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Introduction

Good morning Senator Inouye and members of the Committee. Thank you for the opportunity to speak before you on the impacts of climate change on Hawai‘i’s myriad ocean species at the level of coral reef resilience and resistance to invasive species. My name is Jo-Ann Leong and I serve as Director of the Hawai‘i Institute of Marine Biology. I represent a group of scientists whose major research effort includes the study of coral reef ecosystems and the biological connectivity between the islands and atolls of the Hawaiian Archipelago. We have a memorandum of agreement with the NOAA Pacific Regional Sanctuary office to provide research for the new Papahanaumokuakea Marine National Monument.

Current models for sea surface temperature (SST) and seawater CO2 saturation in the coming decades suggest that the Hawaiian Archipelago will experience rises in sea levels, increased episodes of coral bleaching, and decreased aragonite saturation in its ocean waters (Guinotte, Buddemeier, Kleypas 2003; IPCC, 2007 working group I report; E. Shea, Preparing for a Changing Climate, 2001). Higher sea surface temperatures produced severe bleaching events in the main Hawaiian Islands in 1996 and in the Northwestern Hawaiian Islands (NWHI) in 2002 and 2004. Climate experts are virtually certain that more episodes of coral bleaching are in store for Hawai‘i. Moreover, by 2049, ocean acidification is expected to have a marked effect in the waters surrounding Kure and Midway Atolls. These climate changes will have an impact on the marine resources of the Hawaiian Archipelago.

One of the fundamental questions being addressed by the research at HIMB is what factors are important in coral reef resilience. In particular, we are examining the role of biological connectivity in reef restoration and the role of genetic and species diversity in the ability of reefs to bounce back after a disturbance. In today’s testimony, I would like to focus the following points:

1. Thermal stress and bleaching, coral disease, and ocean acidification are real threats to the coral reef ecosystem in Hawai‘i and particularly in the NWHI.
2. Genetic analysis coupled with spatial and physical measurements are needed to tell us about the role of genetic diversity in coral resistance to temperature stress.
3. Biological connectivity studies indicate that we need to manage coral reefs as individual units and not as a single chain of islands and atolls. Our studies show that

these islands and atolls are not biologically connected and therefore capable of replenishing each other should one member of the chain experience a stress event.

4. Recommendations for controlling the spread of invasive species have been developed for the NWHI and genetic technologies are useful in identifying the origin of invasive species.
5. Ocean acidification will affect the crustose coralline algae as well as the stony corals and that may have an even more dramatic effect on the future of coral reefs.

Coral Bleaching Events in Hawai‘i

Although coral bleaching due to high temperature was first described in Hawai‘i by Jokiel and Coles (1974) off Kahe Point (O‘ahu) electric generating station, the isolated subtropical location of Hawai‘i was thought to be sufficient to protect its corals from the bleaching outbreaks that have ravaged coral communities elsewhere. However, in the late summer of 1996, the first large-scale bleaching event in the main Hawaiian Islands occurred (Jokiel & Brown, 2004) and another major bleaching event occurred in the Northwestern Hawaiian Islands (NWHI) in the summer of 2002 (Brainard, 2002; Aeby et al., 2003). In September 2004, a third Hawaiian coral bleaching event occurred at the three northern atolls (Pearl and Hermes, Midway, Kure) (Kenyon & Brainard, 2005). Clearly, Hawai‘i is not immune to large scale coral bleaching events.

Mean summer monthly temperatures in Hawaiian waters are approximately $27 \pm 1\ ^{0}$C. A 30-day exposure to temperatures of only 29-30 C will cause extensive bleaching in Hawaiian corals (Jokiel & Coles, 1990). Combined with high irradiance (clear days) and low winds, water temperatures can be 1-2 ^{0}C higher in certain coastal regions. The “degree heating weeks” (DHW) (1 week of SSTs greater than the maximum in the monthly climatology) over a rolling 12 week period now serves as an indicator of the likelihood of bleaching. Whether the single factor of temperature increase is sufficient to predict coral bleaching is unclear since hind sight analysis of SST data note the absence of bleaching reports in Hawai‘i when SST data indicated that there should have been bleaching in 1968 and 1974. Nevertheless, DHW is used by NOAA’s Coral Reef Watch program because it gives a first alert to investigators and the public of possible coral bleaching events.

