Turn Down the Heat – An Innovative Citizen Science Pilot Project to Reduce Impacts of Coral Bleaching

Baje el Calor – Un Innovador Proyecto Piloto para Reducir el Impacto de Blanqueamiento de los Corales

Baissez la Chaleur – Un Citoyen Innove un Projet Pilote Scientifique pour Réduire les Impacts de Blanchissement des Coraux

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ABSTRACT

Impacts from climate change on coral reefs are outpacing our ability to protect these important ecosystems. Practical approaches to reduce temperature and light stress to corals during summer bleaching events are greatly needed. The Keys Ocean Rangers (KOR) received the first Ocean Innovation Award from the Gulf and Caribbean Fisheries Institute to develop and test a number of potential technologies that may one day help managers on the ground better respond during periods of peak bleaching stress. In phase one, we designed, tested, and compared several innovative technologies to reduce water temperatures, reduce solar irradiance reaching corals, and increase mixing and oxygenation of the water column. The engineering systems we tested included:

i) Aeration through bubbler and airlift systems,
ii) Sprinklers and misters, and
iii) Shade cloths.

We conducted experiments in a 14,000 gallon pool then scaled up to a saltwater quarry (in excess of several million gallons). Each test measured physical parameters that are an indication of environmental conditions that contribute to stress on corals: light intensity, daily solar heating, water temperature, and water flow/circulation. Each technology was also evaluated for its costs, feasibility for field deployments, and stand-alone capability. Two of these technologies which showed the greatest net benefits, shading and aeration, were then scaled up and tested during phase 2 in an enclosed salt water quarry for their influence on temperature and light stress. Results suggest that combining shading and aeration provides the greatest stress reduction during bleaching events and is feasible with easily available components for areas up to 10mx10m areas and water depths of up to 12 m, with the ability to scale up. While further development and testing of aeration and shade systems for reefs are underway, we hope this pilot feasibility study and the vision of GCFI's Ocean Innovation Award's purpose will encourage others to investigate innovative responses to help managers reduce impacts associated with coral bleaching events.

KEYWORDS: Coral bleaching, management, cooling systems, shading, aeration

INTRODUCTION

Coral bleaching poses one of the most serious threats to tropical reefs around the world. In the Caribbean, coral reefs suffered significant losses of their reef building corals in 1997/98, 2005, 2010, and 2014/15 (Eakin et al. 2005, Eakin et al. 2014). At present, coral reef managers have few tools that can be deployed to prevent or mitigate bleaching related loses to corals. No practical preventative measures that can be taken even for high value reef areas such as dive/snorkel sites or coral nurseries that may occupy less than 100 m^2 of seabed. With sea surface temperatures predicted to continue to increase to levels that are well beyond the current thermal tolerance of corals in the coming decades, there is an urgent need to develop practical solutions that can help reduce bleaching stress to improve the short-term outlook for high value coral reef areas while longer-term strategies to reduce the rate of global climate change are being developed.

Many factors can cause coral bleaching but excess temperatures, increased light or solar heating and lack of mixing or water flow are often cited as key drivers (Fitt et al. 2001, Hoegh-Guldberg 1999, Warner et al. 1996). Corals live within a relatively narrow temperature margin, and unusually high temperatures can induce coral bleaching. During hot summer months, elevated temperature and increased irradiance often occur at the same time especially in shallow-water reefs. The increased light stresses coral's algal symbionts and causes reduction in the rate of photosynthesis further stressing the coral. Corals can be negatively affected by both photosynthetically active radiation (PAR, 400 - 700 nm) and ultraviolet radiation (UVR, 280 - 400 nm) (Banaszak and Lesser 2009, Gleason and Wellington 1993, Jokiel et al. 1997, Torres-Pérez and Armstrong 2012, Torres et al. 2007). Water-flow rates have been found to influence the degree to which corals can tolerate high temperatures and irradiance (Nakamura and van Woesik 2001). Reefs subjected to periods of low circulation or stagnant wind periods may also be exposed to higher water temperatures and hypersaline conditions. Dense, turbid, hypersaline bottom water has been reported on the Florida reef track periodically and may contribute to episodic coral bleaching events (Porter et al. 1999).

Water flow and circulation can be generated naturally (e.g., waves, currents) but also artificially (e.g., airlift/upwelling, bubble screens). Studies of technologies that can be used to manipulate environmental variables such as water flow, temperature, and light have existed for many years but have rarely been applied to coral reef ecosystems (Hollier et al. 2011). To our knowledge, there have been no large-scale examples to manipulate physical and oceanographic conditions through engineering technologies to help corals survive bleaching events.

The Keys Ocean Rangers (KOR) received GCFI's first Ocean Innovation Award aimed at supporting innovative approaches to address coral bleaching events as they arise, with an emphasis on being relevant to Caribbean marine protected areas (MPAs) within the GCFI-NOAA MPA network. This paper summarizes the first phase of our project which was to test various engineering technologies that could be used to reduce the impacts of increased sea surface temperatures and excessive solar radiation on coral reefs. The technologies that were tested included air lift pump, sprinkler, aerator bubblers (diffusers and screens), and shade cloths. With each technology, experiments were conducted in a swimming pool to examine and measure three variables that contribute to reducing coral heat stress: light penetration, daily solar radiative heating, and water flow/circulation. Three of the cooling systems that demonstrated the greatest benefit in the pool were scaled up and tested in an open salt water rock quarry in the Florida Keys to assess overall feasibility of scaling up these technology to a coral reef environment. The goal of our project is to ultimately provide a practical set of "response tools" that might allow managers to proactively alleviate thermal related stress at selected high value reefs. The research presented in this paper stems from the work of our group of young citizen scientists called the Keys Ocean Rangers (KOR), who dedicated over 2,000 volunteer hours to this project.

METHODS

We chose to examine a wide variety of engineering systems drawn from a review of the literature and from discussions with coral reef scientists and managers. The systems we selected to test during the first phase of this project included: air lift pump, sprinkler, aerator bubblers (diffusers and screens), and shade cloths. Each system was evaluated on its ability to influence factors of temperature, light, and water circulation as well the feasibility to scale up to larger scales. For each of these systems, we examined the following questions:

i) Is the system able to significantly influence temperature, light or mixing?
ii) Does the system work at different scales?
iii) What is the feasibility of scaling each system up?

Small-scale Pool Experiments

Systems tested — Four technologies were designed and built for testing in the pool experiments (Figure 1) including - ***Shade cloth:*** A light brown shade screen (8 x 8 m) was placed above the water and secured to the pool edges during shade experiments (Shade cloth manufactured by Easy Gardener -Harvest Wheat rated to reduce 75% of UV penetration). ***Aeration:*** A porous drip irrigation hose (manufactured by DIG) 10m long x 2 cm diameter with a flow rate of 5 liters per meter was used to create a continuous screen of bubbles. The hose was wrapped around the perimeter of the PVC array. The airlift could move 70 liters of water per minute, and the pump was 120 volt, 65 watts. Air was pumped down 1 m and a diffuser was designed and placed inside the pipe to increase flow**.** ***Airlift:*** The air lift pump system used a low pressure air compressor (70 l/m, 120V, 65W) to bring water from the bottom up through a pipe and to the surface. ***Sprinkler:*** A simple cone sprinkler with a 3m range using a pump/hose configuration was floated in the center of the pool. The water pump used to power it was a centrifugal drive pump with 40 l/m flow rate, 110 V, 30 Watts power draw.

