

PROJECT SUMMARY

Intellectual Merit: The Moorea Coral Reef (MCR) LTER was established in 2004 to investigate community and ecosystem effects of pulsed perturbations and slowly changing environmental drivers on coral reefs, ecologically and economically important ecosystems that are at high risk from local and global stressors. The site is the coral reef complex surrounding the island of Moorea, French Polynesia, which includes a lagoon system (with fringing reef and back reef habitats) and a steeply sloping fore reef offshore. The core issue that unifies MCR research centers on ecological resilience, specifically the processes and attributes that affect the capacity of a coral reef to absorb perturbations and reassemble to a community dominated by stony corals without degrading to an alternative state (e.g., one dominated by macroalgae). At the end of MCR I, virtually all of the coral on the outer fore reef surrounding Moorea was killed by a natural but brief outbreak of a coral predator, which was followed by storm waves that removed dead coral skeletons from the fore reef on one of the three shores of the island. These perturbations had little effect on corals in lagoon habitats. Spatial variation in the landscape-scale effects of these qualitatively different perturbations provides the MCR with an unparalleled scientific opportunity to address fundamental, unresolved questions regarding disturbance and recovery of coral reefs, together with the effects of community structure on reef functioning.

The MCR research program addresses two time horizons and hence our proposed research activities are organized into two corresponding themes. Research Theme 1 (*Resilience of Contemporary Reefs*) focuses on factors that promote or inhibit the return of a perturbed reef community to a coral-dominated state under current levels of stressors from Global Climate Change (GCC) and Ocean Acidification (OA). Research Theme 2 (*Structure and Function of Reefs in the Future*) addresses the longer time horizon and seeks insight into how forecasted changes in GCC- and OA-related drivers may alter the structure of the benthic community, together with the consequences of those changes to ecosystem processes. Our integrated research program for these inter-related themes includes question-driven time series measurements, long term field experiments, shorter-term field and laboratory experiments and measurements, and modeling and synthesis activities to integrate and generalize the results.

The six goals of MCR IIB are to: (a) contribute to understanding what factors influence reef resilience and how GCC- and OA-related drivers will affect coral reefs; (b) continue our long term datasets on community dynamics, ecosystem processes and physical and chemical drivers; (c) maintain 3 long term field experiments and initiate 1 new one; (d) develop and test ecological theory; (e) continue to enhance our information management system to more fully meet the needs of the LTER network and the broader scientific community; and (f) maintain the effectiveness of our outreach components.

Broader Impacts: Coral reefs are not just ecologically important - they yield upwards of \$375 billion annually in goods and services (most of it in the developing world) that are vulnerable to human activities and climate forcing. Hence our research has relevance and application to resource managers, policy makers and stakeholders worldwide. Our findings are presented annually to the Minister of the Environment of French Polynesia and have been used in the development of Marine Protected Areas for Moorea. Broader impacts arising from our educational activities include postdoctoral mentoring, research that integrates undergraduate and graduate training, active participation of ROA faculty researchers and K-12 teachers in MCR research, incorporation of MCR findings in teaching curricula, progress towards an ethnically diverse MCR student community, and involvement of faculty and students from predominantly undergraduate and minority-serving institutions. Additional impacts are realized by our outreach efforts, including partnerships with three local schools that serve socio-economically disadvantaged and minority students, with the UCSB REEF (Research Experience & Education Facility) that exposes over 10,000 K-12 and public visitors annually to MCR research, and with the Atitia Center on Moorea to reach Tahitian school children and the public.

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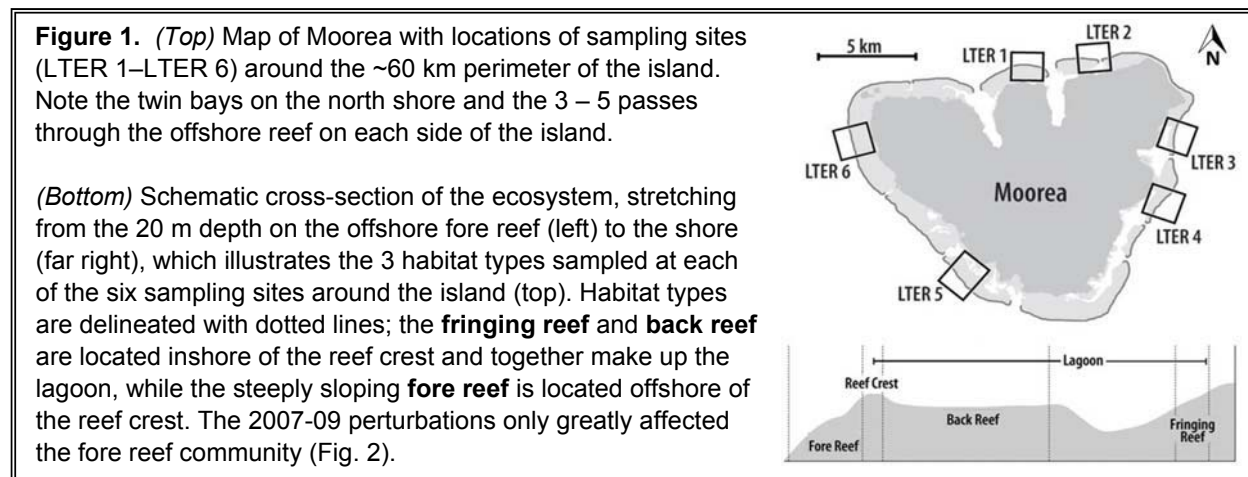
MOOREA CORAL REEF (MCR) LTER - PROJECT DESCRIPTION

SECTION 1 - RESULTS FROM PRIOR SUPPORT

MCR LTER IIA: Long Term Dynamics of a Coral Reef Ecosystem. OCE-10-26851; Funding (2010-2012): \$1,880,000 (excluding supplements)

1.1. RESEARCH

Background The Moorea Coral Reef (MCR) LTER, established in 2004, has been exploring community and ecosystem effects of pulsed perturbations and slowly changing environmental drivers on coral reefs, ecologically and economically important ecosystems that are at high risk from local and global stressors. The site is the coral reef surrounding Moorea, French Polynesia, and includes the fringing reef along the shore, the back reef, and the fore reef seaward of the reef crest (Fig. 1). Toward the end of MCR I, the fore reef of Moorea was perturbed by an outbreak of the corallivorous Crown-of-Thorns Seastar (COTS) followed by a cyclone. These natural events killed almost all corals on the fore reef but had little effect in the lagoon (Fig. 2). Coral reefs always have been impacted by these kinds of massive disturbances, but *never before has there been a reef system with such comparable levels of prior research, high resolution in situ instrumentation and time series measurements made before, during and after such a major set of perturbations.* This is providing the MCR with an unparalleled scientific opportunity to address fundamental, unresolved questions regarding disturbance and recovery of coral reefs. This opportunity to intensively study the development of a complex ecological system contextualized by landscape-scale environmental heterogeneity and long term change is unique and is what LTER sites are specifically intended to accomplish.

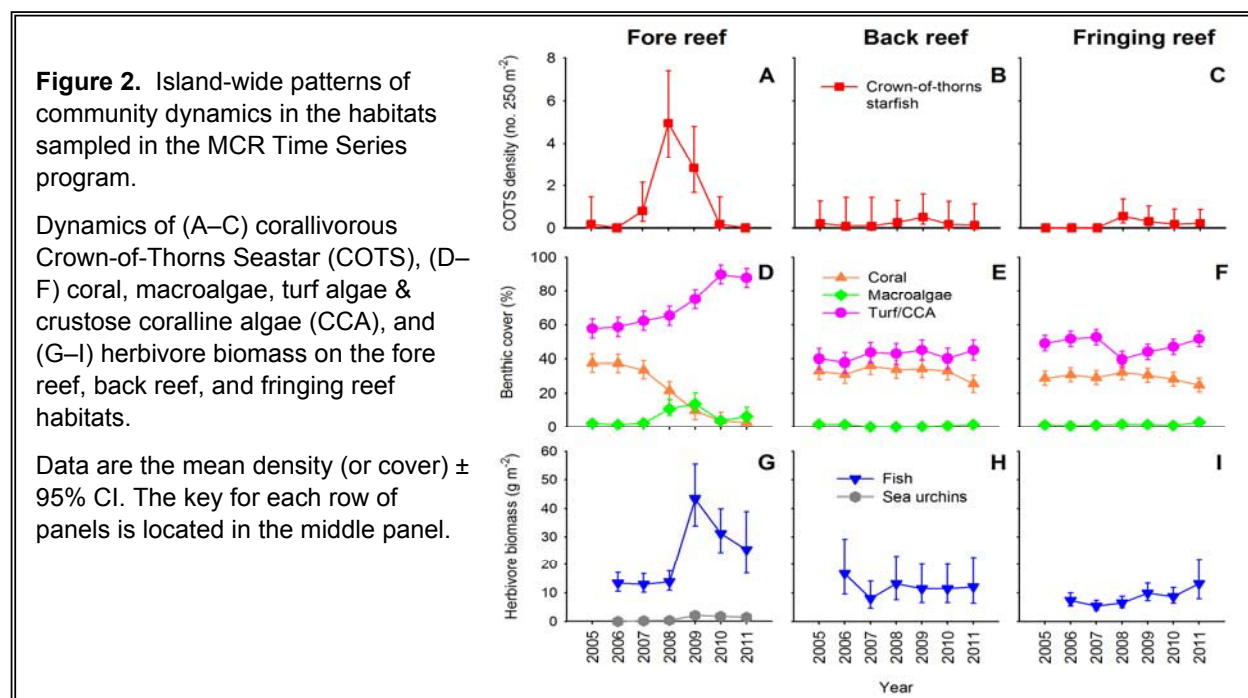


Overarching Theme & Prior Foci The core theme that unifies MCR research to date is *ecological resilience, specifically the processes and attributes that affect the capacity of a coral reef to absorb perturbations and reassemble to a community dominated by stony corals without degrading to an alternative state* (e.g., dominated by macroalgae). In MCR I (2004-2010) we developed an island-scale understanding of community dynamics in relation to variation in physical forcing, and advanced our knowledge of the biology of reef-forming corals to better project how they will respond to local, landscape, and regional-scale drivers of community change. The focus of MCR IIA (2010-2012) was to understand what processes prevent the perturbed fore reef from undergoing a persistent transition to a community dominated by macroalgae following the sudden death of coral, and to explore processes that govern dynamics of key species of corals. As described in Section 2 below, the focus of MCR IIB (2012-2016) extends this perspective by exploring processes and attributes that influence whether and at what rate the fore reef will return to a coral-dominated state.

Major Findings All citations below are MCR publications; 10 of our significant publications that motivate this renewal research are in **bold**. At the beginning of MCR I, we established a time series program to provide an island-wide, landscape perspective on community dynamics in relation to variation in wave exposure, which differs among the three sides of Moorea. Six sites (two on each side) were established with permanent sampling locations in the three coral habitats (fringing reef, back reef, fore reef) (Fig. 1); key biological and abiotic variables are measured at these sites at appropriate spatial and temporal scales. The MCR collected several years of time series data before the recent set of perturbations occurred. Community trajectories from coral reefs in other regions reveal that a rapid return to coral dominance is prevented if macroalgae become widely established following the sudden death of coral, a state shift that is becoming more common in the Caribbean and Pacific and which is believed to be persistent and self-reinforcing. Thus, two of our primary questions were:

- *What processes prevent a shift to macroalgal dominance following the loss of coral?*
- *What are the spatial and temporal scales over which those processes operate?*

Herbivory has long been known to be a critical process on coral reefs that can prevent a state shift to macroalgae, and management strategies to enhance resilience of coral reefs emphasize actions to avoid overfishing herbivores. Despite this, it is not well understood how herbivory operates on coral reefs (**Wilson et al. 2010**), particularly in response to the sudden, widespread loss of coral. MCR's time series data and field experiments provided novel insights into behavioral and dynamical responses of coral reef herbivores that have fundamental implications for management strategies to enhance resilience (**Adam et al. 2011**). Following the recent perturbations to the fore reef, the abundance and biomass of herbivorous fishes increased rapidly island wide, and grazing by these fishes prevented a state shift to macroalgae (Fig. 2). Importantly, the positive response of herbivores to increased benthic primary productivity associated with coral loss was attributed largely to parrotfishes, which initially recruit to nursery habitat (the mounding coral *Porites rus*) within the lagoon before moving to the fore reef later in life. Our work reveals critical connectivity between inshore and offshore reefs, and indicates that protecting nursery habitat of key herbivores is essential for maintaining reef resilience. We also have identified other critical connectivities that govern community dynamics (Price 2010, Edmunds et al. 2010, Adam 2011, Beldade et al. 2012).



Lagoon habitats show strikingly different community dynamics from the fore reef (Adjeroūd et al. 2009; Fig. 2). While coral cover has fluctuated tremendously on the fore reef, it has varied far less in lagoon habitats. However, pulsed perturbations (COTS, bleaching, cyclones) in the early 1980's triggered a persistent and functionally important shift in the species composition of corals in lagoon habitats. Those events greatly reduced the abundance of acroporid corals, especially the thicket-forming staghorn coral *Acropora pulchra*, a major provider of habitat for fishes and invertebrates. Staghorn *Acropora* has recovered little over the past 30 years, but mounding (*P. rus*) and massive *Porites* have increased while abundance of branching pocilloporids has not changed appreciably (Adjeroūd et al. 2009). Consequently we asked:

- *What governs the population dynamics of key species of corals?*
- *How important to resilience are feedbacks between host corals and species closely associated with them?*

Acroporids have lower resilience than pocilloporids in part because of differences in susceptibility of juvenile colonies to corallivory (Lenihan et al. 2011). We found the reason for the slow recovery of staghorn *Acropora* is that they must be defended from corallivores by a territorial farmerfish (Johnson et al. 2011). The interactions between farmerfish and staghorn *Acropora* revealed a general pathway (altered top-down forcing) by which the abundance of coral-associated animals simultaneously can be a cause and a consequence of the rate of habitat provisioning, a fundamental ecosystem process. We also found a second, potentially ubiquitous means by which coral-dwelling fishes can alter the provisioning rate of their coral habitat, which is to alter bottom-up forcing (Holbrook et al. 2008, Holbrook et al. 2011). Numerous species of fishes use coral structure for shelter, which sets the stage for a number of dynamically important interactions (Holbrook & Schmitt 2004, Stewart et al. 2006, Brooks et al. 2007, Schmitt & Holbrook 2007, Schmitt et al. 2009). We found that the abundance of resident fishes is positively related to the size of their coral host, and in turn the growth rate of the coral colony is greatly enhanced by the biomass of its associated fishes due to excretion of nitrogenous waste. Since most of the fish biomass is comprised of planktivores, this represents a functionally important flow of nutrients from the water column to the benthos. While we have long known that the amount of coral on a reef influences the number and type of fishes present, our findings show that the reverse often is true - the type of fishes present can markedly enhance the amount of coral on a reef. Thus our studies of fish – coral interactions are revealing critical roles that fishes play in the resilience and dynamics of corals.

Overfishing and pollution are two of the most important press drivers that are affecting the resilience of contemporary reefs. In addition to these local drivers, we have been focusing on longer-term effects of slowly changing global drivers on structural and functional aspects of reefs of the future. Two questions we initiated in MCR IIA were:

- *What insights do the recent past and present provide about the nature of coral reefs in the coming decades?*
- *Which coral species are likely to become ecologically dominant taxa in the future and why?*

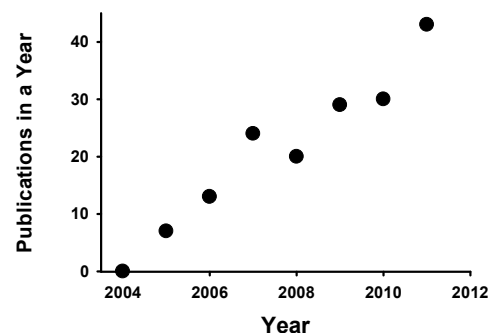
The two main global drivers we have been exploring in this context are rising sea water temperature due to Global Climate Change (GCC) and declining oceanic pH due to Ocean Acidification (OA). These two drivers have distinct modes of action on coral reefs. We primarily have focused on coral taxa that have the potential to emerge as ecological 'winners' in a future ocean of warmer waters and lower pH. Hence we used species of massive *Porites* corals as models to evaluate the extent to which they can resist thermal and pH stressors. We found that massive *Porites* spp. can exploit biomass plasticity to resist the effects of OA on calcification rates (Edmunds 2011). This is an important discovery, as it emphasizes the potential for biological control of mineralization to reduce the impacts of OA on corals. In addition to a variety of mesocosm experiments (Edmunds & Lenihan 2010, Putnam & Edmunds 2011), we have undertaken several synthetic activities regarding reefs of the future.

One product of our synthetic efforts was a comprehensive review of the effects of OA on calcification on scales ranging from the organism to the ecosystem (Hofmann et al. 2010). This

critical review juxtaposed the geochemical and biological views of calcification on coral reefs, and drew attention to the capacity of corals to acclimatize to reduce the impacts of OA. It underscores the need to evaluate the roles of the diverse assemblage of symbiotic *Symbiodinium* in mediating coral acclimatization, fully understand the role of different DIC species in coral calcification, and explore the role of nutrients in modulating the response of corals to OA. Additional synthetic papers involved the participation of MCR scientists in international efforts to: (1) identify critical gaps in our understanding of how assemblages of coral reef fishes will be affected by GCC and OA (Wilson et al. 2010) and (2) explore the negative interaction between human population density and reef fish biodiversity on ecosystem functioning (Mora et al. 2011). A separate synthesis activity was an NCEAS working group led by MCR scientists that convened experts (23 scientists from 5 countries) to address the concept of 'winning' corals and their role in defining the reefs of the future (Edmunds et al. in review). Critically, this group asked whether the fossil record and extant communities provide evidence that some corals are ecological winners. The evidence suggested that winning genera may occur on both Indo-Pacific and Caribbean reefs while other taxa are likely to become extinct.

In addition to models and time series measurements that describe pertinent physical processes that affect reefs of Moorea (e.g., Hench et al. 2008, Rosman & Hench 2011, Carpenter et al. in review, Leichter et al. in review), we developed biological models that help scale across levels of biological organization, including cellular to organismic (Muller et al. 2009), organism to population (Buenau et al. 2007) and population to community (Baskett et al. 2009, 2010, Buenau et al. 2011). For our focus on state transitions and dynamics of coral populations, we developed a structured landscape competition model to describe the conditions under which abrupt community shifts can occur (Buenau et al. 2007) and explored the effect of size-dependency on local interactions between corals and coralline algae in determining the outcome of space competition (Buenau et al. 2011). We also are developing models of reef resilience that reveal attributes and conditions that can result in alternative stable states (see pages 27-28). Regarding our reefs of the future focus, we have expanded Dynamic Energy Budget (DEB) theory to a syntrophic (cross-feeding) symbiotic relationship to describe the response of a model coral to varying light intensities and differing concentrations of nutrients (Muller et al. 2009, Eynaud et al. 2011). We expanded the basic DEB model to achieve synthetic capacity in a compilation of coral trait values (Edmunds et al. 2011) and will use it to explore effects of OA and temperature. Our size structured models of dynamics of coral hosts and their *Symbiodinium* on ecological and evolutionary scales help us evaluate conditions promoting high coral cover in an increasingly disturbed world (Baskett et al. 2009, 2010).

Summary Statistics In the past 6 years, MCR produced 159 publications (134 journal articles, 4 book chapters, 21 dissertations and theses). Our rate of publication has steadily grown during this period (right), reflecting maturation of a new site. LTER funds are leveraged by extramural awards to achieve our long term research goals. The funding level of grants that contributed to MCR research in the last six years was \$10.9 million.



1.2. BROADER IMPACTS

MCR has made significant contributions to postdoctoral, graduate, and undergraduate training, to multi-national public outreach, and to data dissemination. In the past 6 years, the MCR has engaged 24 postdoctoral researchers, 72 graduate and 104 undergraduate (13 REU, 2 ROA) students, 1 ROA faculty researcher and 5 K-12 teachers. They are involved in MCR research and outreach activities and participate in the annual two-day MCR All-Investigator Meeting; students co-organize an annual MCR-SBC-CCE LTER Graduate Student Symposium. A focus of MCR Schoolyard is the development of resources on our website (visited by 99 countries), including (1) a Marine Life in Moorea Encyclopedia, (2) research pages for MCR graduate

students, with photos and descriptions of their projects and (3) a teacher resource section with lesson plans written by 5 teachers who have received RET supplements to work in Moorea. Our RET participants are drawn from our partner schools in Santa Barbara and the Los Angeles area, which have large enrollments of under-represented or economically disadvantaged groups. Teachers in our partner schools use curricula based on MCR research and all 5 traveled to Moorea to gain experience in coral reef research to enhance their background as science educators. MCR graduate students also participate in Schoolyard activities, including hosting annually 110-115 fourth graders (most from under-represented groups) from Washington Accelerated School who visit UCSB to learn about marine biology and MCR science. Graduate students also lead activities targeted at young children at MCR's coral reef booth at the annual Earth Day celebration in Santa Barbara, and lead a marine biology club at a school in Los Angeles to expose children to MCR science through classroom and laboratory exercises. MCR participates in the REEF (Research Experience & Education Facility), which is an interactive marine educational facility at UCSB that serves over 10,000 K-12 and public visitors annually. Outreach in Moorea is made through the Tahitian association *Te Pu 'Atiti'a*, which partners with the Gump Station on outreach and education, and through the World Wide Web (after the U.S., the most public visitors to our website are from French Polynesia).

Coral reefs are not just ecologically important – they yield upwards of \$375 billion annually in goods and services that are vulnerable to human activities and climate forcing. MCR research has great relevance to resource managers, policy makers and stakeholders in French Polynesia and beyond, and we illustrate this with a few examples. MCR provided critical input to the Territorial Government of French Polynesia during the process of establishment of Moorea's Marine Protected Areas and participated in twice-yearly MPA surveys to evaluate their effectiveness (Lison de Loma et al. 2008). In addition, MCR PIs annually brief the Ministry of the Environment of French Polynesia on MCR findings. Recently this has included information central to the sustainable management of a threatened local artisanal fishery (giant clam; Yau 2011), our lagoon circulation studies that have implications for proper land use practices (**Hench et al. 2008**), and our work on resilience (**Adam et al. 2011**) that revealed the critical importance of protecting nearshore nursery habitats that are highly vulnerable to local human activities. MCR's information transfer recently expanded to Saudi Arabia as the MCR provided advice to King Abdullah University of Science and Technology (KAUST) for development of new coral reef research infrastructure and programs in the Red Sea.

