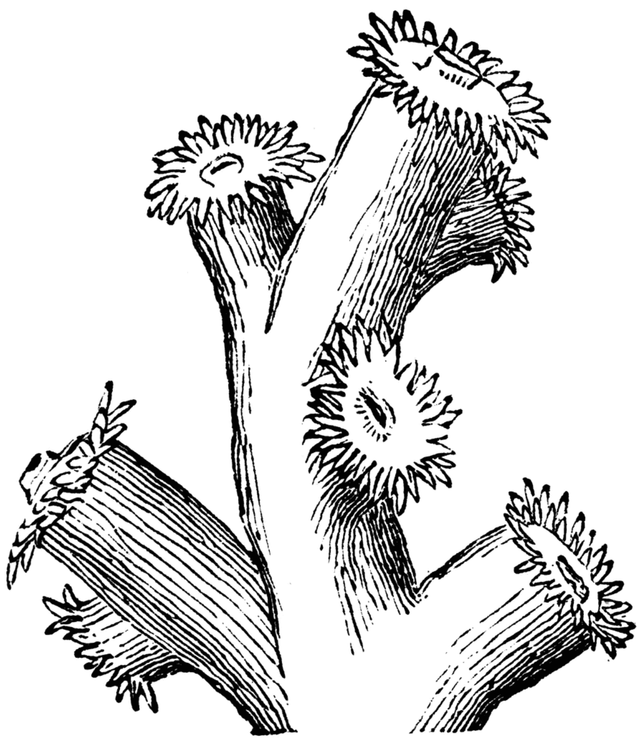
AQUARIUM PROTECTION OF CLIMATE RESILIENT CORALS

REPORT FROM A WORKSHOP CO-CONVENED BY
THE PHOENIX ISLANDS PROTECTED AREA (PIPA) TRUST,
THE WOODS HOLE OCEANOGRAPHIC INSTITUTION AND
THE AQUARIUM OF THE PACIFIC

Hosted by the Aquarium of the Pacific, 18-19 December 2018



Prepared by

Anne L. Cohen, PhD
Woods Hole Oceanographic Institution
Sandy Trautwein, PhD
Aquarium of the Pacific
Jerry R. Schubel, PhD
Aquarium of the Pacific

Acknowledgements

We thank Linda Brown and Adina Metz for the logistical support so necessary to the effective organization and conduct of the workshop. We thank Kim Thompson and Nathaniel Mollica for note-taking, and we thank Jack Lawson for AV support.

We thank the Aquarium of the Pacific for providing the bulk of the support for the workshop including travel and living expenses for all of the participants, and Woods Hole Oceanographic Institution, National Science Foundation and Atlantic Donor Advised Fund for providing Anne Cohen's support to develop and co-chair the workshop, and write this report.

Overview

On December 18-19, 2018 the Phoenix Island Protected Area (PIPA) Trust, the Woods Hole Oceanographic Institution, and the Aquarium of the Pacific co-convened a workshop on Super Corals at the Aquarium of the Pacific. The working definition of Super Corals for the workshop was that Super Corals are coral holobionts that have demonstrated the ability to tolerate or to recover from stress better than the population average, and to successfully reproduce post-stress. We use the term "resilient" to include both the ability to resist stress and to recover from it. Corals that cope with climate-change induced stressors, including ocean warming and acidification, are termed "climate-resilient". The workshop identified ocean warming, both the secular trend and abrupt events (heatwaves), as the most imminent threat to the survival of coral reefs in the 21st century. Ocean acidification was recognized as a sub-lethal threat that compounds the deleterious effects of ocean warming.

The goals identified before the workshop were:

- To clarify the situation facing the world's coral reefs and create a compelling statement of the causes, what's at risk, and the future prospects for coral reefs without active intervention.
- To discuss how climate-resilient corals may play a role in the survival of coral reefs under 21st century ocean change.
- To identify the potential roles of public aquariums in bringing the story of Super Corals and Super Reefs to the public and to create a "live bank" of climate resilient corals for preservation and research that would be available to other aquariums and the research community.
- To draft a plan for the identification, acquisition and propagation of Super Corals and establish a Super Coral exhibit and live bank.

The workshop participants are listed in Appendix A. All participants contributed to the report with specific contributions by Drs Carly Kenkel, Dan Barshis and Austin Bowden-Kerby.

The agenda is in Appendix B, and brief bios of the participant in Appendix C.

The Aquarium of the Pacific committed

- To creating a Science on a Sphere experience on Super Reefs in collaboration with Anne Cohen. This will be completed by March 31, 2019 and uploaded to the SoS network.

- To creating a public live coral exhibit featuring Super Corals from the Phoenix Islands[1] and other areas, including US reefs. . The expectation is that the exhibit would be available for public viewing by the end of 2019 or early 2020. The exhibit is described in this report.
- To create a "Live Bank" which would be made available to researchers. The bank would start with one species by the end of 2019 or early 2020, and grow over time. The Live Bank is described on page 16 of this report.

[1] This assumes we secure permission to collect samples of Super Corals.

Aquarium-based Protection of Climate-Resilient Corals

A Workshop Co-Hosted by the PIPA Trust, Woods Hole Oceanographic Institution and the Aquarium of the Pacific

Introduction

The tropical ocean has warmed almost 1°C over the last 100 years [1], driving an increase in the frequency and duration of marine heatwaves [2], with severe consequences for shallow-water coral reefs. Millions of corals have been killed, and millions more will die as the ocean's temperature continues to rise and with it, the frequency of strong El Niño's[3]. At the same time, the ocean is becoming more acidic, absorbing more and more of the excess carbon dioxide released by humans into the atmosphere[4]. Ocean acidification makes it harder for coral reef organisms to build skeletons, thus threatening the very integrity of the reef structure[5].

The challenges facing coral reefs under anthropogenic climate change has spurred calls for new strategies and interventions to avoid extinctions and ensure coral reef futures. These include i) targeted investment in reef locations where the rate of warming is predicted to be relatively slow[6], ii) enhancing the natural adaptive capacity of coral populations through, for example, assisted evolution [7], iii) the selective propagation, rearing and out-planting of resilient corals to the reef, and iv) protecting demonstrably resilient coral communities within Marine Protected Areas (MPAs)[8]. While climate resilience is not currently a criterion for inclusion of coral reefs in MPA's or Protected Area Networks (PAN's) [8], some coral reef nations have already actively protected climate resilient coral reefs or have committed to doing so (see the Amatuku Declaration from the 2018 Polynesian Leaders Group Summit in Funafuti, Tuvalu).

A potential strategy that has received less attention involves the land-based protection of resilient corals. Advantages of land-based protections include the ability to tightly control the environment in which the corals are housed, and to provide ready access to corals for propagation and scientific study. Large public aquariums have tremendous potential as repositories, exhibits, live banks, and laboratories to protect, propagate and study these corals, and to educate the public about the threats that coral reefs face from climate change. At least 88 public aquariums in the United States serve millions of people each year. Many already host live coral reef exhibits that could accommodate climate-resilient genotypes, and most employ expertise in animal husbandry that could be invested to propagate and grow these corals. Aquariums are considered one of the most trusted sources of information to the public and have the potential to fill critical gaps in awareness of the plight of coral reefs, their resilience, and the incredible efforts of individuals, organizations and governments around the world to facilitate their survival in a changing ocean.

The Aquarium of the Pacific (AoP) is the first public aquarium to commit to establishing a climate-change resilient or "Super Coral" exhibit, with an initial focus on corals that can tolerant extreme temperatures. The exhibit will include educational programming, complete with explanation of what Super Corals are and where they are found. AoP will attempt to recruit other aquariums to join them in this effort. The AoP has also committed to establishing a live bank of Super Corals that will be a source for other aquariums and a resource for the scientific community. Critically, the live bank of Super Corals will enable further scientific discovery of climate resilient corals from around the world. In the future, AoP hopes to develop capacity as a long-term frozen repository for Super Coral DNA. All work toward the effort will be made available to other aquariums at no cost.

Our two-day workshop held at the Aquarium of the Pacific in Long Beach California, brought together scientists, aquarists, coral farmers and stakeholders to provide expert input toward the development of a "Super Coral" exhibit, live bank, and long term genetic repository at the AoP, and possibly other aquariums. A "roadmap" summarizing the key steps toward achieving this goal is provided in Figure 1.

Understanding the mechanisms underlying the resilience of corals to ocean warming and acidification has taken on new urgency, and is an active field of study that has seen many significant advances in the last few years. It is not the goal of this report to add to these advances or review the state of the field. Rather, we highlight here some of the key elements of the workshop discussion on the topic of public aquariums as repositories of climate-resilient corals. We end the report with a description of the first proposed Super Coral exhibit and live bank at the Aquarium of the Pacific.

