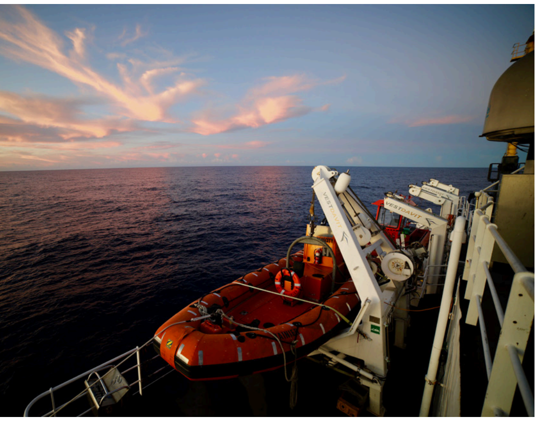
NOAA Coral Reef Conservation Program

National Coral Reef Monitoring Plan





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Authors: Written by the National Coral Reef Monitoring Program (NCRMP) Plan Working Group, listed alphabetically: Mary E. Allen, Hannah Barkley, Nicole Besemer, Jeremiah Blondeau, Courtney Couch, Jacqueline De La Cour, Kimberly Edwards, Ian C. Enochs, Chloe Fleming, Erick Geiger, Sarah Gonyo, Laura Jay Grove, Sarah Groves, Ariel Halperin, Sarah Hile, Chris Jeffrey, Matthew W. Johnson, Tye Kindinger, Jennifer L. Koss, Caitlin Langwiser, Gang Liu, Derek Manzello, Kaylyn McCoy, Harriet Nash, Sarah O'Connor, Thomas Oliver, Francisco Pagan, Tauna Rankin, Seann Regan, Jennifer Samson, Laughlin Siceloff, Joy Smith, Dione Swanson, Erica K. Towle, Bernardo Vargas-Angel, T. Shay Viehman, Bethany Williams, and Ben Zito.

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Message from the Director and Monitoring Program Coordinator

NOAA's Coral Reef Conservation Program administers a gold-standard coral reef monitoring program that covers U.S. states and territories. The monitoring effort integrates benthic, fish, climate, and socioeconomic data to provide a more comprehensive view of the current and future state of the nation's coral reefs.

This updated national monitoring plan found here reflects our strong commitment to collaboration among the different NOAA line offices, programs, and labs participating in monitoring efforts, and chronicles forward-looking improvements and efficiencies. Like the strategic plan for NOAA's Coral Reef Conservation Program, this plan was written to be adaptive, which means future updates will be needed to reflect the constantly changing state of the science, the resource, and recognized best practices for conservation and restoration.

Since the formal inception of our National Coral Reef Monitoring Program in 2013, the data collection teams have gone through at least one, if not several, cycles of repeat data collections for each jurisdiction. We are proud to be at the point in the program's maturity where we can start documenting trends in addition to providing status reports.

Also expanding: the possibilities for using the monitoring data to inform and contextualize science-based decision making and natural resource management. With this report we showcase our commitment to increasing the creation of products and tools that help officials and citizens take full advantage of this wealth of data as they work to protect and restore our nation's coral reefs.

For more information about this document and these programs, please email *erica.towle@noaa.gov* or visit *www.coralreef.noaa.gov*.

Sincerely,

Jennifer L. Koss, Coral Reef Conservation Program Director

Erica K. Towle, Ph.D., NOAA Coral Reef Monitoring Program Coordinator

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Acknowledgments

The National Coral Reef Monitoring Program would like to thank our partners, including NOAA, federal, state, and academic scientists, who commit time and sampling effort for coral reef surveying every year and in all jurisdictions. Your collaboration is greatly appreciated. This national program would not be possible without you.

Additionally, we thank Chris Kinkade and Nina Garfield, from NOAA's Office for Coastal Management, for their review of this plan. The scientific results and conclusions, as well as any views or opinions expressed herein, are those of the author(s) and do not necessarily reflect the views of NOAA or the Department of Commerce.

Executive Summary

The National Oceanic and Atmospheric Administration (NOAA) Coral Reef Conservation Program (Coral Program) invests approximately $5 million of its annual operating budget to support the National Coral Reef Monitoring Program (NCRMP) for biological, climate, and socioeconomic monitoring throughout the U.S. Pacific, Atlantic, Caribbean, and Gulf of Mexico coral reef areas.