Hawai‘i’s coral reefs did recover from the bleaching. During the 1996 episode on O‘ahu, the corals were closely monitored for recovery in Kāne‘ohe Bay. A month after the height of the bleaching episode, the slightly bleached corals regained pigmentation, and two months later, the completely bleached corals had recovered. Overall coral mortality during the event was less than 2%. The rate of recovery was related to bleaching sensitivity, i.e. the first corals to bleach were the last to recover. Most of the bleached corals at Kure, Midway and Pearl and Hermes involved in the September 2002 event also recovered by December 2002 except for the *Montipora capitata*. Estimates of 30% of the montiporids did not recover from this bleaching event in the back reef sections of Midway, Pearl and Hermes Atolls (Kenyon and Brainard, 2006).

A comparison of the sensitivity of different corals to bleaching is shown in Table 1. In general, the montiporid and pocilloporid corals were sensitive to thermal stress and the poritid corals were more resistant. But even these more sensitive corals have resistant members in a bleaching event and scientists are beginning to focus on these coral “survivors” for answers to the question of whether coral reefs will survive to 2100. The first question asked by Steve Karl, a researcher at HIMB, was whether the temperature gradients across a reef were uniform. Thus, if corals responded to thermal stress by bleaching, then perhaps those corals that did not bleach were those corals that inhabited cool spots on the reef. A careful study with miniature temperature monitors placed at 4 M intervals throughout a reef has shown that there are hot spots and cool spots within a reef and this may account for the patchiness of coral bleaching. In addition, Steve and his group have mapped every single coral in the reef and the genotype for each coral is being determined. The question being addressed is whether the corals are genetically distinct (produced by sexual reproduction) or clonally derived (produced by breakage and regrowth from a parent colony). This research may provide some answers regarding the role of genotype in thermal resistance. Steve's study is being carried out at Kāneʻohe Bay, French Frigate Shoals, and Pearl & Hermes Atoll. In addition to the genotype analysis, Steve is working with HIMB researcher Ruth Gates to determine if there are differences in the zooxanthellae symbiont type in the resistant and sensitive corals. Symbiont type has been identified as a key factor in resistance to thermal stress in corals (Baker, 2004; Little, van Oppen, & Willis, 2004; Berkelmans and van Oppen, 2006; Middlebrook, Hoegh-Guldberg, and Leggat, 2008)).

Table 1. Relative resistance of corals to bleaching in Hawaiʻi

	Kāneʻohe Bay 1996	NWHI 2002, 2004
Highly Resistance		
	Porites evermanni	*Porites compressa*
	Cyphastrea ocellina	*Porites lobata*
	Fungia scutaria	*Montipora flabellata*
	Porites brighami	
Moderate resistance		
	Porites compressa	*Porites evermanni* (Maro, Laysan, Lisianski)
	Porites lobata	
	Montipora patula	*Montipora patula* (Maro, Laysan, Lisianski)
	Montipora capitata	
Low resistance (most sensitive to bleaching)		
		Montipora turgescens
	Montipora flabellata	*Montipora patula*
	Pocillopora meandrina	*Montipora capitata*
	Pocillopora damicornis	*Pocillopora damicornis*
	Montipora dilitata.	*Pocillopora ligulata*
		Pocillopora meandrina

.Compiled from Jokiel & Brown, 2004; Aeby, Kenyon, Maragos, and Potts, 2003; Kenyon and Brainard, 2006.