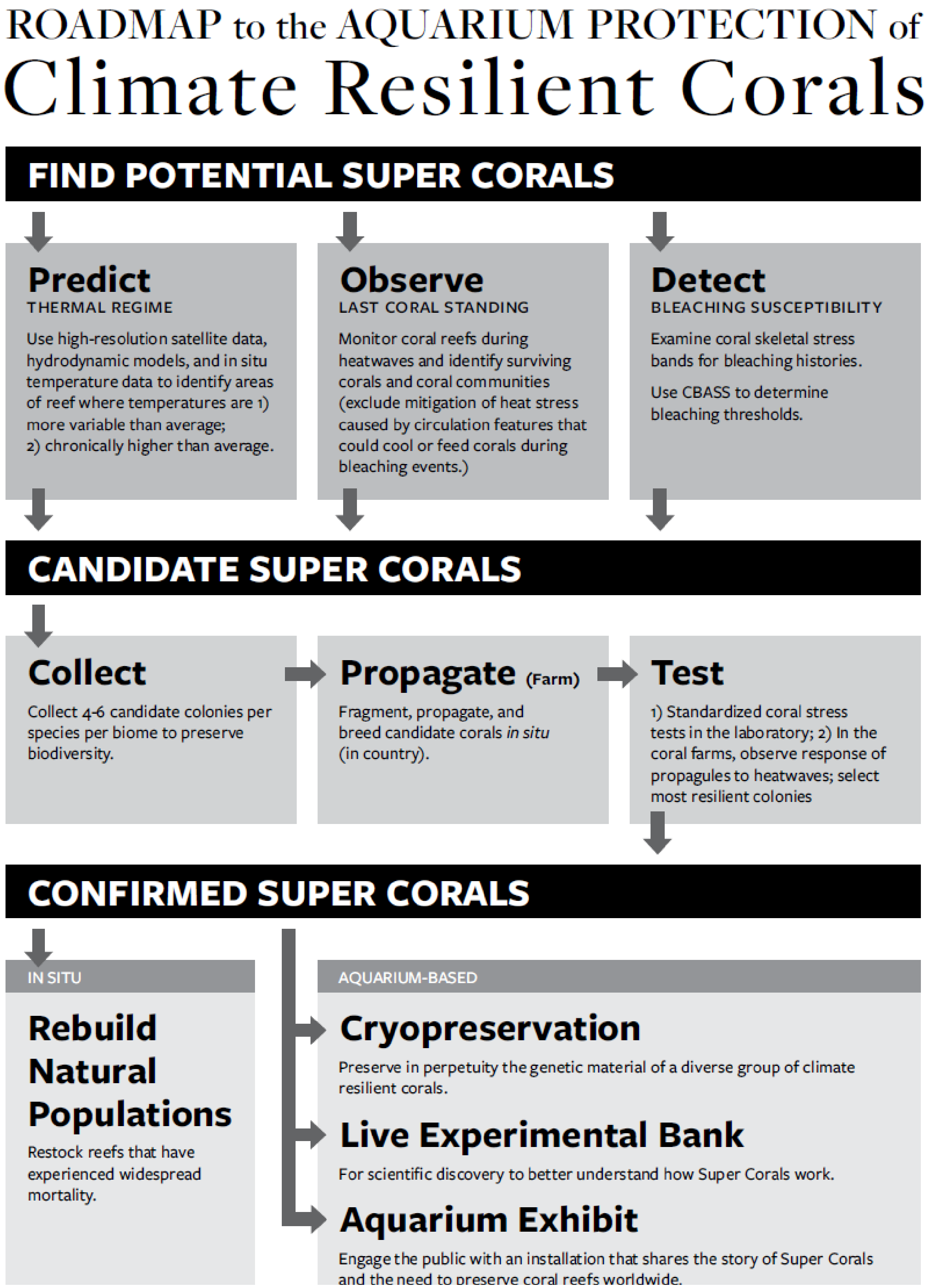


Figure 1: A strategy for the identification, acquisition, propagation and land-based protection of Super Corals.

What are “Super Corals?

The term “Super Coral” has been widely used in the media and scientific literature to describe coral survivors of stress exposure [9]. Its use however, is somewhat controversial, in part because the factors that enable survivorship are wide-ranging and complex, and not always adequately defined. Corals that survive a heatwave because water temperatures in the coral’s microenvironment are mitigated by features of the reef circulation (for example, internal waves) may not be heat tolerant, and are therefore may not be true “Super Corals”. Corals may be tolerant of one environmental stressor, such as heat, but not to pH. They may be “Super” in one context but not in the other. Therefore it is important at the outset, to define the meaning of “Super Coral” for each context in which it is used. In our workshop, and with reference to the initial Super Coral exhibit at the AoP, we use the term specifically to describe coral holobionts that are able to either tolerate or to recover from exposure to *thermal* stress better than the population average, and are able to successfully reproduce post-stress. The capacity for Super Corals to endure extreme heat is genetic and heritable.

Holobionts resilient to thermal stress are those that either bleach at higher temperatures or recover faster and more effectively from bleaching than the population average, and successfully reproduce post-bleaching. Super Coral colonies likely exist within many coral communities (i.e., assemblages representing multiple taxa) because populations and assemblages are composed of individuals representing a range of thermal tolerances.

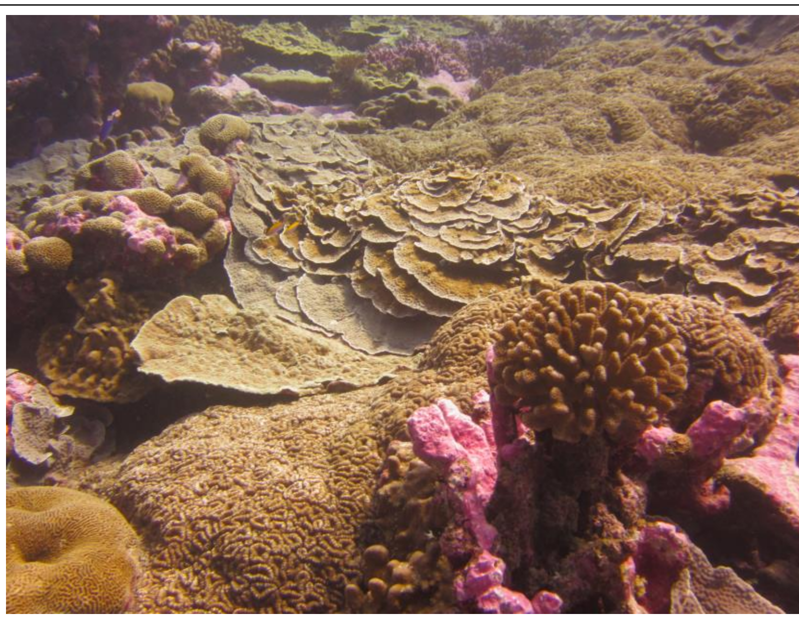


Figure 2: A coral assemblage of mixed taxa in the Phoenix Islands Marine Protected Area (PIPA). This “Super Reef” survived unprecedented heat during the 2015-16 El Niño and performed significantly better than assemblages hosting similar taxa and exposed to equivalent thermal stress in other areas of the PIPA. (Photo by Michael Fox, Cohen Lab, WHOI)

Conversely, "Super Reefs" is a term coined to assist in the identification and protection of coral communities of mixed taxa that have potential to survive ocean warming. Survival may be enabled through oceanographic processes that mitigate thermal stress (and will continue to do so under future warming), or biological factors that enhance thermal tolerance or bleaching survival, including the ability of corals to feed during bleaching[10]. The identification of Super Reefs is most relevant in the design of Marine Protected Areas (MPAs) or Protected Area Networks (PANs) to include reefs with demonstrated capacity to survive climate change, independent of the underlying mechanisms[11]. The distinction between Super Reefs and Super Corals is important in the context of aquarium protections of climate-resilient corals because Super Reefs may or may not harbor Super Corals as they are defined here.

How do Corals become "Super"?

Thermal tolerance arises primarily through two mechanisms: acclimatization and adaptation[12]. More recently, heritable epi-genetic mechanisms have been identified as an additional mechanism through which corals may tolerate climate change. We discuss these mechanisms here because there are important differences between them, and these may be relevant to their preservation in aquarium settings.

1) **Acclimatization** is a physiological readjustment of the thermal tolerance levels of an individual coral within its lifetime that does not involve changes in the underlying DNA sequence. In multiple studies, acclimatization has been linked to exposure to high thermal variability[13,14 15-19]. For this reason, our roadmap (Figure 1) identifies high variability thermal environments as potential locations of thermally tolerant corals for propagation and aquarium preservation. However, unlike adaptation, acclimatization can be a reversible trait[20]. For example, phenotypically plastic corals inhabiting the back reef pools of Ofu, American Samoa appear to have lost their thermal tolerance when moved out of their reefs of origin [17]. In the same study, corals acquired tolerance in a relatively short period of time when transplanted from lower to high variability thermal environments[17], although the transplanted corals never achieved the same level of tolerance as the native corals.

The ability of some corals to both acquire and lose thermal tolerance in a short period of time raised questions about the ability of such corals to maintain their plasticity in aquarium environment and whether aquarium conditions needed to mimic high variability environments in order to maintain their inherent plasticity.

2) **Adaptation** refers to the process of selection for beneficial genotypes in a

population and involves changes in the underlying DNA sequence of the coral. Thermal adaptation may take place over one or many generations during which time the more thermally-sensitive members of a population are eliminated, leaving the more temperature tolerant corals to reproduce and recruit to available habitat[20]. Alternatively, on reefs in chronically hot environments that are connected to neighboring reefs in less extreme environments, selection may take place during the recruitment process when only the most thermally tolerant larvae entering the hot environment can recruit, survive and reproduce. For this reason, our roadmap (Figure 1) identifies chronically hot reef environments as potential locations of thermally tolerant corals. In addition, we propose that candidate Super Corals may be found amongst corals or coral communities that survive heatwaves, in cases where local mitigation of thermal stress can be ruled out.

Unlike acclimatization, adaptation is a fixed effect (or a set of fixed effects) that are not reversible, and remains a characteristic of the coral independent of the environment it is in. For example, recent work on Palau's *Porites lobata* populations shows that colonies inhabiting Palau's chronically hot environments are genetically distinct from conspecifics on exposed barrier reefs [21,22], but that some of the hot pool genotypes make it to the barrier reef where they recruit and grow to mature colonies. Critically, hot pool genoytpes maintain their thermal tolerance in the cool barrier reef environment, and do not bleach during heatwaves. Unlike acclimatization therefore, this mechanism of thermal tolerance is fixed and not environment- dependent. Such corals will maintain their inherent thermal tolerance on the reef, and in an aquarium setting.

