SBC LTER Annual report Year 4, 2021-2022

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Accomplishments

* What are the major goals of the project?

The Santa Barbara Coastal LTER (SBC LTER) is an interdisciplinary research and education program established in April 2000 with the goal of developing a predictive understanding of how environmental drivers interact with terrestrial and oceanic processes to alter material flows and influence the ecology of coastal ecosystems. SBC LTER's principal study domain is the semi-arid coast and nearshore waters of the Santa Barbara Channel in southern California, and its diverse and productive marine forests of giant kelp (Macrocystis pyrifera) serve as the focal study ecosystem. Analyses of our long-term data have identified many of the environmental drivers and ecological processes underlying the production and community dynamics of kelp forests. Still to be determined are the ecosystem consequences of wave disturbance and fishing that alter the area and architecture of giant kelp forests, the processes that sustain kelp growth during warm, low nitrate conditions, the ecological and evolutionary consequences of kelp-induced changes in pH and dissolved oxygen, and the degree to which climate variability

influences forest persistence and trophic subsidies to and from kelp forests. These and other unknowns form the basis of the overarching question that motivates our proposed research: "How do natural and human drivers influence giant kelp dynamics and alter the long-term structure and function of kelp forest ecosystems?". The research proposed to address this question is integrated in a conceptual framework that focuses on the causes and ecological consequences of the dynamics of a relatively short-lived foundation species in a setting of long-term climate change and human use, and is organized in three inter-related themes:

Theme 1 - Environmental drivers of kelp persistence and community structure

Theme 2 - Dynamic biophysical coupling in kelp forest ecosystems

Theme 3 - Spatial dynamics and connectivity of kelp forests and adjacent ecosystems.

* What was accomplished under these goals and objectives (you must provide information for at least one of the 4 categories below)?

Major Activities:

Theme 1. Environmental drivers of kelp persistence and community structure

Theme 1a. *Community and ecosystem consequences of climate variability, disturbance and pathways of recovery*

Last year we initiated a finer-scale long-term experiment to quantify the role of competition for space as a key process governing community structure and recovery in kelp forests. The experiment is designed to measure the effects of giant kelp in mediating competition between sessile invertebrates and understory macroalgae at 10 kelp forest sites using paired circular plots (8 m radius) of two treatments: kelp removal and control. Smaller paired plots (~0.5 m^2) with and without understory algae removed have been nested within the larger kelp control and kelp removal plots to isolate the effects of giant kelp on competition between understory macroalgae and sessile invertebrates. This year we have continued that experiment, which involves quarterly maintenance of the kelp and macroalgal removal treatments. After some refinement, we added tiles and brushes to measure recruitment rates of sessile and mobile species, respectively.

Theme 1b. Ecological consequences of fishing

In 2012 we initiated a new time series on lobster abundance, size and fishing effort in response to the designation of the MPAs. We have continued this dataset as well as used landings data obtained from the CA Dept of Fish and Wildlife (CDFW) to show that the MPAs have resulted in an increase in spiny lobster within the MPAs which has benefited the commercial lobster fishery outside of the MPAs through spillover, an often asserted but seldom documented phenomenon.

Theme 1c. Sources and utilization of recycled nitrogen

To integrate past work on sources and sinks of recycled N in coastal kelp forests, an SBC LTER working group is formulating a comprehensive N budget for the coastal ecosystem. Led by SBC investigators Alyson Santoro and Nick Nidzieko, this analysis will include a full 20-year comparison of along- and cross-shelf motions relevant to transport to and from the kelp forest.

Theme 2. Dynamic biophysical coupling in kelp forest ecosystems

Theme 2a. Effects of kelp on physical and chemical fluxes

To address this aim, we have augmented our long-term kelp forest sites at Mohawk (MK) and Arroyo Quemado (AQ) with additional physical and chemical sensors to quantify the residence time and carbonate chemistry of water within the kelp forest. MK and AQ are well suited for this purpose because many SBC core measurements are made at these sites. Moreover, the difference in size between these two kelp forests (AQ is ~5 times larger than MK) coupled with high seasonal and inter-annual variability in kelp abundance will allow us to examine how residence time varies with kelp forest architecture and alongshore current speed. This year we acquired an additional Seafet pH sensor, a CTD with fluorometer, and dissolved oxygen sensors to ensure continuity of this dataset.

Theme 2b. Effects of kelp on the processing and fate of dissolved organic matter

Quantifying remineralization rates of kelp-derived DOM and its accumulation along a spatial gradient from within the kelp forest to the waters outside of it will provide an estimate of kelp DOM available to kelp forest food webs via the microbial loop vs DOM exported from the kelp ecosystem. Microbial remineralization experiments are being conducted seasonally on DOM released directly from kelp, and on DOM that accumulates in the surface waters (within the kelp forest and up to 1000 m offshore) to determine degradation rates and bioavailability. We have begun using a new high-throughput system for measuring microbial respiration that has made these experiments much more tractable.

Theme 2c. Ecological and evolutionary consequences of kelp-induced changes in seawater chemistry

The massive and dense biomass of giant kelp forests has the potential to significantly alter water chemistry via photosynthesis and respiration. We are investigating the potential for giant kelp to influence the eco-evolutionary dynamics of kelp forest metazoans by examining the consequences of kelp forests as modifiers of seawater properties including DO, pCO_2, and pH in a warmer future, using calcifying sea urchins as model species.

Theme 3. Spatial dynamics and connectivity of kelp forests and adjacent ecosystems

Theme 3a. Demographic connectivity and metapopulation dynamics of giant kelp

To characterize canopy dynamics on sub-meter scales, identify small-scale extinction events and relate local patterns of recolonization to connectivity and environmental factors, we have initiated high-resolution monitoring of select kelp forests along the Santa Barbara coastline using small unoccupied aerial systems (sUAS; quadcopter drones). Starting in February 2021, we began monthly timeseries of 10-band multispectral imagersUAS flights at the Mohawk and Arroyo Quemado kelp forests to examine the dynamics of canopy biomass and physiological condition and relate these changes to demographic and environmental processes. This year, we collaborated with a group from the NASA Jet Propulsion Laboratory to include these sites in weekly high-altitude flights by the Surface Biology and Geology High-Frequency Time Series (SHIFT) campaign, using the AVIRIS-NG (Airborne Visible/Infrared Imaging Spectrometer-Next Generation) instrument. From late February to late May 2022, the plane collected spectral data of land and aquatic plant communities over a 640-square-mile (1,656-square-kilometer) study area in Santa Barbara County and the nearby ocean. In addition, we collected biweekly samples of kelp at Arroyo Quemada for pigment and nitrogen content during the campaign. These data will be compared with AVIRIS and our sUAS data to groundtruth future remote sensing products focused on giant kelp physiological condition.

Theme 3b. Trophic connectivity between kelp forests and beaches

To evaluate connectivity and synchrony between beaches and kelp forests, we are collecting detailed data on the abundance of kelp wrack at our five study beaches, quantifying smaller blades and fronds as well as whole plants. We are also developing methods to use sUAS imagery to get a more spatially comprehensive and rapid estimate of wrack abundance that could be collected in tandem with the kelp forest imagery in Theme 2a used to assess the level of synchrony between kelp standing biomass and kelp wrack abundance and flux, and subsequent connectivity between subtidal kelp forests and intertidal beaches. Kyle Emery, a former SBC LTER Ph.D. student and now an NSF Bio-OCE Postdoctoral Fellow based at UCLA, is leading this effort. Birds and wrack consumers are also surveyed at our sites.

Theme 3c. Trophic connectivity between the coastal ocean and kelp forests

In spring 2021 we began a focused research campaign to better understand the linkage between phytoplankton and reef suspension feeders. Over 2-week periods each season, we are collecting concurrent field measurements at MK and AQ, along with measurements offshore, using SBC's Teledyne Webb G2 glider to quantify cross-shelf fluxes and onshore delivery of phytoplankton to kelp forests and reef suspension feeders that will be contextualized at larger spatial scales through analysis of available satellite data. On the reefs, we are investigating the response of suspension-feeding invertebrates to the supply and taxonomic composition of phytoplankton. Three days per week during each two-week period each season, water samples for chlorophyll, POC, and phytoplankton community composition are being collected in the kelp forest, augmented by near-continuous chlorophyll measurements by moored in situ fluorometers. On a subset of the same days, suspension feeders are also sampled for gut contents to evaluate

feeding selectivity as compared with available phytoplankton assemblages. To supplement microscope counts of phytoplankton, we will analyze water and gut content samples using DNA metabarcoding techniques.

