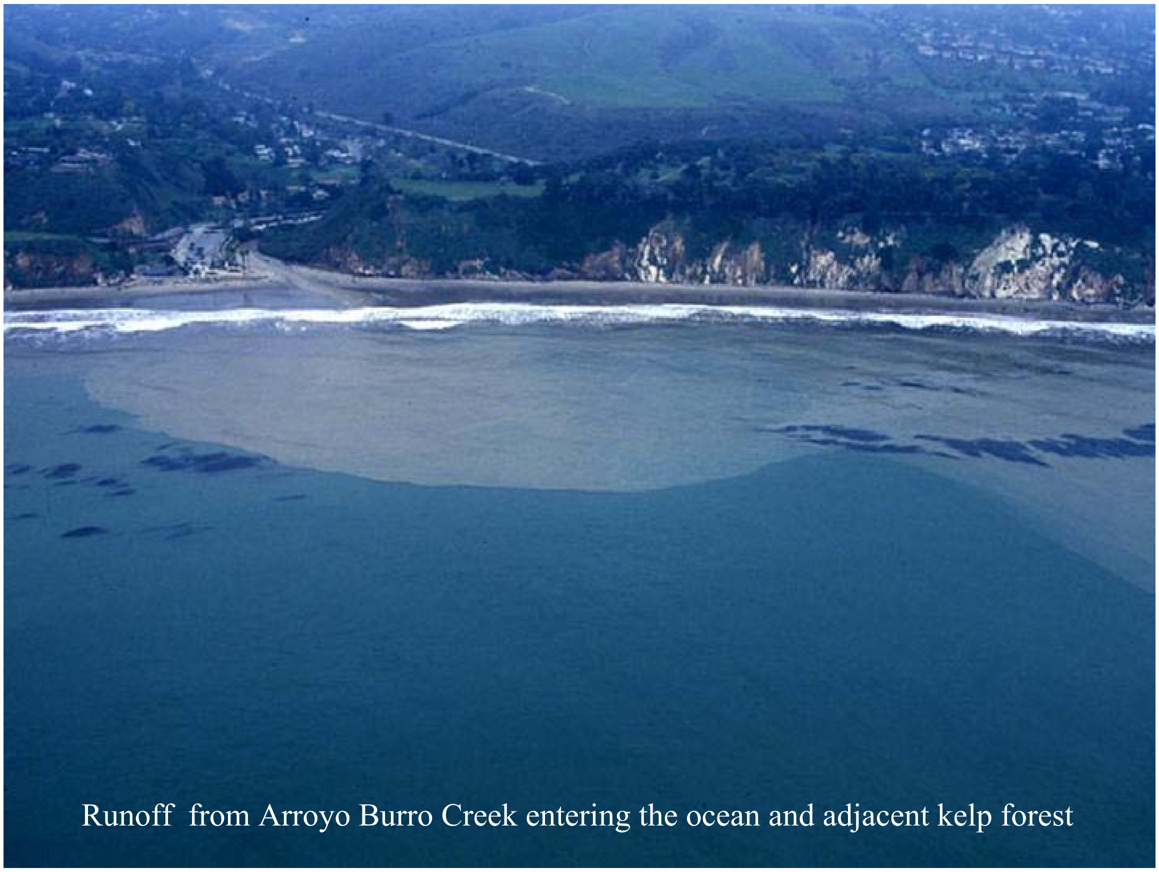
SANTA BARBARA COASTAL LONG TERM ECOLOGICAL RESEARCH

THREE YEAR PROGRESS REPORT – Volume 1


Runoff from Arroyo Burro Creek entering the ocean and adjacent kelp forest

PREPARED FOR THE NATIONAL SCIENCE FOUNDATION SITE REVIEW TEAM

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SANTA BARBARA, CA

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I. Introduction

The primary research focus of the Santa Barbara Coastal (SBC) LTER is on the relative importance of bottom-up processes and allochthonous inputs to giant kelp forests, a highly diverse and productive marine ecosystem that occurs on shallow rocky reefs at the interface of the land-ocean margin along the temperate coasts of western North and South America, southern Africa, Australia and most sub Antarctic islands, including Tasmania and New Zealand. Because of their close proximity to shore, kelp forests are influenced by physical and biological processes, which occur on land as well as in the open ocean. Streams and rivers transport nutrients, dissolved and particulate organic matter, sediments, and pollutants from coastal watersheds to kelp forests, while ocean currents supply larvae, plankton, and dissolved nutrients from adjacent offshore waters (Figure I.1). In return, kelp forests export large amounts of dissolved and particulate organic material to other coastal habitats, such as sandy beaches, as well as deep-water habitats. Short and long-term changes in climate that alter rainfall and ocean currents (e.g., ENSO events and global warming) may cause a change in the relative importance of land and ocean processes in supplying nutrients, sediments, and organic matter to kelp forest communities.

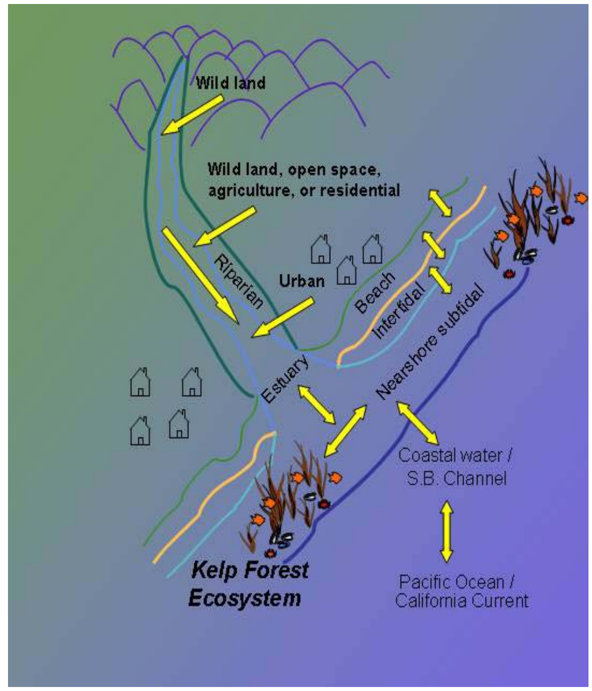

Figure I.1. Sources of material inputs to kelp forests from watersheds and the coastal ocean and the export of materials from kelp forests to other coastal habitats.

Integrative measurements, experiments, and modeling are being used by SBC investigators to determine how variability in subsidies and disturbance from terrestrial, atmospheric, and oceanic sources due to changing land use and climatic conditions affect the structure, dynamics, and function of giant kelp forest ecosystems. There are two working hypotheses motivating our research:

Hypothesis 1: The production and food web dynamics of giant kelp forests are driven by variability in terrestrial, ocean and atmospheric forcing that alter the supply and character of allochthonous and autochthonous resources.

Hypothesis 2: The structure and function of giant kelp forests is determined by the frequency and intensity of biological, chemical or physical disturbance events that reorder space utilization and trophic interactions.

These hypotheses form the basis for the following questions that are being addressed during the first six year funding cycle of the SBC LTER. Answers to these questions will provide us with a mechanistic understanding of the processes involved in testing our two hypotheses.

(1) What are the relative and absolute effects of allochthonous inputs from the land and the coastal ocean on the productivity and extent of giant kelp forests?
(2) What is the relative importance of land- versus ocean- derived carbon and nitrogen to kelp forest food webs, and how is it affected by changes in runoff and ocean climate?
(3) What are the important processes in terrestrial and ocean systems that drive changes in the nature and quantity of subsidies delivered to reefs, and what are the major factors that influence them?
(4) What are the spatial and temporal scales over which terrestrial runoff and ocean forcing perturb giant kelp forests?
(5) How do the short and long-term dynamics of kelp forest populations, food webs, and communities respond to changing ocean, land and atmospheric climatologies?
(6) What are the mechanisms determining the partitioning of nutrients between phytoplankton and benthic macroalgae?

Physical setting and major environmental drivers

The Santa Barbara Coastal LTER is bounded by the Transverse Coastal 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 Basin to the east (Figure I.2). The region offers a rich diversity of watersheds for experimental and observational study that typify the types of watershed found in most Mediterranean climates. Principal habitats in the region, listed in order from land to sea, include coastal mountains, oak woodland, chaparral, riparian woodland, coastal sage scrub, salt marsh, sandy beaches, rocky shore, giant kelp forests, and coastal oceans.

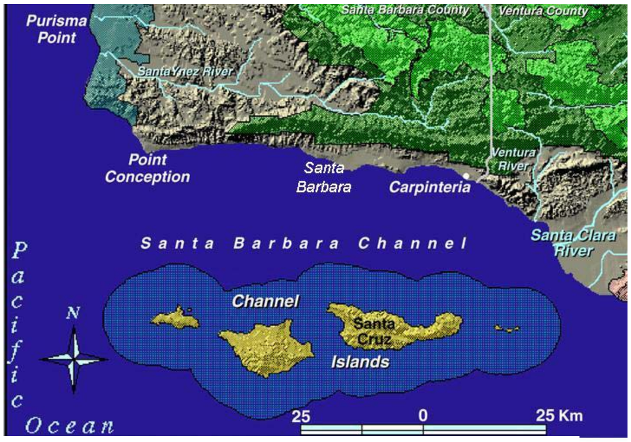

Figure. I.2. Location of SBC LTER.

The Santa Barbara Channel is a site of dramatic physical and biological responses to El Niño Southern Oscillation (ENSO) events. Terrestrial runoff and the associated transport of sediments, nutrients, and pollutants increase greatly because of elevated precipitation during ENSO events. Sea surface temperatures increase and offshore nutrient levels decline as the thermocline deepens. Large-scale patterns of ocean circulation also change substantially, and storm disturbance from waves is often extreme. Corresponding to these physical changes are significant biotic changes including northward range extensions, precipitous declines in the giant kelp *Macrocystis pyrifera*, and unusual changes in the abundance of many species of algae, invertebrates and fish (Tegner & Dayton 1987; Dayton & Tegner 1989).

Primary research habitats
SBC research efforts are concentrated in three general habitats: watersheds, coastal oceanic zone, and kelp forests (research is also being done by SBC investigators in salt marshes and sandy beaches in collaboration with other projects). Below we provide a general description of the primary research habitats. Information on specific research sites and on the data that are collected at them can be found at http://sbc.lternet.edu/sites/researchsites.html

Watersheds
About 40 catchments drain into the Santa Barbara Channel from the coast range called the Santa Ynez Mountains. The drainage basins range in size from small drainages (< 10 km^2) flowing directly into the ocean to the Santa Clara River drainage basin (≈ 2000 km^2). Channels typically fill with sediment during drier periods and are scoured during floods (Scott & Williams 1978; Keller & Capelli 1992). The study region is characterized by a Mediterranean climate with mild, moist winters and moderately warm, generally rainless summers. The El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) combine to produce significant interannual variability in

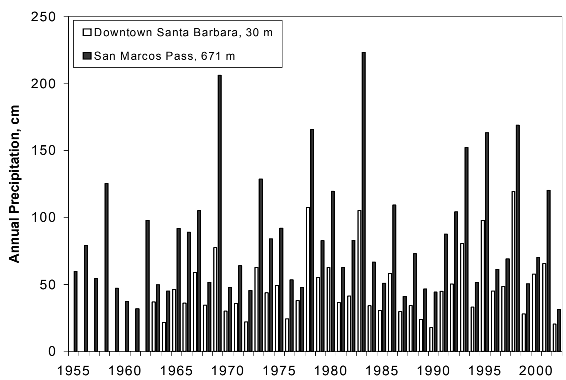

Figure I.3. Annual precipitation for the coastal plain (downtown Santa Barbara, elevation 30 m) and mountains (San Marcos Pass, elevation 671 m) for water years 1955 through 2002.

precipitation that is influenced by orographic precipitation enhancement (Figure I.3). The episodic, often intense, precipitation regime, rapidly rising, rugged topography, fires, and fractured sedimentary rocks combine to yield inordinately large sediment loads to the ocean (Milliman & Syvitski 1992). Due to the seasonal fluctuations in precipitation of the Mediterranean climate, inputs from land are a pulsed phenomenon typically limited to the months of November through April, with storm activity exacerbated during ENSO events (Haston & Michaelsen 1994).

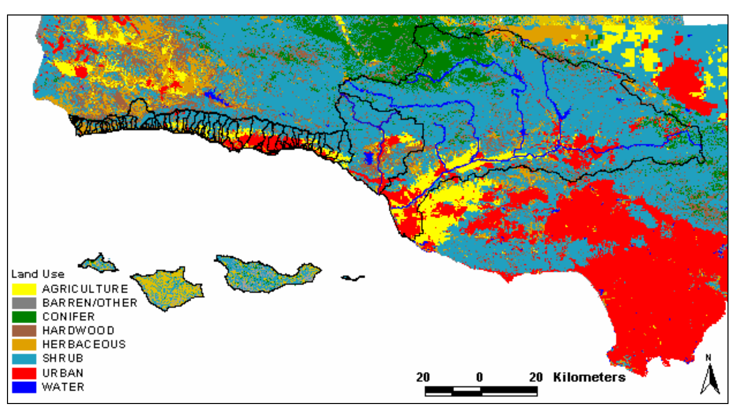

Figure I.4. SBC watersheds (outlined in black) and 2000 land use.

The catchments of the Santa Barbara region vary widely in the proportion of agricultural and urban development, which differentially contribute nutrients and pollutants to the runoff (Figure I.4). Modifications of the frequency or intensity of droughts due to climate change or ENSO events are strongly expressed in the Mediterranean climate of the region. The spatial and temporal variation in climatic and landscape conditions in the upland catchments provides a unique opportunity to assess the diverse effects of terrestrial inputs on kelp forests.

<u>Coastal oceanic zone</u>

The coastal oceanic zone receives runoff from land and contains sediments, various naturally-occurring organic and inorganic substances of terrigenous origin, and organic and inorganic substances of anthropogenic origin. The spatial extent of the coastal ocean influenced by runoff is determined by several factors including the magnitude, rate and timing of runoff, particulate concentration in runoff waters, wind, ocean currents, ocean water column structure, and waves.

In nearshore waters, upwelling is the primary source of nutrients derived from the ocean. The extent of upwelling varies considerably along the west coasts of North and South America. If nutrient inputs from land play a significant role in coastal production anywhere, their influence should be greatest in regions with limited ocean sources of nutrients. Major upwelling does not occur off most of southern and Baja California, including the Santa Barbara Channel. As a result, surface waters in the region are commonly warm, saline, and nutrient-poor compared with waters north of Pt. Conception or in the California Current.

Seasonal flow patterns and water mass distributions suggest that the timing and strength of winter runoff events may be very important in determining how terrestrial inputs disperse through coastal reef habitats of the Santa Barbara Channel. Cyclonic circulation is seasonal in the Santa Barbara Channel. When runoff occasionally occurs between May and October during cyclonic circulation in the western channel, westward advection of terrestrial materials along the mainland is expected. In contrast, during more normal periods of runoff in winter and early spring when cyclonic circulation is absent, eastward advection of inputs from land is expected over most of the Channel. The timing, spatial extent, and residence time of stream inputs to the coastal zone are influenced not only by seasonal and interannual variability in runoff, but also by coastal currents that vary with tidal cycle, wave climate, season, and interannual variability in large-scale ocean forcing. Thus there is a high potential for the effects of runoff on coastal reef communities to be influenced by ocean processes. Consequently, the potential effects of runoff on kelp forests are likely to vary in different ocean domains (southern vs. northern California) and in different oceanic climates (i.e., ENSO vs. non-ENSO years).

<u>Giant kelp forests</u>

The high productivity, large size and three-dimensional architecture of kelps lead them to have an overwhelming influence on community structure and ecosystem function in areas where they occur (Dayton 1985; Foster & Schiel 1985; Duggins et al. 1989). The giant kelp, *Macrocystis pyrifera*, is the world's largest alga and it forms extensive forests in the Santa Barbara Channel, and in many other temperate regions of the world. An adult plant consists of a bundle of vine-like fronds buoyed by small gas bladders and anchored by a common holdfast. Upon reaching the sea surface, the fronds (sometime exceeding 30 m in length) spread out to form a dense canopy. The inshore edge of a giant kelp forest is usually set by wave action, whereas the deeper offshore edge is typically limited by light. In the Santa Barbara region, terrestrial runoff and the resuspension of fine sediments reduce water clarity and light penetration in the nearshore zone. Consequently, giant kelp forests along the mainland coast are largely restricted to depths < 20 m. Coarser sediments and little runoff result in relatively clear waters surrounding the Channel Islands, and kelp forests there frequently extend down to depths of 30 m.

The abundance, areal extent, and condition of giant kelp forests vary dramatically over time in the SBC-LTER. The factors considered most responsible for variation observed in the abundance of giant kelp forests in southern California are intrusions of warm nutrient-poor water, dislodgment during large storms, and excessive grazing by sea urchins. Entire kelp plants and their holdfasts are dislodged from reefs and set adrift during storm and wave events. Large amounts of drift kelp are stranded on beaches following storms. The grazing of large numbers of sea urchins can rapidly reduce the abundance of giant kelp and transform lush kelp forests into "sea urchin barrens", which may persist for years.

Contents of 3rd- Year Progress Report

In the following pages and in the accompanying appendices we summarize our research, education and outreach efforts, and provide supporting documentation on site and information management, personnel, and expenditures. Additional information on the Santa Barbara Coastal LTER can be found at http://sbc.lternet.edu/.

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II. Research Summaries of Programmatic Areas

A. Watersheds

Quantifying the discharge of water, associated solutes and sediments from land to the Santa Barbara Channel is one of the primary objectives of the SBC LTER. To realize this objective, our research activities combine measurements and modeling. To measure the terrestrial export to the ocean and to provide the necessary data for modeling export from different land uses, we have established three sampling and measuring programs: (1) stream discharge, (2) precipitation and (3) aquatic chemistry. Our stream discharge and precipitation networks are designed to augment the existing gauging stations maintained by the U.S. Geological Survey (USGS), the Santa Barbara County Public Works Department (SBCPWD) and the National Weather Service (NWS). Currently, our research is supported by 8 SBC LTER, 16 SBCPW and 12 NWS precipitation gauges, 27 SBC LTER continuous 5-minute stage recorders (i.e., stage data are converted to discharge using a rating curve) and 9 USGS streamflow gauges. Our sampling program is designed to measure hydrological and chemical conditions in numerous watersheds with varied land uses over a range of climatic conditions at a temporal resolution that captures the full range of stream discharge. To determine watershed export, chemical data are combined with discharges, and, by sampling over the full range of discharge, we are able to determine annual export for water, nutrients, sediments and organic material. Sampling at a high temporal resolution is necessary because the short, intense rainfall, shallow bedrock and steep slopes combine to produce rapid responses to rainfall. To model terrestrial export, spatial data characterizing the watersheds are being used to conceptualize and parameterize hydrologic mechanisms and transport processes.

Modeling runoff
We are modeling runoff from a subset of watersheds, which is challenging because of their considerable spatial and temporal heterogeneity. Soil conditions range from dry sandy soils to saturated clays, and steep slopes, large variations in elevation, and patchy storm patterns amplify the problem of spatially and temporally distributed rainfall. To evaluate available data and our understanding of the regional hydrology, our initial modeling effort used the HEC-HMS rainfall-runoff model (USACE 2000). Using Green-Ampt infiltration, kinematic wave routing for both channel and overland flow, and a decay function for baseflow recession, the HEC-HMS model was successfully calibrated to individual runoff events in water year 2001 using 5-minute rainfall and 15-minute discharge for the Mission Creek watershed. Our results indicate that a significant amount of groundwater recharge occurs in the upper portions of the watersheds and that the storm response is sensitive to initial watershed conditions.