MCR is a founding member of a grass-roots international group to develop real-time sensor networks in coral reefs (Coral Reef Environmental Observatory Network; CREON) (Brainard et al. 2010). Founding partners are the Kenting Coral Reef ILTER (Taiwan) and the Australian Institute of Marine Science, with cyber-infrastructure development led by UC San Diego. MCR serves as a test bed for development of real-time capability using open-source software for a variety of instruments, including pH and $p\text{CO}_2$ sensors critical in OA research (Fountain et al. 2009, Hofmann et al. 2011). U.S. participants have contributed significant technology transfer toward the development of the Great Barrier Reef Ocean Observing System. CREON assisted in the establishment a sensor network on coral reefs at Racha Island, Thailand and MCR is helping to facilitate the development of Racha Island into a coral reef ILTER site.

We participate centrally in efforts of the Computer Vision Coral Ecology group at Scripps Institution of Oceanography to develop an automated system to analyze benthic imagery. This likely will accelerate analysis of reef communities and facilitate management around the globe.

MCR participated in the cross-LTER site MIRADA Project (Nelson et al. 2011, McCliment et al. 2012). In addition, MCR Investigator Gates developed and hosts GeoSymbio, a cloud-based web application whose goal is to facilitate data discovery, visualization, and sharing for global research on *Symbiodinium* (the symbiotic dinoflagellate of reef-building corals) (Franklin et al. 2011) (<https://sites.google.com/site/geosymbio/>).

The MCR has further tightened its cooperation with a long term coral reef research site in the Caribbean that is funded through NSF's Long Term Research in Environmental Biology (LTREB) program. We assumed data management of the 25+ year time series data from the LTREB site on St. John (USVI) and host the publically-available data on the MCR web site.

MCR recent research findings have been highlighted in the popular press. Our work regarding how parrotfish prevent phase shifts (**Adam et al. 2011**) was disseminated broadly on the internet, both in the United States and internationally. Our research on ocean acidification (**Edmunds 2011**) was featured by NSF as one of the Top Discoveries from NSF Research (http://www.nsf.gov/discoveries/disc_summ.jsp?cntn_id=122642&org=NSF), and MCR research describing how crabs help corals survive by cleaning sediments from them (Stewart et al. 2006) was featured on the National Geographic Society Kids website (<http://kids.nationalgeographic.com/kids/stories/animalsnature/crabs-clean-up/>). More recently, we were highlighted in a National Geographic Society Special Report on Moorea (<http://news.nationalgeographic.com/news/2011/02/110223-biodiversity-moorea-biocode-barcoding-genetic-sequencing-ecosystem/>), and collected organisms featured in the Tropical Island Infinite Photo in that report and the Cubic Foot article in the print magazine (<http://ngm.nationalgeographic.com/2010/02/cubic-foot/wilson-text>). The MCR also was highlighted in a *Nature* feature that illustrated the scope of science being conducted around the globe (*Nature* 441:1040-1045).

1.3. RESULTS OF SUPPLEMENTAL SUPPORT

Education and Outreach Activities funded by our Schoolyard, REU and RET supplements are described above. An ROA supplement (2010) enabled J. Idjadi (Eastern Connecticut State University) to bring two students to Moorea to conduct field research as well as attend our annual All Investigator Meetings at UC Santa Barbara in 2010 and 2011.

Equipment Supplemental funds for equipment have been used to obtain new OA-related sensors and to replace worn out items (e.g., outboard engines) and several physical oceanographic instruments lost during Cyclone Oli. They have also contributed to the acquisition of two major research assets: (1) a mesocosm facility at the Gump Station, and (2) an oceanographic mooring with an inductive modem and associated oceanographic instruments, which is our test bed for developing real-time data streaming technology.

International Funds from NSF's Office of International Science & Engineering (OISE) have enabled MCR investigators to form two major, ongoing collaborations with international partners, which resulted in 23 publications in the past 6 years. We initiated the first in 2006 with a student and researcher exchange with the Kenting Coral Reef ILTER site (Taiwan), and this effort has matured into (1) an MOU with National Dong Hwa University, (2) ongoing exchanges (including annual meetings) with scientists at Taiwan's Academia Sinica and (3) major NSF funding for research. To date 9 MCR graduate students, 2 undergraduates, 3 postdocs and 7 faculty have conducted research projects with our partners in Taiwan funded by several NSF programs and the National Science Council of Taiwan. Faculty and graduate students from Taiwan also have been hosted by the MCR on our campuses and field site.

Our second major effort involves European and French Polynesian coral reef scientists. Supplements have supported planning visits to France and Monaco to develop collaborations on (1) coral reef community dynamics, (2) larval connectivity and (3) coral calcification and reef metabolism in Moorea. The first two areas of collaboration have resulted in several joint publications and the first reef metabolism project began in early 2012 (see page 26 for participants). Finally, MCR PIs received an OISE award that enabled MCR and SBC investigators to travel to the People's Republic of China to begin building cooperation with marine ILTER sites within the Chinese Environmental Research Network (CERN).

Other / Information Management (IM) With IM supplemental funds, MCR participated with Georgia Coastal (GCE), Santa Barbara Coastal (SBC) and Coweeta (CWT) to implement GCE's relational metadata model. This model is part of an IM system that supports current LTER Network Information System protocols and will support future metadata-mediated data access. Work at MCR and SBC resulted in (1) the adaptation of the central metadata model to the open-source DBMS PostgreSQL, and (2) the creation of modular scripts to build EML data packages via web services and XML export.

SECTION 2 - PROPOSED RESEARCH

2.1 INTRODUCTION & GENERAL FRAMEWORK

Building on our prior research and the unique opportunity afforded by recent perturbations to our site, the MCR is poised to contribute greatly to understanding resilience properties of coral reef ecosystems, together with how key community attributes and ecosystem functioning are likely to be altered by long term environmental drivers. These form the two core questions that underlie the proposed research of MCR IIB.

Core Question 1: *What processes and attributes enhance or weaken the ecological resilience of coral reef ecosystems?*

Core Question 2: *How will environmental drivers alter community composition and ecosystem functioning in the future?*

Ecological resilience (hereafter resilience) has two components: the capacity of an ecosystem to remain qualitatively unchanged in the face of pulse and press drivers, and the propensity to, and the rate at which a community reassembles to its pre-disturbed state following a disturbance. So our focus is on the ability of a coral reef ecosystem to absorb perturbations and to continue to reassemble to the coral state without gradually degrading or rapidly switching to a persistent alternate state (Hughes et al. 2010). Our proposed research is motivated by the recent perturbations at Moorea, our research progress and our analysis of critical information gaps.

Coral reefs are among the most biologically diverse of all ecosystems, but also are among the most threatened (Mumby & Steneck 2008). Recent trends in the dynamical behavior of coral reef communities emphasize the vital *need to understand more fully why some coral reefs degrade while others do not* (Hughes et al. 2003, 2005, 2010). Throughout their evolutionary history, coral reefs have been repeatedly subjected to a variety of perturbations (Aronson & Precht 1997, Pandolfi 1999). Until recently, coral communities demonstrated the capacity to reassemble to their prior state – that is, return to coral dominance – following a pulse perturbation such as a cyclone (Jackson 1992, Aronson & Precht 1997, Pandolfi & Jackson 2006). Observations in the past two decades, however, show that many perturbed reefs either undergo a phase shift to macroalgae or otherwise fail to return to coral dominance (Hughes 1994, Shulman & Robertson 1996, Aronson & Precht 1997, Rogers & Miller 2006, Bruno et al. 2009). The modern paradigm is that coral reefs are an increasingly stressed ecosystem that is structured by strong positive and negative feedbacks (Mumby & Steneck 2008).

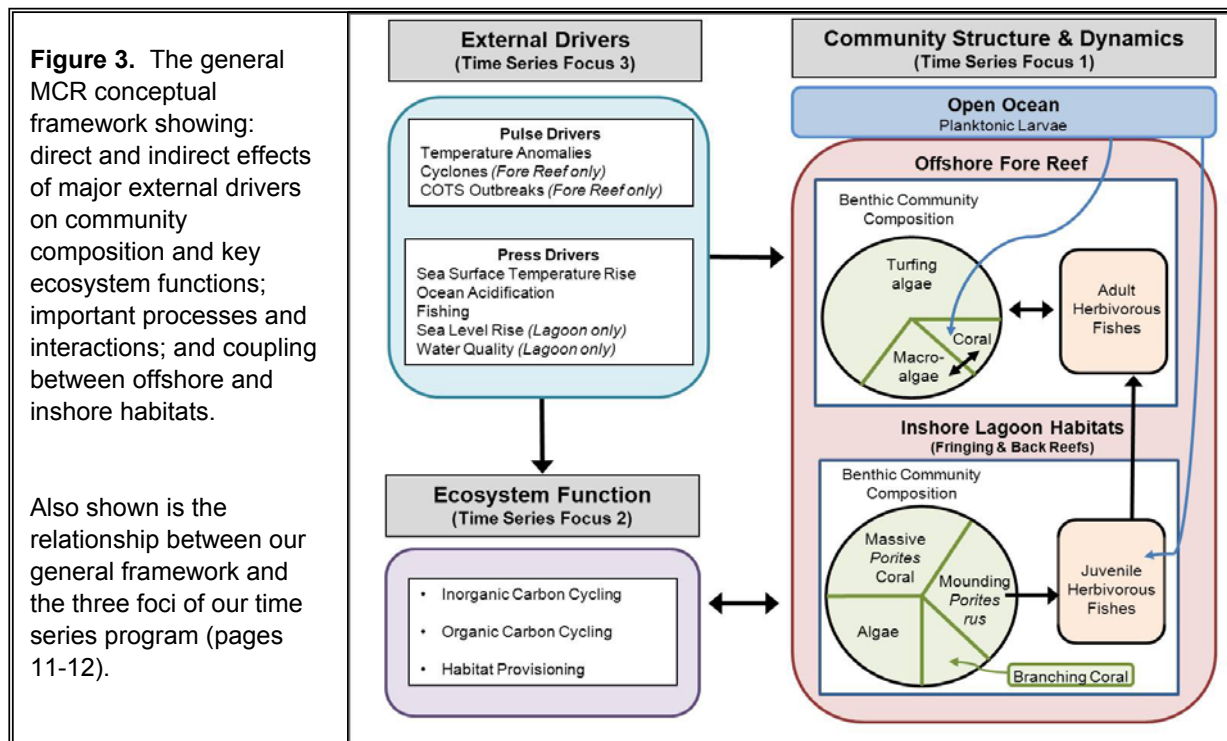
Many of the recent state changes away from corals on tropical reefs, particularly those where fleshy macroalgae come to dominate, are regarded as regime shifts that appear difficult to reverse because of self-reinforcing feedbacks (Hughes et al. 2005, 2010, Mumby & Steneck 2008). The underlying cause of these state shifts has been attributed to a combination of human-induced drivers that lowered the ecological resilience of these systems (Jackson et al. 2001, Bellwood et al. 2004, 2011, Mumby & Steneck 2008, Hughes et al. 2010). Two of the most important press drivers are fishing and pollution (particularly nutrient loading), and both can foster growth of macroalgae (Bellwood et al. 2004, Fabricius 2005, Bruno et al. 2009). However, time series data from some reefs, including Moorea, indicate that in the absence of chronic stress, corals can recover on a decadal time scale (Connell 1997, Connell et al. 1997, Sheppard et al. 2008, Smith et al. 2008, Adjeroud et al. 2009, Trapon et al. 2011).

While overfishing and pollution are immediate threats to coral reefs, these local press drivers occur against a background of intensifying global stresses resulting from increasing concentrations of atmospheric CO₂. For coral reefs, two of the most important global drivers are increasing temperature and declining pH of ocean waters (Pandolfi et al. 2011). Global Climate Change (GCC)-related rises in sea surface temperature (SST) increase the frequency and prevalence of coral bleaching (i.e., loss of *Symbiodinium* from coral tissues) (Hoegh-Guldberg 1999), foster outbreaks of coral disease (Bruno et al. 2007), and possibly increase the frequency and/or intensity of large storms (Walsh & Ryan 2000, Emanuel 2005, Mann & Emanuel 2006). Rising temperatures also result in rising sea level. This is expected to

negatively impact reef communities (Webb & Kench 2010) and increase the frequency with which sudden thermal anomalies exceed bleaching thresholds (Oliver et al. 2009). This makes it critical to understand the capacity of corals to acclimatize or adapt (genotypic response) to rapidly intensifying thermal stress (Edmunds & Gates 2008, Brown & Cossins 2011). Differences in thermal tolerances and capacities for acclimatization may favor a community shift to corals with massive morphologies (Loya et al. 2001, van Woesik et al. 2011).

Some scientists believe that in the future, ocean acidification (OA) may be a greater threat than rising temperature to coral reefs because it may result in a world-wide decline in the calcification rates of corals and other functionally important calcifiers such as crustose coralline algae (Kleypas & Langdon 2006, Doney et al. 2009, Hofmann et al. 2010). Rising concentrations of atmospheric CO₂ are slowly lowering both the pH and the calcium carbonate saturation state (Ω_{arag} for corals, and Ω_{calcite} for many other taxa) of the ocean. As Ω declines, the precipitation of calcium carbonate becomes increasingly difficult and thermodynamically costly (Cohen & Holcomb 2009, Erez et al. 2011). The ecological consequences of reduced Ω are largely unknown, but the most pessimistic projection is that net dissolution of coral reefs may occur within a century (Silverman et al. 2009), with heightened vulnerability to wave energy from weakened skeletons possible in the coming few decades (Madin & Connolly 2006). Although little is known regarding mechanisms corals may use to resist low pH (Hofmann et al. 2010, Tambutté et al. 2011), we have evidence that some massive corals can ameliorate the effects of OA via biological control of mineralization (Edmunds 2011). This suggests there may be coral taxa that have the potential to emerge as ecological ‘winners’ in a future ocean of warmer waters and lower pH. However, the consequences of changes in community composition of coral reefs caused by environmental drivers to major ecosystem functions such as carbon cycling and habitat provisioning are largely unknown (Fabry et al. 2008, Hofmann et al. 2011).

Conceptual Framework Figure 3 shows the general conceptual framework that unifies our proposed research program.



The response of herbivorous fishes that kept macroalgae in control following loss of coral on the fore reef (Fig. 2) highlights two important pathways of habitat connectivity. The first is recruitment of larval fishes and corals from the ocean to the reef, and the second is the

movement of older juvenile parrotfishes from inshore nursery habitat (*Porites rus*) to the fore reef. Subsequent return of coral domination on the fore reef hinges on successful recruitment of coral larvae, so larval connectivity with corals located elsewhere is critical (Hughes et al. 2000). Local press drivers (fishing, pollution) can affect reef resilience and community composition, as eventually will global press drivers (pH, temperature). Changes in community composition caused by these drivers in turn will alter major ecosystem functions and biological processes.

The MCR research program addresses two time horizons and hence we organize our proposed research activities into two corresponding themes.

- Research Theme 1 - Resilience of Contemporary Reefs focuses on factors that promote or inhibit the return of a perturbed reef community to a coral-dominated state under current levels of GCC- and OA-related stressors. This corresponds to *Core Question 1* above (page 7).
- Research Theme 2 – Structure and Function of Reefs in the Future addresses the longer time horizon and seeks insight into how forecasted changes in GCC- and OA-related drivers may alter the structure of the benthic community, together with the consequences of those changes to ecosystem processes. This corresponds to *Core Question 2* above (page 7).

More detailed frameworks for each theme, together with how our research activities relate to them, are presented in the relevant portions of the proposed research section below.

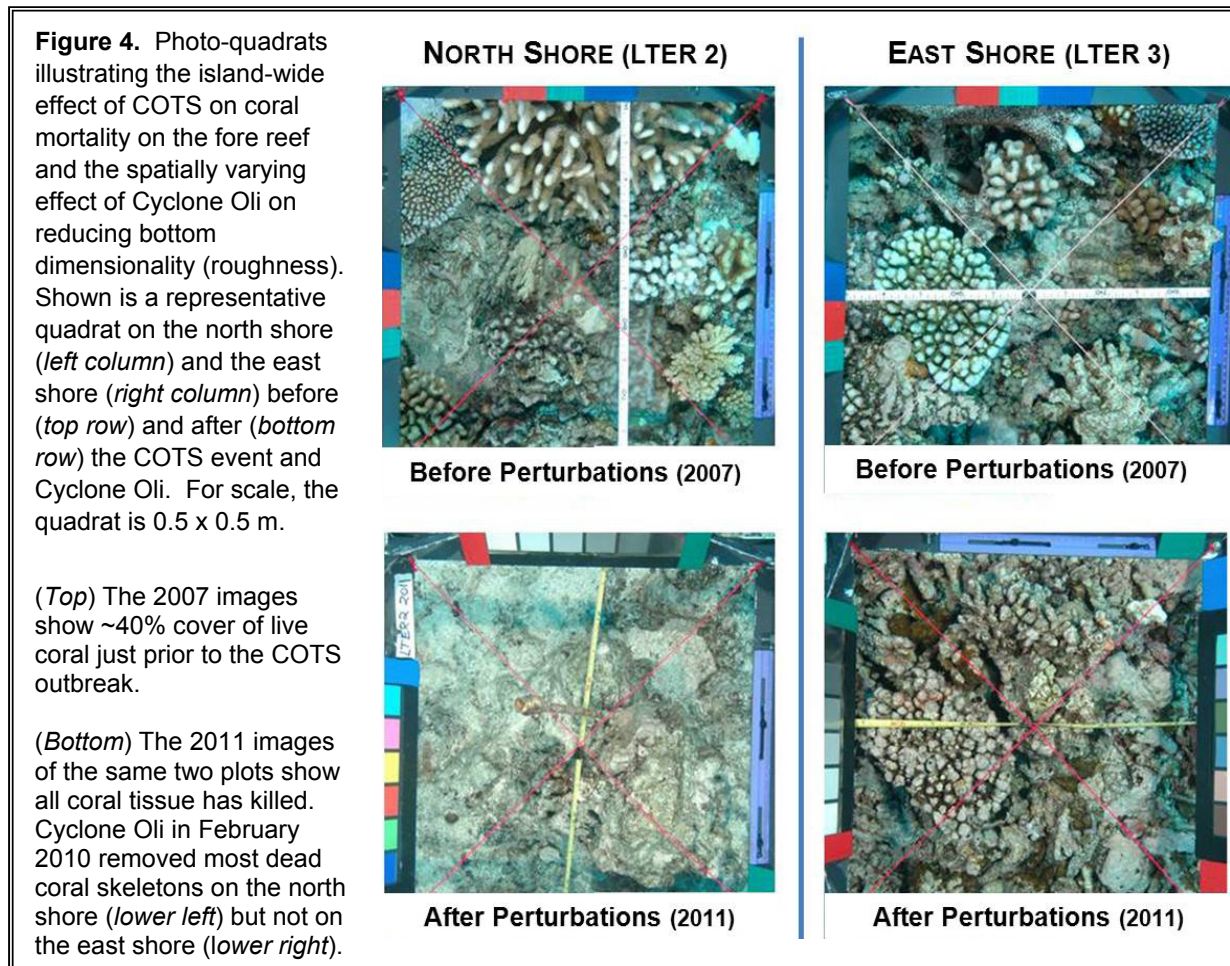
2.2 THE MCR LTER SITE & RECENT COMMUNITY DYNAMICS

Moorea, in the central south Pacific 20 km west of Tahiti, is a triangular volcanic ‘high’ island with a 60 km perimeter and an offshore barrier reef that encloses a shallow lagoon (Fig. 1). The MCR site is the area around the island from shore to the 20 m depth isobath on the fore reef slope. Our site contains three coral reef habitats: fringing reef, back reef and fore reef (Fig. 1). The island slopes steeply to the sea floor; depth 1 km offshore is ~ 500 m. Ocean water enters the lagoon over the reef crest and exits through passes through the reef; offshore wave forcing is a major driver of circulation within the lagoon (Hench et al. 2008). Swell prevails from the southwest in the Austral winter and from the north in the summer, producing seasonal differences in exposure of different island sides to large waves and high flows. Tidal amplitudes are small (≤ 20 cm) as Moorea is near amphidromic points.

The coral communities of Moorea have been subjected to repeated disturbances in the past several decades, including cyclones, bleaching events and outbreaks of Crown-of-Thorns Seastars (COTS) (Done et al. 1991, Adjeroud et al. 2009, Trapon et al. 2011). Nonetheless, when the MCR LTER was established in 2004, cover of coral in each of the three major coral habitats was near historic highs for the past half century (Adjeroud et al. 2009, Trapon et al. 2011). In 2007-08, an outbreak of COTS rapidly reduced the cover of live coral by > 95% on the fore reef (Fig. 2). The dead coral provided a substantial amount of substrata for algal growth, and the cover of macroalgae on the fore reef underwent a modest increase in 2008 and 2009 (Fig. 2). However, by 2010, macroalgae had declined to their low, pre-COTS levels, and ~ 90% of the fore reef is now covered by a mixture of filamentous turf algae and crustose coralline algae (Fig. 2). Between 2008 and 2010, roving herbivorous fishes on the fore reef doubled in density and tripled in total biomass, and they have remained elevated since (Fig. 2). In contrast, there was little or no change on fringing reef or back reef habitats in the cover of live coral, macro- or other algae, and density (and biomass) of herbivorous fishes (Fig. 2). A long term experiment, started in MCR IIA, has revealed the following to date: (1) fleshy macroalgae would have become the primary space holder on the fore reef following the COTS outbreak had they not been kept in check by herbivory; (2) sea urchins and other non-fish herbivores were unable to control macroalgae; and (3) grazing by roving herbivorous fishes – primarily parrotfish – prevented macroalgae from becoming established (Adam et al. 2011). In Moorea, parrotfish larvae settle from the plankton only to lagoon habitats, primarily to the mounding coral *Porites rus*, and juvenile parrotfish remain associated with this nursery habitat for several months before moving offshore to the fore reef (Adam et al. 2011). Consequently, parrotfish populations were able to respond numerically to increased food on the fore reef in part because their nursery

habitat was unaffected by the COTS outbreak and subsequent cyclone.