Coral Disease in Hawaiʻi

Coral diseases have emerged as a serious threat to coral reefs worldwide and Hawaiʻi has its own set of coral diseases. There are at least 17 described coral diseases in Hawaiʻi (Work & Rameyer 2001; Work et al., 2002; Aeby, 2006; Friedlander et al., 2005). In general, coral disease is found to be widespread on reefs but occurs at a low prevalence. However, disease outbreaks with more serious effects are starting to occur in Hawaiʻi. The white syndrome resulting from tissue necrosis and loss in *Acropora cytherea* has appeared at French Frigate shoals, a pristine area presumably free from anthropogenic stressors. In Kāneʻohe Bay on Oʻahu, *Montipora capitata* are showing progressive signs of tissue loss (Figure 1F). The etiology (cause) of these diseases has not been determined because no facility for the safe conduct on this research is available in the Pacific. Nevertheless, we must continue to monitor these outbreaks. Experiences with bleached corals in other parts of the world indicate that bleached corals are more susceptible to disease (Bally and Garrabou, 2007). If this is true, Hawai‘i should expect more disease outbreaks.

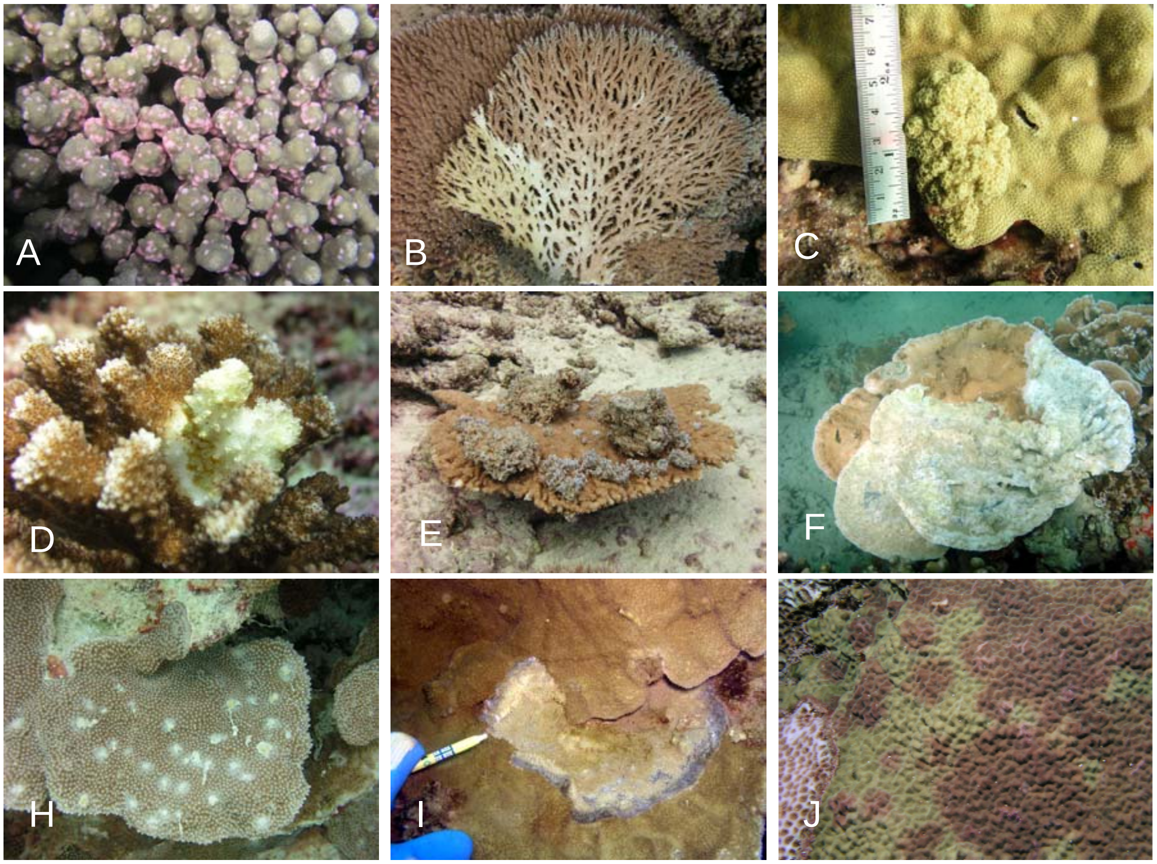

Figure 1. Some coral disease found in Hawai'i. A. *Porites* trematodiases. B. *Acropora* white syndrome. C. *Porites* growth anomalies. D. *Pocillopora* white band disease. E. *Acropora* growth anomalies. F. *Montipora* white syndrome. H. *Montipora* multi-focal tissue loss syndrome. I. *Montipora* dark band. J. Dark spot disease caused by endolithic hypermycosis.

Genetics, Diversity, and Coral Reef Resilience

Resilience of ecosystems was originally defined by C.S. Holling in 1973 as the ability of systems to absorb, resist or recover from disturbances or to adapt to change while continuing to maintain essential functions and processes. For coral reefs, resilience is the term used to describe the ability of coral reefs to bounce back or recover after experiencing a stressful event such as bleaching. Resistance, in turn, refers to the ability of coral communities to remain relatively unchanged in the face of a major disturbance.