3) **Epi-genetics and microbiome considerations:** Genetic adaptation is a slow process especially in corals which have long generation times. However, emerging research shows that some corals also possess heritable non-genetic mechanisms, collectively terms "epigenetics"[23,24] that enable relatively quick response to environmental changes not by altering the genetic code, but by changing the way it is used. This process allows corals to optimize their physiological responses in the face of long-term stress. For example, some studies that periodically subjected corals to high temperatures showed that they retain a higher resilience towards similar future stresses.

Additionally, changes in dinoflagellate symbionts[25] also present viable resilience strategies. Indeed, differences in thermal tolerance amongst *Symbiodinium* types that live in association with individual corals is a well-documented mechanism of coral thermal tolerance. Nevertheless, symbiont clade does not always explain coral thermal tolerance, although much work at the sub-cladal level still needs to be done[26].

How do we Locate Climate Resilient Corals for Aquarium Exhibits?

No single genetic test yet exists to identify corals that are thermally resilient. In our scheme (Figure 1), potential Super Coral locations are first identified based on:

1) Knowledge of reef thermal regime gathered from high resolution satellite data, *in situ* temperature logger data and/or hydrodynamic modeling of the reef. Environments characterized by high amplitude thermal variability (e.g., Ofu in American Samoa)[17] or chronically high temperatures (e.g., Palau, Red Sea)[14,21] have increased likelihood of hosting corals that are either acclimatized or adapted to extreme heat.

2) Direct observation of corals surviving extreme heat events ("last coral standing")[27] may also be indicative of enhanced thermal tolerance, if factors such a thermal mitigation by local hydrodynamics or food supply can be ruled out.

3) *In situ* experimentation to determine bleaching thresholds (CBASS), or whether (or not) corals bleached during past heatwaves (stress bands). CBASS, the Coral Bleaching Automatic Stress System, is a potable "bleaching chamber" that can be used to constrain bleaching thresholds and identify the more thermally tolerant holobionts in the field[16]. Skeletal "stress bands" are skeletal features that corals form during prolonged bleaching events and can be used to identify colonies or assemblages that did not bleached during known heatwaves [22,28]. Stress bands are also being used to constrain the thermal thresholds for bleaching of coral communities(Mollica, in revision #106).

Based on these initial evaluations, "Candidate Super Corals" are selected for initial propagation and further standardized testing to confirm their thermal tolerance (Figure 1). Although putative super corals can be identified based on patterns of survival and/or variation in the water temperature profiles they experience, experimental validation is needed to confirm whether collected corals truly exhibit elevated thermal tolerance and whether that tolerance is retained following translocation to field nurseries and ex situ aquaria. Standardized, diagnostic tests that are capable of being applied in highly controlled, repeated trials will be essential for quantifying baseline coral thermal resistance and/or resilience, as well as any changes in these properties. One example is the inexpensive, highly portable experimental system, CBASS, develped by Dr Dan Barshis, which is capable of performing highly controlled thermal stress exposures, and could be used to measure coral thermal tolerance in the field and in the laboratory. Other standardized tests exist or are under development utilizing different methods, such as metabolite biomarkers and indicators of regeneration potential. We anticipate incorporating a range of tests in the “resilience toolkit” as they become available.

Potential Candidate Super Coral Locations: In targeting locations for Super Coral collections, those hosting corals and coral assemblages observed to consistently survive extreme heat events (in the wild) offer a viable starting point. Multiple locations with these characteristics exist and more are revealed with each bleaching event, but few have been studied in detail to determine the underlying mechanisms for the observed resilience. For example, Jarvis Island (U.S.) in the Pacific Remote Marine National Monument lost 95% of its corals in the unprecedented heat (>20 DHWs) of the 2015-16 El Niño[27,29]. Survivors included isolated colonies of *Porites*, *Hydnophor*a, *Pocillopor*a and *Acropora* that experienced equivalent heat exposure to conspecifics that died. In the central Red Sea, a catastrophic mortality event during the 2010 heatwave exposed resilient colonies of *Stylophora pistallata* [14]. These are a few examples where the “last man standing” can help to identify candidate colonies for sampling, propagation and further study.

The semi-isolated bays of the Palau Rock Islands, including Nikko and Risong Bays, host diverse coral *assemblages* that consistently bleach less and exhibit fewer bleaching-induced stress bands than barrier reef assemblages, despite experiencing stronger heat anomalies during El Niño [21,22]. New genetic data from the Palau Rock Islands indicates that RI corals are genetically distinct from conspecifics on the barrier reef, suggesting that the thermal tolerance of these corals may have a genetic basis (Rivera, et al., 2018). Similarly, Howland and Baker Islands (U.S.), also in the Pacific Remote Marine National Monument, regularly experience levels of heat stress normally associated with catastrophic bleaching and mortality, but have maintained relatively high and stable coral cover over time[29].

In the Phoenix Islands Marine Protected Area (Kiribati), coral assemblages within the Kanton lagoon and on the southern fore-reef survived the unprecedented heat stress of the 2015-16 El Niño[30], while exposed reefs on the leeward side of the island experienced high mortality. While more work is needed to uncover the mechanisms underlying coral survival here (e.g., coral tolerance vs localized mitigation of extreme heat), locations like these offer viable places to start.

Other locations likely exist, where specific reef geomorphology creates isolated or semi-isolated areas of localized environmental variability, or long seawater residence times that lead to chronic high temperature conditions. Such locations however, could be difficult to identify even with high-resolution (4km) satellite data because the scales of spatial variability are often smaller than satellites can resolve. *In situ* temperature data may be the best guide to identifying thermal environments that might host Super Corals and Super Reef assemblages, although most reefs areas lack long-term detailed temperature records.

Permitting considerations

All corals are protected under the Convention on International Trade in Endangered Species (CITES). Within the U.S. Fish and Wildlife grants permits for collection, CITES permits not required to ship from U.S. states or territories to destinations within the United States. For corals sourced outside of the U.S., the situation may be more complex depending on individual country interest in engagement in Super Coral exhibits and their status as a CITES signatory.

Population Genetic Considerations for Creating Thermally-Resilient Coral Exhibits and Repositories

In this segment of the workshop, we discussed how best to represent, in captivity, the genetic diversity that exists among thermally tolerant coral populations, and how to maintain that diversity over time. Further, thermal tolerance is likely facilitated through both host and symbiont genetics, and based on not one, but a combination of many genes.

Addressing this issue requires consideration at two spatial scales: within and between populations. First, resilient corals capable of surviving extreme heat and producing viable offspring exist today across a wide range of environmental conditions (e.g., light, flow, nutrients). Future reef environments will be warmer, but future corals will have to cope with higher temperatures super-imposed on non-thermal environmental variables that are also changing over time. To preserve and propagate thermal resistance and resilience capabilities, representation of different populations of thermally tolerant corals across a broad range of reef environments (e.g., sampling across the multiple reef environments represented by NOAA's PRAMP program) is necessary.

Second, within populations of thermally-tolerant corals, maintaining genetic diversity is critical for population persistence and adaptive potential. Captive populations are much smaller than natural populations, and not all corals contribute to reproduction, thus increasing the chances of propagating deleterious mutations over time. These factors all contribute to reduced genetic diversity and increased chances of extinction.

How many corals do we need to sample to capture a sufficient proportion of diversity? Dr Carly Kenkel presented a summary of findings from the Restoration Genetics Working Group of the Caribbean Coral Restoration Consortium (Baums et al. *in review*). Using allele frequency spectra, they found that sampling 12 individuals is sufficient to capture 90% of the common allelic diversity (alleles > 5% frequency), and 3-4 individuals will likely capture 50% of the common diversity present in the population. Alleles which confer a survival advantage in thermally stressful environments will likely be represented at high frequency, consequently this sampling design may also encompass adaptive in addition to neutral diversity. Importantly, this result was similar for the four coral species analyzed (*Acropora millepora*, *A. cervicornis*, *A. palmata* and *O. faveolata*) and more recent work reports similar values for other Indo-Pacific species (Afiq-Rosli et al. 2019) from which they determined that just 12 individuals are needed to capture 90% of the diversity. Capturing 50% of the diversity requires 3-4 individuals. Based on this calculation, the best strategy for the aquarium exhibit and live bank would be to sample small numbers of individual corals from multiple reefs representing a broad range of environments.

How to Propagate "Super Corals"?

Methods and Considerations in the Sampling, Shipping and Propagation of many Corals from Few Survivors

The question we addressed in this segment of the workshop was how best to sample *in situ*, ship and propagate (or propagate *in situ*, then ship) climate-resilient corals from few survivors, and with minimum impact on the parent coral and coral community. In our favor is the fact that many types of corals, if healthy, are capable of rapid growth and methods of propagation have been tried and tested by the coral farming and restoration communities. "Micro-fragmentation" starts with a donor colony or chunk the size of a fist and breaks them up into even smaller pieces of 1 to 5 polyps. This stimulates the coral tissue to grow into cloned colonies achieving up to 25 to 50 times the growth rate of the original colony. Micro-fragmentation has been successfully demonstrated on a variety of coral taxa and morphologies including branching *Acropora* [31], platy *Montipora* and massive corals including *Porites* and *Orbicella*[32]. In multiple studies, growth rates of fragments are proportional to the initial fragment size, implying larger fragments may be more successful (more rapidly achieve size refuge from mortality and reproductive maturity).

Using micro-fragmentation to produce thermally-tolerant clones serves the dual purpose of providing colonies for an aquarium exhibit, as well as clones that can be sequenced, curated and shared with scientific institutions and other aquariums. These clones can then be used for both display and scientific discovery including temperature and CO_2 manipulation experiments (standardized stress tests) and monitoring of trans-generational and epigenetic effects in long-term, well-monitored conditions. There was also discussion of prompting spawning within the live bank to provide scientists access to reproductive material for preservation.

