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Perspective

Toward a New Era of Coral Reef Monitoring

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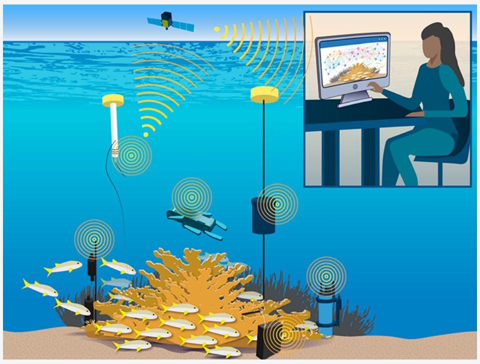
ABSTRACT: Coral reefs host some of the highest concentrations of biodiversity and economic value in the oceans, yet these ecosystems are under threat due to climate change and other human impacts. Reef monitoring is routinely used to help prioritize reefs for conservation and evaluate the success of intervention efforts. Reef status and health are most frequently characterized using diver-based surveys, but the inherent limitations of these methods mean there is a growing need for advanced, standardized, and automated reef techniques that capture the complex nature of the ecosystem. Here we draw on experiences from our own interdisciplinary research programs to describe advances in *in situ* diver-based and autonomous reef monitoring. We present our vision for integrating interdisciplinary measurements for select "case-study" reefs worldwide and for learning patterns within the biological, physical, and chemical reef components and their interactions. Ultimately, these efforts could support the development of a scalable and standardized suite of sensors that capture and relay key data to assist in categorizing reef health. This framework has the potential to provide stakeholders with the information necessary to assess reef health during an unprecedented time of reef change as well as restoration and intervention activities.



KEYWORDS: *coral reef, interdisciplinary, technology, monitoring, sensor, autonomous*

INTRODUCTION

Coral reefs are essential and iconic ocean ecosystems that provide vital services to more than 1 billion people and contribute $2.7 trillion to the global economy.[1] However, climate change, disease, overfishing, pollution, and other human impacts have negatively affected reefs globally,[2−4] with 13.5% of corals lost globally in the past decade.[1] A response to this loss is an enhanced emphasis on conservation and intervention-based approaches, including restoration, or the rebuilding of reef ecosystems harboring complex and interwoven biological, chemical, and physical components.[5] We believe that attention to interdisciplinary-based reef observational and monitoring methodologies could provide new insights into reef function and health and contribute to the advancement of intervention and conservation approaches.

Here, we propose an integrated science and technology plan to accelerate coral reef conservation and restoration. We propose to develop "case study" coral reefs that are equipped with sensors and technologies to quantitatively characterize the biological, chemical, and physical parameters of the reef. Supervised and unsupervised machine learning can then be applied to these data to identify underlying patterns of reef health, highlight parameters in need of additional monitoring, and ultimately drive development of integrated data products that communicate reef health to stakeholders. This new era of coral reef monitoring will reduce barriers to detecting and predicting the health of coral reefs and bridge gaps in our understanding of overall reef function. These advancements will be critical to the successful mitigation of climate impacts and restoration of reef ecosystems in an uncertain future.

CURRENT OBSERVATIONAL AND MONITORING APPROACHES

Long-standing coral reef monitoring practices are based on photographic and diver-based documentation such as fish abundances, coral cover, species assemblages, and the presence of lesions or other health-related visual signs (e.g., AGGRA surveys). Newer structures from motion photogrammetry techniques stitch together reef images into three-dimensional reconstructions, providing added details about individual corals and other noncryptic benthic organisms.[6,7] If reefs are routinely visited, photogrammetry techniques can be used to document coral growth, recovery, and survival changes over time. Globally, reefs are monitored via satellite-based data