Building on the above analysis, a geographic information system (GIS) integrated approach for modeling storm response was devised (Beighley et al., in review-a). To investigate the impacts of urbanization and climatic fluctuations on the magnitude and variability of discharge, the HEC-HMS rainfall-runoff model was parameterized and used to simulate streamflow for a 14-year period (9/1/1988 to 8/31/2002) in the Atascadero Creek watershed for 1929, 1998, and forecasted 2050 land use conditions (8, 38 and 52 percent urban, respectively). Urbanization increased peak discharges and runoff, but decreased annual and interannual variability. This point is illustrated in Figure II.A.1, which shows that the 1929 scenario produces the greatest difference between El Niño and La Niña conditions; the difference between these two extreme climatic conditions decreases with increasing urbanization. However, increased peak discharges and annual runoff were not proportional to increases in urbanization because the effects of urbanization are compounded by orographic rainfall and decreased travel times. Further, only a few large storms dominate runoff regardless of land use.

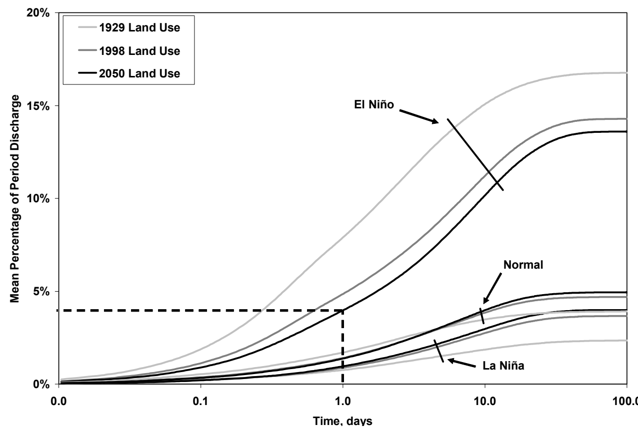


Figure II.A.1. Mean percentage of annual discharge for 1929, 1998, and 2050 land use conditions (normalized by the total 14-year discharge associated with the corresponding land use conditions) exceeded in a given time period from La Niña, El Niño, and normal years, where the annual distribution is ranked from the maximum to the minimum 15-minute discharge (e.g., in 1 day, the average El Niño year for the 2050 land use scenario accounts for 4% of the total 14-year discharge simulated under the 2050 land use conditions).

The significance of variability in runoff to stream habitats was observed in water year 2001, when there was a large storm that cleared the channels of vegetation and accumulated debris. In contrast, water year 2002 had no large runoff events, and at the start of water year 2003, the stream channels were heavily vegetated. As we progress through our study, we will assess the impacts of such variability on stream ecosystems and on the delivery of nutrients, sediment and organic material to the ocean.

While the HEC-HMS model provides meaningful estimates of combined stream flow for varied land use and climate conditions, it is not intended to track separately the various sources of runoff (i.e., surface, interflow and groundwater). Hence, we have developed an improved modeling approach that is better suited for simulating runoff and corresponding constituents from the primary flow sources and pathways. Our approach assumes that basin landscapes possess an identifiable spatial structure, fashioned by climate, geology and land use that affects their hydrologic response (Beighley et al., in review-b). The model utilizes a time step of 15 minutes and source-to-sink routing (Olivera & Maidment 1999) to simulate streamflow at the watershed outlet and other points of interest. The model is spatially averaged at the hydrologic response unit (HRU) scale enabling watershed-scale spatial patterns to be incorporated into the rainfall, runoff generation, and routing processes. Based on the approach of Jakeman & Hornberger (1993), the model is designed to simulate two runoff forms: surface and subsurface. Incorporating hydrogeological interpretation, the two runoff forms are separated into two subclasses: (a) surface – urban or rural and (b) subsurface – interflow or groundwater flow. Comparing measured and simulated streamflow at gauge locations shows that our modeling approach yields reasonable estimates of combined streamflow. In addition, we are using silica concentrations to assess individual runoff components based on an end member-mixing model (Scanlon et al. 2001).

Stream chemistry and transport
On a weekly to bi-weekly and storm (hourly for rising limb and at 2-4 hour intervals on falling limb) basis, water samples from streams are collected and 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. While the SBC LTER is relatively new (i.e., < 3 years of data), there is sufficient chemical data to begin to characterize storm responses and assess annual fluxes (see http://sbc.lternet.edu/sites/coastwatershedmap.html for more information on the locations of our watershed study sites and the data that are collected at them).

During the first year of research (water year 2001), we sampled 18 coastal watersheds to evaluate the range of baseflow and stormflow nutrient concentrations. Concentrations proved to be dependent on coastal plain land use. Nitrate concentrations varied over 3-orders of magnitude, from a few micromoles per liter in relatively undeveloped catchments, to a few hundred micromoles per liter in agricultural and urban watersheds, to thousands of micromoles per liter where intensive greenhouse agriculture dominates. Phosphate concentrations had a similar, but smaller, variation from 1 to 100 µmol/L (Figure II.A.2). Typically, stormflow concentrations of dissolved nutrients decreased in streams with high baseflow concentrations, and increased in streams with low baseflow levels. All streams with appreciable urban development on the coastal plain had a similar response to stormflow: phosphate concentrations rose and fell in parallel with the hydrograph, nitrate was out of phase with phosphate, and ammonium declined after a peak at the beginning of storms. The stormflow responses of non-urban streams lack a common pattern, but, in general, nitrate, phosphate and particulate concentrations follow variations in the hydrograph, and ammonium concentrations remain low.

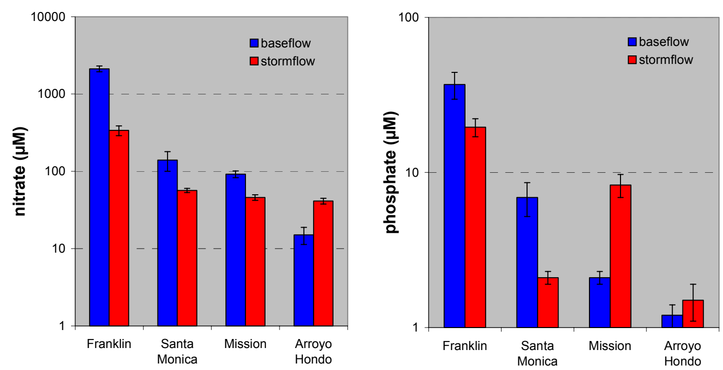


Figure II.A.2. Annual mean concentrations (flow-weighted for stormflow) for four LTER streams in water year 2001. The streams typify coastal plain land uses in the LTER: industrial agriculture for Franklin (greenhouses and nurseries); agriculture for Santa Monica (row crops and orchards); urban for Mission Creek; and relatively undeveloped for Arroyo Hondo (National Forest and fallow ranchland). All streams were sampled at the tidal limit and the error bars indicate standard errors of the mean.

The nutrient concentration-discharge relationships for the urban streams showed hysteresis and fit a 3-compartment baseflow/surface-flow/soilwater model. However, the pattern for each species was different. Our inferences are that high ammonium concentrations are produced by early surface-flow flushing of urban surfaces, high baseflow nitrate concentrations are diluted by impervious surface and soilwater runoff, and phosphate, highly correlated with sediment load, is characterized by a flashy urban effect superimposed on an overall catchment response.

The relative export associated with urban streams was consistent: phosphate export at least 5-times that of ammonium and nitrate at least 5-times that of phosphate. Export on the rising hydrograph limb was most important for ammonium (where 30 to 50 % of the ammonium is lost) and somewhat important for phosphate (~25 % of total export), while most nitrate was exported on the receding hydrograph (85 to 90 %). Export from all coastal watersheds was highly episodic, 90 % of the annual runoff occurred in less than 30 days, the majority of dissolved nutrient export in less than 7 days, and almost all particulate export in less than 3 days.

In the project's second year (water year 2002), we shifted emphasis to more intensive sampling of fewer watersheds. Six watersheds were selected (2 urban, 1 urban with intensive agriculture, 2 agricultural, and 1 undeveloped) and multiple sampling points were chosen in each drainage to monitor changes in nutrient flux and concentration at transitions in dominant land use. The winter of 2002 was relatively dry, and runoff was only about a quarter of the previous year. More importantly, almost no runoff was generated from catchment areas above the coastal plain, providing an opportunity to analyze nutrient export from developed land uses without the confounding effects of contributions from undeveloped areas (Figure II.A.3). Nitrate export was relatively unchanged (~80 %) from the year before, the decrease in runoff being offset by increased concentrations, confirming that coastal plain land uses are the major source of nitrate. Phosphate and dissolved organic nitrogen (DON) concentrations in stormflow increased, but annual export decreased (~50 %) indicating storm intensity (i.e., sediment load) and export from higher elevation catchment areas have important roles in the annual budget for these species. The most significant differences in flux were in particulates; on average, particulate export in 2002 was only 10 % of 2001 export.

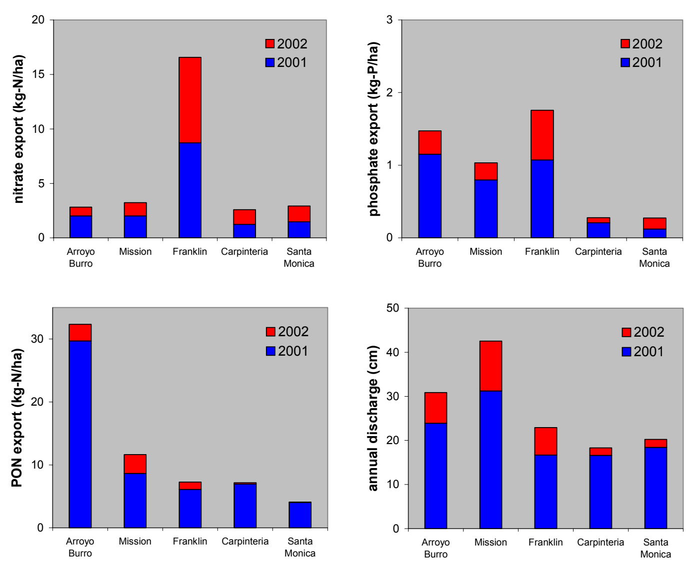


Figure II.A.3. Estimated annual (water-year) fluxes for 5 SBC LTER streams: 2001 and 2002. Annual runoff in 2002 was, on average, only a quarter of 2001, and almost no runoff was generated from catchment elevations above the coastal plain. The lack of appreciable flood flows can be seen in the notably lower 2002 fluxes for particulate organic N (PON) and phosphate, the fluxes for these species being highly correlated with sediment load; however, the nitrate flux was relatively unchanged since nitrate originates, almost exclusively, from developed uses on the coastal plain.

Along a gradient from undeveloped to urban, we observed a steady increase in nitrate and DON. Along Mission Creek, concentrations generally double at the transitions from undeveloped to light residential and from light residential to urban (Figure II.A.4). Phosphate concentrations abruptly increase at the transition from undeveloped to light residential, urban open space or agricultural use. However, dense urban development

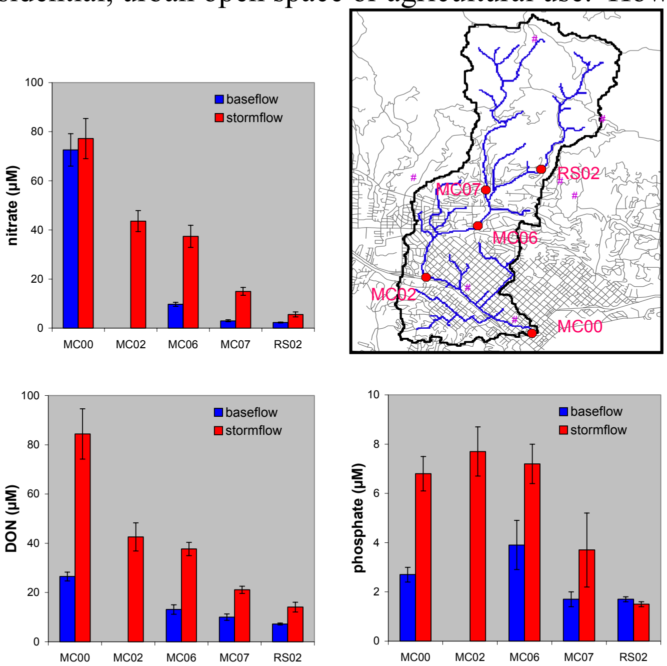


Figure II.A.4. 2002 annual mean (+/- 1 SE) concentrations for stormflow (flow-weighted) and baseflow for 5 sampling locations (shown on the inset map) on the Mission Creek drainage. The sampling stations in the figures are arranged in a gradient from highly urban to undeveloped (from left to right). Increased development produces increasing nitrate and DON concentrations, while phosphate and other sediment-related concentrations decrease with increased amounts of impervious surfaces and channel stabilization in urban areas.

produces a decrease in concentration. Phosphate and particulate fluxes are highly correlated with sediment load, and the extent of channel stabilization (concrete lining, bank stabilization) has a dominant influence on the annual flux in years when most of the sediment load originates from the coastal plain.

In the third year, water year 2003, we have continued the sampling program of 2002 while adding two additional agricultural watersheds, increased sampling on the Ventura River, and modeling of nutrient export in the upper Santa Clara Basin. Fortuitously, large storms have occurred, and, while data analysis is still incomplete, we anticipate the results will offer important insights when contrasted with data from the two previous years.

The Ventura River drains 580 km^2 of mountainous coast and ranges in flow from near 0 to 11 $m^3\ s^{-1}$. Monthly synoptic sampling of nutrients at 15 locations indicates nitrate peaks in early winter, presumably from mineralization and mobilization after the advent of the rainy season, with concentrations decreasing to a minimum by late summer. Phosphate follows a similar pattern. Variation in nitrate (0 to 550 µM) and phosphate (0 to 35 µM) on the river and its tributaries is considerable. During winter stormflow, nitrate concentrations in the lower, urbanized portion of the catchment are decreased by dilution from surface runoff, while phosphate concentrations increase throughout the basin coincident with sediment mobilization. Rainfall in the winter of 2001-02 was only 40 % of the annual mean, insufficient to meet end-of-dry-season soil moisture deficits and generate runoff from upland areas; subsequent groundwater inflows to rivers and creeks were severely diminished. Average flow was 0.15 $m^3 s^{-1}$, in contrast with a 72 yr mean of 4.6 $m^3 s^{-1}$. In the absence of stormflows, which usually scour the channel, exuberant plant growth covered the lower river and macrophytes have replaced algae as dominant primary producers. Phosphate concentrations following the drought winter have remained similar to those measured during the previous year, except where treated sewage effluent is discharged.

The large Santa Clara River watershed has supported significant agricultural activity for more than a century, although it is transitioning to suburban and urban land uses. Funded largely by the Los Angeles Regional Water Quality Control Board (RWQCB), we have developed an N and P source loading and water quality model for the Santa Clara River watershed. The project involves developing a decision-support model for determining a Total Maximum Daily Load (TMDL) for nutrients, allocating the TMDL to point and non-point sources (including agriculture), and evaluating various Best Management Practices. We have implemented the Watershed Analysis Risk Management Framework (WARMF) model using data from local (e.g., United Water Conservation District, Ventura County Flood Control District, Los Angeles County Department of Public Works, Ventura County Farm Bureau, four large wastewater treatment plants, city governments, agricultural associations, environmental organizations, land developers), regional/state (e.g., Southern California Association of Governments, RWQCB, State Water Resources Control Board, California Air Resources Board) and national (e.g., USEPA, USGS, NOAA, USFWS) sources for meteorology, land use, fertilizer application rates, atmospheric deposition, point source flow and concentrations, water quality, gauged flow. The model has been implemented at a daily time step, posing some limitations to our ability to accurately predict loading and load assimilation, since the watershed has flashy behavior.

Initial results indicate that loading of nutrients to the land surface is dominated by agriculture and atmospheric deposition, but that a large fraction (typically > 90%) is assimilated or transformed so that it is not available for transport during storm events. The relative contributions from point and non-point sources vary along the watershed for each nutrient. Although ammonium salts are used as fertilizer and are also found in atmospheric deposition, NH_4^+ is transformed relatively fast to NO_3^-, resulting in little in-stream ammonium loading from non-point sources. Nitrite inputs are low, mostly from the wastewater treatment plants. Nitrate is reaching the river from a number of sources, from direct releases, through stormflow and shallow subsurface flow, and from deeper groundwater that intersects the river at various locations.

Future directions of SBC hydrological and hydrochemical research

As we continue to analyze and interpret our data, future research efforts will focus on estimating nutrient and sediment export using both empirically and physically based approaches. We will determine the impacts of land use alterations on stormflow frequency distributions in southern California coastal watersheds. Separately, we will develop relationships between land use, runoff and nutrient export. Combining the two relationships, we will investigate the impacts of land use and climate change on the distribution of runoff event volumes and translate those impacts to nutrient export from the coastal watersheds to the ocean. In a parallel effort, we will develop and use existing models to simulate the mechanisms and processes related to nutrient and sediment export. We will investigate model scale and complexity using varying watersheds sizes and processes.

Catchment and in-stream processing of and responses to nutrients
An important mechanistic question is what regulates the movement of nutrients from terrestrial ecosystems to ground and surface waters. Our initial work on N cycling in annual grasslands near Santa Barbara indicated that groundwater nitrate concentrations could be quite high, and soil solution nitrate concentrations could be as high as 40-50 μg N L^{-1}. Our initial hypothesis was that cattle grazing (plant removal and N deposition in urine) was responsible for the high nitrate levels, but in experimental cattle exclosures, we found no evidence for reduced N availability or leaching compared to control plots that were grazed. Our alternative hypothesis was that during the fall and early winter, soils become moist and soil microbes become active, but with annual grasses dominating the ecosystem there would be no plant N sink. Thus, N mineralization and nitrification should be active, establishing the possibility for extensive nitrate leaching at the transition from the dry summer to the wet winter. Our research on the movement of nutrients in ground and surface waters has led in two directions: (1) effect of different plant communities on N cycling and ecosystem "leakiness.", and (2) effects of drought and of drying/rewetting events on microbial processes in soils, including mineralization and nitrification. We have found that drying/rewetting processes specifically stimulate nitrifiers, and cause a release of DOC from recalcitrant soil organic matter. Research in these two areas is being done at the Sedgwick Reserve in the adjacent Santa Ynez Valley because the reserve provides a protected area for doing experimental research that is unavailable within the actual LTER watersheds.

Biological processing of nitrogen and phosphorus in streams and coastal wetlands can alter both the form and the total amounts of N and P that are delivered to coastal systems. Understanding the structure and function of the stream biota with regard to nutrient processing is therefore necessary in order to understand the transport and fate of these nutrients. SBC graduate student Julie Simpson has been studying nutrient processing in streams draining small watersheds in the Santa Barbara area exposed to different levels of development. She has found that alga biomass varies greatly depending on the surrounding land use, ranging from 1.6 mg m^{-2} chlorophyll a in an undeveloped watershed site to 4000 mg m^{-2} chlorophyll a at an urban site. Dissolved nutrient concentrations were also highly variable across sites and had a broad range of N:P ratios. Results from nutrient diffuser experiments showed that the accrual of algal growth at the sites in watersheds with little to no development was consistently nitrogen limited. Benthic communities at these sites included diverse diatom assemblages, red algae, and N-fixing cyanobacteria. However, algal growth on the nutrient diffusers did not show a significant positive response to either N or P addition at most of the anthropogenically influenced sites.