Dr Austin Bowden-Kerby discussed his method of rescuing fragments from Super Coral survivors of catastrophic bleaching on Kiritimati and propagating microfragments in the field, creating Super Coral gene bank nurseries *in situ* (Figure 3). These Super Coral farms are viable sources of material for the aquarium exhibit and live bank, as well as for out-planting to regrow the reef (see below and Figure 1). Fragments of open branching corals are planted to ropes strung between a metal frame 'table' established on the shallow reef at a location with good water circulation yet protected from major wave events. For massive, submassive and tightly branched corals- such as corymbose and table *Acropora* species and *Pocillopora*, fragments are planted to 15-20cm cement "button" or "cookie" discs and then secured to a 2x2 inch heavy mesh base using cable ties, located on a metal frame table alongside the ropes. The corals in the nursery are grown into "mother corals" for one or two years, and are then trimmed at least once a year to produce seed fragments for outplanting. Each mother coral or planted rope in the nursery

Figure 3: An example of a coral nursery developed from coral fragments. Second generation fragments are out-planted back to the reef to restore areas devastated by heatwaves. Photo: Austin Bowden-Kerby.

should represent a single genotype, and they can be codified based on location on the ropes or tables.

Second-generation fragments are out planted back to the reef environment to restore sexual reproduction. Termed “out-planting”, this stage effectively restores multiple and diverse breeding populations of corals. The focus is on inclusion of as many diverse genotypes of each species as possible, and creating dense plantings (corals <1m apart), to limited areas at multiple reef sites, creating both a strong settlement signal for incoming larvae, and facilitating the effective spawning of adult colonies at about three years.

Creating a Super Coral Exhibit at the Aquarium of the Pacific

Super Coral Exhibit Goals

This Super Coral workshop identified three key goals regarding the creation of a new exhibit:

1) Increase public awareness about the importance of Super Corals and their potential impact on the future of coral reefs
2) Create a platform to showcase the importance of coral reefs to the ocean and to humanity and to introduce the public to the people who live on, and protect, the islands that the Super Corals come from, including Kiribati and United States reefs.
3) Construct a “live bank” for Super Corals that will be used to increase scientific understanding of the biology Super Coral holobionts.

Figure 4: The 5000 gallon “Sex Change” exhibit at the Aquarium of the Pacific is the current target for the new Super Reef exhibit.

<u>Exhibit Concept</u>

Several exhibit options were reviewed, but the exhibit that best fits these goals is the current *Sex Change* exhibit (Figure 4). This 5,000 gallon closed system display currently features hermaphroditic fish (primarily anthias) and is large enough to house living Super Coral colonies. Since the exhibit is the focal point of a long tunnel, the husbandry team suggests making use of the surrounding rockwork to create an immersive transition zone between the *Tropical Reef* tunnel and the new *Super Coral* exhibit. The transition zone between these two exhibits will be enhanced by adding artificial coral to the exterior rockwork and by replacing cabinetry with rockwork on either side of the exhibit.

Figure 5: The site for the first Super Coral exhibit at the Aquarium of the Pacific

The existing cabinetry on either side of the exhibit (Figure 5) will be replaced with rockwork and artificial corals. Rockwork will be modified to include space for graphics on either side. A video monitor will be installed on cabinetry above the exhibit.

The rockwork walls leading up to the new Super Coral exhibit will contain a combination of bleached and “live” artificial coral skeletons to illustrate the feeling of transitioning into a bleached coral reef. Guests will be able to touch brain, plating, and branching artificial corals that will provide a tactile element to the immersive experience.

As guests approach the new Super Coral exhibit, they will see the bleached artificial corals continue into the exhibit, but in the center of the exhibit is a “beacon of hope” where live coral colonies will reside. A large reef outcropping in the center of the exhibit will feature corals that have survived the bleaching event. Supporting graphics in the form of signage and videos will be used to define super corals, highlight their importance, and showcase the indigenous cultures that rely on coral reef ecosystems. The primary message is one of hope for the future of coral reefs and the people that depend on them around the world.

Figure 6: The New Super Coral Exhibit at the Aquarium of the Pacific: “A Beacon of Hope”

<u>Life Support System Modifications</u>

The life support system on the current *Sex Change* exhibit (Figure 7) will need to be modified (Figure 8). Additional components including LED lights, submersible pumps, filters and reactors will be added to the current life support system in order to maintain living corals and provide optimal water quality for coral growth. These components are similar to those on already existing coral life support systems as shown below.

Figure 7: The current life support system for the proposed Super Coral exhibit will need to be upgraded.

<u>Super Coral Live Bank</u>

A dedicated super coral culture system will be developed to support the exhibit corals and provide a system for Super Coral propagation. This system will be designed to house broodstock colonies that will be used to produce asexually propagated Super Coral fragments. These fragments will be available to researchers on a continuous basis and will be used for basic research associated with Super Corals. In order to fulfill the goal of developing a live bank for Super Corals, we will need to design a system similar to the Aquarium's current coral propagation system (below).

Figure 8: Proposed upgrades to the life support system for the new Super Coral exhibit.

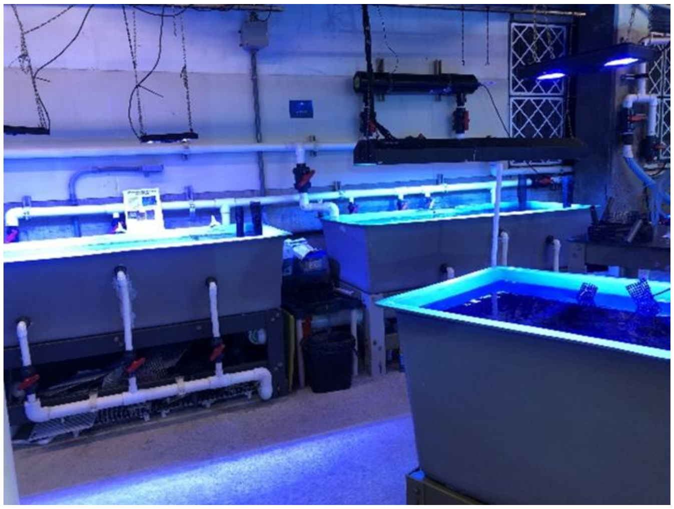


Figure 9: Proposed Super Coral live bank at the Aquarium of the Pacific. The live bank will house Super Corals for purposes of scientific discovery.

The system will include a series of troughs and trays that can house up to 150 broodstock coral colonies and 900 fragments. This estimate is based on the following calculations:

Broodstock:
3 different sites from which Super Corals are acquired (e.g., Kiribati, Jarvis, and American Samoa)
5 keystone species from each site
<u>10 different colonies from each species (up to 10cm in diameter)</u>
Total: 150 broodstock colonies

Super coral fragments:
5 – 6 fragments per broodstock colony
<u>150 broodstock colonies</u>
Total: 750 – 900 fragments

A Note on the Potential for Cryopreservation of Climate Resilient Corals

The next 10 to 20 years will be so perilous for our oceans in terms of loss of species, practical conservation solutions are urgently needed that can preserve cells and their genes in excellent condition for hundreds of years. Cryopreservation is one of the few technologies that offers this opportunity. While a frozen bank is not in the current plans of the Aquarium of the Pacific, it may be added in the future and is discussed briefly here as it relates to preservation of coral DNA.

Cryopreservation involves a series of steps in which water within the cell is extracted and replaced with a cryoprotectant or antifreeze. The partially dehydrated cell then can withstand the extraordinary stress of low temperature exposure, essentially entering a state of suspended animation. When cells are frozen and banked properly, they can retain viability for years (or even centuries) without DNA damage and provides a means to safeguard all existing species and their genetic diversity. More specifically, these 'frozen banks' offer (1) large samples of preserved and protected gene pools that can be used to 'seed' shrinking populations, (2) easy and inexpensive transport of genetic materials among living populations, (3) extended generation intervals and (4) vast improvement of access to biomaterials for scholarly research[33]. Today, we can cryopreserv coral sperm[33,34] and have banked ~30 species around the world. These frozen assets have been used to create small medium-scale restoration populations[35] and larger restoration populations whereby frozen sperm up to 10 years was used to create trans-regional crosses[36], proving that assisted gene flow using cryopreserved sperm could be an effective restoration process. Additionally, we have cryopreserved the larvae of coral[37] which will have massive implications because freeze 100,000's of larvae at a time to create vast insurance, research and restoration populations.

Some Thoughts on Intellectual and Material Property (IP)

Because Super Reefs may contribute to the survival of coral reefs in a warming ocean, we should do everything we can to protect them. Countries that take action to protect Super Reefs within their territorial seas by restricting human activities that generate revenue, such as fishing and coastal development, should be compensated in some way for their sacrifices and should retain the Intellectual Property Rights to genetic material that someday may have financial value.

Kiribati was the first nation to set aside a large area of open ocean home to a number of Super Reefs and prohibited fishing. They received no compensation to offset the losses in revenue and have no formal protection of the genetic resources of their Super Corals and Super Reefs. The Aquarium of the Pacific is a partner with the Phoenix Island Protected Area (PIPA) Trust through having a seat on its board of directors, and some of the Super Corals for our proposed exhibit and live bank might come from the PIPA. The Aquarium pledges to develop a binding Memorandum of Agreement with Kiribati and PIPA that would ensure that Kiribati retains decision-making rights on coral usage, ownership of IP, and shares fairly and equitably in any profits that might result from this initiative consistent with the Nagoya Protocol.

A useful model may be provided by the Amazon Basin (https://www.earthbankofcodes.org/). There are similar discussions concerning an Ocean Bank of Codes that would develop a block-chain means of tracking provenance and potentially reward sound stewardship of ocean resources.

CITATIONS

1 Hawkins, E. *et al.* Estimating Changes in Global Temperature since the Preindustrial Period. *Bulletin of the American Meteorological Society* **98**, 1841-1856, doi:10.1175/bams-d-16-0007.1 (2017).

