Restoration and Natural Recovery of Corals after Unprecedented Mass Bleaching and Coral Death in the Line Islands, Kiribati

Working Paper, December 2018 Update

Austin Bowden-Kerby, PhD, Corals for Conservation, Fiji
Taratau Kirata, Senior Fisheries Officer, Line Islands
Laurence Romeo, Msc, Just World Partnerships, London
abowdenkerby@gmail.com

Abstract

On Kiritimati (Christmas) and Tabuaeran (Fanning) Atolls, Line Islands, Kiribati, over 90% of corals on reefs died from bleaching caused by hot water, during a globally unprecedented fourteen-month period in 2015-16. Branching corals were particularly impacted with some species becoming locally extinct. The ongoing project focuses on the restoration and facilitated natural recovery of the branching Acropora and Pocillopora coral species. Encouraging findings of initial recovery are reported, which are proceeding through two processes, "resurrection corals"- colony regeneration from surviving micro-tissue fragments deep within the coral colony, and larval recruitment from larvae coming in on the currents from other islands, or what may be a form of stress-induced asexual larvae formation resulting from "polyp bail-out". We have also succeeded in finding a small number of adult Pocillopora and Acropora colonies which resisted the bleaching, and we are propagating bits of these within a coral nursery in the hope of growing thermally-resistant "super corals", to begin the process of facilitated restoration and long-term adaptation of the corals to a hotter climate. Through these humble efforts, the Line Islands has become a leading edge in the battle against permanent damage to one of the planet's main life support systems. Additional resources and partnerships must be found to support this work, and this strategy of securing and propagating the "super corals" must also be expanded to other bleaching affected reefs- to assist their recovery and longer term adaptation to increasing temperatures.

Introduction

Kiritimati, or Christmas Atoll (Figure 1), and Tabuaeran or Fanning Atoll (Figure 24), in the Line Islands, Kiribati, experienced mass coral bleaching in 2015 and 2016, due to extremely hot waters caused by a strong El Nino event, super-imposed onto increased ocean temperatures due to climate change. Temperatures remained over the bleaching threshold for corals (>32C) continuously for some 14 months, with considerably hotter patches within enclosed lagoons. This is the first time in recorded history that coral reefs have experienced such hot water for such long a time. In 1997-98 the islands experienced over nine months of bleaching, which was the former global record. Kiritimati is now viewed as an important window into the future of coral reefs globally, as no reef anywhere has ever bleached for so long. http://bulletin.aviso.oceanobs.com/html/produits/indic/enso/welcome_uk.php3 http://www.climatecentral.org/news/coral-reefs-crystal-ball-climate-change-19762

Figure 1. Overview of Kiritimati, showing survey sites as yellow dots, and the Cook Islet nursery in red. The atoll is over 50km long and has the largest land mass of any atoll on the planet. The population of around 7,000 mostly lives in the London/Tabwakea and Banana areas, with an additional settlement at Poland, while Paris is an uninhabited area.

The project began in June 2016 and initial surveys found that an estimated >90% of lobate and massive corals and >99.9% of all branching corals had died (Figures 2), undoubtedly affecting the quality of vital habitat for small fish and crustaceans. This level of coral death due to bleaching is perhaps a first for an entire coral reef system. The inner lagoon was hit particularly hard, with virtually all corals dying (Figure 3), while the outer reef slope and outer lagoon had up to 10-20% survival of massive corals in some areas. Since June 2016, five separate trips have been made to Kiritimati to survey for surviving corals and to work on coral restoration alongside the Line Islands Fisheries Department. One trip was made to Tabuaeran as well. This report discusses the results and findings of these trips, as well as the future plans and needs for coral recovery and restoration efforts in the Line Islands.

Figure 2. Very large completely dead Porites colony of the fore reef, kept clean by fish grazing.

Figure 3. Completely dead staghorn coral thickets of the shallow inner lagoon, June, 2016. Live-coral associated damselfish were still present, but have since all disappeared.

Coral Nursery Establishment

A coral nursery was established in the proposed Cook Islet Conservation Area in mid-June 2016, focused on the preservation and increase of branching corals that had survived. However, in the initial June trip only two *Acropora* corals could be located in spite of three days of searching. Of these, one colony was a small remnant of a much larger adult colony that had died (Figure 4), and one was a small 5cm juvenile.

Figure 4. The last standing *Acropora* coral remnant that could be found, from a shallow tide pool at Cook Islet, June 2016. Greater than 90% of the original colony had died.

Only four surviving adult Pocillopora colonies could be located at that time, one at Paris and three at the pass near the coral nursery (Figure 5). Extensive searching of the lagoon and shallow outer reef slope found expanses of dead corals, with only a few partially alive massive corals remaining, most with only patches of live tissue. Follow up trips were made In November 2016 at four months, in May 2017 at eleven months, in April 2018 at twenty-two months, and in December 2018 at two and a half years, and additional corals were added to the nursery each time, with the corals thriving and growing within the nursery (Figures 6, 7, 8 and 9).

All of the six surviving branching corals found in June 2016 were brought into the nursery. The juvenile *Acropora* coral was collected with the rock it had settled on, and both of the small surviving branches of digitate *Acropora* were brought in and re–fragmented into seven pieces. The *Pocillopora* "super corals" that had survived completely intact were big enough to trim branches for cultivation. A bright purple plating *Montastrea* that had survived in the extreme conditions of the inner lagoon were also included, the only non-massive super coral we could find surviving in that zone (Figure 10). The surviving massive corals were not sampled, as we lacked the required underwater coring machinery, but also because it would have involved thousands of collections. We therefore chose to focus on the more vulnerable genera.

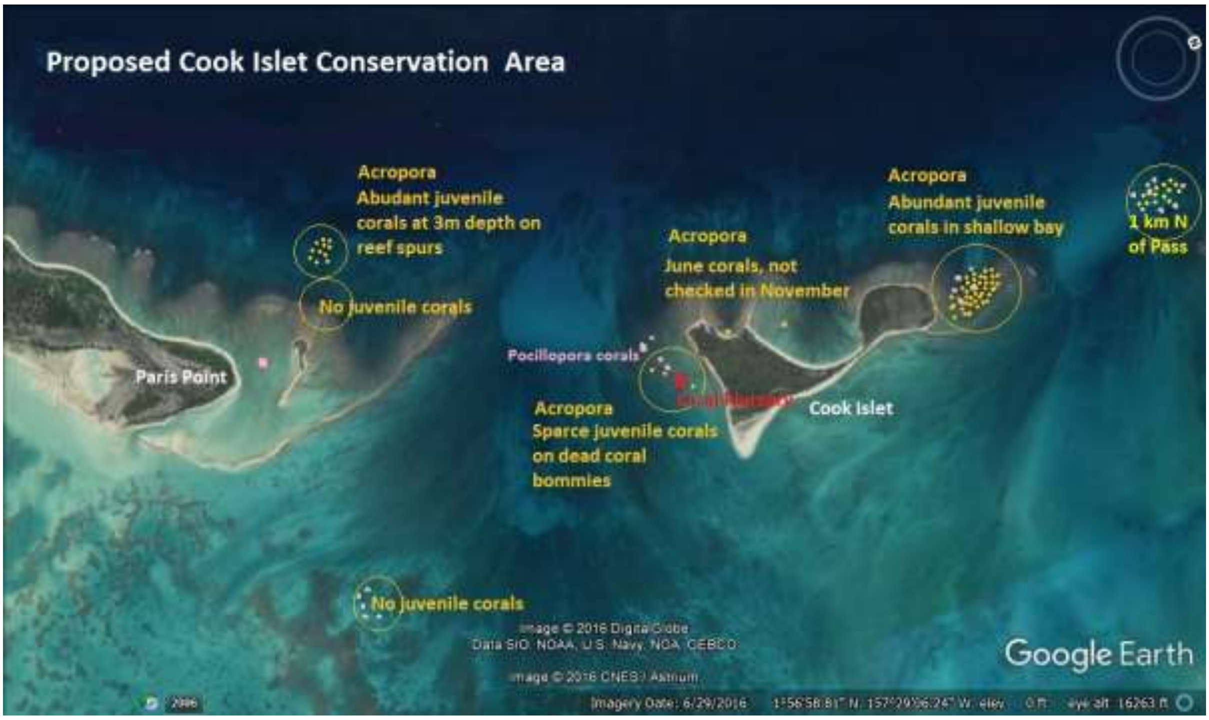

Figure 5. Map of the Cook Islet Conservation Area, Christmas Island, Kiribati, an important seabird nesting island. The location of surviving adult and juvenile corals found at eleven months is marked. *Pocillopora* 'super corals' and colonies regenerating from remnants are in pink. On the fourth trip, at 22 months, many of the outer reef areas at 3-4 meters depth (not marked here) had become colonized with juvenile *Acropora* recruits.

Additional reefs were searched in November, hoping to find additional corals. A scoping of lagoon reefs opposite the pass found no Acropora corals but many other coral species were found to be alive and healthy there, including several massive species such as *Porites*, lobate *Pavona*, and *Leptoserus* brain corals, as well as *Fungia*, *Heliofungia* and four adult colonies of *Pocillopora*. On a site visit to Crystal Beach reef, 8 km North of the pass and in clear waters with abundant fish and sea urchins, one juvenile *Acropora* coral was found, but no living *Pocillopora* corals were seen. The big waves and strong surge confined this search to the deeper portions of the reef flat. An attempt to access the reefs of the North Coast in November failed, due to high surf.