Experimental design — To evaluate these four technologies- airlift pump, sprinkler, aeration, and shade – we conducted tests in a small above ground circular pool (7.3 m diameter x 1.2 m depth; total volume of 51.6 m^3). Each experimental treatment consisted of applying a technology (e.g., "treatment") for five hours between 11am – 4pm (effectively a "day"). At least two replicates were conducted for each technology. Controls consisted of measuring conditions during the same 5 hour period in which no technology was placed in the pool and were done before, during, and after each of the treatments. A total of 20 experimental treatments were tested over a 20 day period between April 26 and May 16, 2016.

Pool water temperature was measured using an array of 12 precision HOBO U22-001 Water Temp Pro v2

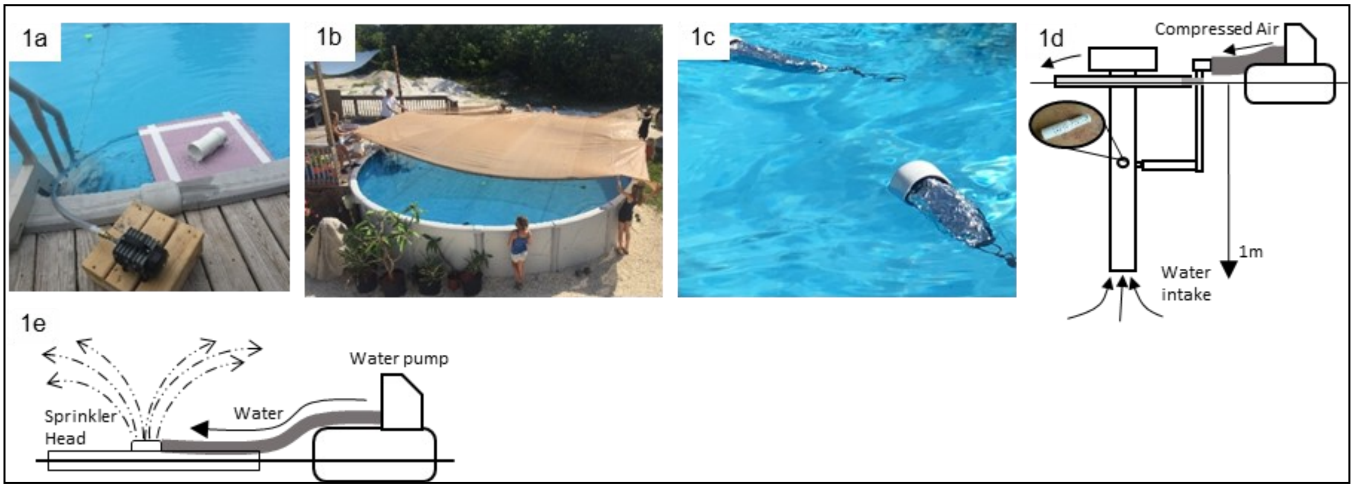

Figure 1. Pool experiments to test sprinkler, airlift pump, bubble hose, and shade. (1a) The airlift pump before deployment. (1b) Deployment of the shade cloth (7x7) over the pool. (1c) Temperature loggers wrapped with reflective tape. (1d) Schematic diagram of initial airlift pump with diffuser to increase flow (inset picture). (1e) Schematic of the initial sprinkler tested.

loggers set synchronously to record every minute. Temperature loggers were placed in a grid pattern around the pool and held in place by fishing line suspended vertically between a large weighted Polyvinyl Chloride (PVC) frame and small styrofoam floats kept just below the water surface. Two temperature loggers (surface (5 cm) and bottom (1 m) were placed at each corner and again at points halfway between the center and the corners (12 total). Light was measured within the pool using 4 HOBO UA-002-64 Pendant temp/light loggers. One additional light logger was placed adjacent to the pool to record ambient conditions. Light loggers were placed in the center of the pool, one at the surface and one at the bottom. To avoid the influence of solar radiation on logged temperature readings (Bahr et al. 2016), each temperature logger was wrapped in reflective aluminum tape leaving only the tip of the sensor end exposed. Prior to pool tests, we compared temperature loggers with and without reflective tape and found loggers without reflective tape recorded readings 0.1-0.2 °C higher. Unlike Bahr et al.'s tests, no biofouling occurred on loggers wrapped in reflective tape after being in the water for two months.

Larger-scale Quarry Experiments

Systems tested — Based on the findings of the pool experiments, several of the engineering systems were selected for testing in a large salt water quarry (90 m wide, 360 m long, and 12 - 18 m deep) located on Grassy Key in the Florida Keys (Figure 2). The systems that were tested included: ***Shade cloth:*** The same light brown shade screen (Easy Gardener –Harvest Wheat) that was used during the pool experiments was used in the quarry. For the quarry experiments the shade was increased from 7 x 7 to 10 x 10 m for the quarry. A sleeve was sewn to hold a 1.3 cm diameter PVC frame for extra stability. The shade cloth was floated on the surface by Styrofoam buoys and attached to the boom by elastic cords. ***Aerator diffuser discs:*** Aeration equipment consisted of commercial scale air pump system made by Vertex which supplied air at 25 PSI with a flow rate of 98,040 L/m. Compressed air was delivered down through hoses to the bottom of the test area where air was released through aeration diffuser discs (25,5 cm diameter) that released air in distinct "plumes" of concentrated air bubbles. ***Aerator hose*:** The same commercial Vertex air pump was connected to drip irrigation or soaker hose (the same as used in the pool experiments). Two of these hoses were attached at about 5 m depth around the PVC array in an octagon shape and connected to the surface air supply system by 1.9 cm diameter PVC tubing. The aerator hose releases bubble as a linear screen of bubbles. ***Shade/Aeration combination:*** A fourth treatment was also tested which included several combination tests of both shade cloth and either the aerator diffusor discs or shade cloth and aerator hose.

Experimental design — A small area on the northeastern end of the quarry was roped off and within that area a 10 m x 10 m section was used for the experiments. Temperature, salinity, and dissolved oxygen profiles through the water column were made of the study area using a Hach Sonde multiparameter water quality meter equipped with a 20 m cable. Water quality data indicated three distinct layers within the quarry- a well oxygenated upper layer (0-7 m), a warm briny mixed layer (7-9 m), and a cool anoxic deep layer (9-18 m) (Figure 3). The lower depth limit of our experimental "cube" was set at 5 meters to avoid influences from the mixed and deep layers.