2 Oliver, E. C. J. *et al.* Longer and more frequent marine heatwaves over the past century. *Nature Communications* **9**, 1324, doi:10.1038/s41467-018-03732-9 (2018).

3 Cai, W. *et al.* Increasing frequency of extreme El Niño events due to greenhouse warming. *Nature Climate Change* **4**, 111, doi:10.1038/nclimate2100 (2014).

4 Doney, S. C., Fabry, V. J., Feely, R. A. & Kleypas, J. A. Ocean Acidification: The Other CO2 Problem. *Annual Review of Marine Science* **1**, 169-192, doi:10.1146/annurev.marine.010908.163834 (2009).

5 Cohen, A. L., McCorkle, D. C., de Putron, S., Gaetani, G. A. & Rose, K. A. Morphological and compositional changes in the skeletons of new coral recruits reared in acidified seawater: Insights into the biomineralization response to ocean acidification. *Geochemistry, Geophysics, Geosystems* **10**, doi:10.1029/2009gc002411 (2009).

6 Beyer, H. L. *et al.* Risk-sensitive planning for conserving coral reefs under rapid climate change. *Conservation Letters* **11**, e12587, doi:doi:10.1111/conl.12587 (2018).

7 van Oppen, M. J. H., Oliver, J. K., Putnam, H. M. & Gates, R. D. Building coral reef resilience through assisted evolution. *Proceedings of the National Academy of Sciences* **112**, 2307-2313, doi:10.1073/pnas.1422301112 (2015).

8 McLeod, E. *et al.* The future of resilience-based management in coral reef ecosystems. *Journal of Environmental Management* **233**, 291-301, doi:https://doi.org/10.1016/j.jenvman.2018.11.034 (2019).

9 Camp, E. F., Schoepf, V. & Suggett, D. J. How can "Super Corals" facilitate global coral reef survival under rapid environmental and climatic change? *Global Change Biology* **24**, 2755-2757, doi:doi:10.1111/gcb.14153 (2018).

10 Anthony, K. R. & Fabricius, K. Shifting roles of heterotrophy and autotrophy in coral energetics under varying turbidity *Journal of Experimental Marine Biology and Ecology* **252**, 221-253 (2000).

11 West, J. M. & Salm, R. V. Resistance and Resilience to Coral Bleaching: Implications for Coral Reef Conservation and Management. *Conservation Biology* **17**, 956-967, doi:10.1046/j.1523-1739.2003.02055.x (2003).

12 Thomas, L. *et al.* Mechanisms of Thermal Tolerance in Reef-Building Corals across a Fine-Grained Environmental Mosaic: Lessons from Ofu, American Samoa. *Frontiers in Marine Science* **4**, 434 (2018).

13 Kenkel, C. D. & Matz, M. V. Gene expression plasticity as a mechanism of coral adaptation to a variable environment. *Nature Ecology &Amp; Evolution* **1**, 0014, doi:10.1038/s41559-016-0014 (2016).

14 Pineda, J. *et al.* Two spatial scales in a bleaching event: Corals from the mildest and the most extreme thermal environments escape mortality.

Limnology and Oceanography **58**, 1531-1545, doi:doi:10.4319/lo.2013.58.5.1531 (2013).
15 Oliver, T. A. & Palumbi, S. R. Do fluctuating temperature environments elevate coral thermal tolerance? *Coral Reefs* **30**, 429-440, doi:10.1007/s00338-011-0721-y (2011).
16 Barshis, D. J. *et al.* Genomic basis for coral resilience to climate change. *Proceedings of the National Academy of Sciences* **110**, 1387-1392, doi:10.1073/pnas.1210224110 (2013).
17 Palumbi, S. R., Barshis, D. J., Traylor-Knowles, N. & Bay, R. A. Mechanisms of reef coral resistance to future climate change. *Science* **344**, 895-898, doi:10.1126/science.1251336 (2014).
18 Safaie, A. *et al.* High frequency temperature variability reduces the risk of coral bleaching. *Nature communications* **9** (2018).
19 Carilli, J., Donner, S. D. & Hartmann, A. C. Historical Temperature Variability Affects Coral Response to Heat Stress. *PLOS ONE* **7**, e34418, doi:10.1371/journal.pone.0034418 (2012).
20 Coles, S. L. *et al.* Evidence of acclimatization or adaptation in Hawaiian corals to higher ocean temperatures. *PeerJ* **6**, e5347, doi:10.7717/peerj.5347 (2018).
21 Van Woesik, R. *et al.* Climate ‐ change refugia in the sheltered bays of Palau: analogs of future reefs. *Ecology and Evolution* **2**, 2474-2484, doi:doi:10.1002/ece3.363 (2012).
22 Barkley, H. C. & Cohen, A. L. Skeletal records of community-level bleaching in Porites corals from Palau. *Coral Reefs* **35**, 1407-1417 (2016).
23 Putnam, H. M., Barott, K. L., Ainsworth, T. D. & Gates, R. D. The Vulnerability and Resilience of Reef-Building Corals. *Current Biology* **27**, R528-R540, doi:10.1016/j.cub.2017.04.047 (2017).
24 Liew, Y. J. *et al.* Epigenome-associated phenotypic acclimatization to ocean acidification in a reef-building coral. *Science Advances* **4**, eaar8028, doi:10.1126/sciadv.aar8028 (2018).
25 Stat, M. & Gates, R. D. Clade D Symbiodinium in Scleractinian Corals: A “Nugget” of Hope, a Selfish Opportunist, an Ominous Sign, or All of the Above? *Journal of Marine Biology* **2011**, 9, doi:10.1155/2011/730715 (2011).
26 Thomas, L. *et al.* Mechanisms of Thermal Tolerance in Reef-Building Corals across a Fine-Grained Environmental Mosaic: Lessons from Ofu, American Samoa. *Frontiers in Marine Science* **4**, doi:10.3389/fmars.2017.00434 (2018).
27 Barkley, H. C. *et al.* Repeat bleaching of a central Pacific coral reef over the past six decades (1960–2016). *Communications Biology* **1**, 177, doi:10.1038/s42003-018-0183-7 (2018).
28 Mollica, N. R., Cohen, A. L. & Brainard, R. Constraining Thermal Thresholds of Coral Reefs using Skeletal Signatures of Bleaching. *Coral Reefs* (in revision).
29 Brainard, R. E. *et al.* Ecological Impacts of the 2015/16 El Niño in the Central Equatorial Pacific. *Bulletin of the American Meteorological Society* **99**, S21-S26, doi:10.1175/bams-d-17-0128.1 (2018).

30 Mangubhai, S., Nand, Y. & Rotjan, R. Discovery of a recovering climax *Acropora* community in Kanton Lagoon in the remote Phoenix Islands Protected Area. *Pacific Conservation Biology*, -, doi:https://doi.org/10.1071/PC18051 (2018).
31 N. Young, C., Schopmeyer, S. & Lirman, D. *A Review of Reef Restoration and Coral Propagation Using the Threatened Genus Acropora in the Caribbean and Western Atlantic*. Vol. 88 (2012).
32 Forsman, Z. H., Page, C. A., Toonen, R. J. & Vaughan, D. Growing coral larger and faster: micro-colony-fusion as a strategy for accelerating coral cover. *PeerJ* **3**, e1313, doi:10.7717/peerj.1313 (2015).
33 Hagedorn, M. *et al.* Preserving and using germplasm and dissociated embryonic cells for conserving Caribbean and Pacific coral. *PloS one* **7**, e33354 (2012).
34 Hagedorn, M. *et al.* Preserving and Using Germplasm and Dissociated Embryonic Cells for Conserving Caribbean and Pacific Coral. *PLOS ONE* **7**, e33354, doi:10.1371/journal.pone.0033354 (2012).
35 Hagedorn, M. *et al.* Producing Coral Offspring with Cryopreserved Sperm: A Tool for Coral Reef Restoration. *Scientific Reports* **7**, 14432, doi:10.1038/s41598-017-14644-x (2017).
36 Hagedorn, M. *et al.* Successful demonstration of assisted gene flow in a threatened coral Acropora palmata across genetically isolated Caribbean populations using cryopreserved sperm *bioRxiv*, 492447, doi:10.1101/492447 (2018).
37 Daly, J. *et al.* Successful cryopreservation of coral larvae using vitrification and laser warming. *Scientific Reports* **8**, 15714, doi:10.1038/s41598-018-34035-0 (2018).

Appendix A
Participants

Clair Atkinson	Aquarium of the Pacific
Daniel Barshis	Old Dominion University
Austin Bowden-Kerby	Corals for Conservation
Rusty Brainard	NOAA
Anne Cohen	Woods Hole Oceanographic Institution
Zac Forsman	University of Hawaii, Manoa
Christine Green	Sea Greene
Mary Hagedorn	Smithsonian
Dennis Hedgecock	Pacific Hybreed
Brittany Huntington	NOAA
Carly Kenkel	USC
Tom Maloney	Revive & Restore
Nathaniel Mollica	MIT-WHOI
Nabuti Mwemwenikarawa	PIPA
Ryan Phelan	Revive & Restore
Hollie Putnam	University of Rhode Island (Via WebEx)
Randi Rotjan	Boston University
Jerry Schubel	Aquarium of the Pacific
Greg Stone	Ocean Renaissance
Kim Thompson	Aquarium of the Pacific
Teburoro Tito	Ambassador to Kiribati
Sandy Trautwein	Aquarium of the Pacific

Appendix B
Agenda
Aquarium-based Protection of Climate Resilient Corals

A Workshop Co-Hosted by the PIPA Trust, Woods Hole Oceanographic Institution and the Aquarium of the Pacific

Dec. 18-19, 2018

Day 1

0830-0900 BREAKFAST in the Meeting Room, Suite 100 at 320 Golden Shore

0900-0910 **Jerry Schubel** (AoP) Welcome

0910-0925 **Greg Stone** (PIPA Trust Representative): The collaboration of government, science and conservation to ensure coral reef futures

0925-0940 **Anne Cohen** (WHOI) Introduction to the workshop: how we got here, where we're going.