Other than cleaning some hydroids and a bit of *Caulerpa* seaweed from the nursery table, the nursery required no maintenance due to the high numbers of herbivorous surgeonfish in the site.

At 11 months, a few coral colonies were removed and re-attached to give more room for growth, as contact was causing *Pocillopora* to kill the purple *Montastrea* colonies. A bright purple genotype of *Pocillopora* was also brought in. At 22 months, the initial *Pocillopora* colonies had grown too big for the table, 25-35cm in diameter, which was sagging and in danger of collapse. The table was reinforced and the original *Pocillopora* corals were out-planted to the reef nearby using cement or placed in shallow reef crevices, discussed later.

Figure 6. Juvenile *Acropora* coral on rock in nursery in June 2016, four months later in November, at eleven months in May, and at 22 months in April 2018. Rapid growth and freedom of seaweed overgrowth of the nursery indicates clean water, good circulation, and abundant herbivorous fish to clean the nursery table.

Figure 7. The Cook Islet coral nursery, showing corals overgrowing the cable strap which secured them to a cement disc and the underlying plastic mesh (left) and the one problematic patch of hydroid which was removed. Note the *Acropora humilis* coral overgrowth onto the cement base.

Figure 8. Digitate *Acropora humilis* coral colony divided into seven fragments, one *Pocillopora* colony divided into eight fragments, and one *Montipora* colony divided into two fragments. At planting, 5mo., 11mo., and 22mo. Growth, overgrowth of cable straps and robust health is striking, even without maintenance or care. Montipora was removed at 12 mo., to prevent it from overgrowing.

Figure 9. Twelve coral fragments harvested from a 60 cm bleaching resistant *Pocillopora eydouxi* "super coral" and planted in the coral nursery. Photos are from mid-June 2016 at planting, mid-November at five months, mid-May 2017 at eleven months, and mid-April, 2018 at 22 months.

Two 40-50cm colonies of pink *Pocillopora* have thus far been found, one to the North of Cook Islet in April 2017 and another on the outer reef flat at Crystal Beach in May 2018, three and five samples respectively were taken and included in the nursery (Figure 10).


Figure 10. Pink *Pocillopora* at one year with *Montipora* of two and a half years.

Larval- Based Coral Recruitment

Searching for corals on subsequent trips became more and more encouraging, as juvenile Acropora corals began recruiting, in November 2016 we found three recruits fairly near the coral nursery, as well as another 47 juvenile Acropora corals in an enclosed reef bay to the North of Cook Islet (Figures 11 and 12). A number of adult Pocillopora corals not previously found were also discovered in this rather warm bay, an indication that bleaching resistance had developed in the past through selection pressure in this particular location. The fact that the Acropora recruits were closely associated with living adult Pocillopora colonies and surviving massive Pavona corals may indicate that these adult corals are serving as a settlement signal for the coral larvae (REF). Tridacnid clams are also particularly abundant at the site and might potentially be a settlement signal? On the May 2017 trip, we found that these juvenile corals had grown to 8-12cm in size, with many smaller corals of the 2-4cm size also found, indicating that settlement had continued in the cove, with this second cohort of corals presumably settling in December - assuming spawning of the parent stock in November? (REF). No adult corals of any Acropora species could be found on Kiritimati which could serve as parent stock, both by our own searching the shallows and by asking divers of the aquarium fish trade who dive daily on many deeper sites in the West and South of the island.

Figure 11. Searching for and finding juvenile *Acropora* corals on the reef North of Cook Islet, Kiritimati. Note the blue juvenile coral colony among the dead coral rocks.

Photos of many of the juvenile corals were taken and several are presented in Figure 12. Further searching in November 2016 resulted in finding 11 juvenile *Acropora* colonies on the Paris reef slope, located in 3 meters of water at the top of reef spurs. The new recruits were found among surviving adult *Pocillopora* colonies which had been overlooked in June, however no juvenile corals and no *Pocillopora* corals were found in shallower waters at that site.

On the outer reef slope off London, one km North of the pass but still under the influence of warm water leaving the lagoon, 14 juvenile *Acropora* corals and about six adult-sized *Pocillopora* colonies were found on the November trip, with no massive corals seen alive. This is a very dead reef, and with murky waters, but with abundant herbivorous fish and some black-spined sea urchins.

The abundant juvenile Acropora corals found in November 2016 and later in May 2017 and April 2018 provide hope for recovery of the coral population over time. Numerous adult and juvenile Pocillopora corals were also observed in this same coral cove area, as with the juvenile Acropora corals, mostly towards the Northern end of the cove (Figure 13). Massive

Porites and *Pavona* corals were the most common corals of the area, and *Tridacna maxima* clams are also common.

Figure 12. Juvenile *Acropora* corals of multiple unknown species, giving hope for the future recovery of the coral reefs on Kiritimati. Their 3-5cm size range indicates that they are about one year old, meaning that they either settled out during the mass bleaching, acquired their symbiotic algae, and somehow survived the hot water or that they were asexual larvae with symbionts hiding in the recesses of the reef, coming forth to settle immediately after the bleaching stopped.

The discovery of so many juvenile corals is a very exciting development in the recovery of the reefs, as we now have multiple genotypes within several of the Acropora species, which gives potential for successful spawning and the formation of planktonic coral larvae in the future, enabling the wider recovery of these locally endangered species through natural larval recruitment processes, and eventually leading to the recovery of this badly damaged coral reef system.

The numerous juvenile corals found on the November 2016 trip must have been present during the initial June 2016 visit, although too small at that time to be seen easily. We can only assume that their parents all died in the mass bleaching shortly after they spawned, or perhaps they came in as larvae from another area, possibly Fanning Atoll, which is over 250 kilometers up-current. Another possibility is that polyps detached from the stressed corals and set out as asexual planula larvae, through a process called polyp bailout. Such asexual larvae contain the symbiotic algae and could therefore possibly swim into shaded microhabitats of the reef, potentially settling temporarily and remaining viable until the waters cooled off, at which point they could emerge and settle on the exposed parts of the reef. https://reefbites.wordpress.com/2018/05/16/bailing-out-of-trouble-can-polyp-bailout-save-the-day/ Regardless of origin, these baby corals are exceedingly precious and important to the recovery of the reefs.

May 2017 Nursery Expansion Using Threatened *Acropora* Recruits

The May visit found all of the corals in the Cook Islet nursery healthy and growing well. The large school of surgeonfish initially seen in the site were still present and had maintained a high level of cleanliness on the nursery table witout any maintenance. No parrrotfish bitemarks or any sort of physical damage was apparent.

The juvenile corals seen in November were revisted, and while they had increased in size, they were still too small for trimming, and not growing as fast as the corals in the nursery. Many were seen with fresh parrotfish wounds and missing branch tips, which appeared to be the main reason for their slower growth. Some of the corals were also being overgrown by *Caulerpa* seaweeds, which were removed. It appears that the corals have recruited in two events, as there seemed to be two fairly distinct size classes, a 20-40mm size class and 80-120mm size class. Photographic data on colony size was taken but has yet to be analyzed, however predation by parrotfish may affect the size class data.

Due to the ongoing damage, resulting from the high abundance of parrotfish in the juvenile coral site, plus a lack of branches long enough for trimming, a decision was made to remove entire colonies- those which could most easily be chiselled off of the hard coral substrate, and to bring then into the expanded coral nursery, away from the threat of so many large parrotfish and overgrowth (Figure 13).

Figure 13. Removing juvenile corals with a hammer and chisel. Note the two surviving lobate coral colonies nearby.

A total of 63 colonies were moved in this way and planted to a new nursery table, which was filled to capacity. Ths collection represents about 10% of an estimated 600 juvenile *Acropora* recruits to the cove (Figures 14, 15, 16).

The new nursery table ws located parallel to the initial table and 2M apart, and the tables were secured to one another by 3M metal bars for added strength and to allow space for rope culture of staghorn corals, as is the common set-up in our other sites in the South Pacific and the Caribbean.

No mortality occurred over 19 months, in spite of parrotfish bites to corals at positions located towards the edges and ends of the table, with corals growing an estimateed 5-10 fold over the period in spite of that, and sometimes growing together and beginning to compete with each other for space (Figure 17).

Figure 14. New coral table planted with juenile corals collected from the field- with the older nursery table in the foreground, planted with three pink Pocillopora corals, taken from the first surviving colony of this color morph found thus far, at the ''coral cove'' location where the abndant juvenile *Acropora* population is found.

Figure 15. Close up of the coral nursery, new corals in the foreground and showing a line containing small broken bits from the juvenile corals, which otherwise would likely die.

Figure 16. Close up view of the newly planted juvenile corals, some planted to cement cookies for easy removal when mature, and some planted onto the plastic mesh secured over 2x2 inch iron mesh. While uncertain due to small size, many individuals appear to be *Acropora nasuta*, *A. tenuis, Acropora selago,* or *A. humulis*.