Microcosm experiments have shown that grazers have large effects on algal biomass and species composition in streams of the Santa Barbara region (Dudley & D'Antonio 1991;

Sarnelle et al. 1993). Because algae are major consumers of nutrients, indirect effects arising from trout predators on grazers may have effects on nutrient spiraling. Furthermore, these effects on nutrient spiraling may change with climatic and hydrological regimes. We have been using stable isotope analyses to gain a better understanding of stream food web dynamics as controls on nutrient retention in streams. The stable isotopes of nitrogen (^{15}N) and carbon (^{13}C) provide powerful tools for estimating carbon sources for consumers in the food web, the number of trophic levels, and the importance of anthropogenic nutrient sources. We examined seasonal changes in the food web of Rattlesnake Creek by sampling all trophic levels in riffles and pools during spring (March), summer (May), fall (September) and winter (December) using standard techniques. Patterns in stable isotope signatures were similar between pools and riffles, and results showed that herbivores had $\delta^{15}N$ values of 0-3 ‰ and predators had $\delta^{15}N$ values of 3-5 ‰. Across all sampling days we found a $\delta^{15}N$ enrichment of ca. 2 ‰ from herbivores to predators. There was little variation in the $\delta^{13}C$ and $\delta^{15}N$ values of predators throughout the year; however, temporal variation in these signatures was higher for herbivores and even higher for POM and periphyton. Isotopic signatures of $\delta^{13}C$ were different among different basal food sources at our study site. $\delta^{13}C$ values for leaf litter were stable (between -28 and -26 ‰), and the values for fine particulate organic matter ranged between -22 and -24 ‰ over the study period. The filamentous green algae *Cladophora* had stable $\delta^{13}C$ isotopic signatures of about -34 and -32 ‰, but $\delta^{13}C$ values for periphyton varied substantially over the year (between -31 and –24. In riffles, *Eubrianix*, Heptageniids, *Baetis*, and Glossomatidae obtained their nutrition from algae whereas Nemourids, Tipulids, and Chironomids appeared to feed on a mixture of leaf litter and detritus. The predators (mostly *Sweltsa*, *Rhyacophila*, *Cordulegaster*, *Argia*, and *Octogomphus*) appeared to feed mostly on algivores, detritivores, and other predators.

The population dynamics and community structure of algal assemblages are often determined by resource limitation and consumer control. The most promising approach for determining the magnitudes of top-down (via consumption by herbivores) and bottom-up (via growth-limiting resources, such as nutrients and light) controls on periphyton community structure is to conduct experiments in which both resources and consumers are manipulated simultaneously. To determine if stream periphyton is controlled by bottom-up or top-down forces, we experimentally examined the responses of algal biomass and species composition to different grazer densities across two different nutrient treatments (ambient vs. augmented) across seasons and in different stream habitats (riffles and pools) in Mission Creek. Results from this experiment indicated that nutrients limited algal biomass accrual in the summer, but that grazers controlled algal biomass in the autumn. The composition of the grazer assemblage differed between summer and autumn, with Chironomids and *Baetis* dominating in summer and caddis larvae dominating in fall. In general, understory algae appeared to be more responsive to nutrients and grazers than overstory algae.

Because bacteria rapidly and measurably respond to their local environment, their assemblages in creeks and coastal lagoons may be determined in large part by human development and pollution. Nutrient input or “inoculation” by sewage-associated bacteria in urban settings are selective pressures that could shift bacterial community composition and/or diversity. To test this hypothesis, we PCR-amplify 16S rRNA genes from community DNA extracts, then we evaluate terminal restriction fragment length polymorphisms (TRFLP) using standard, published protocols and protocols that we have developed for quantifying diversity indices from TRFLP data. Using our approaches in Mission Creek and Arroyo Burro watersheds, we found that bacterial community composition and, more weakly, diversity, correlate negatively with increasing percent urbanization of the surrounding watershed (LaMontagne & Holden, in press). We also found that, during the rainy season, the bacterial community in downstream creek waters (discharging into the coastal lagoon) appeared similar to bacterial communities in lagoon waters. However, during the dry season, the creek and lagoon communities were distinct. This suggests that bacteria, like other "contaminants", are exported from watersheds during rainfall events and leave a measurable imprint on water quality downstream.

We developed and published a mass balance-based mathematical model of bacterial transport and fate through the coastal lagoon at Arroyo Burro (Steets & Holden 2003). Our model predicts lagoon sediment scouring with low water residence time during the rainy season while, during the dry months, sediment-associated bacteria enter with year-round creek flow, settle and accumulate. Coupled with our TRFLP analysis of particle-associated versus free-living communities in the lagoon, this work suggests that the lagoon could strongly modulate coastal water quality for sediment-associated pollutants (chemicals or bacteria) by accumulation during the summer and release during the winter. For bacterial pollutants (e.g. pathogens), the seasonality of coastal water quality could be stronger if, for example, summer lagoon conditions favor amplification. Taken together, our work indicates that bacterial communities are apt tracers of watershed urbanization and that the impact of sediment-associated pollutants, including pathogenic bacteria, on coastal water quality is strongly, albeit seasonally, modulated by coastal lagoons when they are present.

B. Salt Marshes and Sandy Beaches

Impacts of anthropogenic stresses on salt marsh ecosystems
Understanding the impact of multiple anthropogenic stresses on ecosystems is an urgent challenge for environmental management. Salt marshes are among our most valuable natural resources, containing nursery habitats and migration corridors for a variety of commercially and recreationally important species. These ecosystems are also heavily stressed; receiving nutrient and toxicant inputs in runoff from nearby orchards, open agricultural fields, greenhouses and urban development in the foothills and coastal plain. SBC researchers (Holden, Nisbet, Kendall, Melack, and Page) are investigators in the Pacific Center for Estuarine Ecosystem Indicator Research (PEEIR), funded by the US EPA. PEEIR is comprised of over 20 research scientists from Bodega Marine Laboratory (BML), University of California, Davis, and University of California, Santa Barbara (UCSB), as well as several other agencies and institutions.

PEEIR has three research objectives, each based on priority management objectives for west coast estuaries. The first and most important objective is to develop indicators of overall wetland ecosystem health. Research and extensive monitoring activities are underway in several salt marshes, including Carpinteria Salt Marsh, to develop and validate novel techniques to measure wetland health. The second objective is to develop indicators of the biological condition of specific plant, fish, and invertebrate populations within wetlands. The third objective is to develop indicators of toxicant-induced stress and bioavailability for wetland biota. Physical and biological data, collected in Carpinteria Salt Marsh, as part of PEEIR sponsored research, are being integrated with data collected in the watershed of this marsh and adjacent coastal ocean by the LTER to expand our understanding of the importance of tidal wetlands in modulating the transport of nutrients, sediments, and other materials in runoff to offshore reefs.

Effects of nitrogen enrichment in salt marshes
Many coastal embayments are influenced by nitrogen inputs from agricultural and urban development in adjoining watersheds. Elevated dissolved inorganic nitrogen concentrations in coastal environments can cause eutrophication because these ecosystems are usually nitrogen limited. Nitrogen enrichment in salt marshes and shallow lagoons may alter the biological community by stimulating algal and plant growth, and reducing nighttime levels of dissolved oxygen. Indicators are needed that reflect the potential biological effects of nitrogen enrichment on salt marsh ecosystems. Benthic microalgae, and especially diatoms, are known to be very sensitive to changes in water quality, and were investigated as bioindicators in Carpinteria Salt Marsh, a site within the SBC LTER with previous and on-going studies on the sources, fates, and effects of watershed-derived nutrient inputs. Nitrate concentrations in the marsh channels exceed values in the coastal ocean by 10 to 100 fold. Within the marsh we chose 14 sampling sites, representing different levels of nutrients and salinity. Water samples and sediment pore-water samples for nutrient analyses were collected from the channels in the marsh. Temperature, salinity, and conductivity were measured at the same sites *in situ*. Simultaneously, samples of benthic microalgae were taken to determine the species composition of diatoms. We also measured densities of the dominant grazer, the snail

Cerithidea californica, at the sites. We explored spatial and temporal patterns in diatom communities in relation to nutrient concentration and salinity using diversity indices as well as cluster analysis using the relative abundances of component species.

We found a total of 125 diatom species in Carpinteria Salt Marsh. Cluster analysis differentiated five diatom assemblages. Correlation analysis between these assemblage groups and environmental factors revealed a variety of relationships. The Class 1 assemblage was found on sediments with high organic content ($p<0.05$), the Class 2 assemblage was associated with a low density of snails ($p<0.05$), and the Class 3 assemblage was positively correlated with increasing nitrate and phosphate concentrations ($p<0.01$) and high salinities in overlying water ($p<0.05$). The Class 3 assemblage also was positively related to increasing silicate concentrations in pore water ($p<0.05$) and increasing densities of snails ($p<0.05$). The Class 4 assemblage was positively correlated with increasing temperatures ($p<0.05$) and negatively correlated with increasing snail densities ($p<0.01$), whereas the Class 5 assemblage was associated with high concentrations of nitrate in overlying water.

Biological and physical attributes of salt marshes

To mitigate for impacts to fishes caused by the operation of the San Onofre Nuclear Generating Station (SONGS), Southern California Edison (SCE) is required by the California Coastal Commission (CCC) to create or substantially restore a minimum of 150 acres of tidal wetland. The restoration project will be conducted at San Dieguito Lagoon, which is located in northern San Diego County. As part of the CCC's technical oversight, monitoring and management responsibilities, SBC researchers (Page and Reed) are monitoring physical and biological attributes of San Dieguito Lagoon and other southern California wetlands that are being used for reference, including Carpinteria Salt Marsh. The project is intended to continue for the operating life of the power plant (expected to be about 20 – 30 years), and funding for study is provided by SCE as required by the CCC. Data that are being collected as part of this study include: water quality, cover of marsh vegetation, and densities of macroinvertebrates, fishes and birds. Research is also being done to develop sampling designs that can be used to effectively evaluate spatial and temporal changes in wetland habitats without exacting undue damage to the resources that are being measured. These studies are providing much needed information on optimum sample sizes, sampling frequency and sampling locations. Data on land use and runoff in the Carpinteria watershed collected by SBC are being coupled with data on water quality and wetland biota from the SONGS mitigation project to provide information on how terrestrial runoff and ocean forcing influence the physical and biological characteristics of this important ecosystem. That comparable physical and biological data are being collected by the SONGS mitigation project at other wetlands in southern California allows the results gather from the Carpinteria Salt Marsh to be placed in a broader regional context.

Kelp subsides to sandy beach communities

The condition and productivity of kelp forests may directly affect that of other coastal habitats that depend on allocthonous subsidies of kelp drift material. Exposed sandy beaches are a dominant coastal habitat in the SBC-LTER region, making up over 50% of the mainland shoreline. The rich macrofauna of beaches in the region depend largely upon allocthonous sources of organic matter and carbon because relatively little primary production occurs on the beach itself. Kelp forests are important sources of organic matter and can provide large subsidies of drift macrophytes (>450 kg m^{-1} y^{-1}) to sandy beach food webs in the Santa Barbara region much like which has been described for other coastal ecosystems (Polis and Hurd (1996). The export of macrophytes to sandy beaches is also an example of bottom-up control of marine intertidal community structure (sensu Menge 1992; Bustamante & Branch 1996). Our results suggest that subsidies of macrophyte wrack strongly influence macrofaunal community structure and the availability of prey resources to higher trophic levels on exposed sandy beaches in California (Dugan et al., in press). With support from University of California Sea Grant and Minerals Management Service, SBC investigators Dugan and Page are studying the responses of infaunal invertebrates, shorebird predators, sediments and dune vegetation to macrophyte subsidies from coastal reefs using comparative surveys and manipulative field experiments.

Macrophyte wrack deposited on SBC beaches consists primarily of giant kelp, *Macrocystis pyrifera*, and surfgrasses in the genus *Phyllospadix.* The mean standing crop of macrophyte wrack varied by over an order of magnitude among beaches, and among surveys (Figure II.B.1). Dynamics and condition of kelp forests and coastal reefs may be closely linked to variation in the standing crop of wrack on beaches. For example, the standing crop of wrack was consistently very low at Santa Claus Lane, a beach adjacent to our core reef site at Carpinteria. That reef was dominated by sea urchins and supported little foliose macroalgae during this study period. Species richness and abundance of wrack-associated invertebrates were also low at this beach.

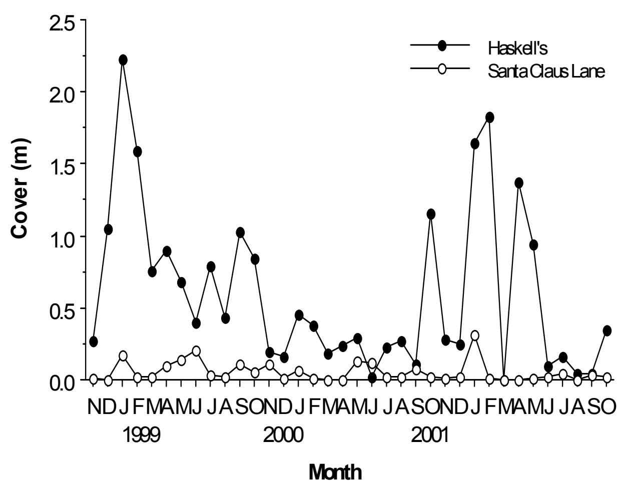


Figure II.B.1. Time series of the mean cover of *Macrocystis pyrifera* wrack at two beaches, Haskell's and Santa Claus Lane, located near core reef sites, Naples and Carpinteria, respectively, from October 1998 – October 2001.

Results of our field studies suggest that changes in the amount and type of macrophyte wrack available can significantly influence the diversity, structure and dynamics of the infaunal community on sandy beaches, and alter prey availability to higher trophic levels, such as shorebirds. Wrack-associated invertebrates, including amphipods, isopods, and insects, made up an average of >37% of the macrofaunal species on sandy beaches.

Overall species richness and abundance, and the species richness, abundance, and biomass of wrack-associated fauna and taxa were significantly correlated with the standing crop of macrophyte wrack. The response of higher trophic levels to wrack subsidies was also significant. The abundance of two species of shorebirds that forage visually, Black-bellied Plovers and Western Snowy Plovers, was positively correlated with the standing crop of wrack and with the abundance of wrack-associated invertebrate prey on beaches.

Surveys of beaches that are regularly groomed to remove accumulations of wrack provided us with an opportunity to assess the importance of wrack subsidies to macrofauna communities in a large-scale manipulative "experiment". Over 160 km of the southern California coast is subject to regular beach grooming to remove drift macrophytes, trash and other debris. Our comparative surveys found that species richness, abundance, and biomass of wrack-associated macrofauna were significantly depressed on groomed beaches compared to ungroomed beaches with high or low standing crops of macrophyte wrack (Figure II.B.2).

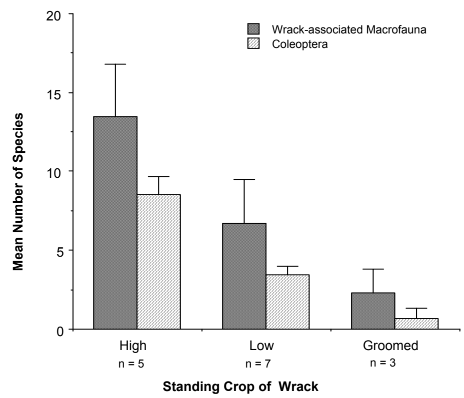


Figure II.B.2. Mean species richness of wrack-associated macrofauna (solid bars) and Coleoptera (hatched bars) for beaches with high and low standing crop of macrophyte wrack, and for groomed beaches. Error bars represent standard errors.

C. Coastal Oceanic Zone

A substantial subsidy of nutrients from either ocean currents or terrestrial runoff is needed to support the high productivity in kelp forests. The seasonal features of temperature, nutrient concentration, and solar radiation in nearshore kelp forests are generally the same as those affecting phytoplankton productivity in the euphotic zone of the adjacent, larger-scale basin. In the Santa Barbara Channel, winter and spring are characterized by cold, high-nutrient surface water, a shallow thermocline/nutricline, and episodes of terrestrial inflow, while summer and fall are characterized by warm, low-nutrient surface water and a deep thermocline/nutricline. These seasonal differences, and the transitions between the two extremes, are the primary factors influencing productivity in surface waters of the channel and, to first order, drive productivity of the giant kelp, *Macrocystis pyrifera*. A primary objective during the first three years of our project has been to develop an understanding of the dominant processes driving oceanic conditions on nearshore reefs where kelp forests occur, and to assess rates of nutrient supply to them. Routine measurements taken for this purpose include: moored observations of nitrate concentration, horizontal currents, temperature, salinity, optical backscatter, and chlorophyll fluorescence at our reef sites; hydrographic surveys (both channel-wide and at the shallow reefs); phytoplankton standing stock and productivity; satellite measurements of sea surface temperature (SST), chlorophyll concentration (Chl) and water turbidity, high-frequency radar measurements of surface current distributions, wind stress and climate data obtained from NDBC buoys (NOAA), and rates of nutrient input in stream runoff collected by the SBC-LTER watershed group.

Below, we discuss how large-scale seasonal changes affect phytoplankton productivity and nutrient supply in the open Channel, and we develop a process-level description of the most important mechanisms delivering nutrients to shallow coastal reefs where kelp

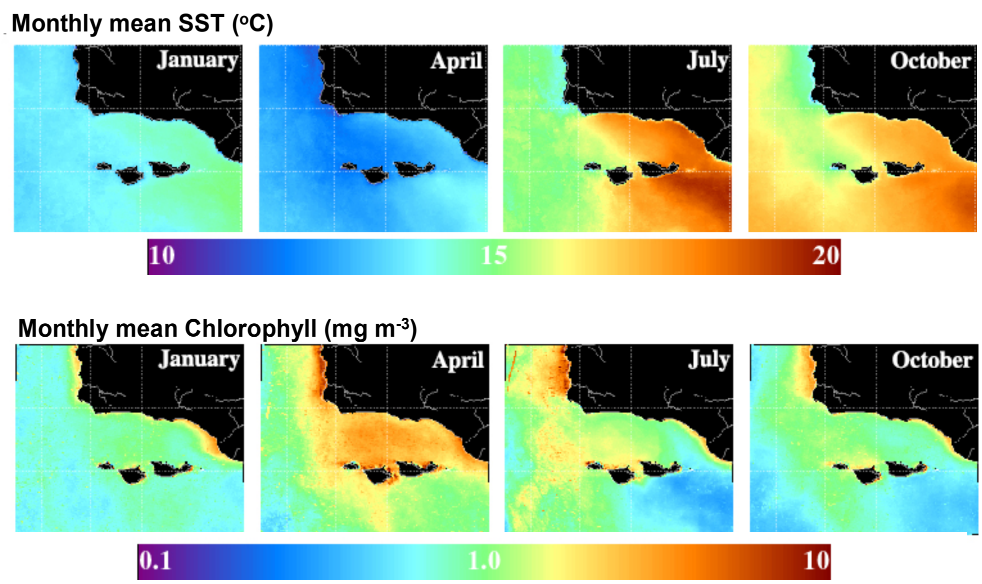


Figure II.C.1. Satellite derived climatologies of sea surface temperature and chlorophyll concentration over the Santa Barbara Channel. Monthly averages for January, April, July and October are made using observations from 1997 to 2002 (taken from Otero & Siegel, 2003).

forests occur. Finally, we compare our nutrient supply budget for our kelp reefs with measurements of kelp biomass and nitrogen content.

