Coral Reef Ocean Acidification Monitoring: Development of a US Monitoring Strategy

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ABSTRACT

The *Coral Reef Ocean Acidification Monitoring Portfolio (CROAMP) Workshop* was hosted by the NOAA Ocean Acidification Program and the National Coral Reef Institute at the Nova Southeastern University Oceanographic Center in August, 2012. Researchers and project managers from around the world engaged in coral reef ocean acidification monitoring sought to define a suite of metrics to optimally include as part of long-term coral reef monitoring. These metrics comprise a listing of high-level strategic guiding questions towards which an observing network should ideally be configured. These metrics are proposed as best able to discern specific attribution of changes in coral reef ecosystems in response to ocean acidification. The metrics necessarily constrain the observing requirements comprised of a suite of biogeochemical, ecological, hydrologic, and meteorological measurements. We also clarify expectations for what sustained ocean acidification monitoring can and cannot offer. Achieving the full CROAMP requirements identified here will demand extensive leverage of existing national and international initiatives particularly in an environment of increasing fiscal constraint.

I. INTRODUCTION

Ocean acidification poses many challenges to the long-term sustainability of coral reefs primarily (although not exclusively) due to its capacity to reduce the rates of both biocalcification and inorganic precipitation of carbonate minerals. Both individual organism and net community calcification rates have generally been experimentally observed to decrease under expected future OA conditions [e.g., Gattuso et al., 1998; Marubini et al., 2001, 2002; Marshall and Clode, 2002; Ohde and Hossain, 2004; Borowitzka, 1981; Gao et al., 1993; Langdon et al., 2000, 2003; Langdon and Atkinson, 2005; Leclercq et al.,2000, 2002; Anthony et al., 2008]. Even under contemporary conditions, field studies have revealed periods of net community dissolution [cite] with the expectation that these periods could increase under continued ocean acidification. Any decline in net community calcification by coral reef organisms would likely compromise the long-term persistence of many coral reef ecosystems because even the growth of healthy, undisturbed coral reefs are known to only slightly outpace rates of loss due to physical and biological erosion [see Glynn, 1997 for review].

As US coral reef monitoring initiatives increasingly consider incorporation of ocean acidification aspects into their designs, it’s important that these investments be strategically directed towards best informing our understanding of ecological consequences and feedbacks. Frequently, monitoring studies offer only limited capacity to discern specific agents of change. Indeed, a central challenge of field research is interpreting results amidst the sheer complexity of the natural environment where change reflects the net result of multiple factors. Still, there remains a desire to engineer diagnostic monitoring most capable of testing response predictions of coral reef ecosystems to ocean acidification as one means by which to identify potential refugia or “hot spots” and while no metric has been identified which is exclusively sensitive to OA alone, there is consensus that some are better than others. This report details those metrics and outlines the measurement requirements necessary to derive them.

II. CROAMP WORKSHOP

A working group of nearly fifty cross-disciplinary multinational federal and academic scientists was hosted by the NOAA Ocean Acidification Program and the National Coral Reef Institute at the Nova Southeastern University Oceanographic Center, Center of Excellence for Coral Reef Ecosystem Science, Dania Beach, FL on August 28-29, 2012. The workshop comprised 11 panel discussions detailing the current state-of-science and offering proposed monitoring metrics centered around five thematic areas: direct chemical changes, organism response, biodiversity impacts, dissolution/bioerosion, and community-scale feedbacks. In addition, seven capacity presentations were offered reviewing current and developing monitoring research efforts around the world across multiple agency and academic efforts. A series of breakout sessions worked to develop a portfolio of proposed metrics to be recommended for coral reef ecosystem monitoring which would offer valuable insights into how coral reef ecosystem may be changing in response to ocean acidification.

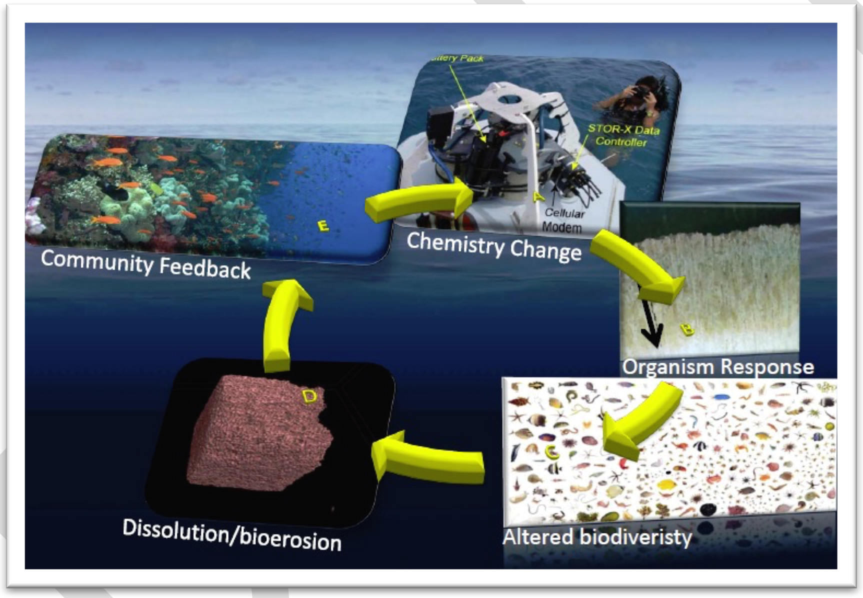


Figure1. Ocean acidification is anticipated to impact coral reefs in several ways. CROAMP discussed monitoring for changes across five overarching thematic areas: A. detecting direct chemical changes with the coral reef waters attributable to OA, B. detecting specific organism responses to OA, C. tracking changes in biodiversity most susceptible to OA, D. quantifying changes in dissolution and bioerosion rates, E. discerning changes and feedbacks to whole-community metabolism.

The changing status of these metrics over time should aid in assigning specific attribution to OA, though it was recognized that there will likely be multiple factors driving observed changes we must be vigilant of co-variants. These workshop outcomes are intended to inform national and international long-term OA monitoring efforts within coral reef ecosystems.