Ensuring reef resilience is an important aim for all present and future marine protected areas in Hawai‘i. The Nature Conservancy (TNC) has done an admirable job in developing a model of reef resilience. The four principles of reef resilience that TNC have identified are:

1. Provide adequate replicates of habitat types to decrease the risk of catastrophic events, such as bleaching, from destroying the entire ecosystem.
2. Identify as high priority conservation targets those areas vital for the survival and sustainability of the coral reef ecosystem, i.e. nursery habitats, regions of high diversity.

3. Ensure connectivity among reefs to ensure replenishment of coral communities and fish stocks to enhance recovery in case of a catastrophic event.
4. Reducing threats to the environment by effective management.

In the HIMB-Monument research partnership, we are examining the issue of biological connectivity among the reefs and atolls in the Northwestern Hawaiian Islands and its possible connectivity to the Main Hawaiian Islands. The work of HIMB researchers Rob Toonen and Brian Bowen and their colleagues shows that the answer to this question differs greatly among species, and that single studies of individual species tell us little about how to manage any other population (Bird et al., 2007). Although these are preliminary results, the extensive survey currently underway suggests that many of the fishes are well-connected throughout the archipelago. In contrast, the corals and other invertebrates that form the reefs are far more isolated, and must therefore be managed carefully on a local scale to persist. Despite the differences among species, however, some striking patterns of isolation emerge; there are consistent breaks in exchange of individuals across many species that divide regions of the Hawaiian Archipelago (Figure 2). Notably, there is a consistent break between populations found at the Big Island, Kauai, and between the Main and NWHI, with the predominant direction of exchange being to the northwest rather than to the southeast. Additionally, even for fishes - which show the highest degree of connectivity in our studies - the rate of exchange is too low to subsidize fisheries stocks in the Main Hawaiian Islands, suggesting that regional or community-based management will be the most effective route for the future (Bird et al., 2007).

