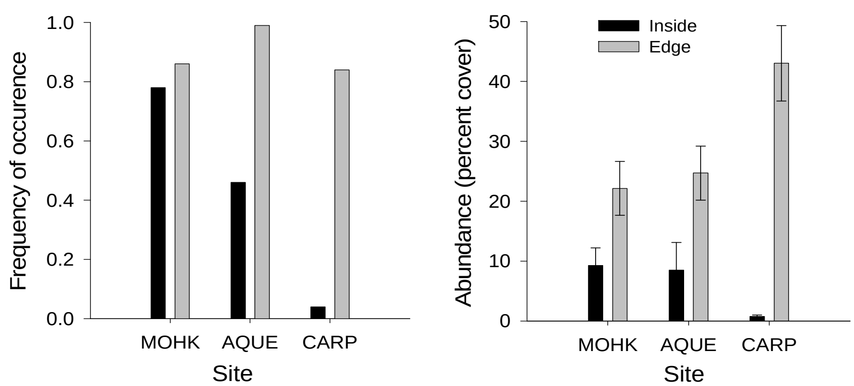


Figure 17. The frequency of occurrence and percent cover of *Membranipora* on kelp blades inside and at the outside edge of the kelp forests at Mohawk Reef (MOHK) Arroyo Quemado (AQUE) and Carpinteria Reef (CARP).

influence the biotic structure of the kelp forest community, and they highlight the importance of environmental drivers of giant kelp in influencing the entire kelp forest community.

Effects of wave disturbance on food web structure -

While the last twenty years have witnessed an explosion in research detailing the general structure of ecosystem food webs in nature {Dunnet et al 2007}, we know much less about how abiotic and biotic forces shape the structure of food webs at the community level. This is a particularly pressing need, as in the next century climate change will influence the frequency and intensity of a variety of press and pulse disturbances in marine ecosystems. Indeed, in California the last fifty years have witnessed an increase in both the frequency and intensity of winter storms {Graham and Diaz 2001; Bormoski et al 2002}. Here at the SBC LTER, we are using our long-term data to address how these disturbances both directly and indirectly alter the structure of kelp forest food webs.

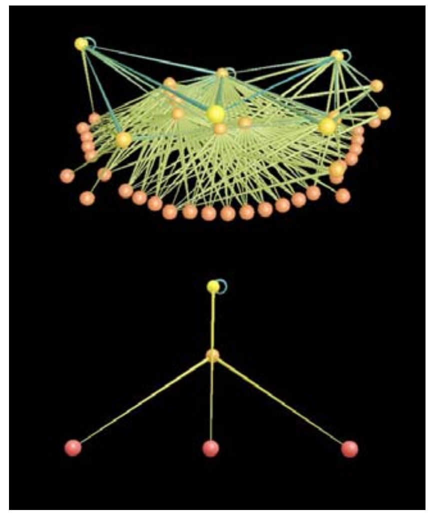


Figure 18: Food webs from Carpinteria Reef in 2008 (top) and Arroyo Hondo in 2005 (bottom). Note that webs differ in both species richness as well as the number and pattern of trophic links.

We are using structural equation modeling in conjunction with data from our ongoing long-term monitoring of kelp forest community structure at 11 sites to examine both direct and indirect effects of wave disturbance on the structure of the kelp forest food web. Wave height projections for our sites are obtained from the Coastal Data Information Program (CDIP). Using available literature, institutional archives and conversations with experts we were able to discern predator-prey relationships between all taxa that we have encountered in our long-term kelp forest monitoring. We are using this information along with the data to determine the network structure of the food web for each site in every year sampled. We found that these webs differ greatly in topology in both space and time (Figure 18). With these webs, we calculated different network metrics to describe each individual web (e.g., richness, density of trophic linkages, and ratios of biomass and richness between different trophic groups).

We constructed a general structural equation model that independently examines the direct and indirect effects of waves on each of these structural metrics. For each structural metric, our model contains a direct path between average monthly peak wave orbital velocity (i.e., the amount of strong wave disturbance) and the structural variable. It also contains an indirect path; wave disturbance connects to kelp frond density and kelp frond density is then allowed to influence a given structural metric. We have also included a variable representing the cover of sand that works the same way as the wave disturbance variable. Disturbance by sedimentation can have profound impacts on the structure of rocky reefs, and alter the composition of the local biota (Reed et al. 2008). In some models, we are using multiple structural metrics with paths connecting them in a manner consistent with our knowledge of food web theory. For example, linkage density often positively scales with species richness. Similarly, the number of intraguild interactions increase with the richness of species in higher level trophic groups.

Our results to date (Byrnes et al. 2011) show that wave disturbance directly and indirectly increased local species richness and the density of links (# of links / # of species) of food webs (Figure 19). Site-years with high wave disturbance had higher species richness. High wave disturbance also removed large adult kelp, and led to dense thickets of juvenile kelp. Higher kelp density led, in turn, to higher species richness. Higher species richness also led to higher linkage density, which is consistent with theory.

Future models will explore other structural variables to obtain a more detailed understanding of how wave disturbance alters the structure of kelp forest food webs. We also plan to decouple the effect of physical structure of kelp from its role as a food source by using satellite imagery to estimate total kelp biomass available to consumers. Our projections should provide much needed insight into the consequences of altered disturbance regimes caused by climate change.

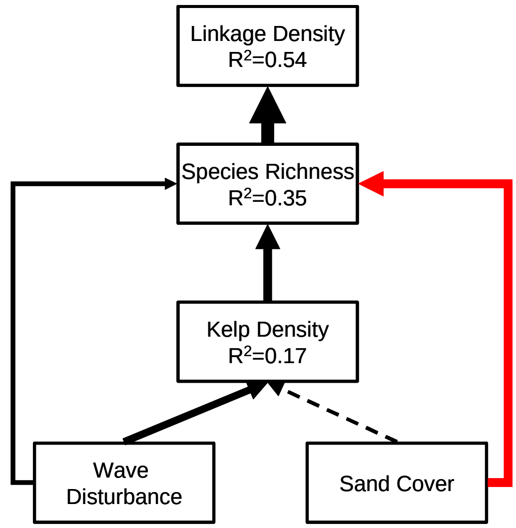


Figure 19: Results from a structural equation model linking different forms of disturbance with kelp density, species richness, and food web linkage density. Path width is proportional to effect size. Red paths are negative. Black paths are positive. Dashed paths are non-significant at p=0.05

Phase shifts and resilience of kelp forest communities in response to pulse and press drivers

Kelp forest landscapes tend to consist of mosaics of patches in distinct community states, and switches between states within each patch are often sudden and dramatic. These patterns are commonly thought of within the framework of phase shifts and alternative stable states, but they also have important implications for understanding how the ecosystem responds to pulse and press drivers. If alternative stable states are present, then the response of the system to a change in one driver will be dependent not only on the condition of the other drivers, but also on the current state of the system. Long-term research in this case is crucial because each community state can persist for many years and because the full behavior of the system cannot be understood without studying how each state responds to changes in different environmental drivers.

The effect of sea urchins on kelp provides a well understood example of the interaction between community state and environmental drivers. When present at high densities, sea urchins actively graze and prevent the establishment of kelp and other organisms, whereas at low densities they remain sedentary and feed passively by capturing drifting pieces of algal detritus. Because of

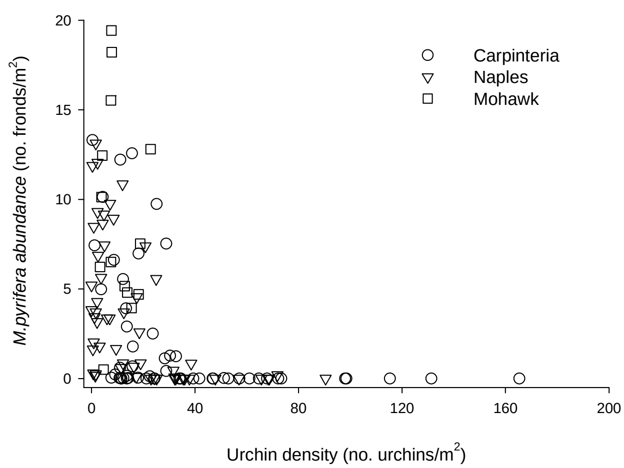


Figure 20. The relationship between kelp frond density and sea urchin density at three reefs in the Santa Barbara Channel. Data represent mean densities observed on a given transect during a given year.

this behavioral switch, an environmental driver that promotes kelp recruitment will have little effect on kelp abundance when sea urchin densities are high, but lead to large increases in kelp abundance when sea urchins are rare. We have used LTER monitoring data to show that this feedback is important in Santa Barbara, as giant kelp is only present when urchins are below a certain threshold density (28 urchins m^{-2}), regardless of other conditions (Figure 20). Although the effect of sea urchins on kelp is best known, we have shown that their presence has important effects on other taxa, maintaining low densities of sessile invertebrates and algae and clearing enough bare space that the space competition which typifies these sessile communities is minimized (Arkema et al. 2009).