The monitoring program is unique for its national scale across a vast geographic area as well as its progressive inclusion of social science integrated with biophysical science. The effort provides a consistent flow of information about the status and trends of environmental conditions, natural resources, and the people and processes that interact with coral reef ecosystems. The overarching goal is to collect the scientific data needed to evaluate changing conditions of U.S. coral reef ecosystems, which are among the most biologically diverse and economically valuable ecosystems on earth, providing billions of dollars in food, jobs, recreational opportunities, coastal protection, and other important ecosystem services.

This publication updates the original monitoring plan (2014) and defines the national coral reef monitoring effort. Results are reported through periodic jurisdictional and national-level status and trends reports. Data are used to help evaluate the efficacy of place-based investments in coral reef conservation, which in turn help ensure that the Coral Program's goals and objectives are achieved, and that U.S. coral reef ecosystems—and the communities that depend on them—benefit from conservation activities.

This plan builds upon over nine years of work since the inception of the national monitoring program in 2013. The program focus remains on four monitoring themes: benthic community structure, fish community structure, climate impacts, and socioeconomic condition.

- Within the benthic theme, the core indicators include: coral species abundance and size structure, coral diversity, coral condition, benthic percent cover, key coral and mobile invertebrate species, and reef rugosity.
- Within the fish theme, the core indicators include: fish species abundance and size structure, fish diversity, and fish key taxa. Benthic and fish monitoring are conducted using a diver-based stratified random-sampling design throughout shallow water coral reefs (0-30 m).
- Within the climate theme, the core indicators include: temperature stress, thermal structure, carbonate chemistry, coral growth rate, carbonate budget, and community structure. Satellite monitoring of regional thermal stress (heat stress) complements *in situ* measurements of ocean temperature. Carbonate chemistry water sampling is conducted at a subset of the stratified random biological survey sites in every jurisdiction, as well as at a smaller number of fixed stations with variable configurations of instrumentation, including ocean acidification monitoring buoys at five locations.
- Socioeconomic monitoring is conducted using human dimension surveys of a random sample of residents in each populated jurisdiction approximately every seven years.

The Coral Program continues to support jurisdictional monitoring activities that occur at more refined spatial scales and address specific local or jurisdictional management needs. The monitoring program purposefully seeks opportunities to work with partners to enhance the value of joint observations and maximize the value of conservation activities.

Introduction

Coral reefs provide an estimated $9.9 trillion in net benefits in goods and services to world economies each year, including tourism, fisheries, and coastal protection (Costanza et al. 2014), and an estimated $3.4 billion annually in total economic value to the U.S. (Brander and van Beukering 2013).

The Coral Reef Conservation Act of 2000 (CRCA 2000) authorized a national program that includes "monitoring [and] assessment . . . that benefits the understanding, sustainable use, and long-term conservation of coral reefs and coral reef ecosystems." Since 2001, NOAA's Coral Reef Conservation Program has produced sound scientific information on coral reef ecosystems under the legislation's broad mandate of "assess and characterize U.S. coral reefs."

In 2010, the Coral Program began to develop the National Coral Reef Monitoring Program (NCRMP) as it exists today to ensure consistent and standardized monitoring efforts. The national monitoring program is a strategic framework for conducting sustained observations of biological, climatic, and socioeconomic indicators in all U.S. states and territories with shallow, tropical coral reefs. The resulting data provide a robust picture of the condition of U.S. coral reef ecosystems and the communities connected to them.

The Coral Program commits approximately $5 million annually for this monitoring effort, including data collection, analyses, dissemination, annual reporting, and coordination. The original monitoring plan (NOAA, 2014) was the culmination of many workshops to develop and refine it as the standardized national monitoring program that it is today. Implementation formally began in 2013, and since then, improvements have been made to maximize efficiency in data collection. This 2021 update reflects the current suite of indicators (see Table 1) and describes the methods employed. Much of this 2021 plan is consistent with the original; however, some indicators have been refined, added, or removed based on practicality and feasibility.