Because predation by COTS removes live coral tissue but leaves their skeletons intact, the COTS outbreak did not alter the architectural complexity of the fore reef. However, in February 2010, Moorea was struck by Cyclone Oli. Waves generated by Oli removed most of the dead coral skeletons from the fore reef on the north shore, but had little effect on the other two sides of the island (Fig. 4). Cyclone Oli did not reduce the amount of live coral in lagoons (Fig. 2).



2.3 RESEARCH PROGRAM

Our proposed research program takes full advantage of the extraordinary opportunity afforded by the recent sequence of – and spatial variation in – perturbations to the fore reef of Moorea. COTS and Cyclone Oli created landscape-level heterogeneity (Fig. 4) that enables us to explore responses to the two qualitatively different disturbances that affect coral reefs - those that immediately reduce bottom complexity and those that do not. More generally, these events provide the MCR with an unrivalled opportunity to address fundamental, unresolved questions regarding resilience of coral reefs, how those properties may be altered by long term environmental drivers and what the community and ecosystem consequences will likely be in a stormier, warmer and more acidic future ocean. Data absolutely essential to address these issues are gathered in our Time Series component, which is designed around three core foci that encompass the five general LTER research areas (<http://mcr.lternet.edu/data/topic/>) and is intended to be sustained for multiple decades. Our research program consists of: the time series component; long term field experiments; shorter-term field and laboratory observations and experiments; and modeling and synthesis to integrate and generalize results.

A. Time Series. Our time series program provides information on three key aspects central to our general framework (Fig. 3) and research themes [Table 1 (page 13); Table 2 (page 23)].

Time Series Focus 1: Community dynamics within each major coral habitat and long term trends of key functional groups

Abundances of corals, other macro-invertebrates, algae and fishes are estimated yearly on the fore reef, back reef, and fringing reef at six sites, two on each side of Moorea (Fig. 1). Estimates are made visually along permanent band transects or from permanent quadrats that, depending on the taxon, are surveyed either *in situ* (e.g., sea urchins) or later from photo-quadrats (e.g., corals; Fig. 4). Organisms (about 400 taxa) are identified to the lowest taxon possible (typically species or genus). We have quantified the morphological attributes and associated fishes of 66 colonies of *Porites rus*, one of the most important habitat-providing corals at Moorea, annually since 2000. In addition, we measure coral recruitment using settlement tiles deployed for 6-month periods as well as yearly visual counts of juvenile colonies on the reef substrata. Inter-annual variation in recruitment of reef fish is estimated from annual counts of fish < 1 year old at all permanent sampling locations. Daily settlement of fish larvae is estimated for a model species (a planktivore) by quantifying larval settlement on Gump Reef every morning between June - September (done annually since 1994). These datasets reveal different responses of inshore and offshore reefs to COTS and Cyclone Oli, and provide new insights into attributes that influence reef resilience (Adam et al. 2011).

Regarding analyses of photo-quadrats, we collaborate on G. Mitchell's (Scripps Institution of Oceanography; SIO) NSF-funded Computer Vision Coral Ecology (CVCE) Project, the goal of which is to develop computer vision technology to achieve rapid cyber-enabled image analysis. The MCR time series photo-quadrats are a critical resource for the CVCE project because of the number, quality and consistency of the images, as well as the detailed human annotation of the images that provides the crucial cross reference for the cyber-enabled analysis. The next phase of our collaboration is a multi-lab, blind test of human versus cyber-enabled analyses. We anticipate incorporating some of the technology in the near future, which will greatly reduce the time needed to process MCR photo-quadrats.

Time Series Focus 2: Temporal patterns in rates of key ecosystem processes and the influence of benthic community composition

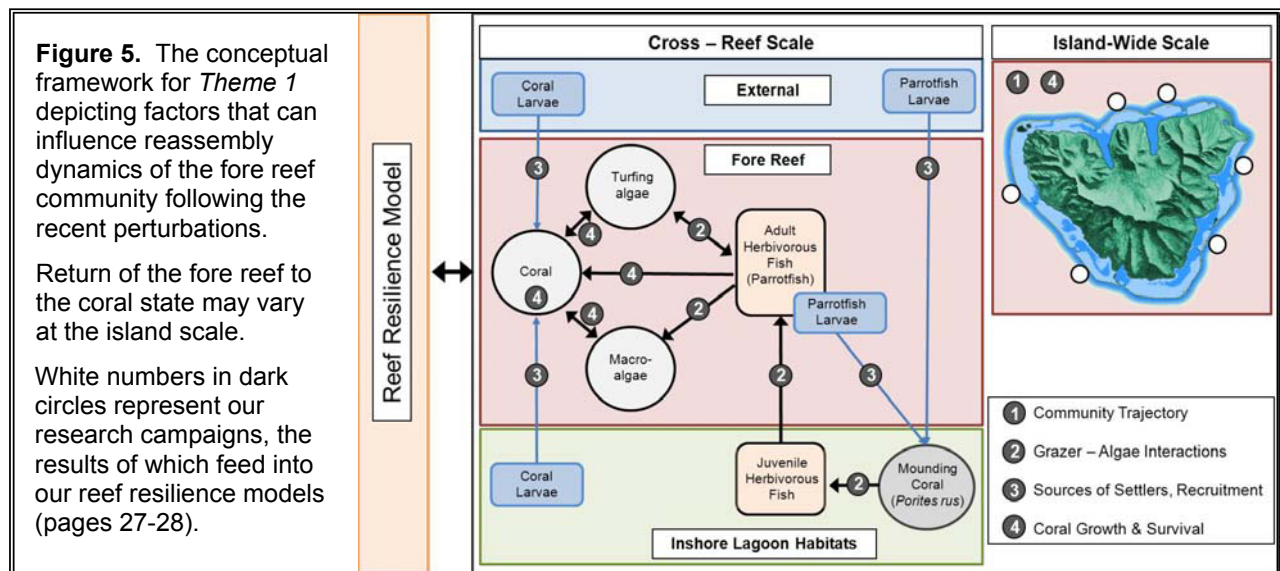
Rates of reef metabolism (primary production and respiration) are estimated twice annually along with photosynthetically active radiation (PAR) at two permanent locations on the north shore using a control volume approach. Rates of primary production of three important reef components (coral, algal turfs, macroalgae) are estimated in flume studies. In addition to the benthos, we estimate water column primary production in vertical profiles using standard ¹⁴C tracer/bottle techniques at several offshore, inshore and back reef sites. Coral reefs typically have very low production in the water column and very high rates of gross benthic primary production (GPP). Because reef heterotrophs normally consume almost all of that production each day, the net primary production (NPP) of the community typically approaches zero (Atkinson 2011); our data fit this paradigm. Variation in gross production is driven largely by differences in light and water flow that determine the fluxes of DIC and nutrients. Concentrations of nutrients (NO_2^- , NO_3^- , PO_4^{3-} , SiO_4^{2-}) are estimated concurrently with water column primary productivity (along with bacterioplankton biomass, DOC and POC concentrations, phaeopigments, Chl a, and turbidity). We also estimate nutrients (NO_2^- , NO_3^- , PO_4^{3-} , SiO_4^{2-}) at these locations biweekly (since 2007). Concentrations of nutrients in Moorea are low and typically near detection limits and because coral reefs do not respond to brief spikes in concentration (Atkinson 2011), current velocity is typically the dominant component of nutrient flux. Accordingly, we measure current velocities on appropriate spatial and temporal scales (see next), and also use estimates of CHN levels in two macroalgae (*Sargassum*, *Turbinaria*) in all three habitats as an integrated estimate of nutrient flux over longer periods.

Time Series Focus 3: Patterns of temporal and spatial variation in major abiotic factors that influence coral reefs

Coral reefs are physically-forced systems, and we have instrumented the reefs with multiple (~ 80) sensors to measure factors known to influence coral reefs [water temperature, salinity, current speed and direction, offshore wave statistics (height, direction, period), water levels]. Simultaneous measurements of wave heights and currents are critical given that water flow in lagoons and local circulation patterns are driven primarily by the offshore wave climate. We established two instrumented sites on each of Moorea’s shores where biotic surveys are conducted. Time series information on regional scale properties such as currents, water mass variability and meso-scale eddies comes from satellite remote sensing of sea surface topography (TOPEX Poseidon, ERS), temperature (AVHRR), and ocean color (SeaWiFS, MODIS). Oceanographic measurements are complemented by surface environmental data from our met station (solar irradiance, atmospheric pressure, wind speed and direction, air temperature, relative humidity and rainfall) at the Gump Station, and by data obtained from additional meteorological stations operated by Météo France around the island.

In addition to sea level and sea water temperature, we measure pH / DIC, which is related to OA. We measure the extremely slowly changing pH / DIC of the ocean due to increases in atmospheric CO₂ at a station 5 km off the island (bottom depth ~ 1,000 m), which minimizes island effects on the estimate. These samples are analyzed by A. Dickson at Scripps Institution of Oceanography. To date we have sampled on six dates. However, DIC is inversely correlated with sea water temperature, which can give rise to a detectable seasonal signal (Winn et al. 1998); hence we will increase offshore sampling to quarterly to capture possible seasonal variation. We also will conduct a short term sampling effort to assess within-season stability of pH / DIC estimates at our offshore station. Average pH of the ocean has declined by ~ 0.1 units from the pre-industrial period to the present (Doney et al. 2009). By contrast, metabolic processes of reef organisms can cause pH to fluctuate *daily* by 0.1 units or more on inshore reefs at Moorea (Hofmann et al. 2011). We are collaborating with scientists from UC San Diego to field test new pH sensor technology (Martz et al. 2010) (that eventually can transmit the highly precise estimates of pH continuously in real time). In 2012, the MCR will deploy these sensors (SeaFETs) across the reef as part of a cross-site project with SBC and CCE to delineate spatio-temporal patterns of variation in pH at our respective sites. Results of this project will guide MCR in designing a longer term program to measure pH across the reef as a new component of Time Series Focus 3.

B.1. Research Theme 1: Resilience of Contemporary Reefs.



Our ongoing and proposed research for Theme 1 addresses information gaps identified in recent reviews (Wilson et al. 2010, Graham et al. 2011). While coral reef degradation has been well documented, ecological determinants of recovery are largely unknown (Graham et al. 2011). In the coming decade we will address factors that influence whether - and at what rate - the fore reef will reassemble to its pre-disturbed state. Factors important to reassembly dynamics of the fore reef community are depicted in our Theme 1 framework (Fig. 5). Table 1 summarizes the research activities for each Theme 1 campaign question (Q) described below.

Table 1. Theme 1 Research Activities & Data Sources	Campaign Questions					
	Q 1	Q 2.1	Q 2.2	Q 3.1	Q 3.2	Q 4
Time Series Focus 1 – Community Dynamics	✓	✓	✓	✓		✓
Time Series Focus 3 – Abiotic Drivers				✓	✓	✓
Coral Recruitment Plots	✓			✓		
Rugosity Measurements	✓			✓		
Bathymetry Measurements				✓		
UNOLS Oceanography Cruise				✓		
Coral Population Genetic Studies					✓	
Parrotfish Population Genetic Studies					✓	
Demographic Analysis of Herbivorous Fishes			✓			
Coral Demographic Study						✓
Long Term Rugosity Experiment	✓					
Long Term Grazing Intensity Experiment		✓				
Macroalgal Consumption Experiment		✓				
Long Term Grazer Composition Experiment		✓				
Long Term Grazer – Coral Experiment						✓
Reef Resilience Modeling	✓	✓	✓	✓	✓	✓
ROMS Circulation Modeling				✓	✓	
Island & Local-scale Circulation Modeling				✓	✓	
Population Trajectory Modeling (Matrix & IPMs)	✓					✓

Campaign 1 – Community Trajectory & Reassembly ①

Question 1: How do the type of pulse perturbation and differences in structural heterogeneity affect the subsequent reassembly of the perturbed fore reef community?

Rationale: Campaign 1 addresses two unresolved issues regarding the response of coral reefs to pulse perturbations (Connell et al. 1997, Berumen & Pratchett 2006, Graham et al. 2011): (1) what factors cause variability in the rate at which different reefs return to a coral-dominated state; and (2) how similar is the community composition of the pre-disturbed versus the reassembled community? Structural heterogeneity provided by coral skeletons has long been thought to be a major determinant of resilience of tropical reefs following a disturbance (Colgan 1987, Connell et al. 1997). Pulse perturbations that harm reef-forming coral can be grouped into two distinct categories: those that kill coral tissue but leave coral skeletons intact (e.g., bleaching, COTS), and those that both kill tissue and remove their skeletons (e.g., storm waves, blast fishing). The former category does not immediately alter the three-dimensional structure of the reef, and it has been hypothesized that recovery to the coral state following this type of disturbance will be more rapid because ecological processes associated with structural heterogeneity may facilitate recovery (Colgan 1987, Connell et al. 1997). The meta-analysis by Graham et al. (2011) revealed a trend for more rapid recovery following disturbances that left structure intact, although the difference was not statistically significant. We are testing **the hypothesis that structural complexity from skeletons of dead coral enhances the probability and rate of return to a coral-dominated state.**

Approach: We are using two approaches to test this hypothesis. First, data from our time series program enable us to compare community trajectories at fore reef sites (LTER 3-6) that were perturbed mainly by COTS with two sites (LTER 1-2) where coral tissue was consumed by

COTS and their skeletons removed by Cyclone Oli. In addition to collecting our standard time series data at these locations, we will quantify reef roughness periodically at each site using the standard chain length rugosity technique (ratio of contour-following vs. linear distance between two points; Alvarez-Filip et al. 2009) to make coarse measurements, and a pencil-beam altimeter to make higher-resolution measurements needed to estimate boundary-layer properties. These features will be related to important demographic processes (recruitment, growth of coral) and biotic interactions (herbivory, corallivory). We established a new set of 5 x 5 m plots (Coral Recruitment Plots) on the fore reef at each of our six sites around Moorea in 2010 to make these measurements without disturbing our permanent time series transects. We will also monitor community development in these plots as well as within our regular time series transects, and use the new plots as platforms for shorter term observations and experiments.

Our second approach is a long term Rugosity Experiment initiated in 2010 to isolate the influence of dead coral structure on the return to coral dominance. Replicate 5 x 5 m plots at 12 m depth on the fore reef at LTER 3 (east side) were assigned to two treatments at random and divers removed dead coral skeletons from half of the plots and left skeletons intact on the remaining plots. Our manipulations reduced rugosity in removal plots by 65% and this treatment now has a rugosity that is very similar to the fore reef on the north shore following Cyclone Oli. Biological characteristics of these plots are being followed with visual surveys and photo-quadrats to estimate density or cover of major space holders, coral recruits and fish. Early indications suggest that the presence of coral skeletons may accelerate the rate of return to the coral state. Data from 2011 revealed that recruitment of juvenile coral was 3 times greater to plots with intact skeletons compared to plots where we removed skeletons.

Prior to the most recent set of perturbations, the relative abundance of coral morpho-types, structural heterogeneity of the habitat and characteristics of the fish assemblage varied spatially on the fore reef in a manner predicted by the strong gradient in exposure to wave energy around the island (Figs. 6, 7). The two recent perturbations each reduced spatial differences in the dominant space holders, which affected the local fish assemblages (Fig. 7). For each site, we are evaluating whether the biota is reassembling to the characteristic community structure of that locality just prior to the outbreak of COTS, and whether the rate of convergence and ultimate similarity vary with exposure to wave energy. An early pattern is that variation among the sites in the abundance of juvenile *Pocillopora* and *Acropora* in 2011 was negatively correlated with their respective cover in 2005 (prior to the COTS outbreak). We are following growth and survivorship of these recruits (Campaign 4), as well as their source locations (Campaign 3).

Figure 6. MCR time series measurements of maximum significant daily wave height (m) on the fore reef of the north (LTER 1) and southwest (LTER 5) shores (for locations, see Fig. 1 on page 1).

Waves exceeded 3 m (*dashed lines*) on the north shore only once - during Cyclone Oli in Feb. 2010 when they reached ~ 6 m (*top*). By contrast, 4 – 5 m waves are common on the southwest shore (*bottom*). MCR time series data revealed a strong gradient in wave intensity around the island, with LTER 5 exposed to the greatest cumulative wave energy and LTER 3 (not shown) the least.

See Figure 7 (next page) for the disproportionate effect of Cyclone Oli on the fish community at the north shore sites (LTER 1 & LTER 2).

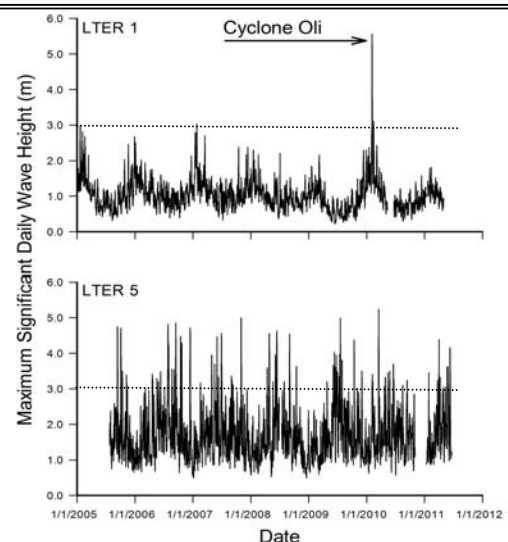
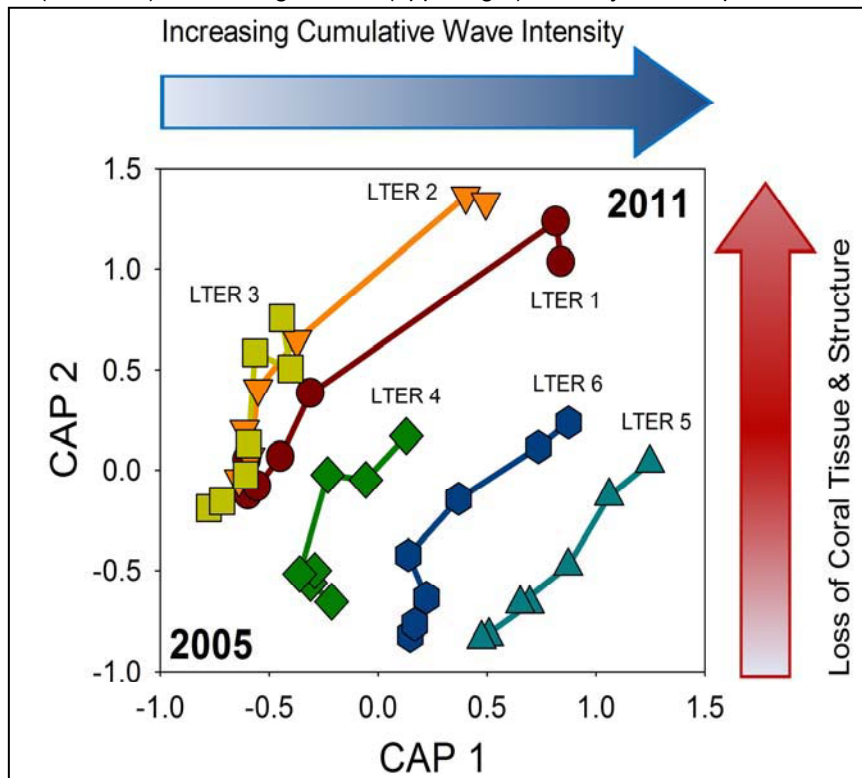


Figure 7. Spatial and temporal changes in the fish community on the fore reef at each MCR Time Series site as revealed by ordination analysis based on species specific abundances. For each site, a line connects successive years starting with 2005 (lower left) and ending in 2011 (upper right). Initially, sites separated primarily along the x-axis reflecting differences in species composition related to spatial differences in the cumulative wave intensities. The y-axis reflects temporal shifts associated with loss of coral tissue and, for LTER 1 & 2, a subsequent reduction in reef rugosity.

All sites followed similar trajectories following the 2007-09 COTS outbreak, revealing broadly similar responses of the fish communities to loss of coral tissue.

In Feb 2010, Cyclone Oli removed dead coral structure only on the north shore (LTER 1 & 2). The reduction in structural heterogeneity at these two sites resulted in large shifts in ordination space toward sites with greater chronic exposure to high wave energy (LTER 5 & 6).



Campaign 2 – Grazer – Algae Interactions, Feedbacks & Fishing ②

Question 2.1: What herbivores and grazing intensities are required to prevent the establishment of macroalgae or to enable its removal once established?

Rationale: Grazer - algae interactions are critical following perturbations because macroalgal populations grow faster than corals when not controlled by herbivores, stands of macroalgae prevent recruitment of corals, and established macroalgae may have self-reinforcing feedback mechanisms (Steneck 1988, Hughes et al. 2010, Hoey & Bellwood 2011). A common press driver that can alter grazer control of macroalgae is fishing. On tropical reefs this can reduce the biomass of such herbivores as parrotfish (Russ & Alcala 1989); their overfishing is a major contributor to regime shifts to macroalgal dominance (Bellwood et al. 2004, 2011, Burkepile & Hay 2006, Hughes et al. 2007, Mumby et al. 2006). Simulation modeling for Caribbean reefs suggests that reef resilience is highly sensitive to the fishing intensity on parrotfish, with even intermediate levels of exploitation resulting in a decline in coral cover (Mumby 2006). Marine no-take reserves frequently have elevated biomass of grazing fishes, higher grazing intensities, and lower abundances of macroalgae than non-reserve areas (Hughes et al. 2007). However, there is little information regarding just how much grazer biomass - or intensity of grazing - is required to prevent establishment of macroalgae or to remove it once it becomes abundant. Additionally, the fishes responsible for preventing the buildup of macroalgae can differ from those that could potentially bring about a reversal. On the Great Barrier Reef, for example, a variety of parrotfish and surgeonfish maintain low macroalgal abundance, but on inshore reefs, a batfish species was responsible for removal of mature macroalgae (Bellwood et al. 2006).

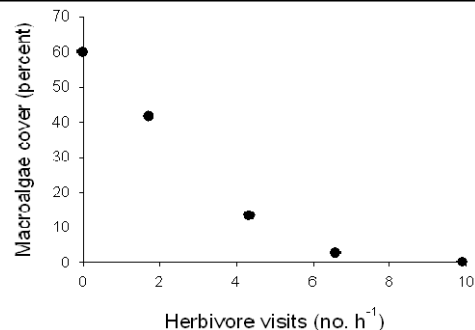
In MCR IIA we initiated our long term Grazing Intensity Experiment to estimate how variation in grazing pressure affects the establishment of macroalgae on the fore reef. Here we propose additional long term experiments and observations **to test the hypotheses that: (1) it**

is less difficult for herbivores to prevent the establishment of fleshy macroalgae than to remove it after they become dominant space holders, and (2) greater functional diversity of the herbivore assemblage results in greater control of macroalgae because different suites of herbivores are responsible for preventing versus removing mature stands of macroalgae. We also will expand our behavioral studies to better understand the functional roles of different herbivores (Bellwood et al. 2011), estimate vulnerabilities of different life stages of macroalgae to grazing, and explore the potential for associational defenses.