We have also been studying another important community shift that appears to exhibit alternative stable states, in which a macroalgal dominated community is replaced by one dominated by the filter feeding sea cucumber *Pachythyone rubra*. Such shifts in community structure have obvious negative effects on primary production, as autotrophs are replaced by heterotrophs, but they also have cascading effects on the entire food chain, with the loss of macroalgae leading to a reduction in micro-crustaceans and in their associated fish predators. We have been studying shifts between these states at a number of sites off Santa Cruz Island in the Santa Barbara Channel and we have documented very rapid shifts and also the persistence of a single state for many years (Figure 21).

We have experimentally explored the interactions between macroalgae and *P. rubra* to determine the mechanisms that explain the shifts between community states and the maintenance of each state (Rassweiler 2008). We found that the sea cucumbers and macroalgae compete strongly for space, which is consistent with results from analogous systems. More surprisingly, we found that the sea cucumbers consume algal spores at a sufficient rate to have a strong effect on algal settlement. This web of interactions, in which one species consumes its competitor (known as intraguild predation) is often associated with alternative stable states. We have used analytical models and spatially explicit simulations to show that in this system intraguild predation reinforces the *P. rubra* aggregations, and may even create alternate stable states (Rassweiler 2008).

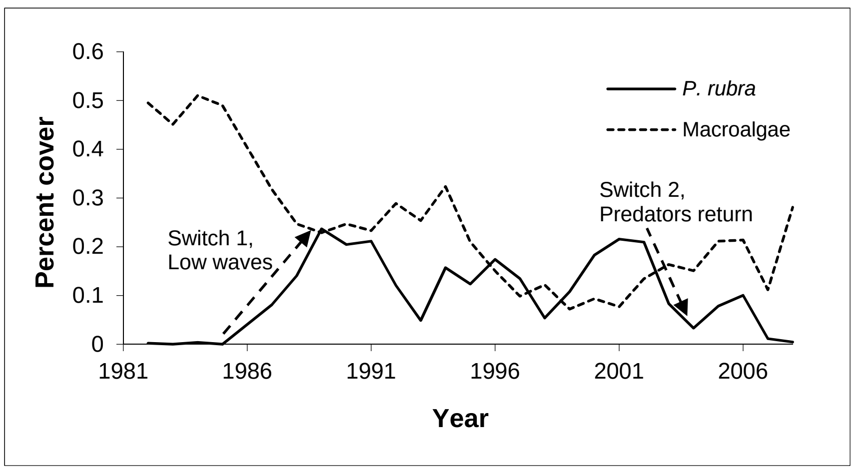


Figure 21 Mean cover of *Pachythyone rubra* and macroalgae at SBC-LTER sites at Santa Cruz Island. Switches in 1986 and 2003 are marked with dotted arrows.

We have also analyzed our time-series of *P. rubra* and macroalgal abundance alongside long term data on potential physical and biological drivers. We found that the switch into the high *P. rubra* phase was most likely triggered by a period of low waves (Figure 21). Because macroalgae rely on waves and water motion to compete for space, their competitive ability was reduced during this period and *P. rubra* was able to establish. Although the low waves were only temporary, representing a pulse disturbance, other mechanisms such as intraguild predation were sufficient to maintain *P. rubra* dominance once it was established. We found that a different mechanism explained the end of the high *P. rubra* state, with the sea cucumbers' reduction coinciding with the appearance of its major predator, the sunflower sea star *Pycnopodia helianthoides.* This predator represents a press disturbance in the system, and its continued presence explains the continued low density of sea cucumbers. It appears that interactions between the key press and pulse drivers are important in structuring this system, as the initial switch to *P. rubra* dominance was only possible because of the absence of its main predator. A similar pulse disturbance of low waves would be unlikely to allow *P. rubra* to increase if it occurred today given the current levels of predation.

Our work on kelp-urchin state change and our study of shifts between macroalgal and filter feeder dominated communities mesh well with a broader cross-site LTER interest in phase shifts and alternative stable states. To this end we have been collaborating with scientists from other LTER sites (Jornada, California Current Ecosystem, Moorea Coral Reef, Palmer Station and Harvard Forest) on general processes and mechanisms promoting phase shifts in ecological systems. We gathered examples of state change from LTER datasets and subjected each time series to the same set of analyses. We found that several of the recently proposed methods for detecting or predicting state change were unreliable even when presented with 30+ years of data and a very obvious change and community state. However we also found that the combined results of multiple analyses were often much more illuminating, and could be used to distinguish between different types of state change (e.g. identifying hysteresis in some cases and simple threshold phenomenon in others). This work has led to a cross-site manuscript that is currently in review.

THEME 3: The indirect effects of pulse and press drivers on kelp forest community structure and function and the feedbacks between structure and function

Direct and indirect effects of disturbance-driven fluctuations in giant kelp abundance on benthic community structure

The giant kelp *Macrocystis pyrifera* is considered both a foundation species (*sensu* Dayton 1975) and an ecosystem engineer (*sensu* Jones et al. 1994) because not only does it provide food and shelter for a diverse array of species, but it also drastically alters the physical environment in which it lives. Hence press and pulse drivers that affect the abundance of giant kelp should have corresponding effects on species that associate with it. Kelp forest communities are characterized by a trophic structure that is unique to shallow reef ecosystems in that the primary space holders (i.e., macroalgae and sessile suspension feeding invertebrates) occupy different trophic levels and thus do not compete for resources other than space. However, competition *within* the two space holder groups for other resources may indirectly affect the strength of competition for space *between* them. For example, shade from the canopy of the giant kelp negatively affects understory algae, which raises the possibility that giant kelp indirectly facilitates sessile invertebrates, via suppression of understory algae. We took a two-fold approach to examine this phenomenon (Arkema et al. 2009). First, we experimentally removed giant kelp from 40 m x 40 m study plots and measured the responses of understory algae and sessile invertebrates. We found a negative effect of giant kelp on both light availability and understory algal abundance and a positive effect on the abundance of sessile invertebrates, which was consistent with an indirect effect mediated by shade from the kelp canopy. Secondly, because frequent disturbance causes kelp populations to fluctuate greatly in space and time, we used observational data on kelp forest community structure from long-term monitoring sites to examine whether the interactions among kelp, understory algae and sessile invertebrates observed experimentally in space led to predictable patterns over time. We found that interannual variability in the abundances of understory algae and sessile invertebrates were significantly and positively related to interannual variability in the abundance of giant kelp ($r^2 = 0.74$, $P < 0.001$ for understory algae and $r^2 = 0.46$, $P = 0.03$ for sessile invertebrates). Results from structural equation modeling indicated that giant kelp negatively affects understory algae via canopy shading, understory algae negatively affects sessile invertebrates through space competition, and giant kelp indirectly facilitates sessile invertebrates (Figure 22). In fact, the magnitude of the indirect effect of giant kelp frond density on sessile invertebrates (-0.39 x -0.74 = 0.29), was nearly six times greater than the magnitude of the direct effect (= -0.05). The coefficient for the path representing the direct effect of giant kelp frond density on sessile invertebrates was not significantly different from zero, nor were the paths between the percent cover of giant kelp holdfasts and the percent cover of understory algae and sessile invertebrates, suggesting that the significant effects of kelp resulted from shading by kelp fronds rather than competition for space by kelp holdfasts. Our results suggest that the dynamic structure of the kelp forest community is driven in large part by variability in the abundance of a single structure forming species (giant kelp) that has indirect positive, as well as direct negative effects on associated plants and animals.