Specific Objectives:

Theme 1a. *Community and ecosystem consequences of climate variability, disturbance and pathways of recovery*

Marine heatwave (MHW) events are emerging as dominant and disruptive extreme disturbance events on the Pacific coast. Effects on key kelp forest species, especially at vulnerable early life stages, are poorly understood. We assessed the effect of high temperature stress that resembled local MHW conditions on the larval stages of the Kellet's whelk, *Kelletia kelletii*, a kelp forest predator and an emerging seafood species in California (Clare et al. 2022). After exposure of larvae to a range of temperatures (15°C–37°C) in acute thermotolerance trials (1 h), the mortality of veligers and hatchlings occurred at similar temperatures. In contrast, temperatures that induced developmental abnormalities for both encapsulated veligers and hatchlings were lower than temperatures that caused mortality. These results provide some of the first insights on effects of environmentally relevant MHW temperatures on larval forms of the Kellet's whelk, and suggest the potential decline of populations *in situ* in response to continued stress from local MHW events.

Theme 1b. Ecological consequences of fishing

We are using data from other research and monitoring programs in the region to address questions about effects of fishing in kelp forest ecosystems. In 2008, a collaborative fisheries research effort that included SBC LTER investigators detected substantial lobster population increases within reserves, and an indication of the possible spillover of adult lobsters across reserve borders. To estimate whether and how much populations within reserves, and spillover from reserves, have increased through time, we repeated the sampling program 10 years later in 2018 at two of the three original reserves (Lenihan et al. 2022). Results showed that legal-sized lobster abundance in traps (catch per unit effort) increased by 223%–331% at sites near to reserve borders, and by nearly 400% just outside of reserve borders over the 10-year period, thus indicating a substantial increase in spillover across reserve borders. This study demonstrates how spillover scales with biomass buildup and that collaborative fisheries research can be used to assess the efficacy of marine reserves as fishery management tools worldwide.

Theme 1c. Sources and utilization of recycled nitrogen

We examined the capacity of the giant kelp, Macrocystis pyrifera, to exhibit surge uptake as a mechanism to enhance nitrogen assimilation during seasons when nitrate is depleted. (Cedeno et al. 2021). Incubation experiments showed evidence of surge uptake lasting up to 5 min for ammonium and 1 min for nitrate during the summer only, and little capacity for surge uptake of urea regardless of season. The ecological importance of the patterns

of surge uptake observed for ammonium and nitrate, moreover, is questionable, given the small scale and ephemeral nature of ammonium pulses most likely experienced by giant kelp, and the longer duration pulses of nitrate associated with internal waves and upwelling. Rather it seems more likely that uptake of ammonium and urea at ambient concentrations, combined with normal uptake of nitrate during longer duration pulses of high concentrations, sustains giant kelp growth during seasons when ambient concentrations of nitrate are low.

Theme 2a. Effects of kelp on physical and chemical fluxes

We are working to develop residence time estimates that are a function of stratification, kelp forest area, and kelp density. In prior research we estimated water residence time in the kelp forest at Mohawk Reef to be ~1 hour based on mean velocities and forest area, but more recent estimates derived from observed changes in dissolved oxygen were several times longer. Our ongoing research on this topic strives to quantify spatial and temporal scales of variation in seawater properties (i.e., temperature, salinity, and dissolved oxygen) inside, outside and offshore of the kelp forest as it varies naturally through time in its footprint area and kelp density.

Theme 2b. Effects of kelp on the processing and fate of dissolved organic matter

The microbial community living on kelp itself may use kelp DOM and influence kelp physiology and condition. In marine microbial communities, assembly order can shape the rate of organic matter processing, especially when pioneer taxa "unlock" substrates for subsequent arrivals. To address such phenomena SBC graduate students Sevan Esaian and An Bui are investigating community assembly of the kelp microbiome through time and over depth. Their results suggest that deeper blade communities do assemble over time, while surface blades tend to track ambient conditions. In-progress analysis is identifying taxa that drive these shifts in community composition.

Theme 2c. Ecological and evolutionary consequences of kelp-induced changes in seawater chemistry

Seawater parameters can have drastic impacts on organismal physiology across life history stages. Carry-over effects, where parents confer tolerance to progeny, may alleviate stress during ocean warming and acidification. We are examining carry-over effects in purple sea urchins, under laboratory conditions, thus far focusing on warming.

Theme 3a. Demographic connectivity and metapopulation dynamics of giant kelp

Spatial synchrony is a ubiquitous and important feature of population dynamics, but many aspects of this phenomenon are not well understood. In particular, it is largely unknown how multiple environmental drivers interact to determine synchrony via Moran effects, and how these impacts vary across spatial and temporal scales. Using new wavelet statistical techniques, we used SBC LTER Landsat-based giant kelp canopy time series over 33 years (1987–2019) to characterize synchrony in populations of giant kelp,

and related synchrony to variation in oceanographic conditions across >900 km of coastline in California (Castorani et al. 2022). Our findings demonstrate that understanding and predicting synchrony, and thus the regional stability of populations, relies on resolving the synergistic and antagonistic Moran effects of multiple environmental drivers acting on different timescales.

Theme 3b. Trophic connectivity between kelp forests and beaches

Four closely related species of highly mobile intertidal detritivores, talitrid amphipods, inhabit sandy beaches in southern California. Their coexistence suggests that mechanisms, such as niche separation, are operating to weaken competition among these species. To evaluate this possibility, we explored how tidal phase may mediate temporal and spatial patterns of habitat use among these closely related congeners (Emery et al. 2022). We found significant effects of tide phase and species identity on mean intertidal positions and separation of burrowed amphipods. Our findings suggest that mobile intertidal species, like these sympatric talitrid amphipods, can avoid interspecific competition by shifting their activity patterns with tide phase and beach condition. As rising sea levels reduce beach habitat, interspecific competition among these important intertidal consumers may increasingly influence their behavior and coexistence.

Theme 3c. Trophic connectivity between the coastal ocean and kelp forests

Quantifying phytoplankton composition is critical to predicting marine ecosystem structure and function. We integrated DNA meta-barcoding and HPLC pigment observations to determine eukaryotic phytoplankton composition in the Santa Barbara Channel, California. Covariation network analysis revealed that diverse assemblages of phytoplankton and other protists covary with distinct suites of biomarker pigments. We suggest a path to monitor eukaryotic plankton communities on unprecedented spatiotemporal scales based on the covariation of unique phytoplankton and protistan assemblages with remotely sensible phytoplankton pigment concentrations (Catlett et al. In Press).

Significant Results:

Theme 1a. *Community and ecosystem consequences of climate variability, disturbance and pathways of recovery*

Giant kelp provides habitat and food for a diversity of marine life. Kelp biomass varies in response to changing ocean temperatures, but physiological responses as reflected in the nutritional quality of kelp tissue are poorly understood. Using a 19-year SBC LTER time series of kelp tissue carbon and nitrogen content, we found that nutritional quality of giant kelp tissue declined; nitrogen content of giant kelp tissue declined by 18%, while carbon content proportionally increased (Lowman et al. 2022). This decline in nutritional quality was associated with increasing seawater temperatures and with regional and local scale processes including upwelling as indicated by the biologically effective upwelling transport index, the El Niño-Southern oscillation and the North Pacific Gyre oscillation.

Changes in kelp stoichiometry with seawater temperature have important implications for nutrition and behavior of key consumers, such as sea urchins. Our results suggest that the consequences of projected declines in kelp abundance due to climate change may be compounded by reductions in its nutritional quality.

Theme 1b. Ecological consequences of fishing

When herbivore abundance is high, heavy grazing can severely defoliate primary producers and, in some cases, even drive ecosystem to undergo regime shifts from a high productivity state to a denuded, low productivity state. While the phenomenon of herbivore-driven regime shifts is well documented, we only partially understand the mechanisms underlying these events. Fishing for sea urchins and their predators may directly or indirectly influence grazing rates in kelp forest ecosystems. We combined herbivory experiments with 21 years of SBC long-term monitoring data of kelp forest ecosystems to test the hypothesis that herbivores drive regime shifts when herbivory exceeds primary production (Rennick et al. 2022). To test this hypothesis, we quantified how the foraging habits of sea urchins change with increases in sea urchin biomass and trigger regime shifts to giant kelp. Using experiments, we quantified how the grazing capacity of urchins increases as urchin biomass increases, then we combined these estimates of urchin grazing capacity with SBC estimates of kelp NPP to predict when and where urchin grazing capacity exceeded kelp production. When grazing capacity exceeded kelp production, sea urchins caused a 50-fold reduction in giant kelp biomass. Our findings support the hypothesis that the balance between herbivory and production underlies herbivore-driven regime shifts in southern California kelp forests and provides insight into when and where urchins are likely to force regime shifts in kelp forest ecosystems.