Figure 17. The coral tables 11 months later in in April 2018, and again in December 2018, with crowding clearly apparent, ready for trimming in the planned January 2019 visit.

The Discovery of Regenerating Coral Colonies via Surviving Tissue Fragments

In spite of the difficulty of accessing the reef front zone, site visits were made in May 2017 to the shallow <0.5M reef flat zone at Poland on the southwest of the Atoll, at Crystal Beach on the northwest, and to the reef flat at the Airport on the northeast of Kiritimati (Figure 18). After extensive searching, we found multiple small *Acropora* colonies regenerating in the northern two of the three sites, at Crystal Beach and at the Airport reef, all in direct association with dead Acropora colonies. In the 2018 visits additional regenerating populations were found west of the Airport. Rather than being larval recruits, these "resurrection corals" appear to have regenerated from micro-tissue remnants on much bigger micro-atoll coral colonies in the extreme shallows, all very near the shore. From one to twenty small colonies were found per remnant poplation, with all multiple colonies within a population having identical and distinct coloration- yellow with green polyps, blue tipped, purple, cream, or brown, and representing what appears to be more than one tightly-branched coral species (Figures 19, 20). These remnant colonies were always found on dead acropora branches of similar growth form, most often on the dead colony edges (Figure 19). Single colonies with these characteristics are also assumed to be remnants, although that is uncertain (Figure 21). From the apperance of the remnant colonies, it appears that small areas of coral tissue must have survived in the shaded depths of the original larger colonies, or perhaps on the colony edges under shaded overhangs.

Figure 18. Airport reef flat, with the location of remnant Acropora corals marked. An estimated 700 meters of the nearshore was surveyed and 6-7 genotypes found of what appears to be *Acropora nasuta* and perhaps one or two other species.

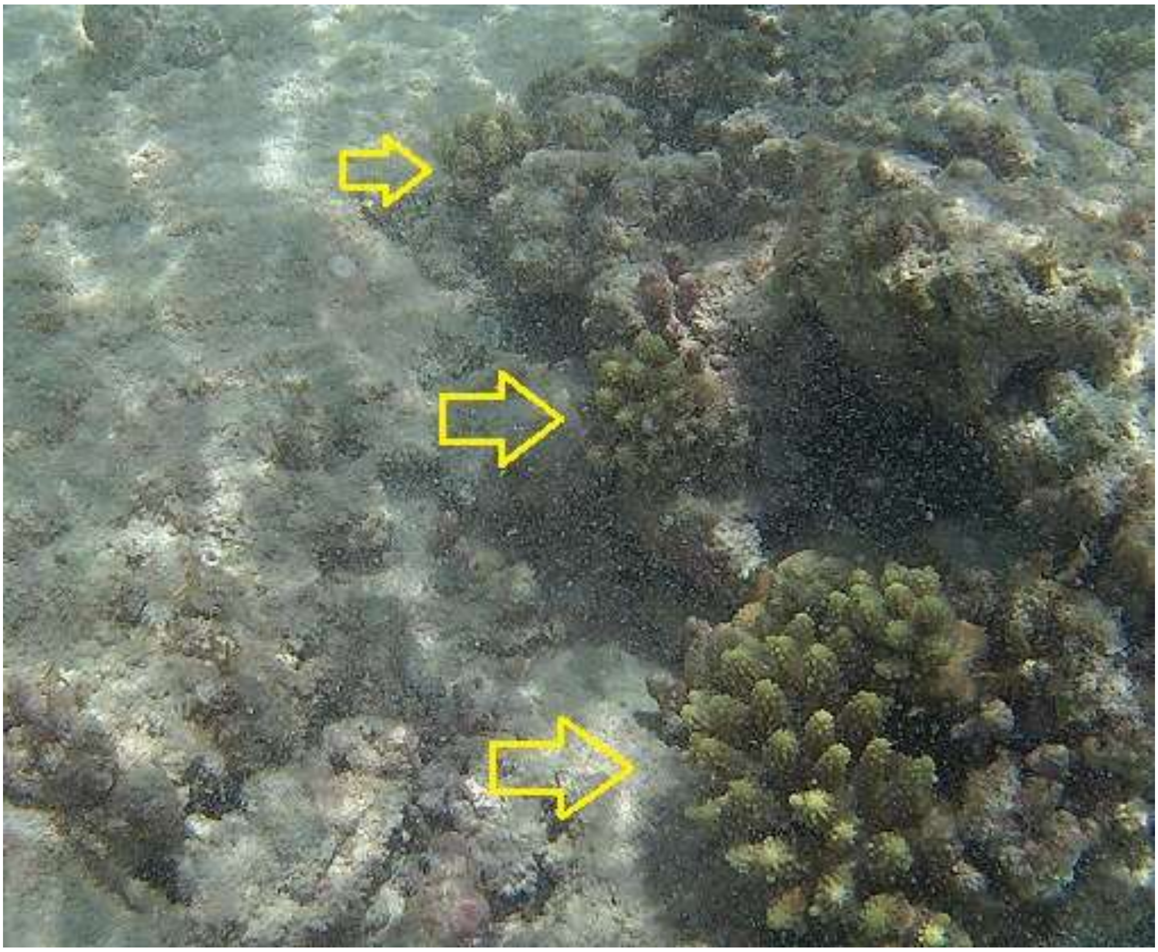
Figure 19. Remnant colonies of *Acropora*, possibly *A. nasuta*, with over 15 small colonies of identical form and coloration found in this immediate location.

A total of what is though to reprsent six different genotypes of coral were found at Crystal Beach, with eleven found at the airport reef flat, indicating that there could be thousands of genotypes of reef flat adapted Acropora corals surviving on Kiritimati, a very promising finding indicating a slow recovery of formerly abundant species in progress.

Ressurrection coral colonies were collected from Crystal Beach in May 2018 and from the Airport in December 2018 (Figures 22, 23) and brought into the coral nursery.

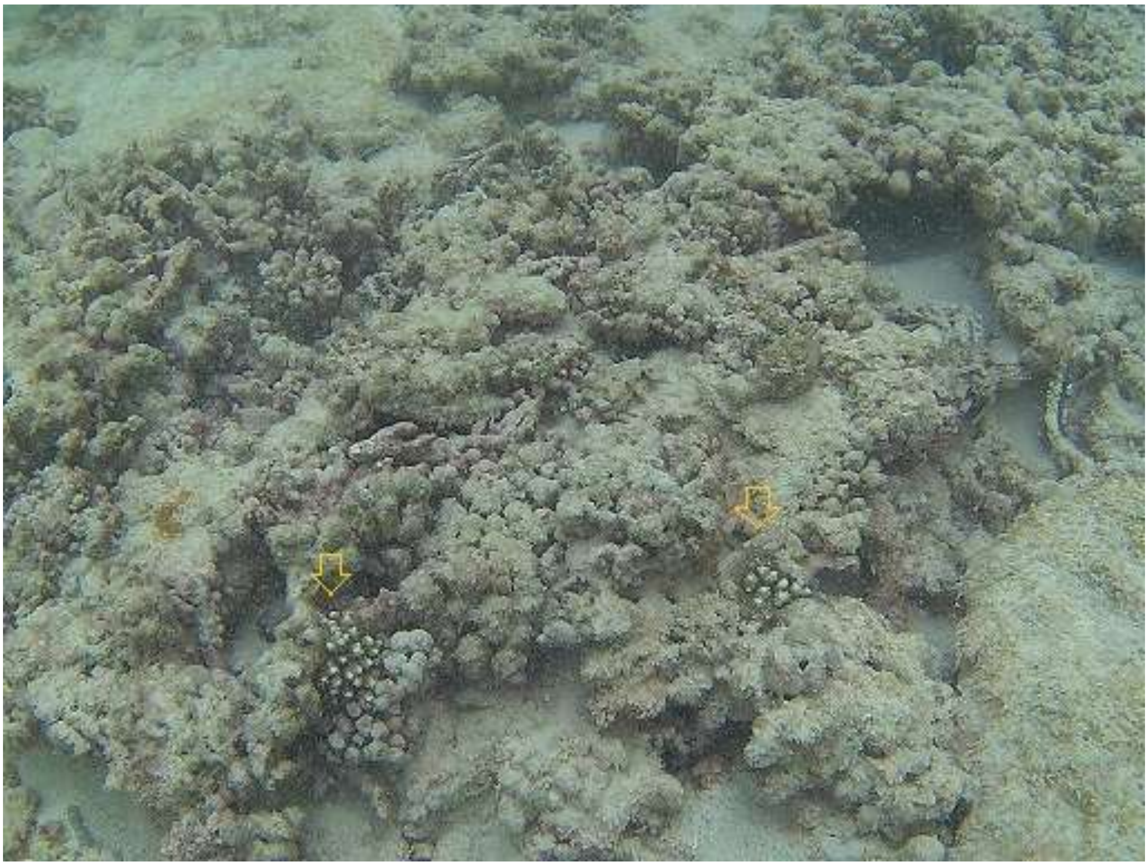

Figure 20. Remnant colonies on the edges of a once much larger reef flat colony of *Acropora*. Over one year since the die off, coraline algae are infilling between the dead branches and overgrowth of algal turf is making the original skeleton more and more difficult to discern.