The experiment area (10 x 10 m) perimeter was delineated with a white floating boom (46 cm diameter) anchored with ropes on the corners to the rocky shoreline. A weighted 10x10 m underwater PVC frame was built and suspended 5m underwater from the boom by polypropylene lines to provide a floating "floor" for the experimental area above the anoxic deeper waters of the quarry. Water temperature and light was measured using the same high resolution HOBO temperature (U22-001) and light (UA-002-64) loggers. A total of 16 loggers were used and each was synchronized and calibrated in advance. Temperature loggers were attached to polypropylene lines at two depths, five loggers at the surface (30 cm below water surface) and five loggers at the bottom (5 m below surface). The temperature loggers were arranged with one at each corner and one in the center at the two different depths. Similar to the pool tests, temperature loggers were wrapped with reflective tape. Light loggers were positioned one in the center and one halfway between the center and the corner. A 2 x 3 m platform (CANDOCK Modular Dock) was moored along one side of the boom and used as a platform to support the power and aeration systems. The aerator systems had four basic components – a power source, a compressed air pump, a series of four supply hoses and either a diffuser disc or a bubble hose. Power was supplied from a Honda EU20000I 2000W Super Quiet Inverter Generator with a 13 Amp 120 V output that was converted to propane for better energy efficiency. The generator had a 14 hour run time on a single 20 lb propane tank.

The three different technology treatments (shade, aeration, combined) were tested in the quarry. Each treatment was set up and run for 8 hours (10:00am-6:00pm) and was effectively a "day". At least three replicates were conducted for each technology. Controls consisted of measuring conditions during the same 8 hour period in which no technology was placed in the test area and were done before, during, and after each of the treatments. To evaluate potential influences of the boom and PVC frame on the experiments, several loggers were also placed on a mooring line (depths 0.5 m and 5 m) approximately 20 meters away from the boomed area near the center of the quarry and used for comparison. A total of 16 experimental treatments were tested over a 19 day period between July 23 - August 20, 2016.

Data Analysis

Data loggers for both temperature and light were removed from the pool and quarry test areas after the first 10 days of experiments and all data downloaded onto laptop computers. The loggers were then reset and redeployed to the same locations. Temperature and light data for the pool and quarry experimental periods (5 and 8 hours respectively) were extracted and grouped by treatment. Averages and standard deviations were determined for surface and bottom levels. Stratification and mixing were evaluated by comparing the temperature data from the 4 outer surface loggers to the 4 outer bottom loggers over a 1 hour period late in the afternoon (3 to 4 pm) when solar heating was near its daily peak. Cooling was evaluated using only the 8 surface loggers and comparing the average degree of solar heating over a 5 hour period between 11am and 4 pm. The climatology during the both the pool and quarry experimental periods was recorded at the Marathon Airport (respectively 5 and 10 km away) and any days of high cloud cover (> 50%) or rain (> 1 cm) were eliminated from the experiments.

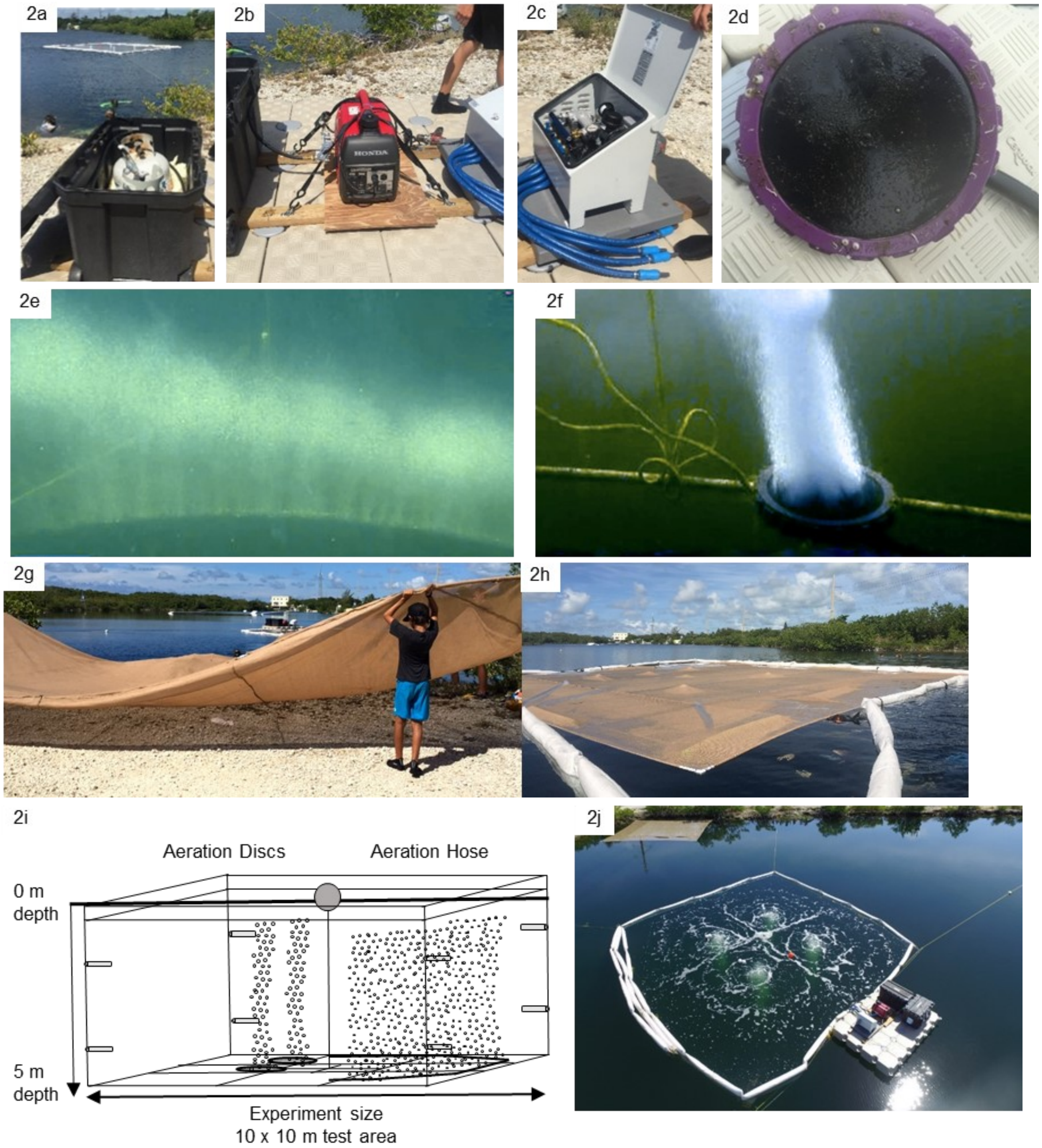

Figure 2. Quarry experiment to test aeration (diffuser/bubble hose), shade, and shade/aeration. (2a) Propane fuel for the generator to allow longer runtime. (2b) Generator used to power air compressor. (2c) Vertex Water Features air compressor used to provide air to the aeration hose and discs. (2d) Diffuser disc did not bio-foul after being submerged for 2 months. (2e) Example of bubble curtain created by aeration hose. (2f) Example of bubble plume created by diffuser disc. (2g) Shade cloth being deployed (10x10 m). (2h) Shade cloth deployed in the floating boom. (2i) Schematic diagram of the aeration tests. (2j) Overhead drone picture of the experimental set-up in the quarry (note: upper left corner shows shade cloth, center of photo shows bubbles from aerator discs, adjacent is floating platform with generator and air compressor).