Theme 1c. Sources and utilization of recycled nitrogen

The benthos and terrestrially-derived sediments are a potentially significant source of locally regenerated N to kelp forests during otherwise low-nutrient oceanographic conditions. We examined the distribution and processing of terrestrial organic material, derived from the disposal of material from a massive debris flow event following a major wildfire in a coastal California catchment in intertidal and nearshore subtidal marine sediments (Lowman et al. 2022). Organic matter biomarkers, pyrogenic carbon and lignin phenols, were used to trace the distribution of terrestrial debris material in marine environments. Terrestrial biomarkers demonstrated that the disposed material was not detected in the top 20 cm of intertidal sediment but was retained in subtidal sediment offshore of the disposal site. Results suggest coastal management should incorporate consideration of the effects of debris disposal activities on nearshore benthic communities and biogeochemical cycling.

Theme 2c. Ecological and evolutionary consequences of kelp-induced changes in seawater chemistry

We employed a quantitative genetics experiment with the purple sea urchin, *Strongylocentrotus purpuratus*, to decompose family-level variation in transgenerational and developmental plastic responses to ecologically relevant temperature and pCO_2 (Strader et al. 2022). We found evidence of family-level phenotypic plasticity in response to different developmental environments. Among developmental environments, there was substantial additive genetic variance for one body size metric when larvae developed under upwelling conditions, although this differed based on parental environment. Furthermore, cross-environment correlations indicate significant variance for genotype-by-environment interactive effects. Therefore, genetic variation for plasticity is evident in early stages of *S. purpuratus*, emphasizing the importance of adaptive evolution and phenotypic plasticity in organismal responses to global change.

Theme 3a. Demographic connectivity and metapopulation dynamics of giant kelp

New work is investigating the finer-scale patterns and drivers of resistance and resilience of giant kelp populations throughout the region using remote sensing. We found that nutrient supply was linked to regional scale (>1 km) physiological condition dynamics, and kelp forest stands were more persistent where nutrient levels were consistently high. However, on local scales (<1 km), internal senescence processes related to canopy age demographics determined patterns of biomass loss across individual kelp forests despite uniform nutrient conditions. (Bell & Siegel 2022). Emerging remote sensing technologies that provide simultaneous estimates of abundance and physiology can quantify the roles of environmental change and demographics governing plant population dynamics for a wide range of aquatic and terrestrial ecosystems.

Theme 3b. Trophic connectivity between kelp forests and beaches

The coastal zone provides foraging opportunities for insular populations of terrestrial mammals, allowing for expanded habitat use, increased dietary breadth, and locally higher population densities. We examined the use of sandy beach resources by the threatened island fox (*Urocyon littoralis*) on the California Channel Islands using scat analysis, surveys of potential prey, beach habitat attributes, and stable isotope analysis (Page et al. 2021). Consumption of beach invertebrates by island fox varied with abundance of these prey across sites. Abundant allochthonous marine resources on beaches, including inputs of giant kelp, may expand habitat use and diet breadth of the island fox, increasing population resilience during declines in terrestrial resources associated with climate variability and long-term climate change.

Theme 3c. Trophic connectivity between the coastal ocean and kelp forests

Sessile animals that depend on phytoplankton and other seston may be particularly vulnerable to anomalous warming given constraints in food acquisition and reproduction imposed by sessility. We used SBC long-term data to address how kelp forest suspension feeders may be affected by warming oceans (Michaud et al. 2022). In temperate reef ecosystems, sessile suspension feeding invertebrates provide food for an array of mobile

species and act as a critical trophic link between the plankton and the benthos. Using 14 years of seasonal benthic community data across five coastal reefs, we evaluated how communities of sessile invertebrates in southern California kelp forests responded to the "Blob", a period of anomalously high temperatures and low phytoplankton production. We showed that this event had prolonged consequences for kelp forest ecosystems. Changes to community structure, including species invasions, have persisted six years post-Blob, suggesting that a climate-driven shift in California kelp forests is underway.

Key outcomes or Other achievements:

LTER Network cross site projects

Former SBC post doc and present Associate Investigator Thomas Lamy, now faculty at the French National Research Institute, participated in a cross-site working group to synthesize the general relationships between metacommunity parameters and stability across a diverse range of ecosystems. Several products resulted, as reported in previous years. This year, the group published a synthesis on Diversity Stability Relationships (DSRs) and whether regional DSRs hold across a broad range of organisms and ecosystem types (Wisnoski et al. 2022) by compiling a large collection of long-term spatial metacommunity data spanning a wide range of taxonomic groups (e.g., birds, fish, plants, invertebrates) and ecosystem types (e.g., deserts, forests, oceans). At the local scale, compositional DSRs suggested that higher local (α) diversity was associated with lower variability in animal populations but higher variability in plant populations, while aggregate DSRs supported the classic stabilizing effects of diversity. However, at the regional (γ) scale, the group found no aggregate DSR, but a positive compositional DSR. Across a broader range of taxa, the results suggest that high γ-diversity does not consistently stabilize aggregate properties at regional scales without sufficient spatial β-diversity to reduce spatial synchrony.

Former SBC postdoc Max Castorani, now Investigator and faculty at UVA, where he is also a PI on VCR LTER, participated in a cross-site working group using LTER data from several sites including SBC to integrate population and community approaches to synchrony to understand drivers of ecosystem stability. One important aspect of spatial synchrony is that it may be tail-dependent, that is, stronger when populations are abundant than scarce, or vice-versa. The group formulated a general theory of how the distribution and correlation structure of an environmental driver translates into tail-dependent spatial synchrony through a non-linear response, and used SBC LTER giant kelp canopy data along the California coastline to examine empirical evidence for predictions of the theory (Walter et al. 2022). In sheltered areas, kelp declines synchronously (lower-tail dependence) when waves are relatively intense, because waves below a certain height do little damage to kelp. Conversely, in exposed areas, kelp was synchronized primarily by periods of calmness that cause shared recovery (upper-tail dependence). The study found evidence for geographies of tail dependence in synchrony, which helps structure regional population resilience: areas where population declines are asynchronous may be more resilient to disturbance because remnant populations facilitate reestablishment. In another study, the group combined simulation and empirical analyses

to elucidate mechanisms that underlie patterns of synchronous versus compensatory dynamics (Shoemaker et al. 2022). In both simulated and empirical communities, they showed that synchronous and compensatory dynamics are not mutually exclusive but instead can vary by timescale, driven by multiple mechanisms that can generate timescale-specific patterns, including different environmental drivers, diverse life histories, dispersal, and non-stationary dynamics. Traditional metrics for quantifying synchronous dynamics were often biased toward long-term drivers and may miss the importance of short-term drivers. These findings indicated key mechanisms to consider when assessing synchronous versus compensatory dynamics and provided a pathway for disentangling these dynamics in natural systems.

SBC Co-PI Reed led an LTER synthesis paper on the long-term effects of climate change on coastal ecosystems (Reed et al 2022). The study included five other coastal LTER sites, Florida Coastal Everglades, Georgia Coastal Ecosystems, Moorea Coral Reef, Plum Island Ecosystems, and Virginia Coast Reserve, and reviewed the results from decade-scale research on coastal ecosystems shaped by foundation species (e.g., coral reefs, kelp forests, coastal marshes, seagrass meadows, mangrove forests, barrier islands) to show how climate change is altering their ecological attributes and services. The paper demonstrated the value of site-based, long-term studies for quantifying the resilience of coastal systems to climate forcing, identifying thresholds that cause shifts in ecological state, and investigating the capacity of coastal ecosystems to adapt to climate change and the biological mechanisms that underlie it.

Margaret O'Brien, SBC's former lead Information manager and current IM advisor, is a co-PI helping to lead the EMERGENT synthesis working group, which is advancing efforts to harmonize molecular information for microbial taxa, streamlining their use in syntheses with related ecosystem level data and spurring future microbial ecology research at LTER sites.

Non-LTER cross-site and broader scale research

SBC Investigators Jenifer Dugan and David Hubbard, along with NSF Postdoctoral Fellow Kyle Emery, participated in a global review of how wrack and carrion provide spatial subsidies that shape the structure and functioning of sandy-beach ecosystems (sandy beaches and adjacent surf zones), which typically have little *in situ* primary production (Hyndes et al. 2022). They also examined the spatial scaling of the influence of these processes across the broader land- and seascape, and identified key gaps in our knowledge to guide future research directions and priorities. Global declines in seagrass beds and kelp forests (linked to global warming) were predicted to cause substantial reductions in the amounts of marine organic matter reaching many beach ecosystems, likely causing flow-on effects for food webs and biodiversity. Similarly, future sea-level rise and increased storm frequency are likely to alter profoundly the physical attributes of beaches, which in turn can change the rates at which beaches retain and process the influxes of organic matter.