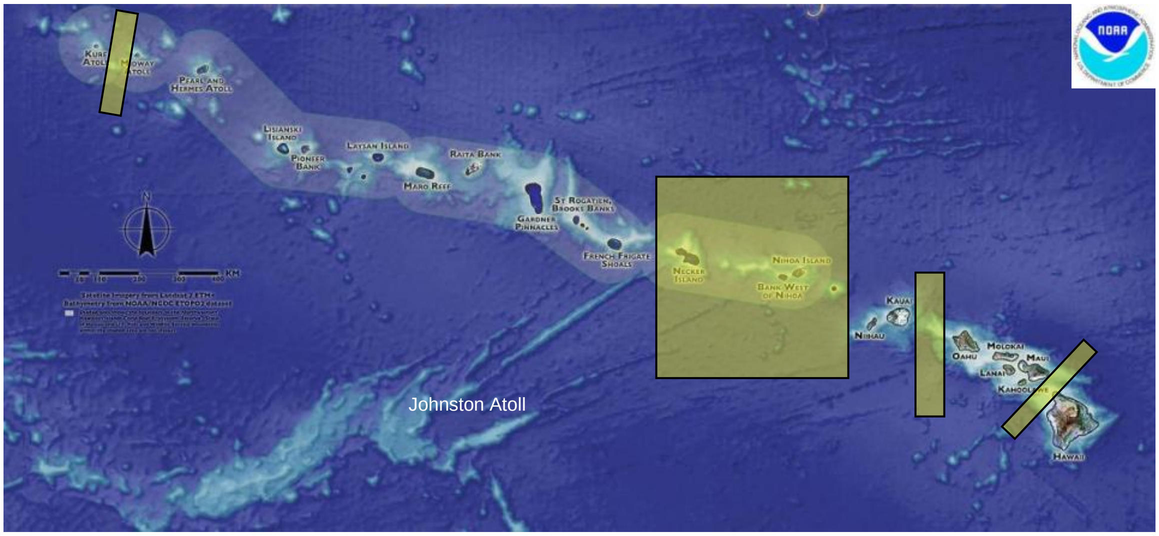

Figure 2. Shared genetic breaks among diverse species (including Spinner dolphins, sharks, opihi, tube snails, lobsters, and sea cucumbers) across the Hawaiian Archipelago. Although patterns of population structure differ by species in each case, the four regions highlighted in this figure appear to limit exchange across a broad range of marine taxa.

A major contributor to reef resilience is species diversity at both the organismal level and the genetic level. Although we have a listing of the species found in the Hawaiian Archipelago to date, the actual species diversity in the NWHI is largely unknown. A recent Census of Marine Life Cruise to French Frigate Shoals uncovered 30-50 invertebrate species new to science, 58 new ascidian records, 33 new records of decapod crustaceans, and 27 new opistobranch mollusks of record (R. Brainard, personal communication). It is clear that we don’t know the extent of species diversity in the NWHI and it is critical that we find out if we are to understand how that ecosystem functions and what levels of redundancy in function are available (McClanahan, Polumin, and Done, 2002). HIMB scientists are beginning to examine the genetic diversity of different coral species in Hawaiʻi.

Symbiont diversity, we are learning, is a vital factor in the resistance of corals to bleaching. The symbiotic dinoflagellate genus *Symbiodinium* is genetically diverse containing eight divergent lineages (clades A-H). Corals predominantly associate with clade C *Symbiodinium*, although clades A,B,D,F, and G are also found to a lesser extent in corals. There is ample evidence that some type of symbiont "shuffling" occurs during the process of acclimatization of corals to higher thermal stress (Berkelmans and van Oppen, 2006; Middlebrook, Hoegh-Guldberg, and Leggat, 2008). In fact, there is growing evidence that corals with clade D symbionts are more resistant to thermal stress than the same species with clade C symbionts, the more common coral symbiont clade in the Pacific region. HIMB researchers Ruth Gates and Michael Stat found *Symbiodinium* clade A1, a rare symbiont type, and clade C associated with the *Acropora cytherea* corals at French Frigate Shoals. The A symbiont type is rare, and genetic evidence suggests that this clade was introduced with *Cassiopea* (Stat & Gates, 2007). Moreover, the presence of clade A was highly associated with disease. None of the diseased corals had clade C as the dominant symbiont (Stat & Gates, preliminary communication).