III. The CROAMP Framework

The CROAMP Framework was developed around the guiding principle that the observing requirements should be derived from high-level overarching questions addressing how key aspects of coral reef ecosystems might be anticipated to change over-time based upon the current state-of-the-science. Within each thematic area, the following was developed:

Strategic Monitoring Goal (SMG) – These represent the high-level overarching goals towards which an observing portfolio is intended to answer. It indicates "*what"* we seek to know about the system with regards to its ultimate response to ocean acidification. Each strategic monitoring goal includes units of measure or is explicitly reported as unitless as applicable.

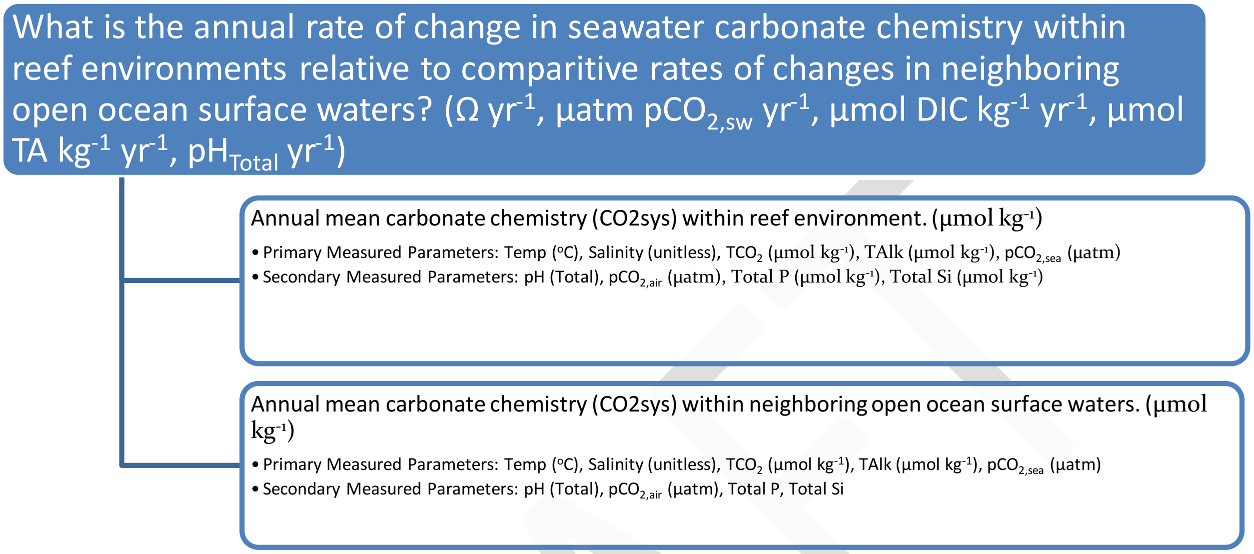
Tactical Monitoring Metric (TMM) – A TMM represents one or more specific tasks necessary to achieve each of the strategic monitoring goals. These detail "*how*" we will acquire the requisite information including the methods, associated measured parameters, and optimal frequency of measure. As is the case with the Strategic Monitoring Goal, each Tactical Monitoring Metric also includes units of measure. While various methods may be available to meet the tactical requirements, the intent of this document is not to provide an exhaustive detail of all methods that could be employed, but simply to offer valuable examples. Other important considerations in developing each of the TMM's included the feasibility of adoption into proposed monitoring initiatives and what site criteria would be most amendable towards deriving the proposed TMM. Finally, a critical aspect which was discussed as part of each TMM is the number and importance of co-variants which represent factors other than OA which will convolute assigning specific attribution. In nearly all cases, multiple co-variants were identified and are reflected in the amount of secondary measurements which would need to be obtained simultaneously.

Figure 2. A guiding principle of CROAMP is that observing requirements are determined by first carefully formulating tactical metrics that specifically inform strategic requirements within each thematic area. Therefore, the primary emphasis of CROAMP was upon developing the strategic requirements in a deliberate "top-down" fashion.

1. Direct Chemistry Changes in Response to Ocean Acidification

By far the most certain consequence of ocean acidification are the direct chemistry changes in response to rising atmospheric CO_2 concentration which are reflected in surface waters as reduction in pH, an enrichment in total dissolved inorganic carbon, and a decrease in the availability of carbonate ion. Such changes are already apparent in the extended time-series observations at the Bermuda Atlantic Time-Series (BATS) and Hawaii Ocean Time-Series. While changes in the hydrologic cycle, ocean circulation, and primary productivity may augment these rates regionally over decadal time-scales, generally the seasonally detrended changes observed in the surface waters (upper 50m) at these stations closely approximated near equilibrium with rising atmospheric CO_2. However, there is reason to suspect that such rates may not precisely equate to the rates observed within many coral reef environments due to local feedback and buffering processes. The relative influence local processes will have on the overlay ocean acidification rate will be dependent upon several factors including water mass residence time, benthic community composition, and net community metabolism. These feedbacks will be considered more closely in the next section.

A first-order question any ocean acidification monitoring observatory needs to be able to answer is if the rates of ocean acidification are consistent with the regional oceanic average, or are they decoupled. If they are decoupled then answering “why” will likely be addressed in the subsequent thematic areas. To evaluate “if” they are decoupled demands that one monitoring not only carbonate chemistry dynamics within the reef environment of interest, but also have careful constraint on the rate of changes of neighboring oceanic waters where the relative influence of coastal and benthic processes in negligible. This allows one to normalize the observed rates of change within the reef environment to the broader regional rates of change.