Approach: In 2010 we initiated our long term Grazing Intensity Experiment, which is the first manipulative field experiment where a wide gradient in grazing pressure is maintained to quantify the level of grazing necessary to prevent the establishment of macroalgae. Fishing on tropical reefs reduces both the abundance and average size of herbivorous fish (Russ 1991), and our manipulation simulates variation in fishing pressure by restricting various sizes of fish that can gain access to the bottom. The experiment consists of unglazed terra cotta tiles affixed to the fore reef in one of six treatments: four are wire cage exclosures (2.5 cm mesh) that have one of four different sized access holes limiting the maximum body size of fish that can access the tiles, and the remaining two are no cage and a cage control that allow access of any sized fish (tiles in these last two treatments are compared to the adjacent natural bottom). This produces a strong gradient in the visitation rate and size distributions of herbivores (Fig. 8). After a year, fleshy macroalgae (*Sargassum*, *Turbinaria*) became established, but only at the lowest grazing intensities (Fig. 8). At the highest grazing intensities, the tiles - like the adjacent natural substrate - were covered with closely cropped turfing algae and crustose coralline algae. We will follow this experiment for several more years to examine patterns in coral and algal recruitment and growth.

Figure 8. Macroalgal response to experimentally-imposed variation in grazing pressure on the fore reef.

Data are the median percent cover of macroalgae that developed in our long term Grazing Intensity Experiment after 1 year plotted as a function of the hourly visitation rate of herbivorous fishes to each experimental treatment.



In 2012, we will initiate a short term Macroalgae Consumption Experiment on the fore reef to test the hypothesis that herbivores can more easily prevent the establishment of macroalgae than remove it once it becomes dominant (Hoey & Bellwood 2011). Mature *Turbinaria* and *Sargassum*, the two most abundant macroalgae in the system, will be placed in cages designed as described above, and the loss of biomass under different grazing intensities will be assessed. We will deploy underwater video cameras to document the identities of the species that consume the algae. Pilot feeding assays and analysis of videos conducted in 2011 revealed that *Sargassum* was readily consumed but *Turbinaria* was highly resistant to grazing. We hypothesize that mature stands of *Sargassum* but not *Turbinaria* will be removed by herbivorous fishes, and we will measure stage-specific vulnerabilities of the algae to grazing, together with whether mature stages provide an associational defense to nearby juveniles. To date, we have identified just two herbivores (Blue-spine Unicornfish; Orange-spine Unicornfish) that consume mature macroalgae on the fore reef and these species are both targeted by artisanal fishers. By contrast, we have identified 42 species of herbivorous fishes that graze turfing algae and newly-recruited small stages of fleshy macroalgae.

Finally, we will use natural spatial variation in composition of the fish grazer assemblage to explore the hypothesis that greater species or functional diversity of the herbivore assemblage results in greater control of macroalgae over the long term (Burkepile & Hay 2008, 2010, Cheal et al. 2010). Because our time series data suggested that an initial rise in abundance of

macroalgae on the fore reef in 2008-2009 was suppressed quickly by the growing populations of herbivorous fish (mostly parrotfish but also to a lesser degree surgeonfish), we will continue to explore spatial and temporal patterns of abundance of these fish groups, especially identifying differences in development of algae among sites that differ in their absolute or relative abundance. We will explore the joint and separate effects of surgeonfish and parrotfish by initiating Grazer Composition Experiments at each of our six permanent sites where the relative abundance of these herbivorous fishes differs naturally. Treatments will involve tiles in cages, cage controls and totally exposed (described above for Grazing Intensity Experiment) as well as two additional cage treatments where different shaped openings (circular vs. slits) allow access of one fish group but not the other.

***Question 2.2:** How does fluctuation in cover of turf algae on the fore reef feed back to increased production of parrotfish biomass?*

Rationale: Consumption of algae by herbivores is the largest trophic flux on coral reefs (Russ 2003). The high productivity of algal turfs potentially can maintain high standing stocks of grazing fishes, despite the low biomass of turfs (Carpenter 1986). However, population sizes of herbivorous reef fish often are assumed to be limited by fishing (and natural mortality), supply of recruits, or territoriality, not their food resources (Williams & Polunin 2001, Newman et al. 2006). Knowledge of the factors that limit abundance of herbivorous fish has important management implications because of the effects of fish on controlling algae. The increase in the number and biomass of herbivorous fish in our time series (Fig. 2) suggests that these populations were food limited. We propose **to test the hypothesis that key herbivorous fishes are food limited in Moorea and there is dynamic feedback between their algal food supply and demographic performance**. We will investigate patterns of temporal variation in recruitment, growth and survivorship of key species of parrotfish and surgeonfish. Possible feedbacks between local fecundity and recruitment of parrotfish will be made in conjunction with Campaign 3 by estimating self-recruitment of this key group on Moorea.

Approach: We will take two approaches. First, we will use our time series data on size-specific densities of parrotfishes to measure temporal variation in recruitment to nursery habitats and estimate survivorship as a function of availability of turf algae. We will use standard methods for estimating these attributes from size-frequency distributions. Second, we will estimate variation in growth rates of individual herbivorous fish retrospectively by reconstructing size-at-age relationships for fish from different year classes. Fish will be aged by counting rings on their otoliths (ear bones), a well-established technique for herbivorous fishes on tropical reefs (Lou 1992, Choat et al. 2003). We currently are analyzing otolith structures for four major herbivores in Moorea (two parrotfish and two surgeonfish species) to test the hypothesis that increases in cover of turf algae resulted in enhanced growth rates of individual herbivores.

Campaign 3 – Recruitment Variation & Sources of Settlers ③

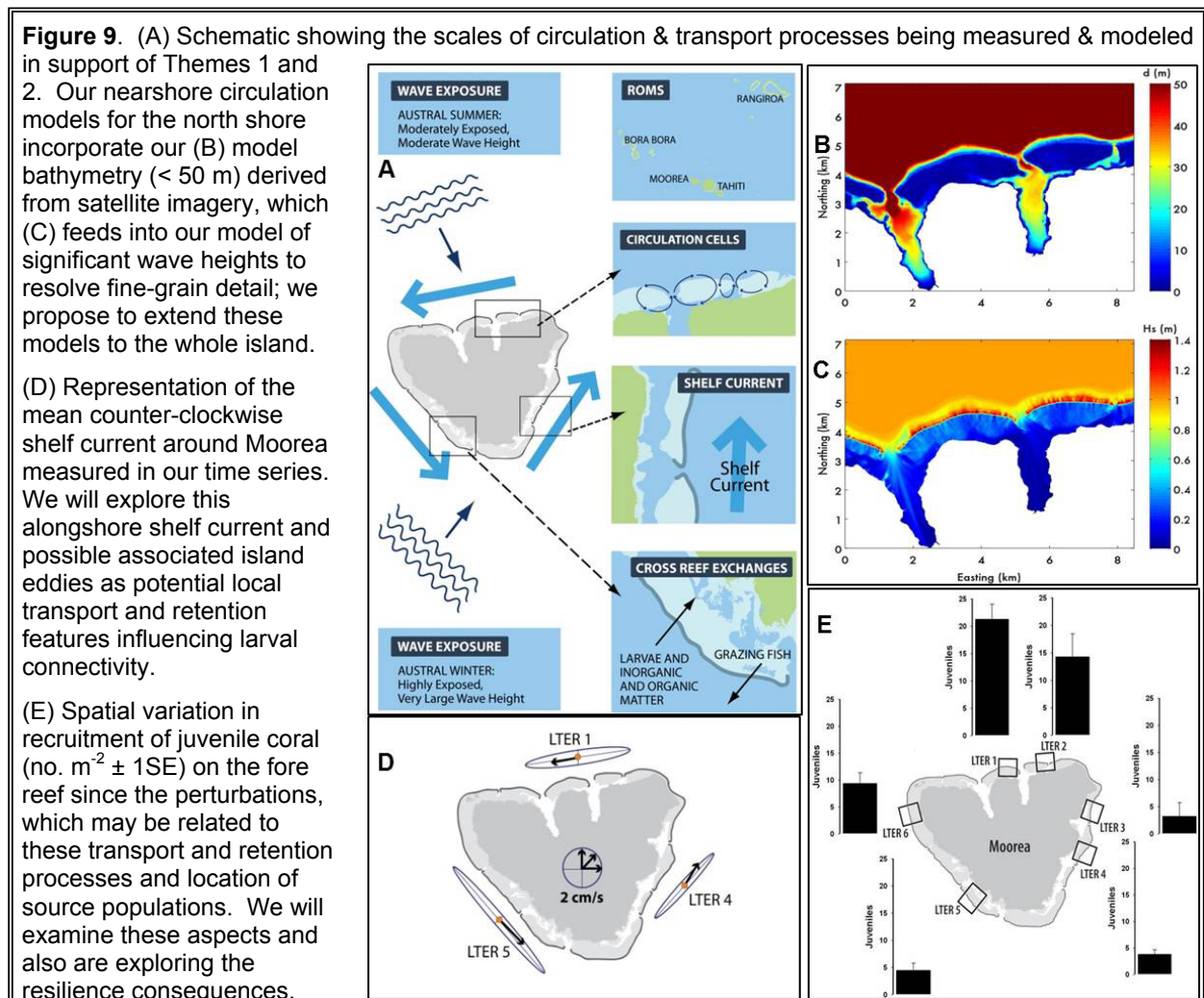
***Question 3.1:** What are the physical drivers of landscape-scale variation in coral recruitment?*

Rationale: Failure of sexually-produced coral propagules to recruit will prevent return of a perturbed reef to coral dominance, and the causes of both failed and successful coral recruitment are major gaps in our understanding of coral reef dynamics (Hughes et al. 2000, 2005, Vermeij & Sandin 2008). As scleractinian corals have planktonic larvae, the rates of coral settlement are affected by the flux of larvae, the availability of appropriate settlement microhabitat, and positive and negative interactions with the local benthic community (Vermeij & Sandin 2008). Several studies in the Caribbean and Indo-Pacific have shown that rates of coral recruitment can be positively related to population fecundity (adult density and the proportion of colonies that breed) of coral across several spatial scales (Hughes et al. 2000, Hughes & Tanner 2000, Vermeij & Sandin 2008), giving rise to the specter of reproductive failure due to low population density and low gamete concentrations (i.e., an Allee effect) (Knowlton 2001). Our data on recruitment of coral to the fore reef of Moorea (Fig. 9E), however, do not support an Allee effect despite exceptionally low coral populations in that habitat due to the COTS

outbreak. Coral recruitment has been substantial since the loss of adults, and in 2010-11 was the highest we have measured to date. As expected, the majority of recruits are ‘weedy’ species (e.g., branching *Pocillopora*), although juveniles of more slowly recruiting corals such as massive *Porites* also are present. A striking pattern is the variability in recruitment among the three sides of the island (Fig. 9E); the density of recruits on the north shore was roughly twice that of the west and four times that of the east shores (Fig. 9E). This pattern for coral recruitment qualitatively matches what we found for self-recruitment of a reef fish (a clownfish) where we used genetic parentage techniques to identify the locations of the parents and offspring. Here we **test whether local oceanographic transport and retention processes can explain the greater settlement of larval organisms on the north shore fore reef than on the other two shores**. As described next, we have identified several candidate processes.

Approach: As part of our time series, recruitment of corals is being estimated twice annually using settlement tiles deployed for 6 months at locations mostly along the north shore. We also are counting juvenile corals (each year) large enough to see on the reef by a diver (~ 5 to 40 mm) at two permanent sites on the north shore. In 2010 - 11 we established replicate 5 x 5 m Coral Recruitment Plots at all six of our permanent sites where we quantify juvenile colonies of *Pocillopora*, *Acropora* and *Porites* to augment our existing time series measurements of coral recruitment and densities of juvenile corals; these plots will be sampled annually.

With respect to physical transport and retention processes, we have been making measurements and developing models of circulation across relevant spatial scales (Fig. 9A).



Regional Scale Circulation. At the largest spatial scale, we are collaborating with A. Miller at SIO to develop a ROMS (Regional Ocean Modeling System) model to describe regional scale flows around Moorea. A prototype ROMS model for a 200 x 200 km domain with a 3 km resolution is under development. When ready, model outputs will be compared against existing data from drifter studies in the region to refine the initial model. Our goal is to use the ROMS model to explore the relationship between climate forcing, large-scale ocean currents, meso-scale circulation and nearshore and lagoonal circulation at Moorea (as described by our smaller scale models - see next).

Island- & Local-scale Circulation. We are developing 3D models of circulation, wave and particle tracking models for the reefs of Moorea. Prior to the MCR, essentially no bathymetric data appropriate for our needs existed for the lagoon or fore reef of Moorea, which greatly hindered our ability to develop adequate circulation models. In support of our 3D circulation / wave modeling, we have pursued several methods for obtaining sufficiently accurate bathymetry data. For shallow reefs, LIDAR is a preferred method (Lowe et al. 2009, Hoeke et al. 2011), however it has proven cost prohibitive for French Polynesia (> \$1 million). As a time-intensive alternative, we have been collaborating with a French colleague at CRILOBE (Collin & Hench in review) to quantify bathymetry using Worldview-2 hyperspectral satellite imagery (Stumpf et al. 2003). The imagery was calibrated with new depth measurements made over a limited area using acoustic instrumentation from a small boat. The resulting bathymetric database for the shallow reef (< 7 m depth) has 50 cm horizontal resolution (Fig. 9B). We are expanding coverage to shallower reef areas of the entire island. Further offshore where we cannot use satellite imagery, we propose to collect large-scale, multi-beam bathymetric data as part of a UNOLS cruise (see attached ship time request).

In MCR IIA, we constructed a preliminary coupled 3D circulation/wave/particle tracking model of the north shore of Moorea using the open-source model codes Delft3D (Lesser et al. 2004) and SWAN (Booij et al. 1999; Ris et al. 1999). The present model domain spans a large section of the north shore (Fig. 9C) with a horizontal grid resolution of 20 m and 15 vertical levels. Model depths range from > 1200 m offshore to < 1 m on the back reef. The wave model is forced with a JONSWAP wave spectrum based on observed directional wave parameters and water levels from our time series. The model captures much of the spatial variability and cross-reef flows observed in the system (Hench et al. 2008), but needs calibration and a quantitative assessment, which require a non-standard approach for coral reefs (Rosman & Hench 2011). We will use a field data set from a previous NSF-funded project (led by Hench) to complete calibration and verification work on the model for a 2-month period that included a wide range of wave events. Refined boundary conditions will be obtained from the large domain ROMS model. The resulting model will help address our questions on connectivity and self-recruitment.

Our time series measurements of oceanographic processes on the three sides of Moorea revealed a mean counter-clockwise shelf current (ca. 3-4 cm/s; Fig. 9D). While this oceanographic feature is consistent with our observed patterns of recruitment for clownfish and corals, it is variable in both direction and magnitude. We hypothesize that much of the variability in recruitment of planktonic larvae of corals and perhaps fishes can be explained by variability in this circulation. To clarify this physical-biological coupling, we plan to use the 3D circulation model to plan our intensive field measurements (e.g., determine optimal sampling locations), and then use it in hind cast mode to explain the observed patterns in recruitment. We also will use particle tracking to quantify connectivity and discern transport mechanisms that are retentive and/or dispersive such as headland eddies (Signell & Geyer 1991) and Stokes drift (Monismith 2004). In support of this campaign, we will characterize the physical oceanographic processes for time periods relevant to ecologically important events (e.g., periods of high or no recruitment). We will deploy a spatially dense array of ADCP moorings on the NE corner of Moorea and concurrently conduct shipboard ADCP / CTD sampling, and release surface drifters around the NE headland of the island.

UNOLS Request. As a supplement to our core MCR proposal we request a cruise on a UNOLS Ocean/Intermediate class vessel. These cruises will help the MCR connect large scale

oceanographic and water mass properties in the South Central Pacific to patterns observed on the reefs of Moorea. Cruise tasks will include: (1) multi-beam sonar measurements to obtain high resolution bathymetry in the waters around Moorea and Tahiti; (2) CTD/ADCP profiles to obtain hydrography around the islands; (3) water column sampling of nutrients and DIC, DNA structure, and a full microbial suite; and (4) depth distribution and isotopic composition of POC and DOM. We also will use coordinated sampling with small boats to obtain a radiative sampling grid around the islands, to link the deep and shallow water measurements.

***Question 3.2:** What are sources of coral recruits to the fore reef and parrotfish juveniles to their inshore nursery habitats?*

Rationale: The extent of self-recruitment and scales of larval connectivity have critically important dynamical and management implications. Following the near elimination of adult coral on the fore reef, the strong recruitment pulse we observed there this past year raises the question of where are the source populations. Larvae may come from adults in lagoon habitats and/or they may arrive via longer-distance dispersal from adjacent islands in the region. The same is true for parrotfish. ***Here we will: (1) estimate the degree of local versus more distant sources of recruits for corals and parrotfish to the fore reef of Moorea, and (2) evaluate the extent to which physical transport and retention features we are modeling can explain the contributions of various sources of recruits*** (see pages 18-19).

Approach: For identifying sources of coral recruits, we will develop microsatellite loci for *Pocillopora*, *Acropora* and *Porites lobata* using the 454 pyrosequencing platform (Abdelkrim et al. 2009, Concepcion et al. 2010, Fernandez-Silva et al. in review). These microsatellites will allow us to look for structure among coral populations (Toonen et al. 2011) between Moorea and the surrounding Society Islands that range from 15 to 165 km away. We will first determine the scale of population structure among coral species in the region and whether the recruits are differentiated from the local adults. We will also test the average relatedness of recruits to evaluate the potential for 'sweepstakes' recruitment where chance events determine which adults produce them (Hedgecock 1994). If recruits are unrelated and differentiated from local populations in lagoon habitats, it is unlikely that locally-produced recruits are replenishing the fore reef. We will sample adjacent islands to determine potential source populations using multilocus assignment tests (Pritchard et al. 2000, Rosenberg 2004, Hubisz et al. 2009) with sampling informed by our oceanographic models (Selkoe et al. 2010, White et al. 2010).

For parrotfish, we will focus on the two most abundant and functionally important species (palenose parrotfish, bullethead parrotfish) and study connectivity at four different spatial scales. First, we will determine how different habitats are connected. Adult parrotfish mainly occur on the fore reef, but recruits are always in the lagoon. We will sample these habitats and assess their degree of genetic exchange based on gene flow data and parentage analysis. We expect to have enough power to detect parentage if it is present as we have experienced with other species (e.g., clownfish). Second, we will determine population structure within the island of Moorea. For example, we have shown genetic discontinuities in populations of clownfish and three-spot dascyllus (Bernardi et al. 2001, Beldade et al. 2012). Third, we will evaluate the amount of migration present between adjacent islands and Moorea, especially Tahiti (20 km distant), Tetiaroa (50 km) and Maiao (75 km), which all sustain large populations of parrotfishes. Finally, we will determine the levels of gene flow at the level of the Society and Tuamotu islands (~ 350 kms). To obtain the genetic information to assess connectivity at each spatial scale, we will use Illumina sequencing with multiplexed lanes to identify and exploit hundreds of Single Nucleotide Polymorphisms (SNPs) (Narum et al. 2008, Davey et al. 2011). SNPs have been used for many applications relevant here, from parentage analyses (Hauser et al. 2011) to population surveys (Seeb et al. 2011).

Campaign 4 – Coral Growth & Survivorship ④

***Question 4:** How do patterns of growth and survival of coral recruits on the fore reef vary at the landscape scale, and what are the underlying mechanisms?*

Rationale: Return of the fore reef to a coral-dominated state not only depends on recruitment of corals (Campaign 3), but also on the growth and survivorship of those recruits. As noted above, recent recruitment of coral varies tremendously among sites (Fig. 9E), which differ in physical and biological attributes that can affect subsequent colony growth and survivorship. Potentially important physical constraints on coral performance at our fore reef sites include current velocity and wave energy; biotic constraints include interactions with major space holders (macroalgae now, other corals later) and corallivory (Cole et al. 2008, Emslie et al. 2008, Lenihan et al. 2008, 2011, Rotjan & Lewis 2008, Adjeroud et al. 2009). Neighborhood densities of conspecifics and heterospecifics can have profound effects on survival of young corals (Vermeij & Sandin 2008). Currently there are virtually no corallivorous fishes left on the fore reef, but we anticipate their importance to grow as coral returns. However, some herbivorous fishes, such as parrotfish, occasionally target living corals and/or impart incidental mortality of young corals as they feed on turf algae (Rotjan et al. 2006, Mumby 2009), so for juvenile corals, the positive indirect effect of parrotfish on coral survival (via control of macroalgae) can be offset by direct consumption. As coral colonies grow to a size sufficient to host resident fishes, a positive feedback can occur between the biomass of resident fish and growth rate of colonies (Holbrook et al. 2008, 2011). This relationship motivated us to initiate an ambitious program in MCR IIA to estimate growth and survival of coral recruits at each of our six fore reef sites. In addition, we began a major field experiment in 2011 ***to test the hypothesis that growth and survival of corals are comparatively the greatest at intermediate levels of grazing pressure, reflecting a balance of the indirect positive (consumption of algae) and direct negative (incidental consumption of coral) effects of herbivorous fishes.***

Approach: In July-August 2011, we initiated an unprecedented, long term Coral Demographic Study by uniquely numbering, measuring, and mapping thousands of colonies of the three major coral taxa (*Pocillopora*, massive *Porites*, *Acropora*) on our LTER fore reef sites (corals also were tagged in lagoon habitats as part of Campaign 5; see page 23). We anticipate censusing these corals annually to assess growth and survivorship (Lenihan et al. 2011) over the next decade or longer. For purposes of our demographic models, we focused largely on recruits but also included other size classes of coral. To model the dynamics of coral populations, we will construct size-based Integral Projection Models (IPM) (akin to matrix models; Easterling et al. 2000, Ellner & Rees 2006) and parameterize them using data from this demographic study and the recruitment study described in Campaign 3 (see Yau 2011). We will use IPMs to model dynamics for each coral genus at each LTER site, as well as explore how dynamics of coral populations differ among sites having differing abiotic and biotic drivers. In our time series program we measure current velocities, wave energy and temperature at these sites, as well as types, sizes and abundances of herbivores and corallivores.