Invasive species

Living in Kāneʻohe Bay, we are confronted daily by the invasive algae that impact our coral reefs. Our associates, Cindy Hunter, Celia Smith, the Division of Aquatic Resources, and The Nature Conservancy are part of an organized effort to keep the algae from taking over our reefs. As part of our efforts to prevent this from ever happening in the NWHI, we have developed a set of recommendations to restrict the transport of non-indigenous species to the NWHI. They include hull inspections for vessels planning to enter the NWHI and requiring treatment of ballast water. Copies of the document are provided for the members of the committee: S. Godwin, K. S. Rodgers, and P. L. Jokiel (2006) Reducing Potential Impact of Invasive Marine Species in the Northwestern Hawaiian Islands Marine National Monument.

The power of the genetic tools we use to detect invasive species can also be used to uncover the origins of invasive species and I provide this example for our discussion. When the snowflake coral, *Carijoa riseii*, was first observed growing at high densities on the black coral beds in Hawai'i, it was labeled as a foreign invasive from the Caribbean. It was thought to have been brought in by ships coming to Hawaiʻi from the continental United States. Genetic evidence no longer supports this finding (Concepcion et al., in review). Rather, the "Hawaiian snowflake coral" was closer genetically to the snowflake corals identified throughout the Pacific Islands, and that there are multiple species of Hawaiian snowflake coral (Concepcion et al., 2007). It is clear that this is not a Caribbean introduction and the data cannot rule out a natural colonization of Hawaiʻi by the snowflake coral. If that is the case, then the ecology of the black coral ecosystem has been altered to allow the snowflake coral to overgrow these precious coral beds.