What is the annual rate of change in seawater carbonate chemistry within reef environments relative to comparitive rates of changes in neighboring open ocean surface waters? (Ω yr^{-1}, µatm $pCO_{2,sw}$ yr^{-1}, µmol DIC kg^{-1} yr^{-1}, µmol TA kg^{-1} yr^{-1}, pH_{Total} yr^{-1})

Annual mean carbonate chemistry (CO2sys) within reef environment. (µmol kg^{-1})

- Primary Measured Parameters: Temp (°C), Salinity (unitless), TCO_2 (µmol kg^{-1}), TAlk (µmol kg^{-1}), $pCO_{2,sea}$ (µatm)
- Secondary Measured Parameters: pH (Total), $pCO_{2,air}$ (µatm), Total P (µmol kg^{-1}), Total Si (µmol kg^{-1})

Annual mean carbonate chemistry (CO2sys) within neighboring open ocean surface waters. (µmol kg^{-1})

- Primary Measured Parameters: Temp (°C), Salinity (unitless), TCO_2 (µmol kg^{-1}), TAlk (µmol kg^{-1}), $pCO_{2,sea}$ (µatm)
- Secondary Measured Parameters: pH (Total), $pCO_{2,air}$ (µatm), Total P, Total Si

Figure 3. The CROAMP requirements for long-term monitoring of the *direct changes in chemistry* in response to OA.

Estimates of the rate of change in aragonite saturation state (Ω_{arg}) within tropical surface waters is on the order of 0.1 Ω_{arg} per decade. While such rates are readily discernible from multi-decadal time-series stations within oceanic waters using sampling frequencies as coarse as monthly, the variability within reef environments can be an order of magnitude greater demanding much high sampling frequencies. ……TO ADD QUANTITATIVE ANALYSIS OF TIME SERIES DATA TO EVALUATE MINIMUM FREQUENCY.

For monitoring within the reef environments, subdaily (3-hourly) is probably preferred to avoid aliasing the data but bi-weekly discrete sampling is probably the minimum sampling frequency. If adequate preliminary data is available, an appropriate frequency should be determined using a

Fourier series. The oceanic reference station will depend on the open ocean ecosystem chosen for comparison, but in many cases, seasonal to monthly measures may be adequate.

Site criteria… To skillfully detect changes in response to OA it will be important to select sites where local biogeochemistry is reasonably constrained and coastal processes are a minimal influence. However, it is recognized that at least a few sites should be chosen to monitor such changes within the context of local anthropogenic influences for comparative purposes. At those sites, additional effort may be required to characterize influencing coastal processes. This tactical monitoring index is best suited to fixed time-series stations as it is unlikely that stratified sampling could be conducted at sufficient temporal frequency to avoid aliasing the data for regression analysis. However, in systems of relatively lower short-term variability (e.g. low residence time systems) it may be possible to derive this index from stratified sampling provided it was maintained for several decades.

co-variants - Most of these measures will co-vary with temperature, salinity, and any processes which might alter the CO2SYS.

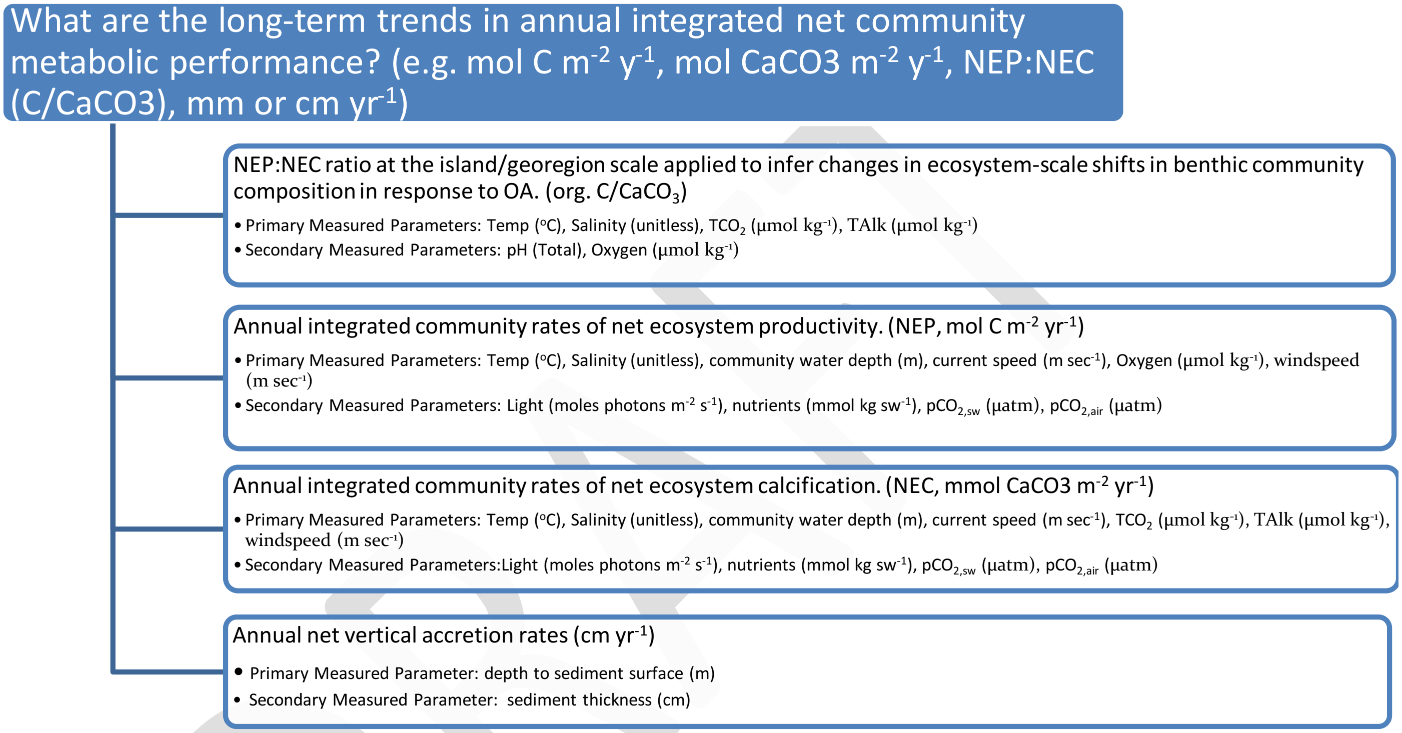
Methods:

Provided a measure of any two of these four parameters, the other two can theoretically be solved. To do so, the CO2 System needs to be solved using selected dissociation constants. The carbonate equilibria calculations should use the Mehrbach et al. [1973] formulations of the K1 and K2 dissociation constants as refit by Dickson and Millero [1987].   The sensitivity with which the saturation states and CO2−3 can be calculated is dependent on the parameter measured; pH and pCO2 yield the greatest uncertainty, followed by the TA, DIC pair. While triple constraint is advised within coastal systems, if only two parameters are to be measured, pH or pCO2 with DIC yields the greatest precision, closely followed by pH or pCO2 and TA. All measurements should follow procedures and protocols outlined in the Best Practices guides (Dickson et al., 2007; Riebesell et al., 2010).