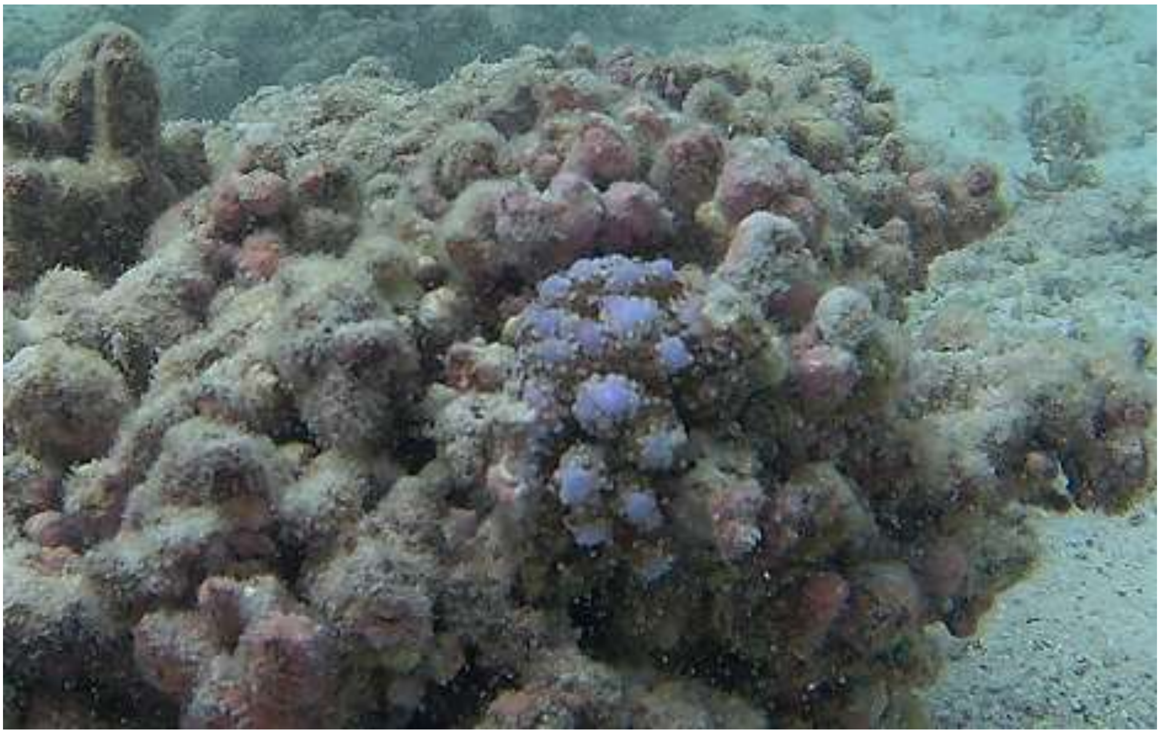

Figure 21. Solitary coral assumed to be a remnant "ressurection" coral growing from within the deep branches, rather than a sexual recruit. Note the old, dead Acropora seleton.

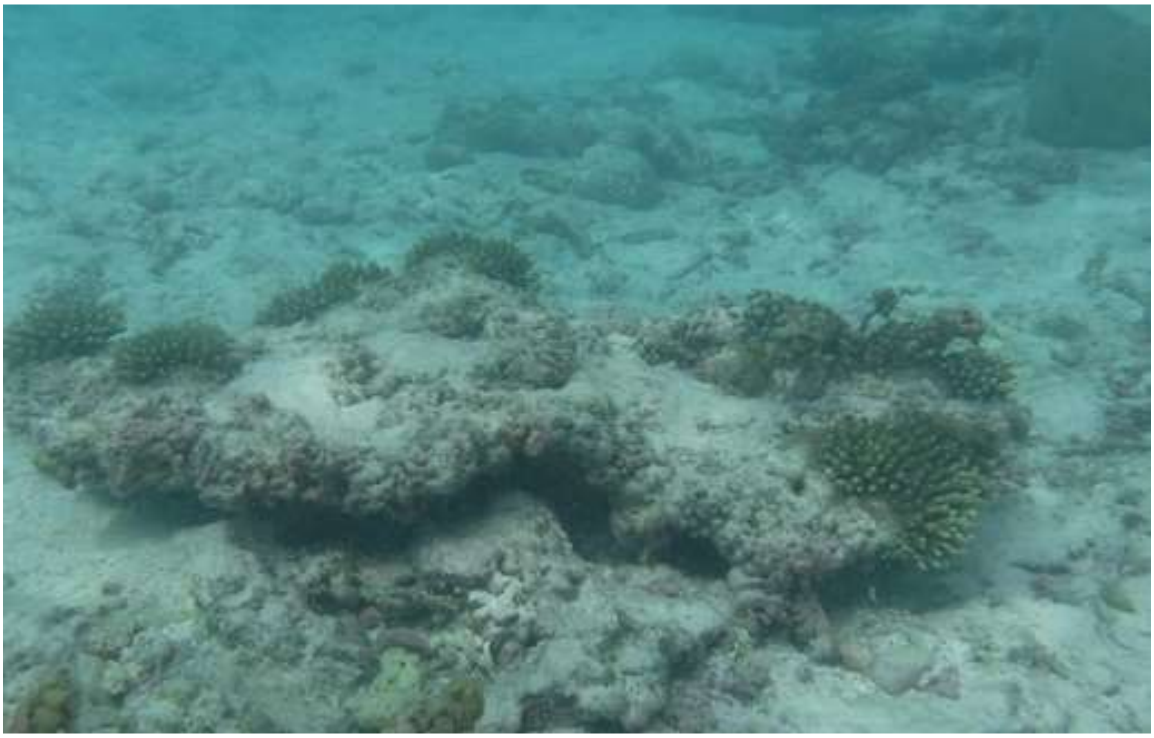

Figure 22. December 2018, two years post-bleaching, with the ‘ressurection’ corals growing and spreading and gradually rejuvenating the original coral colony on the reef flat.

Figure 23. Close up of the *Acropora* ‘resurrection’ corals at two years post bleaching. Note the *Pocillopora* larval recruit towards the top of the photo. Surviving *Pocillopora* corals have the ability of re-seeding the reef with asexually generated, internally brooded, coral larvae. Such recruits would have the same internal algae and thus the same thermal tolerance as their mother.

Recovery via resurrection corals is patchy and is not everywhere. A similar extensive search at the Poland reef flat on the south of the atoll found no such remnants, in spite of an abundance of dead Acropora skeletons.

Tabuaeran Findings

A trip to Tabuaeran, also known as Fanning Atoll (Figure 24), some 200km distant from Kiritimati, was carried out in May 2017 to assess the impact of the mass bleaching there, and to seek out staghorn corals which had apparently become extinct on Kiritimati. Due to logistics and time, only one scoping trip into the lagoon was possible, accompanied by the local Fisheries officer. We surveyed a transect of lagoon reefs from north to south. The devastation of many of these reefs was virtually complete - almost no corals found alive, and with some of the very biggest Pocillopora coral heads I had ever seen completely dead. However, on four reefs, among the devastation of dead and standing colonies, we found four surviving populations of staghorn coral, *Acropora muricata*, as well as *A. vaughani* and possibly 1-2 other *Acropora* species to be confirmed at a later date.

Figure 24. Tabuaeran or Fanning Atoll, showing the approximate area surveyed.

The fact that no coral-killing COTS were seen and only few Drupela snails were present may have been significant in the survival of these corals after the demise of a conservatively estimated 90% of the coral population in the lagoon.

Due to the rough seas, and despite two attempts, we were unable to get out to the oceanic outer reefs, however several fishermen confirmed that while most of the corals are now dead, some living corals of the sorts that are often blue or purple- the Acropora corals, continue to survive. While this must be confirmed at a future date, the hypothesis that the small juvenile corals coming into Kiritimati are from Tabuaeran has been strengthened.

Samples of 10cm coral branches were taken from each of the staghorn coral populations that we found, and put on board in a shaded bucket filled with seawater, changing the water several times during the day. The purpose was to collect as diverse a set of corals as possible for inclusion in the coral nursery on Kiritimati, the voluen of which amounted to about half of a four gallon bucket full, and representing both fine and robust branched species and a diversity of color morphs within each species. It is impractical at this point to create a coral nursey or gene bank on Fanning Atoll, as it is quite difficult and expensive to get to for follow up.

The sampled corals were immediately taken to shore and planted onto ropes which were then temporarily strung between existing metal stakes in the subtidal zone near the main settlement. These planted ropes were removed two days later, three hours before the flight back to Christmas Island, carried on board in a bucket, periodically sprinkled with seawater during the 45 minute flight. We were met by Kiritimati Fisheries officers on landing, and the corals were rushed by land to a waiting boat, and taken into the coral nursery and planted by simply tying the ropes onto the expanded nursery structure (Figure 25).

Our underlying assumption with moving these corals is that the corals of Fanning are quite close to Christmas Island geographically, existing with mere days upccurrent, so that they share the same ecoregion with Christmas Island. Moving corals between ecoregions is not promoted in our work.