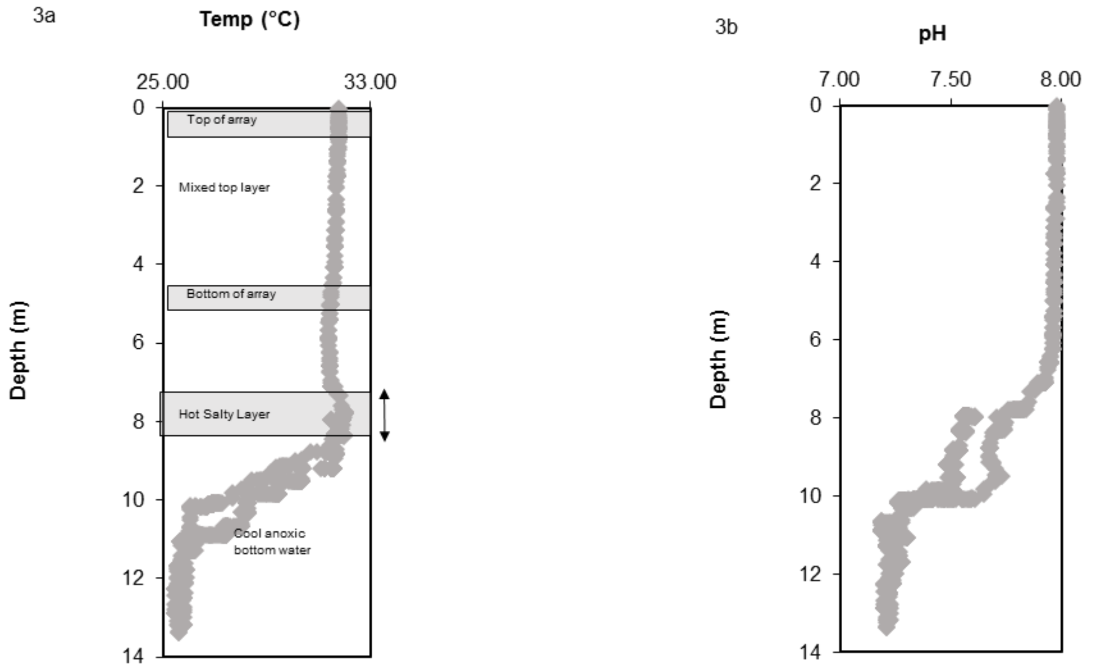

Figure 3. Quarry water quality profiles. A hand held multi-parameter water quality meter with a 20 meter cable was used to make water quality measurements of the quarry at the location of the experiment. Based on the readings, we divided the quarry water column into three zones- 1) upper- fairly well mixed top layer extending to a depth of 8 meters **(3a)** 2) mixing boundary- a narrow (0.5 m) , turbid layer at 8 m , and 3) bottom water- anoxic and cool deeper water layer **(3b)**. For quarry experiments, we placed our array within the upper mixed layer to avoid upwelling deeper anoxic bottom waters with aeration.

RESULTS

Small-scale Pool Results

Each of the systems affected the three parameters of temperature, light and water mixing differently (Figure 4). ***Light and Temperature:*** The artificial shade system provided the largest decrease in the amount of daily solar heating measured by the temperature loggers. Pool waters heated up 50% less compared to control days. None of the other three systems had a significant influence on the daily solar heating. Shading technology also provided the greatest reduction in light penetration through the pool compared to the other systems, eliminating about 90% of the light that reached the bottom of the pool in the control tests. The sprinkler provided the next most effective reduction in light transmission, but only reduced about 5% of the light compared to the control. The aerator bubbler technology may have had the effect of increasing the amount of light penetrating the pool possibly through slight wave lensing. ***Mixing:*** For stratification of the water column, the aeration hose (bubbler screen) technology was the most effective of the four systems tested in the pool, nearly eliminating stratification between the upper and lower layers. The air lift pump, which was supplied by the same amount of air as the bubbler system and had its intake near the bottom of the pool showed only a minor improvement in reducing stratification compared to the control. Similarly, the sprinkler system showed only a minor decrease in stratification compared to the controls. One factor which may have affected the airlift pump's poor performance was depth. The deeper an airlift pump's intake is, the more effective it is. For both the air lift and sprinkler systems, the rate of water flow was 18.7 GPM and 10.5 GPM, respectively. Given the pool volume of 50 m^3, the turnover rate for the entire pool volume was 11.18 hours for the aeration and 19.92 for the sprinkler system. Thus, during our 5 hours of testing, the flow rates for these pumps with a single intake located in the center bottom of the pool appears to have not been high enough to substantially reduce stratification at the edges of the pool during daily solar heating. An example of 24 hour temperature data from an example control day is given showing time series results for 12 Hobo temperature loggers spaced around the pool in a grid at Top (0.25 m below the surface; 8 loggers) and Bottom (1 m below the surface; 4 loggers) (Figure 5). Daily solar heating was typically 2 - 3°C with a peak around 6 pm. Mixing or stratification of the water column, was evaluated by comparing four surface loggers to four bottom loggers at the distal corners of the grid between 3 and 4 pm. An example of 24 hour temperature data from the aerator bubble screen experiment is given for one day showing time series with a high degree of mixing between the surface and bottom temperature loggers.

Large-scale Quarry Results

The systems tested in the quarry affected the three parameters of temperature, light and water mixing differently. ***Temperature:*** Both average temperature and change in temperature were evaluated in the quarry. Average temperature results (Figure 6) suggest conditions during aeration tests were significantly warmer than other tests. Otherwise, temperature conditions within surface of