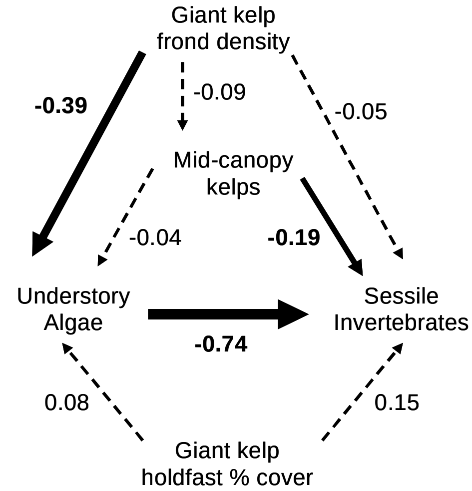


Figure 22. The fitted competition and facilitation model used to estimate the strength of direct and indirect effects. Values are standardized coefficient estimates. Solid lines indicate significant paths ($P < 0.05$). Dashed lines are non-significant.

Disturbance, assemblage structure and the partitioning of primary production among giant kelp, understory macroalgae and phytoplankton

Giant kelp forests are highly productive ecosystems, rivaling those of tropical rain forests. This productivity and its associated standing biomass, however, vary greatly both within and among years in large part due to disturbance from waves (Reed et al. 2008). Such variation in turn affects the entire kelp forest assemblage of primary producers, which are negatively affected by kelp canopy shading (Arkema et al. 2009). To date, estimates of kelp forest production have focused mainly on *Macrocystis*, excluding the diverse community of phytoplankton and understory benthic algae from consideration. Strong competition for light with giant kelp in the forest may cause populations of these two groups of autotrophs to vary out of phase with *Macrocystis*, which may serve to dampen the variability in ecosystem production by kelp forests. To the extent that *Macrocystis* dominates total reef ecosystem NPP, variation in *Macrocystis* canopy will drive corresponding variation in total ecosystem NPP. Alternatively, if NPP of understory algae and/or phytoplankton increases in response to reduced *Macrocystis* canopy, then variability in ecosystem NPP will be reduced. The amount of such compensatory productivity will depend upon the magnitude and temporal lag in the production of understory algae and phytoplankton to the more favorable light conditions associated with kelp loss following disturbance. Phytoplankton are likely able to respond rapidly as the biomass of phytoplankton in the kelp forest is determined by larger scale processes that affect the regional production and transport of phytoplankton (see "Theme 1 Transport of offshore shelf C and N to the inner shelf). In contrast, the recruitment and growth of understory algae is influence by conditions within the forest, and because of their slower growth rates and seasonal recruitment NPP by understory algae in the kelp forest may lag substantially behind that of phytoplankton following kelp loss.

To examine the role of disturbance in partitioning NPP among different groups kelp forest producers we developed methods for measuring NPP by understory algae *in situ* (Miller et al. 2009) and used these methods to compare rates of NPP by understory macroalgae with those by phytoplankton and giant kelp in an area where giant kelp was removed and in an area was it was left in place. The study was done at Mohawk Reef over a 17-month period in 2007-2008 during which time wave disturbance caused substantial variability *Macrocystis* standing crop and production. We hypothesized that the *Macrocystis* canopy would negatively affect the productivity of understory macroalgae and phytoplankton, and that these effects would vary with *Macrocystis* standing crop. We predicted that understory algae, unlike phytoplankton, would be unable to respond immediately to reductions in *Macrocystis* shading, and one of our goals was to estimate the magnitude of this time lag,. Finally, we compared NPP by *Macrocystis* with that by understory macroalgae and phytoplankton to determine whether natural fluctuations in *Macrocystis* biomass, led to similar fluctuations in the NPP of the entire kelp forest ecosystem.

We found strong evidence that the presence of the giant kelp canopy suppressed production by phytoplankton and understory algae (Miller et al 2011). As predicted, increased NPP by phytoplankton occurred immediately following disturbance-induced reductions in the kelp canopy, while NPP by understory algae displayed a substantial time lag in response to kelp loss due to the time required to increase its biomass via recruitment and growth. Importantly, we found that in the absence of giant kelp NPP by phytoplankton and an established understory was comparable to that of an established kelp forest community (Figure 23a). Somewhat surprising was our finding that phytoplankton and understory algae contributed on average about one third of ecosystem NPP at the *Macrocystis* canopy control site (Figure 23b).

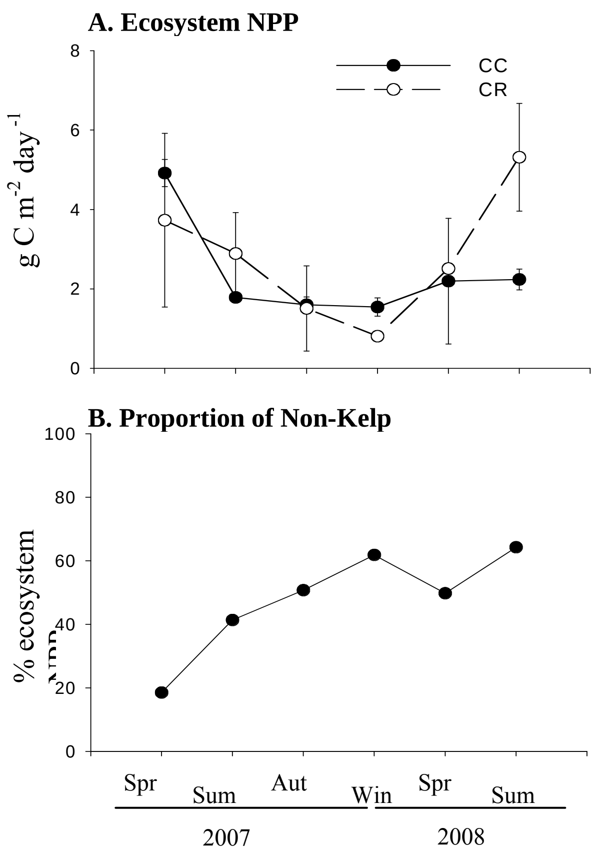


Figure 23. (a) mean ecosystem NPP, including *Macrocystis*, understory, and phytoplankton NPP at the kelp canopy removal (CR) and kelp canopy control (CC) sites at Mohawk Reef. Error bars are 1 standard error. (b). Percentage of non-kelp NPP (Understory + Phytoplankton NPP) inside the kelp forest (canopy control site).

These results illustrate how indirect effects of pulse and press drivers can influence important aspects of kelp forest structure and function and how the structure of kelp forests as defined by the biomass and species composition of their autotrophs feeds back to influence net primary production, which is a critically important ecosystem function.

While the use of benthic incubation chambers has allowed us to investigate the contribution of understory algae to the productivity of the kelp forest ecosystem, logistical constraints render them less useful for longer-term comparative studies and experiments, which are needed to better understand the patterns and controls of primary production by macroalgae and their ecological consequences. To this end we developed a simple physiologically-based model of benthic macroalgal production using three components: (1) bottom irradiance obtained from PAR sensors mounted to the sea floor, (2) taxon-specific macroalgal photosynthesis versus irradiance (P vs. E) parameters measured in the laboratory, and (3) taxon-specific foliar standing crop measured non-destructively in the field using allometric relationships developed by SBC LTER (Miller et al. in review). To test the model we compared its predicted estimates of production to measured estimates obtained with the benthic chambers deployed in situ and found a near 1-to-1 correspondence. This model is being applied to data collected in our long-term kelp removal experiments to investigate the extent to which increases in mortality rates of giant kelp (an expected consequence of climate change) lead to changes in ecosystem NPP and foodweb structure. We are also using data collected from these experiments to investigate the extent to which biomass alone predicts annual NPP of understory algae much like we did for giant kelp (Reed et al 2009). We found a strong relationship between the biomass of understory algae in summer and annual NPP of the understory algal assemblage ($r^2 = 0.75$) that we can apply to our ongoing 11-year time series of kelp forest community structure at our long-term study sites (Harrer 2010).