Seasonal patterns in temperature and nutrient concentrations in the Santa Barbara Channel.

In the Santa Barbara channel, the dominant spatial gradient in nutrient concentration is set by the large-scale coastal currents of the eastern Pacific. Cold water influenced by the equatorward-flowing California Current enters the channel from the north delivering relatively high nutrient levels. Warmer, low-nutrient waters of the Southern California Counter Current enter the eastern boundary from the Southern California Bight (SCB). The effect on SST and Chl are seen in monthly satellite climatologies (Figure II C.1; from Otero and Siegel, 2003). The “front” between cold, northern CA water masses and warm, southern CA water masses moves seasonally.

During spring, relatively cold waters are found throughout the channel, while during the summer and fall, warm waters from the south are found. Changes in the net transport through the eastern channel are part of the larger-scale pressure systems and wind flows over the Pacific and the North American continent. Their dynamics and the transitions between them are described in Winant et al. (2003). There are other cross-channel differences. For example the south western region of the Channel is strongly influenced by cold water flowing in from the California Current. This region is also affected by open-ocean Ekman pumping, caused by the strong wind stress divergence in the Point Conception region, and elevated mixing near the islands (Munchow, 2000). Both processes lead to elevated nutrient concentrations at the surface. However, nutrient delivery to surface waters also occurs on the mainland side of the channel. Work by SBC graduate students Warrick (2002) and Otero (2002) demonstrates that input from terrestrial plumes can lead to surface phytoplankt-on blooms near the coast on the northern/northeastern side of the Channel. Vertical nutrient and temperature gradients also play a critical role in determining

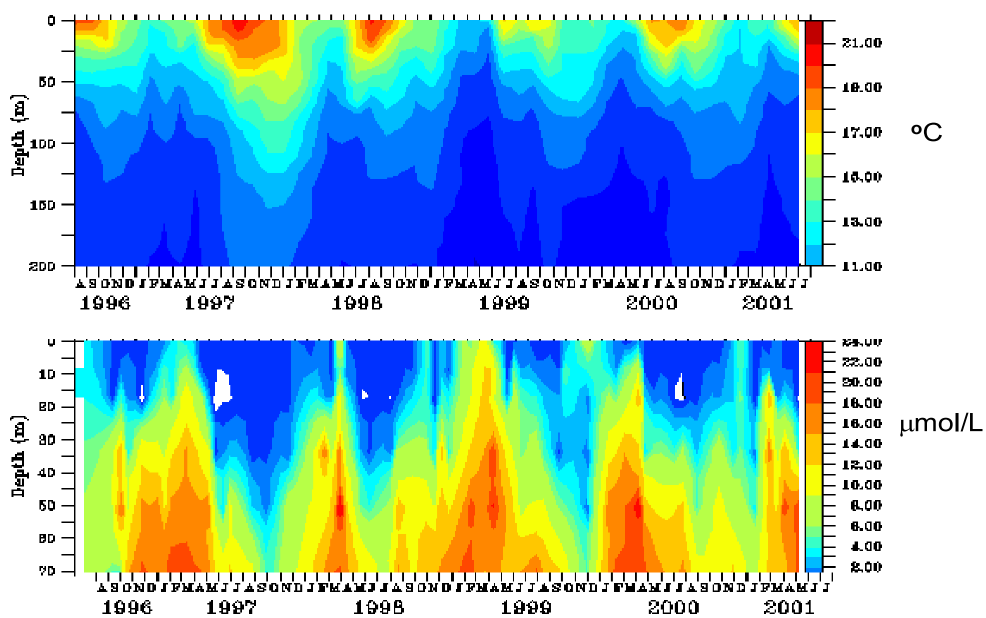


Figure II.C.2. Time depth contours from a mid-channel station: temperature (upper panel) and nitrate (lower panel) from the mid Santa Barbara Channel.

nutrient availability for productivity in near-surface waters. There is large seasonal variation in the depth of the thermocline and nutricline (Figure II.C.2). In a typical mid-summer period (July through September), the 13° isotherm and corresponding nitrate levels of ~5 to 10 μmol l^{-1} are found at depths between 50 and 75 m. In contrast, between March and April, these cold temperatures and high nutrients are found closer to the surface, typically between 5 and 20 m depth. During the spring, vertical motion in the water column or slight increase of vertical mixing can transport high nutrient waters to shallow depths, where they can be utilized by phytoplankton and benthic algae. In the summer, however, such events are rare. There are also seasonal differences in shelf currents, winds, and baroclinic processes that drive such exchange. Further, there are large inter-annual changes in thermocline and nutricline depths driven by El Nino (97/98) and La Nina (98/99) events (Figure II.C.2).

How do seasonal conditions affect primary productivity in the channel?
Phytoplankton blooms occur in two general locations in the Santa Barbara Channel. The first is the western Channel where productivity is influenced by inflow and vertical Ekman pumping of cold, high-nutrient waters. These blooms are observed in satellite data as well as with data collected during the LTER cruises. These cruises, scheduled three times per year, have provided an assessment of phytoplankton biomass and primary productivity associated with mid-channel blooms. The second location of focused surface blooms is the coastal waters influenced by local river plumes, predominantly from the Santa Clara River in the eastern Channel (Otero and Siegel, in review, Warrick et al. in review- ab). These have been primarily observed through satellite measurements, as well as in recently conducted "event" surveys, in which depth profiles of temperature, salinity, assorted nutrients and chlorophyll a, were collected from a small boat in the nearshore immediately after a big rainstorm to assess the hydrographic and nutrient conditions caused by terrestrial plumes. Phytoplankton primary production is measured seasonally during our UNOLS cruises from the surface to the 1 % light depth along seven stations in the center of the CTD grid (also the line used in Plumes and Blooms sampling), and at 5 m depth at each station of the channel-wide CTD grid using ^{14}C labeled bicarbonate incorporation (see http://sbc.lternet.edu/sites/coastoceanicmap.html for locations of sampling sites). Productivity

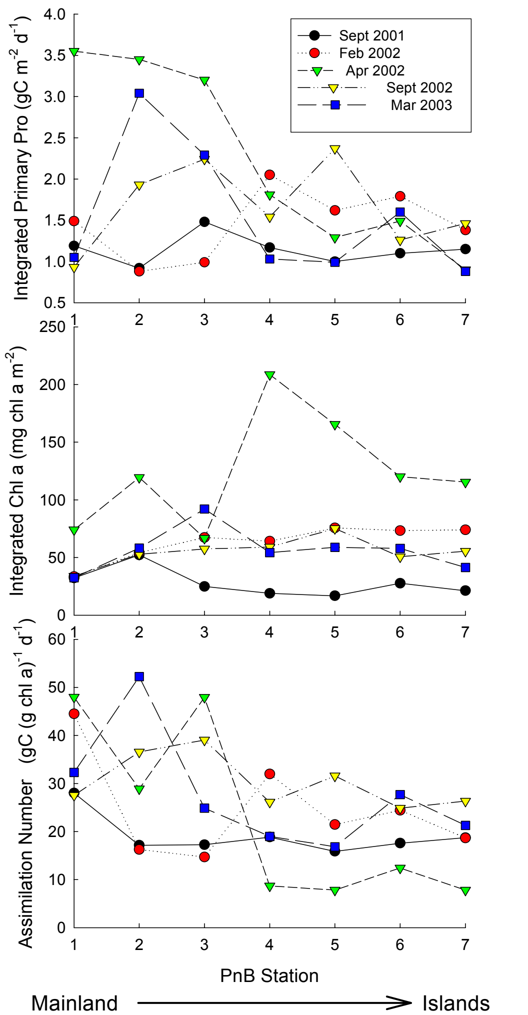


Figure II.C.3. Integrated Primary Productivity, chlorophyll concentration and assimilation number along the cross Channel transect.

tends to be higher along the mainland with the highest integrated primary productivity occurring in April/May 2002 (Figure II.C.3). An important trend is that peaks in both primary production rates and assimilation numbers (primary production normalized to chl a concentration) are skewed toward the mainland side of the channel. This pattern is not as evident in the integrated chlorophyll data suggesting that phytoplankton removal processes are higher near the mainland. The peaks in phytoplankton primary productivity coincided with the coldest sea water temperatures and highest nutrient conditions observed for that year. This demonstrates the importance of seasonal climate and the effects of spring upwelling on channel-wide primary productivity. Productivity in February and September of both years was lower than in spring, with no clear seasonal difference between winter and fall.

One of our long-term goals is to establish a time series of primary production within the basin to examine how phytoplankton respond to climatic forcing such as El Nino and the Pacific Decadal Oscillation. Our data set is presently inadequate to address these issues, but the average integrated primary production along the Plumes and Blooms line is beginning to reveal a seasonal trend (data not shown). We will be using these data along with maps of primary production from our CTD grids and satellite imagery to interpolate monthly rates of phytoplankton production over the entire basin.

Terrestrial inputs to kelp forests also vary seasonally. A satellite depiction of a proxy for suspended sediments from the El Nino storms of 1998 shows extensive nearshore regions where ocean turbidity is elevated (Figure II.C.4). In this image high values of ocean turbidity resulted from outflow of the Santa Clara River in the eastern channel and watersheds north of Point Conception to the west. The influence of the smaller watersheds along the channel and island coasts is also seen. Mertes and Warrick (2001) have found that these small water sheds discharge disproportionately large amounts of sediment to the channel given their small drainage areas. The timing of terrestrial discharges is highly seasonal with elevated levels in the late winter and early spring

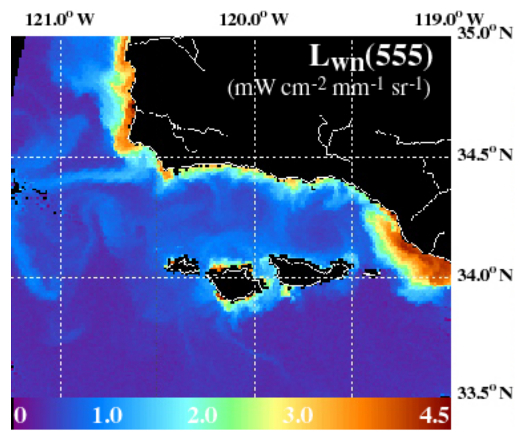


Figure II.C.4. SeaWiFS ocean color image from 15 February 1998 showing an index for suspended sediment concentrations (the normalized water leaving radiance at 555 nm) during the El Nino storms (taken from Otero & Siegel, 2003).

How do seasonal and channel-wide dynamics affect nutrient supply to shallow nearshore reefs?

Time series measurements obtained from moored instruments and monthly water samples at three mainland reef sites provide important information on the temporal features of temperature, salinity, currents, and ambient nutrient concentrations in water masses surrounding the kelp forests. Our longest time series is from Naples Reef, the most centrally located of the three reef sites (Figure II.C.5; the location of Naples is denoted by a red triangle in Figure II.C.7). The same seasonal pattern characterizing open-channel conditions also dominates the temperature and nutrient "climate" at the shallow reef sites. Pulses of cold water (< 11^{o}) and high salinity occur in spring. These bring the highest nutrient peaks (nitrate concentration > 20 µmol per liter) lasting 4 to 8 days. These pulses are due to local coastal upwelling and occurred during the spring of 2001 and 2002.

Aside from the period of spring upwelling, nutrients at the surface (green line, Figure II.C.5c) tend to be fairly low. However, nutrients in the bottom half of the water column inferred from temperature (blue line), and in-situ measurements (pink line) are

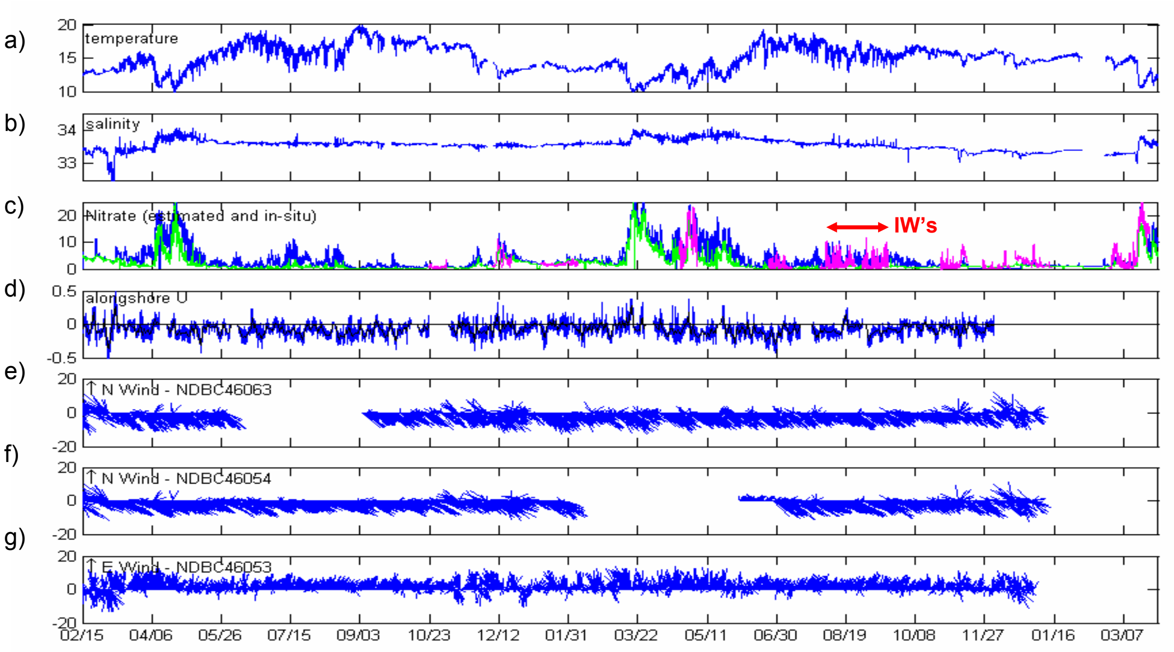


Figure II.C.5. Time series of water constituents at the LTER Naples site: a) temperature; b) salinity; c) measured nitrate near bottom (pink) and nitrate regressed from temperature at surface (green) and bottom (blue); d) alongshore velocity; e) winds at NDBC buoy 46063; f) winds at NDBC buoy 46054; g) winds at NDBC buoy 46053.

substantially higher. In situ nitrate measurements were initiated after May 2001. The nitrate time series demonstrates the importance of water column stratification on the nearshore habitat. Although surface waters are warm and have low nitrate concentrations throughout the summer, the nitrate measured at 12 to 14 m depth experiences frequent fluctuations and pulses up to 5 to 10 µmol per liter. For example, a period of internal wave activity occurred around 08/19/2002 and produced large pulses of nitrate concentration (internal waves at this time are identified in Figure II.C.5 by the double-ended red arrow labeled IW's). These fluctuations are caused by diurnal-frequency internal waves, which are most energetic during the strong stratification of summer. These internal motions can lift cold water and high nutrients from depths greater than 20 to 30 m to the shallow reef. The internal waves often do not have a surface expression, yet they have a profound effect on the temperature and nutrient conditions at reef waters greater than 8 meters depth. Kelp biomass spans the depth range from bottom (20 m) to surface and thus may use these pulses of nutrients, which frequently bathe the bottom half of kelp plants approximately once per day during summer.

The effects of strong coastal upwelling on spatial patterns of temperature, salinity, and nutrients are event from data collected during our spring 2002 UNOLS cruise (Figure II.C.6). Concentrations of nitrate and phosphate (and other constituents not shown here) reached high levels at this time due to upwelled deep water masses. Such intense upwelling events in the Channel appear to be associated with strong westerly (eastward) winds inside the channel and some interesting reversals in the north-south winds near Pt. Conception.

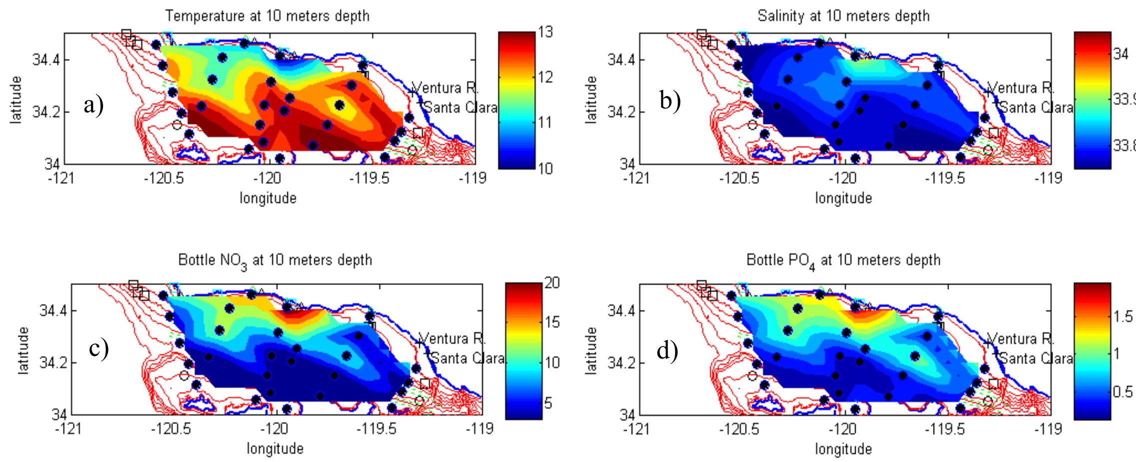


Figure II.C.6. Contours of a) temperature (ºC); b) salinity; c) nitrate (µM); and d) phosphate (µM) from the LTER ship survey of April - May 2002 showing the effects of strong wind-driven upwelling within the channel.

During November and December of both 2001 and 2002 we observed additional nitrate peaks with durations greater than several days (Figure II.C.7). These events coincided with episodic reversals of the alongshore shelf current, which has a mean westward (poleward) flow. However, significant cooling events that bring deep water up to the shallow reefs were often accompanied by reversals when the current direction switched to eastward. These cold pulses and flow reversals occur concurrently at all three mooring sites, suggesting that such events are a channel-wide phenomenon. We hypothesize that these synoptic-frequency, large-scale events may be governed by: 1) dynamics relating geostrophic shelf currents to changes in the wind stress field; or 2) coastal-trapped wave dynamics. The same dynamics may be responsible for onshore transport events observed during both the spring and fall seasonal transitions.