The corals suffered no mortality despite the stress of collection and transport, and all corals were thriving when visited a year later (Figure 26). However, growth at one year was dissappointing, as the corals had only doubled or tripled in size, less than the expected ten to fifteen fold increase which is typical of staghiorn corals usingh similar methods globaly. The reason for this slow growth soon becauie apparent, as numerous parrotfish bites covered the corals, with the staghorn corals particularly targeted (Figure 27). The *Acropora* corals on the tables were also impacted (Figure 28).

Two of the staghorn ropes were moved to a new nursery site at Motutapu reef where parrotfish are scarce, and the positive results are seen six months later in Figure 29, however the problem of parotfish predation seems to have lessened by December 2018.

Figure 25. Overview of the expanded and completed coral nursery at the Cook Islet site, Christmas Island, 1st June 2017, with table culture for tight-branched Acropora and *Pocillopora* coral species and with rope culture for the open-branched staghorn Acropora species.

Figure 26. Rope nursery planted with several species of bleaching-resistant staghorn corals brought from Fanning Atoll to the Christmas Atoll nursery, at planting May 2017, and one year later, May 2018.

Figure 27. Parrotfish bite marks clearly visible in May 2018, resulting in slower growth, but no mortality occurring.

Figure 28. Corals on the nursery table at one year, some damaged by parrotfish bites.

Figure 29. Cook Islet nursery at 17 mionths, December 2018. Comparisons of staghorn coral lines grown at Cook Islet (top and bottom left) and Motutapu (bottom right) for six months, with obvious branch shortening due to parrotfish bites, versus the site with few parrotfish.

Discovery of Surviving Staghorn Corals on a Kiritimati Reef Flat

In December, 2018 while scoping for regenerating corals on the reef flat, a remnant population of thick branched, blunt tipped, staghorn corals, *Acropora robusta?*, was discovered to the West of the Airport at "Crusher Reef". This area has the widest reef flat on the island (Figure 30). Among the dead and standing coral colonies scattered on the reef flat (Figure 31), were a few surviving branches (Figure 32a), plus one coral thicket was alive on all sides- which looks to be a true "super coral" not suffering from any significant mortality during the bleaching (Figure 32b). Surviving *Acropora humilis* remnants were also found (Figure 33).

Figure 30. The reef flat at Crusher Reef, with remnant staghorn corals marked.

Figure 31. Dead and standing *Acropora* and *Pocilliopora* corals two nearly three years after their death in 2015-16. A living massive *Porites* colony is in the foreground.

Figure 32. Three color morphs of regenerating/ remnant *Acropora robusta?* staghorn corals, each thought to be a different coral genotype (top). And the sole intact adult staghorn coral colony survivor of the 14-month bleaching event (bottom), found in December 2018 among dead and standing coral colonies of the same species on the shallow reef flat at Crusher Reef, Kiritimati.

Figure 33. Dead *Acropora humulis* coral colony and a regenerating *A. humulis* "resurrection coral" at Crusher Reef flat.

Out-planting of Corals from the Nursery

In May of 2018 the original nursery table was being weighed down by heavy adult-sized corals, which had grown from small fragments over the two years. All of the original 24 colonies of four genotypes had survived and grown 20-30cm in diameter at 22 months (Figure 34). These *Pocillopora* corals were harvested and planted nearby, some cemented securely to dead corals, but as that proved difficult due to the motion of the currents, the majority of the colonies were then planted without any attachment onto the reef about 30 meters away. Each of these colonies were set within the grooves of a large dead lobate coral head into a 3-4 meter circular area (Figure 35). In December, six months later, all colonies were healthy, with no mortality or partial mortality, and most of the colonies had self-attached firmly to the substrate. Two colonies had turned sideways, but most were still in the cookie-down position. This genetically diverse cluster should be ready and able to spawn, and is located where they can continue to serve as mother colonies for trimmed fragments in the coming months and years.

Figure 34. ***Pocillopora*** **coral colonies at 22 months ready for removal for outplanting.**

Figure 35. Harvested *Pocillopora* corals at 22 months (top) and the result of out-planting six months later- self-attached and healthy.   24 colonies of four genotypes ~30cm in diameter, have now become a diverse cluster able to spawn, and located where they can continue to serve as mother colonies to produce trimmed fragments for more work.

An experimental out-planting of small 2-3cm branches of *Acropora selago* corals, trimmed from colonies growing on the nursery table, was also trialed in May 2018. Multiple branch tips of the same genotype were set together into balls of wet cement placed onto dead corals near the nursery, however parrotfish bit the branches completely off within 48 hours. It was thought that the corals were dead, however in December, some five months later, we found that tiny micro fragments of flesh had survived and grew together to form viable patches of live coral tissue, 5-10cm wide (Figure 36).

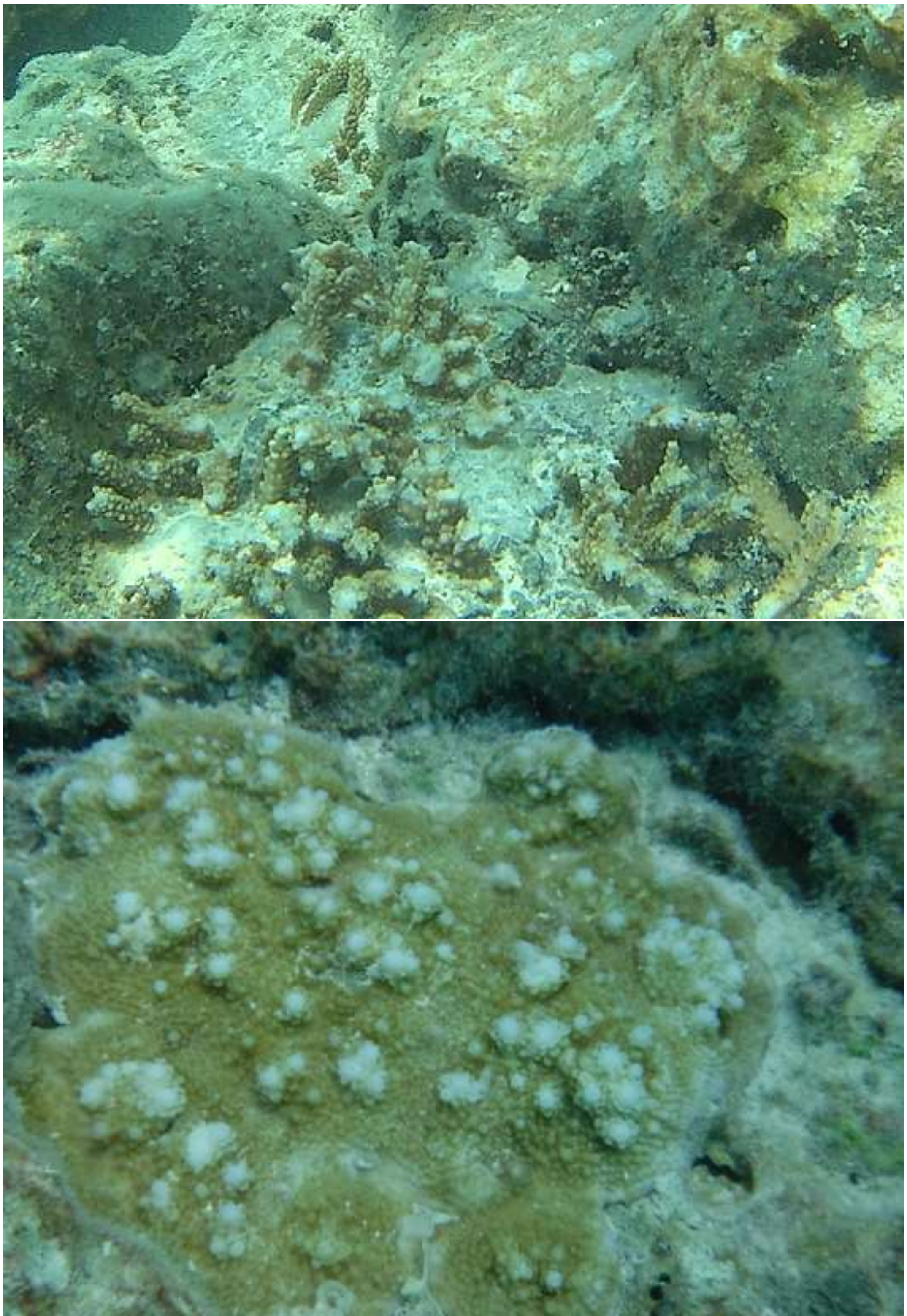

Figure 36. Corals planted and then bitten off by parrotfish at 24 hours, and BY 48 hours all the way to the bases, May 2018 (top). Surviving micro-fragments merge at six months (bottom).

Branches are now seen forming in the tissue discs, and an upright elongation is expected in the coming months. The tightly branched growth form of this species appears to protect coral branches from being bitten off, but this protection is lost when branches are taken out and planted alone or far apart, as we had done in May.

Discussion

Is Adaptation of the Line Islands Corals to Climate Change Possible?