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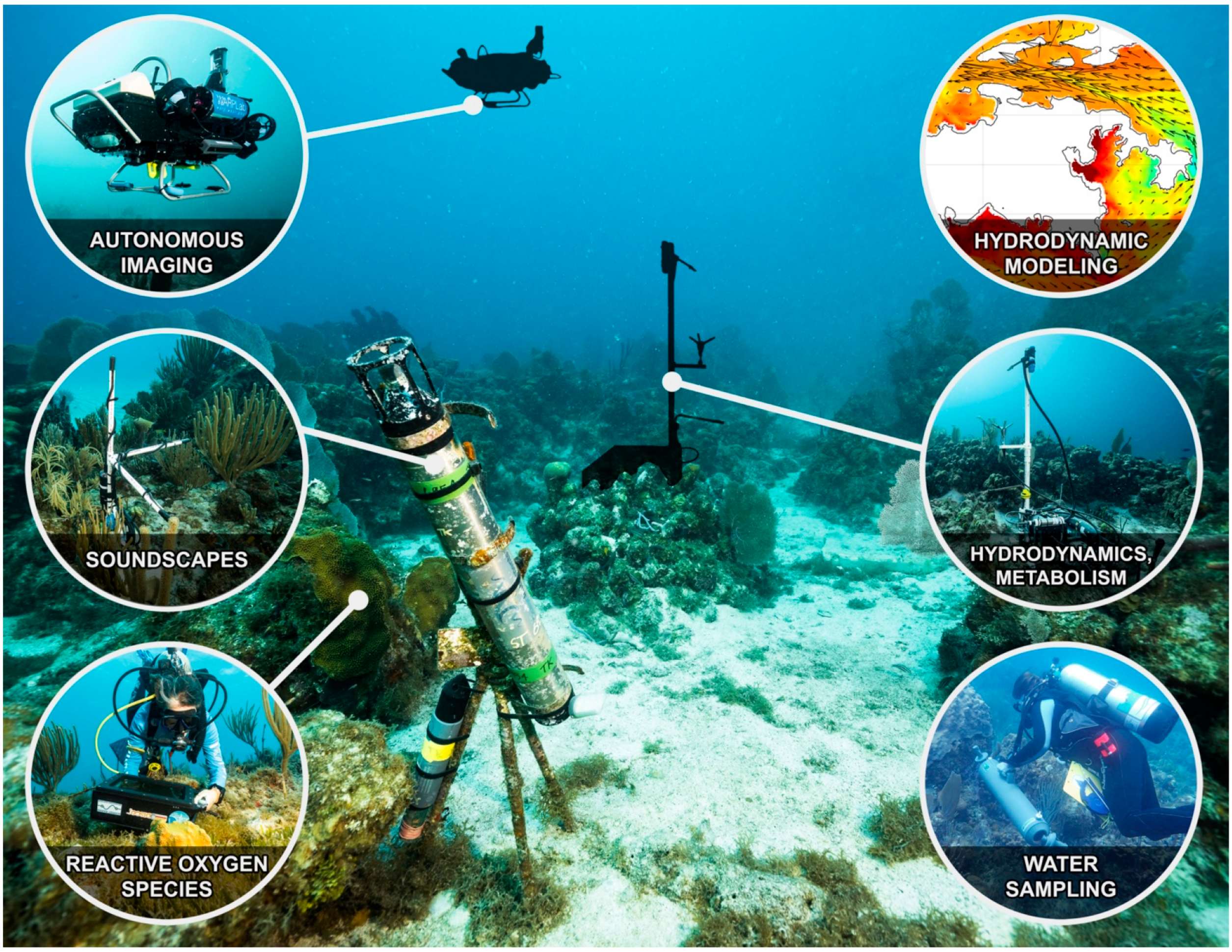

Figure 1. Conceptual diagram of case study reefs in which multiple diagnostic measures of reef health are collected in parallel by moored equipment, divers, and autonomous instruments to examine biological, chemical, and physical reef components and processes represented in Table 1. Measurements and equipment from the top right, moving clockwise, include hydrodynamics simulated using numerical models; assessment of reef metabolism using an acoustic Doppler instrument coupled to chemical sensors and hydrodynamics measured *in situ* using sensors, such as a Doppler current meter; water sampling using Niskin bottles (or other collection devices) to obtain samples for reef water microbes, eDNA, and metabolites; measurement of reactive oxygen species *in situ* using the DISCO instrument; a hydrophone to record the reef soundscape; and an autonomous vehicle capable of imaging the reef benthic and fish communities.

acquisition and modeling (e.g., NOAA's Coral Reef Watch), a framework that provides valuable information and local-scale predictions related to thermal heat stress on reefs.[8,9] Additionally, some monitoring programs provide integrated frameworks, such as the Florida Keys National Marine Sanctuary Water Quality Protection[10] and AIMS Long-Term Monitoring[11] programs. While a standardized index for describing reef health based on benthic, fish, and culture-based microbial data known as The Coral Health Index was created to integrate some of these data,[12] it is not widely used. We agree that a health index is needed to assess the state of global reefs and evaluate restoration or intervention approaches. However, we believe that such an index should include an expanded set of indicators that better integrate the biological, chemical, and physical parameters to describe reef health at an ecosystem level and contextualize these with the unique oceanographic conditions present on coral reefs.