0940-0950 Self Introductions (Name, Title, Organization)

0950-1000 Desired Outputs and Outcomes (Jerry Schubel, Anne Cohen)

1000-1020 BREAK

1020-1040 **Daniel Barshis** (Old Dominion University) "Super Corals – an introduction to climate resilient corals and coral communities: genetics, environment, state of knowledge".

1040-1100 Group Discussion: Define Super Corals and Super Reefs. Where are critical knowledge gaps in the identification and location of Super Corals? What role can Super Corals play in the preservation of coral reefs in an era of unprecedented climate change?

1100-1130 **Rusty Brainard and Brittany Huntington** (NOAA) "Super Corals and Super Reefs: Observations from NOAA's coral reef monitoring and restoration efforts in the Pacific and Caribbean"

1130-1150 Group Discussion: Identification and location of Super Coral and Super Reefs. Can Super Coral locations be predicted? What opportunities and obstacles for collection?

1150-1210 **Austin Bowden-Kerby** (Corals for Conservation) "Discovering and preserving Super Corals through field-based coral restoration projects and gene bank nurseries"

1210-1230 Discussion: Potential and challenges of field-based propagation and preservation of Super Corals; the use of coral restoration projects as field-based Super Coral nurseries

1230-1330 LUNCH

1330-1350 **Zac Forsman** (University of Hawaii) "Propagating Super Corals: methods and considerations in the propagation of many corals from few survivors"

1350-1410 Group Discussion: Methods and challenges for shipping and propagating live corals from remote reef locations

1410-1430 **Carly Kenkel** (USC): "Population Genetic Considerations for Coral Collection, Propagation and Restoration"

1430- 1450 Group Discussion: Mix it up? Representation of multi-ocean and multi-taxa in aquarium-based "Super Coral" exhibits and repositories

1450-1510 **Mary Hagedorn** (Smithsonian Conservation Biology Institute) "Toward Repositories of Climate Resilient Corals: viability of coral genome preservation, egg and sperm banks – state of knowledge"

1510-1530 Group Discussion: Considerations and challenges to establishing aquarium-based Super Coral repositories

1530-1550 BREAK

1550-1610 **Sandy Trautwein** (AoP) "Building a Super Coral Aquarium Exhibit – advantages for Super Coral preservation, outreach and education, and special considerations"

1610-1630 Group Discussion: Do Super Corals have Super Needs? How to optimize aquarium conditions (T, Light, pH, flow, food) for corals with different thermal thresholds? Is there anything special that needs to be done or can be done to maintain their naturally high thermal thresholds in captivity? Who and what minimum number of coral genera should be targeted to "represent" Indo-Pacific and Caribbean reefs?

1630-1700 **Anne Cohen + group** Summarize key insights from the day's discussion

1700-1800 Adjourn to the Aquarium - Science on a Sphere: View an Experience & Discuss Development of an SoS experience on "Super Reefs"

1800-1830 Visit potential site of live exhibit of Climate Resilient Corals and Monitor

1830-1900 Hard-hat tour of Pacific Visions (optional)

1900 DINNER on the Veranda

Day 2

0830-0915 BREAKFAST in the Meeting Room, Suite 100 at 320 Golden Shore

0915-0930 **Nabuti Mwemwenikarawa** (Executive Director, PIPA Conservation Trust) "Bring PIPA Home"

0930-0950 **Dennis Hedgecock** (Pacific Hybreed, Inc): "Aquaculture vs conservation: what can aquaculture teach us about the aquarium preservation of Super Corals and maximizing resilience?"

0950-1010 Group Discussion: How can an exhibit/gene bank/experimental facility located at the AoP best support further research on climate resilient corals and reefs? What critical knowledge gaps exist in our understanding of climate resilient corals and coral communities that can be addressed in an aquarium setting?

1010-1030 BREAK

1030-1140 **Hollie Putnam** (URI) **and Mary Hagedorn (**SI) "Parallel scientific efforts with similar goals: strategies and status"

1140-1200 **Nabuti Mwemwenikarawa/Greg Stone/Randi Rotjan** (BU) "The central role of coral reef nations in the identification, propagation and aquarium based preservation of climate resilient corals"

1200-1300 LUNCH

1300-1430 **Jerry Schubel and Anne Cohen** Summary and Next Steps

14:30 - Closing Remarks by **Mr. Teburoro Tito**, Ambassador to the US and Permanent Representative to the UN, Kiribati Mission

Adjourn

Appendix C
Brief Bios of Participants

Super Coral Workshop Bios
December 18 & 19, 2018

Dan Barshis
Dan is currently an Assistant Professor of Marine Biology at Old Dominion University in Norfolk, VA. He did his undergraduate at the Evergreen State College in Olympia, Washington, MS and Ph.D. at the University of Hawai'i at Manoa, a postdoc at the Hopkins Marine Station, and a second postdoc at NOAA Fisheries, Santa Cruz. Dan's work primarily examines the evolutionary basis behind stress tolerance in reef-building corals. He employs a combination of field transplantation, controlled acclimation experiments, and advanced genomic techniques to uncover the relative roles of adaptation and acclimatization in determining coral tolerance limits and sensitivity to climate change impacts.

Austin Bowden-Kerby
Austin Bowden-Kerby received his PhD in Marine Science from the University of Puerto Rico at Mayaguez in 2001, his MS from the University of Guam in 1985, and his BS degree in Marine Biology from UNCW in 1977. Recognized as one of the worlds pioneers of 'Coral Gardening', he was among the first to work on coral restoration in the Pacific and Caribbean, focusing on endangered *Acropora* coral species. Many of the low-maintenance coral nursery and out-planting field methods used globally were developed by ABK, and are presently being used in Belize, the Dominican Republic, Fiji, Kiribati, Tuvalu, and Vanuatu. Adding to these methods, Austin has in recent years developed and implemented pre and post beaching management strategies for coral reefs facing mass bleaching and die-off of corals; strategies to identify, secure, and propagate bleaching resistant 'super corals' in gene bank nurseries. Austin presently operates projects addressing mass bleaching in Tuvalu, Kiribati, and Fiji, funded mostly through donations and small grants.
https://www.globalgiving.org/projects/emergency-response-to-massive-coral-bleaching/

A dual US/ Fiji citizen, Austin operates a 37 acre permaculture farm and hatchery for climate adapted chickens and runs a small NGO in Fiji called 'Corals for Conservation'. C4C works with communities and the tourism industry on coral restoration, coral reef management, sustainable farming, and the promotion of free range chickens as alternative protein to fish to support no-fishing areas.
https://www.globalgiving.org/projects/happy-chickens-for-food-security-and-environment-1/
A recent achievement has been the creation of coral gardening as a new profession for the tourism industry in Fiji, with twelve Marine Studies graduates trained, and

with several of them employed and working to propagate super corals and restore reefs. www.youtube.com/watch?v=7PRLJ8zDm0U
Austin's coral work has been the focus of three BBC TV documentaries. He was also winner of the prestigious National Geographic Ashoka Changemakers Award for the Environment in 2011.

Rusty Brainard
Dr. Rusty Brainard is a Supervisory Oceanographer and founding Chief of the Coral Reef Ecosystem Division (CRED) at the National Oceanic and Atmospheric Administration's (NOAA) Pacific Islands Fisheries Science Center in Honolulu (2001-present). Rusty leads CRED's 60-member interdisciplinary, ecosystem-based research program that conducts integrated ecosystem observations, long-term monitoring, and applied research of the coral reefs of the U.S. Pacific Islands to support ecosystem-based management and conservation. Rusty's team monitors the distribution, abundance, diversity, and condition of fish, corals, other invertebrates, algae, and microbes in the context of their diverse benthic habitats, and changing ocean climate conditions, including ocean warming and ocean acidification.

Since 2010, Rusty has served as NOAA's Technical Lead for the US Coral Triangle Initiative's Ecosystem Approach to Fisheries Management (EAFM) theme to provide technical assistance and capacity building for the CTI on Coral Reefs, Fisheries, and Food Security, a 6 country ocean governance agreement to address the threats facing the marine resources of the most biologically diverse and ecologically rich regions on earth. In 2010-2011, Rusty chaired the Biological Review Team in developing a Status Review Report assessing the status of and risk of extinction to 82 species of corals petitioned for listing under the US Endangered Species Act. Since 2010, Rusty has served as co-PI of a NOAA-NSF project "Comparative Analysis of Natural and Human Influences on Coral Reef Community Structure, Diversity, and Resilience". Rusty serves on the Ocean Carbon & Biogeochemistry Ocean Acidification Subcommittee, whose mission is to study ocean acidification's effects on marine ecosystems and biogeochemistry. From 2005-2010, Rusty was co-PI of the Census of Coral Reef Ecosystems project of the Census of Marine Life developing tools to systematically monitor the biodiversity of coral reefs.

Anne Cohen
Dr Anne Cohen is a Tenured Scientist at the Woods Hole Oceanographic Institution and faculty in the MIT-WHOI Joint Graduate Program in Oceanography. Author of more than 90 scientific papers on climate change and climate impacts on coral reef ecosystems, Dr. Cohen served as expert witness to the US House of Representatives Committee on Fisheries Conservation, Wildlife and Oceans, the Science Steering Committee for the Intergovernmental Panel on Climate Change (IPCC) (Impacts of Ocean Acidification on Marine Ecosystems) and the Stanford University Center for Ocean Solutions Working Group on Corals and Climate Change.

Cohen was nominated by the US State Department to present the keynote speech on Ocean Acidification at the 2015 Our Oceans Conference and is currently a member of the NOAA Science Advisory Board Ecosystems Sciences and Management Working Group. Dr. Cohen's work has been featured on Discovery Channel (US and Canada), BBC, WGBH NOVA, Public Radio International, WCAI Living Lab and BBC World Service, and National Geographic Magazine.