Geographic Coverage

The National Coral Reef Monitoring Program surveys shallow water (0-30m) tropical coral reef ecosystems in the following Coral Program priority geographic areas (Miller et al. 2011):

- American Sāmoa
- Commonwealth of the Northern Mariana Islands
- Guam
- Hawaiʻi, including the Main Hawaiian Islands and the Northwestern Hawaiian Islands
- Florida, from Martin County through the Dry Tortugas
- East and West Flower Garden Banks
- Pacific Remote Island Areas, including Wake, Johnston, Palmyra, and Kingman Atolls and Howland, Baker, and Jarvis Islands
- Puerto Rico
- U.S. Virgin Islands

NCRMP was developed to support conservation of the nation's coral reef ecosystems through evaluating the status and trends of the core indicators (Table 1). This plan details a long-term approach to provide a cohesive, NOAA-wide ecosystem approach to monitoring benthic, fish, climate, and socioeconomic indicators in a consistent and integrated manner. Through the implementation of this plan, the Coral Program can clearly and concisely communicate results of national-scale monitoring to national, state, and territorial policy makers, resource managers, policy makers, and the public on a periodic basis.

Themes, Key Questions, and Indicators

The Coral Program's national status and trends monitoring focuses on four priority themes with indicators defined for each of the themes (see Table 1):

- reef-associated benthic communities (emphasizing scleractinian corals)
- reef-associated fish communities
- climate change resilience and adaptation (thermal/heat stress and ocean acidification)
- human dimensions related to perceptions of, and interactions with, coral reef ecosystems

The key monitoring questions to address to support conservation of the nation's coral reef ecosystems include, but are not limited to:

1. What is the *status* of U.S. coral reef ecosystems?
    a. What is the status of coral reef biota?
    b. What is the status of human knowledge, attitudes, and perceptions regarding the importance and uses of coral reefs?

2. What are the *trends* in conditions of U.S. coral reef ecosystems?
    a. How is the community structure of coral reef biota changing over time?
    b. How are temperature and carbonate chemistry in waters surrounding coral reefs changing over time?
    c. How are human uses of, interactions with, and dependence on coral reefs changing over time?

In addition to answering these foundational questions, the monitoring program is also starting to use these data to investigate ecological processes underpinning emerging patterns, as well as to compare patterns and processes in natural habitats to those at coral restoration sites. Data needed to answer questions that are outside of the core indicators as identified by this program (Table 1) may be acquired via partnerships, or through complementary sampling efforts.

The monitoring program strives for sound scientific approaches for meeting the indicator requirements, but acknowledges that logistical considerations, particularly between the Atlantic/Caribbean and Pacific basins, may require some differences in specific methods. This is interpreted to require methodological consistency within a jurisdiction over time, but allows limited differences across regions and jurisdictions, *where necessary*. Therefore, for each indicator (see Table 1), specific approaches are detailed in their section in the plan where they vary due to funding or logistics considerations between the Atlantic/Caribbean, which is conducted biennially via small boat operations, and the Pacific, which is conducted triennially via ocean-going NOAA ship operations.

Table 1: National Coral Reef Monitoring Program Themes and Core Indicators

Theme	**Indicator**
Biological - Corals and Benthos	Coral species abundance and size structure
	Coral condition (bleaching and disease incidence, partial mortality)
	Benthic percent cover
	Benthic key species
	Rugosity
	Coral diversity
Biological - Reef fish	Fish species abundance and size structure
	Fish diversity
	Key fish taxa
Climate - thermal (heat) stress	Temperature
	Vertical thermal structure
Climate - Ocean Acidification and Ecological Impacts	Carbonate chemistry
	Coral growth rates
	Carbonate budgets (accretion and bioerosion rates)
	Community structure
Socioeconomics	Participation in coral reef activities
	Perceptions of resource conditions

Theme	Indicator
	Attitudes toward coral reef management strategies
	Awareness and knowledge of coral reefs
	Cultural importance of reefs
	Awareness of coral reef rules and regulations
	Participation in behaviors that may improve coral reef health
	Population changes and distribution
	Economic impacts of coral reef fishing
	Economic impacts of dive/snorkel tourism in coral reefs
	Physical infrastructure
	Community well-being
	Governance

Partnerships

The National Coral Reef Monitoring Program welcomes opportunities to work with partners to leverage and optimize the ability to effectively monitor the status and trends of the nation's coral reef ecosystems. The Coral Program continues to support jurisdictional monitoring outside of the national program's effort via domestic grants to the states and territories. These monitoring activities are generally at smaller spatial scales, address more direct management needs, or may address different questions than national-level status and trends monitoring. Jurisdictional monitoring programs can benefit from the broad spatial context that the national effort can provide, and the program strives to work closely with these local monitoring programs. The Coral Program also continues to support monitoring to address targeted management effectiveness questions, such as the efficacy of marine protected areas (MPAs) or the impacts of watershed restoration work upland of priority reefs.