Colonies tagged for the Coral Demographic Study are adjacent to our sets of 5 x 5 m Coral Recruitment Plots in which we are measuring recruitment at our fore reef sites. We will investigate additional aspects of the coral assemblage in these plots, including changes in absolute and relative abundance of major coral genera, changes in colony size distributions, and abundances, species composition and affiliations of coral-associated fishes. Similar information on coral abundance and size structure will be obtained from our photo-quadrats on our permanent transects, although these do not provide information on coral-fish relationships due to the small scale of the photo-quadrats. In the future when branching corals reach a size where they can host resident fishes, we will estimate the strength of the positive growth effect of fish biomass on coral growth (Holbrook et al. 2008, 2011). We also anticipate possible strong competition between coral colonies for space on the fore reef, but this is unlikely to occur over the next four years. The major interactions that will occur in the near future are between corals, algae and herbivores, and in 2011 we initiated a Grazer – Coral Experiment to explore these.

The aim of the long term Grazer – Coral Experiment is to examine how grazing directly and indirectly affects the growth and survivorship of coral recruits. The experiment uses the same caging scheme and treatments as our Grazing Intensity Experiment (Campaign 2, page 16) to create variation in grazing pressure on terra cotta tiles affixed to the fore reef. Juvenile

Pocillopora corals (10-15 mm diam.) were glued to tiles in each replicate (800 total corals transplanted with no handling mortality after 1 month), and growth and survivorship of these corals will be followed for the next four years and beyond, along with the algal community on the rest of the terra cotta tiles. Performance of these corals will be compared to adjacent natural corals in our Coral Demographic Study.

B.2. Research Theme 2: Structure and Function of Reefs in the Future.

GCC and OA are predicted to have strong negative impacts on coral reefs, especially through increased frequency and perhaps intensity of storms, temperature excursions above current thermal bleaching tolerances, and for critical reef calcifiers (stony corals, crustose coralline algae), an impaired capacity to calcify at reduced sea water pH. While the present and recent past provide an empirical means to gauge the impacts of these stressors, the true impacts of these stressors will be contextualized by the biological attributes of future reefs, and in this regard, it is certain that they will differ from what we have experienced in the last century. Addressing such problems – altering intensities of pulse and press disturbances that are superimposed on a hugely dynamic biological system – is what LTER programs are designed to do, and we intend to fully exploit our unique (and growing) time series on reef structure and function to give context to our future studies.

Increased frequency of pulse disturbances in the future may favor rapidly colonizing, ‘weedy’ corals such as *Pocillopora*, although these structurally complex corals may be at higher risk to elevated temperature and reduced pH compared with massive corals such as *Porites* (Loya et al. 2001, van Woesik et al. 2011). Changes in the relative and absolute composition of the benthic community will certainly alter key ecosystem functions. Here we address the longer time horizon of likely GCC- and OA-related changes in community composition and expected consequences of those changes to organic and inorganic carbon cycling and the provision of habitat for other organisms. To enable projections about likely changes in ecosystem function in the future, we first need a better understanding of the processes that influence and control those functions on contemporary reefs. Figure 10 represents the conceptual framework for Research Theme 2 and interrelationships of the campaigns, and Table 2 summarizes the research activities and sources of data for the Theme 2 campaign questions.

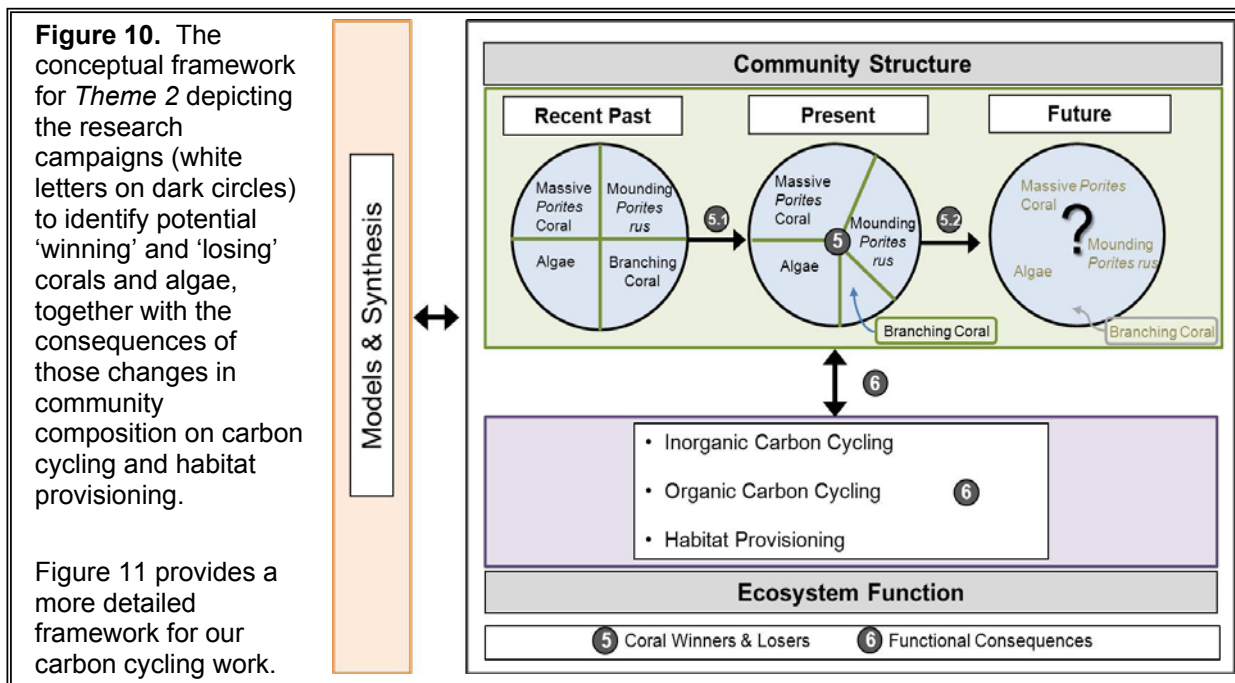


Table 2. Theme 2 Research Activities & Data Sources	Campaign Questions		
	Q 5.1	Q 5.2	Q 6
Time Series Focus 1 – Community Dynamics	✓	✓	✓
Time Series Focus 2 – Ecosystem Functioning			✓
Time Series Focus 3 – Abiotic Drivers	✓	✓	✓
Coral Recruitment Plots			✓
Coral Demographic Study	✓		
POC & DOM Flux Studies			✓
Reef Metabolism & Calcification Studies			✓
Mesocosm Experiments		✓	
Microbial Remineralization Experiments			✓
Dynamic Energy Budget Modeling	✓	✓	
Population Trajectory Modeling (Matrix & IPMs)	✓		✓

Campaign 5 – Evaluating which Corals will be Ecological Dominants on Future Reefs 5

Question 5.1: Which corals have selective advantages under contemporary conditions?

Rationale: There is mounting evidence that in recent decades, there have been striking declines in abundance of some coral taxa on a global basis, across a range of reef habitats and depths. However, initial projection of a complete loss of reef corals and coral reefs, possibly within this century (Knowlton 2001, Hoegh-Guldberg et al. 2007) is being replaced by a more nuanced scenario in which future coral reefs will be comprised of a small subset of corals and other calcifying taxa that have been described as ‘winners’ (Loya et al. 2001, van Woesik et al. 2011, Pandolfi et al. 2011). **Here we will continue to mine and augment our time series data to identify corals that have selective advantages under contemporary conditions on the reefs of Moorea, as well as conduct demographic studies of key species.** Consistent with prominent literature, we consider this an analysis of coral winners and losers (sensu Loya et al. 2001, van Woesik et al. 2011). We recognize that whether a taxon displays ecological success depends on the time scale over which such performance is evaluated, and success over a few years might be followed by stasis or failure over many decades (van Woesik et al. 2011). Our analyses, therefore, identify potential winners and losers based on what we know (Question 5.1), and, based on what we can elucidate regarding their functional biology, forecast what taxa will occur on reefs in the future (Question 5.2).

Approach: We propose two approaches. First, our lengthening time series data will reveal trajectories of change in abundance of coral taxa and enable us to detect winners (species whose abundances are increasing or remaining unchanged) and distinguish them from losers on a decadal time scale. Our analyses will include explicit consideration of the holobiont through an evaluation of the biological and functional diversity of *Symbiodinium* algal and microbial consortia associated with coral colonies. The composition of the coral holobiont plays an important role in determining the fitness of reef corals (Ainsworth et al. 2010), and in a future affected by GCC and OA such effects are likely to strengthen. Second, we will expand our application of size- and stage-structured population growth modeling to several key taxa including massive *Porites* spp. and mounding *P. rus*, which we (and others; Fabricius et al. 2011) have identified as potential winners over the past decade, and to *Pocillopora* and *Acropora*, which are regarded as potential future losers (van Woesik et al. 2011). Our modeling will rely on our extensive Coral Demographic Study (Campaign 4) to evaluate the growth and survival of corals. As in Campaign 4, we will construct Leslie Matrices (Elahi & Edmunds 2007) and Integral Projection Models (IPMs) (Yau 2011) to project community structure over several decades, and conduct sensitivity analyses to identify the factors most influential in determining those trajectories. We have been following colony growth and survival of a set of 66 colonies of *P. rus* in the north shore lagoon since 2000, and will add 100 more colonies in 2012 to capture the full range in size in lagoon habitats, as well as initiate a new study of 100 large colonies of

massive *Porites*. Together with our Coral Demographic Study (Campaign 4), we will follow all marked corals for a decade or longer to evaluate ecosystem function, including habitat provisioning for fish (Campaign 6, page 26). Further, the comprehensive analysis of the fate of large numbers of coral colonies, spanning multiple taxa and the full size range of colonies, will provide an unrivalled data set with which we can project future reef structure and function.

Question 5.2: Which reef taxa are likely to have selective advantages under **future conditions?**

Rationale: For Question 5.1 we will identify winners and losers on contemporary reefs of Moorea, but here we will turn to the future that is informed by the most recent representative concentration pathways (RCP) of global atmospheric CO₂ (van Vuuren et al. 2011). **We propose to identify processes and mechanisms that cause taxa to function as winners and losers to better understand their biology, and thus sharpen our capacity to predict community structure in the future.** We will use empirical work and theory to integrate results through Dynamic Energy Budget (DEB) modeling.

Approach: In contrast to Question 5.1 where we focus on biological data, here we explore bio-physical coupling to identify which biological traits are sensitive to which physical conditions, then conduct experiments to establish cause and effect relationships, and finally, integrate the outcomes through modeling. We will explore covariance in the physical and biological aspects of the time series data to help identify physical drivers that are associated with biological trends (e.g., changes in abundance, growth, survival). While single factors may explain a large portion of the biological variance (for example, high temperatures vs. coral bleaching; Donner 2011), we will exploit a multivariate framework to evaluate the extent to which physical drivers (temperature, wave regime, pCO₂, light, etc.) affect organism success. We also propose to enhance our current deployments of pH (SeaFETS) and pCO₂ (ProOceanus) sensors to characterize *in situ* variation in pH / pCO₂ on the reefs of Moorea. We have already detected variation between day and night (Hofmann et al. 2011) and among sites. These micro-environments afford a unique opportunity to characterize the response of calcifying taxa to a variety of pCO₂ regimes, and through reciprocal transplant experiments, to establish cause-and-effect relationships between pCO₂ and organism function.

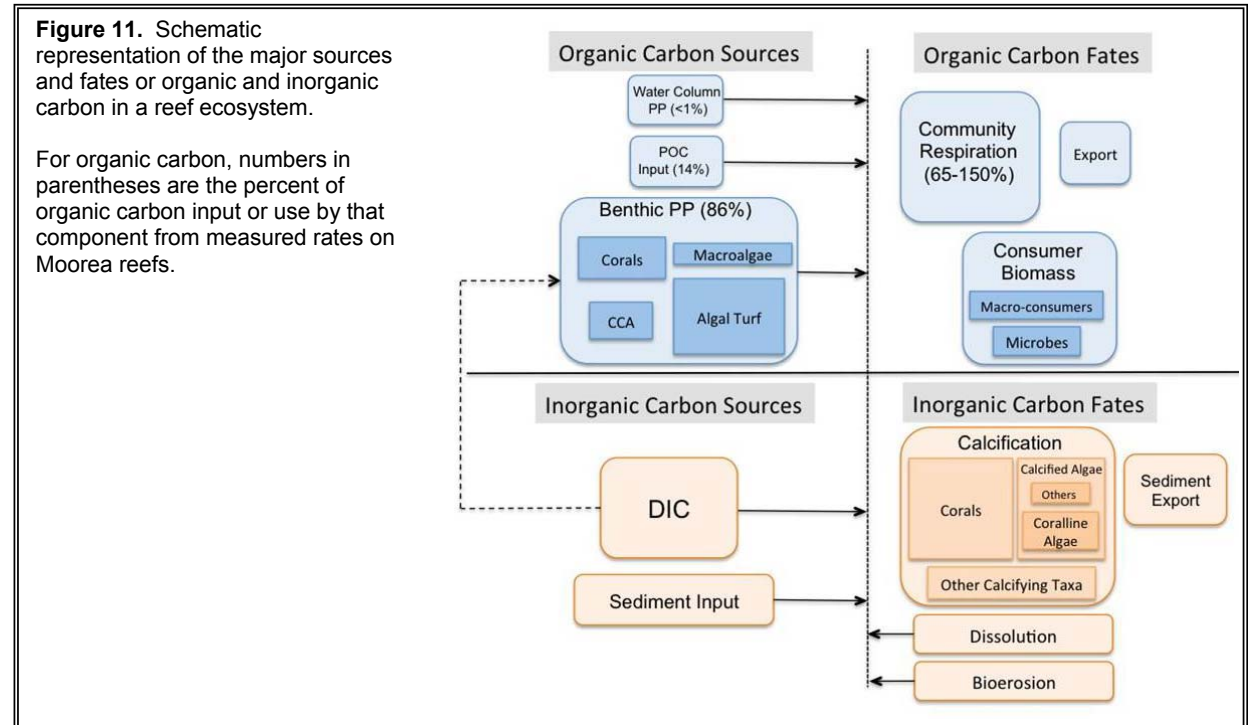
We also are using our state-of-the-art laboratory mesocosm system to investigate the effects of major GCC and OA drivers on the function (calcification, photophysiology, protein content, *Symbiodinium* genotypes) of reef organisms through a 4-year NSF award to MCR investigators. This award aims to provide an integrated understanding of the effects of GCC and OA drivers at multiple functional scales ranging from species-level analyses of corals and calcified algae to ecosystem approaches on the reefs of Moorea. The project focuses on both reef corals and calcified algae to: (1) parameterize the functional relationship between pCO₂ and calcification, (2) describe the interactive effects among light intensity, temperature and pCO₂ on calcification, (3) evaluate the extent to which nutrients can mitigate the effects of high pCO₂ on calcification, (4) assess the effects of pCO₂ on ecological processes (coral settlement and bioerosion) using mesocosms, (5) assess the effects on reef-scale calcification through *in situ* experiments (which will grow out of our mesocosm experiments), and (6) develop a DEB model and conduct two workshops to integrate empirical results across multiple functional scales. We are also collaborating with French colleagues at CRIOBE to explore how the treatment conditions in our experiments affect gene-level responses.

Our initial work in exploring the effects of pCO₂ and other drivers on corals and algae, together with the burgeoning literature on the topic, underscores the complexity of the science involved (Edmunds 2011). Advancing general understanding from the diversity of results arising from these experiments requires an integrated approach. To achieve this, we will elaborate on our Dynamic Energy Budget models, which we already have applied in a basic form for corals (Muller 2011, Muller et al. 2009). We have submitted a proposal to develop more advanced DEB, population and community models based on our mesocosm work.

Campaign 6 – Forecasting Ecosystem Functions of Future Reefs 6

Question 6: How does altered community composition affect key ecosystem functions?

Rationale: Reefs of the future will be more than the sum of their parts, and while our program seeks to identify the parts (i.e., winning and losing corals and algae) that will populate these reefs, we also focus on how functioning of the reefs differs as a consequence. **Our purpose is to ask how the changing physical and biological context will alter the ways that reefs function**, particularly with regard to their delivery of goods and services of ecological and human interest. We will focus in the next four years on two key ecosystem functions - organic and inorganic carbon cycling (Fig. 11), and habitat provisioning.



Based on our ongoing studies of reef primary production, we know that Moorea reefs are highly productive with the vast majority of GPP originating from the benthos. Since NPP is near zero, most of the organic carbon is consumed within the reef community. The important processes that govern how this organic carbon is processed within the reef are not fully understood. We know that the reef on the north shore is consistently depleted in concentrations of both DOC and bacterioplankton and enhanced in PO_4 and NO_3 relative to offshore waters (Nelson et al. 2011, time series data). Additionally, the community structure of reef-associated microbes is consistently different from those offshore or in a nearby embayment. It appears that this reef system is a “sink” for suspended and dissolved organic matter that is otherwise recalcitrant to degradation by offshore bacterioplankton and that the processing of organic matter is enhanced on the back reef relative to offshore waters. We need to achieve a better understanding of how microbially-mediated processes affect the fates of organic carbon on contemporary reefs in order to better predict how these pathways might be altered by changes in community structure of future reefs. Inorganic carbon forms the physical structure of coral reefs and the processes that enhance or reduce calcification / dissolution are central to continued coral reef growth. We will make measurements and conduct experiments on the cycling of inorganic carbon by key calcified organisms and at the reef scale to develop predictions of how this critical ecosystem function might change in the future as a result of GCC and OA. The physical structure of corals and coral reefs provides key habitat for a diversity of

associated reef taxa (Campaign 1, Q1). Our second ecosystem function focus will be on how changes in the abundance and types of corals affect the species that use live coral for habitat and will inform predictions of how reef-associated diversity will change as future reefs become dominated by coral winners.

Approach: Organic / Inorganic Carbon Cycling - Prior MCR research shows that the gross rates of primary production (GPP) fluctuate little, but net primary production (NPP) is highly dynamic with changes occurring as the result of variation in respiration (R) (Carpenter et al. in review). The origins of this temporally variable carbon demand will be one focus of our new efforts as we build on studies of microbially-mediated shifts in DOC availability across the reef and the flux of POC and DOM from fore reef to back reef environments. We will test possible DOM removal mechanisms, including biological removal via water column or benthic microbes or abiotic processes such as photolysis or adsorption to non-living reef surfaces (sand or coral rubble). We will address these questions using biogeochemical surveys and discrete microbial remineralization experiments with benthic chambers and tents and sample concentrations of organic and inorganic nutrients and microbial activity over the reef to quantify uptake or loss rates. We will conduct these studies on the three shores of Moorea which experience differing physical and biological conditions. These studies will be linked to our time series measurements of reef metabolism and nutrient concentrations, and will be integrated to the physical drivers that modulate rates of reef metabolism (light, water flow).

To broaden our studies of inorganic carbon cycling and gain a historical perspective, we will address how calcification of reefs on the north shore has changed over the past 20 years using an already funded separate NSF award to MCR investigators. In 2012, we will begin measurements of coral reef metabolism and calcification across the reef at Tiahura where these measurements were first made in 1991 (Gattuso et al. 1993). Since then, decreasing sea water pH has reduced the aragonite saturation state of offshore waters from 4.01 to 3.48 in Moorea and there have been significant changes in community structure with branching acroporid corals being replaced by more massive poritids. To quantify the relative contributions of OA and changes in community structure to changes in inorganic carbon precipitation (calcification) and dissolution of the reef at Tiahura, we will compare present day rates of calcification / dissolution at Tiahura to present day rates on adjacent reefs where cover of corals and crustose coralline algae brackets the community structure (i.e., lower and higher cover) that was present in 1991. The international team consists of MCR personnel plus J.P. Gattuso (LOV/U. Paris/CNRS), M.J. Atkinson (Hawaii), J. Kleypas (NCAR), P. Cuet (U. La Reunion), and S. Planes and Y. Chancerelle (CRIOBE, CNRS). These measurements will be the first to specifically address how recent changes due to OA affect inorganic carbon cycling at the coral reef scale, while accounting for concurrent changes in reef community composition. We also will make annual measurements of calcification across our own reef transects (concurrent with metabolism measurements) that will be benchmarks for comparisons of reef-wide calcification over decadal time scales.

Approach: Habitat Provisioning - A critical aspect of ecosystem function on coral reefs is their capacity to provide habitat for other taxa (Beukers & Jones 1998, Idjadi & Edmunds 2006, Holbrook et al. 2008, 2011). How the habitat provisioning function of corals has been altered by qualitatively different types of perturbations is being explored in three main ways. The first is by assessing temporal variation in habitat provisioning by massive *Porites* and *P. rus* in lagoons (see Campaign 5.1, Holbrook et al. 2002a, b). Second, as the juvenile corals that recruit to the 5 x 5 m fore reef Coral Recruitment Plots (Campaign 3.1) grow larger, they will begin to host fish and invertebrates; this will likely begin toward the end of the period covered by this award. Then we will be able to quantify the habitat provisioning afforded by corals of different species and morphologies at our sites around the island. Third, we will undertake a Fish Community Trajectory Analysis to calculate how local fish assemblages likely will be altered by shifts in relative abundance of major habitat-providing corals as revealed by knowledge of habitat-specific fish associations (Brooks et al. 2007, Johnson et al. 2011) and our analyses of 'winners and losers' on future reefs (Campaign 5).

C. Ecological Modeling and Synthesis. We do two types of syntheses. The first occurs in the form of synthetic publications such as our recent articles in *Journal of Experimental Biology* (Wilson et al. 2010), *Annual Review of Ecology, Evolution and Systematics* (Hofmann et al. 2010), *Trends in Ecology and Evolution* (Ainsworth et al. 2010), and *Oecologia* (Edmunds et al. 2011). Several additional synthetic publications are planned, including an analysis of historical data to evaluate attributes of corals that promote persistence. The second is to use analytical models to integrate and synthesize the results of our empirical work to extend its generality.

We use two complementary modeling approaches in addition to our Leslie Matrix and Integral Projection Models to project community structure based on empirical data. For *Theme 1*, our Reef Resilience Models start with intentionally simplistic formulations (Fig. 12), describing the system in broad terms, such as “coral” and “macroalgae”, to investigate the effects of general processes on the overall state of the system and then progressively build in biological details. The Dynamic Energy Budget models in *Theme 2*, by contrast, start with a very detailed bookkeeping of the elements and nutrients within a coral (Fig. 13), and predict the effects of processes such as nitrification or OA on the individual’s growth and survival. The predictions of the DEB models can then be used to scale up to the population, community, or reef level.