* What opportunities for training and professional development has the project provided?

Education and training are tightly integrated into all aspects of SBC LTER research. During the past year (year 4 of SBC IV), 9 postdoctoral fellows, 35 graduate students, 5 REU students, and 90 undergraduate students participated in SBC research and outreach activities. REU students work closely with SBC researchers on a wide range of topics and many choose to pursue an advanced degree following their undergraduate education. A number of SBC investigators, postdocs, and graduate students also mentored REU students in the Global Change Biology program at UCSB. UCSB undergraduates have a high propensity to get involved in sponsored research and SBC programs contribute substantially to this trend. In addition to gaining research experience, many undergraduates earn academic credit or receive monetary compensation for participating in SBC research as interns and honors students. This year 18 students participated in SBC's undergraduate research training program. Students in the program actively assist in the collection, processing and analysis of core data. In the first term, students read primary literature to gain a foundation in core research areas, key findings, current research objectives and methods of the SBC LTER. Next, students gain hands on laboratory and field research experience. Post-graduation, many SBC student participants are accepted into graduate studies, begin careers in their field or obtain highly competitive internships.

The focus of SBC's mentoring and training of postdoctoral scientists is on providing them with strong interdisciplinary skills, professional development opportunities, and the experience, and support required for them to transition to career faculty positions. In addition to the specific training associated with the SBC project, postdoctoral scientists are mentored through grant proposal development and writing and the job application and interview process by SBC investigators and via access to UCSB's resources for postdoctoral scientists.

SBC graduate student and postdoctoral training are coordinated with several programs on the UCSB campus to promote opportunities for interdisciplinary graduate training in ecology, physiology, geology, geography, hydrology, oceanography, and coastal policy. This enables valuable cross-training on environmental issues pertaining to coastal ecosystems, provides a common language for communicating scientific information on these issues, and contributes to the creation of a diverse scientific community of students and postdocs that fosters respect and appreciation across disciplines. SBC graduate students and postdocs were first authors on nine journal articles and gave 11 papers at national conferences this year. This year three SBC graduate students completed their PhD degrees. Seminars hosted by SBC faculty, the SBC Midterm Review and SBC workshops on key research themes served to engage SBC graduate students in the culture and diverse research offered by SBC.

Opportunities for training in public education and student mentoring arise from SBC's partnership with UCSB's teaching aquarium, the REEF, which is also designed to provide UCSB undergraduates majoring in Aquatic Biology with training in communicating their marine ecology knowledge. The REEF features SBC LTER research and provides a wide range of training and professional development opportunities. A total of 42 undergraduate interns were trained in this rigorous and pedagogically sound program this year. The REEF also serves as a teaching facility for UCSB courses in Earth Sciences, Ecology Evolution & Marine Biology,

English and Teacher Ed programs through the Gevirtz Graduate School of Education and for many area colleges including Cal Lutheran University, California State University Channel Islands, and local community colleges. One of the joint goals of the SBC LTER and the REEF programs is to provide UCSB undergraduates majoring in Aquatic Biology, with a solid foundation in marine ecology and research. REEF training provides them with the basis for communicating this knowledge in an educational format. To that end, The REEF develops its *Oceans-to-Classrooms* curriculum around a number of research programs at UCSB and SBC LTER is the most significant contributor to this endeavor. Support from the SBC Schoolyard LTER program has allowed the REEF to obtain teaching supplies and equipment for curriculum as well as provide salaries for professional staff and undergraduate internships. SBC graduate students, research staff, and post-docs also train REEF interns, which, in turn, enhances their training as laboratory and field assistants and research divers for SBC research.

* Have the results been disseminated to communities of interest? If so, please provide details.

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

- SBC LTER data and studies are showing the effects of marine reserves on ecosystems and fishing. New work showing spillover bolsters the case for marine reserves as management tools and may help improve the design of future reserves and networks.
- SBC LTER expertise and data on patterns and drivers of kelp productivity is informing the possibility of kelp farming for biofuels off the coast of CA. DOE is funding several projects on this topic; one is using SBC LTER data to develop a model for kelp farm siting.
- SBC investigators and students are collaborating with the Bureau of Ocean Energy Management, to assess factors affecting the spread and ecological impact of the invasive bryozoan *Watersipora subatra*, which is rapidly increasing at SBC study sites.
- SBC LTER is providing data on water parameters (salinity and temperature) to the City of Santa Barbara to assist with monitoring effects of a new desalination plant.
- SBC LTER investigators are assisting with Natural Resource Damage Assessment (NRDA) studies for the 2021 Huntington Beach oil spill
- SBC investigators serve as science advisers for public and non-governmental agencies tasked with managing coastal resources.

* What do you plan to do during the next reporting period to accomplish the goals?

Theme 1. Environmental drivers of kelp persistence and community structure

Theme 1a. *Community and ecosystem consequences of climate variability, disturbance and pathways of recovery*

In 2021 we initiated a finer-scale long-term experiment to quantify the role of competition for space as a key process governing community structure and recovery in kelp forests. In the next year we will begin doing preliminary analyses of the results.

Theme 1b. Ecological consequences of fishing

In the next year we plan to do further analyses of long-term data from inside and outside marine protected areas to inform on the indirect effects of fishing beyond trophic cascades.

Theme 1c. Sources and utilization of recycled nitrogen

We predict N regeneration rates in the water column will vary with the structure of planktonic communities and associated shifts in remineralization processes. In the coming year we will begin testing this prediction by quantifying seasonal rates of N regeneration in the water column (this research was delayed by COVID). Water column regeneration rates will be determined at the three kelp forests where kelp NPP and oceanographic properties are measured as part of our long-term studies. Monthly measurements of concentrations of urea, ammonium, nitrate, POC, PON and phytoplankton chlorophyll a will be augmented with rate measurements of urea and ammonium regeneration in spring, summer and fall, with particular emphasis on the stratified summer periods when the relative contribution of recycled N to kelp N demand should be highest. Isotope pool dilution will be used to quantify microbial urea and ammonium regeneration. An SBC graduate student, Natalie Dornan (Santoro lab), will be leading this research.

Theme 2. Dynamic biophysical coupling in kelp forest ecosystems

Theme 2a. Effects of kelp on physical and chemical fluxes

In the next year we will continue working to develop residence time estimates that are a function of stratification, kelp forest area, and kelp density.

Theme 2b. Effects of kelp on the processing and fate of dissolved organic matter

The microbial assemblages in close proximity to kelp and associated DOM production may alter the bacterial community to one capable of turning over DOC at a higher rate regardless of its source. Future work will include the monitoring of initial microbial assemblages using 16s rRNA gene metabarcoding to identify the initial and responding community along transects and in experiments.

Theme 2c. Ecological and evolutionary consequences of kelp-induced changes in seawater chemistry

To continue testing whether kelp-induced changes in the environment influence the provisioning of offspring by sea urchins via parental effects, we are continuing in situ experiments using caged and fed adult purple sea urchins within and outside of the kelp forests at MK and AQ from

late summer to early winter when adults undergo gametogenesis. Cages will be co-located with pH sensors in order to capture differential abiotic exposures during gametogenesis.

Theme 3. Spatial dynamics and connectivity of kelp forests and adjacent ecosystems

Theme 3a. Demographic connectivity and metapopulation dynamics of giant kelp

Starting in February 2021, we began monthly timeseries of 10-band sUAS flights at the Mohawk and Arroyo Quemado kelp forests to examine the dynamics of canopy biomass and physiological condition and relate these changes to demographic and environmental processes. These surveys will be continued over the coming year and augmented as needed to validate the use of additional sensors, and we will be analyzing the data to develop a kelp demographic model based on remotely sensed canopy data.

Theme 3b. Trophic connectivity between kelp forests and beaches

To evaluate connectivity and synchrony between beaches and kelp forests, we will continue collecting detailed data on the abundance of kelp wrack at our five study beaches, quantifying smaller blades and fronds as well as whole plants. We are also in the midst of developing and calibrating methods to use sUAS imagery to obtain more spatially comprehensive and rapid estimates of wrack abundance that can be collected in tandem with the kelp forest imagery in Theme 2a. Along with long term datasets, this new approach will be used to assess the level of synchrony between kelp standing biomass and kelp wrack abundance and flux, and evaluate the connectivity between subtidal kelp forest and intertidal sandy beach ecosystems.

Theme 3c. Trophic connectivity between the coastal ocean and kelp forests

In the coming year, to supplement microscope counts of phytoplankton, we will analyze water and gut content samples using DNA metabarcoding techniques. This campaign will begin to define whether kelp forest food webs rely on specific groups of phytoplankton more than others and the physical drivers and transport processes that deliver these crucial trophic resources to the reef.