Feedbacks between benthic diversity and grazing intensity in giant kelp forests

In seeking to understand the complex dynamics of communities, researchers have typically concentrated on factors that either regulate community structure or community function. Nowhere has this dichotomy been more evident than in biodiversity research, where separate research traditions have attempted to tease apart either the causes or the consequences of biodiversity. Both are inextricably linked. For example, theories such as the Intermediate Disturbance Hypothesis state the biodiversity is maximized at intermediate levels of disturbance {Connell 1978}. On the other hand, biodiversity ecosystem function research has shown repeatedly that high levels of biodiversity can actually reduce the intensity of disturbance {Hillebrand and Cardinale 2004; Hughes and Stachowicz 2004}. We hypothesize that these two relationships form a feedback between species diversity and disturbance (Figure 24).

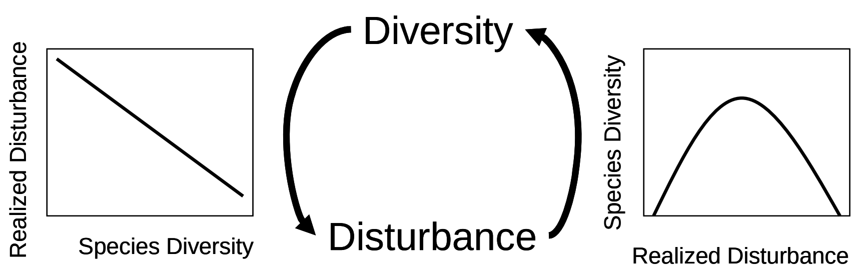


Figure 24: Hypothesized feedbacks between species diversity and disturbance. Diversity of an assemblage determines how much disturbance results from a particular event (e.g., highly diversity communities will potentially experience very little disturbance). The amount of disturbance realized by a community in turn feeds back to alter the diversity of the subsequent assemblage.

Within kelp forests, biological disturbance by sea urchins can drastically alter levels of primary productivity. Sea urchins prefer to feed on kelp detritus, but when starved for drift kelp they change their mode of feeding to one of active grazing. Dense aggregations of grazing sea urchins are common in kelp forests worldwide and their ability to denude the bottom substrate of most sessile species has been well documented. However, yet to be determined is the extent to which the diversity of the benthic assemblage that sea urchins attack influences their effect on the structure of that assemblage and the extent to which the realized amount of disturbance to assemblage in turn feeds back to alter the diversity of the recovered community by altering recruitment, growth, and species interactions.

To investigate the feedbacks between sessile species diversity and sea urchin disturbance, we initiated an experiments in summer 2009 in which we manipulated densities of the purple sea urchin (*Strongylocentrotus purpuratus*) in caged 0.5 m^2 plots that varied in sessile species diversity. Densities of sea urchins were augmented within the caged plots in a response surface design such that plots at all levels of diversity were subjected to a complete range of grazing intensity. The grazing component of this experiment was run for three weeks, after which time we removed the sea urchins and recorded changes in percent cover and species richness of sessile organisms within each plot. We found that sessile species richness enhances urchin grazing activity, but only at low urchin densities (Byrnes et al. in prep). This effect of species richness was stronger at higher levels of sessile species evenness. Our results suggest that either the balanced diet or toxin minimization hypothesis leads to enhanced levels of consumer activity at higher species diversity in kelp forests.

<u>Long-term experiment: Implications of climate change on kelp forest structure and function</u>

Modeling and correlative analyses of our long-term data coupled with cause and effect relationships gleaned from an assortment of short-term mechanistic experiments are providing us with considerable insight into our overarching question of *How do abiotic drivers acting over different spatial and temporal scales interact to influence kelp forest structure and function?* Longer-term manipulative experiments conducted at ecologically relevant temporal and spatial scales offer a powerful means of verifying predictions generated by our correlative analyses and short-term experiments. Because the giant kelp *Macrocystis* extends throughout the water column it is easily dislodged by large waves associated with winter storms. With this in mind we initiated a long-term experiment in January 2008 to test an assortment of predictions concerning the consequences of consistent annual kelp loss arising from increases in the frequency and intensity of winter storms, which is a trend that has been observed in California over the last 50 years {Graham and Diaz 2001; Bormoski et al 2002}.

To simulate the consequences of increased storm activity we remove all giant kelp once per year in winter from permanent 40 m x 40 m plots at four of our long-term study sites (Arroyo Quemado, Naples Reef, Mohawk, and Carpinteria Reef). Adjacent 40 m x 40 m plots at each site where kelp is left undisturbed serve as controls (Figure 25). These sites vary in wave exposure and level of sea urchin grazing. As such we hope to gain valuable insight over the long-term with respect to how the effects of selectively removing giant kelp vary with different levels of physical and biological disturbance.

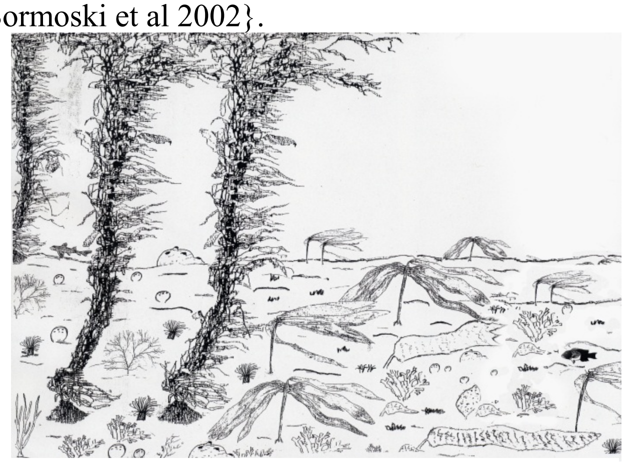


Figure 25. Schematic of the long-term kelp removal experiment showing a giant kelp removal plot with abundant understory kelps and algae on the right and a kelp canopy control plot with giant kelp and a sparse understory on the left.

We are following changes in the biological structure (species abundance and richness of algae, invertebrates and fish), and various ecosystem processes (e.g., NPP by macroalgae, detrital accumulation) 2x per season in fixed transects and quadrats located in each plot. Because there are no off the shelf methods for estimating NPP by understory macroalgae we have been developing a non-destructive approach for examining patterns of understory NPP using species-specific allometric relationships (to estimate biomass) coupled with a bio-optical model. Our bio-optical model incorporates algal biomass, photosynthetic efficiency (derived from laboratory derived photosynthesis vs. irradiance curves for ~20 species that comprise over 95% of the biomass), and photosynthetically active radiation measured once per minute by sensors anchored to the bottom in each kelp control and removal plot.

Our initial results show that giant kelp is among the first species to colonize in spring following its removal in the preceding winter. Dense thickets of young giant kelp have colonized sites with low grazing in each of the first two years. We hypothesize that colonization by giant kelp into the kelp cleared plots will decrease over time as other understory species become established and monopolize light and space. Such changes will undoubtedly influence a diverse assemblage of kelp forest consumers that depend directly and indirectly on giant kelp for food and/or shelter.

In addition to examining potential consequence of climate change, the long-term removal of giant kelp will also provide a wealth of information on how the kelp forest system responds in the absence of its foundation species. Moreover, the design of our experiment (in terms of plot size and replication among sites) allows it to serve as a template for both short and long-term investigations that explore a wide variety of ecological issues and questions pertaining to the presence (or absence) of giant kelp. Indeed our current studies of kelp forest food webs and feedbacks between ecosystem structure and function were designed to make use of the long term experiment

INFORMATION MANAGEMENT FINDINGS

SBC's IM activities have continued to focus on metadata components, which facilitate management of our major resources and products and provide the basis for general website subject areas such as maps or description of projects (e.g., experiments). Additionally, we are collaborating on a common relational data model with three other LTER sites (MCR, CWT, GCE), and are applying innovative ontological approaches to SBC measurement descriptions. Our metadata system continues to be closely aligned with the network data exchange specification, Ecological Metadata Language (EML), and contributes to the broader Network efforts. Results of recent information management projects at SBC are summarized below.