Another mechanism producing nearshore current reversals and transport of nutrients to the inner shelf are small-scale eddy features, which is a recent finding of SBC LTER. The eddy patterns and their effects are revealed in spatial patterns of surface currents from the high frequency radar at Coal Oil Point and Refugio Beach (yellow circles in center panels) along with times series measurements from our moored instruments at Naples Reef. Panels on the left in Figure II.C.7 show patterns of surface currents around the Naples mooring (red triangles) on 10, 13, and 15 December 2001. Blue shading on the maps from 10 and 15 December mark the positions of near shore, anti-cyclonic eddies which are just offshore from the Naples mooring. The absence of this pattern on 13

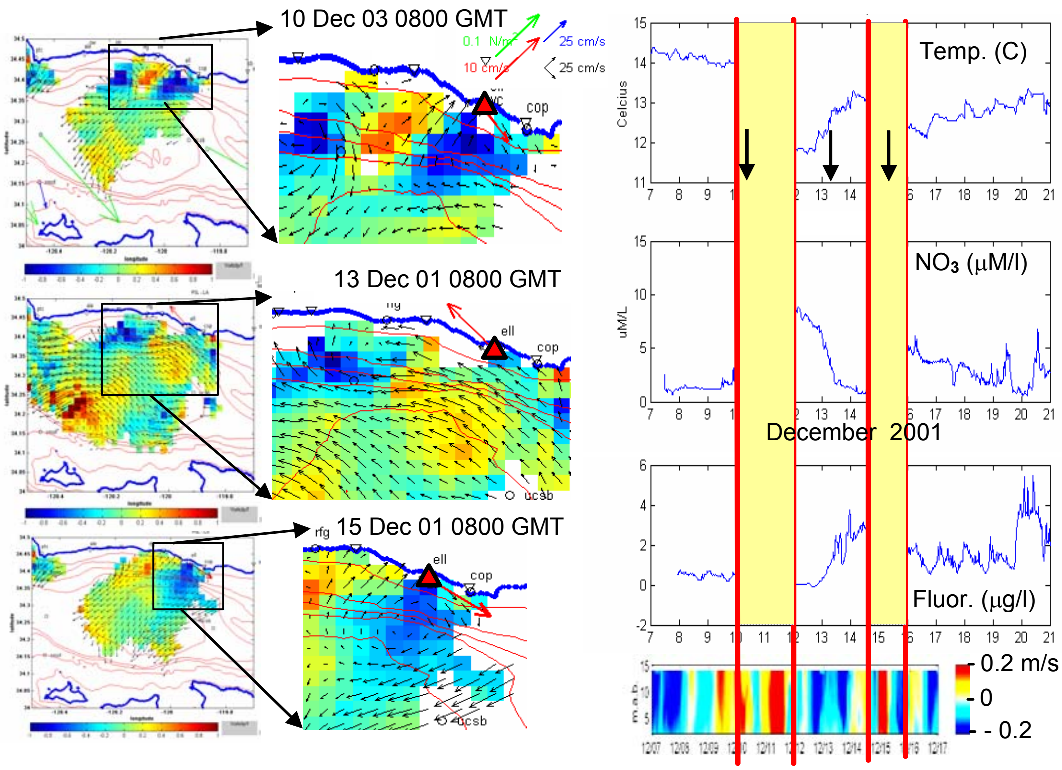
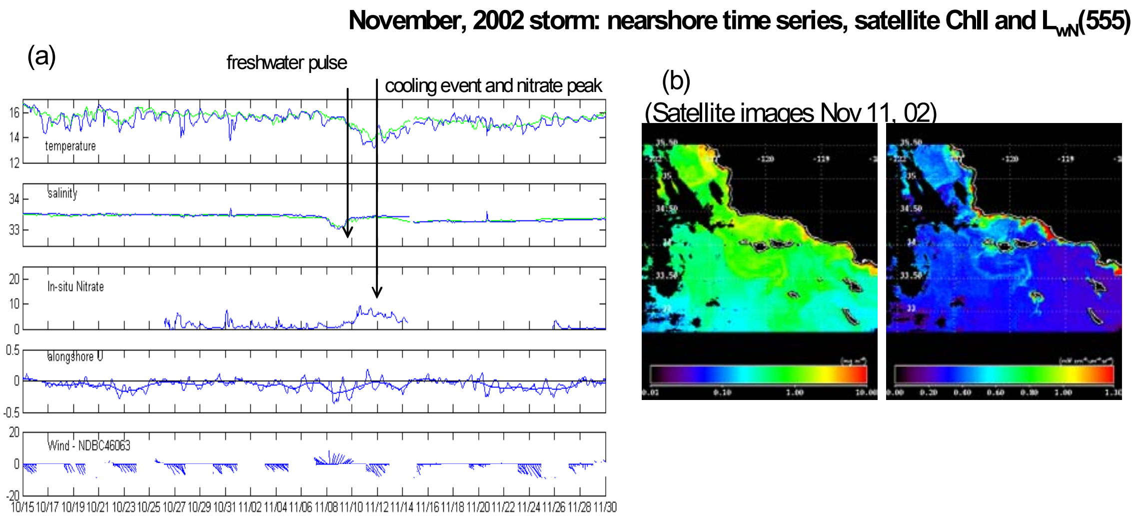


Figure II.C.7. Panels on left show evolution of near shore eddy structures from 10-15 Dec 2001. Cooling and increased nitrate concentration accompany the eddies which also cause nearshore flow reversals as shown by center and right-hand panels. Arrows along the x-axis in the upper right panel show times of the three surface current maps. In center panel red triangles indicate mooring at Naples and yellow circles are HF radar locations. Time-depth contours in lower left panel show along shore velocities over 15 m water column. Eastward flow is red and westward flow is blue.

December indicates that the eddy patterns change rapidly. Eastward flow due to the eddies is evident in the near surface vectors from the ADCP (red arrows in current maps) and in the ADCP time-depth contours at the lower right. When the eddy first appeared on 10 December, temperatures at the mooring dropped by over 2ºC and nitrate concentrations (measured in situ every 20 minutes by a moored sensor) increased by about a factor of eight. Cooling and elevated nitrate concentrations return with another eddy on 15 December. An increase in chlorophyll fluorescence indicating a phytoplankton bloom beginning on 13 December followed the first eddy by about 2 days. A future research direction will be to understand the importance of these flow structures as nutrient delivery mechanisms to the kelp forest.

Terrestrial inputs
Terrestrial input of freshwater and nutrients was a relatively weak signal in the overall time series, however, evidence of the large storm occurring March 3-6, 2001 shows up in the salinity record as a strong low-salinity pulse near the beginning of the record (Figure II.C.5c). The in situ nitrate analyzer was not available during this storm event, and because temperature does not function as a proxy for nutrients during storm events, we have no record of the nitrate concentration at the reef associated with this event. However, using nitrate concentration values from streams collected by the SBC LTER watershed team, we estimated the likely nitrate concentration based on freshwater



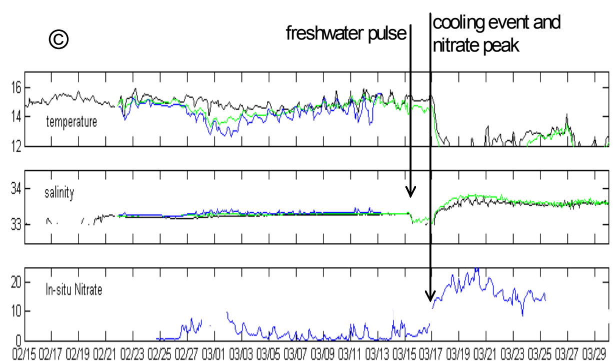


Figure II.C.8. Time series of water properties and wind along with satellite images for storms in November 2002 and March 2003.

dilution. The results suggest a peak of between approximately 4 and 8 µmol per liter with a duration of 2 days. Measurements from more recent rainstorms of November 2002 and March 2003 suggest that the nutrient response to such events is constrained to surface waters. Low-salinity was observed at 4.5-m depth during these events (Figure II.C.8), however, the in situ nitrate sensor located at a depth of 12 m, did not measure elevated nitrate in response to the storm. Nonetheless, an interesting storm effect occurred in which wind reversals and a sudden switch to eastward currents at the shore coincided with abrupt cooling for a day or so after each storm. Thus, low-frequency dynamics driving onshore transport of cold, deep water appear to be important for nutrient elevation after storm events. The low-salinity signal of the November rainstorm (Figure II.C.8a) also appeared in satellite measurements of water-leaving irradiance (L_{WN}555), a proxy for near-surface suspended sediment (Figure II.C.8b), as plumes spreading near the coast at several locations. However, corresponding satellite Chl a measurements indicate no nearshore phytoplankton bloom was associated with the terrestrial inflow.

The relative importance of different mechanisms of nitrate delivery.
Table II.C.1 shows the amount of nitrogen delivered to kelp forests during the period July 2001-July 2002 by the four transport mechanisms that we have identified to date. These rates do not account for loss processes such as biological uptake. Spring upwelling dominates the annual nitrate delivery budget, but both flow reversals and internal wave

processes together account for a significant (18%) fraction of the nitrate delivered to kelp forests. The fact that these processes occur during the summer stratified period when ambient surface nitrate concentrations are extremely low suggests that they are major supply terms sustaining kelp productivity during summer. Terrestrial input is small although the storms were infrequent during 2001-2002.

Table II.C.1 Annual nitrate supply budget to giant kelp forest (July 2001 - July 2002)

Mechanism of nutrient delivery	Time (days)	% of year	Nitrate Supply Rate (μmol l^{-1} d^{-1})	Contribution to Annual Nitrate Supply (%)
Spring Upwelling	74	21	0.7	76
Flow Reversal Events	19	5	0.4	13
Summer Internal Waves	48	13	0.07	5
Terrestrial Inputs (Storm Events)	0 (6 d in 2001-2002)	0	0.1	0 (~1% in 2001)
<u>Background Conditions</u>				
Winter	127	27	0.03	5
Summer/Fall	97	34	0.01	1

Response of Macrocystis to the supply of nitrate

Nitrogen is the nutrient that most commonly limits growth and reproduction in giant kelp. SBC undergraduate Kristen Green has been working with SBC investigators (Brzezinski and Reed) in investigation the extent to which temporal changes in the nitrogen content of *Macrocystis* in the Arroyo Quemado kelp forest is related to seasonal changes in the supply of nitrate. This work entailed constructing time courses of: (1) the average kelp nitrogen content normalized to wet weight using data on kelp biomass (see section II.D. *Primary production in giant kelp)* and the nitrogen content of different kelp tissue types, and (2) the supply of nitrate to the reef from time series of temperature measured by thermister arrays moored at the site, and the relationship between temperature and nitrate concentration established from our deployments of the *in situ* nitrate analyzer. The result was a continuous record of nitrate concentration at three depths that was integrated over depth and time to provide an estimate of the nitrogen supplied to the reef for the 30 days preceding each monthly estimate of kelp nitrogen content.

Kelp N content generally followed the pattern of nitrate delivery in spring and early summer with a lag time of about one month between N delivery and the corresponding change in the N content of kelp (Figure II.C.9). Kelp tissue N increased late in the year without a concomitant increase in nitrate supply suggesting that a nitrogen source other than nitrate may support kelp production at this time.

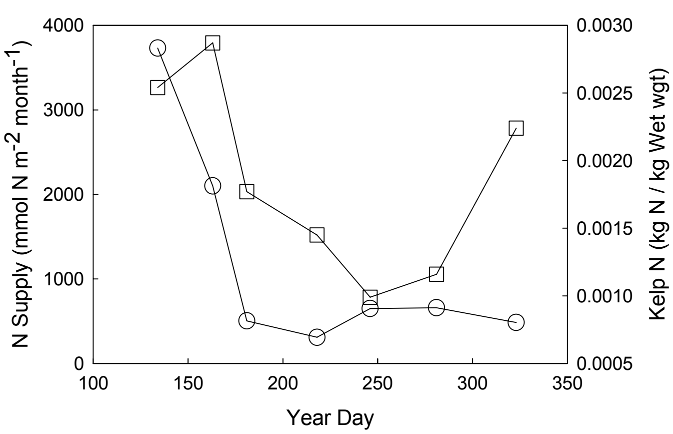


Figure II.C.9 Comparison of nitrogen concentration in kelp tissue (squares) to nitrate supply to the reef during the intervening month (circles).

D. Kelp Forests

Kelp forest community structure and dynamics

Tracking long-term patterns in species abundance and diversity is essential for understanding how ecosystems change in response to natural and human-induced fluctuations in the environment. We initiated an annual kelp forest monitoring program in the summer of 2000 (the first year of our project) in which the abundance (and in some cases the size) of over 150 taxa of kelp forest plants and animals are recorded along permanent transects at nine reef sites located along the mainland coast of the Santa Barbara Channel (see http://sbc.lternet.edu/sites/reefsitesmap.html for information on the locations of the sites and the information that is collected at them, see http://sbc.lternet.edu/research/c1.html for a downloadable copy of "A Field Guide to Common Subtidal Plants and Animals"). Our study sites were specifically selected in areas close to and far from sources of terrestrial runoff along an east-west oceanographic gradient that spans the channel to facilitate our objective of determining the extent to which regional and temporal (short and long-term) variability in the structure and dynamics of kelp forest communities is influenced by the magnitude and composition of terrestrial and oceanic inputs to coastal reefs.

Results from the first three years of our monitoring indicate the species assemblages on reefs that have been deforested by grazing sea urchins are highly variable. At one end of the spectrum is Carpinteria Reef, which has little foliose algae (< 1%) and is dominated by encrusting coralline algae with relatively few reef-associated fish. In contrast, the abundances of understory algae (mainly red algal turf) and fish on Naples Reef are relatively high. Interestingly, the algal turf on Naples Reef is usually associated with aggregations of the clonal sea anemone, *Corynactis californica*. The mechanisms causing the species assemblages at Carpinteria and Naples to differ are unclear. One possibility is that sea urchins avoid the stinging tentacles of sea anemones. As a consequence, sea anemones provide a spatial refuge from grazing and allow patches of red algae to persist despite high densities of grazing sea urchins. The conspicuously low abundance of clonal anemones at Carpinteria Reef could result from high rates of sedimentation, which inhibits suspension feeders as well as turf algae. One important source of sedimentation on nearshore reefs is terrestrial runoff, which likely differs between the two sites. Unlike Naples Reef, which is located offshore relatively far from sources of runoff, Carpinteria Reef is situated inshore close to the outfall of a major drainage system in a heavily developed watershed. Thus, sedimentation from runoff could reduce algal abundance and the forage base for fishes on Carpinteria Reef directly via burial, or indirectly by reducing the abundance of sea anemones that provide them refuge from grazing sea urchins. We have obtained matching funds from the University of California Marine Council for stipend support for a graduate student (Stu Levenbach) to work

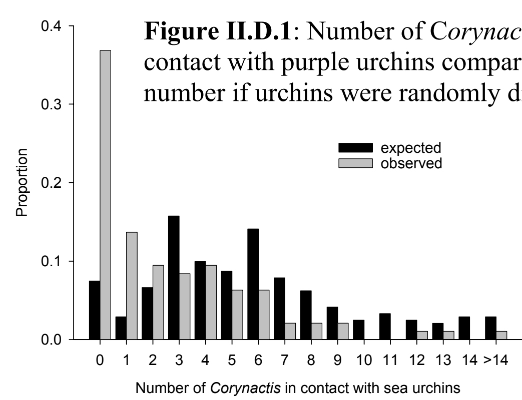


Figure II.D.1: Number of *Corynactis* in contact with purple urchins compared to the number if urchins were randomly distributed on testing these and other related hypotheses for his dissertation. Mr. Levenbach's results to date indicate that sea urchins do indeed avoid clonal sea anemones (Figure II.D.1). Experiments are underway to determine (1) threshold densities of *Corynactis californica* needed to illicit an avoidance response in sea urchins, and (2) the role of sediment in determining the distribution and abundance of *Corynactis californica*.

In addition, to our mainland reef sites we continue to monitor 11 reefs at Santa Cruz Island, which have been sampled yearly (or more often) for several decades, as part of ongoing research by Sally Holbrook and Russ Schmitt. Long-term sampling at these sites and at other sites on the mainland has revealed some dramatic ecosystem changes in reef communities along the California coast that are related to climate oscillations that produce abrupt regime shifts that typically occur every 20-35 years (Minobe 1997, 1999). We have seen shifts to dominance by southern species in kelp forest fish as well as large changes in standing stocks of reef fishes and invertebrates (Holbrook et al. 1997; Brooks et al. 2002). Since the early 1970's the proportion of species in fish assemblages that are cold-water, northern species has dropped by about half, while the proportion of southern, warm-water species has increased nearly 50 percent. Overall, there has been a substantial decline in total fish abundance, which correlates closely with declines in productivity. These patterns suggest an ongoing redistribution of marine species along the coast of California that is consistent with predicted northward shifts in species' ranges in response to ocean warming.

Historical database on giant kelp abundance

ISP Alginates (formerly Kelco Co.) has collected information on the abundance of giant kelp in California and Mexico from routine (approximately monthly) aerial surveys since 1958. ISP Alginates has provided us with copies of all their archived records, which we have used to create a digital database on the historical abundance of giant kelp throughout its range in California and Mexico http://sbc.lternet.edu/data/research/reef/historical-kelp-data/. This database enables us to more easily evaluate long-term trends in the abundance of giant kelp and allows us to place our observations of kelp abundance within SBC into a much broader regional perspective. SBC graduate student Brian Kinlan is using these data to investigate the spatiotemporal dynamics of giant kelp forests throughout their range in California and Mexico. He has found that canopy biomass varied interannually at dominant periods of 4-5 y, 11-13 y and ~20 y, and at spatial scales ranging from local (~30 km) to mesoscale (~100-150 km) and

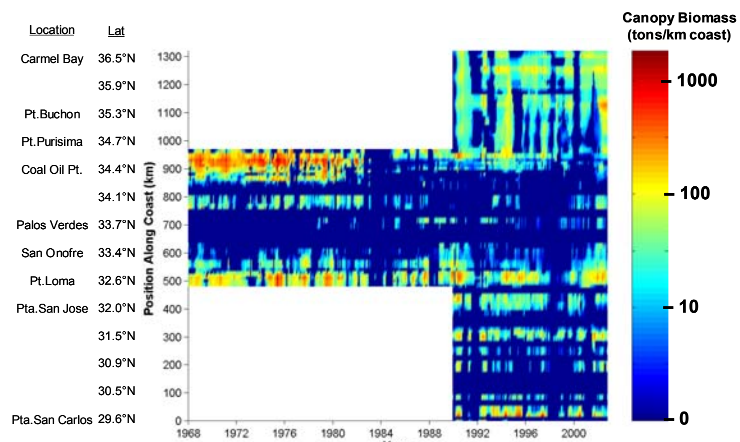


Figure II.D.2. Space-time distribution of kelp forest canopy biomass in the NE Pacific, based on monthly aerial surveys from ISP Alginates/Santa Barbara Coastal LTER. White = no data. Missing values interpolated by ordinary kriging.

regional (~330 km) (Figure II.D.2). Temporal dynamics were strongly related to basin-scale climate fluctuations (El Niño-Southern Oscillation, Pacific Decadal Oscillation) and spatial patterns were correlated with coastline geomorphology. Digital canopy maps reveal that changes in biomass are associated with shifts in the spatial structure of the kelp habitat.

Primary production in giant kelp

In 2001, we initiated field studies designed to examine spatial and temporal patterns of variation in the production of the giant kelp *Macrocystis pyrifera* and the factors that control them. *Macrocystis* is the largest alga in the world, and it is believed to be one of the most productive organisms on earth. A single individual can be more than 30 m tall and consist of over 100 fronds. Plants may live up to four to six years, while individual fronds live about 4 - 6 months. In 2002, we refined the methodology that we use to estimate changes in standing stock over time, and we have implemented this new methodology in our monthly surveys since May 2002. The methodology consists of (1) estimating the density and length of all fronds > 1 m tall along fixed transects at three sites (Mohawk Reef, Arroyo Burro, Arroyo Quemado; (2) measuring frond turnover (i.e., birth, and death) on marked individuals at each site; and (3) whole plant dissections in the laboratory for estimating weight-length relationships of fronds, and for determining the chemical composition (C, N) of different tissue types. Net primary production (NPP) of giant kelp is estimated as the change in biomass + the loss in biomass as follows:

$$NPP = [B_{t+1} - B_t] + [B_t p + B_t(1-p)f]$$

where: B is the dry mass of kelp carbon m^{-2}, p is the fraction of plants lost during the period between t and $t+1$, and f is the fraction of fronds lost by plants that survived the period between t and $t+1$.