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Products

Books

- Bock, C., P De Wit, GE Hofmann, CJM Hoppe, JM Hall-Spencer (2021). *Advances in Ocean Acidification* Scientific Research Publishin. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Book Chapters

Inventions

Journals or Juried Conference Papers

View all journal publications currently available in the NSF Public Access Repository for this award.

The results in the NSF Public Access Repository will include a comprehensive listing of all journal publications recorded to date that are associated with this award.

- Cavanaugh, Kyle C. and Bell, Tom and Costa, Maycira and Eddy, Norah E. and Gendall, Lianna and Gleason, Mary G. and Hessing-Lewis, Margot and Martone, Rebecca and McPherson, Meredith and Pontier, Ondine and Reshitnyk, Luba and Beas-Luna, Rodrigo and Carr, Mark and Caselle, Jennifer E. and Cavanaugh, Katherine C. and Flores Miller, Rebecca and Hamilton, Sara and Heady, Walter N. and Hirsh, Heidi K. and Hohman, Rietta and Lee, Lynn Chi and Lorda, Julio and Ray, James and Reed, Daniel C. and Saccomanno, Vienna R. and Schroeder, Sarah B.. (2021). A Review of the Opportunities and Challenges for Using Remote Sensing for Management of Surface-Canopy Forming Kelps. *Frontiers in Marine Science*. 8 . Status = Deposited in NSF-PAR doi:https://doi.org/10.3389/fmars.2021.753531 ; Federal Government's License = Acknowledged. (Completed by Reed, Daniel on 10/31/2022) Full text Citation details
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- Castorani, M.C.N. (2018). *Coastal connectivity: A population perspective from two temperate marine LTER sites*. LTER All Scientists' Meeting. Pacific Grove, CA. Status = OTHER; Acknowledgement of Federal Support = Yes
- Comstock, J., Santoro, A., Carlson, C. (2020). *Comparison of bacterioplankton community structure across extraction methods and filter type. AtlantECO Workshop on standard sampling methods for microbiomes in November 2020.*. AtlantECO Workshop on standard sampling methods for microbiomes. virtual. Status = OTHER; Acknowledgement of Federal Support = Yes
- Michaud, K and KK Emery and J Dugan and R Miller (2018). *Differential use of wrack resources provides niche separation in intertidal consumers on California beaches (poster)*. LTER All Scientists' Meeting. Pacific Grove, CA. Status = OTHER; Acknowledgement of Federal Support = Yes

- Castorani, M.C.N., S.L. Harrer, R.J. Miller, and D.C. Reed. (2021). *Disturbance structures canopy and understory productivity along an environmental gradient: evidence from a 10-year experiment at Santa Barbara Coastal LTER.*. 106th Annual Meeting of the Ecological Society of America.. Virtual. Status = OTHER; Acknowledgement of Federal Support = Yes
- Hofmann GE (2018). *Ecological-evolutionary dynamics in long-term ecological research in marine ecosystem*. LTER All Scientists' Meeting. Pacific Grove, CA. Status = OTHER; Acknowledgement of Federal Support = Yes
- Kozal, LC and U Hoshijima and GE Hofmann (2018). *Environmental Variability and Transgenerational Plasticity in the Santa Barbara Channel 2018 (poster)*. LTER All Scientists' Meeting. Pacific Grove, CA. Status = OTHER; Acknowledgement of Federal Support = Yes
- Dugan, JE, S Hamilton, K. Neumann, M. Colwell, D. Hubbard, D. Robinette, K. Lindquist, K. Nielsen, J. Marin-Jarrin, J. Madden, M. Ladd (2020). *Evaluating performance of California's MPA network through the lens of sandy beach and surf zone ecosystems. Talk,.* Western Society of Naturalists Meeting. Virtual. Status = OTHER; Acknowledgement of Federal Support = No
- M Strader, L Kozal, TS Leach, JM Wong, JD Chamorro, MJ Housh, G Hofmann (2020). *Examining the role of DNA methylation in transcriptomic plasticity of early stage sea urchins*. AGU Ocean Sciences Meeting. Virtual. Status = OTHER; Acknowledgement of Federal Support = Yes
- Chamorro, J, L Kozal, G Hofmann (2020). *Exploring Plasticity-Associated Traits Across an Intertidal Gradient: Variation in Adult DNA Methylation and Maternal Effects in California Mussels (Mytilus californianus)*. AGU Ocean Sciences Meeting. Virtual. Status = OTHER; Acknowledgement of Federal Support = Yes
- Chamorro, J. and L.C. Kozal and G.E. Hofmann (2018). *Exploring mechanisms of TGP in California mussels (Mytilus californianus)*. LTER All Scientists' Meeting. Pacific Grove, CA. Status = OTHER; Acknowledgement of Federal Support = Yes
- Bogan, SN, ME Strader, GE Hofmann (2021). *Gene regulatory roles of DNA methylation during transgenerational plasticity in the sea urchin Strongylocentrotus purpuratus*. Society for Integrative and Comparative Biology Meeting. Virtual. Status = OTHER; Acknowledgement of Federal Support = Yes
- Washburn, L., B Emery, C Ohlmann, A Kirincich, and D Iglesias-Rodriguez (2022). *Improvements and new applications of high-frequency radar for coastal ocean observing systems*. Ocean Sciences Meeting. Virtual. Status = OTHER; Acknowledgement of Federal Support = Yes
- Libe Washburn and Paul Matson and Chris Gotschalk and David Siegel and Debra Iglesias-Rodriguez (2018). *Interpreting phytoplankton bloom development using high-frequency radar and satellite ocean color imagery (Poster)*. American Geophysical Union. Washington, D.C., US. Status = OTHER; Acknowledgement of Federal Support = Yes
- Strader, M.E. and G.E. Hofmann (2019). *Intra- and transgenerational plasticity of DNA methylation in the purple sea urchin, Strongylocentrotus purpuratus*. ASLO 2019 Aquatic Sciences Meeting. San Juan, Puerto Rico. Status = OTHER; Acknowledgement of Federal Support = Yes

- Leach TS and GE Hofmann (2019). *Investigating the role of maternal conditioning on offspring performance and DNA methylation patterns in the purple sea urchin*. ASLO 2019 Aquatic Sciences Meeting. San Juan, Puerto Rico. Status = OTHER; Acknowledgement of Federal Support = Yes
- L Kozal, MJ Housh, C Nelson, TS Leach, JM Wong, M Yamamoto, G Hofmann (2020). *Kelp Associated Changes in Seawater Chemistry Connect to Transgenerational Effects in the Purple Urchin, Strongylocentrotus purpuratus*. Ocean Sciences Meeting. Virtual. Status = OTHER; Acknowledgement of Federal Support = Yes
- Jenifer E Dugan (2018). *Life on a sandy edge: conserving beach ecosystems in the face of rising seas*. 9th National Summit on Coastal and Estuarine Restoration and Management. Long Beach, CA. Status = OTHER; Acknowledgement of Federal Support = Yes
- Castorani, M.C.N. and Reed, D.C. and Miller, R.J (2018). *Loss of foundation species: disturbance frequency outweighs severity for kelp forest biodiversity*. LTER All Scientists' Meeting. Pacific Grove, CA. Status = OTHER; Acknowledgement of Federal Support = Yes
- Castorani, M.C.N. and Reed, D.C. and Miller, R.J (2019). *Loss of foundation species: disturbance frequency outweighs severity in structuring kelp forest communities*. 12th International Temperate Reef Symposium. Hong Kong. Status = OTHER; Acknowledgement of Federal Support = Yes
- Cavanaugh, K.C, K.C. Cavanaugh, C.C Pawlak, T.W. Bell. (2020). *Mapping bull kelp refugia and the environmental drivers of their resilience along the north coast of California.*. Western Society of Naturalists Annual Meeting. Virtual. Status = OTHER; Acknowledgement of Federal Support = Yes
- Lowman, H., M. Hirsch, M. Brzezinski, J. Melack (2021). *Marine Sediments Surrounding Giant Kelp Forests Supply Recycled Nutrients to the Overlying Water Column*. Coastal and Estuarine Research Federation Conference. Virtual. Status = OTHER; Acknowledgement of Federal Support = Yes
- Detmer A. R., B. P. DiFiore, R. J. Miller, D. C. Reed, T. W. Bell, A. C. Stier, and H. V. Moeller (2022). *Modeling the effects of variable disturbance regimes on kelp forest community dynamics*. Ecological Society of America Meeting (ESA). Montreal, Quebec, Canada. Status = OTHER; Acknowledgement of Federal Support = Yes
- Libe Washburn and Brian Emery and A. Kirincich and Chris Gotschalk (2019). *Near-shore eddies detected by HF radar and their effects on kelp forest ecosystems*. Radiowave Oceanography Workshop. Victoria, BC, Canada. Status = OTHER; Acknowledgement of Federal Support = Yes
- Emery, KA (2022). *New approaches to drone-based research in CA intertidal ecosystems*. DroneCamp 2022. Virtual. Status = OTHER; Acknowledgement of Federal Support = Yes
- Dugan, JE and DM Hubbard and B Joab and NK Schooler and KE Emery and B Duke (2018). *Oil Spills on Sandy Beaches: Population responses of intertidal talitrid amphipods to the Refugio Beach Oil Spill, Santa Barbara County 2015*. SETAC North America 39th Annual Meeting. Sacramento, CA. Status = OTHER; Acknowledgement of Federal Support = Yes