2. Community Metabolism Response and Feedbacks to Ocean Acidification

Changes in community-scale processes including net community productivity (P), respiration (R), calcification (G), and dissolution (D) can significantly impact the local surrounding chemistry thereby overprinting the affects of OA in some cases. Understanding the interactions between coral reef communities and the surrounding chemical environment is critical towards improving our understanding with regards to how OA is unfolding within these systems and what local processes might prove dominant.

Ocean acidification may profoundly affect the basic ecological interactions which structure coral reef ecosystems, providing even greater challenges for local management strategies aimed at retaining or regaining coral dominance. A recent meta-analysis of available experimental data suggests that such ‘phase shifts’ might increase in response to OA. Specifically, as calcification is reduced, algae (non-calcifying) and sea grass may benefit [Hendriks et al., 2010].



What are the long-term trends in annual integrated net community metabolic performance? (e.g. mol C m^{-2} y^{-1}, mol CaCO3 m^{-2} y^{-1}, NEP:NEC (C/CaCO3), mm or cm yr^{-1})

NEP:NEC ratio at the island/georegion scale applied to infer changes in ecosystem-scale shifts in benthic community composition in response to OA. (org. C/$CaCO_3$)

- Primary Measured Parameters: Temp (°C), Salinity (unitless), TCO_2 (µmol kg^{-1}), TAlk (µmol kg^{-1})
- Secondary Measured Parameters: pH (Total), Oxygen (µmol kg^{-1})

Annual integrated community rates of net ecosystem productivity. (NEP, mol C m^{-2} yr^{-1})

- Primary Measured Parameters: Temp (°C), Salinity (unitless), community water depth (m), current speed (m sec^{-1}), Oxygen (µmol kg^{-1}), windspeed (m sec^{-1})
- Secondary Measured Parameters: Light (moles photons m^{-2} s^{-1}), nutrients (mmol kg sw^{-1}), $pCO_{2,sw}$ (µatm), $pCO_{2,air}$ (µatm)

Annual integrated community rates of net ecosystem calcification. (NEC, mmol CaCO3 m^{-2} yr^{-1})

- Primary Measured Parameters: Temp (°C), Salinity (unitless), community water depth (m), current speed (m sec^{-1}), TCO_2 (µmol kg^{-1}), TAlk (µmol kg^{-1}), windspeed (m sec^{-1})
- Secondary Measured Parameters:Light (moles photons m^{-2} s^{-1}), nutrients (mmol kg sw^{-1}), $pCO_{2,sw}$ (µatm), $pCO_{2,air}$ (µatm)

Annual net vertical accretion rates (cm yr^{-1})

- Primary Measured Parameter: depth to sediment surface (m)
- Secondary Measured Parameter: sediment thickness (cm)

Figure 4. The CROAMP requirements for long-term monitoring *Community Metabolism Response* to OA.

An alternative approach to paired TA and DIC measures might be tracking shifts in the regression slope of pH vs O2. While simpler to implement than the paired measurements, this approach remains largely speculative at this point and needs to be better documented. Good quality autonomous instruments are increasingly available for short duration (e.g. weeks to a few months) deployments. High quality pH measures are best obtained through discrete sample collection according to best practices. Spectrophotometric determination can then be performed post-collection. Discrete samples need to be measured within an hour of collection.

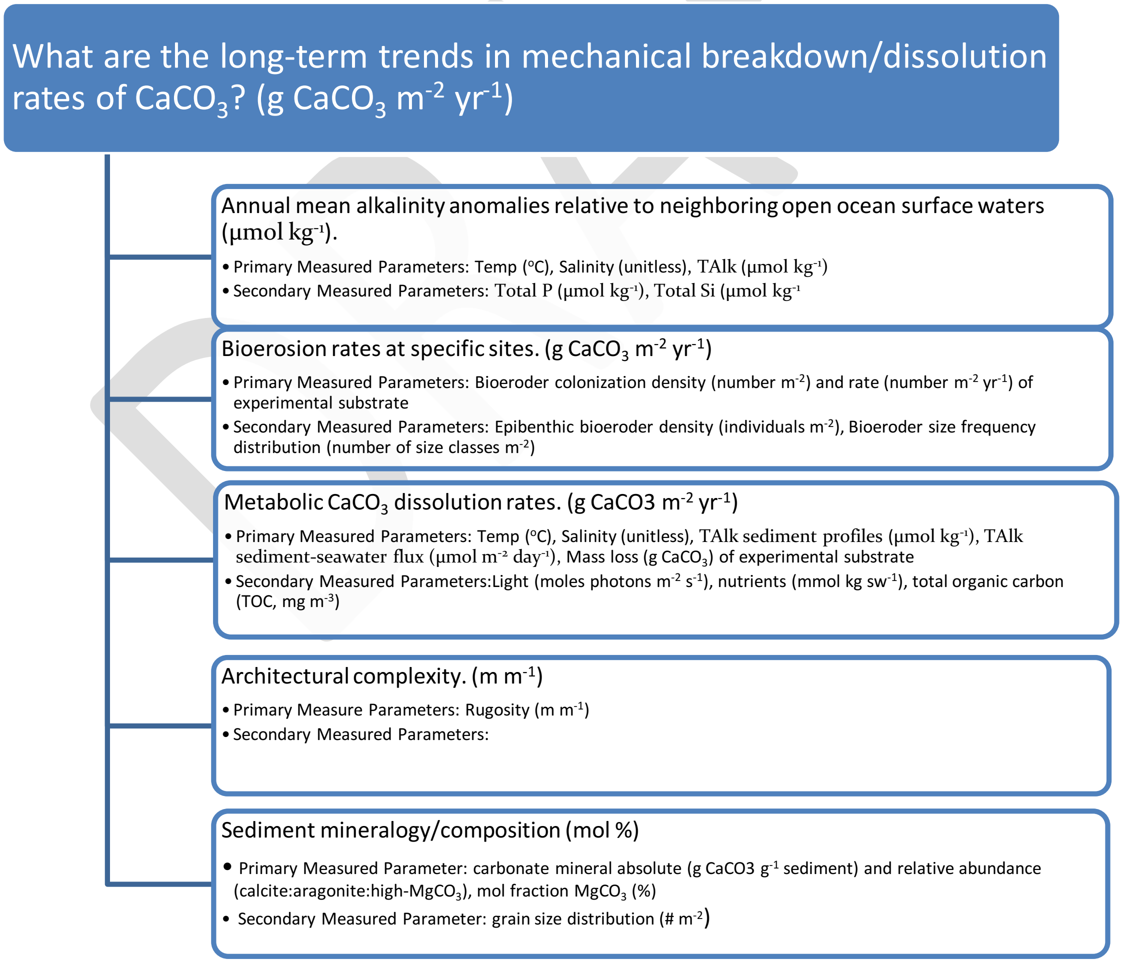
Site criteria - To skillfully detect community changes in response to OA it will be important to select sites where local biogeochemistry is reasonably constrained and coastal processes are a minimal influence. However, it is recognized that at least a few sites should be chosen to monitor such changes within the context of local anthropogenic influences for comparative purposes.