NPP in giant kelp was substantial during the period May – December 2002, averaging 3.8 g C $m^{-2}d^{-1}$over all sites (Figure II.D.3). Variation in NPP was explained in large part by standing crop, which decreased at all sites in the fall when nutrient concentrations decreased (see Figure II.C.2) and storm activity increased; significant frond loss was observed following several large storms in October. The large fluctuations in NPP observed at Mohawk during the first three months reflect the loss of the canopy portion of fronds due to kelp harvesting. Partial frond loss is not accounted for in our loss term due to the logistical difficulty of measuring individual frond size.

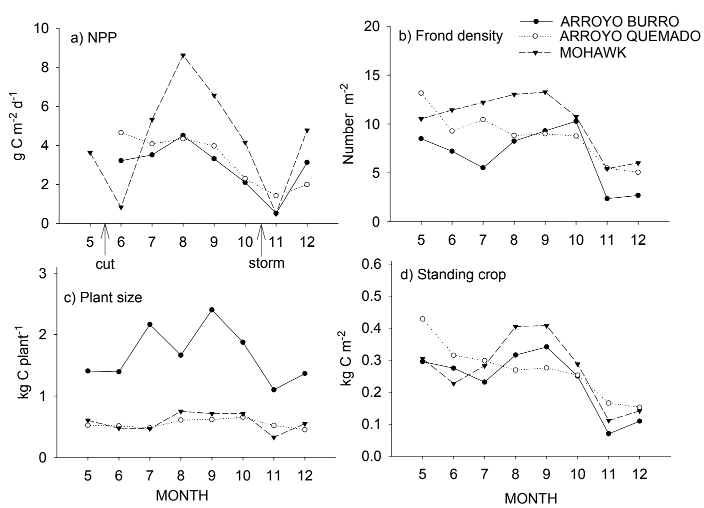


Figure II.D.3. Monthly changes in: (a) kelp NPP, (b) frond density, (c) plant size, and (d) standing crop at three reef sites. "Cut" in (a) indicates that a kelp harvester removed the surface portion of many fronds at Mohawk reef only.

We have since worked with harvesters to develop a plan that eliminates harvesting at our study areas.

The methodology used above for estimating NPP is quite labor intensive, and thus is difficult to apply over a broad region. We are exploring the potential for estimating plant standing crop and productivity using in situ spectroscopy. In this method, a radiometrically calibrated HydroRad spectroradiometer fitted with cosine collectors is mounted to a portable frame for underwater operation by a SCUBA diver. Downwelling irradiance spectra are being measured along the same transects at our three kelp forest sites where we are measuring kelp productivity using the more labor-intensive diver measurements. Canopy absorbance of spectral irradiance is determined by differences in downwelling irradiances measured inside and outside the kelp forest. The resulting absorbance spectra are converted to equivalent blade area using spectrophotometrically determined absorbances of individual kelp blades measured in the laboratory. The optical data are used to calculate a Blade Area Index (BAI) for use in estimating standing crop. Estimates of standing crop based on BAI are compared to those obtained from diver measurements to determine the validity of using optical data for assessing standing crop in giant kelp. Data collected to date suggest that optical data provide as good a predictor of standing biomass as the more labor intensive diver counts (Figure II.D.4). The shallow slope between optically determined BAI and diver measurements (0.1105) indicates a significant package effect with respect to light harvesting by the plants and blade distribution within the canopy. This package effect (less light absorption per unit blade area than predicted from laboratory measurements of blade absorbances) probably results from the aggregation of blades near the stipe columns and surface canopy, rather than being randomly dispersed throughout the water column, and perhaps from angular orientation of the blades relative to the incoming light field. Nonetheless, the highly predictive relationship to Diver Measured BAI indicates that the optical measurement can provide a reliable estimate of kelp standing crop for about 1/3 the effort required for direct counts.

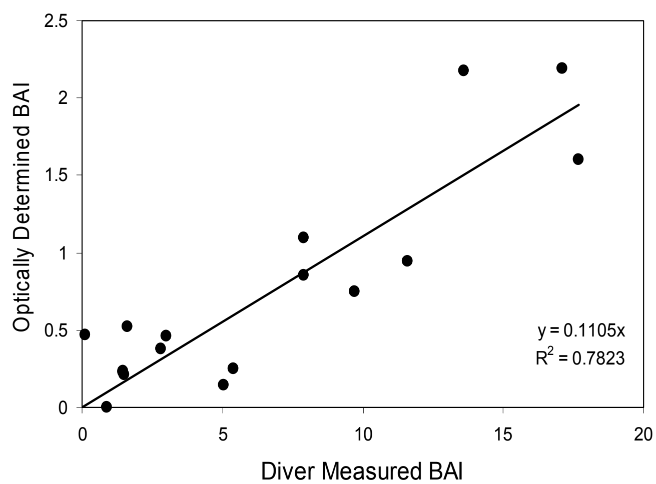


Figure II.D.4. Relationship between Blade Area Indices (BAI) measured by direct diver counts of stipe abundance and frond morphology and optical measurements of light absorption by the intact kelp canopy. Inverting the slope provides a robust calibration coefficient (1/slope = 9.05) to convert optical measurements to standing crop.

Nitrate consumption and phytoplankton grazing within kelp forests

Currents impinging on the kelp forest transport nutrients, plankton and organic carbon that can substantially subsidize the kelp community. The kelp forest in turn modifies the flow around and within its boundaries, and forest producers and consumers alter the flux of nutrients and particulates within the forest. We began investigating these processes in a collaborative study with investigators from Stanford University (Drs. Steve Monosmith and Jeff Koseff, and Rob Dunbar) and Eilat University, Israel (Dr. Amatzia Genin). In May 2002, we measured the concentrations of chlorophyll *a*, POC, PON, DOC, and nutrients at three stations along a transect extending from 20 m upcurrent of the edge of a bed to 41 m inside the *Macrocystis* forest at Mohawk Reef. Our measurements show a remarkable decrease of chlorophyll *a,* POC, and PON, primarily near the bottom, and a similarly remarkable decrease of nitrate, nitrite and phosphate in the upper water column inside the kelp forest (Figure II.D.5). These trends indicate the occurrence of intense,

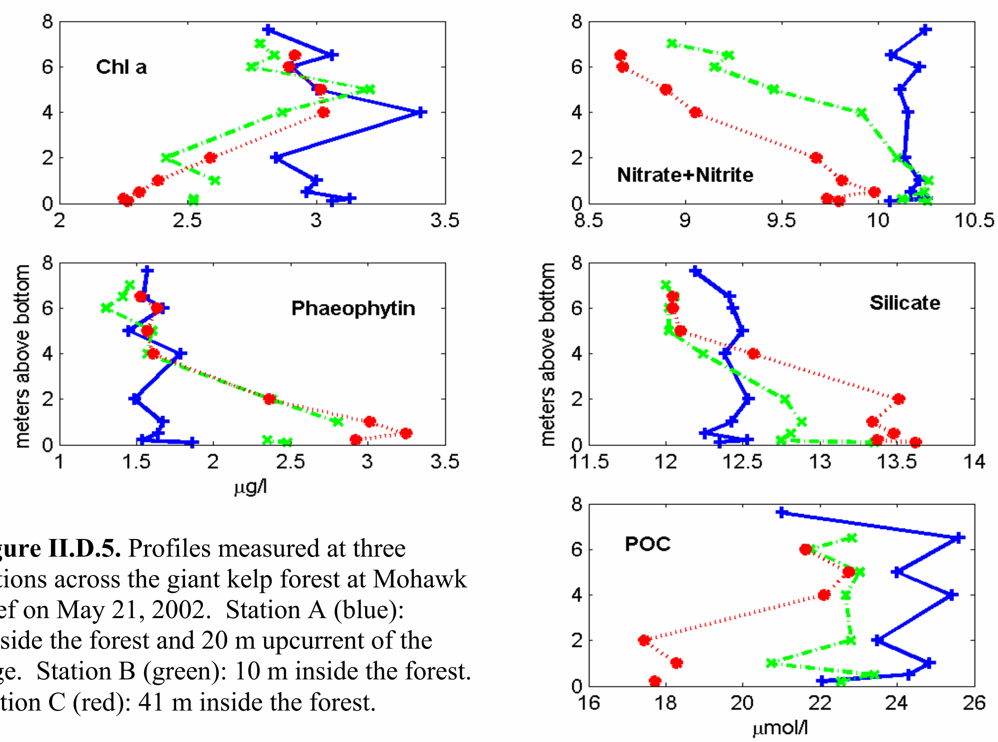


Figure II.D.5. Profiles measured at three stations across the giant kelp forest at Mohawk Reef on May 21, 2002. Station A (blue): outside the forest and 20 m upcurrent of the edge. Station B (green): 10 m inside the forest. Station C (red): 41 m inside the forest.

previously undocumented grazing on phytoplankton and other organic particles near the bottom and pronounced uptake of nutrients closer to the surface where most of the kelp biomass is located. The large increase in phaeophytin near the bottom corroborates the conclusion that grazing was intense, while the corresponding near-bottom increase in silicate suggests significant benthic regeneration of silica. Assuming an average flow velocity of 2 cm s^{-1} and a distance of 41 m between station C and the edge of the forest (station A), the water column-integrated decline in chlorophyll was 2.07 mg m^{-2} and that of POC was 29.9 mmol C m^{-2}. Extrapolating these values to 24 hrs and converting chlorophyll to carbon (using C: Chl ratio of 100 for this region), the estimated decline from outside to 41 m inside the forest was 8.7 g C m^{-2} d^{-1} and 15.1 g C m^{-2} d^{-1}, for chlorophyll and POC, respectively - high compared to the estimated community productivity of 9.5 g C m^{-2} d^{-1} for the *Macrocystis* forest in Point Loma, San Diego (Jackson 1977). These values indicate that nutrient uptake by kelp and grazing on oceanic phytoplankton by benthic suspension feeders within the bed can be quite high.

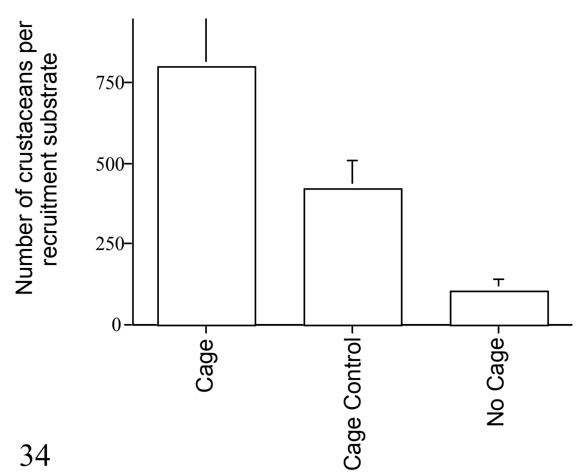
Kelp forest food webs and the role of nutrients in trophic interactions

Kelp forests have two major food webs: a well studied one in which macroalgae are consumed directly by large grazers (i.e., sea urchins), which in turn are consumed by large predators (i.e., sea otters), and a little studied one in which macroalgae serve as a substrate for periphyton and small crustacean grazers, which are preyed upon extensively by benthic reef fish. A question of considerable interest to SBC is the degree to which nutrients control species interactions within each food web. To address this question, we began devising a suite of short and long-term experiments in 2002 to investigate how changes in nitrogen supply influence trophic interactions in the little studied macroalgal/periphyton based food web. The experiments feature a multi-factor design in which nutrients, primary producers (macroalgae, periphyton), and consumers are manipulated and responses in the species composition, numerical abundance, and biomass of different trophic levels are being be followed. We plan to follow these experiments through time to track both short-term (weeks-months) and long-term (years-decades) responses. Much of the work done in 2002 focused on testing various techniques of delivering nutrients to reef benthos, and measuring the response of microalgae and macrofaunal crustacean, polychaete, and molluscan fauna.

In summer 2002, we initiated a long-term press experiment to investigate the main and interactive effects of elevated nutrient supply and sea urchin grazing on benthic community structure at one of our experimental reef sites, Naples Reef (12-13 m water depth). The experiment consists of fourteen 14 m^2 plots, seven of which exclude sea urchins. Three 0.5 m^2 plots were established in the center of each of the 14 m^2 plots and were randomly assigned one of three nutrient treatments (diffuser with nutrients, diffuser without nutrients, and no diffuser). At the beginning of the experiment the species composition, abundance, and biomass of algae and invertebrate fauna of the benthic community were sampled using the same methods employed in the reef community monitoring section described above.

In Fall, 2002, a short-term (i.e. two-week) field experiment was set up to test whether predation by benthic reef fishes alters the species composition and abundance of their primary food (meso-crustacean grazers) under nutrient replete conditions when crustacean grazers are most likely not food limited. This was done by placing artificial algal substrates on nutrient diffusers within and outside of fish exclusion cages. Results from this experiment indicate

Figure II.D.6 Total numbers of crustaceans found on artificial algal substrates in October 2002.



that reef fishes can substantially reduce the abundance of their small crustacean prey (Figure II.D.6), thereby potentially indirectly influencing the standing crop of periphyton upon which the meso-crustaceans graze.

In Winter 2003, another two-week field experiment was set up at Naples Reef to test whether the addition of nutrients, sea urchin grazing, and fish predation interact to influence the standing crop of periphyton, and the assemblage of meso-crustacean grazers that feed on it. While sea urchins do not graze periphyton on benthic algae, they may have indirect effects on periphyton by grazing on larger algae (e.g., kelps) that outcompete periphyton for light. In this experiment, we varied nutrient supply by placing artificial algal substrates on nutrient diffusers with and without time-release fertilizer. Substrates on diffusers with and without fertilizers were placed within and outside of fish exclusion cages in plots with and without sea urchins. In addition to quantifying the abundance and species composition of crustacean grazers, we also measured chlorophyll and phaeophytin on recruitment substrates as a means of quantifying the production of periphyton. Sea urchin grazing had a strong effect on both the total abundance of meso-crustacean grazers (Figure II.D.7a) and the total concentration of chlorophyll and phaeophytin (Figure II.D.7b); numbers of crustaceans and the production of periphyton both were greater in plots grazed by urchins. We did not observe the same top-down effect of fish grazing in this experiment that we observed in the Fall, 2002 experiment. These results suggest that sea urchin grazing can have a positive indirect effect on periphyton (possibly though the reduction of canopy-forming kelps that shade the bottom), which in turn may lead to greater abundances of meso-crustacean grazers. Further experimental work is underway to examine these complex interactions among top-down effects of predation and grazing, and the bottom-up effects of nutrient addition.

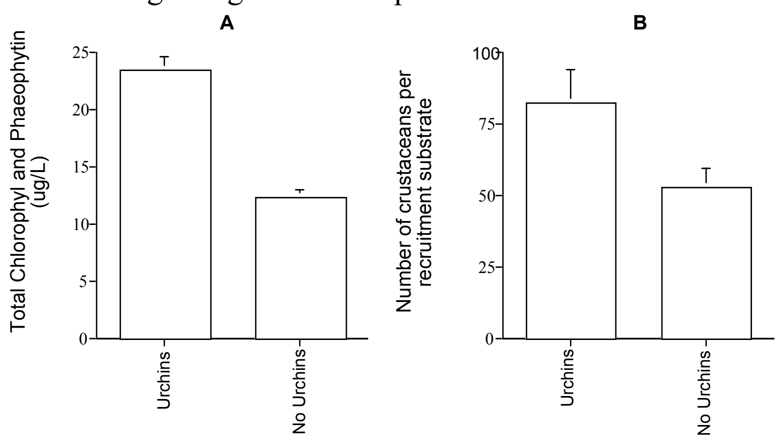


Figure II.D.7. A. total concentration of chlorophyll and phaeophytin measured on recruitment substrates. B. Total numbers of meso-crustacean grazers found on recruitment substrates

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III. Integration and Synthesis

The Santa Barbara Coastal LTER is taking a multi-faceted approach to investigating linkages between kelp forests and neighboring land and ocean ecosystems. Much of our research involves taking integrative measurements on a wide variety of state variables to obtain information on patterns and rates of material exchange, and their effects on community structure and ecosystem function. Short and long-term experiments are used to determine the mechanisms that cause the ecological responses in kelp forest populations, communities, and food webs that are observed in time series measurements. Lastly, static and dynamic modeling of physical and biological process allow us to extend our measurements to larger temporal and spatial scales, aid in predicting responses to environmental change, and provide direction for future research.

Below we describe two areas of research that we are pursuing that examine physical/biological coupling among terrestrial, oceanic and kelp forest ecosystems.

1) The dynamics of nitrogen supply, uptake and production in giant kelp
The goal of this mechanistic modeling effort is to understand the role of N limitation in structuring kelp forest communities both from the perspective of kelp in modifying the physical environment, and from the perspective of the varying quality of kelp as food for reef inhabitants. Nitrogen is the most limiting nutrient for *Macrocystis pyrifera*. N-stressed giant kelp plants have fronds largely denuded of blades dramatically altering the physical structure of the habitat, and low rates of frond initiation that eventually lead thinning canopy cover and loss of productivity. During the first three years of our project we have been identifying and quantifying mechanisms of nitrate delivery to the kelp forest (see section II. C. above). We have begun to relate nitrate supply to the physiological status of giant kelp (Figure II.C.9) but a mechanistic understanding that relates changes in N supply to giant kelp production, nutrient uptake and growth require a more integrated approach. SBC LTER investigators Dave Siegel, Erika McPhee-Shaw, Dan Reed, Mark Brzezinski and Dick Zimmerman have been working towards developing a biophysical model of the response of giant kelp to shifting N supply driven by a variety of physical supply mechanisms (see Table II.C.1). The model will simulate kelp nitrate uptake in response to changes in nitrate supply using uptake kinetics of kelp for nitrate and our developing understanding of the loss terms affecting kelp stocks. During summer months, useful nitrate are restricted to deep regions of the kelp forest (see ocean section). Thus, translocation of N from subsurface portions of fronds to the surface canopy where light levels are sufficient to drive nitrate assimilation represents a potentially important but unverified pathway for maintaining productivity.

We will continue to collect the data required to parameterize the kelp N model. Additional work on the physical processes delivering nitrate to the reef are required. Our flow data show the importance of current reversals and high frequency intrusions of deep water for kelp N delivery (e.g. tidally driven internal waves), but our understanding of the physics driving these processes is presently inadequate to construct predictive models. Through an ONR DURIP grant we will purchase additional moored nitrate sensors allowing us to obtain unbroken time series of nitrate concentration at a single site, to sample multiple sites simultaneously, or to deploy multiple sensors at a given site. This capability will facilitate better understanding of the N delivery mechanisms, especially during storm events when temperature is a poor proxy for nitrate concentration. We have also purchased an optical nitrate sensor using DURIP funds to be fitted to the towed platform deployed on our thrice yearly basin wide surveys. This will allow a detailed 3D view of the nitrate field in the basin and its relationship to physical structure and currents. Additional physiological studies on giant kelp are planned to help parameterize the physiological component of the biophysical model. Within the kelp forest we plan more detailed analysis of kelp nitrogen metabolism including better assessment of uptake rates, translocation and the coupling of kelp primary production (C production) and N production as our preliminary data indicate a strong decoupling between C and N metabolism during summer when nitrate supply is low.

2) The incorporation of land and ocean carbon and nitrogen subsidies into kelp forest food webs: evaluation using stable isotopes

We are exploring the use of stable carbon and nitrogen isotopes to investigate linkages between the kelp forest food webs and those of neighboring land and coastal oceanic ecosystems. Stable isotope analysis is a powerful tool that can potentially identify dietary sources because of the similarity between the isotopic composition of a consumer and its diet. The carbon isotope value (expressed as $\delta^{13}C$) of a consumer closely reflects the value of dietary carbon, while the stable nitrogen isotope value (expressed as $\delta^{15}N$) is typically enriched in ^{15}N from 3 to 4 $^{o}/_{oo}$ relative to dietary nitrogen. Important sources of carbon and nitrogen to primary consumers on shallow subtidal reefs include phytoplankton, macroalgal-derived detritus, and for locations adjacent to sources of freshwater runoff, terrestrially-derived particulate organic material (POM).