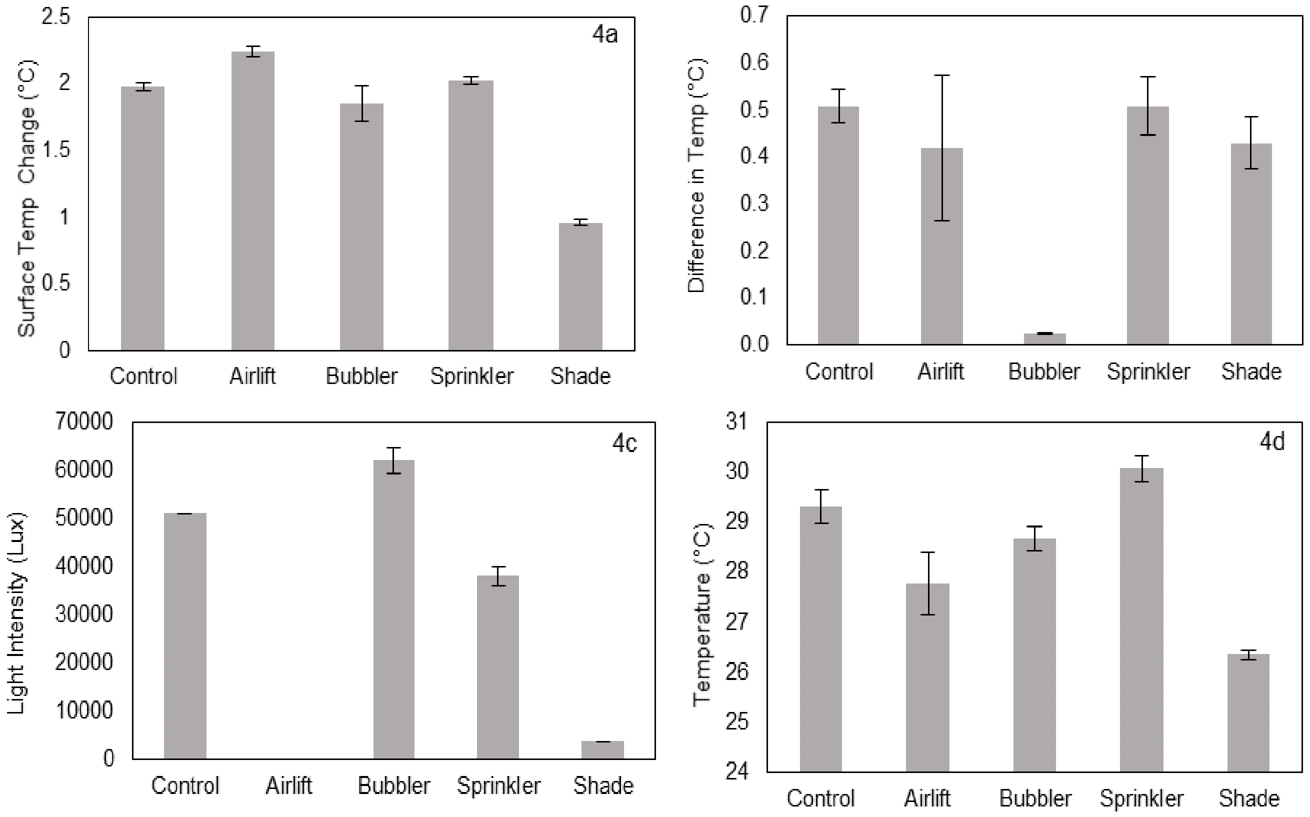

Figure 4. Example of 24 hour temperature showing time series for 12 Hobo temperature loggers spaced around the pool in a grid at surface (10” below the surface; 8 loggers) and Bottom (40” below the surface; 4 loggers). Loggers A1-D1 are at the surface corners, E1- H1 are at the surface in the center, and loggers A2-D2 are at the bottom corners. Daily solar heating was typically 5-7 degrees F with a peak around 6 pm. Mixing was evaluated by comparing 4 Surface loggers to 4 Bottom loggers at the distal corners of the grid between 3 and 4 pm. **(4a)** (control) shows a large difference in temperature readings between the surface and bottom sets of loggers. **(4b)** (bubble screen) shows almost no difference in stratification meaning

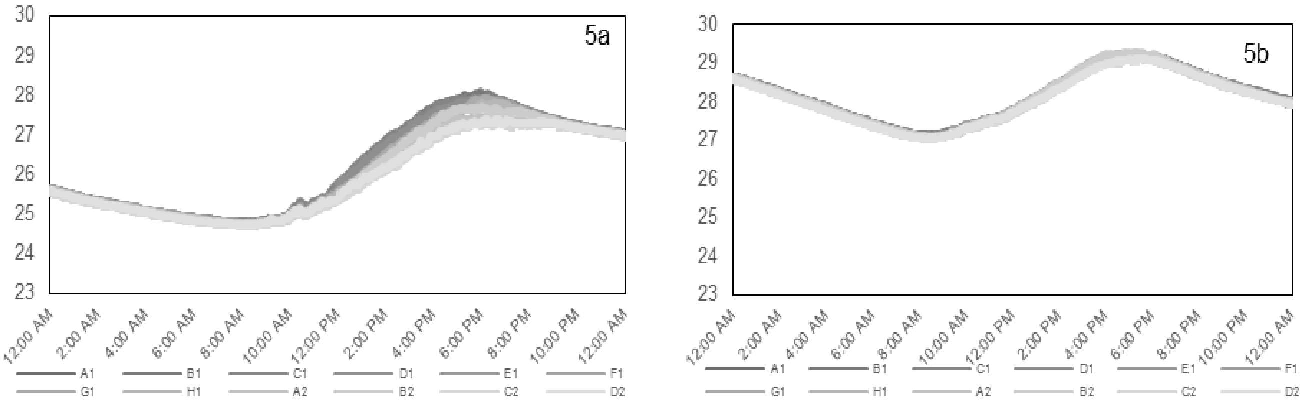

Figure 5. Pool results: **(5a)** shows relative surface water heating during 5 hour test periods for four technologies and control shows that shade was the only technology that significantly reduced daily heating (by ~1 °C). **(5b)** shows relative mixing as measured by the difference between the average surface and bottom temperature between 3 and 4 pm. The bubbler showed a 96% decrease in stratification as compared to the control. **(5c)** shows average surface light intensity measured over 5 hours for three technologies as well as control (No airlift data). The shading technology decreased about 93% of light reaching surface loggers. **(5d)** Average temperature was used to evaluate whether some days were warmer than others.