Zac H. Forsman

Dr. Zach Forsman is a Research Associate (extramurally funded) at Hawaii Institute of Marine Biology ("HIMB"). He received a B.S. in Ecology and Evolutionary Biology and a B.A. in Japanese from the University of Arizona, and a PhD from the University of Houston. His work on reef building coral has resulted in discoveries of new cryptic species, hybridization between species, chimerism, depth specialization, and adaptation across habitat extremes. He discovered and co-developed a micro-fragmentation method that results in rapid growth over a variety of surfaces, with applications for cultivation, biological assays, and reef restoration. He has worked with the US Fish and Wildlife Service, NOAA, and the State of Hawaii on projects such as: the review of corals petitioned to be listed under the US Endangered Species Act, the damage assessment for the grounding of the *m/v Cape Flattery*, the effects of beach nourishment on benthic communities in Waikiki, and the development of coral cultivation facilities at the Waikiki Aquarium, Kewalo Marine Laboratory, HIMB, and the Coral Restoration Nursery at Anuenue Fisheries Research Center (AFRC). He is currently focused on the use of genomic data and coral growth assays to inform conservation and management of reef building coral.

Christine Green

Christine is Honorary Counsel to the United States for the Sovereign Republic of Kiribati and the Cultural Ambassador to the Phoenix Islands Protected Area Trust. Along with these roles, Christine has founded SeaGreene, an organization whose mission is to conserve the ocean and Kiribati, one of the first nations predicted to have its islands consumed by rising sea levels caused by global climate change. Christine was born in the Central Pacific on Tarawa, Kiribati one of the Gilbert Islands in Micronesia. Her first memory was floating along the edge of an island lush with coconut trees, and a sparkling blue-green ocean teeming with fish, dolphins, sea turtles, and iridescent corals. These memories have served as her lifelong inspiration in most of her professional endeavors. Her early career in modeling and advertising photography took her throughout the world, where she gained a global view of culture, language, business, and the need to conserve the ocean that she loves so dearly. She now resides in the Pacific Palisade and runs a successful business designing jewelry with an exclusive line inspired by the Pacific Ocean.

Mary Hagedorn
Dr. Mary Hagedorn received her Ph.D. in Marine Biology from Scripps Institution of Oceanography and has been a Research Scientist at the Smithsonian Institution for the past 17 years. She has worked in aquatic ecosystems around the world from the Amazon to Africa, has taught many university-level classes, lectures frequently to lay audiences, maintains an active laboratory with graduate students and post docs, and is a successful researcher and active grant writer. In the past years, she has received several multi-million dollar research grants from the National Institutes of Health to support her research and has collaborators in over 30 institutions throughout the US, Caribbean, Europe and Latin America. In 2000, she received the prestigious George E. Burch Fellowship in Theoretic Medicine and Affiliated Theoretic Sciences and in 2005 she was nominated for the Pew Fellowship in Marine Conservation, and she sits on the scientific boards of conservation and governmental organizations. Dr. Hagedorn is a marine physiologist whose work has broad conservation implications. In her current research, she has developed parallel research interests related to the conservation of fish and coral species using cryobiology- the study of cells under cold conditions. In this approach, cells are frozen and placed into liquid nitrogen where they can remain frozen, but alive for decades in a genetic bank. Dr. Hagedorn has created the first genome repository for endangered coral species and has distributed this germplasm to three banks around the world. If necessary, these banks could one day help reseed our oceans.

Dennis Hedgecock
Dennis Hedgecock holds a Ph.D. in Genetics, from the University of California, Davis. He is currently the Paxson H. Offield Professor in the Department of Biological Sciences and Interim Divisional Dean for Natural Sciences and Mathematics in the USC Dornsife College of Letters, Arts and Sciences at the University of Southern California. Hedgecock is a founder and Chief Scientist of Pacific Hybreed, Inc., a shellfish breeding company incorporated in the State of Washington. Hedgecock has published 140 articles on the population, quantitative and evolutionary genetics and genomics of marine fish and shellfish. His most cited papers concern the hypothesis of Sweepstakes Reproductive Success in highly fecund marine animals, discovery and quantification of a high genetic load in the Pacific oyster, and sequencing and mapping of the Pacific oyster genome. Hedgecock is a Fellow of the American Association for the Advancement of Science, an Honored Life Member of the National Shellfisheries Association, a member of the American Genetics Association, the Genetics Society of America, and the Society for the Study of Evolution. Hedgecock also serves on the editorial boards of *Aquaculture* and the *Journal of Shellfish Research*.

Brittany Huntington
Dr. Brittany Huntington began her research and science diving career in 1999 at the University of California, Los Angeles during her bachelor degree. She relocated to San Francisco State to pursue a master's degree in seagrass community ecology as a EPA Science to Achieve Results (STAR) Fellow. She has pursued community ecology in varied climates from fresh water lakes in Tanzania, to costal lagoons in the

Solomon Islands, to the cold waters of the San Juan Islands, to the tropical patch reefs of the Caribbean. Brittany's current research interests in benthic ecology include marine reserve design and performance, landscape ecology, and adaptive management. To this end, she has collaborated on several projects over the past few years investigating algal removal effects on corals (McClanahan et al. 2011), evidence of cascading reserve effects on corals (Huntington et al. 2011), parrotfish grazing impacts on coral recruitment and survival, variation in reserve performance (Karnauskas et al. 2011), and coral nursery projects (Lirman et al. 2010). Brittany defended her PhD dissertation in October 2011 at the Rosenstiel School of Atmospheric Science. She now serves as a National Research Council Post-Doctoral Fellow with NOAA and the Southeast Fisheries Science Center. She works with Dr. Margaret Miller to develop best practices in coral nursery out-planting techniques using naturally recovering Acropora populations as a model.

Carly Kenkel
Carly Kenkel is a Gablian Assistant Professor in the Department of Biological Sciences at the University of Southern California. She received her Ph.D. in Ecology, Evolution and Behavior from the University of Texas at Austin and was an NSF International Postdoctoral Fellow at the Australian Institute of Marine Science before establishing her own lab at USC in 2017. She is fascinated by variation in the physical characteristics of organisms and her work seeks to understand how ecology, or organism-environment interactions, induce or select for different phenotypes and how these ecological interactions influence and are influenced by the evolutionary trajectories of populations and species.
Using a variety of tools, ranging from field experiments to ecophysiology to genomic analyses, she has established patterns of, and processes contributing to local adaptation of corals in the Florida Keys and Papua New Guinea. She also has a strong interest in "translational ecology", turning scientific findings into tools for conservation management and has worked to discover and validate diagnostic and predictive biomarkers of coral performance. In addition, she serves as a core member of the Coral Restoration Consortium's Genetics Working Group and is currently conducting an Acroporid transplant experiment in collaboration with Mote Marine Laboratory aimed at improving survival outcomes in the Florida Keys.

Tom Maloney
In his role as Director of Conservation Science at Revive & Restore Tom works to develop and expand the organization's programmatic impact in the application of genomic technologies to biodiversity conservation and restoration. Tom brings to Revive & Restore more than 20 years of experience as a conservationist, environmental advocate, natural resource planner and ecologist.

Tom started his career on the Connecticut River as the first River Steward for the Connecticut River Watershed Council. Tom left the Watershed Council to join The Nature Conservancy to establish the Plymouth Pinelands Program in Plymouth, MA where the focus was the conservation of globally rare pine barrens and coastal plain ponds. In 2005 Tom joined the California Program of The Nature Conservancy where the focus was a mix of private rangeland conservation and engagement on federal lands management. In early 2009 Tom left TNC to start the 240,000 acre Tejon Ranch Conservancy. Most recently Tom served as the Executive Director of the California Ocean Science Trust. Tom holds a BA in Economics from Boston University and a MS in Resource Management from Antioch New England. Since 1997, Tom has also served as a natural history tour guide on three continents.

Nathaniel Mollica
Nathaniel is a graduate student at Woods Hole Oceanographic Institution. Some of his research work and published articles include:

- Repeat bleaching of a central Pacific coral reef over the past six decades (1960-2016)
- Ocean acidification affects coral growth by reducing skeletal density

Nabuti Mwemwenikarawa
Mr. Nabuti Mwemwenikarawa is the Executive Director of the PIPA Conservation Trust. Joined PIPA Trust in 2016. Prior to this he was Member of Kiribati Parliament for 15 years (2000-2015) during which time he was Minister of Finance & Economic Development from 2003 to 2007 and Leader of the Opposition from 2008 to 2010. He has also previously held top management postioons in government corporations including President of the Kiribati Chamber of Commerce. He is currently a committee member of the Kiribati Sovereign Wealth Fund and the Kiribati Provident Fund.

He holds a Bachelor of Commerce 7 Administration degree from Victoria University of Wellington NZ and a MA (International Relations & Trade) from the Australian National University.

Ryan Phelan
Ryan Phelan is the Co-founder and Executive Director of Revive & Restore, with a mission to enhance biodiversity through the genetic rescue of endangered and extinct species. Ryan works with some of the world's leading molecular biologists, conservation biologists, and conservation organizations to develop pioneering genetic rescue projects using cutting-edge genomic technologies to solve previously intractable wildlife conservation challengers such as those posed by inbreeding, exotic diseases, climate change, and destructive invasive species.