The application of stable isotope analysis to identify sources of carbon and nitrogen can be constrained by the presence of multiple food sources, source isotope values that overlap, and spatial and temporal variation in source values. To address these issues, our research to date has focused on characterizing temporal and spatial variability in the isotope values of phytoplankton, kelp, and stream-derived POM to evaluate whether these values differ enough from one another to permit the use of mixing models to estimate the contribution of each source to the reef food web. In addition, Roger Nisbet, John Allen, and Mark Page are developing a model of nitrogen isotope dynamics during the growth of an individual using dynamic energy budget theory. Model parameters include the isotope ratio in the food of the organism as well as the isotope ratio of the organism. The model is being developed with funding from EPA to aid in determining the mechanisms that lead to nitrogen-15 enrichment with increasing trophic position in California wetlands. This work should assist us in constructing nutrient-driven food web models of reef communities.

Preliminary data are encouraging in showing separation in the isotope values of terrestrially derived POM in storm runoff (~-26$^{o}/_{oo}$) and kelp (~-12.4 $^{o}/_{oo}$). Marine POM consists of a mix of phytoplankton, macroalgal detritus, terrestrially-derived POM, and other material (Figure III.1). Our data also show separation in the values for marine POM and kelp during much of the year, although overlap occurs between these values in the fall. The fall months are periods of low phytoplankton standing stock, and marine POM values may reflect a predominance of sources other than phytoplankton. To investigate sources of variability in values of marine POM, including contributions from phytoplankton, kelp detritus and terrestrial inputs, we are collecting samples of POM further offshore, at locations less likely to be influenced by inputs from kelp or terrestrial runoff and more likely to reflect a primarily phytoplankton source. We will continue to collect and analyze samples of these source materials to extend our data set.

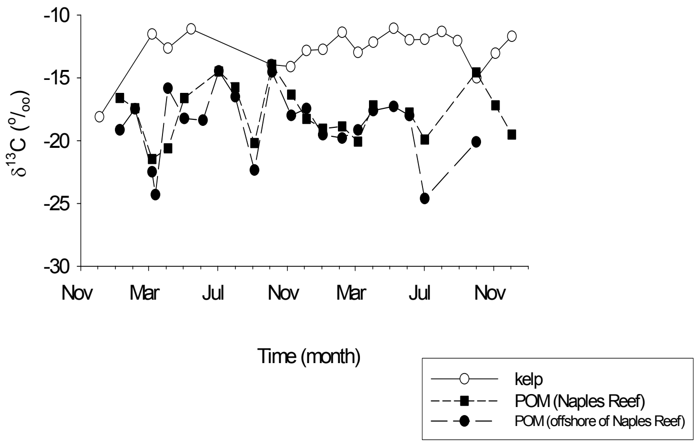

Figure III.1. $\delta^{13}C$ values for the giant kelp, *Macrocystis pyrifera*, and marine POM sampled on and offshore of Naples Reef.

To identify food sources used by reef consumers under different conditions of runoff, ocean climate and kelp production, we have begun sampling a variety of reef consumers chosen to represent different trophic levels. Tissue samples were collected in April, 2002 from the same species of consumers at four reef sites (Carpinteria, Naples, Mohawk, Arroyo Quemada), which vary in their proximity to sources of runoff and in their standing stock of giant kelp. The $\delta^{13}C$ values of these consumers at all sites reflected marine rather than terrestrial sources of carbon with values of the filter-feeding tunicate, *Stylea*, similar to values for offshore marine POM and values for the sea urchin, *Strongylocentrotus*, similar to values for kelp, the preferred food of this genus (Figure III.2). Values of other taxa were between these two extremes, suggesting that both phytoplankton and macroalgal-derived carbon contributed to the diet of these consumers. Similar tissue samples were collected from the same sites in April 2003, which followed a winter that had above average rainfall. These samples are currently being analyzed. We anticipate collecting similar samples in future years to take advantage of natural variation in rainfall and kelp standing crop.

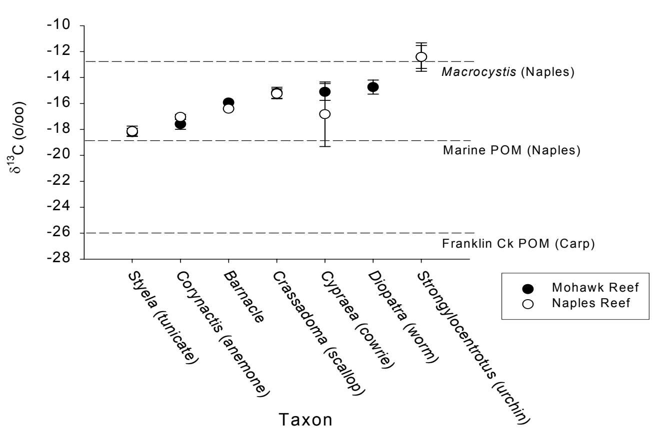

Figure III.2. $\delta^{13}C$ values for common invertebrate consumers from Naples and Mohawk Reefs together with mean values (dotted lines) for the giant kelp, *Macrocystis*, offshore POM from Naples Reef, and POM values from Franklin Creek (1997-98). Consumer data from samples collected in March 2000. Mean values 1±SD, n=5.

We are also collaborating with the Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO) on experiments that use small mussels transplanted to strategic locations to evaluate the effects of runoff, ocean climate, and kelp production on the sources of carbon and nitrogen used by reef consumers. Experimental populations of small mussels (*Mytilus californianus*) will be deployed to the LTER moorings located at Carpinteria, Naples, and Arroyo Quemado. Carpinteria and Arroyo Quemado are close to a runoff source while Naples Reef is less influenced by runoff. Mussels will also be transplanted to existing PISCO mooring sites north of Pt. Conception (Jalama, Purisima, and Pt. Sal) where upwelling and phytoplankton production are quite high relative to that in the Santa Barbara Channel. Small mussels grow rapidly, providing sufficient tissue increase, and thus carbon and nitrogen turnover, to reflect local dietary sources of POM. To investigate possible temporal changes in the importance of food sources to reef consumers, mussels will be transplanted during periods of lowest (August) and highest (December to March) terrestrial runoff.

IV. LTER Network-Level Activities and Cross-Site Research

During its first three years SBC has had a visible presence in network-level functions. Three SBC investigators (Brzezinski, Cooper and Melack) participated in the Comparative Aquatic Research Workshop held in Salt Lake City in February 2000. The major purpose of this meeting was to identify aquatic topics of broad interest to the network. Modeling watershed biogeochemistry was one of four topics identified and John Melack and Tom Dunne organized a workshop on this at the 2000 LTER All Scientists Meetings. As Principal Investigator, Dan Reed is a member of the LTER Coordinating Committee and attends the semi-annual meetings. He also serves on a sub-committee to develop a joint ERF-LTER session at the 2003 All Scientists meetings, which will include two presentations from SBC investigators. SBC has been active in information management at the network level through its participation in Climb-DB, Hydro-DB, and the Global Fiducial Library. Archived climatological and hydrological data from SBC have been linked to Climb-DB and Hydro-DB web harvesters, and are easily accessed via SBC's website. In November 2001, SBC organized and sponsored a symposium titled "The effects of human activities on ecosystems at the land/ocean margin" for the annual meetings of the Western Society of Naturalists. The symposium was attended by more than 400 people (scientists, students, and the general public) and featured LTER and non-LTER speakers from all over the continental US and Hawaii.

In collaboration with investigators from other LTER sites, SBC investigators Melack and Schimel have obtained LTER network funds to conduct a cross-site investigation on the role of organic nitrogen in the N cycle. Samples are being collected from several LTER sites, including Hubbard Brook, Plum Island, Luquillo, Santa Barbara, Niwot Ridge, Baltimore, HJ Andrews, McMurdo Dry Valley, Toolik Lake, and Bonanza Creek, as well as an alpine non LTER site (Emerald Lake, California). The purpose of this research is to quantify the importance of DON inputs and outputs at the watershed scale in an effort to: 1) compare DON dynamics in a diverse array of watersheds in order to suggest determinants of observed patterns; 2) explore the relationships between physical and biological characteristics of streams and their watersheds (topography, soil standing stocks of C and N); and 3) reveal deficiencies in the available data on DON dynamics at the watershed scale. Results from this research should provide guidance to the LTER network on methods for DON sample collection and analysis.

LTER investigators from SBC and PAL have been actively planning cross-site research to compare pelagic food web structure in the SBC and off the Antarctic Peninsula. Planning currently involves Robin Ross and Langdon Quetin from PAL and David Siegel, Libe Washburn, Craig Carlson and Mark Brzezinski from SBC. Discussions are currently focused on comparative studies of the role of euphausiids (*Euphausia superba* in the Antarctic and *E. pacifica* in the SBC) in the pelagic food webs and of the partitioning of carbon fixed by phytoplankton between the particulate and dissolved pools of organic carbon.

Many of SBC's cross-site activities come by way of collaborations with projects outside of the LTER network (see Appendix III. Collaborative Projects). SBC has formed a very close collaboration with the Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO), a large-scale interdisciplinary marine science research program funded by the David and Lucile Packard Foundation (http://www.piscoweb.org). PISCO is a collaboration of scientists from four west coast universities (Oregon State, UC Santa Cruz, Stanford, and UCSB), and its research mission is to advance the understanding of large scale ecosystem dynamics of the U.S. West Coast. PISCO's research at UCSB is tightly linked with the Santa Barbara LTER, and there is considerable sharing of resources and data in studies pertaining to physical, chemical, and biological oceanography, and informatics. PISCO also provides a larger scale context within which the more intensively local studies of SBC can be grounded, and brings a strong focus on the input of larval recruitment to reef populations, another population subsidy that complements the focal subsidies of SBC. Another important collaboration formed by SBC is with the NASA-funded Plumes and Blooms project (PnB), which investigates marine plankton blooms associated with runoff (http://www.icess.ucsb.edu/PnB/PnB.html). The goal of this project is to develop new satellite ocean color algorithms to use in coastal waters influenced by terrigenous materials (sediments, dissolved organic materials, etc.). SBC and PnB have broad overlapping interests and engage in considerable sharing of data, personnel, and ship time.

V. Information Management

Objectives
The primary objective of the SBC LTER information management (IM) team is to facilitate current and future research and outreach efforts at SBC by means of providing readily accessible and robust software and hardware systems. The IM team has implemented a number of underlying services, with a focus on data organization and integrity, ease of access, and long-term preservation of the SBC data archive and its accompanying documentation. Likewise, the IM team is committed to supporting communication among the SBC LTER, its partner institutions, outside agencies, and members of the public with an interest in the stewardship of the land-ocean margin along the Santa Barbara coast.

Facilities and Operation
The SBC LTER consists of multiple researchers with diverse, discipline-specific backgrounds. It has been important for the IM team to implement systems in an open, cross-platform fashion that is largely based on Internet standards rather than vendor-specific technologies. The information management approach has been to leverage existing systems where possible, and build subsequent systems with a focus on collaboration and interoperability, which reduces total implementation costs and fosters communication. The SBC LTER leverages the UC Santa Barbara campus network infrastructure, and expertise from the National Center for Ecological Analysis and Synthesis (NCEAS), the Institute for Computational Earth Systems Science (ICESS), and the Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO). PISCO has provided the server-side software and hardware systems to support the SBC LTER information management program.

The UCSB research network infrastructure consists of a 1 Gigabit switched Ethernet backbone that connects departments and laboratories on campus. The Marine Science Institute (MSI), ICESS, NCEAS, and the Life Sciences network internally maintain 100 Megabit switched Ethernet networks for individual workstation connections. The SBC LTER server is a dual processor IBM Netfinity 6000R running Redhat Linux. The server is equipped with 1.5 Gigabytes of physical memory, redundant power supplies, and an external uninterruptible power supply to protect the server from power outages and surges. The total disk storage is 0.5 Terabytes in both internal and external enclosures. The U160 SCSI disks are configured as a RAID 5 array, which includes a hot swap failover disk. The backup system consists of a 14 slot IBM 1/2" DLT tape auto-changer. A dual processor Dell Precision workstation running the same Redhat Linux setup acts as a development server and emergency fileserver replacement. The backup schedule follows a daily (level 9) and weekly (level 5) incremental scheme, with a (level 0) entire system backup once each month. The servers are configured with firewall and intrusion detection software to safeguard against internet-based exploits. The servers support Macintosh, Windows, and Linux/Unix client connections over HTTP, SMB, Appletalk, and SSH protocols.

Approach
The SBC LTER has adopted the simple practice of using ASCII text for long-term data table and metadata storage, with the exception of original binary formats such as raster images. Each major research group (identified by land, ocean, and reef) is responsible for the implementation of the discipline-specific protocols in data collection, as directed by the lead principal investigators for that group. The IM team consists of a liaison from each research group (Ed Beighley – land, Margaret O'Brien – ocean, Bryn Evans – reef), and the Information Manager (Wei-Yee Luan). This team works in close collaboration with PISCO's Information Systems Coordinator (Christopher Jones), and Systems and Network Administrator (Jim Woods) to implement the data handling protocols as data flow from the field and directly onto the SBC LTER fileserver. Figure V.1 shows how data from field instruments and manually collected data sheets are first downloaded or entered on local workstations, and are immediately copied to the fileserver for archive and backup. The server is accessed via a web client, Windows SMB client, an Appletalk client, or via command line or graphical SSH clients. Data are initially stored in 'internal' (SBC only) working folders and are processed according to QA/QC protocols as specified by the land, ocean, and reef groups. Once processed, they are copied to 'internal' final folders, where the data are used in analyses (see Figure V.2). From this point, they are ingested into a desktop data management application called Morpho, which is being developed at NCEAS. The data are documented in the Ecological Metadata Language, which is a simple yet comprehensive, text-based metadata syntax implemented in XML (an Internet-standard markup language). Once documented in Morpho, the data/metadata packages are uploaded into the SBC LTER data catalog. Certain documents, such as protocol manuals that are too large to convert to EML at the moment, are placed in 'external' final working folders that are accessible via the SBC LTER web page (http://sbc.lternet.edu/), and are referenced from within the EML data packages.

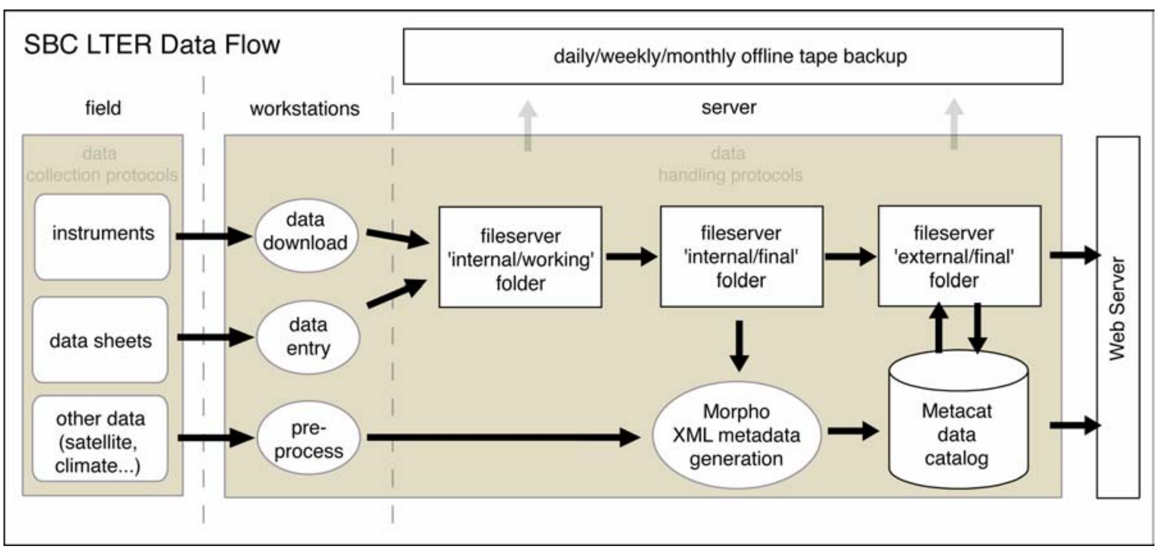

Figure V.1. Flow of SBC LTER data from field sampling and other publicly accessible data sources, to the SBC LTER server and data catalog, where data and metadata are accessed via the web site.

Data that are used in SBC analyses, but that are not directly collected by SBC researchers, such as publicly available remote sensing data, GIS layers, images, etc., are pre-processed for SBC use, and the products are documented in the data catalog along with the other primary datasets. URL pointers to the original data are included in the documentation of these data sources.

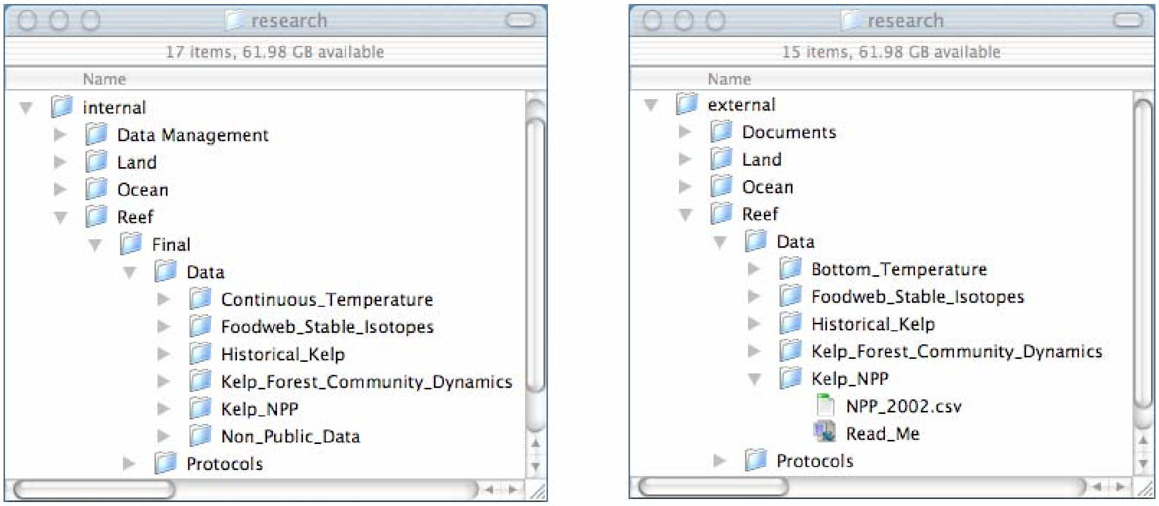

Figure V.2. Examples of the 'internal' and 'external' folders for each SBC research group.

The SBC data catalog is a web-based server that responds to HTTP and HTTPS requests, and is able to store both data and XML-based metadata. The server software is actively being developed at NCEAS, and is generously provided to help research stations develop, store, and serve rich, structured metadata and data for both human consumption, and more advanced machine processing and analyses. Figure V.3 shows the interaction between the web and/or desktop-based clients and the Metacat server, which is implemented as a java servlet that dispatches various requests to the software subsystems. The subsystems comprise of a series of java classes that perform discrete tasks, such as querying, inserting, updating, and deleting records in the SQL database, where the metadata are stored. The system is built in a modular manner, such that back-end database technologies may be swapped out. For instance, the SBC Personnel Directory, which stores user account information, email addresses, etc., is used to authenticate users when they log into the database. This LDAP database could be replaced in the future as directory technologies advance. Likewise, a web-accessible portion of the Linux file system is used for the storage of actual data entities, but in the future may be augmented by additional storage from an SQL database adapter.