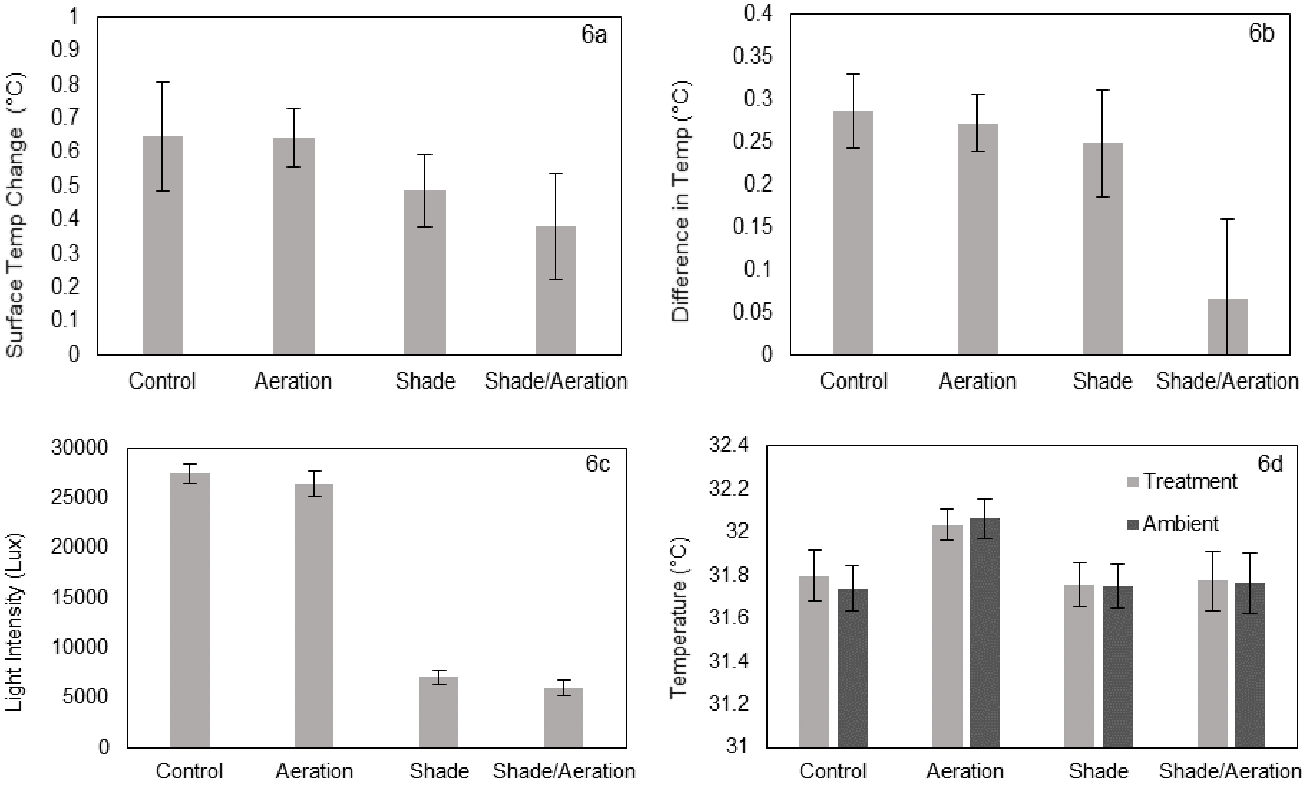

Figure 6. Quarry Results: **(6a)** Relative surface water heating during the 8 hour test periods for three technologies and control. Shade cloth alone or with aeration showed a minor decrease in heating (0.25°C decrease). **(6b)** Relative mixing as measured by the difference between the average surface and bottom temperature between 3 and 4 pm. The most significant mixing was measured when aeration was combined with shade cloth. Aeration alone showed similar stratification to shade and control. **(6c)** Average surface light intensity measured over 8 hours for three combinations of tech as well as control. The only significant decrease in light was shown by the shade cloth with (74% decrease) and without aeration (77% decrease). **(6d)** Average surface temperature over the 8 hour test period for experiments and control. Ambient = values which were measured outside of 10 x 10 m test area.

test area were similar to temperatures outside test area. Shade cloths alone reduced daily solar heating of the upper portion of the water column by approximately 25%. Aeration (through diffusers or bubble screen hoses) had a minimal effect on daily heating. However, when aeration was combined with shade, daily solar heating of the upper water column was reduced by up to 40%. ***Light:*** In the quarry, average light intensity during controls was around 26,000-27,000 lux. The shade cloths reduced light down to 7000 lux, representing a 75% decrease. The shade/aeration combination was even more effective and decreased light by almost 80%. Aeration alone (either through diffuser discs or bubble screen hoses) showed no measurable difference. ***Mixing:*** During the quarry tests, the aeration once again showed the greatest influence on water column stratification, but only when combined with shade cloth. Reasons for this are still unknown, but we hypothesize that the shade cooled the surface enough so that the difference in temperature between surface and bottom was less. The shade and aeration by themselves did not show any measurable effect.

DISCUSSION

The purpose of the first phase of this pilot study focused on investigating the ability of low-cost, manmade technologies to affect temperature, light and mixing at small scales and the feasibility of scaling up these systems. The pool and quarry experiments conducted as part of this study verified that shade cloths were the most effective of the systems in reducing light and to a small degree temperature (1°C) compared to the small-scale airlift pumps, sprinklers, or aeration bubble curtain systems we designed. Our experiments also confirmed that it is possible to influence water flow and light at moderate spatial scales (~100 m^2) with fairly inexpensive, available materials. The project demonstrated the ability to easily scale up the application of these systems to larger spatial areas in regards to feasible deployment and reasonable costs. While none of the pilot small scale systems reduced water temperatures significantly (e.g., +3 - 5 °C), these findings do not preclude their importance or potential to be more effective through redesigning them, particularly the air lift pump. Reducing elevated water temperatures are a main concern during bleaching events, but these technologies may also prove to be useful in mitigating other synergistic impacts on corals that coincide with thermal stress events such as elevated irradiance, lack of water flow/mixing and co-occurrence of coral disease. Below we discuss an overview of the technologies based on our findings, suggest potential applications for coral reefs and recommend considerations for management.

Aeration Diffusers and Bubble Curtain

Aeration systems deliver compressed air below the water and can oxygenate the water while also mixing the water column through the vertical movement of air bubbles rising to the surface. Underwater aeration technology has had a long history in aquaculture and is increasingly applied in lakes to reduce stratification and improve water quality. Large scale applications also include creating air curtains as barriers to floating seaweed around the mouths of canals or harbors (Briceno and Serna 2016), the use of bubble curtains to reduce noise impacts on marine mammals from marine construction activities (Lucke et al. 2011) or as booms to contain oil pollution or improve water quality at larger scales (e.g., Grochowska and Gawrońska 2004, McGinnis et al. 2004, Liang and Peng 2005, Fan et al. 2013, McClimans et al. 2013, Zhang et al. 2016, Wang and Xu 2017). The use of large scale aeration on coral reefs has, to our knowledge, not been attempted but could have a number of benefits. Water flow can benefit corals in numerous ways during coral bleaching events at the colony level (Nakamura and van Woesik 2001, Finelli et al. 2006, van Woesik et al. 2012) and reef level (Leichter et al. 1996, Rogers et al. 2016). Comparisons between aeration systems and air lift pumps show aeration systems require more air and energy than air lift pumps to achieve the same vertical flow; however, underwater aeration may be more conducive for reef applications where the need is to influence the bottom of the sea floor where corals are located and cover as large an area as possible. Larger, more efficient air compressors and the development of micro-bubble membranes make it practical to disperse air through perforations or diffusers positioned along underwater horizontal hoses connected to a single air source. Aeration can also increase oxygen saturation within the water column and reduce the potential of hydrogen sulfide conditions near the seabed.

Our pool experimental results suggested that the aeration through the perforated irrigation soaker hose was the most efficient system for eliminating diurnal vertical temperature stratification across the entire pool area. We did not test the air lift pump in the quarry but did compare between aeration with diffusers discs versus aeration with soaker hose. The Vertex air supply system we used delivered an estimated ~30 cubic meters of air per minute at 5 m. Dispersing the same volume of air through the soaker hose provided a contiguous linear air flow or "screen of bubbles" compared to the clumped dispersion 'plume' associated with the Vertex diffuser membranes. The quarry experiments did not show a significant difference in the water column temperature stratification (central and distal) between the two systems. Both systems mixed the water column in the center of the 10 x 10 m area but showed less of a mixing influence around the perimeter. The Vertex packaged system with diffusers was easy to set up and mount in a variety of configurations and delivery through each disk can be adjusted and balanced with controls. The company also offers larger aeration systems that can deliver up to 50 cubic meters at 10 m - (see www.vertexwaterfeatures.com). In contrast, air flow through the irrigation soaker hose could not be balanced. The hose was positively buoyant and caused more air to be released in places where the hose bowed up between anchoring points. An improvement in our design would have been to weigh the soaker hose equally and negatively. An interesting observation was that biofouling was negligible on the tops of the diffuser discs and around the soaker hose during the 2-month period suggesting that periodic bubbling significantly reduced marine growth. More tests between continuous air dispersion versus clumped dispersion are needed before stronger conclusions (pros and cons) can be drawn between the two configurations for coral reef applications.