While the discovery of an ongoing and accelerating natural coral recovery processes is encouraging, a big question is whether the juvenile corals that are recruiting or regenerating from surviving tissues, once they become adult colonies, will be better able to withstand future bleaching events than the corals which died out. The hope is that they are indeed more bleaching resistant, having more resistant algae, or having acquired them. The fact that newly settled juvenile *Acropora* corals initially have no symbiotic algae inside them, and they must take up the algae they need for photosynthesis from the water, gives them a greater capacity to adapt. Assuming that the only corals left on the reef after fourteen months of bleaching are bleaching resistant individuals, it is hoped that the newly settled corals have acquired bleaching resistant symbiotic algae (zooxanthellae) after settlement.

The first cohort of settled corals, which must have settled during the bleaching event, must have experienced warmer waters, potentially filled with algae expelled during the bleaching. If the algae available were dominated by those dumped by the corals of the extremely hot inner lagoon, which would travel on tidal currents and exit the lagoon on either side of Cook Islet, they would potentially be available for acquisition by the juvenile coral recruits. The two pass areas do appear to have the highest densities of juvenile corals, which might help confirm this hypothesis. Genetic tests of the surviving corals, to determine the specific algal clade and thermal tolerance regime, should be done at some future date. Regardless, future bleaching events are inevitable, which will test the corals to determine if they are bleaching resistant or not.

The intention is that the coral nursery will serve as a gene bank of branching corals and their algae, especially the few individuals of *Acropora* and *Pocillopora* which have surviving the mass bleaching, becoming a “Noah’s ark” of bleaching resistant corals for the restoration of the reefs of Kiritimati.

Our restoration strategy does not envision replanting large areas with corals, but rather to replant smaller patches of corals of multiple genotypes capable of spawning, in order to re-boot sexual reproduction and the formation of coral larvae, so that nature can reseed the reefs naturally over time.

The prediction is that bleaching temperatures will become more and more frequent in the coming years, and so it is questionable whether the reefs will be able to adapt to such increasing levels of stress. As sea level rises, healthy and growing corals are out best defense, and so global warming must be controlled by greenhouse gas reductions for two reasons- coral reef health and to lessen sea level rise. The future of Kiribati as a nation is gravely threatened, and international action is needed. Kiribati has been placed squarely in in the forefront of the problem, and so Kiribati must become the leader in presenting the solutions. 'The first shall be last and the last shall be first."

Protecting the Restoration Sites

Because this restoration work is so important to the future of the reefs of Kiribati, it is very important to set aside the main restoration reefs into a no-fishing marine protected areas (MPAs), to strictly limit the number of people visiting the sites and placing fishing lines, nets, or stepping on the reefs, as this will break the regenerating corals. We also need a high density of grazing fish to clean the nurseries and the dead corals, so that living corals thrive and so that once coral larvae are generated through spawning of restored coral populations, they can find a clean place to settle out on and grow. This ban on fishing should apply to all subsistence and commercial fishing activities in the restoration zone.

Controlled tourism activities and visits to the nursery and restoration sites should only be permitted on a case by case basis and assuming that the visitors will be well-controlled, not stand or kick the reef, not wear toxic types of sunscreen, and anchors should not be used on the reef, rather mooring buoys installed. Tourism activities might be used to generate income, through fees or solicited donations to fund the work.

Support for alternative livelihoods among the fishing families who have traditionally used this area should be given if possible in the form of seaweed farming, other types of fishing, and perhaps poultry as an alternative to fish as a protein source.

Proposed 500M no-go no-fishing area around Cook Islet

I addition to providing extra protection to the nesting birds of Cook Islet, a 500 meter no-fishing area is needed in order to protect the corals on the reef (Figure 37), which were badly damaged in the fourteen-month 2015-16 coral bleaching, with an estimated 95% of the corals dying. Abundant fish are needed to clean the dead coral skeletons of the reef, and to help facilitate the recruitment of coral larvae, a recovery process which fortunately is already occurring, with at least three *Acropora* corals now coming in on the currents as larvae, possibly from Tabuaeran, which was less badly impacted from the bleaching and mass mortality. The coral reefs around Cook Islet appear to have the highest remaining coral cover of any of the reefs of Kiritimati, with 10% cover in some areas, and as such, these reefs need protection from excessive boat anchors and related damage.

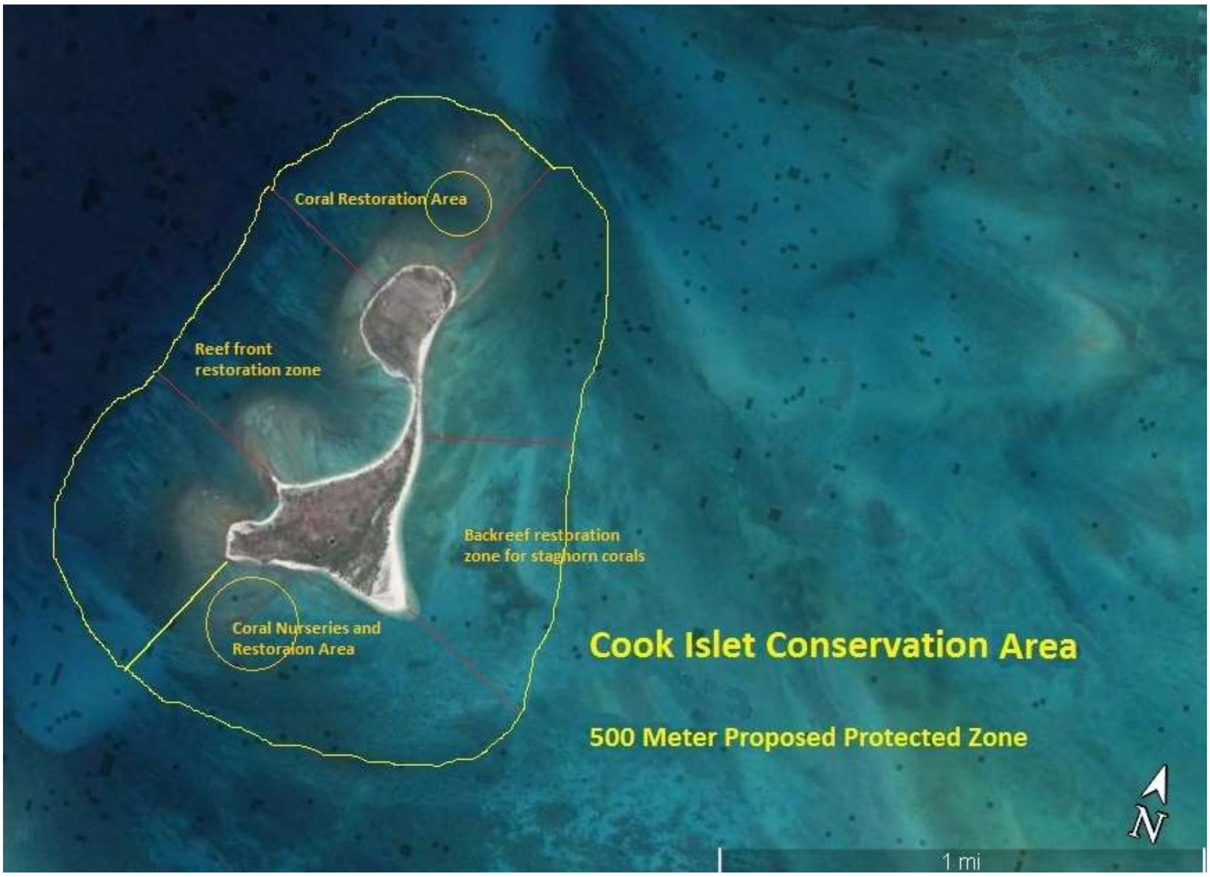

Figure 37. Proposed no take zone around the Cook Islet Conservation Area.

A process of out-planting the now rare branching corals has begun from the nursery, and these restoration patches require protection. The restoration strategy is to re-establish diverse breeding populations of rare branching corals within the protected area, which will facilitate a wider restoration of corals to the reefs of Kiritimati through the production of abundant coral larvae, which will spread to nearby reefs through the currents. Establishing a no-take area is very important in securing breeding populations of not only corals, but also of tridacnid clams, reef fish, and other species in danger of over-exploitation, and would be a big step forward for conservation and restoration of Kiritimati's wildlife.

Justification for a 500 M no-go (no-fishing) exclusion zone around Motutabu Island.

A 500 meter exclusion zone is proposed for Motutapu Island (Figure 38). In addition to providing extra protection to the bird nesting colony there, the reef around Motutabu represents the heart of the former staghorn Acropora coral zone, a zone of diverse marine life which until recently dominated the lagoon on Kiritimati, and which, since the 2015-16 mass coral bleaching, is now dominated by dead coral skeletons. The branching staghorn corals formerly provided a key nursery habitat for juvenile snappers, groupers, and other commercially important reef fish, which is of concern to the Fisheries division, as these corals are now thought to be completely extinct from Kiritimati, with negative implications for future coral reef diversity and reef fish abundance. If confirmed, this coral die-off represents the first localized coral species extinction due to coral bleaching anywhere on the planet.