EML Dataset Management

With supplementary funds and in collaboration with MCR, we began adapting the GCE relational database schema "Metabase" for use at SBC and MCR. The system at GCE has proven adaptable and capable of quickly producing high-quality datasets. We plan to implement the data model to replace some of the more manual steps in SBC dataset management. This upgrade will enhance our ability to produce high quality dataset quickly. To date, all GCE Metabase database tables have been ported to PostgreSQL on the SBC/MCR database server. The first exports from the database have been SBC "projects", which are somewhat smaller than datasets, but of the same format (i.e., EML) and which will be used as content for the SBC website. Lessons learned from the initial exports will be applied to dataset generation. We have begun work on XSL tools for extracting content from our existing EML datasets to populate Metabase for datasets. This code is deliberately generalized to enable further development as a network resource.

SBC expanded its data holdings in 2011 with its existing system. We have begun incorporating legacy datasets from Santa Cruz Island reefs and kelp forests (dating to 1982), and for invertebrate larval recruitment (dating to 1992). Data for our core measurements program now include beach wrack surveys and the cross-shelf research campaign (2008-2009). Other datasets have been enhanced with keywords from the recently developed LTER Controlled Vocabulary and units from the LTER Unit Dictionary as part of our regular update process, also using our existing system.

SBC's information manager (O'Brien) received LTER Network funds to use new network information system (NIS) code to evaluate EML data packages for automated upload with a tool called the EML Congruence Checker (ECC). This work stems directly from SBC's use of the "EML Data Manager Library" code, which is incorporated in SBC's EML Dataset Query application (EDQ, 2006), and is currently being further developed in the NIS Provenance Aware Synthesis Tracking Architecture (PASTA) system. As of mid-2011, the ECC code is not fully functional and so provides only a first look at data package usability. However, we were able to produce initial reports for all SBC datasets (Table 3). The PASTA Data Manager/ECC currently accommodates about two-thirds of SBC data packages, and of those about one-third of data tables can be ingested. This is similar to SBC's experience using the Data Manager code in the EDQ (anecdotal). However, the new regular reporting schema makes it clear that when certain data typing issues are resolved, all currently reportable SBC datasets are likely to be uploaded. Even in its current developmental state, SBC's reporting scheme can be used on any dataset in the LTER network, and further development as a regularized tool will make it invaluable for dataset evaluation and as feedback to PASTA developers.

A. Data Package Summary

Total	87	SBC data packages with reports
No report	40	Data packages that ECC cannot yet report on

B. Data Entity Summary

Total	109	Number of entities found in all data package reports, of any type (data tables, etc).
Working URLs	109	Number of data URLs that are valid.
Not attempted	16	These are KML or binary files (e.g., images)
URLs with data	93	Number of entity URLs which stream data
Tables loaded	28 (65)	Number of data tables which could be loaded into a database from their EML metadata. In (parentheses) is the number of additional tables that can be loaded after resolution of time and date format compatibility.
Total rows loaded	1,595,761	Sum of rows loaded, all data tables

Table 3. Summary for SBC data packages from the EML Congruence Checker (v0.1), August 2011. A). Data package summary. B) Summary of data entity reports (from total SBC data packages in part A). SBC holdings in the network total 127 data packages comprised of 192 data tables and 49 other data entities.

Website

Progress has been made on two enhancements for SBC's website. First, sampling sites from all data packages are described in standardized format, and will be used to create a map application showing core sampling activities and locations. Secondly, the project information from Metabase is being used to display descriptive information about SBC's research projects and activities. Both schemas are compatible with EML.

Measurements Dictionary and Ontology

Work continues on SBC's dictionary of measurements, an extension of the Extensible Observation Ontology (OBOE) developed by a related NSF project Semantic Tools for Data Management (Semtools, DBI-0743429), which is providing software for increased data access, discovery, and integration using semantically annotated metadata. Through this project, SBC has access to knowledge modeling experts in building a detailed dictionary of its own ecological and environmental measurements. Recently, another partner, the Salmon Juvenile Recruitment project, joined the OBOE extensions group, which expands our pool of experts and validation scenarios. This work has been presented to the LTER IM Committee, and also will contribute to the broader measurement standardization efforts in the LTER network.

TRAINING AND DEVELOPMENT

Education and training are tightly integrated into all aspects of SBC LTER research. As of August 2011, 14 post docs, 54 graduate students, 12 REU students and more than 225 undergraduate students have participated in SBC research during the last 5 years representing our current award. UCSB undergraduates have a high propensity to get involved in sponsored research and the SBC LTER contributes substantially in this regard. In addition to gaining valuable research experience, many undergraduates earn academic credit or received monetary compensation for participating in SBC research as interns and honors students. SBC investigators, graduate students and staff serve to mentor independent research by undergraduates and local high school students. SBC LTER is an active participant in NSF's Research Experience for Undergraduates program and in several other mentorship programs sponsored by the University of California. REU students work closely with SBC LTER researchers on a wide range of topics and most choose to pursue an advanced degree following the undergraduate education

SBC LTER graduate student and postdoctoral training is coordinated with several graduate programs on the UCSB campus most notably, the Interdepartmental Graduate Program in Marine Science, the Department of Ecology, Evolution and Marine Biology and the Bren School of Environmental Science and Management. SBC LTER work with these programs to promote opportunities for interdisciplinary graduate research that examines how coastal ecosystems change in response to natural and human-induced alterations in the environment. Students and post docs work on topics in terrestrial, aquatic, and marine environments with interests ranging across ecology, physiology, geology, hydrology, oceanography, modeling 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. In Winter 2011 SBC investigators organized a 10 week graduate seminar on focused on major SBC research themes for 30 SBC graduate and advanced undergraduate students. Each seminar began with a presention by SBC investigators or postdocs and proceeded to a graduate student-led discussion of that week's paper and seminar, providing ample opportunity for interactive learning across disciplines. Our students, postdoctoral fellows, and investigators attend SBC LTER's Annual Science Meeting and the triannual LTER Network All Scientists Meeting and present results from their SBC research and collaborative projects in poster sessions and oral presentations. In February 2011 graduate students from SBC, MCR and CCE LTERs met at the Marine Science Institute at UCSB for the 2nd California LTER Graduate Student Symposium. This year's event, organized and hosted by graduate students from SBC and MCR LTERs (the first California LTER Graduate Student Symposium was organized hosted by CCE LTER in 2008). Student participants represented the University of California campuses at Santa Barbara and San Diego, (UCSB, UCSD) and California State University at Northridge (CSUN). This all-day event featured more than 20 presentations of student research in talks and posters.

SBC LTER is actively working to provide opportunities for research training to students from non-traditional research universities. To this end we recently received supplemental funding for a NSF Research Opportunity Award (ROA) to collaborate with students and faculty from Chapman University a small, liberal arts college that does not offer a graduate degree, and is an RUI-eligible institution. The collaborative project seeks to examine some potential ecological consequences of implementing the Marine Life Protection Act, which restricts or prevents exploitation of designated rocky reefs throughout California. The ability to accurately predict these consequences is intimately tied to a comprehensive understanding of the ecological system encompassed by SBC LTER. The collaboration between SBC LTER and Chapman University will broaden the institutional and geographic scope of SBC LTER, and deliver intensive training to young scientists just starting their careers. SBC LTER also hosted two visiting graduate students from the University of Bologna in Italy. The students worked with SBC researchers to conduct field experiments on the effects of artificial light on kelp consumption by beach consumers for their master's degree programs.

OUTREACH

SBC LTER is engaged in a wide range of outreach programs that target a diverse audience. The activities of these programs are described below.