- Joab, B and JE Dugan and DM Hubbard and B Duke and R Donohoe and G Baker (2018). *Polycyclic aromatic hydrocarbon uptake in three sandy beach invertebrate tissue types and porewater with corresponding forensic matches to source oil following the Refugio Beach Oil Spill, Santa Barbara County, 2015*. SETAC North America 39th Annual Meeting. Sacramento, CA. Status = OTHER; Acknowledgement of Federal Support = Yes
- Dugan JE and DM Hubbard and KE Emery and R Miller and C Ohlmann and J. Madden (2018). *Quantifying ecological responses to trophic connectivity between sandy beaches and kelp forests (poster)*. LTER All Scientists' Meeting. Pacific Grove, CA. Status = OTHER; Acknowledgement of Federal Support = Yes
- Okamoto, D.K. (2021). *Recruitment and mortality in dynamic sea urchin barrens.*. Western Society of Naturalists. Virtual. Status = OTHER; Acknowledgement of Federal Support = Yes
- Dugan, JE (2022). *Sandy Beach and Surf Zone Ecosystems*. Ask the Researcher Marine Protected Area Monitoring Series. Virtual. Status = OTHER; Acknowledgement of Federal Support = Yes
- Dugan, JE, DM Hubbard, KE Emery (2021). *Sandy beach ecosystems: long term studies of life on the edge. Invited presentation,*. First International Symposium on Coastal Ecosystems and Global Change,. Xiamen, China & Virtual. Status = OTHER; Acknowledgement of Federal Support = Yes
- Jenifer E Dugan (2018). *Santa Barbara Coastal LTER and Climate Change*. LTER All Scientists' Meeting. Pacific Grove, CA. Status = OTHER; Acknowledgement of Federal Support = Yes
- Jenifer E Dugan (2018). *Santa Barbara Coastal LTER: Organic Matter at the Sea & Sand Interface*. LTER All Scientists' Meeting. Pacific Grove, CA. Status = OTHER; Acknowledgement of Federal Support = Yes
- Siegel, D.A (2022). *Seaweed Sinking MRV: What is Needed??*. ARPA-E Marine Carbon Sensing Workshop,. Boston, MA. Status = OTHER; Acknowledgement of Federal Support = Yes
- Clare, X. and G.E. Hofmann (2019). *Snails on the menu? Using long-term ecological data to contextualize performance of a California kelp forest predator and emerging fishery species, K. kelletii.*. World Congress of Malacology. Monterey, CA. Status = OTHER; Acknowledgement of Federal Support = Yes
- Bisson, K. and S. Kramer and A. Fischer and D. Catlett and J. Allen and D. Siegel (2018). *Spatial patterns and optical analysis of wildfire-derived ash in the Santa Barbara Channel (poster)*. XXIV Ocean Optics Conference . Dubrovnik, Croatia. Status = OTHER; Acknowledgement of Federal Support = Yes
- Castorani, M.C.N. and T.W. Bell and L.W. Sheppard and J.A. Walter and D.C. Reuman (2019). *Spatial synchrony in giant kelp metapopulations: patterns, scales, and drivers*. 104th Annual Meeting of the Ecological Society of America. Louisville, KY. Status = OTHER; Acknowledgement of Federal Support = Yes
- Kraskura, K (2022). *TEMPERATURE INFLUENCES INTRA-SPECIFIC SCALING OF METABOLIC AND HEART PERFORMANCE IN AN INDICATOR BEACH ZONE SPECIES, BARRED SURFPERCH*. International Congress on the Biology of Fishes. Montpellier, France. Status = OTHER; Acknowledgement of Federal Support = Yes

- Libe Washburn (2019). *The evolving role of surface-current measuring radar in coastal oceanography: New observations and technology developments*. Gordon Research Conference on Coastal Ocean Dynamics. Manchester NH. Status = OTHER; Acknowledgement of Federal Support = Yes
- Emery, KA, JE Dugan, T Lenihan, RJ Miller, NK Schooler, DM Hubbard. (2021). *The role of cross-ecosystem subsidies and consumer populations in sandy beach ecosystem CO2 fluxes*. Coastal Estuarine Research Foundation. Virtual. Status = OTHER; Acknowledgement of Federal Support = Yes
- Brokaw, R.J., D.A. Siegel, and L. Washburn (2022). *The role of surface circulation on spatial patterns and temporal variability of productivity in the Santa Barbara Channel*. Ocean Sciences Meeting. Virtual. Status = OTHER; Acknowledgement of Federal Support = Yes
- Hardison, E (2022). *The roles of diet in determining thermal acclimation rate and capacity for maximum heart rate in a marine ectotherm (Girella nigricans)*. Society for Experimental Biology Meeting. Montpellier, France. Status = OTHER; Acknowledgement of Federal Support = Yes
- Cavanaugh, K.C. and Bell, T. W. and J.G. Allen and D.A. Siegel (2018). *Three decades of variability in California's giant kelp forests from the Landsat satellites (poster)*. AGU Fall Meeting. Washington DC. Status = OTHER; Acknowledgement of Federal Support = Yes

Other Products

- *Software or Netware.*

  Developed a bioinformatics pipeline for use in assessing gene expression and performing analysis of DNA methylation in the progeny from the larval crosses of methylation of the purple urchin during transgenerational plasticity; This product has been publicly shared on Github (Bogan and Strader 2021). https://github.com/snbogan/Sp_RRBS_ATAC

Other Publications

Patent Applications

Technologies or Techniques

Thesis/Dissertations

- Kraskura, K. *Causes and consequences of body size-specific vulnerability to warming in fishes*. (2022). University of California, Santa Barbara. Acknowledgement of Federal Support = Yes
- Emery, KA. *Coastal connectivity: structure and function of recipient beach ecosystems respond to variation in kelp subsidies*. (2021). University of California, Santa Barbara. Acknowledgement of Federal Support = Yes

- Yorke, CE. *Kelp as a trophic resource to reef food webs*. (2019). UC Santa Barbara. Acknowledgement of Federal Support = Yes
- Lowman, H.E.. *Nutrient and organic matter cycling in the nearshore ocean and marine sediment of the Santa Barbara Channel.*. (2020). University of California, Santa Barbara. Acknowledgement of Federal Support = Yes
- Catlett, Dylan. *Phytoplankton community determinations and dynamics in the Santa Barbara Channel, CA*. (2021). University of California, Santa Barbara. Acknowledgement of Federal Support = Yes
- Leach, TS. *The Role of Pre-and Post-Spawning Temperature Stress on Fertilization Dynamics within Santa Barbara Channel Sea Urchin Species*. (2022). University of California, Santa Barbara. Acknowledgement of Federal Support = Yes

Websites or Other Internet Sites

SBC-LTER project website: https://sbclter.msi.ucsb.edu/

Participants/Organizations

What individuals have worked on the project? See full report

What other organizations have been involved as partners?