TOWARD A NEW ERA OF MONITORING: CASE STUDY REEFS

We envision selecting several dozen geographically separated case study reefs representing different reef types (e.g., patch, fringing, barrier, and lagoon) and oceanographic settings that will be outfitted with a suite of advanced sensors and sampling devices in addition to being the focus of diver-based measurements. Ideally, these reefs will already be part of existing monitoring programs to leverage efforts by local divers, scientists, funding, and management resources to build additional monitoring capacity. Selection of reefs could include the Moorea Long-Term Ecological Research site,[13] those identified as Mission Blue Hope Spots,[14] or those included within the 100 Island Challenge,[15] among others. These case study reefs need to be joined together though common instrumentation and observation methodology as well as a shared data integration and analysis framework. A similar framework has already been put in place by the U.S. National Science Foundation's Ocean Observatories Initiative, which includes real-time ocean instrument arrays and data integration in six geographic regions used for scientific exploration and coastal protection purposes.[16,17] We believe this initial focus on a small number of case study reefs will provide valuable overlap in measurements while also allowing time to address logistical challenges specific to each region. Admittedly, the initial cost burden of reef instrumentation and monitoring is large but is being reduced by the development of low-cost instruments. The funding needed to support this endeavor could come from philanthropy, coral reef investment strategies designed to enhance the economic benefits of reefs, such as through the Global Fund for Coral Reefs,[18] or underwriting initiatives that provide insurance funding for reef monitoring for the purposes of coastline protection. In the US, $2.5B annually is spent on national park maintenance.[19] A fraction of this raised through state and federal coastal protection programs could cover the expense of establishing case study reefs, an investment that is easily justified by the erosion-mitigation, ecotourism, and biodiversity benefits.

■ TOWARD A NEW ERA OF MONITORING: MEASUREMENTS

We envision deploying instruments and diver-based sampling on case study reefs that provide a holistic measure of the coral and reef ecosystem health and the surrounding oceanographic conditions. Below we offer a broad overview of some of the techniques that we have been employing on reefs in St. John, U.S. Virgin Islands (Figure 1), which we believe may be ideal for use on case study reefs, and these techniques are specifically summarized in Table 1.

Reef Imaging. Visual observations provide indispensable knowledge about macro-organismal presence and diversity on reefs as well as insight into growth, predation, and herbivory processes. Recent advancements in underwater camera systems now allow for cameras to be embedded throughout coral reefs and left for long-term deployments to enhance temporal-based observations, including coral recruitment and postsettlement selection events[20] as well as of fish and other mobile reef organisms for diversity, biomass, and abundance estimates.[21] Deployment of camera systems on autonomous underwater vehicles (AUVs) will further enhance spatial coverage of reef imaging efforts, including depths challenging for divers.[22] While our focus here is on *in situ* measurements, we acknowledge that integration of satellite and airborne mapping approaches[23−25] with *in situ* imaging could bridge the gap between capturing detailed and broad-scale reef changes.

Soundscapes. Many coral reef fish and invertebrates make sounds, signals that travel efficiently in water. These acoustic cues collectively comprise the reef soundscape and inform animal presence, such as invasive species,[26] species diversity, responses to chemical−physical changes, occurrence and rates of specific behaviors, including spawning, and even patterns of reef recovery from restoration.[27] Due to decades-long advances, acoustics technologies are increasingly utilized and cost-effective, allowing for temporally continuous monitoring of reef soundscapes. Acoustic recorders include SoundTraps,[28] HydroMoths,[29] and others (compared in ref 30), which are typically moored onto a reef. Enhancing the spatial resolution of reef-scale soundscapes is accomplished by mooring multiple recorders on reefs and integrating hydrophones onto AUVs. A new advancement is real-time telemetered soundscape observations, which removes the laborious instrument maintenance while also offering insight into real-time reef alterations as well as vessel traffic.[31] Currently, soundscape data are analyzed by trained individuals using custom algorithms.