The SBC-LTER Summer Program

Our Schoolyard LTER (SLTER) program is organized around a theme of watershed ecology. This approach allows for an integrated program that includes K-12 students, K-12 teachers, undergraduate and graduate students, and staff. For the last few years we have focused on developing long-term connections with local, regional and state middle and junior high schools through a partnership with the American Association of University Women's Tech Trek Program. Tech Trek is a math/science summer program designed to develop interest, excitement and self-confidence in young women who will enter eighth grade in the fall. It features hands-on activities in math, science and related fields. Tech Trek is a campus residential program that includes educational and recreational activities, all of which are located on a university campus where camps are held. Tech Trek is part of an interdisciplinary partnership involving science, technology, engineering, and math departments at UCSB through the Office of Academic Preparation and Education Outreach (APEO). The goal of APEO is to build college-going communities that improve student learning, increase college-going rates in underrepresented populations, and provide equal access to higher education for California's diverse students. With the infrastructural support of Tech Trek and APEO, the SBC SLTER program has been able to continue its successful programs to engage middle school students and teachers through the academic year and summers, and throughout their secondary school education. Our successful program format incorporates training and education of several types. First, we continue to work with our undergraduate interns in a rigorous and pedagogically sound program of training in marine science and science pedagogy. These interns engage directly with middle school students as teachers and role models. Second, we continue to develop and adapt marine science lesson plans that engage students with learning about the local environment. These lesson plans incorporate ongoing SBC LTER research and include working with data generated by monitoring and experiments. The program is developed to build student's skills in scientific inquiry through activities that move from structured or guided investigation to open-ended experimentation. Third, our program includes a combination of school-based activities, field trips, and an on-campus residential experience that immerse students in the environment of a college campus. In working with Tech Trek, the SBC SLTER program engages a group of approximately 150 girls from junior high and middle schools from counties surrounding Santa Barbara (SLO, Ventura, Kern, LA, etc). The participants are diverse, representing a broad range of socioeconomic and demographic groups. During their week-long residential immersion at UCSB, students participate in "core" science courses focus on science basics, that include; physics, math, chemistry, and biology. These courses are then complimented through practical application activities where students are engaged in SBC LTER research- based learning activities, conduct field activities, and explore the possibility of attending a 4-year college. Activities include explorations of ecology and adaptation at the UCSB aquarium, SBC LTER research site monitoring protocols, and a Floating Lab trip, on a 75' catamaran, into the Santa Barbara Channel. An additional benefit expected in future years is the long-term connection we will maintain with participating students both through APEO support (they work with some of these same students throughout their high school years) and through continued engagement with students as they move into high school and college. We envision a program that supports interested students with science fair projects, summer research opportunities, and mentoring opportunities with our middle school program. Through this long-term commitment, we are now seeing former program participants enrolling in UCSB. Two former participants are now working at the Research Experience & Education Facility (REEF).

Research Experience & Education Facility (REEF)

The SBC SLTER outreach, education and training programs benefit from a close association with the University of California at Santa Barbara's Research Experience & Education Facility, better known as The REEF, an interactive aquarium facility. The REEF is equipped with state-of-the-art, aquaria and touch tanks, ranging from 2 to 2,000 gallons. The REEF also utilizes a high-tech life support system for the Research Tank, which highlights current, on-going research at UCSB and the Marine Science Institute, including SBC and MCR LTER research. One of the joint goals of the SBC LTER and the REEF programs is to provide UCSB undergraduates majoring in Aquatic Biology, with a solid foundation in temperate marine ecology and research. The REEF training provides them with the basis for communicating this knowledge in an educational format. To that end, The REEF develops its curriculum around a number of research programs at UCSB. The SBC LTER is a significant contributor to this endeavor. Support from the SBC LTER schoolyard program has allowed the REEF to obtain teaching supplies and equipment for curriculum and teacher professional development, as well as provide stipends for teachers, undergraduate and graduate internships. The REEF also utilizes graduate students from the SBC LTER to train REEF undergraduate staff, which, in turn, enhances their training as laboratory and field assistants and research divers for SBC LTER research.

The REEF program was, again, very busy during 2011, through continued outreach visits to schools, community events and on-campus programs, The REEF provided marine science and environmental education to over 17,000 children and adults. This included hosting educational visits from primary and secondary schools from Porterville in the San Joaquin Valley, Los Angeles Co, Ventura Co, San Bernardino, and as far east as Las Vegas, Nevada! The REEF also continues to serve as a marine laboratory for many colleges including Cal Lutheran Thousand Oaks, CSU Channel Islands, Oxnard and Ventura Community VColleges and UCSB. At UCSB, The REEF serves as an interdisciplinary laboratory for undergraduate courses including: Geology 4 (Intro to Oceanography), EEMB 3 (Intro Biology), EEMB 106 (Biology of Fishes), Writing 2 and Writing 109 ST. This year the REEF had over 3,500 on-campus visitors.

Math-Science-Partnership (MSP) Project: Pathways to Environmental Literacy

The MSP project, which was launched in October 2008, connects the research and education strengths in the environmental sciences of universities and sites within LTER with teacher professional development in science and mathematics of partner middle schools and high schools. It extends across the nation and involves four LTER research sites the Shortgrass Steppe (SGS), Baltimore Ecosystems Study (BES), Kellogg Biological Station (KBS), and Santa Barbara Coastal (SBC) and their partnering institutions, the LTER Network Office, and a group of 22 K-12 schools and districts that will directly impact over 250 science and mathematics teachers and up to 70,000 students from diverse backgrounds. The SBC LTER site has continued working closely with the entire science department at La Cumbre Junior High School in providing teacher professional development to develop in-class science curriculum based on SBC LTER field study sites, data and ecological principles. The MSP project provided funds to support a program coordinator, a post-doctoral fellow, and 1 SBC LTER graduate student fellow, a Teacher in Resident (TIR) and 4 undergraduate teaching and administrative assistants. The project participants worked with science teachers at a local school, La Cumbre Junior High School, implementing programming that impacted all 450 junior high schools students. In particular, participants (program coordinator, post doc, TIR, etc.) worked in the 7th and 8th grade science classrooms developing and implementing LTER science based curriculum. All participants were actively engaged in developing and leading two field trips that brought all students to a nearby LTER monitoring site and on-campus for a visit to The REEF. A number of SBC graduate students, post-docs and investigators gave talks on their research and led activities for the MSP field trips and programs. This year, SBC hosted “From the Ground Up,” a summer PD workshop that included 22 new junior high and high school teachers from Santa Barbara and Ventura Counties from five different school districts. The SBC MSP team, which also included a researcher from the Colorado SGS MSP team lead teachers on a week-long workshop that included training on curricula associated with the projects environmental literacy strands of Biodiversity, Carbon and Water, as well as a theme-based, Citizenship activity. Participants were also led on a tour of one of the SBC LTER watersheds. Each day was highlighted with a strand focused research seminar led by SBC graduate researchers, post-docs and senior scientists.

CoastLines

In Summer 2010 SBC co-hosted a 2 week workshop for 30 educators from all over the country as part of the CoastLines (http://www.coastlines.ws) project. CoastLines is a three-year comprehensive project for students and teachers funded by the Information Technologies for Students and Teachers program at the National Science Foundation. It introduces fundamental concepts about information technologies (IT) to grade 7-12 schools by involving teachers and students in using geographic information systems (GIS) and global positioning systems (GPS) to conduct scientific studies of coastal ecosystems in the National Science Foundation's Long-Term Ecological Research (LTER) network. CoastLines builds on lessons learned by the Center for Image Processing in Education and other practitioners about offering GIS-based training to K-12 educators.

The 2009-2010 CoastLines project focused on SBC LTER research. During Spring 2010 teachers participated in several online webinars during which they were introduced to the SBC LTER research themes, sites, and data to prepare for the 2-week workshop held on the UCSB campus. During the workshop teachers worked with existing SBC LTER data to build GIS maps in order to virtually explore the SBC LTER research sites. Teachers also collected and geo-located their own environmental data to import into their GIS software. SBC LTER researchers and staff gave presentations, led field trips, and assisted teachers in developing research questions of their own. The workshop culminated with the development of GIS-based lesson plans that were implemented in their classrooms in the fall semester with SBC LTER staff support.

Science Fairs

SBC investigators and students also regularly mentor local K-12 students in science fair projects. In 2007 SBC LTER students participated in the *OceansAlive!* program of the UCSB Marine Science Institute (MSI), a collaboration with a number of UCSB departments and research programs to provide 125 local junior high, middle school and high school students with UCSB undergraduate and graduate student mentors for science fair projects. These secondary school students then competed at the local level with the opportunity to progress to the state and national levels. In 2007, students mentored by SBC investigators won best project in the Senior Life Science division and as well as best senior project at the Santa Barbara County Science Fair and went on to win 2nd place in the senior zoology category at the California State Science Fair.