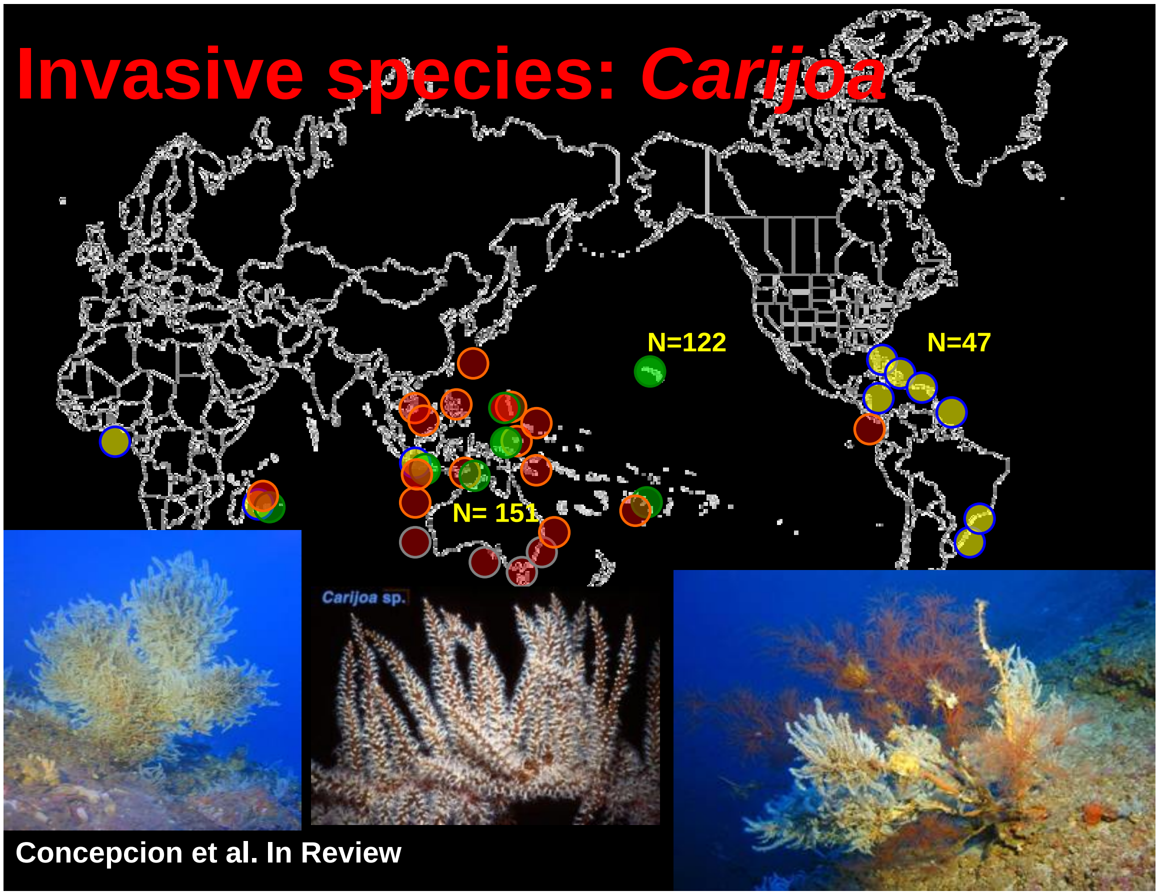

Fig. 3. Distribution of genotypes of Carijoa riseii. Each colored circle is characteristic for a specific genotype of Carijoa. Note that Hawai'i does not share any genetic types with the Caribbean.

Ocean acidification

Several models for changes in aragonite saturation at today's CO2 concentration (375-380 ppm) to the projected saturation state for years 2040-2049 (465 ppm) indicate that Kure Atoll and Midway Island will be affected by rates of aragonite saturation that are marginal for coral growth (Guinotte, Buddemeier, & Kleypas, 2003; Hoegh-Guldberg et al., 2007). Experiments in mesocosms containing corals exposed to lower pH suggest that coral calcification rates will slow (Ries, Stanley, & Hardie, 2006; Marubini & Atkinson, 1999).and, in some cases, the corals will actually decalcify to form sea anemone-like soft bodied polyps (Fine and Tchernov, 2007). Ilsa Kuffner and her colleagues at HIMB have shown that crustose coralline algae are dramatically affected by acidified ocean water (Figure 4). This is an important finding because members of this group of calcifying algae act as framework organisms, cementing carbonate fragments into massive reef structures, providing chemical settlement cues for reef-building coral larvae, and is a major producer of carbonate sediments (Kuffner et al., 2008). .

Figure 4. Encrusting algal communities on experimental cylinders. Control cylinder on the left was exposed to normal seawater at pH 8.17 and shows the pink crustose coralline algae colonies. On the right, this cylinder exposed to seawater at pH 7.91 shows growth of on non-calcifying algae.

Recommendations:

Management strategies will need to focus on increasing coral reef resilience, usually by managing other stressors on reefs, i.e. nutrient overload, sediments, human induced disturbances, resource extraction. Management will also require

1. An accurate survey of the biodiversity of the coral reef ecosystems in Hawai‘i.
2. A study of ecosystem function in these reefs to identify keystone species and redundancy in the system.
3. Management must be based on an accurate assessment of the biological connectivity between the different reefs and atolls. Temporal and spatial contributions to replenishment from healthy reefs must be determined.
4. Coral reef ecosystem management and fisheries management must work together to provide sustainable harvest while preserving habitat and ecosystem functions.
5. Research needs include:
    a. Identification of the etiologic agents of coral disease within an appropriate containment facility.
    b. Understanding the epizootiology of coral diseases (transmission, rate of spread, virulence, etc.)
    c. Measurement of the impacts of reduced calcification on a wide range of marine organisms including pteropods, coccolithophores, foraminifera...
    d. Determine the calcification mechanisms across many different calcifying taxa.
    e. Large mesocosms equipped with seawater that can be regulated for temperature, flow rate, wave action, pH and CO2, and light are needed to conduct replicate studies on the effects of these thermal stress and/or lowered pH on coral reefs.
6. We support the recommendations of the report: Impacts of Ocean Acidifcation on Coral Reefs and Other Marine Calcifiers: A guide for future research. Authors: J. A. Kleypas, R. A. Feely, V. J. Fabry, C. Langdon, C. L. Sabine, and L.L. Robbins.

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