Table 1. Overview of Proposed Biological, Chemical, and Physical Measurements for the Case Study Reefs

measurement and description	how is data collected	temporal scale	spatial scale	cost	future technology or science needs	relevant studies
reef imaging: composition and growth of reef organisms	mooring-, diver-, or AUV-based camera systems	moored cameras can be continuous	moored, <50 m^2; diver, <200 m^2 per dive; AUV, ~1200 m^2 per deployment	moored, $15−500; diver, $200−800; AUV, $15000−25000	improve power delivery, imaging sensors, image processing, and motion-detection systems	20, 66−68
soundscape: behavior of sound-producing organisms	moored or tethered hydrophone	generally hourly recordings; can be continuous	meters to kilometers	$500−5000 depending on model	streamlining data processing for non-experts	26, 69
microbes/eDNA: diversity and composition of microbes, flora, and fauna	water (60 mL to 100 L) collected and biomass sequenced using marker genes or bulk sequencing	single-point; costly autonomous samplers available	volume and collection rate scale with reef area represented	at least $50−1000 per sample	integrated reef databases for data comparison	34, 35, 45, 46
reef water metabolites: diversity and composition of dissolved metabolites in reef seawater	water (20 mL to 2 L) collected and analyzed using mass spectrometry (targeted and untargeted)	single-point	volume and collection rate scale with reef area represented	$50−100 per sample	integrated reef metabolome database; continued development of volatile methods	39
reef metabolism: reef ecosystem photosynthesis, respiration and calcification rates	acoustic Doppler instruments measure physical transport and specialized chemical sensors calculate benthic fluxes	subhourly resolution for durations of days to weeks; long-term deployable instruments in development	10−1000 m^2 depending on instrument configuration and site conditions	$30000−100000 for flux systems; additional costs for sensors and batteries	streamlining data processing; long-term systems with better sensor technology and energy solutions	49, 51
reactive oxygen species: indicate organism health and stress	diver- or vehicle-hosted chemical sensors	*in situ* sensors collect data continuously over the course of the dive	centimeter scale for each data point	~$20000 for a custom system	long-term deployable microfluidic and electrochemical sensors	55, 70
hydrodynamics: physical environment and water movement in and around reefs	moored/lowered CTD, moored ADCP, moored tilt meters, distributed temperature sensing, fiber optic cable (recorded or real-time)	time series resolving variation in seconds to interannual	point measurements; cross-shore/vertical profiles	$100−100000 for each instrument or platform	long-duration batteries, antibiofouling technology, underwater acoustic/optic data transmission and telemetry	71

Robust open-access software to support reef soundscape monitoring by nonspecialists is still needed to advance soundscape analyses and allow it to be integrated into reef monitoring protocols.

Reef Water Microbes, Metabolites, and eDNA. Given the fast rate of microbial growth and organismal-based metabolite production and consumption on reefs, microbial and/or metabolite profiles in reef water can provide noninvasive, temporally sensitive measures of reef and environmental conditions. Observations of reef water microbial communities capture microbial processes on reefs, which are often linked to water quality, macro-organismal composition, protection and conservation status, oceanographic and biogeographic patterns,[32−36] and even pathogens.[37] Additionally, reef organisms excrete distinct metabolites into reef waters, which contribute to reef biogeochemistry and microbial processes,[38−41] coral heat stress,[42] and cues for recruitment and predation processes.[43,44] Reef water also contains environmental DNA (e.g., eDNA) from eukaryotic organisms, including fish and other mobile organisms, and eDNA provides insights into reef biodiversity and community patterns.[45,46] To capture eDNA as well as microbial and metabolite patterns on reefs, discrete volumes of water are collected by divers using Niskin bottles or syringes or vessel-based sampling devices. The water is filtered, and the samples are preserved, followed by lab-based analysis, which is available at a growing number of sequencing (microbes and eDNA) and mass spectrometry (metabolomics) facilities. Data analysis can be conducted with a variety of open-access software platforms. Interpretation of data trends generally requires some experience with these data types, and further streamlining software for use on reef data sets could advance these monitoring efforts.

Increasingly, *in situ* samplers (e.g., Remote Access Samplers, McLane Laboratories, Inc.) are available for filtration and capture of eDNA and microbial biomass, allowing continuous temporal monitoring. Additionally, AUVs with integrated sampling devices will enhance the spatial coverage of measurements. As this type of approach works to identify key microorganisms, metabolites, or eDNA patterns diagnostic of reef condition, there is potential to develop specific sensors for real-time detection and reporting.