Name	Type of Partner Organization	Location
American Assoc. University Women Tech Trek	Other Nonprofits	Santa Barbara, CA
California Dept of Fish and Wildlife	State or Local Government	Sacramento, CA
Point Blue	Other Nonprofits	California
Santa Barbara Unified School District	School or School Systems	Santa Barbara, CA
Scripps Institution of Oceanography	Academic Institution	La Jolla, CA
Southern California Coastal Ocean Observing System (SCCOOS)	Other Organizations (foreign or domestic)	La Jolla, California
The Bay Foundation	Other Nonprofits	Santa Monica, CA
The Nature Conservancy	Other Nonprofits	California
US Geological Survey	Other Organizations (foreign or domestic)	Santa Cruz, CA
University of Auckland	Academic Institution	Auckland, New Zealand
University of California, Davis	Academic Institution	Bodega Bay, CA
University of California, Los Angeles	Academic Institution	Los Angeles, CA
California Sea Grant Extension	Academic Institution	La Jolla, CA
University of California, Santa Cruz	Academic Institution	Santa Cruz, CA

Name	Type of Partner Organization	Location
University of Quebec a Montreal	Academic Institution	Monteral, Quebeck Canada
University of Wisconsin	Academic Institution	Milwalkee, WI
Channel Islands National Marine Sanctuary	Other Organizations (foreign or domestic)	Santa Barbara, CA
Channel Islands National Park	Other Organizations (foreign or domestic)	Ventura, CA
City of Santa Barbara	State or Local Government	Santa Barbara, CA
County of Santa Barbara	State or Local Government	Santa Barbara, CA
Moss Landing Marine Laboratory	Academic Institution	Moss Landing, CA
Ocean Education Trust	Other Nonprofits	Kingston, RI
Pepperdine University	Academic Institution	California

Were other collaborators or contacts involved? If so, please provide details.

Nothing to report

Impacts

What is the impact on the development of the principal discipline(s) of the project?

Project data and personnel contributed to a greater understanding of the general relationships between metacommunity parameters and stability and diversity and ecosystem function across a diverse range of ecosystems, key problems in contemporary ecology. Work in the past year synthesized information on Diversity Stability Relationships (DSRs) and whether regional DSRs hold across a broad range of organisms and ecosystem types (Wisnoski et al. 2022) by compiling a large collection of long-term spatial metacommunity data spanning a wide range of taxonomic groups (e.g., birds, fish, plants, invertebrates) and ecosystem types (e.g., deserts, forests, oceans). At the local scale, compositional DSRs suggested that higher local (α) diversity was associated with lower variability in animal populations but higher variability in plant populations, while aggregate DSRs supported the classic stabilizing effects of diversity. However, at the regional (γ) scale, the group found no aggregate DSR, but a positive compositional DSR. Across a broader range of taxa, the results suggest that high γ-diversity does not consistently stabilize aggregate properties at regional scales without sufficient spatial β-diversity to reduce spatial synchrony.

What is the impact on other disciplines?

A key question in fisheries management is whether spatial management tools like marine protected areas (MPAs) are effective and benefit fisheries in addition to ecosystems. In 2003, a network of no-take marine reserves was established in the Northern Channel Islands (NCI) of

southern California (CA) to conserve biodiversity and to eventually enhance local fisheries through spillover of larvae, juveniles, and adults. The reserve network impacted the local CA spiny lobster (*Panulirus interruptus*) fishery by removing about 20% of fishing grounds in the NCI. In 2008, a collaborative fisheries research effort that included SBC LTER investigators detected substantial lobster population increases within reserves, and an indication of the possible spillover of adult lobsters across reserve borders. To estimate whether and how much populations within reserves, and spillover from reserves, have increased through time, we repeated the sampling program 10 years later in 2018 at two of the three original reserves (Lenihan et al. 2022). Scientific trapping was conducted prior to the fishing season along a spatial gradient beginning deep within the reserves to reference sites located outside (≥2 km) of reserve borders. Results showed that legal-sized lobster abundance in traps (catch per unit effort) increased by 125%–465% deep inside reserves, and by 223%–331% at sites near to reserve borders, and by nearly 400% just outside of reserve borders over the 10-year period, thus indicating a substantial increase in spillover across reserve borders. A similar pattern was observed in lobster biomass caught in traps at the two reserves. This study demonstrates how spillover scales with biomass buildup and that collaborative fisheries research can be used to assess the efficacy of marine reserves as fishery management tools worldwide.

What is the impact on the development of human resources?

Efforts to increase the participation of under-represented groups are achieved through our ongoing Schoolyard program, which targets middle school students in traditionally underserved, low-achieving schools (see Section VII. Outreach, education, training and benefits to society). We also link with campus programs devoted to increasing educational opportunities for low-income students and groups underrepresented in higher education. Since 2001, the number of domestic Underrepresented Minority (URM) undergraduate students at UCSB has increased by 89%, and in fall 2014 UCSB was recognized as a Hispanic Serving Institution (HSI) for achieving 25% Latino undergraduate enrollment. It is the first HIS in the prestigious Association of American Universities, which is an association of 62 leading research universities in the United States and Canada. Women and URM students, post docs and faculty participating in SBC have access to professional development training and mentoring in team science leadership, management, and proposal writing. This year, the Marine Science Institute started an annual scholarship program for underrepresented students interested in scientific diving, with the goal of supporting them through the prerequisites of open water certification and practice dives; as the most active local scientific diving program at UCSB, SBC LTER has committed to incorporating these students into our field program to build their experience level.

What was the impact on teaching and educational experiences?

SBC partners with UCSB's Research Experience & Education Facility (REEF), a teaching aquarium and marine ecology educational facility for UCSB and K-12 schools and colleges in Santa Barbara and Ventura counties. SBC's Schoolyard LTER (sLTER) program is organized around a theme of kelp forest ecology and is developed around and delivered through the REEF's *Oceans-to-Classrooms* curricula. We focus on long-term connections with underserved, low-achieving schools that include year-round on- and off-campus programs. SBC sLTER curriculum is rich in STEM content, meets California State Science Standards, Common Core

Standards and the Next Generation Science Standards as well as NOAA's Climate and Ocean Literacy Principles. Our programs reached >5800 students in grades K-12 in the past year, including visits by schools from numerous southern and central California counties as well as a group of students from Taiwan. During the pandemic we rapidly developed new remote content and utilized live distance learning strategies to deliver SBC-sLTER content beginning in Spring 2020. This included the creation of the *VirtualREEF* YouTube channel, and development of infrastructure needed to deliver live content from the REEF Aquarium. As of fall 2022, *VirtualREEF* had >6500 views, and we shared the science and marine life of the SBC with 48 different schools and groups including students in Chicago, Costa Rica and Colombia. We continue to develop and adapt marine science lesson plans that engage students with learning about the local environment by incorporating ongoing SBC research and working with project data with the goal of building skills in science through activities that move from structured or guided investigation to open-ended inquiry and experimentation. These lessons incorporate ongoing SBC research and include working with SBC data. The program is developed to build students' skills in scientific inquiry through activities that move from structured or guided investigation to open-ended inquiry and experimentation. It also includes a combination of school-based activities, field trips, and on-campus experiences that immerse students in the environment of a college campus. Our approach supports an integrated program that spans academic year activities, as well as summer programs, and includes undergraduate and graduate students, K-12 teachers and students, the UC Community and the general public.While we have seen changes, and challenges, due to the pandemic, in-person programming continues to increase. Our education and outreach efforts, through the REEF delivered SBC science content to over 10,000 K-12, college and general public visitors in 2021-2022.

In the past year SBC collaborated with three partnership programs to deliver its sLTER content: 1) the American Association of University Women's Tech Trek Program, an on-campus summer residential science and math program designed to develop interest, excitement and self-confidence in young women entering the 8th grade 2) Santa Barbara County Education Office (SBCEO), and 3) UCSB's Gevirtz Graduate School of Education and the Harding University Partnership School (HUPS) with whom we collaborated on a Fourth/Fifth Grade published anthology, "Dive Deep into Writing," which included poetry, fiction, and non-fiction writings.

This year, sLTER continued to focus on partnership programs, 1) teacher professional development through our work with the SBC-LTER and the NSF-funded Authentic Research Experiences for Teachers (ARETs) in a cross-site project along with the Arctic (ARC) and Andrews Forest (AND) LTERs, and 2) the American Association of University Women's (AAUW): Tech Trek Program,

Tech Trek is an on-campus residential science and math summer program designed to develop interest, excitement and self-confidence in young women entering the eighth grade. Tech Trek is part of an interdisciplinary partnership involving science, technology, engineering, and math departments at UCSB through the Office of Education Partnerships (OEP). The goal of OEP is to build college-going communities that improve student learning, increase college-going rates in underrepresented populations, and provide equal access to higher education for California's diverse students. In working with Tech Trek, the SBC sLTER program engaged two groups of 80 girls each (160 TOTAL) from junior high and middle schools from San Luis Obispo, Santa

Barbara, Ventura, Kern and Los Angeles counties, representing a diverse range of socioeconomic and demographic groups. During a weeklong residency at UCSB, students participated in "core" science courses. This year the program focused on solutions to three real-world challenges, Ocean Exploration and Climate Change, Space Exploration, and Robotics. Participants enrolled in a "core" class based on their interests: Physics, Math, Engineering, or Marine Science. Students also engaged in a number of place-based, hands-on, activities that promoted concept application and citizenship, including a boat trip to SBC Kelp Forest study sites and SBC-based Floating Lab that focused on marine ecology and ecosystem services. We are now seeing former program participants enrolling in UCSB.