Additional SBC Outreach Activities

SBC LTER research and expertise are regularly shared with the public through a variety of media outlets including local and national newspapers, magazines, internet news feeds, podcasts, blogs, radio, and televison. Recent topics covered by local and national media include remote sensing of kelp forests from satellite, giant kelp genetics, effects of increased frequency and intensity of coastal storms on kelp forests, coastal ocean circulation in the SBC study area, local history, interviews on the Deep Water

Horizon oil spill and a visit to SBC and UC Santa Barbara by "Dreams Come True" foundation recipient, Caroline Roy http://www.ia.ucsb.edu/pa/display.aspx?pkey=2513 . SBC investigators also serve as participants and advisers to several community groups to provide educational and scientific perspectives including the Santa Barbara Community Environmental Council, Friends of the Santa Clara River, Santa Barbara Creeks Council, and the UCSB Shoreline Preservation Fund.

Direct outreach to the public is an active area for many SBC investigators and students. Al Leydecker, an SBC post-doctoral fellow, assists and helps direct stream and river monitoring, education and sampling programs for several community environmental organizations, including Santa Barbara Channel Keeper, Ventura Surf Rider and the Friends of the Santa Clara River. In 2009, Co-investigators Bradley Cardinale and Jenifer Dugan gave talks to the local groups including Audobon Society and the Santa Ynez Natural History Society. In 2011 members of the Schimel lab were directly involved in mentoring K-12 students, including a "Soil's Alive!" presentation and demonstration of soil ecology for 10th graders from the local Santa Ynez Valley Union High School District. In 2010 Shannon Harrer presented an overview of the SBC LTER project, its goals and objectives and how undergraduates can become engaged in the project for the UCSB Freshmen Start Program.

To raise public awareness of marine ecosystems, SBC LTER investigators, staff and students jointly hosted an public outreach booth with the MCR LTER at the Santa Barbara Earth Day Festival in April 2011, which attacts more than 20,000 people. SBC offered children's activities including making algae prints using tempura paint on paper, coloring pages and ink stamp activities. Site research posters and brochures were set up for viewing and SBC researchers and students were on hand to field questions and lead activities.

SBC investigators also serve as participants and advisers to several community groups to provide educational and a scientific perspectives including the Santa Barbara Community Environmental Council, Friends of the Santa Clara River, Santa Barbara Creeks Council, and the UCSB Shoreline Preservation Fund.

Educational opportunities at SBC are not limited to university students and post docs. Teachers and numerous volunteers from the general public regularly participate in our stream sampling program and gain considerable knowledge on the constituents of runoff and of the processes that influence their concentrations.

CONTRIBUTIONS WITHIN DISCIPLINE

The understanding of ecosystem level processes in giant kelp forests has lagged behind the increasing body of knowledge at the species, population, or community level of kelp forests over the last four decades. Results from our reef studies are helping to address the growing need for research at the ecosystem level in kelp forests. Of particular significance are our studies of 1) primary production, 2) integrating kelp forest population dynamics and genetics on local to basin-wide spatial scales and across temporal scales 3) kelp forest food webs using stable isotope analyses, 4) the role of nutrients from multiple sources, including N-recycling, in altering these food webs and meeting nutrient demands of kelp forest ecosystems 5) the effects of wave disturbance on the complexity and diversity of kelp forest food webs and 6) links between kelp forests and sandy beach food webs.

Our coastal ocean research has identified several physical transport mechanisms important for delivering nutrients to kelp forest ecosystems. Examples include upwelling, runoff, and internal tides, and we are quantitatively assessing the flux of nutrients associated with each mechanism. This research is providing valuable information about transport processes on the inner shelf, which are poorly understood. Quantifying fluxes into and out of the inner shelf is extremely important for understanding the cross-margin transport of carbon, nutrients, and sediments. Most inner-shelf process studies to date have been conducted on the Atlantic coast of North America. Our work in the Santa

Barbara Channel thus fills an important gap and is one of the first studies to focus on a coastal upwelling system.

Our oceanographic research is also helping to further our understanding of physical mixing of freshwater plumes as they enter the coastal ocean. Satellite ocean color estimates of sediment content show that less than 0.01% of sediment discharged in runoff events remains suspended in offshore plumes. Presumably the remainder settles quickly onto the inner-shelf substrate, and some of it may then be redistributed through resuspension or via buoyancy-driven flows. Our measurements will be important for determining the fate of this sediment, and this may have important consequences for the distribution of nutrients after the runoff season is over. Our moored instruments, with their combination of hydrographic and biological sensors allow us to measure outflow events even from very small streams. This allows us to better characterize the transport of materials from land to ocean ecosystems.

Our extensive and intensive measurements and models of solute and particulate concentrations and export from the steep, flashy catchments along the central/southern coast of California provide important comparative information to the field of watershed science that is otherwise lacking. The hydrologic model that we are developing will aid in predicting how climate, land-use, and the physical and biological structure of coastal streams influence the runoff of material constituents. The model simulates rainfall-runoff and routing processes from three sources (surface, shallow soils and groundwater) for both undisturbed and urban lands and will ultimately be integrated with water quality modules to simulate the discharge of water, associated solutes, and sediments from the land to the ocean.

CONTRIBUTIONS TO OTHER DISCIPLINES

The research mission of SBC LTER is very interdisciplinary in scope. As such, our research contributes to a wide range of disciplines including: terrestrial, aquatic and marine ecology, physical, biological and chemical oceanography, hydrology, geology, geography, toxicology, environmental history, science education and informatics. Coordinated studies among the many disciplines represented by SBC LTER are leading to an improved understanding of the patterns and processes that link land and ocean environments and their consequences for coastal ecosystems. This improved understanding is not only contributing to furthering the many disciplines listed above, but is of considerable value to those interested in studying the extent to which society contributes to and is influenced by impacts to coastal systems. For example, Investigator Lenihan leads a collaborative fishery research program, CALobster (http://www.calobster.org/), focused on the spiny lobster fishery with a goal of promoting and conducting community-based research that lead to the best management practices and help maintain working harbors. Similarly, Investigators Page and Dugan conducted collaborative research on crab fisheries with local trap fisherman and are investigating aquatic invasive species in southern California harbors in cooperation with state marine advisors. Investigators Guerrini and Dugan are writing and editing an interdisciplinary multi-authored book on the deep human and environmental history of a Santa Barbara coastal wetland and watershed.

CONTRIBUTIONS TO HUMAN RESOURCE DEVELOPMENT

Our project provides significant opportunities for research and teaching in science at multiple levels including: K-12, university undergraduate, graduate and post doctoral levels, and the professional development of project research staff.

In addition to the training of our project's participants, our faculty-level investigators actively incorporate the activities and findings of SBC LTER research into their teaching and curriculum development, thereby extending the project's contributions to the broader student body. Many investigators give guest lectures and class demonstrations on SBC LTER research to university courses. They along with the project's post docs, graduate students and support staff routinely integrate undergraduate students into their research activities and also mentor them and high school students on their own research projects. In 2010, Investigator Carlson taught an immersion course on Microbial Oceanography at the Bermuda Institute of Ocean Sciences. This lecture and laboratory course provided training in various techniques in microbial ecology and oceanography used in both the LTER programs and the Microbial observatory program and was attended by students from SBC LTER. Investigator Washburn used his SBC LTER research results in teaching an upper division, undergraduate physical oceanography class in 2010. In 2011, AVIRIS data processed by SBC LTER were used extensively in computer-based laboratory exercises for graduate level courses in Geography. Investigator Schimel taught an upper division and graduate level course on science writing in 2011, authored a book and produced a series of online science writing lectures on this topic http://apecs.is/webinars/videos/2408-201011016-schimel>http://apecs.is/webinars/videos/2408-201011016-schimel. Pre-college teachers and non-scientists from the local community routinely participate in our ongoing stream sampling program and gain considerable knowledge on the constituents of runoff and of the processes that influence their abundance. In 2011, SBC hosted their first Earth Day Festival Booth in collaboration with MCR LTER.