Reef Metabolism. Determining rates of photosynthesis, respiration, and calcification of reefs is a central component to reef ecosystem health monitoring. Physical−chemical approaches use changes in chemical constituents (e.g., O_2, CO_2, and alkalinity) and the transport of water across the reef to infer metabolic rates. The gradient exchange and eddy covariance techniques incorporate high-frequency physical−chemical measurements and are ideal for reef monitoring. These techniques couple temporal or spatial changes in chemical constituents with physical measurements of water turbulence to directly measure metabolic and calcification rates *in situ*[47−50] using custom-built measurement platforms utilizing commercially available sensors (e.g., refs 48, 49, and 51). These high-frequency measurements are currently limited to short time scales (days) but provide ecosystem-scale analysis (∼10−1000 m^2 spatial resolution) that incorporates all organisms that contribute to reef metabolism and calcification. Thus, physical−chemical measurements have the potential to capture entire reef ecosystem function over time and can serve as powerful indicators of reef change due to climate impacts as well as human restoration and interventions. Advancing these ecosystem-scale physical−chemical approaches for repeatable and long-term analyses of reefs, coupled with reef photomosaics, automated classification of taxa, and three-dimensional reconstructions (e.g., refs 52 and 53), could provide information-rich, detailed analyses of reef-scale rates and greatly improve our ability to monitor and diagnose reef degradation.

Reactive Oxygen Species. The reactive oxygen species (ROS) superoxide (O_2^-) and hydrogen peroxide (H_2O_2) are produced by organisms for a host of physiological reasons, including cell signaling, tissue repair, and defense.[54] While these two ROS are produced by healthy organisms, concentrations are increased in response to external stress (e.g., pathogens, heat, and light) and may indicate stress symptoms prior to visible signs (e.g., bleaching). A submersible hand-held sensor (DISCO) overcomes the challenges associated with the short lifetime of ROS (seconds to hours) to measure O_2^- within shallow reefs (<30 m).[55] A DISCO is a diver-deployed and -operated instrument, and it is most useful for measuring ROS in key indicator species and specific times, such as during potential stress events. Hydrogen peroxide may be a more ideal target for understanding the health of corals because it can cross biological membranes and thus reflects internal stress levels and also has a longer lifetime (hours to days).[54,55] Hydrogen peroxide can be measured at discrete times using a DISCO *in situ* or in filtered water samples using lab-based fluorescent or chemiluminescent instruments shortly after collection. Adapting a DISCO within a microfluidics platform and/or developing targeted electrochemical sensors for long-term autonomous deployments would enable hydrogen peroxide to be an organismal health proxy.

Hydrodynamics. Due to complex interactions among flows, atmospheric forcing, and reef terrain, coral reef hydrodynamics vary dramatically over fine spatial scales (e.g., meters) and short temporal scales (e.g., hours). This can lead to reef-scale variations in residence times, dispersal patterns, and connectivity. Even widespread deployment of an array of sensors and robotic sensing platforms may not fully capture these fine-scale dynamics. Therefore, high-resolution, high-fidelity computational simulations of reef hydrodynamics with widely used community ocean models, such as the Regional Ocean Modeling System (ROMS)[56] in conjunction with strategically positioned *in situ* and remote-sensing platforms and arrays, are crucial for bridging observational gaps in space and time, quantifying the ever-changing reef environment, and examining the influence of large-scale atmospheric and oceanographic processes on coral reefs (e.g., ref 56). The platforms and arrays should concurrently measure meteorological conditions (e.g., air temperature, humidity, winds, and solar radiation) and hydrodynamic conditions (e.g., water temperature, salinity, pressure, flow velocity, and wave period and height) over the reefs. These targeted measurements provide key data for forcing, calibrating, and validating the models, and the models provide both regional context and fine-scale variability of the reef hydrodynamic environment. These environmental measurements and modeling together provide an oceanographic backdrop for a systematic understanding of the interaction of different components of the reef biophysical systems (e.g., refs 57 and 58). Model-observation-integrated systems also provide the capacity to quantify the variability of reef parameters on the scale of meters (e.g., across a lagoon or bay) and hours (e.g., at different phases of internal waves). Meanwhile, predictive simulations with the validated models forced by projected future atmospheric and oceanic conditions will provide crucial information for more targeted reef conservation and restoration efforts and thus improve the efficiency and effectiveness of the efforts.