SBC LTER's partnership with O_2C and the REEF completed another very successful year in teacher professional development, as well as academic support in participant classrooms. We remain committed to equipping educators with the tools they need to teach ocean and environmental science, foster science literacy, and cultivate the next generation of ocean stewards. UCSB began developing a significant relationship with the UCSB Learning Centers. We co-hosted a Summer Data Literacy workshop, in collaboration with Dataspire, that focused on the importance of place-specifically, the kelp forest (SBC), Temperate Rainforest (AND) Arctic ecosystems (ARC). We have continued developing a significant relationship with the UCSB Learning Centers to develop curricula that uses SBC science. We continue to use our SBC LTER Schoolyard Series book, The Golden Forest, to broaden our K-12 outreach efforts. Our book highlights connections between giant kelp forest and sandy beach ecosystems and has been provided to hundreds of K-8 teachers as part of our partnership with the SBCEO to enhance science content knowledge. Other programmatic outreach efforts include: (1) developing SBC's Subtidal Field Guide and (2) annually hosting a booth at the Santa Barbara Earth Day Festival, to raise public awareness about LTER research. Our popular booth features a model of a kelp forest in which SBC students and staff act as 'dive buddies' for children who tour the forest and collect data on kelp forest species using underwater dive slates, and a kelp holdfast dissection activity. In 2022, SBC participated in the first in-person Earth Day festival since the pandemic.

SBC Investigators, postdocs and students contributed to stories in the press.

Kelp wrack consumers are prey for the dwarf island fox

https://www.news.ucsb.edu/2022/020574/beachy-buffet

The power of collaboration in ocean research

https://www.news.ucsb.edu/2022/020653/all-ocean

Urchins emerge to forage on living kelp when drift kelp is scarce

https://www.news.ucsb.edu/2022/020679/prickly-situation

Researchers track movement of debris disposed at Goleta Beach following the catastrophic 2018 Montecito debris flow

https://www.news.ucsb.edu/2022/020689/after-debris-flow

A special issue of BioScience reveals impacts of climate change across different ecosystems

https://www.news.ucsb.edu/2022/020695/broad-look-climate-change

Remote sensing and field observations paint a clearer picture of giant kelp dynamics

https://www.news.ucsb.edu/2022/020540/view-above

Scientists connect diet and temperature to metabolism in a fish

https://www.news.ucsb.edu/2021/020487/opaleye-opening-result

Nutritional value of giant kelp decreases as sea temperatures increase

https://www.news.ucsb.edu/2021/020445/warmer-water-less-nutrition

What is the impact on physical resources that form infrastructure?

Research facilities on campus extensively used by SBC researchers also include a flow-through seawater system, small boat and diving operations, analytical chemistry instrumentation, and computational resources provided by MSI and the Earth Research Institute. Our research activities contribute significantly to justifying the continued support of this infrastructure by the University, which benefits students and other research and education endeavors.

What is the impact on institutional resources that form infrastructure?

SBC's research and education programs greatly benefit from and support infrastructure provided by UCSB's Marine Science Institute (MSI), which offers SBC participants efficient and friendly service in contracts and grants, personnel, budgets, purchasing, and travel, and expert analytical chemistry services via MSI's Analytical Laboratory. Our research activities contribute significantly to justifying the continued support of this infrastructure by the University, which benefits students and other research and education endeavors.

What is the impact on information resources that form infrastructure?

Among the total of 234 SBC's publicly available datasets published in the repository of the Environmental Data Initiative (EDI), seven new datasets were added since Oct 2021. Most of these recently added datasets were specifically designed to meet journals' increasingly frequent requirement to post data along with research papers. Among the new data packages, five datasets were from students and postdoctoral scholars. The long-term ongoing time series datasets (a total of 39 data packages) have had at least one update since Oct 2021. All metadata are available in the XML specification Ecological Metadata Language (EML), and all data packages are accessible from the SBC data catalog, EDI repository, BCO-DMO data page, and DataOne. Between Oct 2021 and Sep 2022, SBC data packages had a total of 22983 public downloads.

Recent IM accomplishments and progress

- To expand the data service and improve users' understanding of the SBC datasets, Li Kui has actively collaborated with graduate students and researchers on data analysis, which significantly speeds up the journal publications and dissertation/thesis completion. The primary projects include 1. Research on the effect of the marine heatwave on urchins in the Santa Barbara Channel and kelp recovery trajectory in the post-disturbance period. 2. Data liaison for the synthesis group focusing on consumer mediated nutrient dynamics in marine ecosystems and their responses to disturbance events. 3. QA/QC for the data collected by the graduate students. 4. Producing datasets for K-12 education activities as well as researchers from NASA, NOAA, and other research institutes.
- During the last mid-term review, one suggestion for the Information Management was to upgrade older metadata so that there is consistency in the "Data Set Usage Rights". SBC upgraded the intellectual rights of all SBC data packages (a total of 234) to CC By 4.0, which is recommended by the LTER network office.
- LTER network office has launched a new system to store and maintain the personnel and email groups at each site. SBC worked with the network office to update our personnel to reflect the current active research team.

SBC webpage has enhanced the news sharing function by embedding the news feed from Instagram and tweets, which were updated weekly/daily.

What is the impact on technology transfer?

Li Kui led a meetup discussion organized by the National Center for Ecological Analysis and Synthesis (NCEAS) to share a data publication workflow using tabular strategies for metadata collection, which aims to benefit a broader data science community. The discussion content was put into a journal article and published in Ecology and Evolution to provide data publication tools for the community: Lortie, C. J., Vargas Poulsen, C., Brun, J., & Kui, L. (2022). Tabular strategies for metadata in ecology, evolution, and the environmental sciences. Ecology and Evolution, 12, e9245. https://doi.org/10.1002/ece3.9245

The SBC's website system has incorporated Jekyll, JavaScript, and Metabase as frontend display and backend information storage, which was free and easy to maintain. Several LTER sites have recently planned to rebuild their website system and are searching for recommendations among LTER sites. SBC has shared the website scripts with the other LTER sites and research groups to help their website development. The uniqueness and completeness (especially our data catalog) of our website system received high compliments in the network.

What is the impact on society beyond science and technology?

- SBC LTER data and studies are showing the effects of marine reserves on ecosystems and fishing. New work showing spillover bolsters the case for marine reserves as management tools and may help improve the design of future reserves and networks.
- SBC LTER expertise and data on patterns and drivers of kelp productivity is informing the possibility of kelp farming for biofuels off the coast of CA. DOE is funding several

projects on this topic; one is using SBC LTER data to develop a model for kelp farm siting.
- SBC investigators and students responded to the Refugio Beach oil spill in May 2015 and more recently to the 2021 Huntington Beach Oil Spill. For the Refugio Beach oil spill, they worked with agencies to determine the impacts and advise on restoration. SBC LTER data was critical in documenting natural communities at impacted sites to calculate the Natural Resource Damage Assessment (NRDA) settlement finalized in 2020 and dispersed this year for the Refugio Beach oil spill. They are currently assisting with NRDA studies for the 2021 Huntington oil spill.
- SBC investigators and students are collaborating with the Bureau of Ocean Energy Management, to assess factors affecting the spread and ecological impact of the invasive bryozoan *Watersipora subtorquata*, which is rapidly increasing at SBC study sites.

SBC investigators serve as science advisers for public and non-governmental agencies tasked with managing coastal resources.

What percentage of the award's budget was spent in a foreign country?

Nothing to report.

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Changes/Problems

Changes in approach and reason for change

Nothing to report.

Actual or Anticipated problems or delays and actions or plans to resolve them

The original schedule we planned for SBC's research campaigns was significantly affected by Covid. For the most part, Covid shifted these campaigns over by 1.5-2 years. For the benthic competition experiments and the drone surveys in theme 3A, this is not too concerning from our viewpoint because these were intended to be longer-term activities that would extend into the next cycle of SBC if not beyond. However it does push the other campaigns, 1B, 2B, 2C, 3B and 3C to the end of the project. This is not ideal, since it does not give us much time to plan for the renewal with all the results in hand that we'd like. As these campaigns proceed, we plan to adaptively manage them, doing analyses and reconsidering the timelines as results come in, to compensate for some of this effect. However, it may be that some of the same or similar topics continue into our renewal proposal for SBC V.

Changes that have a significant impact on expenditures

Nothing to report.

Significant changes in use or care of human subjects

Nothing to report.

Significant changes in use or care of vertebrate animals

Nothing to report.

Significant changes in use or care of biohazards

Nothing to report.

Change in primary performance site location

Nothing to report.