Increased exposure to the SBC LTER research is achieved through its extensive outreach programs (see the Outreach Activities section of this report), which primarily target k-12 students and teachers. We hosted several workshops from 2009 -2011 as part of an innovative Pathways to Environmental Literacy project, which is a cross-site targeted partnership in math and science funded by NSF involving four LTER sites and the LTER Network Office. The project focuses on the critical education junction of middle school through high school to develop a program of teacher professional development in science and mathematics driven by framework of environmental science literacy surrounding the learning progressions of core science and math concepts. The goal is to connect the research capabilities of partner universities and LTER sites with K-12 teacher professional development in science and math at partner schools. In 2011, SBC hosted a one week summer PD workshop "From the Ground Up," that involved 22 new junior high and high school teachers from Santa Barbara and Ventura Counties from five different school districts. The workshop included training on curricula associated with the projects environmental literacy strands of Biodiversity, Carbon and Water, as well as a theme-based, Citizenship activity.

We also co-hosted a two week CoastLines workshop for educators from all over the country in summer 2010. This program introduces fundamental concepts about information technologies (IT) to grade 7-12 schools by involving teachers and students in the use of geographic information systems (GIS) and global positioning systems (GPS) for conducting scientific studies of coastal ecosystems in the LTER Network.

Our contributions to human resource development extend beyond that which involves our project's participant and K-12 students and educators. In fall 2007 we hosted the Ecological Society of America's SEEDS field trip. ESA's SEEDS (Strategies for Ecology, Education, Development and Sustainability http://www.esa.org/seeds/) program mission is to diversify and advance the profession of ecology through opportunities that stimulate and nurture the interest and involvement of underrepresented undergraduate students. Twenty three students and six advisors arrived from all over the country for the field trip at SBC LTER and were taken on field trips to local watersheds, sandy beach and rocky intertidal habitats, and offshore kelp forests, and visited with local Native American elders to learn about the historical and cultural aspects of the Chumash tribe.

CONTRIBUTIONS TO RESOURCES FOR RESEARCH AND EDUCATION

Physical resources

NSF funds from our project are used to maintain a custom 22' research vessel that is specially designed for scuba and oceanographic research. Other research groups on the UCSB campus have access to this vessel for their research needs as well.

Information Resources

SBC's website contributes to information resources by providing the scientific community and the general public access to unique datasets that are of interest to a diverse array of people. Some examples of such datasets include: historical data on giant kelp abundance in the northeast Pacific, SST imagery from NOAA-AVHRR polar orbiters of the Santa Barbara Channel, high frequency radar data of surface currents in the Santa Barbara Channel, precipitation data and soil mapping and land-use coverage of the Santa Ynez Mountains. In 2009 and 2010 access and format of these datasets were enhanced on our website which was redesigned to fit LTER network standards and updated for content.

CONTRIBUTIONS BEYOND SCIENCE AND ENGINEERING

SBC LTER investigators are very active in applying their knowledge of Santa Barbara's coastal ecosystems to inform and implement changes in local and regional policies. Investigators serve as advisors and committee and board members for a number of local and national groups concerned with conservation and management of natural resources.

Investigator Gaines serves on several committees and advisory groups concerned with fisheries and marine conservation including the Science Advisory Panel for the California Marine Life Protection Act, the Science Advisory Group for the Interagency Ecological Program of the California Department of Water Resources, the Joint Ocean Commission and the Marine Life Protection Act Baseline Science Management Panel. Other SBC investigators actively worked with the Science Advisory Panel and stakeholder groups to integrate SBC LTER data and core measurements, provide information needed to develop the regional profile and evaluate proposals for reserve network design for the South Coast region. Designation of this new network of marine reserves has been approved and is scheduled for October 2011.

Investigators Reed and Page work with the staff of the California Coastal Commission (CCC) on a large multi-dimensional program designed to mitigate for the loss of coastal marine resources caused by the operation of the San Onofre Nuclear Generating Station (SONGS), a coastal power plant located in north San Diego County. The major emphasis in this program is compensation for lost marine resources via wetland and kelp forest restoration. Reed and Page’s primary responsibilities are to consult with the employees of the power plant (Southern California Edison), the CCC and their staff, and other resource agencies on ecological issues relating to the design of the mitigation projects and to develop and implement monitoring programs capable of determining whether the biological and physical performance of these projects meet pre-determined standards. Much of the science done on these mitigation projects is quite complementary to that done by SBC LTER and there is considerable exchange of information and ideas between the two projects.

Our researchers are also engaged in shaping policy towards local watershed issues as well. We have developed mutually beneficial, cooperative associations with local and national government agencies and departments, and NGOs. Santa Barbara County's Project Clean Water is engaged in sampling local creeks during the initial rise of the hydrograph and measuring a suite of pollutants including metals, pesticides and herbicides. Our intensive sampling of nutrients and particulates during the entire hydrograph for most storms complements the County's effort, and we cooperatively share data and interpretations. We assist with field measurements and monitoring, and perform high quality nutrient chemistry analyses on water samples from local streams and rivers for regional NGO groups, including Santa Barbara Channelkeeper, the City of Santa Barbara, Ventura Surfrider and Friends of the Santa Clara River. Co-Investigator Melack serves on the Technical Advisory Committee for Friends of Santa Clara River water quality monitoring program and the Board of Directors for the Santa Barbara Community Environmental Council. In 2011, he met with staff of the Environmental Defense Fund in

San Francisco, to explore collaborative activities related to EDF's new initiative in Land, Water and Wildlife. Post-doc Al Leydecker provided regular reports on the status of algal blooms and eutrophication to interested parties involved in the TMDL regulatory process managed by the Regional Water Board. Investigator Cooper advised and contributed input to city and county agencies and departmental programs on a variety of topics including impacts and design of studies related to UV treatment of stream waters (City of Santa Barbara), the Southern Coastal Santa Barbara Creeks Bioassessment Program (Creek Division of the City and Project Clean Water of the County of Santa Barbara), and Storm Water Management Plan (City of Goleta). He has provided input to federal and local agencies on fish species management including the Southern California Steelhead Recovery Plan (NMFS), statewide fish stocking policies (Calif. Dept. of Fish and Game), and the Tidewater Goby Working Group (City of Santa Barbara) and proposed activities related to the removal of the Matilija Dam on the Ventura River (Army Corps of Engineers).

The three major fires, the Gap Fire in July 2008, Tea Fire in November 2008 and the Jesusita Fire in May 2009, in the Santa Barbara area, resulted in large scale evacuations of residents and the loss of nearly 300 homes. The total acreage burned in less than one year in these three fires exceeded 20,000 acres of watershed lands located in and above the cities of Santa Barbara, Montecito and Goleta. Our long-term measurements of stream hydrology and chemistry in local catchment are providing information on the short and long term effects of these three major fires. We have worked with NGOs and county and federal agencies to document effects of the fires and contributed to planning and preparation for post fire impacts by providing input and advice to County of Santa Barbara Flood Control and environmental organizations on post-fire mitigation activities and hydromulch experiments in meetings and by coordinating field trips and interactions between SBC LTER researchers and agency representatives from the County of Santa Barbara. SBC investigators, Melack, Cooper, Schimel, D'Antonio, Roberts, and Bookhagen built new collaborations and obtained support for more intensive studies of the burned catchments that were initiated in 2009.

The conservation and management of sandy beach ecosystems lags behind that of coastal wetlands and riparian habitats. Our research findings from sandy beaches has led to the recognition of kelp and other macroalgal wrack as an ecological resource by local and state agencies and contributed to the development of new policies for coastal management. Investigators Dugan and Page are working with California State Parks to develop and evaluate new restoration strategies for wrack-associated invertebrates on beaches that support breeding snowy plovers, a federally listed shorebird. Dugan plays an active advisory role with coastal consortiums and groups concerned with improving the conservation and management of beach ecosystems including the NSF-funded Coastal Barrier Island Network (CBIN), which focuses on the management of barrier island ecosystems under the pressure of global climate change and urbanization, the California Coastal Commission, and the Beach Ecology Coalition, a professional organization for beach managers that provides a forum for education, outreach, training and development of best practices and cooperative research on sandy beach ecosystems in California.