Fortunately, some massive coral species (Porites and Pavona), have survived and remain on the reefs around the island. Fisheries has succeeded in finding a few surviving populations of staghorn corals in the lagoon of Tabuaeran Atoll, and have brought back living samples to Kiritimati for re-introduction, establishing them in the coral nurseries at Cook Islet and Motutabu. These staghorn coral genotypes represent hot-water adapted survivors, and are thus presumed to be bleaching resistant, and will in the coming years be tested for their ability to live and thrive around the Motutabu site. The reefs around Motutabu are thus proposed as the primary coral restoration site for the staghorn corals, to re-establish a vital fisheries nursery ground, while trialing an important climate change adaptation measure for coral reefs. These Motutabu reefs are also proposed as a testing ground for thermal tolerance among the other coral species being propagating at the Cook Islet coral nursery, with the plan being to bring in samples of each of the corals for testing in the warmer waters of the Motutabu nursery site. The reefs around Motutapu are therefore quite important to the coral reef restoration and climate change adaptation trials for the Line Islands, and the work to restore a locally endangered coral species and a badly damaged and highly endangered lagoon ecosystem.

Figure 38. Proposed no-take area around Motutapu Island, Kiritimati

Ciguatera Fish Poisoning Outbreak Begins, October 2018, Caused by the Death of the Coral Reefs

During the December 2018 trip to Kiritimati, we were informed that fish poisoning had recently become a problem, starting in Late September and October. Even parrotfish have been affected, indicating a high density of the toxic dinoflagellates in the environment. The reported problem area is at Bay of Wrecks on the eastern side of the atoll and off of Rondon.

I had first-hand experience with this problem after eating reef fish at a local restaurant on 8th December, suffering from repeated vomiting and itching, especially the hands and feet, and back and joint pains, requiring a visit to the hospital. Senior Nursing Officer Mrs. Ueata Maneaua was very helpful in going through the hospital records and reporting back to me that over ten severe cases had been admitted or treated at the hospital over the past two months, while in past years there might only be one case every year or so. Like my own out-patient case, which was not recorded, those hospitalized must represent a fraction of this developing problem. I helped the SNO develop a data sheet to also record the type of fish eaten and location the fish was caught, so that the community can be informed and cautioned.

Gambierdiscus toxicus, the toxic dinoflagellate micro-algae responsible for ciguatera lives on dead corals and the surface of fleshy algae, and so is typically not a problem for live coral dominated coral reef systems (REF). However, the reefs of Kiritimati have been transformed into dead coral reefs- ideal habitat for the toxic algae species (Figure 39). Ciguatera is thus an entirely new health risk for the community, and is directly related to the mass bleaching and death of the corals. With this new development, we can see that climate change is actively impacting both the food security and health of the Line Islands.

With this new crisis, resources must be found to closely monitor the situation, to facilitate health statistics, to sample the physical environment for *G. toxicus* abundance, to map the fishing areas most affected, and if possible, to test the fish being caught. Community awareness must also become a priority once the facts are known, and measures to facilitate the recovery and restoration of the corals should be given proper attention and funding as the only recourse to diminishing the problem. Restoration of high coral cover back to the reefs is the only long-term solution.

Figure 39. Dead corals make an ideal habitat for the toxic dinoflagellate microalgae *Gambierdiscus toxicus*, which lives on the surfaces of the dead coral rocks. They create a golden-brown film over the rocks, much like that pictured above.

Strategy for the Future

The various staghorn and plating *Acropora* corals within the nursery will be grown into ''mother colonies'' which will then be trimmed once or twice per year to produce hundreds of second generation coral fragments for replanting into restoraion patches on limited areas on the main reef, both inside the lagoon and outside, creating diverse aggregations of each species (Figure 40). The stategy is to restore reproduction among the corals and thus facilitate natural coral reef recovery.

We do not plan to replant extensive areas with corals, but to rather create numerous genetically diverse patches for each species within limited 3 x 3 meter areas. The methods planned can be seen in Figures 41, 42, and 43. For tightly branched species of *Acropora*, only the cementation method will be used, due to their short branches and slower growth.

Figure 40. Proposed restoration plan for 2019-21 Cook Islet Nursery, Kiritimati Atoll.

Figure 41. An example of the method proposed for the Kiritimati restoration sites. The nursery corals grow into 'mother corals" and are trimmed to produce multiple second-generation branches for each specific coral genotype, and these are then cemented together onto the reef. The monogenetic branches grow and merge into a single adult colony, growing upwards and with the base spreading outward to quickly create a strong attachment to the reef. The example on the right above, from Belize, is at one year after planting.

Figure 42. Pegged rope method of coral outplanting. The corals are trimmed from mother stock to create single species outplanting ropes of diverse coral genotypes, which are then pegged onto dead reef areas with concrete nails. A single rope will grow into a genetically diverse population capable of breeding. Photos from Belize.

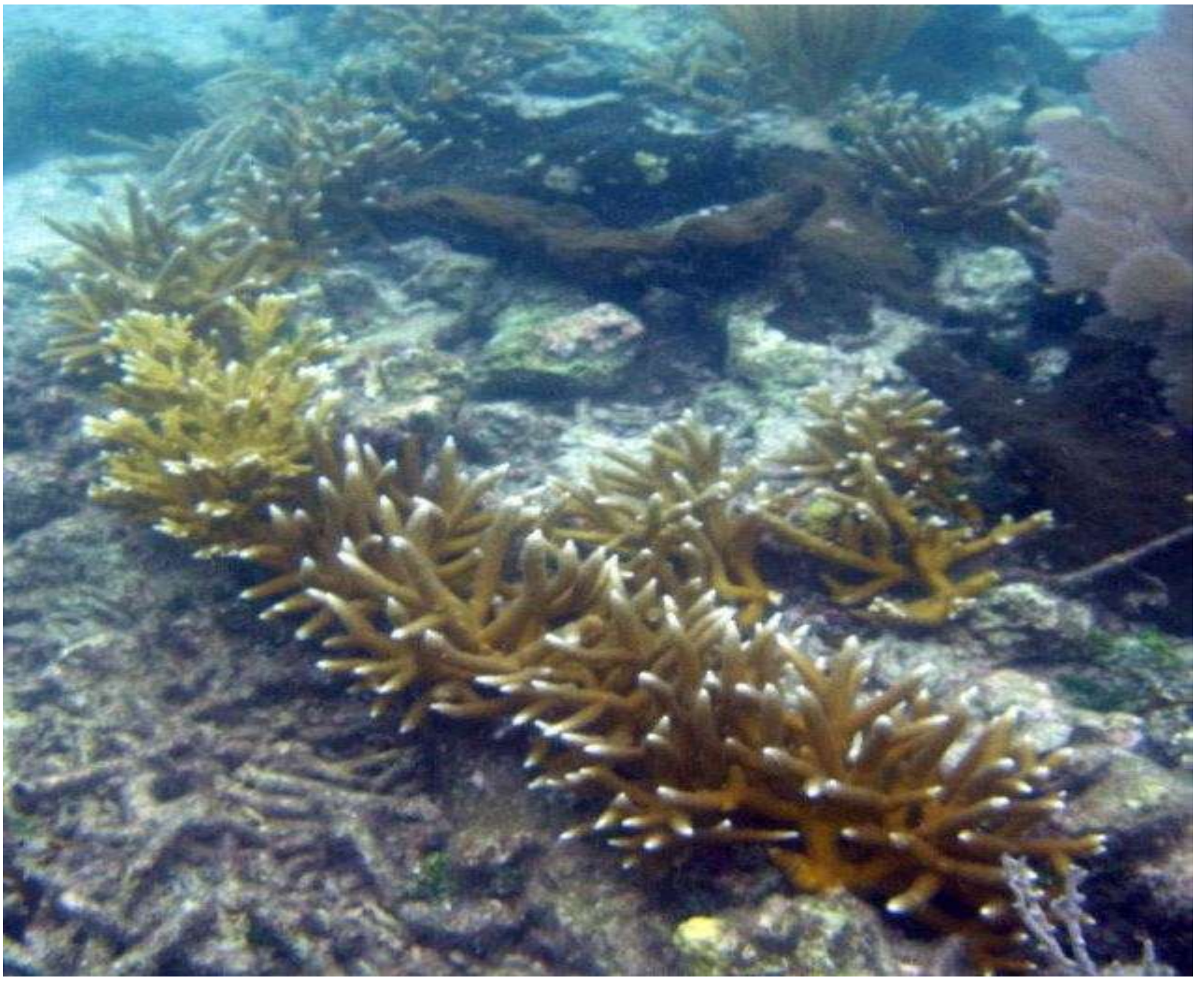

Figure 43. Pegged rope outplants at one year. The corals are strongly self-attached to the reef and have merged into a linear super-colony of diverse genotypes capable of spawning. At least three outplanting ropes are used per restoration site to increase the chances of successful breeding.

“REEFS OF HOPE” CORAL REEF RESTORATION STRATEGY FOR KIRIBATI

Christmas Island, Kiritimati, is a very large Atoll, and millions of corals have perished in the recent mass bleaching event, therefore it will be impossible to replant corals everywhere on the island’s damaged coral reefs. This is not our strategy, rather the “Reefs of Hope” strategy is to help facilitate natural coral recovery process.