3. Dissolution and Bioerosion Response and Feedbacks to Ocean Acidification

Some species exhibit a natural tolerance or local environmental conditions can compensate for global OA effects. It has now been well established that coral calcification rates are, in fact, a function of multiple factors including light, temperature, carbonate chemistry and nutrient supply.

Beyond the potential direct effects for coral calcification, OA poses additional concerns for coral reef ecosystems. These include dissolution of coral reef sediments which often contain appreciable amounts of more soluble carbonate minerals [Morse et al., 2006]. Sediment dissolution may outpace carbonate production on many reefs by 2030 [Yates and Halley, 2006].

Furthermore, current-day areas where upwelling causes chemistries comparable to future OA conditions (i.e. a tripling of atmospheric CO2) exhibit poorly cemented and highly bioeroded coral reefs [Manzello et al., 2008]. These effects may compromise coral reef framework integrity and resilience in the face of other acute threats such as coral bleaching, diseases, increases in storm intensity, and rising sea level [e.g., Silverman & Calderia, 2009]. Indeed, in CO2 enriched waters of the Galapagos Islands, reef structures were completely eroded to rubble and sand in less than 10 years following one acute warming disturbance [i.e., 1982-83 El Nino event: Manzello, 2009].



What are the long-term trends in mechanical breakdown/dissolution rates of $CaCO_3$? (g $CaCO_3$ m^{-2} yr^{-1})

Annual mean alkalinity anomalies relative to neighboring open ocean surface waters (µmol kg^{-1}).

- Primary Measured Parameters: Temp (°C), Salinity (unitless), TAlk (µmol kg^{-1})
- Secondary Measured Parameters: Total P (µmol kg^{-1}), Total Si (µmol kg^{-1}

Bioerosion rates at specific sites. (g $CaCO_3$ m^{-2} yr^{-1})

- Primary Measured Parameters: Bioeroder colonization density (number m^{-2}) and rate (number m^{-2} yr^{-1}) of experimental substrate
- Secondary Measured Parameters: Epibenthic bioeroder density (individuals m^{-2}), Bioeroder size frequency distribution (number of size classes m^{-2})

Metabolic $CaCO_3$ dissolution rates. (g CaCO3 m^{-2} yr^{-1})

- Primary Measured Parameters: Temp (°C), Salinity (unitless), TAlk sediment profiles (µmol kg^{-1}), TAlk sediment-seawater flux (µmol m^{-2} day^{-1}), Mass loss (g $CaCO_3$) of experimental substrate
- Secondary Measured Parameters:Light (moles photons m^{-2} s^{-1}), nutrients (mmol kg sw^{-1}), total organic carbon (TOC, mg m^{-3})

Architectural complexity. (m m^{-1})

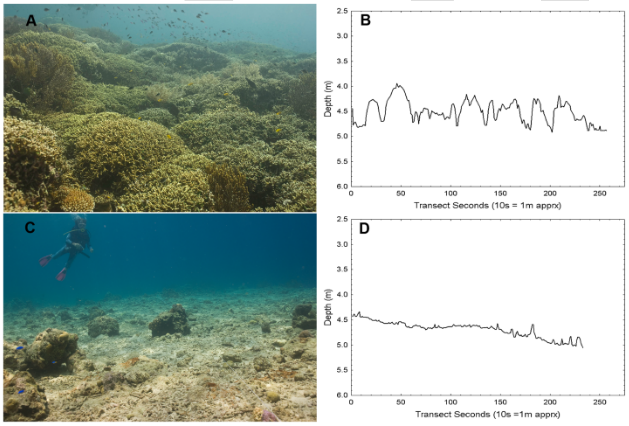
- Primary Measure Parameters: Rugosity (m m^{-1})
- Secondary Measured Parameters:

Sediment mineralogy/composition (mol %)

- Primary Measured Parameter: carbonate mineral absolute (g CaCO3 g^{-1} sediment) and relative abundance (calcite:aragonite:high-$MgCO_3$), mol fraction $MgCO_3$ (%)
- Secondary Measured Parameter: grain size distribution (# m^{-2})

Figure 5. The CROAMP requirements for long-term monitoring of the *Dissolution and Bioerosion Response* in response to OA.