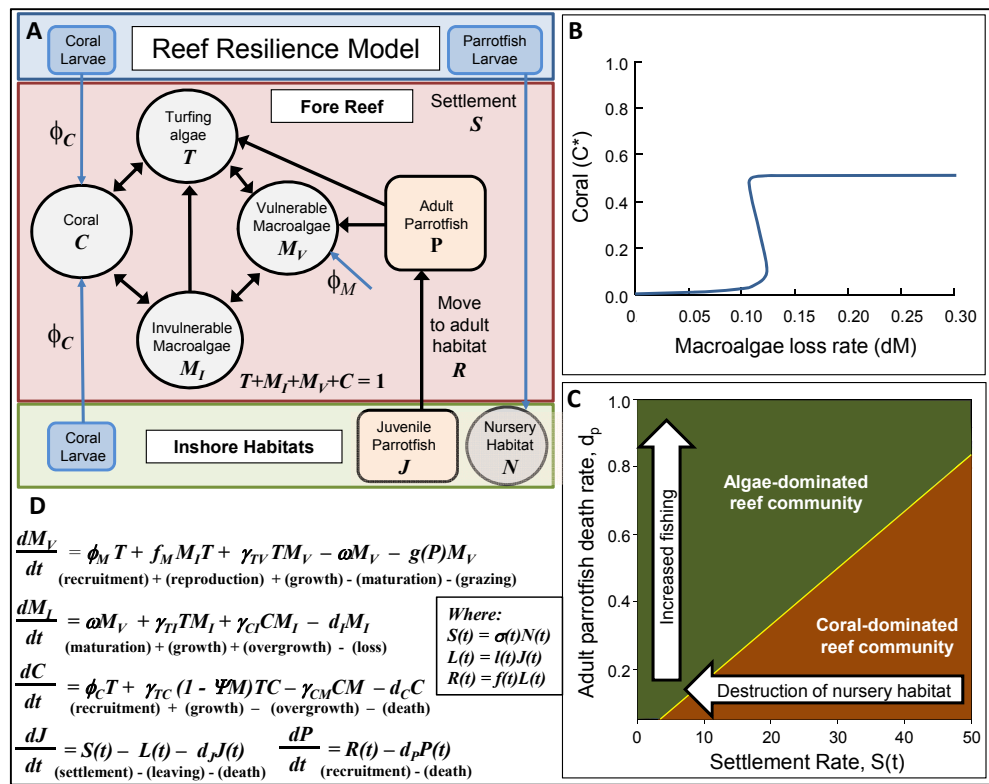
Working towards the development of a general theory of coral reef resilience, we are developing mathematical models to investigate how all of the biological and physical processes illustrated in the framework of Theme 1 (Fig. 5) interact to determine the resilience of the reef system to various perturbations and anthropogenic stressors. Several recent modeling efforts (Mumby et al. 2007, Fung et al. 2011, Blackwood & Hastings 2011) have used simple mathematical descriptions of the interactions between coral, macroalgae, and turf algae to investigate the processes that lead to rapid shifts from coral-dominated to algae-dominated reefs, and that prohibit the ready return to a coral-dominated state.

Figure 12. Model of reef resilience with stage-structured macroalgae and explicit dynamics of parrotfish, the key herbivore. (A) Model structure. (B) Bifurcation diagram showing that if the parrotfish grazing rate is reduced below a critical threshold, the system undergoes a phase shift from a coral-dominated to a macroalgae-dominated state.

(A) Model structure. The system displays hysteresis, in that the grazing rate must be restored to a higher rate than the critical threshold for the system to return to coral domination.

(B) Phase plane diagram showing the coral – algal state shift threshold for various combinations of fishing pressure and loss of parrotfish nursery habitat.

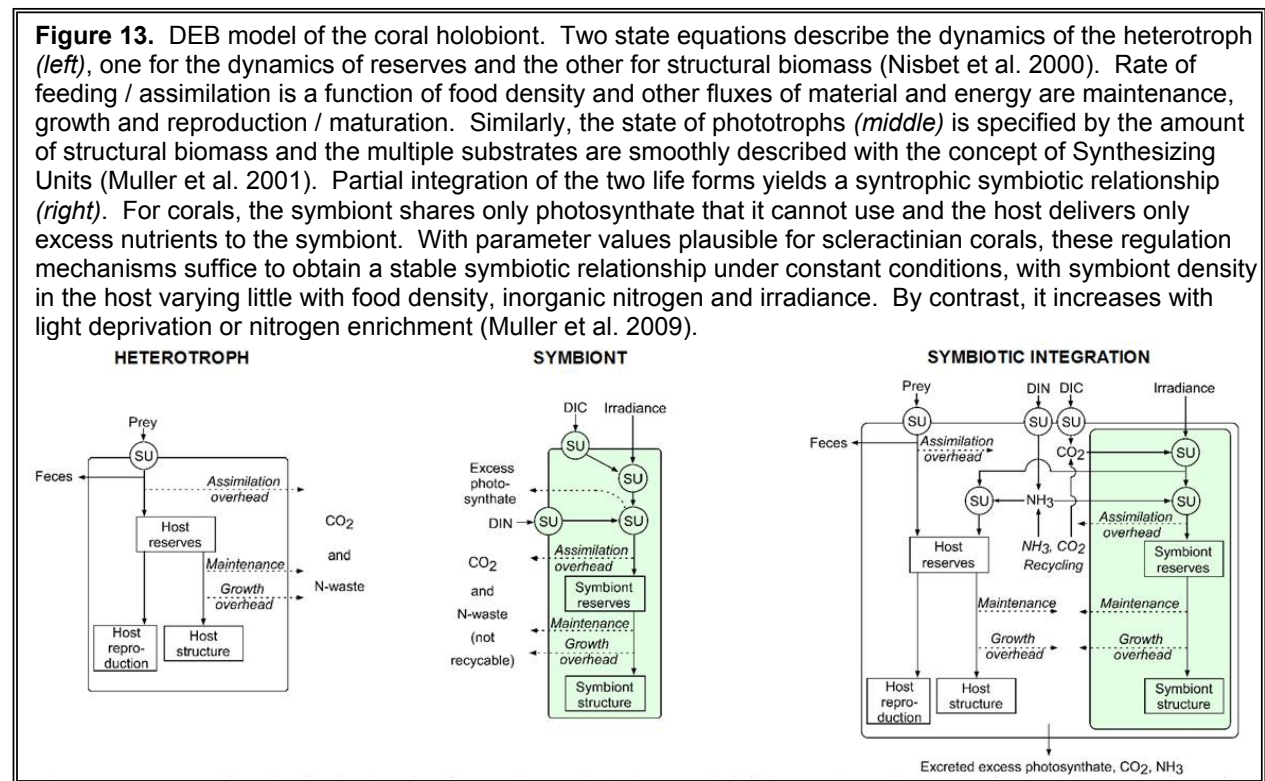
(C) The equations.



Our initial model (Fig. 12) follows the approach of these other authors and models the fraction of space on the fore reef occupied by coral, macroalgae, or free space (with turf algae immediately covering any free space). Two unique features of our model are: (a) we explicitly model the dynamics of the herbivore (parrotfish) population, which controls establishment of macroalgae, and (b) we include the spatial structure inherent in the Moorea system, which includes nursery habitat for the herbivores in the lagoon, such as the *Porites rus* habitat of juvenile parrotfish. Variants of the model also include stage-structure of the macroalgae, such that only macroalgae in the small size class are vulnerable to herbivory, while macroalgae in the large class are invulnerable (similar to what we are finding for the alga *Turbinaria*).

Figure 12 illustrates that our Resilience Model can readily produce dynamics that can lead to both rapid phase shifts and alternative stable states. We will use the parameterized model to investigate how likely these outcomes are under ‘normal’ conditions, and how these predictions are likely to be altered by various disturbances affecting coral reefs. Some perturbations, such as increased nutrient loading, may affect multiple processes in the model (e.g., growth rate of both macroalgae and coral), whereas other perturbations, such as reduction of nursery habitat due to coastal development, may alter single key parameters (parrotfish settlement rate).

An analogous modeling effort supports research on Theme 2. Underpinning the models of coral responses to changing environments is our dynamic energy budget (DEB) model that describes the interaction of the coral host and its symbiont(s) (Muller et al. 2009) (Fig. 13).



We have already used this model as the foundation of a synthesis of physiological rates in 5 families of coral (Edmunds et al. 2011) and in a theoretical investigation of photo-damage and coral bleaching (Eynaud et al. 2011). The current model describes fluxes of energy, C and N, but extensions to describe calcification are feasible, thereby paving the way for modeling the effects of OA (this is the focus of a recent grant submission to NSF). Methodology in Baskett et al. (2009) can be used in the DEB model to represent changes in the symbiont community due to evolution and/or substitutions, and if necessary these can be coupled with the interactions modeled under Theme 1 (see Baskett et al. 2010). Our DEB models offer an integrative

framework that will allow consideration of the many simultaneous components of anticipated environmental change. Thus, changed rates of biogenic calcification will be modeled within a conceptual framework applicable not only to corals but to other reef taxa (notably crustose coralline algae). The approach is integrative in that the formalism readily handles changes at multiple time scales in the irradiance, the nutrient environment, and in temperature. The challenge in many applications of DEB theory is lack of data for parameterization, but with the growth of the body of information from the many MCR process-based investigations, the approach will become increasingly useful.

SECTION 3 - EDUCATION & OUTREACH

Education MCR education activities include the training of undergraduate and graduate students and postdoctoral fellows. At all three levels, students are integrated in MCR research, participate in the annual MCR All-Investigator meeting, the annual MCR-SBC-CCE Graduate Student Symposium and joint SBC-MCR seminar courses at UCSB. Undergraduate students are involved in MCR as REU participants, research assistants on investigator projects and as recipients of mentoring by graduate students, postdocs and investigators. Our site fosters international partnerships and collaborations with other coral reef research groups including our student exchange program with the Kenting Coral Reef ILTER site in Taiwan and our new research project with French and Tahitian scientists on coral calcification and reef metabolism.

Outreach We have an active program involving local outreach in California, outreach in French Polynesia, and web-based projects to reach the broadest possible audiences. MCR students, particularly graduate students, participate in many of our outreach activities.

Local outreach in California: The REEF (Research Experience & Education Facility) is an interactive marine educational facility at UCSB that provides educational tours for K-12 and community groups and serves over 10,000 visitors annually. REEF programs support California State Science Content Standards and are developed in partnership with the Channel Islands National Marine Sanctuary, Center for Ocean Sciences Education Excellence (COSEE) and Marine Activities, Resources and Education (MARE) at the Lawrence Hall of Science. The REEF provides visitors with a hands-on, inquiry-based experience into marine science and research conducted at UCSB, including the MCR LTER. MCR science is showcased to visitors by MSI staff and UCSB undergraduate interns. In addition to continuing to work with The REEF staff, we will maintain our special partnership with Washington Accelerated School (Pasadena Unified School District) to bring all 4th graders (~ 115 students; 90% economically disadvantaged; 40% English language learners) on a trip to UCSB. Students visit the REEF and participate in interactive presentations and demonstrations led by MCR graduate students.

We work with teachers from our partner schools, including Washington Accelerated, Kellogg Elementary School (Goleta Union School District) and Carpinteria Middle School (Carpinteria Unified School District), to develop science curricula based on MCR research themes. Kellogg Elementary is a local public school that serves 3,700 elementary students (47% Hispanic, 28% classified as English language learners). Carpinteria Middle School has an especially large Hispanic (72%) and economically disadvantaged (68%) student population. The NSF RET program has been instrumental in developing our partnerships. To date, 5 teachers have been awarded RETs to work with us in Moorea, and we will continue to pursue additional RET opportunities. We will expand our collection of inquiry-based curricula (<http://mcr.lternet.edu/education/lessonplans.html>). The units are written in collaboration with K-12 teachers (particularly our RET recipients), are aligned with the California State Science Content Standards and refined using feedback from local teachers. At the high school level, we will continue our Marine Biology Clubs in which students are exposed to LTER research through classroom presentations and hands-on laboratory exercises. We host such a club at Viewpoint School, and in 2012 we will extend this program to Sun Valley High School in Los Angeles.

The MCR will continue its community outreach activities at the annual Earth Day education event in Santa Barbara. We continue to develop outreach materials regarding the status of and

threats to coral reefs (including MCR research) to showcase at our booth. We provide hands-on activities for K-12 students that demonstrate concepts related to MCR site science. These activities change each year; they have recently included a design-your-own fish and fish morphology activity, mazes, word searches, and the like. While children are working on projects, parents talk with MCR personnel and view information about MCR research. The event draws up to 30,000 visitors, and > 500 children participate in our activities each year.

Community Outreach in Moorea: We will continue to work with the Atitia Center, the public outreach unit of the Gump Station (<http://moorea.berkeley.edu/outreach/atitia/>), and the Association Te Pu 'Atiti'a, to make MCR LTER personnel and education resources available to K-12 students and the public on Moorea. For example, the Marine Biology Research Camp brings classrooms of Tahitian students (ages 10-15) to the Gump Station for three days for hands-on exercises that expose them to research findings that are relevant to local citizens. This provides us with an appropriate forum for outreach in Moorea since local regulations preclude our direct involvement in classrooms. We also are working with the Atitia Center to translate our upcoming LTER children's book, *Kupe and the Corals*, into French and Tahitian.

Web Presence: We will add to our online collection of inquiry-based curricula and to our Online Encyclopedia of Marine Life website (<http://mcr.lternet.edu/education/encyclopedia/index.php>). The Encyclopedia now highlights over 125 common reef organisms. Information is displayed as taxonomically organized species identification cards that are linked to websites containing additional biological information. Our online content describing MCR graduate student research continues to grow as new students provide additional photos and 'plain language' descriptions of their research. We will add additional videos (<http://mcr.lternet.edu/education/research.html>) featuring MCR Investigators.

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FACILITIES, EQUIPMENT AND OTHER RESOURCES

Laboratory

All MCR LTER investigators have laboratory space (typically ~1,000 sq. ft. each), modern instrumentation for a broad range of chemical and biological analyses, computing facilities and a variety of other support services at their home institutions. The UCSB Marine Science Institute (MSI) Analytical Laboratory is a professionally managed, shared-use instrumentation and chemical analysis facility that is well equipped to perform all of the chemical analyses anticipated for this project. Major capabilities of the Analytical Lab include elemental analysis of inorganic and organic substances, stable isotope ratio determination of biological materials, and automated determination of nutrients in natural waters. Major equipment in the MSI Analytical Lab include: two atomic absorption spectrophotometers (AAS) with auto samplers, one instrument equipped for flame atomization, and the other a dedicated furnace system with Zeeman background correction; a microprocessor-controlled gas chromatograph (GC) with various detectors, including flame ionization and photo-ionization; and two automated organic elemental analyzers for CHN analyses, an isotope ratio mass spectrometer interfaced with a CHN sample introduction system, and an automated 5-channel wet-chemical analyzer (FIA) for nutrients. Water samples from the MCR Offshore Station are analyzed by the Oceanic Carbon Dioxide Quality Control Analytical Laboratory operated by A. Dickson at Scripps Institution of Oceanography.

Clinical

Not required for this project.

Animal

Schmitt, Holbrook and Brooks will maintain fishes in laboratory tanks for brief periods of time while certain field experiments are initiated in accordance with IACUC standards. The UC Berkeley Gump Station has appropriate laboratory aquaria and ponds for studies involving fish. These tanks are supplied by fresh seawater from a once-through delivery system. The collection, care, and final disposition of fishes will be done in accordance with Federal standards as ensured by the UCSB Animal Care authority. Our animal care protocol is approved and reviewed on an annual basis. Schmitt, Holbrook, and Brooks (as well as technicians and graduate students) have completed all Federal and campus mandated Animal Care training, and they currently have an approved IACUC protocol and associated Standard Operating Procedure (SOP) for the proposed research (UCSB Protocol 639, 2/1/2012 – 2/1/2015).

Computer

Internet service is provided to all users of the Gump Station on its secure, password protected wireless network. In addition, the MCR LTER operates two additional secure, internet connections through Mana, the local internet service provider; one connection is dedicated to data transmission from our growing real-time environmental sensor network and a second is for general internet use by MCR LTER personnel. The MCR LTER maintains 2 desktop and 2 laptop PCs for the exclusive use of MCR LTER personnel while in Moorea. All investigators in this project maintain computing capabilities at their respective institutions commensurate with their specific research activities and most travel to the field with wireless equipped laptop PCs.

Data management for the MCR LTER uses the computing capabilities of the Marine Science Institute (MSI). MSI has a 1000Mb/s connection to the UCSB campus backbone, which provides shared access to a 622Mb/s CALREN-2 connection, which in turn provides access to the Internet. MSI supports the research servers. The main data server providing network file sharing (Samba and NFS) is a running RedHat Enterprise Linux 5 (64-bit). The data server also runs SVN for revision control systems, SAS, Matlab, GSLIB and PERL for scientific applications. Currently we have 11.5 TB of storage (expandable) available on that system. The second

server is running RedHat Enterprise Linux 5 (64-bit), which runs the Apache web server, and the Tomcat java servlet engine. A third server running RedHat Enterprise Linux 4 (64-bit) is the primary database server, running PostgreSQL, MySQL and the personnel database (LDAP). The Server room is connected to E-Power, and redundant power is provided by an APC 6000 UPS battery backup. Distributed server backups (via Amanda) are coordinated with MSI. The UCSB Earth Research Institute (ERI) provides computational support for the processing of satellite imagery. It consists of a network of more than 50 UNIX servers, workstations, and clusters. A Linux cluster is used for high performance MATLAB post-processing and analysis of satellite imagery. It has 16 Quad-Core 2 GHz AMD 8350 CPU's, with 16 GB of RAM and 5.5 TB of disk. We also have access to a 1008 CPU MPI cluster that was funded on a NSF Major Research Infrastructure grant (<http://csc.cnsi.ucsb.edu/clusters/knot>).

Office

In addition to office space and equipment provided to visiting researchers at the Gump Station, we have a dedicated office that has a telephone/fax machine, photocopier, dry work space, internet connectivity, and a printer. An additional 240 sq. ft. of dedicated office space is available to long-term MCR researchers and technical support staff. This space includes a printer, flatbed scanner, two general use computers and internet connectivity. All investigators have adequate office space provided at their home institutions to meet their needs and those of the postdocs and graduate students associated with this project. All offices are equipped with phone and internet services.

Other

All field work will be conducted at the Richard Gump South Pacific Biological Station (<http://moorea.berkeley.edu/>) on the island of Moorea in French Polynesia. The Station, which is administered by the University of California Berkeley, has all of the equipment and facilities needed to support extensive marine research. There are facilities to support scuba diving (dive lockers, Bauer 10 MiniVerticus air compressor, scuba tanks, fully equipped machine shop). Diving operations, under the auspices of the UC Berkeley Diving Safety Office (AAUS member), are conducted out of small boats within the lagoons and slightly larger Whaler-type boats for work on the outer reef slope. An NSF Field Station Improvement Grant recently supported the purchase of a new, 8 m, twin engine boat that has been modified to support offshore research. Boats may be launched from the on-site launch ramp and moored at the Station dock immediately adjacent to the SCUBA facility at the lab. The Station has a running seawater system with sufficient water tables and large outdoor tanks to support our proposed work. With funds from MCR, this facility was upgraded to support (1) a tank "farm" of 15 large (750 liter) outdoor tanks suitable for holding fish and large invertebrates, and (2) an indoor wet lab designed to meet the needs of our seawater flumes, mesocosm, and indoor-wet-table needs. Additional research space includes a wet laboratory, a dry laboratory and air conditioned office space. A multi-use laboratory containing a large teaching lab (~25 students), smaller research labs, a molecular lab, library, meeting room, collection and visualization lab, IT center, chemical and storage rooms, and office space was completed in 2008 with support from the Gordon and Betty Moore Foundation. A small fleet of vehicles is available for general transportation. Station housing options include a dormitory building, and seven hillside bungalows that can each accommodate 4 visitors. In addition to facilities, the Station has a permanent on-site staff of 7, which consists of a director, facilities manager, book-keeper / administrative assistant, an outreach coordinator / liaison with the Territorial Government, two maintenance persons, and a housekeeper.

UCSB is highly supportive of the MCR and will provide additional resources (e.g., salary support, foreign travel and field costs, analytical costs). This will be done on an annual basis to ensure that the project meets its research objectives. As per university policy, CSUN will provide teaching release time to enable Edmunds and Carpenter to participate in the project.

MAJOR EQUIPMENT

During MCR I, the equipment context at the Gump Station changed vastly due to (a) generous gifts from the Gordon and Betty Moore Foundation (to both the MCR and the Gump Station), (b) equipment purchased through the MCR LTER grant and NSF supplements to the award, and (c) equipment purchased by the Gump Station (e.g., through the NSF FSML program).

The MCR LTER itself has a fleet of research boats (10 total), including eight skiffs (four 3.9 m with 25 HP engines, four 5.1 m with 40 HP engines), an offshore-capable vessel (6.1 m with 150 HP engine), and a larger vessel capable of deploying oceanographic instruments (8 m "Safeboat" with 250 HP engine). Additionally, we have a Land Rover 130 pickup truck (extended crew cab), and have trailers for all boats to facilitate servicing and shore-based deployment. With the opening of the new lab building in 2008, we acquired \approx 1000 sq. ft. (2 rooms) of dedicated space that has been allocated equally to organismic / ecology research and molecular / physiology research. DSL/wireless internet is available throughout the laboratory building. Our laboratory spaces in the new building are equipped with a wide range of microscopes (graduate-grade compound and dissecting microscopes, through to a state-of-the-art compound microscope), scintillation counter, water purifier, gel doc system, balances, fluorometer, spectrophotometer, refrigerator, freezer, drying ovens, muffle furnace, stabilized power supplies, tissue disruptor, centrifuge, PCR machine, and autoclave. Also, we have additional dedicated air-conditioned space for the storage of all sensitive equipment and to provide clean work space for the maintenance and programming of oceanographic instrumentation.