Fanning Atoll, Tabuaeran, may be in an up-current position and from where the recently recruited juvenile corals may be coming from, however larval recruitment may be limited unless and until we re-establish local breeding populations of corals on the reefs of Christmas Atoll.

The reefs have essentially suffered an ecological extinction event of vital branching coral species, and major changes will likely occur in the coming years to the fish and other fauna. While a very few, scattered and isolated adult colonies of *Pocillopora* have been found, only one adult-sized colony of the genus *Acropora* has been found. Therefore, the ecological function of branching corals as a group is now essentially gone. Coral recovery of the *Pocillopora* species group will likely occur eventually, however it will be delayed and could take many decades, as surviving colonies are for the most part hundreds of meters apart from each other so that fertilization will not be likely, however asexual production of larvae may help overcome this problem to a certain extent for this species group.

The situation with *Acropora* will take even more time, as all the existing corals are juveniles, and will not spawn effectively for a few years. However, this recent find of numerous juvenile *Acropora* corals both recruiting from larvae and recovering from mostly dead colonies is very promising and offers hope for the future of these reefs. If left on their own, these corals have the potential to grow to form a viable spawning population of *Acropora* corals of several species, but natural recovery processes might take several decades, and many more bleaching events will undoubtedly set back recovery, potentially preventing it altogether.

Our strategy will be to cultivate as much of the genetic diversity as possible within the nurseries, and then to use trimmed second generation branches to create discrete and genetically diverse patches of spawning corals at intervals along the wider reef, to reseed the reefs naturally with larvae. Certainly, more colonies and additional species will be found in time, and pairing those surviving corals with con-generics will help ensure effective spawning. Collecting and propagating additional coral samples within the nurseries will vastly increase the genetic and biological contribution that each of the surviving coral genotypes makes to the future recovery of the island’s reefs. Our long-term goal is to have the coral nursery expanded to include hundreds of distinct genotypes, of each surviving *Acropora* and *Pocillopora* species. Each genotype should be genetically tested for its algae symbionts, to determine if the coral is sensitive to high temperatures, or if it is bleaching resistant.

The coral restoration patches, the “reefs of hope” sites, will serve as spawning aggregations for the natural production of coral larvae, and should be located in areas where the currents are more likely of transporting the larvae to other reefs, and not areas where they are more likely of being swept out into the deep ocean and lost. Some data on current flow would be helpful in developing this strategy and determining the best up-current locations.

Additional coral genotypes and species should be sought out, and additional nursery tables constructed as required. More *Pocillopora* corals should be included, with separate gene bank nurseries created, but only if additional financial and human resources can be found.

A high priority should be placed on creating a second duplicate nursery site, located in an area more sheltered from storm surges, which do occasionally reach these waters and could potentially severely impact the present nursery site. This secondary nursery ideally should be located in the sheltered lagoon, but in an area of good water circulation. Mother colonies of each of the *Acropora* corals should be trimmed and duplicated between the two sites, as insurance against long-term loss. Over the years, as more corals are added to the gene bank nurseries, the work will grow in importance and impact. The mother colonies should be trimmed over and over again, once or twice per year in order to maintain their vigor. Untrimmed corals lose their vigor, begin to grow more slowly, and can become susceptible to disease.

The coral restoration program should be expanded to Fanning and Washington Atolls as resources permit, and with the mass bleaching of the main Gilbert Islands, the need for the work throughout Kiribati has vastly increased. Community training and involvement may be possible, and youth would find the work encouraging and interesting as a service project.

Restoring and securing the original species of corals found on each Island prior to the mass bleaching should be our long-term goal, with each species reproducing effectively and expanding its local range through natural larval recruitment processes. However, if after several years, a particular coral species can't be found on an island any longer, it should be assumed to be locally extinct and an effort to find and bring the species from other reefs of the same island group should be made, exchanging between nurseries if possible. If a coral species is composed of only a single or a few genotypes, more genotypes should be brought in from the nearest local source available, but never from different eco-regions.

Severe bleaching can be expected to come again to the Gilbert, Line, and Phoenix Islands in the coming years due to rapidly changing climate and global warming. However, the corals that have survived the last hot water bleaching event are assumed to be bleaching resistant, offering some hope that adaptation is occurring. Our goal now is to propagate and replant populations of these bleaching resistant corals, which will then spread into the environment and restore the reefs through natural larval production and recruitment processes. The restored reefs should in turn carry bleaching resistance adaptations, and should be in a much better position to survive the hot water. Theoretically, the next mass bleaching will leave the reefs in a much less damaged position, and with many more unbleached corals.

This work gives us hope that we can help coral reefs survive into the future, in spite of the severe challenges of climate change. Restored and bleaching resistant coral reefs will in turn help secure the ecological, food security, and livelihood services that this precious ecosystem provides to the peoples of Kiribati and the world.

The work on Christmas Island goes beyond the simple recovery of this remote atoll's reefs, rather if we can establish the effectiveness of this "Reefs of Hope" program on Christmas Island, it would be vastly relevant to all coral reefs of the nation and of the planet, facing an uncertain future in a rapidly changing world. What better place to start this pioneering climate change adaptation work?

As the work thus far has been entirely based on volunteerism, what is most important at this time is to identify funding for continuing and expanding this vital and unique program. The work should ideally expand to include more extensive reef surveys on all parts of the island, to try to identify more of the surviving corals, the monitoring of restoration patches, genetic testing of corals and their symbionts, increased and intensifying nursery work, awareness raising work within the communities, nation, and region, as well as work to secure the no-take status of Cook Islet Conservation Area and other areas as special and sensitive to restoration and therefore of critical importance to the larger coral reef system and the nation of Kiribati.

List of Acropora coral species found in the Line Islands thus far, with comparisons to the species list from Fanning Atoll by Marigos, 1974.

Species confirmed

<u>*Acropora muricata*</u> (synonym for *A. formosa*) staghorn coral of lagoons. Dead and standing thickets of this species dominate the inner lagoon of Kiritimati, but now apparently locally extinct. Found in the lagoon on Tabuaeran at several sites and brought into the Kiritimati nursery.

<u>*Acropora vaughani*</u> (similar to *A. horrida*), forms bushy clumps on upper reef slope and lagoons, at micro-level it takes on a small staghorn growth form. Absent from Christmas Island, collected in Fanning Lagoon and brought into the Christmas Island nursery.

<u>*Acropora humilis*</u> finger-like Acropora, similar to *A. gemnifera* which has more tapered branches, reef slopes and flats. Found as remnants of a large colony at Cooke Islet and Crusher Reef flat, and some appear to be coming in as larval recruits.

Species potentially found as new recruits

<u>*Acropora cerealis*</u> (synonym of *A. cymbicyathus*) Forms small tables with interlocking branches. May be coming in as new recruits or as recovering remnants on reef flats.

<u>*Acropora nasuta*</u> delicate tubular branches similar to *A. cerealis*, but without interlocking branches, upper reef slopes. May be a major component of the new recruits and the major recovering reef flat species regenerating from surviving micro tissues.

<u>*Acropora selago*</u> (synonym of *A. delicatula*) similar to A tenuis but forming tables, upper reef slopes and lagoons. May be coming in as new recruits.

<u>*Acropora cytherea*</u> (synonym of *A. reticulata*) large, flat, table corals, blue, cream, or brown, upper slopes and lagoons. May be a component of the new coral recruits.

Species not yet found

Acropora florida (synonym of *Acropora polymorpha*), large upright staghorn corals with very short side branches

Acropora longicyanthus, (synonym of *Acropora syringodes*), bottlebrush Acropora of lagoons

Acropora abrotanoides Thick-branched, reef front staghorn species

(*Acropora corymbosa* Listed by Maragos, not presently considered a valid species and unsure which species this represents)

Reference

Maragos, J.E. Reef Corals of Fanning Island. Pacific Science (1974), Vol. 28, No.3, p. 247-255

ACKNOWLEDGEMENTS

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Funding for earlier trips was provided by numerous small donations through Global Giving: https://www.globalgiving.org/projects/emergency-response-to-massive-coral-bleaching/
Boat, fuel, nursery materials, and staff were provided by the Kiribati Fisheries Department, kindly facilitated by Mr. Taratau Kirata, Senior Fisheries Officer. Accommodation was kindly provided f.o.c. during the initial two visits by Ereti Tekabwaia through the Tekabwaia lodge.

CORALS FOR CONSERVATION

Coral reefs are the most sensitive ecosystem to climate change and are predicted to be the first ecosystem to collapse due to increasing temperatures and altered water chemistry.

Although it will be difficult, if we can save the coral reefs we can save the planet, but if the corals go, geological processes and entire economies and societies will also go with them… and which system will be next? Coral reefs must become the front-line in saving the planet, and where we must now take our stand.

On Christmas and Fanning Atolls in Kiribati, over 90% of corals on reefs died from bleaching caused by hot water in 2015-16. While some branching coral species appear to have become locally extinct, we have succeeded in finding ''super corals'' of many coral species which resisted the bleaching and survived, and we are propagating bits of each of these within a coral nursery, to begin the process of restoration and adaptation to a hotter climate. Christmas Island has now become the leading edge of the battle against permanent damage to the planet's life support systems. Additional resources and partnerships must now be found to support this work.