Hollie Putnam
Dr. Hollie Putnam is an Assistant Professor at the University of Rhode Island in the Department of Biological Sciences. She received a Master's of Science from California State University Northridge in 2008 studying the effects of fluctuating temperature on coral physiology, with fieldwork conducted in French Polynesia, Taiwan, and the US Virgin Islands. Her PhD on coral acclimatization and transgenerational plasticity (TGP) was awarded in 2012 from the University of Hawai'i at Mānoa. Dr. Putnam currently has projects on coral and clam epigenetics,

reproductive plasticity, TGP, assisted evolution, and biomineralization in Hawaiʻi, Mo'orea, Seattle, and Bermuda. Putnam's work in relation to environmentally resistant corals, is in the areas of assisted evolution (van Oppen et al 2015 PNAS), TGP (Putnam and Gates 2015 JEB, Torda et al 2017 Nat Clim Ch) and epigenetics and environmental priming (Putnam et al 2016 Evol App, Eirin-Lopez and Putnam 2019 Ann Rev Mar Sci). She is currently on the steering committee for the World Coral Conservatoire, a project to *"build a Noah's ark for corals that will serve as a reservoir for conservation purpose, research laboratories, restoration of coral reefs and will first of all preserve these magnificent ecosystems that provide major services to humankind."*

Randi Rotjan

Dr. Rotjan is a Research Assistant Professor at Boston University in both the Biology Department and the Boston University Marine Program. She received a B.S. from Cornell University, a Ph.D. from Tufts University, and was a postdoctoral fellow at Harvard University. She was an Associate Research Scientist at the New England Aquarium, where she worked for 8 years while simultaneously holding positions at UMass Boston and the Smithsonian Institution. She is the co-Chief Scientist of the Phoenix Islands Protected Area (PIPA) Conservation Trust, where she leads the science program for the worlds' largest and deepest UNESCO World Heritage Site, fully closed to all commercial extractive activities. Rotjan is also the founder and co-Chair of the PIPA Scientific Advisory Committee. In addition, Rotjan currently sits on the board of The Nature Conservancy (Caribbean Division).

Research in the Rotjan lab focuses on global change in the oceans. The main goal is to examine how marine species, communities, and ecosystems respond to the complex multitude of stressors emerging in the contemporary world ocean, and how these systems will respond to the future ocean change that we expect in the coming decades. The Rotjan Lab takes a spatially-explicit, integrated approach to ecology that incorporates both ocean exploration and hypothesis-driven research. The Rotjan lab is interested in two complementary dimensions of Ocean Global Change: [38] biological response to changing ocean dynamics, and [38] opportunities for human-mediated action via conservation, restoration, and/or management. Rotjan teaches a course in coral reef resilience and restoration, where she works collaboratively with Fragments of Hope in Belize. In the Phoenix Islands Protected Area, Rotjan has been leading and coordinating PIPA science since 2010, and has worked collaboratively with the Kiribati government since she first got involved in 2008.

Jerry Schubel

Dr. Jerry R. Schubel has been president of the Aquarium of the Pacific since 2002. He is president Emeritus of the New England Aquarium. From 1974-1994 he was Dean of Stony Brook University's Marine Sciences Research Center, and for three years was the University's provost. He is Distinguished Service Professor emeritus. He works at the science-management-policy interfaces on ocean issues. He is widely published and has served on and chaired numerous advisory panels including:

NOAA Science Advisory Board; National Sea Grant Review Panel; National Research Council's Marine Board; NRC's Committee on the St. Lawrence Seaway; Ocean Research and Resources Advisory Panel, and the NRC Committee on the Value and Sustainability of Field Stations in 21st Century. He is a member of California's Ocean Science Trust. He created the Aquarium of the Pacific's Aquatic Forum, Marine Conservation Research Institute and the Aquatic Academy—all designed to bring to the public the best and most current science.

Greg Stone

Globally celebrated marine scientist Greg Stone knew the sea was his future from the time he was a boy in Boston. 12,000 dives later, he has explored every ocean top-to bottom, from tropical reefs to submarine mountains and frozen Antarctic seas. Thousands of hours of research investigation using SCUBA, underwater habitats, deep dives to 18,000 feet in research submarines and seafloor probes with robotic vehicles give him unparalleled knowledge of the ocean and its life.

With outstanding ability to communicate ocean science and natural history Greg has published hundreds of scientific and popular articles, four books, documentaries for Discovery and National Geographic, a TED talk, Davos lecture, and numerous radio and television appearances. His book 'Ice Island: Expedition to Antarctica's Largest Iceberg' won the National Outdoor Book Award.

Greg targets his research and thought leadership toward finding ways for humans to use the oceans in sustainable ways. He is a key proponent for ocean preserves worldwide and architect, in partnership with the government of Kiribati, Conservation International and the New England Aquarium, of the world's first large open-ocean protected area, the Phoenix Islands Protected Area (PIPA). PIPA, now a UNESCO World Heritage Site, protects the pristine corals, reef fishes, sharks, manta rays, turtles, tuna stocks and ocean-dependent human communities in an area more than 400,000 square kilometers, approximately the size of California.

Greg co-founded the Ocean Health Index, the first global open-science system for measuring how sustainably humans are using the ocean in every country and on the high seas. His most recent book, 'Soul of the Sea in the Age of Algorithm' (2017) proposes revolutionary tools and financial models for ocean management as a guide for sustaining human and ocean health into the future.

Honors to Greg include National Geographic Hero, Explorers Club National Fellow, Peter Benchley Award for Ocean Solutions, John A. Knauss Marine Policy Fellowship, Pew Fellow for Marine Conservation, Boston Sea Rover's Diver of the Year, Order of Kiribati Medal, the U.S National Science Foundation/Navy Antarctic Service Medal, and National Academy of Underwater Arts and Sciences's NOGI award, often called the 'Oscar of the Ocean World.'

Greg currently serves as Chief Ocean Scientist for Deep Green Resources, where he is responsible for finding sustainable ways to extract metal-rich nodules from the seafloor of the Clipperton Fracture Zone to provide minerals needed for the global transition to renewable energy. He is also President of Ocean Renaissance. His past positions include EVP-Chief Ocean Scientist and Head of Global Marine Program for Conservation International; Senior Science Advisor to the UN Special Envoy for Oceans; Oceans Council Chair for the World Economic Forum; Senior VP for New England Aquarium; and Underwater Research Scientist with top secret clearance for the US National Oceanic and Atmospheric Administration.

Kim Thompson
Kim Thompson is the Program Manager of Seafood for the Future at the Aquarium of the Pacific. She works closely with various stakeholders in the seafood industry to promote healthy and responsible seafood choices. Thompson has built strong relationships within the local fishing community as well as with aquaculture producers and has managed the promotion of local seafood and responsible aquaculture priorities for the program. She has both participated in and led multiple stakeholder workshops on the topic of responsible aquaculture and has co-written scripts for educational programs on the topic, including the Science on a Sphere program, *Aquaculture: Farming Seafood for People and the Planet* in partnership with NOAA Fisheries

Teburoro Tito
Mr. Teburoro Tito is currently the Permanent Representative of the Republic of Kiribati to the United Nations Headquarter in New York as well as the Kiribati Ambassador to the United States.
After graduating with a Bachelor of Science degree (majoring in Organic Chemistry and Marine Ecology) from the University of the South Pacific, Mr. Tito served as a public administrator (1980-1987) member of Parliament for 30 years (1987-2017) during which time he represented the parliamentarians of the Pacific Islands on the Executive Committee of the Commonwealth Parliamentary Association(CPA) in London. He was elected and served as the President of Kiribati (1994-2003) during which period he moved the international date line to put the whole country on the western side of the line, welcomed the new millennium sunrise on behalf of humanity at the dawn of 1st January, 2000 with a message and song on the theme " World Peace in Harmony with Nature", took Kiribati to the membership of the United Nations (Sept. 1999); and assumed Chairmanship of the Pacific Islands Forum (PIF) (2000), in which the historic Biketawa Declaration was adopted by the PIF leaders at Biketawa Atoll in Kiribati which declaration provided for a collaborative framework for all member countries to help restore law and order in any part of the Pacific upon the request and invitation of the affected country. Was awarded an Honorary Doctorate of World Peace from the Maharishi University in Holland (2001.). He addressed the General Assembly of the United Nations every year from 1999 to 2002 and was one of the signatories of the UN Millennium Development Goals.

After serving as President he was appointed into the Eminent Persons Group of the Pacific in 2003 to review the future directions of the Pacific Islands Forum (PIF) which resulted in the Pacific Vision and Mission for greater integration and collaboration of the region.

As the Kiribati ambassador to the UN he focuses his attention on the priorities of Kiribati on climate and ocean issues and on developmental strategies for small island developing. He was recently appointed as Chairman of the governing Board of the Phoenix Islands Protected Area (PIPA) Trust Fund and has succeeded to elevate the status of the PIPA by having it recognized in the UN Ocean and Law of the Sea Resolution recently adopted by the General Assembly as a very practical and productive multinational marine conservation effort in collaboration with marine conservation NGOs, entities, agencies , universities and scientists from the US and other countries.

Sandy Trautwein
Dr, Sandy Trautwein is the Vice-President of Animal Husbandry at the Aquarium of the Pacific. She oversees the health and welfare of the Aquarium's 10,000 animals. Trautwein also supervises the veterinary, water quality, dive operations and research/conservation programs associated with the husbandry department. Trautwein is an active AAUS certified diver and has participated in research/conservation trips in local waters as well as those in Guam, Palau, Pohnpei, and Alaska.

As a member of the senior management team, Trautwein participates in the development of new animal exhibits and programs. She oversees the conservation and research programs associated with sea otters, penguins, diving birds, Guam Kingfisher, giant sea bass, corals, and white abalone. Trautwein and her team participate in several AZA (Association of Zoos and Aquariums) species survival plans that help promote the conservation of threatened or endangered species.

Trautwein helped open the Aquarium of the Pacific in 1998 and has been part of the Aquarium team since February 1997. She received a B.S. in Biology from Towson State University. She received a M.Sc. degree in Marine Biology with an emphasis in coral from the University of Charleston, South Carolina, 1996. She completed her Ph.D. in Biology at the University of California in Los Angeles, 2013.