***Proposed application of aeration diffusers and bubble screens to coral reefs* —** The use of aeration diffusers and bubble screens could have a number of practical applications on Florida Keys reefs during bleaching episodes. In high value areas such as coral nurseries or outplant areas, aeration could be used to increase vertical water flow around coral nursery trees or platforms. The system could be used to disperse bubbles directly around the coral tissues and to create vertical flow in the nursery area. An important consideration for aeration is the source of power. Some type of fixed platform (similar to the dock system in our study) or temporary platform (e.g., boat) will likely be necessary to house the power source and the aeration equipment above or near the area (in contrast to bubble screens used in Florida Keys canals that rely on nearby land-based power sources). While solar power could be utilized on floating platforms for small aeration systems (<10 cubic meters of air per minute at 10 meters water depth), generator supplied power will be necessary for larger scale applications. It is also possible that eventually wave or tidal sources of power ay be incorporated and used to support submerged aeration systems. The design and anchoring system of these fixed platforms is a consideration for use in coral reef areas. Anchoring over sand bottoms (where most coral nurseries are currently located) can easily be done with either screw anchors or duckbills-either of which should provide up to 400 kg of holding force per anchor point. Over hard bottom and coral reef areas, anchoring will most likely require drilling and epoxy setting of mooring pins or using existing structures (e.g., mooring buoys, markers or marine structures).

Underwater aeration could be an effective way to disrupt, deflect or mix hot saline and turbid bottom water layers that appear on the Florida reef tract occasionally. These dense layers of bottom water are thought to originate from Florida Bay and other semi-enclosed water bodies of the Lower Keys during periods of extended calm, hot conditions and are transported out to the reefs through tidal channels between the islands (Porter et al. 1999). A similar phenomenon can occur during prolonged winter cold fronts that can generate cold bay waters that are released onto the reef tract though tidal channels causing mass coral mortality (Lirman et al. 2011). Small scale underwater bubbling could be applied to reefs near tidal channels or coral nurseries to mix up this bottom water and prevent damage. On a larger scale, underwater air curtains placed across tidal channels of the Keys would be a cost-effective way to break up these dense bottom layers before they could be transported out to the reefs. Shallow nearshore and mid-channel patch reefs in the Florida reef tract that now contain the highest remaining densities of important reef-building corals would see the greatest benefit. Placing horizontal air curtains beneath the existing bridges would also be fairly cost-effective as fixed structures and power are readily available along the Keys.

Shade Cloths

Our initial feasibility study results showed that artificial shading technology was effective in reducing light (~80 - 90%) and temperature (at least 0.5°C) and can be practically applied at moderate to large spatial scales in the marine environment. The shade cloth we selected was readily available and fairly inexpensive to purchase and costs could have been further reduced by buying in bulk quantities. For our tests, we selected beige-colored shade nets as brighter colors have higher levels of PAR reflectance and lower absorbance, while still allowing for some transmittance (Al-Helal and Abdel Ghanny 2010). Our volunteer team was able to sew the initial pool shade cloth (7 x 7 m) then redesign and scale up for the quarry tests (10 x 10 m). The material was light-weight, durable, and was easily deployed frequently by 1 - 2 members of the team. After 2 months of extended use sitting in the sun, being dragged over rocky ground at the quarry and sitting on the surface of the salt water for prolonged periods (+20 days), the shade material showed very little wear and no loss of material integrity. Biofouling is an important feasibility consideration for management as it can change the reflectance properties and density. While the polypropylene ropes and floating dock accumulated a large amount of biofouling organisms (barnacles, tunicates etc.), after a two month period, no biofouling was observed on the shade cloth. Interference with marine wildlife is another important consideration for scaling up. While deployed, we observed small fish aggregating under the shade cloth and no interference with birds or trapping of other marine organisms present in the quarry.

Proposed application of shade cloths to coral reefs — Our original concept for shading of reefs was to make use of the major influx of *Sargassum* mats that occurred in 2015 to create natural floating shade (through temporarily aggregating/ releasing drifting *Sargassum* mats in a boom over selected reefs to increase shade). However, in further exploring the concept, we learned that floating *Sargassum* contained in booms in the Yucatan during 2015 lost their buoyancy after several days and sank to the bottom degrading water quality and causing localized inshore coral mortality. Based on our pool and quarry tests, we now think artificial cloths are a better solution to achieve shading in the open reef environment. As a next step, we would like to deploy shade cloth over a coral nursery tree and platform located adjacent to existing trees (as controls). The shade cloth would be configured in a shape to best suit the test area and temporarily anchored to the seafloor with removable anchors. Deployment would be timed to coincide with the highest sea surface temperatures and maximum solar irradiance (for about two –three weeks during August/September). These open water tests with live coral will allow a direct examination of coral condition responses (e.g., bleaching, mortality) and environmental conditions (e.g., temperature, light, PAR, water flow). Since individual coral species respond differently to UV radiation/PAR (Gleason and Wellington 1993, Torres et al. 2007, Banaszak and Lesser 2009), it may be useful in the future to measure radiometric PAR and UVR properties of different net colors and materials to examine the response of corals and determine if there is a preferred color/material that allows for ‘optimal growth or survival’ during thermal stress periods. Previous research has shown a correlation between incidence of coral disease and coral bleaching (Kuta and Richardson 2002, Jones et al. 2004, Bruno et al. 2007). With the history of disease occurring in association with warm water bleaching events, we may consider deploying the shade screens if a disease outbreak occurs. This would allow the opportunity to further examine findings from earlier studies showing artificial shading reduced PAR/UVR and decreased the progression of coral disease (Muller and van Woesik 2009).

Airlift Pumps and Chillers

Air lift pumps are similar to aerators in that they utilize compressed but differ in that the air is used to create a vertical lift (or flow) within a pipe positioned through the water column. They have widespread application for artificial upwelling and are being extensively tested in China and other countries as an efficient approach to mix the water column or increase productivity of surface waters (Zhang et al. 2016). Generally, airlift pumps are ideal for artificial upwelling and are best suited for places where the water column is stratified - often in deep water fjords or lakes where a reservoir of cooler bottom water is present. One source of cool sea water that could be upwelled using airlift technology is adjacent deep ocean waters. In south Florida, deep water that is 2 °C cooler than shallow surface water (0-30 m) can be found 7-10 km offshore in water depths of 70 m or greater during the August/September time of year. While transporting it to the surface is quite feasible, moving this cool water inland to where the reefs are located would be challenging and potentially expensive. Using deep ocean water to cool reefs would be most feasible in places where reefs are closest to deep water. In the Florida Keys, this would include the outer high relief spur and groove reefs such as Looe Key but not practical for inshore and mid-channel reef areas. Another potential source of deep cool water is the shallow groundwater underlying the Florida Keys (and reefs) that maintains a year round temperature around 25 ℃. The high permeability of the limestone would allow groundwater to be easily drawn up with an air lift pump. Shallow underwater well heads could be drilled into the limestone around selected reef areas and capped until they are needed as has been done for several other groundwater studies (Reich et al., 2002). The Grassy Key salt water quarry contained bottom water that is probably in chemical composition and temperature to groundwater. Undoubtedly, we could have reduced surface water temperatures within our test area by several degrees °C within only a few hours had run an airlift pump with a vertical pipe extending to the bottom of the quarry (18 m). A major problem in using deep quarry water and groundwater is that it is slightly anoxic and can be detrimental to marine life. Saltwater aquaria and marine labs in the Keys that utilize groundwater to support marine life tanks must invest in aeration treatments before the water is suitable for use. So until there is a way to practically oxygenate the cooler groundwater, it is not practical to use with air lift pumps. Mechanical chilling is another technology that could potentially be used to reduce surface water temperatures. We did not test mechanical chilling as part of our project in part, because the technology would require many times more energy/costs than the systems we tested and probably not practical for use in Caribbean countries with limited resources. In the Keys, chilling technology would be most practical to apply to reefs close to shore or around large existing fixed platforms such as the Keys' lighthouses where a large power source is readily available or could be stationed. Efforts are currently underway in Australia to examine chilling and other technology to help alleviate coral bleaching related stressors (Marshall and Schuttenberg 2011, Hollier et al. 2011).