MCR LTER oceanographic instruments include 1 profiling CTD (SBE 19+), 1 DO sensor (SBE 43), 75 thermistors (SBE 39), 10 temperature/pressure instruments (SBE 39), 4 wave-tide gauges (SBE 26+), 10 CTDs (SBE 37), 1 CTD (SBE 16+), 4 ADCPs (RDI Workhorse), 5 ADPs (Nortek), 2 ADVs (Nortek), 1 diving PAM (Waltz), and 4 DO sensors, 2 Li-Cor 1400 light meters in UW housings with sensors, a variety of underwater still and video cameras, and an *in situ* underwater video system with infrared illumination.

With NSF supplemental funding, we have constructed a state-of-the-art Ocean Acidification mesocosm facility at the Gump Station. The facility currently consists of 12 tanks in which light, temperature and $p\text{CO}_2$ can be controlled precisely. The system uses gas mixing technology (Qubit Systems, Ontario, Canada) to manipulate $p\text{CO}_2$ and create step-less adjustment within a range simulating atmospheric conditions expected under contemporary climate projections. The system is scalable, can support experimental volumes ranging from 2–200 liters and can be used in combination with both tanks and flumes. In 2011, we augmented this system in two significant ways. First, we replaced the metal-halide lamps with state-of-the-art, high intensity LED systems. These provide similar light intensities (to $\sim 1,200 \mu\text{mol quanta m}^{-2} \text{ s}^{-1}$) to the metal halides, but they operate at a fraction of the power and have almost no heating effect. Additionally, they are fully scalable and programmable, offering the potential to simulate sunlight in a sine curve. Second, through separate NSF funding for OA research, we added a 300 g acclimation tank to stage corals between field collection and experimental treatments. The acclimation tank has independent heating and lighting, and is fitted with a rotating table (4 revolutions d^{-1}) to remove position effects as the corals adjust from field to laboratory conditions. The mesocosm and acclimation systems are matched with a seawater analysis facility (equipped in a manner consistent with the SOP for DIV analysis of Dr. Andrew Dickson, SIO) in which we can evaluate the DIC treatment conditions we create. Recently we have duplicated this system at CSUN to facilitate training of MCR personnel prior to arrival in Moorea, and to create the potential for REU projects pertinent to the research effort in Moorea.

The MCR LTER maintains several climate and other monitoring platforms at the Gump Station. These platforms include a research-grade weather station (Campbell Scientific) incorporating wind speed and direction, rainfall, solar irradiance, barometric pressure, relative humidity and

temperature sensors and, on the reef adjacent to the Station, a Seacat SBE-16+ CTD (SeaBird Electronics) incorporating sensors for measuring conductivity, ocean temperature and ocean pressure (depth). We have installed a stationary video camera (Axis Technology Inc) with a view of Cook's Bay. All climate and oceanographic data are stored using internal data loggers (CR-1000 for weather data and flash memory for oceanographic data). Additionally, climate and oceanographic data and video are streamed in near real-time (every 5 min) via the internet to a DataTurbine (www.dataturbine.org) server located at the UCSD/CalIT² Data Center. Data are displayed in near-real time for the general public via the MCR LTER website (<http://mcr.lternet.edu/data/realtime>). More sophisticated data visualizations of weather, oceanographic and video feeds as well as the ability to write and execute custom event-detection algorithms and alarms are available to MCR (and other) researchers via a DataTurbine Real-time Data Viewer incorporating a Tivo[®]-like playback interface.

We have an experimental oceanographic mooring that is used as a testbed for development and testing of real-time oceanographic instrumentation. This mooring is deployed in Cook's Bay approximately 50 m from shore, directly adjacent to the Gump Station. Unlike our existing Seacat SBE-16+ CTD which is cabled to shore in order to provide streaming oceanographic data, this new mooring employs a Campbell CR-1000 data logger linked via an inductively coupled modem to an array of oceanographic sensors (three SBE-39 thermistors, two SBE-39 thermistors with pressure sensors, two SBE-37 CTDs, one SBE-26+ wave/tide recorder and one RDI Workhorse Sentinel Acoustic Doppler Current Profiler) and a standard 802.11 wireless receiver/transmitter to stream data in near real-time (every 5 min) back to a collection point at the Gump Station and then, via the internet, to the DataTurbine server at the UCSD/Cal IT² Data Center.

OTHER RESOURCES

Major equipment available to this project owned by the Gump Station includes one 6 m Whaler-type boat with 150 HP engine, a new 8 m aluminum boat for offshore research (with twin 150 HP engines), and two smaller 4 m Whaler-type boats with 15 HP engines. The lab building provides air conditioned space for group meetings/classes (equipped with AV/computer technology), additional lab space for "spill-over" projects, and office space for visitors (each hillside bungalow also has air conditioned space for office work). A wet lab facility provides access to flowing seawater pumped directly from Cook's Bay and supplied in a cascade system to sea tables and aquaria (and our tank farm, above). The Station also has a -80°C freezer for storage of samples.

The Gump Station has a facility and personnel for the repair of small boats and outboard engines. More extensive repairs can be made in Papeete on the island of Tahiti (30 minutes away by ferry). The Station has a small machine shop and UCSB has at Gump a 500 sq. ft. machine shop, containing a table saw, radial arm saw, band saw, drill press and a full complement of small hand and power tools. More extensive fabrication requirements can be handled by commercial operations on Moorea or Tahiti. The Integrative Oceanography Division at SIO maintains an instrument calibration center at the Hydraulics Laboratory with facilities to calibrate temperature sensors and instrument compasses. Equipment necessary to fabricate and maintain buoys and drifters is provided at the Hydraulics Laboratory.

SUPPLEMENT 1 - MCR DATA MANAGEMENT PLAN

The MCR LTER Information Management System (IMS) serves both site needs and network goals. Information Management facilitates the archival cataloging of data for long term preservation, and also enables the discovery of data and enhances its suitability for synthesis. Network capabilities must grow for the LTER Network to maintain its lead in ecological data archiving and synthesis. MCR is contributing to these advances and has a plan in place to meet expected future requirements (e.g., the goals outlined in section 5 of the [LTER Strategic and Implementation Plan](#)).

The MCR Information Management System

The MCR IMS meets or exceeds all [Criteria for Review of Site IM Systems \(version 1.1 2009\)](#) provided by the LTER Information Managers Committee and NISAC. These specifications post-dated our midterm site review, which took place in 2007. As a result, during 2009 and 2010 the entire MCR IM system was internally reviewed and redesigned.

IT Resources and System Features: The Marine Science Institute (MSI) provides infrastructure and IT resources (see Facilities statement) including a web server, database server, and filesystem server with a Storage Area Network (SAN) supporting snapshots. Purposeful redundancy in backup systems provides for disaster recovery with off-site copies stored in a separate building on UCSB, and for file restores from more frequent on-site backups. The entire data catalog inventory is cached annually as a DVD archive off campus. Features and specifications of the MCR IM system are summarized in Table 1.1.

Table 1.1 Key Features of MCR Information Management System

Type	Feature	Specification
Website, searchable catalogs and directories	^{\$} http://mcr.lternet.edu [#] Bibliography [#] Personnel directory [#] Data catalog Signature datasets Sampling sites	XHTML, CSS2, PHP, Perl, XSLT, Javascript EndNote & PostgreSQL LDAP EML EML KML & EML
Datasets in LTER Network Catalog	43 data packages (100 data tables & non-tabular data files)	EML 2.1.0
Database	^{\$} MCR_Metabase, Metadata exchange	GCE Metabase2, PostgreSQL EML
Servers and user accounts	Web, database, file systems with backup 84 user accounts	LINUX Apache, SAN, EXT4, rsync LDAP
Code Repository	^{\$} Versioning of code, database models, website revision control and system documentation	SVN, schemaSpy, mediaWiki

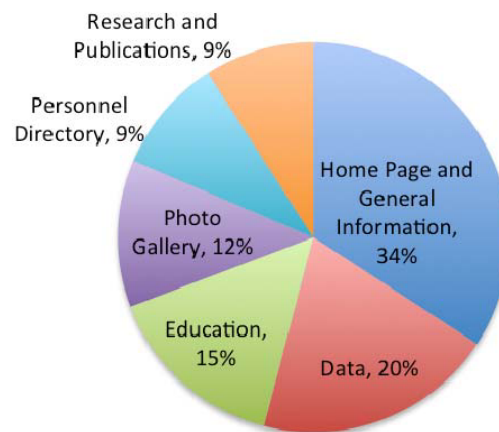
Footnotes: [#]searchable by creator, LTER core area, topic and/or publication type and year
^{\$}further described in text

Database Design: In 2009, MCR recognized the need for database-driven metadata storage and product generation. In 2010, MCR led a review and comparison of metadata databases in the Network. Components were identified for the expected linkages of a well cross-referenced LTER website. Database elements were mapped to their corresponding metadata elements to generate complete EML. Many LTER sites contributed material to this effort, which is summarized in a poster (Gastil-Buhl et al. 2010). As a result of this review, MCR and Santa Barbara Coastal (SBC) LTER selected the metadata database model that drives the Georgia Coastal Ecosystems (GCE) IMS, also recently implemented at Coweeta (CWT). GCE Metabase has been in production for over a decade at GCE, produces high quality EML and has proved capable of efficient adaptation to increasing expectations and LTER Network standards. In collaboration with SBC, MCR ported Metabase to PostgreSQL. MCR and SBC will maintain collaborations with both GCE and CWT as this database model continues to develop. Metadata documents in EML 2.1 dynamically derived from Metabase are more efficient to maintain and adapt to the increasing utility and future best practices expected of LTER metadata than are manually edited documents. This implementation and collaborations with GCE and CWT show that LTER sites can effectively share IMS components even when they have diverse infrastructure.

Public Website: The website is the most publicly visible part of the IM system. The MCR website (<http://mcr.lternet.edu/>) meets or exceeds the [Guidelines for LTER Website Design and Content \(version 1.1 2009\)](#). We use hierarchical navigation to provide single-click access to the data catalog, publications and research foci. All recommended links and features are implemented. The data catalog is searchable by the five LTER Network Core Research Areas, MCR research theme or activity, measurement or derived variable, category and topic or investigator. Core (“Signature”) datasets are highlighted. Publications are searchable by Core Area, investigator, year, publication type or free text search. The MCR personnel directory is searchable by name, field of research, email or title and each person is cross referenced to their publications, datasets, and research activity involvements. We continually update the website to present fresh content and up-to-date indexes. The website seamlessly integrates both static content and dynamic content from a database. Both scientific and outreach areas of the website receive significant traffic (Fig. 1.1).

Figure 1.1 Website Traffic

We track our public website traffic using Google Analytics. From Jan. 1, 2010 to Dec. 31, 2011 <http://mcr.lternet.edu/> had 22,775 visits, with 9,468 unique visitors; 41% of these visitors were seeing our website for the first time and 19% of visitors were from outside the United States (from a total of 99 countries to date).



Internal Website: To foster intra-site science synthesis, internal web pages containing quick-look data overviews allow investigators to share preliminary results from new data early in the interpretation process. These were prompted by the MCR Data Mining Workshops to view temporal and spatial dataset coverage, graphs and brief descriptions. The internal website also contains logistics for field work, internal documents, meeting announcements, a 374-page searchable and categorized Wiki documenting IM practices and other content appropriate for MCR personnel. The database models that drive website content and store dataset metadata are documented graphically in browse capable schematic representation generated dynamically from the database itself by schemaSpy.

Data Access Policy and Data Distribution

MCR data use policy and data release policy are consistent with the LTER Network policies and use “Type I versus Type II” terminology. With few exceptions that conform to LTER data policies, all MCR data are Type I (publicly available). There is no delay in releasing MCR data to the public once Quality Assurance has been verified. In accordance with LTER policy, graduate student thesis data are archived and cataloged as Type II, not released until thesis publication. MCR collects data use information upon acknowledgement of the data access policy. We have experimented with sending out dataset update notices to those who registered use for Academic Research.

Table 1.2. Public downloads of data from the MCR Data Catalog by user affiliation.

Internal and testing downloads are omitted. Download tracking began mid-2007. MCR datasets are not split by year; new data are appended to the existing dataset. This practice ensures that a user will receive the complete, quality-assured dataset for all years in one download.

	2007	2008	2009	2010	2011	Total
Academic Research	60	105	331	171	163	830
Education (College)	0	9	32	47	86	174
Education (K12)	12	1	4	8	8	33
Government Agency	2	1	0	4	4	11
Non-Profit Org.	0	0	0	0	4	4
Other	3	36	9	17	4	69
Total	77	152	376	247	269	1121

Metadata

All MCR data packages now conform to the most recent (August 2011) version of [Best Practices for LTER dataset EML](#). Metadata features include embedded or online links to methods and protocols, full temporal, spatial, and taxonomic coverage, keywords from the MCR vocabulary, the NBII thesaurus, and/or the LTER Controlled Vocabulary, and units registered in the LTER Unit Dictionary. All EML is version 2.1.0. All data tables are congruent as far as the EML Congruency Checker is able to check in its preliminary version (0.1). Beyond the required elements, some MCR datasets provide explicit indexing keys and table-joining keys to facilitate cross-dataset synthesis.

Dataset Management (Data Life Cycle)

Assuring current and long term usefulness of MCR data requires metadata of the highest quality. Datasets vary in update frequency (e.g., monthly for weather station data, annually for the biotic surveys). Data reach the IM office in different stages of maturity depending on their type. Physical oceanographic data and water column profile data are fully processed including Quality Control (QC) in Matlab before submission to the IMS. A subset of our core time series datasets are further controlled by maintaining these data in a relational database where taxonomy, location and observation metadata are constrained to controlled vocabularies and value bounds. Biotic surveys require reformatting within the IMS prior to uploading to the database. QC is done first automatically within the database, flagging further QC for human inspection. Planned refinements to this process include scripting more of the quality assurance metrics. Scripting takes substantial investment of time because each dataset requires knowledge of the expected characteristics and custom definition of the quality control criteria and quality assurance metrics, but the return on investment is high and immediate.

Each new proposed research project at MCR requires a data management plan. Investigators provide an outline of expected data products and the relationships to ongoing projects. The information manager provides advice on naming conventions, guidance for file organization and format, and designates space on the server to back up raw files from the field. The MCR Deputy Program Director (Brooks) ensures the information manager is aware of new projects and coordinates investigators before projects are initiated. Continued participation in core activities is contingent upon timely contribution of collected data to the MCR catalog. Brooks is responsible for ensuring data are added to the catalog in a timely fashion.

IM Staff

M. Gastil-Buhl is the information manager for MCR. M. O'Brien, information manager for SBC LTER, works in close collaboration with Gastil-Buhl, and both are sufficiently familiar with each IM system of the other site that they cover for one another when necessary. During 2011, NSF supplemental funds to the two sites were combined to support a shared assistant during the porting and adoption phase of GCE Metabase. C. Gotschalk performs data analysis and quality control for the physical oceanographic and meteorological data. High-level system administration is provided by J. Woods, computing resources manager for UCSB's Marine Science Institute. Brooks provides oversight and logistical support to the IMS.

LTER Network Activities

Gastil-Buhl contributes regularly to LTER Information Managers' Committee (IMC) activities. At the 2010 IMC meeting, Gastil-Buhl led a session comparing metadata databases in use at LTER sites (Gastil-Buhl et al. 2010). At the 2011 IMC meeting, she led a clinic to interpret preliminary assessment of Network EML data package quality. She served as Databits editor in 2010, and participates in the following IMC working groups: (1) IMC Website Redesign, (2) EML Best Practices, (3) Web Services / Network DB Redesign, (including the Personnel DB redesign), (4) EML Metrics and (5) SensorNIS. She serves on NISAC along with MCR Associate Investigator Washburn. As a member of two NIS Tiger Teams (Metadata Quality and Data Package Manager) she advises on NIS design. MCR presented a poster on the Digital Moorea sensor network in collaboration with the Open Source DataTurbine group from CalIT2 at the SensorNIS workshop in 2011 (Fountain et al. 2011). MCR regularly contributes site content to LTER Network databases (PersonnelDB, BiblioDB, SiteDB, ClimDB) and the LTER Network Data Catalog (Metacat).

Other Activities outside of LTER

MCR collaborates with other Coral Reef research teams in informatics as well as science. Gastil-Buhl serves as IM for Co-PI Edmunds' LTREB project at the Virgin Islands National Park. At the NCEAS working group 'Corals of the Future' (November 2010), Gastil-Buhl demonstrated the MCR IMS facilitation of coral data synthesis. In January 2011 the MCR IM office provided consultation to a research group in Panama (led by Professor Peggy Fong of UCLA) for their Data Management Plan for their NSF proposal, on recommendation of the NSF program office.

Response to Prior Review

Here we address concerns raised by the 2010 NSF panel. *REVIEW CRITERION 3: Information Technology: The Panel commented that (1) they were disappointed that model code and descriptions were not archived on the website, (2) bathymetric data were not posted, and (3) legacy data from the Gump Station be accumulated and added to the MCR archive.* For comment (1), we are unaware of requirements or standards for posting model code and descriptions on site websites and await guidance. To address this concern we have created public web pages that describe MCR modeling efforts in more detail. With respect to (2), as noted in our prior submission, no bathymetric data needed for our hydrodynamic modeling

efforts existed for Moorea; bathymetric measurements we subsequently have made are posted on our website. For (3), Gump Station has no legacy data for the MCR to archive.

Recent Accomplishments

2009 – All metadata documents upgraded to EML 2.1.0 in the LTER Data Catalog (Metacat).

Deliverable: tighter quality control on metadata.

2010 – Website redesigned to add database-driven cross-referenced dynamic content.

Deliverable: searchable publications, directory, data catalog.

2011 – GCE_Metabase ported from SQL-Server to PostgreSQL. **Deliverable:** open-source version of already-proven metadata database.

– All metadata accordant with the August 2011 version of EML Best Practice for LTER Sites. **Deliverable:** content-rich, high-quality datasets.

Future Directions and Challenges: Proposed Products and Milestones

We continue toward our goal of a more cohesive, efficient and user-friendly system, taking advantage of Network resources as they become available.

2012 – Current manual processes for EML document creation will be replaced by generation of EML from Metabase. **Deliverable:** EML generation tool.

– Once the LTER NIS prototype becomes available in 2012, MCR will submit all MCR datasets to the Provenance-Aware Synthesis Tracking Architecture (PASTA) prototype.

Deliverable: feedback to NIS developers.

2013 – Research projects web pages will be replaced with the LTER-developed ProjectDB architecture, generated from Metabase, leveraging SBC implementation. **Deliverable:** web pages with network-consistent presentation.

– Incorporation of GCE Data Toolbox as a quality control and data reformatting tool into the MCR IM system. Data Toolbox automates metadata collection for Metabase.

Deliverable: efficiency in metadata collection and quality control.

2014 – PASTA is due for completion in 2014; MCR datasets will be submitted. **Deliverable:** PASTA-ready datasets.

– Adapt additional features from the GCE IMS. **Deliverable:** lower skill requirement to enter metadata and more efficient report generation.

2015 – Current manual synchronization of local site databases for publications and personnel will be replaced by web service enabled synchronization with the LTER Network databases BiblioDB and PersonnelDB. **Deliverable:** web service client.

2016 – MCR LTER will adopt the Best Practices for quality control and archiving of streaming sensor data, which the LTER working group SensorNIS will establish. **Deliverable:** improved quality assurance.

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SUPPLEMENT 2 - MCR POSTDOCTORAL MENTORING PLAN

The collaborative and interactive nature of the MCR LTER program will help to hone the specific research skills of the postdoctoral researchers as well as prepare them for professional interactions and job interviews. The training of postdocs will focus on both research and teaching. Regarding research, their training and mentorship will include guidance in designing and executing collaborative and interdisciplinary field and laboratory research programs. Individuals will receive training in field and laboratory techniques as well as data reduction and analysis, web and journal publication and professional presentations (including job seminars, conference talks and posters). They will also gain experience in supervising and working with technicians, graduate students, and REU students, to set up, maintain, and collect data from experiments in the lab and field. Each postdoc will work in a specific laboratory of an MCR LTER investigator, and will participate fully in all MCR LTER programmatic activities such as the annual MCR All Investigator Meeting, regular working group meetings, and seminars. There will be ample opportunity to present research findings and receive feedback. In addition, postdocs will be encouraged to participate in LTER Network-wide activities, such as the All Scientists Meeting, workshops and working groups, and training programs, as appropriate. Guidance will be provided in preparation of new research proposals. Additional aspects of postdoctoral mentoring include advising about long-term employment options and opportunities, facilitation of professional networking, and providing research opportunities such as visiting other labs, trips to scientific meetings and to research sites. Regarding teaching, the postdocs also will be provided opportunities to improve their mentoring skills as they work with graduate and undergraduate students. In addition, we also will make available opportunities to teach, for example, through guest lectures in undergraduate and graduate classes. The MCR LTER has developed a vibrant outreach program with local schools, and we will entrain postdocs into these activities to give exposure to this important aspect of their science career.

SUPPLEMENT 3 - MCR SITE MANAGEMENT PLAN

Site Governance

MCR is governed by an Executive Committee that consists of the Lead PI (Schmitt), the three Co-PIs (Holbrook, Carpenter, Edmunds) and four Associate Investigators (currently Alldredge, Briggs, Gates, Leichter). Associate Investigator members of the committee serve three year rotating terms. The Deputy Program Director (Brooks), Information Manager (Gastil-Buhl) and Outreach Coordinator (O'Connor) serve on an Ex-Officio basis. As such, members of the Executive Committee represent the major science and programmatic elements of the site. The Committee addresses science and budgetary priorities, advises on program policy issues, reviews progress on major program elements, identifies potential new science initiatives, sets priorities on supplement requests, and helps with communication to the broader MCR community. The Executive Committee will continue to develop and implement policies regarding (1) data access and sharing, (2) use of MCR vehicles, boats, instrumentation and mesocosm facilities, and (3) collaborative activities with groups outside the MCR LTER. These policies, along with the Executive Committee meeting minutes, are posted on the internal MCR website. The Executive Committee also plays a central role regarding the composition of the MCR research team, including the identification of potential new Associate Investigators and Collaborators and members of the MCR External Advisory Committee. With respect to selecting new Associate Investigators, the Executive Committee considers the need to broaden diversity as well as attract younger investigators to the site. Decision making typically is by Committee consensus; in the rare event that consensus is not reached, the Lead PI (Schmitt) makes the final decision. As recommended by the last NSF Panel, we convened a large working group (supported by NCEAS) of international coral reef experts that met several times over the past two years, and constituted an External Advisory Committee to give scientific input to the Executive Committee. Committee members are Terry Hughes (Director of the Australian Research Council's Centre of Excellence for Coral Reef Studies, James Cook University), Barbara Brown (founding member of the International Society of Reef Studies, past Editor-in-Chief of *Coral Reefs*, U. Newcastle) and Karen McGlathery (Lead PI, VCR LTER, U. Virginia).