ROBOTS FOR ENABLING REPRODUCIBLE HIGH-RESOLUTION OBSERVATION AT SCALE

There are new types of robots (e.g., ref 59) coming online that would be ideal additions to the case study reefs. These new robots are enabled by machine learning and artificial intelligence and can safely and adaptively operate in complex, dynamic environments such as coral reefs. Precision collision avoidance and adaptive path planning capabilities, similar to what has been demonstrated in aerial vehicles (e.g., ref 60), could enable repeated sampling at low altitudes and at precise locations on the reefs that, until now, have required divers. AUVs that automatically characterize habitat types (e.g., ref 61) can also be used to adaptively target specific habitat types (such as marginal seagrass or high-coral cover habitats) with minimal prior planning and mapping.

Informative path planning (IPP) is a general class of algorithms for adaptively planning robot paths, while optimizing information gained toward answering a specific question or reducing the uncertainty in estimates of a variable of interest. IPP-based approaches have been used extensively to scale up environmental monitoring.[62,63] In the context of coral reefs, IPP-based approaches provide a natural framework for enabling robots to adaptively focus their observations to spatial and temporal locations on reefs that could inform most about changes in reef health or biodiversity. IPP-based approaches can also be used to take advantage of the vehicle and environment dynamics such as reef hydrodynamics, thus enabling much longer and more energy-efficient missions.

CASE STUDY REEFS: TOWARD HEALTH PROFILE REPORTS AND SCALABLE SENSING

Combining observations and data from multiple sensing technologies provides an opportunity to assemble a more holistic view of reefs. We envision that data will first be individually examined according to data product, to first determine typical measurement values or patterns. We believe that the wealth of data from the case study reefs will help in the development of a "profile report" that is a combined report of the values or patterns from the different types of measurements. This concept is similar to a human comprehensive metabolic panel, in which a series of parameters are measured (e.g., glucose, calcium, creatinine, etc.), and the results are listed alongside an established normal range for each measurement. The profile could augment common indices used in reef assessment and management, such as percent coral cover, providing more comprehensive parameters of the reef ecosystem.

In addition to creating a profile of the results from individual reef tests, there is an opportunity to integrate the data products emerging from each instrument or measurement (such as data from the approaches presented in Table 1 and Figure 1). Integrating data from different instruments and sensors is challenging due to the fact that these observations or their derivatives take on various forms and may have been collected over different spatial or temporal scales. This variation in data types and spatiotemporal components makes it difficult to apply standard statistical or machine learning techniques to examine the reef ecosystem. We therefore call for the development of novel machine learning and statistical approaches to characterize reef health. Approaches for semantic dimensionality reduction (for high-dimensional data such as images, sounds, or microbial communities) will need to be identified, so that all sensing modalities can be processed jointly by a neural network trained to quantify reef health into a simpler parameter. A similar approach exists for forest monitoring for management purposes.[64] Also, the Blue Cross Blue Shield Health Index quantifies ≥300 human health conditions to provide U.S. regional-based health assessments related to longevity and quality of life.[65]

We envision that this combined approach of examining case study reef measurements using profiles in an integrated fashion will help us identify key parameters that may be most indicative of reef health. To enable a rapid reef diagnostics platform, sensors need to be developed for identified physical, chemical, and biological targets of reef health, which would provide a mechanism for scaling these measurements to reefs beyond the case study reefs, such as reefs undergoing restoration or other interventions.

Our vision is to leverage new technologies and research that provide a holistic accounting of the diverse components that comprise biodiverse and complex reef systems. This information could help us develop specific indicators of anomalies in reef systems that will facilitate diagnosis of the connections between changes and reef health, ultimately serving as a quantitative measure of intervention success. Importantly, universally consistent measures that holistically capture reefs will empower further studies that deepen our understanding of ecological links between organisms living in or close to reefs that are essential for the development of intervention strategies for reefs. We envision a path through which key parameters of reef health are identified using a suite of advanced sensors and instruments within case study reefs. Ideally, this approach could facilitate the development of affordable, real-time versions of a reef health monitoring system that can be applied globally to even remote reef locations.

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Notes

The authors declare no competing financial interest.

Biography

Dr. Amy Apprill is an Associate Scientist at the Woods Hole Oceanographic Institution (WHOI) and Team Leader of WHOI's Reef Solutions Initiative. The Reef Solutions Initiative is a team of interdisciplinary scientists and engineers who are focused on finding solutions to the coral reef crisis. Their convergence research approach integrates knowledge, expertise, and methods across disciplines to develop and apply novel technologies and experimental frameworks to enable solutions that will help save coral reefs and the coastal communities that reefs protect and support. The team is excited to collaborate with the larger coral reef, ocean observing, and technology communities to work toward a new era of coral reef monitoring.

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