A measure of small-scale variations or amplitude in the height of a reef surface. Rugosity is a measure of architectural complexity which is presumed to be an indicator of the amount of habitat available for colonization by benthic organisms, and shelter and foraging area for fish. Tracking rugosity over time can be a useful metric to examine structural changes in reefs as the framework building corals die, rates of bioerosion overtake accretion, and the reefs eventually flatten [18] although care must be taken to account for acute disturbance events (e.g. storm effects and mass wasting) when assigning attribution to long-term trends. Structural complexity is classically measured with a reef rugosity index, which is the ratio of a straight line transect to the distance a flexible chain of equal length travels when draped over the reef substrate, however recent advances in digital reef rugosity (DRR) have greatly reduced that labor required to obtain a rugosity measure while making it a more objective and repeatable measure useful in statistical analysis. Dustan P, Doherty O, Pardede S (2013) Digital Reef Rugosity Estimates Coral Reef Habitat Complexity. PLoS ONE 8(2): e57386. doi:10.1371/journal.pone.0057386



4. Organism Response to Ocean Acidification

Other expected impacts of OA include a potential lowering of the thermal thresholds for bleaching [Anthony et al., 2008], the impairment on early life stages of corals such as reduced fertilization success, reduced larval settlement, and reduced growth and survival rates of newly settled corals [Albright et al., 2008; Cohen and Holcomb, 2009; Albright et al., 2010, Morita et al., 2010; Suwa et al., 2010]. These species-level impacts are particularly relevant given the potential extension of Endangered Species Act protection for additional scleractinian coral reef species as this Act provides for potent conservation actions for species at risk of extinction, and impacts on population bottlenecks such as recruitment may pose more direct extinction risk then calcification and growth impacts.

The affects of OA on some non-calcifying organisms may indeed be just as serious as the affects to calcifiers but are largely unexplored.

In addition, predictions of coral reef ecosystem responses to OA are further complicated due to the fact that reef organisms secrete species-specific types of calcium carbonate mineralogies (i.e., aragonite, calcite, and magnesium calcite) which exhibit a range of solubilities.

What are the long-term regional changes in growth rates of target taxa in response to OA?

Growth rates of select calcifiers.

- Primary Measured Parameters: Coral skeletal linear extension rate (mm yr^{-1}), density (g cm^{-3}), and mass (g)
- Secondary Measured Parameters: *Halimeda spp.* (or other calcified algal taxa) growth rate (g yr^{-1}), Other taxa (e.g. forams, urchins) growth rate (g yr^{-1})

Growth and productivity rates in select non-calcifiers. (g $colony^{-1}$ yr^{-1})

- Primary Measured Parameters: seagrass spp. plant mass (g), shoot density (# m^{-2}), and photosynthetic rate (µg C µg chlorophyll a^{-1} hr^{-1}); fleshy algal spp. plant mass (g) and photosynthetic rate (µg C µg chlorophyll a^{-1} hr^{-1})
- Secondary Measured Parameters: Temp (°C), Light (moles photons m^{-2} s^{-1}), nutrients (mmol kg sw^{-1})

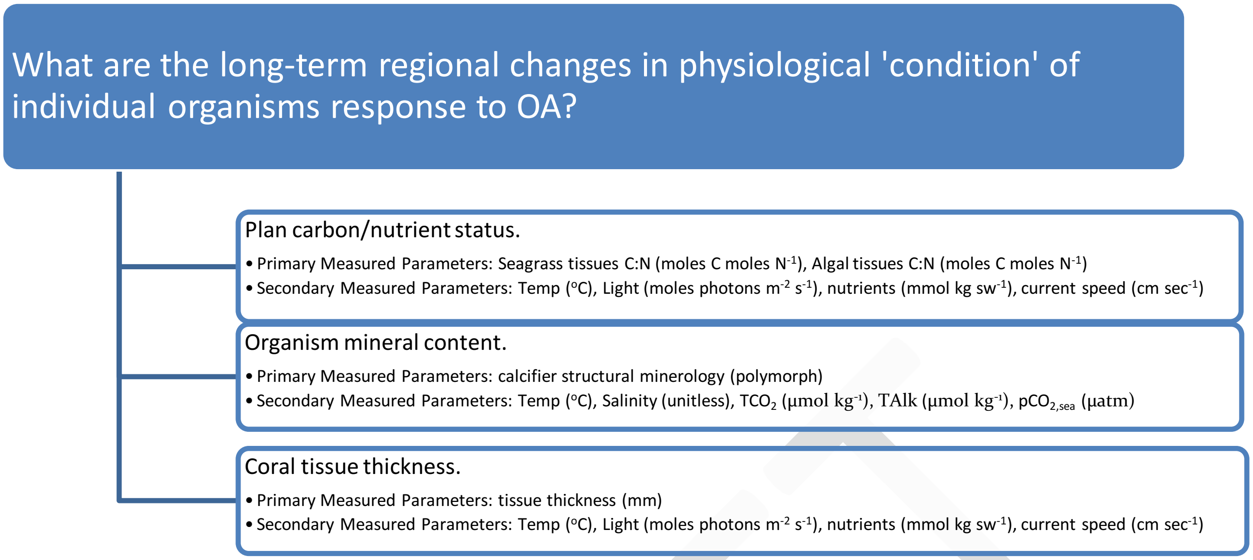
What are the long-term regional changes in 'recruitment' rates of target taxa in response to OA.

Crustose coralline algae accumulation rate (CCA, mm yr^{-1}).

- Primary Measured Parameters: CCA accumulation rate on standardized substrates (mm yr^{-1})
- Secondary Measured Parameters: Temp (°C), Light (moles photons m^{-2} s^{-1}), nutrients (mmol kg sw^{-1}), current speed (cm sec^{-1}), grazing rate (g $grazer^{-1}$ d^{-1})

Calcifying epiphytes accumulation rate. (µg Chl *a* cm^{-2} yr^{-1})

- Primary Measured Parameters: seagrass epiphyte density (µg Chl *a* cm^{-2})
- Secondary Measured Parameters: Temp (°C), Light (moles photons m^{-2} s^{-1}), nutrients (mmol kg sw^{-1}), current speed (cm sec^{-1}), grazing rate (g $grazer^{-1}$ d^{-1})



What are the long-term regional changes in physiological 'condition' of individual organisms response to OA?

Plan carbon/nutrient status.

- Primary Measured Parameters: Seagrass tissues C:N (moles C moles N^{-1}), Algal tissues C:N (moles C moles N^{-1})
- Secondary Measured Parameters: Temp (°C), Light (moles photons m^{-2} s^{-1}), nutrients (mmol kg sw^{-1}), current speed (cm sec^{-1})

Organism mineral content.