Project Management

The MCR LTER is administered by UC Santa Barbara and field operations are based at the Gump Research Station on Moorea, which is administered by UC Berkeley. Lead PI Schmitt serves on the Gump Research Station Advisory Committee, which reports to the Vice Chancellor for Research at UC Berkeley. The University of California and the Territorial Government of French Polynesia have a formal cooperative agreement that enables the MCR to operate from the Gump Station. Scientists must hold a research permit issued by the Territorial Government, and the Gump Station handles the paperwork and facilitates the process.

The Lead PI (Schmitt) serves as the Project Director and is responsible for the overall quality and direction of the research. He is the point of contact with the NSF Program Officers, serves as a member of the LTER Science Council, and is the liaison between the MCR and the UC administration. In close cooperation with the three Co-Principal Investigators, Schmitt oversees day-to-day operations of the project and implementation of all of its components. The four PIs meet several times monthly, either in person or via video conference. A half-time Deputy Director (Brooks) is in daily contact with the PIs and assists with all aspects of project management. He is an important liaison between the project's investigators and (1) the Information Management team, (2) the Education and Outreach specialist, (3) various University committees (e.g., Diving Safety, Small Boat Safety), and (4) the Gump Research Station. Together, this 5 person management team coordinates the activities of MCR research teams, plans MCR meetings and events, prepares project reports, and prepares responses to inquiries from the LTER Network Office, NSF and many other entities.

Information transfer among researchers of the MCR LTER site is crucial because individuals are located at six universities, and considerable effort goes into maintaining open channels of communication and maximizing the input of all participants. Each year we hold a 2-day MCR All Investigator Meeting at UC Santa Barbara, which is attended by > 50 investigators,

postdocs, graduate students, undergraduates (including REU students), ROA and RET participants, MCR staff and national and international collaborators. Activities at these meetings include presentations and posters, working group meetings for research synthesis and planning, and training sessions. The MCR All Investigator Meeting is one means we use to introduce potential collaborators or new Associate Investigators to the project, and it has proven to be an effective recruitment tool. These individuals participate in all meeting activities and their meeting costs are paid by the MCR.

The annual All Investigator Meeting also is a platform for initiating actions to address upcoming events, such as mid-term reviews, renewal proposals, and potential new research and synthesis opportunities. Follow up typically is done by our standing working groups that carry out the site research. These meet regularly (weekly to monthly) during the academic year. Currently there are three working groups: physical – biological coupling (led by Carpenter), reef resilience (led by Holbrook), and reefs of the future (led by Edmunds). Modeling (led by Briggs) and physical oceanography (co-led by Hench & Leichter) are integrated into each group. The Lead PI (Schmitt) meets at least monthly with the leaders of the working groups during the academic year and ensures communication and coordination among the groups.

The MCR LTER website is another valuable tool for communication with both MCR personnel and other entities. The website and data server are important vehicles for sharing project-related information, data and documents. MCR LTER research occurs at a distant research station in Moorea, French Polynesia, and our internal website provides researchers with information regarding travel and research station logistics and scheduling, visas, permits, requirements for SCUBA and boating certifications, and so forth.

Interactions & Integration with Non-LTER Scientists

The MCR does not have formal agreements with any Federal agency or other entity that supports the research and outreach missions of our program. For site-based research, the MCR relies heavily on fostering interactions with scientists who do – or could – conduct research on Moorea. One major avenue for this has been to build collaborations with scientists in French Polynesia (e.g., Le Centre de Recherches Insulaires et Observatoire de l'Environnement de Polynésie Française (CRIOBE), Institut de Recherche pour le Développement (IRD), Université de la Polynésie Française). This has resulted in a number of collaborative projects (e.g., assessment of the effect of marine protected areas; a retrospective analysis of CRIOBE time series data; studies of population genetics and connectivity of fishes; recruitment dynamics of corals and fishes; isotopic study of trophic status of reef fishes; a retrospective study of reef metabolism and calcification; effects of ocean acidification on corals and other calcifying organisms; lagoon bathymetry; GIS mapping of Moorea). These activities are further fostered by the participation of MCR leadership in the Moorea Ecostation Initiative, the Moorea Marine Protected Area Advisory Committee, and an annual CRIOBE-Gump-MCR Roundtable Meeting. MCR provides resources for the participation of MCR scientists in these collaborative activities and the Executive Committee has placed a priority on funding these projects. This year the Office of the President of the University of California signed an MOU with all French agencies that conduct coral reef research in the Pacific (*'International Research Network (GDRI) Agreement for Biodiversity of Coral Reefs'*). The four named UC participants in the agreement are the Lead PI Schmitt, Co-PI Holbrook, MCR Associate Investigator Bernardi and the Director of the Gump Station (Davies). We anticipate that this recently signed agreement will further facilitate collaborative activities at our site.

As a second avenue, the MCR has reached out to US scientists to offer our assistance in their efforts to provide research collaboration opportunities with our personnel and site, as well as to secure extramural funding. This has led to several collaborative proposals that have been funded by NSF and the Gordon and Betty Moore Foundation. The MCR provides infrastructure support to these projects and the collaborating scientists participate in MCR activities (e.g., the All Investigator Meetings). Finally, the MCR has provided seed funding to targeted US scientists to engage them in collaborative projects with MCR personnel; some of these

individuals subsequently have become Associate Investigators on the MCR project while others remain as collaborators that enable them to use MCR infrastructure on joint projects.

Because coral reef science is an interdisciplinary and international endeavor, from the beginning the MCR Executive Committee has been pro-active in developing interactions and collaborations with international partners at other coral reef sites. Our strategy for achieving this has been to secure funding from NSF (mostly OISE) for planning trips (e.g., Taiwan, France, Monaco), international workshops (Taiwan, People's Republic of China), and, via an NSF EAGER award, collaborative research (Taiwan and Japan). These programmatic efforts have resulted in a robust partnership with the Kenting Coral Reef site in Taiwan, recently formalized with an MOU. MCR Investigators have secured funding from NSF and other sources for collaborative research projects and cross-site comparisons, as well as for extended research exchanges. To date, 9 graduate students, 3 postdocs and 7 MCR investigators have conducted research in Taiwan, and several Taiwanese scientists and students have visited our site and campuses for varying lengths of time and participated in our All Investigator Meetings. One important funding mechanism for MCR graduate students to participate in our partnership with Taiwan has been the NSF East Asia and Pacific Summer Institutes for US Graduate Students (EAPSI) program. The Executive Committee has been pro-active in fostering student interest, ensuring their applications are competitive and assisting them with their projects.

We actively have sought collaborations with scientists and engineers interested in using the MCR site as a test bed for technology development that is relevant to the MCR in particular and the coral reef scientific community in general. Projects our site has facilitated include efforts to develop real time environmental sensor networks, cyber-enabled image analysis, true-color subtidal imaging technology, autonomous robotic vehicles, underwater data transmission technology and underwater navigation (e.g., Hensch & Rosman 2010). The MCR is beginning to incorporate some these developments into its research, and plans to continue to be receptive to similar opportunities to serve as a test bed for emerging environment-related technologies.

With respect to efforts to increase participation of under-represented groups, the Executive Committee seeks new Associate Investigators and collaborators from these groups to the fullest extent possible. Where we can be more pro-active is in the recruitment of postdocs, graduate students and undergraduates. Our efforts to recruit under-represented students include our participation in formal outreach efforts at our campuses as well as individual efforts by MCR investigators. We have been successful at attracting undergraduate and Master's students from under-represented groups at one Hispanic-serving MCR campus (CSUN) who subsequently go on to graduate programs and postdoctoral positions with faculty at other MCR campuses.

Planning for the Future

We propose no change in the leadership for the coming cycle but have continued to engage young and mid-career scientists as Associate Investigators. The addition of new investigators is accomplished by active recruitment to fill a specific research need or by invitation to already collaborating scientists who have expressed interest in a more formal association with the project. Two years ago we brought on three new Associate Investigators (early to mid-career) and in this proposal we add another mid-career scientist. Short term continuity of leadership will be achieved by a Co-PI filling the role of Lead PI should Schmitt become unable to continue. Longer term continuity in leadership will be achieved by the inclusion and rotation of Associate Investigators on the Executive Committee with the goal of adding one or two of these individuals as Co-PIs at the next renewal. We anticipate that a planned transition of the Lead PI will occur mid-cycle in the future, with the successor Lead PI functioning as a Co-Lead in preparing and directing the program for the initial three years of the transition cycle.

SUPPLEMENT 4 - MCR ELECTRONICALLY ACCESSIBLE DATASETS

Current inventory of variables measured or derived, spatial and temporal extent, dataset identifiers, and usage. Datasets are categorized as MCR long term time series, MCR experiments or short-term intensive process studies, and reference (exogenous) data assembled by MCR LTER. Only public direct-access datasets are included in this inventory. Usage is measured by counting public data downloads. Statistics of usage subdivided by purpose are in Table 1.3 in the MCR Supplement 1: Data Management Plan. Usage is for the period from mid-June 2007 through 2 February 2012. Some datasets have been in the catalog for fewer years and so have accumulated fewer downloads. Each dataset is keyed with a unique identifier number following the prefix “knb-lter-mcr” in accordance with the Network standard. Downloads originate from the Network Data Catalog (<http://metacat.lternet.edu/>) or the MCR site (<http://mcr.lternet.edu/data/topic/>) catalog. These catalogs contain identical dataset inventories.

Category	Variables	Spatial extent	Temporal coverage	Sampling frequency	Dataset IDs	Public usage
Time series	Dissolved Nutrients (PO ₄ , SiO ₄ , NO ₃ , NO ₂)	3 habitats x 1 site	2007-ongoing	2 Weeks	knb-lter-mcr.1034	4
	CTD Profile (Temperature, Salinity, Depth) Water Column Nutrients PO ₄ , SiO ₄ , NO ₃ , NO ₂ , POC & PON, DOC & DIC, TOC, Phaeopigment, Chlorophyll a, Fluorescence, Turbidity	5 stations	2005-ongoing	6 Months	knb-lter-mcr.10	116
	Primary Production (bottles) Alkalinity, DIC	5 stations 5 stations	2006-ongoing 2005-2006	6 Months Quarterly		
	Offshore Ocean Acidification (Water Column Alkalinity, DIC, Barometric Pressure, CTD Profile)	1 station	2005-2006, 2012-ongoing	Quarterly	knb-lter-mcr.1037	0
	Satellite Ocean Color, Light Absorption / Particulate Backscattering, Sea Surface Temperature, Chlorophyll a Concentration	4 deg long x 3 deg lat	1985-ongoing	Weekly & Monthly	knb-lter-mcr.5	66
	Meteorological/Climate (Temperature, Rainfall, Wind, PAR, Barometric Pressure, Relative Humidity)	1 station	2006-ongoing	5 Minutes	knb-lter-mcr.9	67

	Forereef Significant Wave Height and Dominant Wave Period, Island-wide Current Speed & Direction, Salinity, Temperature, Depth	1 habitat x 3 sites	2005-ongoing	2 hours, 20 Minutes	knb-lter-mcr.30 knb-lter-mcr.31 knb-lter-mcr.32	40 6 6
	Fringing Reef Salinity, Temperature, Depth	1 habitat x 1 site	2006-ongoing	2 Minutes	knb-lter-mcr.4004	6
	Bay Water Column Temperature	1 habitat x 1 site	2005-ongoing	Resampled to 20 Minutes	knb-lter-mcr.33	5
	Benthic Water temperature	4 habitats x 6 sites	2005-ongoing	Resampled to 20 Minutes	knb-lter-mcr.1035	2
	Coral Cover (expanded scale)	50 quads x 15 sites	2005, 2010	Once per 5 Years	knb-lter-mcr.4003	0
	Coral Cover Annual Survey (fine taxonomy, genus)	40 quads x 3 habitats x 6 sites	2005-ongoing	Yearly	knb-lter-mcr.4	142
	Coral Cover Annual Survey (coarse taxonomy)	20 quads x 1 habitat x 6 sites	2005-ongoing	Yearly	knb-lter-mcr.1038	0
	Benthic Cover Annual Survey	10 quads x 5 transects x 4 habitats x 6 sites	2005-ongoing	Yearly	knb-lter-mcr.8	69
	Invertebrate Count Annual Survey	4 quads x 5 transects x 4 habitats x 6 sites	2005-ongoing	Yearly	knb-lter-mcr.7	66
	Fish Count and Biomass Annual Survey	4 transects x 3 habitats x 6 sites	2005-ongoing	Yearly	knb-lter-mcr.6	132
	Benthic Metabolism Rate (<i>in situ</i>)	2 sites	2006-ongoing	1 to 3 per Year	knb-lter-mcr.18	13
	Component Primary Production (flume)	1 habitat	2006-ongoing	Yearly	knb-lter-mcr.19	8
	Macroalgal CHN	4 habitats x 6 sites	2005-ongoing	Yearly	knb-lter-mcr.20	11

	Species Richness, Abundance of Reef Fish (age/size structure)	1 shore x 7 sub-sites	2000-ongoing	1 season per Year	knb-lter-mcr.1	188
	Abundance of Adult <i>D. trimaculatus</i>	16 transects	1992-ongoing	Daily June-Sep	knb-lter-mcr.2	65
	Settlement/Recruitment (key taxa)	1 reef	1993-ongoing	1 season per Year	knb-lter-mcr.3	24
	<i>Symbiodinium</i> population structure (DNA)	3 habitats x 6 sites +1	2007	Once per 5 years	knb-lter-mcr.15	45
Short-term	Sand Infaunal Survey	53 cores on 5 transects x 4 distances	2004	once	knb-lter-mcr.5001	2
	Water Profiles (CTD Transects)	5 cruises x ~ 20 casts each	2010	once	knb-lter-mcr.5003 knb-lter-mcr.5004	0 0
	Coral Growth Response to Alkalinity	lab	2010	once	knb-lter-mcr.5005	0
	Bathymetry	One side of island	2010-2011	once	knb-lter-mcr.1036	0
	Zooxanthellae, Primary Production, Coral Respiration and Growth	1 habitat x 1 site	2005		knb-lter-mcr.2002	0
Reference	Fish Trophic Groups and Morphometry	-- na --	-- na --	-- na --	knb-lter-mcr.6001	3
	Landsat tm	1 scene	2001-2010	6 dates over 4 years	knb-lter-mcr.6002	0
	Landsat 7	1 scene	1999-2000	1 date in 2 years	knb-lter-mcr.6003	0
	Landsat MSS	1 scene	1979	1 date	knb-lter-mcr.6004	0

The above table excludes Type II datasets which require an internal login or special arrangement to download, such as student thesis or other unpublished data.

SUPPLEMENT 6 – MCR UNOLS SHIP TIME REQUEST

UNOLS Ship Time Request Form - Section ONE - Project Information

Project Title: LTER: MCR IIB: Long Term Dynamics of a Coral Reef Ecosystem
Project Short Title: MCR LTER Project Status: Submitted
UNOLS Project ID #: 103298 Version #: 1
Last Modified: 2/13/2012 5:47:00 PM Date Submitted: 2/13/2012
Project Created By: Russell Schmitt

P.I. Name: Russell Schmitt Institution: UCSB
Phone: (805) 893-2051 Fax:
Email: schmitt@lifesci.ucsb.edu

Institution: UCSB - University of California, Santa Barbara
Address: Santa Barbara, CA 93106 USA

Co P.I. Name	Institution	Phone	Email
No Associated Co-PI			

Science Discipline: BioOce Large Program Abbr: LTER
If Other Science Discipline, specify:
Large Program Comments:

Project Status: Renewal
Agency/Division/Program Grant/Project Number Agency Funding Status
NSF/OCE/BIO To Be Submitted

Institutional Proposal #:
Proposal Deadline submitted for: 3/22/2012
Project Start Date: 9/1/2012 End Date: 8/31/2016
Project Budget: \$3,920,000

Ship(s) Requested	Total	Repeat/Multi-ship/
Year (Name or Size)	Days Req.	Start Date Clearance Req./Estimated Cost
2014 Kilo Moana	23	7/1/2014 No/No/Yes/\$796,420

Project Webpage:

Summary of Field Work: As a supplement to our MCR-LTER proposal we request one 20-day cruise on a UNOLS Ocean/Intermediate class vessel. This work will be used to help the MCR connect large scale oceanographic and biological properties in the South Central Pacific to patterns observed on the reefs of Moorea. Cruise tasks will include: 1) multi-beam sonar measurements to obtain high resolution bathymetry in the waters around Moorea and Tahiti; 2) CTD/ADCP profiles to obtain hydrography around the islands; 3) water column sampling of: nutrients, POC, DIC, DNA structure, distributions of zooplankton and larval fish to assess connectivity, and a full suite of microbial samples. We will also use coordinated sampling with small boats to obtain a radiative sampling grid around the islands, to link the deep and shallow water measurements. The cruise will enter the territorial waters of French Polynesia. This project will be a collaboration between A. Alldredge (UCSB), C. Carlson (UCSB), J. Hench (Duke), J. Leichter (Scripps), and L. Washburn (UCSB).

Summary of Facility Requirements: For a successful project we require full use of the ships facilities including: XBT, CTD with Niskin bottle rosette, winch suitable for net tows, ADCPs, EM122 and EM710 multi-beam systems, flow through sea water, compressed air, full complement of bunks available for scientists, radioisotope van with hook-ups, uncontaminated seawater for in laboratory analyses, MET data, and 'live' internet (as available) for public outreach. We request use of small boats (RHIBs) to conduct radiative sampling transects between the ship and shallow nearshore waters. We also request the services of the Hawaii Mapping Research Group (HMRG) staff for seafloor mapping work. Much of the area of interest is in water too shallow for the R/V Kilo Moana to safely conduct mapping, therefore we also request the full use of HMRG's 25' survey launch R/V Ahi, including its 240-kHz multibeam, POS-MV system, and Seabird CTD (http://www.soest.hawaii.edu/pibhmc/pibhmc_ahi.htm). The R/V Ahi would transit to the field site in Moorea aboard the R/V Kilo Moana.

Summary of Other Requirements or Comments:

UNOLS Ship Time Request Form - Ship Request #1 Information

Project Short Title: MCR LTER UNOLS Project ID #: 103298
 PI Name: Russell Schmitt Version #: 1
 Last Modified: 2/13/2012 5:47:00 PM Date Submitted: 2/13/2012
 Institution: UCSB - University of California, Santa Barbara
 Funding Agencies: NSF/OCE/BIO

UNOLS Request ID #: 1005206 Last Modified: 2/13/2012
 Request Type: Primary Date Submitted: 2/13/2012
 Submitted By: Russell Schmitt

Year	Ship/Facility	Optimum Start	Earliest Start	Latest Start
2014	Kilo Moana	7/1/2014	6/8/2014	9/15/2014

Dates To Avoid: Cruise needs to be during Austral winter (June - September)

	Science Days	Mob Days	DeMob Days	Transit Days (Est)	Total
Op Days Needed	20	2	1	0	23

Multi-Ship OP? No Description:
 Repeating Cruise? No # of Cruises: 0 Interval:
 Repeating Description:

Schedule Justification: We are requesting the R/V Kilo Moana (or higher Global Class) because of its high berth capacity, proximity to the study site, and bathymetry mapping capability (with HMRG staff/equipment). The number of science days assumes embarkation in Papeete, French Polynesia (on Tahiti), and 10 days of dedicated bathymetry/ADCP/hydrographic mapping, plus 10 days to conduct the biological sampling. The mapping time estimate is based on a cruise track comprising of concentric laps around (and between) Moorea and Tahiti between the 50-m to 2000-m isobaths. This assumes 24-hr operations on the R/V Kilo Moana, 510 km per lap at ship speed of 10 km/hr (~ 5 days), plus 5 days total on stations for hydrocast profiling. In parallel with the R/V Kilo Moana surveys, we plan to use the R/V Ahi to conduct shallow water multibeam bathymetry mapping between the 10-m and 200-m isobaths. For the R/V Ahi, we request 20-days of field operations (assuming 8-hrs/day and 10 km/hr survey speed). This would translate into 1 lap per day around Moorea's approximately 60-km perimeter. Assuming a

5x water depth swath width, we expect to need about 6 laps around Moorea to obtain sufficient overlap. We also plan to use the R/V Ahi to survey the 12 reef passes on Moorea, and bays and lagoons. Once these primary objectives are met, if weather/time permits we would also survey the nearshore areas of the northwest shore of Tahiti. The second 10-day leg will sample a grid of stations between Moorea, Tahiti and Tetiaroa for hydrographic and biological parameters. 3 mobilization days are requested: 2 on the front end to set up equipment and 1 to unload equipment and samples.

	Lat/Long	Marsden Grid	Navy Op Area
Beginning:	17° S/149° W	350	SP02
Ending:	17° S/149° W	350	SP02

Op Area Summary: South Pacific
Op Area Size:
Op Area Details: Our cruise will be limited to waters around Moorea, Tahiti, and Tetiaroa, French Polynesia.

Foreign Clearance Required: Yes
Coastal States:
Foreign Clearance Comments:

Start Port: Papeete, Tahiti, French Polynesia
Intermediate Ports: None
End Port: Papeete, Tahiti, French Polynesia
Port Explanation: Our cruise will be limited to waters around Moorea, Tahiti, and Tetiaroa, French Polynesia.

Chief Scientist: Russell Schmitt
in Science Party: 28 # of Science Teams: 5 # of Marine Techs: 7
Science Party Explanation: Science party includes the chief scientist, PIs from other institutions, technicians, and graduate students. It also includes two (2) sea technicians to help operate the CTD and ADCP (24 hour operations) and facilitate deck operations, one (1) sea tech to operate RHIB for our radiative grids sampling near shore, and four (4) HMRG staff to operate and process data bathymetry mapping system and maintain 24/7 watches on deep-towed vehicle.

Science teams include: A. Alldredge (UCSB), C. Carlson (UCSB), J. Hench (Duke), J. Leichter (Scripps), and L. Washburn (UCSB)

Instrumentation that affects scheduling
Dynamic Positioning
Multibeam
Radioisotope use - briefly describe
Instrumentation Explanation: Radioisotopes are requested to estimate primary production (¹⁴C DIC) and bacterial production (³H-LEU)

Major Ancillary Facilities
Ancillary Facilities Explanation:

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