One of the immediate advantages of storing EML metadata in the catalog comes from the ease of transformation into web pages that are viewable on the SBC site. SBC uses the built-in XSLT processor in the metadata catalog to provide customized web pages that expose the contents of the data catalog to the public (see http://sbc.lternet.edu/data). The replication subsystem will also be utilized to synchronize SBC data packages with the LTER Network office in order to participate in projects involving network-wide synthesis.

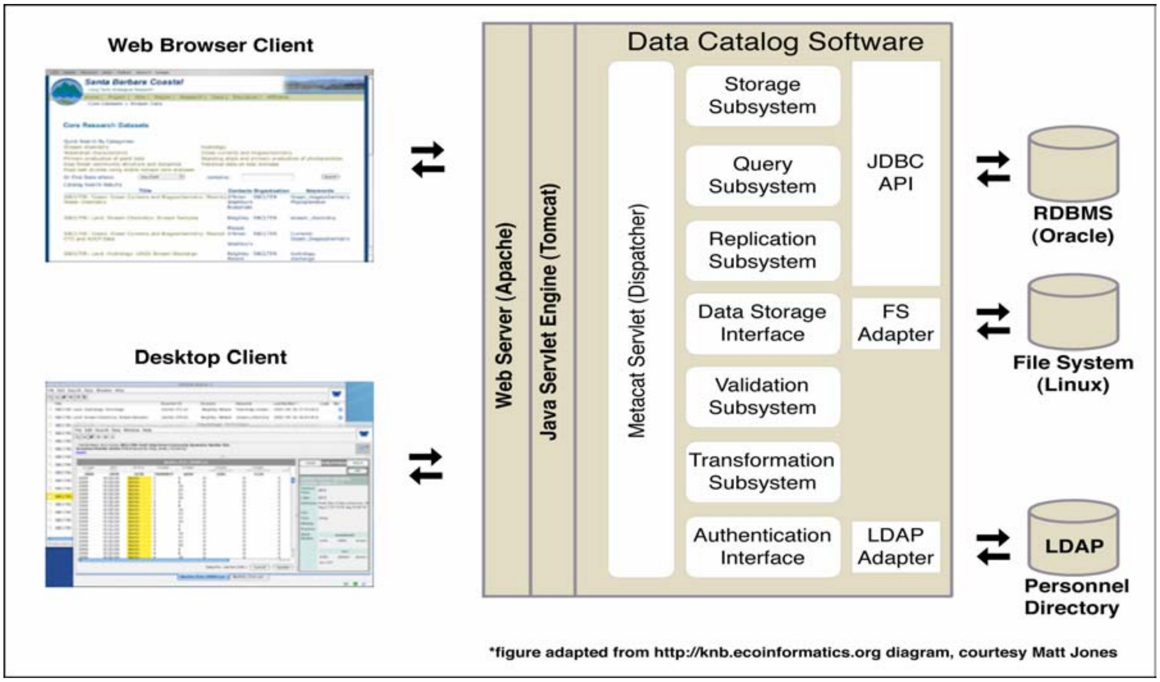

Figure V.3. A schematic diagram showing web browser and desktop (Morpho) access to the data catalog software. The data catalog servlet acts as a dispatcher for requests going to backend data, metadata, and authentication databases.

Future directions

The next steps in SBC information management will involve greater use of the XML metadata that are already developed. Currently, SBC generates the 2.0.0beta6 version of EML, and will soon transition to the 2.0.0 version. During the transition, the data packages will be enhanced in order to enable semi-automated processing of the SBC data sets via the metadata descriptions. This will involve the integration of an EML analysis tool called Monarch, which is also being developed at NCEAS. Such a tool will help integrate SBC data across the disciplinary boundaries, while using common analytical environments (e.g., SAS, Matlab, etc.) for the processing. We also intend to integrate the spatial research at SBC into the metadata framework in order to enable researchers to explore the biological and physical couplings found in the coastal datasets. To enhance the efficiency of data collection/entry and reduce transcription errors, we are working closely with the NSF funded Jalama project, a joint effort of NCEAS, PISCO, and SBC scientists and data managers. The Jalama project is developing a general solution for collecting data using handheld computers in the field that is integrally linked to the larger NCEAS metadata database effort. This program includes software development for both handhelds and desktop applications that will allow researchers to create easily customized data entry forms for any specialized research project. The fruits of this effort will allow environmental researchers to readily sync data to the larger data catalog from handheld computers without intermediate steps. SBC LTER will be a future test bed of this technology. Lastly, SBC participates in the Data Table of Contents (DTOC), and the HydroDB and ClimbDB projects by providing static URLs for the harvesters. Future work will allow us to generate these products from the data catalog, which will help keep the content up to date.

VI. Site Management

Management of the Santa Barbara Coastal LTER entails project governance, project resource acquisition and allocation, agency, university and public relations, and day-to-day operations. As lead investigator, Dan Reed serves as the project's primary point of contact with NSF, the LTER Network, and campus administrative units. He is responsible for the day to day operations of the project, and in overseeing the implementation of all its components. A halftime Research and Education Coordinator (Jenny Dugan) assists the lead PI in the day-to- day operations and supervises the project's education and outreach activities, including SBC's web site. Research direction, strategic planning of major tasks, initiatives, policies, and the acquisition and allocation of project resources are decided on by consensus by an Executive Committee of project investigators. The nine member Executive Committee meets biweekly and its members are chosen to insure an equal representation of the three major research groups: land (John Melack, Josh Schimel, and Trish Holden), reef (Sally Holbrook, Steve Gaines and Dan Reed), and ocean (Mark Brzezinski, Dave Siegel, and Libe Washburn). The minutes of all Executive Committee meetings are made available to all SBC participants via email, and are archived on the SBC LTER internal server.

Research and resource allocation at SBC are structured around the three major programmatic areas: watersheds, shallow rocky reefs, and the coastal ocean; research in a fourth area (marshes and sandy beaches) is being done largely in collaboration with other projects using non-LTER funds. Project funds are allocated annually to each of the three research groups, and specific decisions on research priorities, staffing and expenditures within each group are made internally. The general direction of research in each programmatic area is set by the Executive Committee.

Information transfer among researchers in the different programmatic areas is an ongoing activity of the Santa Barbara Coastal LTER. Much of SBC research is very interdisciplinary, and requires frequent communication and collaboration among investigators and students with different science backgrounds. This exchange of ideas and expertise is facilitated by the fact that all but one of the 29 investigators affiliated with SBC reside at UCSB, which permits frequent in-person discussions among investigators, post docs, students and support staff. The SBC web site and server serve as important vehicles for sharing project-related information, data, and documents. Additional cross-disciplinary interactions occur via the SBC LTER graduate seminar course, and the annual all-day SBC retreat for all SBC participants and collaborating partners. The focus of the retreat is typically on synthesis and integration of the disparate types of SBC data.

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VII. Education & Outreach

Education

Education and training are tightly integrated into all aspects of Santa Barbara Coastal LTER research. Four post docs, 25 graduate students, five REU students, and more than 33 additional undergraduate students participated in SBC research during its first three years. In addition to gaining valuable research experience, many of the undergraduate students earned academic credit or received monetary compensation. One of our past REU students is Hispanic and recently graduated from UCSB with a degree in biology. He continued to work on our project as a research technician, and was accepted into the graduate program at Columbia University beginning spring 2003. Several of our undergraduate students (Cherlyn Seruto, Kristin Green, and Lea Ow) have received awards to pursue independent studies associated with SBC research activities. Cherlyn is now in a graduate program at UC Irvine. Our project's research also finds its way into the classroom as SBC investigators routinely incorporate activities and findings of SBC-sponsored research into their teaching, thereby extending the project's contributions to the broader student body. Educational opportunities at SBC are not limited to university students and post docs. Two pre-college teachers and several non-scientists from the local community routinely participate in our ongoing stream sampling program and gain considerable knowledge of the constituents of runoff and of the processes that influence their abundance.

The Santa Barbara Coastal LTER has jointly developed a graduate student training program with three other existing programs on the UCSB campus: the Center for Estuarine Indicator Ecosystem Research (CEIER) funded by U.S. Environmental Protection Agency, the UC Coastal Toxicology Program funded by University of California, and the Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO) funded by the Packard Foundation. This program emphasizes interdisciplinary research to examine how coastal ecosystems change in response to natural and human-induced alternations in the environment, and seeks to create a diverse scientific community of students that have a respect and appreciation for other disciplines. The program includes graduate students and four postdoctoral fellows, whose research interests span terrestrial, aquatic, and marine ecology, physiology, geology, oceanography, and policy. Students and postdoctoral fellows in the training program participate in a quarter-long graduate seminar at UCSB, present posters on their research at an annual UC Toxic Substances Research and Teaching Program Symposium and attend the Annual Coastal Toxicology Retreat at the Bodega Marine Laboratories to discuss research integration among faculty and graduate students. Many of the participants in this program also enroll in a week long interdisciplinary short course on eco-toxicological research, which is offered annually at Bodega Marine Laboratories. In addition, students, postdoctoral fellows, and Senior Investigators participate in an Annual SBC-LTER Science Meeting, where results from SBC research are presented.

Outreach

Increased exposure to SBC's research comes by way of collaborative educational efforts with two existing outreach programs: the South Coast Watershed Resource Center and

UCSB's *Oceans into the Classroom Program*. These two programs offer K-12 students, teachers, and the general public the opportunity to connect local environmental issues with basic principles of science education for a lifetime of learning. A main focus of these two programs is to engage K-12 teachers in watershed and marine science, and aid them in developing curricula based on research by SBC and other research entities that can be integrated into their lesson plans. The South Coast Watershed Resource Center (SCWRC) is located at the mouth of the Arroyo Burro Creek (a study site of SBC). Its mission is to develop sets of educational tools and resources aimed at informing the public about: (1) the importance of our watershed resources, (2) the connections between watersheds and coastal ocean ecosystems, (3) how these resources are impacted by human activities, (4) the role watershed restoration plays in improving water quality, and, (5) ways that the community can actively protect our creeks, wetlands, and ocean. SCWRC opened its doors in August 2001, and has since provided education programs for numerous elementary schools, organized public workshops on a variety of environmental issues, and hosted numerous meetings and tours for a wide variety of non-profit environmental awareness groups. SBC researchers worked with SCWRC staff to develop displays depicting ongoing research in the watersheds and nearshore waters in the Santa Barbara area. Schoolyard funds supplied by NSF have been used to purchase start-up equipment for the school programs as well as the production of student journals that were used by all the students who participated in the programs.

In 2002 the main focus of the SBC's Schoolyard program was the development of an interactive computer animation model of the Arroyo Burro watershed, which empties into the ocean at the site of SCWRC.. The computer animation model provides an interactive tool for 4-8th grade students, instructors, and the general public using SCWRC. The animation model, which is available on-line through SBC LTER's website (http://sbc.lternet.edu/education/index.html), has three main components: 1) an animated fly over tour of the Arroyo Burro watershed that introduces the user to the various habitats, ecosystems and land uses in the watershed; 2) a more detailed natural history guide of the Arroyo Burro watershed complete with photos and text that describe the ways in which land use alters the natural ecosystems found in the catchment, and 3) an interactive animated water surface response of Arroyo Burro Creek as it flows by the SCWRC that allows the user to alter various land use and rainfall configurations. The animation program provides an interactive educational tool that emphasizes both the spatial distribution of the various ecosystems and land uses within the Arroyo Burro watershed, and the effects of land use change on flooding. Extending the animation program to include plumes of terrestrial runoff in the ocean and their effects on ocean productivity are the focus of SBC's 2003 Schoolyard project.

SBC is expanding its outreach efforts to better engage students and teachers in its marine research by partnering with UCSB Marine Science Institute's *Oceans into the Classroom* program. This program offers educational research cruise experience for 6th -8th-graders aboard the 75' vessel Condor Express. Working under the direction of MSI professional staff and UCSB students, 6th -8th graders and their teachers conduct oceanographic research in the Santa Barbara Channel that is related to ongoing research at UCSB. Plans are underway to develop one of the six shipboard research stations with a focus that engages students and teachers in SBC LTER research. Each of the six stations builds on State Science Standards to introduce students and teachers to critical issues in marine science.

Listed below are other outreach activities that SBC has participated in.

The JASON PROJECT (http://www.jason.org/jason14/home) is a multi-disciplinary educational program that sparks the imagination of students and enhances the classroom experience by developing and supporting curricula that enable students and their teachers to do field work from the classroom and exposes students to leading scientists and their research as they examine basic biological and geological questions. SBC-LTER investigators worked with the JASON PROJECT in the development of *JASON XIV: From Shore to Sea,* which is now available for school year 2002-03. In this new program, the JASON team explores the terrestrial and marine ecosystems that extend from California's coast to the Channel Islands Marine Sanctuary.

SBC played host to Eagle Scout Tim Brox, selected by NSF's Polar Programs to visit US research stations in Antarctica. A cross-site LTER outreach effort (in conjunction with the Palmer Station LTER) introduced Tim to ongoing studies at the SBC LTER and emphasized the value of long-term research efforts.

Dan Reed served as a science and technical advisor for *Waves, Wetlands, and Watersheds*, a classroom-based hands-on science activity guide that integrates California Coastal Commission areas of critical concern (wetlands, coastal processes, marine debris and pollution, and endangered species) with California Science Content Standards for grades three through eight (www.coastforyou.org).

Tim Robinson, a SBC graduate student doing his dissertation research in the Carpinteria watershed, is an active participant in the Carpinteria Creek Watershed Coalition, whose mission is to restore and preserve Carpinteria Creek sufficiently to reestablish a steelhead run (steelhead is an endangered species in California). The Coalition has become a hallmark for community-led watershed planning and restoration efforts in southern California. It has obtained over $500,000 in grant funding to develop a watershed plan, remove fish barriers and do public outreach. Tim coordinates a bi-monthly column in the local newspaper (The Carpinteria Coastal View) entitled “In the Watershed”, where farmers, citizens, researchers, agency representatives and regulators can express their interests in watershed management. To date, six SBC scientists have contributed articles about their research for the column.

Jenny Dugan, the SBC-LTER science and outreach coordinator, gave seminars on sandy beach ecology and participated in a 3-day workshop with high school teachers and marine educators for LiMPETS (Long-term Monitoring Program and Experiential Training for Students) funded by the NOAA’s National Marine Sanctuary program in March 2003. She is also working with the Santa Barbara Museum of Natural History on the design and content of new exhibits about sandy beaches in the Sea Center in Santa Barbara.

Many SBC investigators and students routinely give lectures in local K-12 schools on LTER related topics (e.g. kelp forest ecology, sandy beach ecology, watershed processes, ocean circulation, etc.). In addition to these many lectures, SBC post doc Erika McPhee-Shaw co-taught a classroom project through the "Kids do Ecology" program, which is run through NCEAS, and has some direct ties with Los Marineros http://www.nceas.ucsb.edu/nceas-web/kids/main_pages/classweb.htm. Additional outreach activities done by SBC investigators include: a segment on live TV for Project Oceanography (http://www.marine.usf.edu/pjocean/) on SBC research in the Santa Barbara Channel, a radio broadcast on beach grooming impacts for the "Ocean Report" http://www.seaweb.org/campaigns/OR2000.html, assisting the Channel Islands Marine Sanctuary in developing curriculum on associations between terrestrial runoff and phytoplankton blooms, and giving a number of public presentations on SBC LTER related research to non-scientist groups each year.

VIII. Broader Impacts

SBC investigators have been very active in applying their knowledge of Santa Barbara's coastal ecosystems to implement changes in local and regional policies.

The Channel Islands National Marine Sanctuary (NOAA) and the California Department of Fish and Game have developed a joint state and federal process to consider marine reserves in the Channel Islands National Marine Sanctuary (http://www.cinms.nos.noaa.gov/nmpreserves.html). This joint federal and state process stems from a shared concern for sustaining California's marine resources, as well as areas of overlapping and complementary jurisdiction. The public process is based on both extensive stakeholder input and the best available science. A Science Panel was formed to assimilate, analyze and interpret all scientific data pertinent to the process. Seven of the 15-member Science Panel are senior investigators associated with SBC. Many of the recommendations made by the Science Panel were based, in part, on first-hand knowledge obtained by SBC investigators. Relying heavily on information compiled by the Science Panel, the California Fish and Game Commission voted to implement a network of no-take marine reserves in the Channel Islands that went into effect on April 9, 2003. The marine reserve network at the Channel Islands is one of the largest in the world. The process of establishing marine reserves in California is ongoing through the Marine Life Protection Act. SBC investigators are continuing to play an important and active role in working with state and federal agencies on these issues. One (Gaines) is a member of the state-wide Master Planning Team; another (Warner) is the science representative for the regional working group focusing on the Santa Barbara Channel.

Santa Barbara Channel has a long history of oil and gas development. Many of the platforms in the channel are nearing the end of their operating lives and there is much controversy over whether decommissioned platforms should be dismantled and removed, or abandoned in place to serve as artificial reefs for fish and other reef-associated organisms. Co-PI Holbrook chaired the UC Marine Council committee that wrote a report commissioned by the California State Legislature on scientific issues related to decommissioning California oil platforms. She and other committee members drew upon their knowledge of reef ecosystems in the Santa Barbara Channel and evaluated all other existing information on issues relating to production on artificial and natural reefs. The report was released in fall 2000, and can be found at http://www.ucop.edu/research/ucmc_decommissioning/.

With additional funding from the Minerals Management Service (MMS), SBC researchers (Page, Dugan, and Lenihan) are investigating the quality of offshore platforms as reef habitat. This research includes a comparison of indices of ecological performance (e.g., size, individual growth, and production) of selected fishes and their invertebrate prey between platforms and natural reefs over time. Two natural reefs selected for the MMS-sponsored project are also SBC study sites. Comparable methods of data collection and analyses between the MMS sponsored project and SBC allow for a more regional perspective of the role and relative contribution of platforms to the ecology of shallow reefs. Information on this topic is currently lacking, yet it is of critical importance to policy makers charged with determining the fate of decommissioned platforms.

SBC research is playing a prominent role in shaping policy aimed at local watershed issues as well. We have developed mutually beneficial, cooperative associations with local government 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 and they share data and interpretations. To further communication with Project Clean Water, we attend their monthly stakeholder meetings, and have given public presentations of our results in that forum. The City of Santa Barbara recently obtained special funding through a voter-approved tax increase to reduce polluted runoff that has resulted in beach closures. Two of our intensive catchments (Mission and Arroyo Burro) are within the city, and we are working with city staff to help them plan their restoration efforts. The Santa Barbara Land Trust has purchased the lower half of the Arroyo Hondo catchment, a parcel owned for generations by a couple of families and only slightly altered; the upper portion is administered by the US Forest Service as natural watershed. As part of a UCSB Bren School's Masters of Environmental Science and Management thesis project, we developed a natural resources management plan for the Land Trust. Further, the catchment is one of the sites that we sample intensively, and we will continue to provide useful information to the Land Trust as they protect and manage the property. The Santa Barbara Channel Keepers conduct monthly collections along the Ventura River, and we participate in this field work and complement their in situ measurements with high quality nutrient chemistry. Co-PI Melack serves on Common Ground, a stakeholder group formulating plans for long-term preservation and economic viability for the Gaviota coast. SBC graduate student Tim Robinson serves on the Technical Advisory Committee to the Santa Barbara County Task Force, Southern California Wetlands Recovery Project.

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