- Primary Measured Parameters: calcifier structural minerology (polymorph)
- Secondary Measured Parameters: Temp (°C), Salinity (unitless), TCO_2 (μmol kg^{-1}), TAlk (μmol kg^{-1}), $pCO_{2,sea}$ (μatm)

Coral tissue thickness.

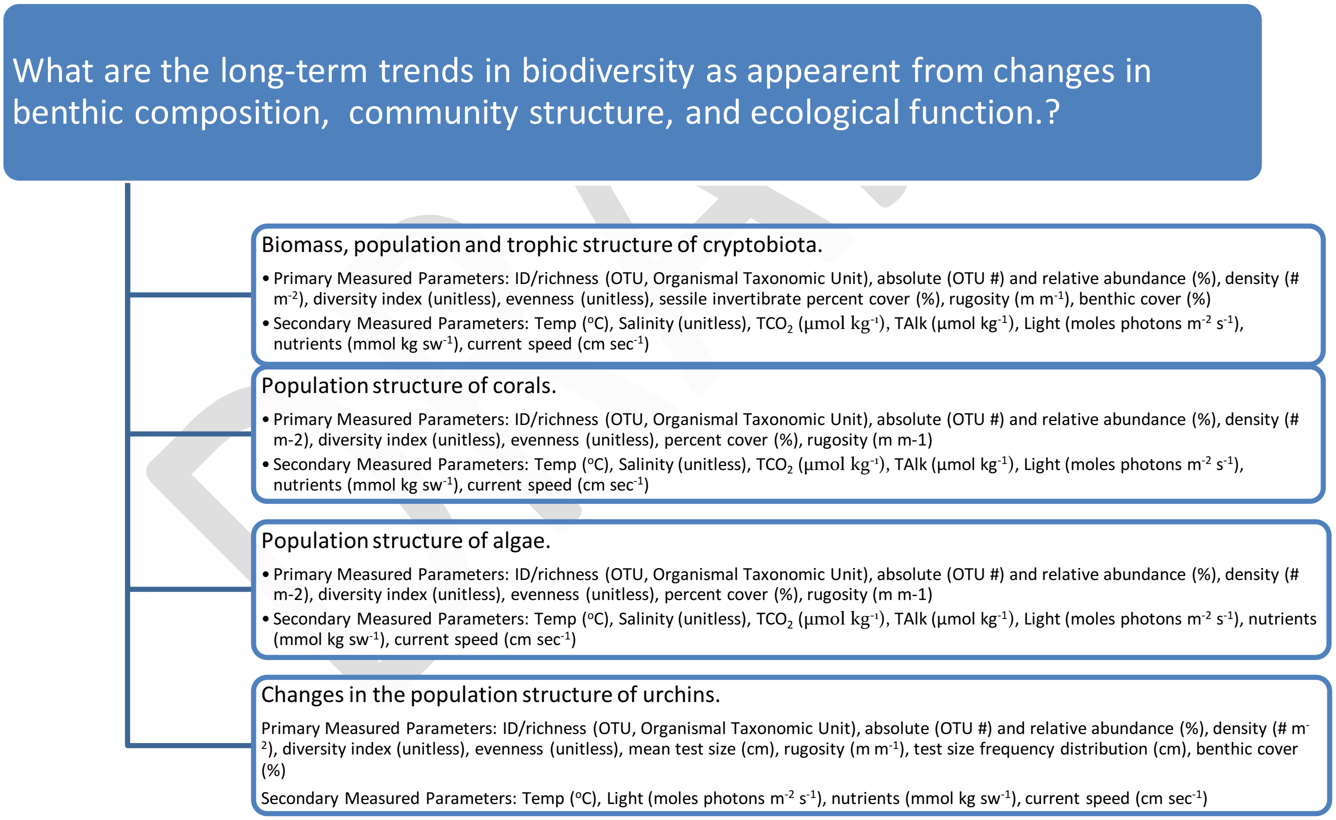
- Primary Measured Parameters: tissue thickness (mm)
- Secondary Measured Parameters: Temp (°C), Light (moles photons m^{-2} s^{-1}), nutrients (mmol kg sw^{-1}), current speed (cm sec^{-1})

Figure 6. The CROAMP requirements for long-term monitoring of the *Organism Response* **in response to OA.**

5. Changes in Coral Reef Biodiversity to Ocean Acidification

While coral reefs are considered the most biologically diverse of all marine ecosystems this diversity varies greatly across spatial and environmental gradients. How this variation influences reef resilience and adaptation to climate change and OA is poorly understood. Much of the biomass and biodiversity of reefs lies within the complex architecture of the reef matrix [Ginsburg, 1983; Small et al., 1998; Sala and Knowlton, 2006; Knowlton et al., 2010]. The potential effects of OA on this community of organisms, collectively known as the cryptobiota [Macintyre et al., 1982], remains largely unknown.

Understanding the biodiversity and community structure of coral reef ecosystems is therefore necessary in recognizing and predicting shifts in community structure in response to OA.



What are the long-term trends in biodiversity as appearent from changes in benthic composition, community structure, and ecological function.?

Biomass, population and trophic structure of cryptobiota.

- Primary Measured Parameters: ID/richness (OTU, Organismal Taxonomic Unit), absolute (OTU #) and relative abundance (%), density (# m^{-2}), diversity index (unitless), evenness (unitless), sessile invertibrate percent cover (%), rugosity (m m^{-1}), benthic cover (%)
- Secondary Measured Parameters: Temp (°C), Salinity (unitless), TCO$_2$ (μmol kg^{-1}), TAlk (μmol kg^{-1}), Light (moles photons m^{-2} s^{-1}), nutrients (mmol kg sw^{-1}), current speed (cm sec^{-1})

Population structure of corals.

- Primary Measured Parameters: ID/richness (OTU, Organismal Taxonomic Unit), absolute (OTU #) and relative abundance (%), density (# m-2), diversity index (unitless), evenness (unitless), percent cover (%), rugosity (m m-1)
- Secondary Measured Parameters: Temp (°C), Salinity (unitless), TCO$_2$ (μmol kg^{-1}), TAlk (μmol kg^{-1}), Light (moles photons m^{-2} s^{-1}), nutrients (mmol kg sw^{-1}), current speed (cm sec^{-1})

Population structure of algae.