Considerations for Feasibility

With sea surface temperatures predicted to increase, the likelihood of more frequent and intense bleaching events will continue to cause stress on coral reefs. Cooling, shading or aerating systems that reduce solar radiation or temperature and increase water flow may likely lessen bleaching stress on corals. While there are certain inherent challenges with spatially scaling up cooling or aerating systems, the systems proposed here may be best suited for helping areas endure thermal stress events so that the corals do not die. In the Florida Keys, SST's are at their maximum during approximately the last two weeks of August/ first two weeks of September, thus the duration for deploying cooling technology may only be necessary for short time periods, thus reducing costs and simplifying logistical considerations while allowing for some scalability. Integral to the practicality of implementing small-scale cooling technologies is the need to pinpoint reefs or areas within a reef which are at greatest risk and where there would be the greatest return on investment. This can be done by using a combination of predictor tools like NOAA's Coral Reef Watch Products; habitat, current, or bathymetry data to understand driving factors; and ecological reef data (e.g., Florida Reef Resilience Program) to understand history of coral condition during bleaching events. Subsequently, a ranking system can be developed to prioritize highest risk/value reefs based on Risk/Value Criteria (highest SSTs, shallow water/low circulation, endangered elk/staghorn corals, coral nurseries, tourism hot spots) or Feasibility Criteria (networks of GCFI-NOAA MPA managers, volunteers, cost, effort, scalability). Prioritizing reefs suitable for utilizing cooling systems includes first identifying these high *value* reefs and high *risk* reefs and feasibility considerations, with an end goal of developing Value/Risk and Feasibility Criteria. The specific cooling system response to be used would then be selected based on that reef's specific biological and ecological characteristics and ranking criteria. Below are examples of potential options that could be used to develop future value/risk and feasibility criteria.

***High value reef examples* —** High *value* reefs include reefs that are economically important such as popular tourism reefs (e.g., Molasses Reef or Looe Key Reef in the Florida Keys) or coral restoration sites. Coral restoration sites in the Florida Keys, include both coral nursery and coral outplanting sites that are contributing to the long-term survival or recovery of endangered species such as acroporids. The amount of time and resources invested into coral restoration alone makes these sites of high value. Since the number of restoration sites has increased in the Florida Keys, it may not initially be feasible or necessary to deploy cooling systems at all restoration/outplant sites along the reef tract but instead identify scenarios for those with highest exposure risk or reefs with greatest recovery needs. Based on reef-scale trends in a Florida *Acropora* spp studies, Miller et al. (2016) found two reefs in particular, Grecian Rocks and Watsons Reef in the Upper Keys, experienced a significant loss of *A. palmata* where entire thickets were reduced to a few scattered individual colonies. Thus, one management scenario would be to narrow the focus from 15 outplant reefs to just those two outplant reefs that had the highest loss of *A. palmata* and based on their maps, the specific location of the colonies could be identified, further reducing the size of the area to deploy a cooling system. A different management scenario could focus on the species more susceptible to thermal stress. In that same study, they observed *Acropora cervicornis* outplants experienced reduced densities during an elevated thermal event in 2014 - 2015, thus a management priority may be to protect reef areas with the highest number of *A. cervicornis* outplants (i.e., nearly 7,000+ outplants at Pickles Reef). With the area of concern focused, the reef area can be evaluated to determine if a cooling technology would be feasible to deploy and if so, what the design would entail.

***High risk reef examples* —** High *risk* reefs include reefs with a reoccurring history of coral bleaching, disease or associated mortality possibly due in part to underlying environmental factors or the presence of certain susceptible coral species. Utilizing existing monitoring data from programs such as the Florida Reef Resilience Program (www.frrp.org), one management scenario would be to focus on responding to areas experiencing the highest bleaching prevalence. For example, in summer of 2016, portions of the Upper Florida Keys had greater signs of thermal stress with a high prevalence of coral bleaching and paling (> 50%), high disease (35% on inshore reef areas), and high recent mortality (> 10%) compared to the Middle and Lower Florida Keys, thus management responses with 'cooling' systems could focus on just a portion of the reef tract. Another approach would be to focus management efforts on prioritizing those reefs that have the highest density of living reef-building corals, especially those inshore and midshore reef areas that may experience greater thermal stress.

Feasibility considerations **—** Other considerations that should be taken into account when evaluating where to deploy a cooling system are practical in nature such as safety and security as well as potential conflicts with other users of the area. A well thought through site plan which details how a cooling system would be safely moored and properly equipped with navigational markers is essential. Given the time of year, a contingency plan for demobilization should also be in place for hurricanes or other large weather systems that may strike during deployment. Careful consideration will also need to be made around potential conflicts with tourists and other stakeholders.

Incorporating citizen scientists **—** The inclusion of citizen science into marine conservation and management is growing. Several case studies have shown citizen science has multiple benefits especially in the ability to scale up management response efforts (Cigliano et al. 2015). In the Florida Keys, for example, citizen science has enhanced the ability to increase the spatial and temporal scope of data collection (e.g., REEF Fish Surveys); provide early detection of episodic events like coral bleaching (e.g., MOTE's Coral Bleach Watch); reduce invasive lionfish through volunteer removal programs; and increase awareness and stewardship of restoring coral reefs (e.g., Coral Restoration Foundation, SCUBAnauts).The ability to scale up and deploy the 'cooling' systems tested as part of this study will depend, in part, on the involvement and support of citizen science groups and the public. The research presented in this paper stems from the work of our group of young citizen scientists who dedicated over 2,000 volunteer hours to test potential technologies to reduce coral bleaching at high risk areas in our Florida Keys 'backyard'.

Summary

With support for our pilot project by the first Ocean Innovation Award from the Gulf and Caribbean Fisheries Institute, we tested the feasibility of several 'cooling' systems with the hope that these prototypes may one day help managers on the ground better respond during periods of peak bleaching stress. While the proposed technologies to reduce thermal stress to coral reefs may be challenging to scale up and costly, there is an urgent need to explore the feasibility of alternative tools that managers can draw on to combat rising sea surface temperatures. While further development and testing of aeration and shade systems are underway, we hope this pilot feasibility study and the vision of GCFI's Ocean Innovation Award's purpose will encourage others to investigate innovative responses to help managers reduce impacts associated with coral bleaching events.

The following conclusions can be made from the results of this paper:

i) Technologies exist that can be applied at moderate scales (up to 100 x 100 m) to reduce bleaching stress on corals,
ii) Low cost shading technology can reduce daily heating of SST's by 30% and light by 90%,
iii) Aeration technology (diffusers and bubble screens) can reduce stratification by 50% or more,
iv) Combining shading and aeration technologies together can is possible and will achieve even greater benefits,
v) The cost to cover a 100x100 m area of reef with a shade/aeration combination is ~$22,000 USD, and
vi) Field tests on the reef tract are needed to better quantify benefits to coral animals and overall feasibility and costs.

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