- Primary Measured Parameters: ID/richness (OTU, Organismal Taxonomic Unit), absolute (OTU #) and relative abundance (%), density (# m-2), diversity index (unitless), evenness (unitless), percent cover (%), rugosity (m m-1)
- Secondary Measured Parameters: Temp (°C), Salinity (unitless), TCO$_2$ (μmol kg^{-1}), TAlk (μmol kg^{-1}), Light (moles photons m^{-2} s^{-1}), nutrients (mmol kg sw^{-1}), current speed (cm sec^{-1})

Changes in the population structure of urchins.

Primary Measured Parameters: ID/richness (OTU, Organismal Taxonomic Unit), absolute (OTU #) and relative abundance (%), density (# m^{-2}), diversity index (unitless), evenness (unitless), mean test size (cm), rugosity (m m^{-1}), test size frequency distribution (cm), benthic cover (%)

Secondary Measured Parameters: Temp (°C), Light (moles photons m^{-2} s^{-1}), nutrients (mmol kg sw^{-1}), current speed (cm sec^{-1})

Figure 7. The CROAMP requirements for long-term monitoring of the *Coral Reef Biodiversity* **response to OA.**

IV. Existing Ocean Acidification Monitoring Capacity

V. Existing Ocean Acidification Monitoring Capacity

VI. Summary

the ability and rate of calcium carbonate production by many marine calcifiers is anticipated to decrease while rates of bioerosion and dissolution could increase. Such affects would have important consequences for the role and function of coral reefs and compromise the ecoservices they afford us.

References.

Tables.

Summary of Measurements

Measurement (units)	**Description**	**Methods**	**References**
Physicochemical			
Nutrients (mmol kg sw^{-1}) –	These include all dissolved inorganic nutrients (ammonium, silicate, nitrate, nitrite, and phosphate).	Discrete water sample collection followed by post-collection analysis according to best-practices.	
Oxygen (µmol kg-1) –		Discrete water sample collection followed by post-collection analysis according to best-practices.	
pCO2,air (µatm) –			
pCO2,sw (µatm) –			
pH (Total) –			
Salinity (unitless) –	Salinity is a fundamental measurements for interpreting carbonate chemistry and must be obtained contemporaneously with any measurement of CO2SYS.		
TAlk (µmol kg-1) –			
TCO2 (µmol kg-1) –			
Temperature (oC) –	Temp. is a fundamental measurements for interpreting carbonate chemistry and must be obtained contemporaneously with any measurement of CO2SYS. Furthermore, it imparts a fundamental control on biology and thus needs to be a key measurement ecological monitoring.	Autonomous temperature sensors (e.g. CTD). Do not rely solely on manufacturers' stated accuracy; regular lab calibrations and at---sea comparisons are recommended	
Total organic carbon (TOC, mg m-3) –			

Total P (µmol kg sw-1) –			
Total Si (µmol kg sw-1) –			
Ecological			
[Coral, algae, urchin and algae] absolute (OTU #) and relative abundance (%) –			
[Coral, algae, urchin and algae] benthic cover (%) –			
[Coral, algae, urchin and algae] diversity index (unitless) –			
[Coral, algae, urchin and algae] ID/richness (OTU, Organismal Taxonomic Unit) –			
[Coral, algae, urchin and algae] percent cover (%) –			
[Coral, algae, urchin and algae]density (# m^{-2}***) –***			
[Coral, algae, urchin and algae]evenness (unitless) –			
Algal tissues C:N (moles C moles N-1) –			
Bioeroder colonization density (number m^{-2}***) –***			
Bioeroder colonization rate (number m^{-2} ***yr***$^{-1}$***) –***			
Bioeroder size frequency distribution (number of size classes m^{-2}***) –***			
Biomass –			
Calcifier structural			

minerology (polymorph) –			
Coral skeletal density (g cm^{-3}) –			
Coral skeletal linear extension rate (mm yr^{-1}) –			
Coral skeletal mass (g) –			
Coral tissue thickness (mm) –			
Crustose coralline algae accumulation rate (CCA, mm yr^{-1}) –			
Density of individuals (per m^{2}) –			
Epibenthic bioeroder density (individuals m^{-2}) –			
Fleshy algal spp. Photosynthetic rate (µg C µg chlorophyll a^{-1} hr^{-1}) –			
Fleshy algal spp. plant mass (g) –			
Grazing rate (g grazer^{-1} d^{-1}) –			
Halimeda spp. (or other calcified algal taxa) growth rate (g yr^{-1}) –			
Identification –			
Mass loss of experimental substrate (g CaCO3) –			
Other taxa (e.g. forams, urchins) growth rate (g yr^{-1}) –			
Percent cover (%) –			
Seagrass epiphyte density (µg Chl a cm^{-2}) –			

Seagrass spp. photosynthetic rate (μg C μg chlorophyll a^{-1} hr^{-1}) –			
Seagrass spp. plant mass (g) –			
Seagrass spp. shoot density (# m^{-2}) –			
Seagrass tissues C:N (moles C moles N^{-1}) –			
Substrate type –			
Hydrodynamic and Structural			
Carbonate mineral absolute abundance (g $CaCO_3$ g^{-1} Sediment) –			
Carbonate mineral relative abundance (calcite:aragonite:high-MgCO3) –			
Community water depth (m) –			
Current speed (m sec^{-1}) –			
Depth to sediment surface (m) –			
Grain size distribution (# m^{-2}) –			
Mole fraction $MgCO_3$ (%) –			
Rugosity (STD depth, m) –	***A measure of small-scale variations or amplitude in the height of a reef surface. Rugosity is a measure of architectural complexity which is presumed to be an indicator of the amount of habitat available for colonization by benthic organisms, and shelter and foraging area for fish.***	**digital reef rugosity (DRR)**	**Dustan et al., (2013)**

Sediment thickness (cm) –			
TAlk sediment profiles (µmol kg^{-1}) –			
TAlk sediment-seawater flux (µmol m^{-2} day^{-1}) –			
Meteorological			
Light (moles photons m^{-2} s^{-1}) –			
Windspeed (m sec^{-1}) –			