Partnerships with the state, territorial, and local governments of American Sāmoa, the Commonwealth of the Northern Mariana Islands, Florida, Guam, Hawaiʻi, Puerto Rico, and the U.S. Virgin Islands, as well as federal agencies (including U.S. Environmental Protection Agency, U.S. Fish and Wildlife Service, U.S. Geological Survey, U.S. National Park Service), academic institutions (including Nova Southeastern University, University of Hawaiʻi, University of Miami, University of Puerto Rico, and University of the Virgin Islands), and non-governmental and private organizations (e.g., The Nature Conservancy, HJR Reefscaping, Coastal Survey Solutions) will continue to contribute valuable monitoring data (particularly at various long-term fixed-site locations), logistical support for field operations, scientific research, and statistical analyses that will contribute to the implementation of the national monitoring program and status and trends assessments. Additionally, the Coral Program coastal management and coral liaisons as well as the Coral Program fisheries liaisons to each jurisdiction are critical to monitoring success.

A partnership with the NOAA Ocean Acidification Program and Pacific Marine Environmental Laboratory enables the National Coral Reef Monitoring Program' carbonate chemistry measurements in Coral Program priority areas, as well as support both programs' scientific goals regarding ocean acidification (Feely et al. 2010; Gledhill and Tomczuk 2012). This partnership allows the corals monitoring program and the Ocean Acidification Program to assess coral reef ecosystem ecological responses to ocean acidification (e.g., changes to coral reef carbonate budgets, coral growth rates, accretion, and bioerosion). These important and informative indicators include: targeted benthic community characterization, fine-scale rugosity assessments, indices of cryptic biodiversity, coral coring, and crustose coralline algae recruitment and accretion rate monitoring.

Partnerships with the NOAA Office of National Marine Sanctuaries, including the Florida Keys National Marine Sanctuary, the Flower Garden Banks National Marine Sanctuary, the National Marine Sanctuary of American Sāmoa, and the Papahānaumokuākea Marine National Monument, support the biological and climate monitoring in various ways, including sharing vessels and field staff. Coral monitoring teams work closely with National Sanctuary personnel to ensure that monitoring meets management needs for coral reef ecosystem data, and to increase efficient and effective cost-sharing and resource leveraging to extend the coral reef monitoring investment.

Partnerships with the NOAA Integrated Ocean Observing System Program and regional associations, including the Caribbean Regional Association for Coastal Ocean Observing, Gulf of Mexico Coastal Ocean Observing System, Pacific Islands Ocean Observing System, and the Southeast Coastal Ocean Observing Regional Association, support data dissemination and delivery, data standards, and *in situ* instrumentation at the coral reef monitoring program's climate stations.

The National Coral Reef Monitoring Program's scientific and technical staff members are supported by the Coral Program and across four NOAA line offices and many program offices including: NESDIS Center for Satellite Applications and Research, NMFS Pacific Islands Fisheries Science Center, Southeast Fisheries Science Center, NOS Office for Coastal Management, NOS National Centers for Coastal Ocean Science, and OAR Atlantic Oceanographic and Meteorological Laboratory. Support for data stewardship is provided by the Coral Reef Information System, NESDIS National Centers for Environmental Information, and the NOAA Central Library. Support for NOAA ship operations is provided by the Office of Marine and Aviation Operations.

Goals and Coral Program Strategic Plan Support

The goals of National Coral Reef Monitoring Program are to:

- develop and implement consistent and comparable methods and standard operating procedures (SOPs), which detail specific field, laboratory, and/or analytical procedures and best practices, for all indicators (with periodic updates to reflect new technologies or logistical considerations).
- develop and maintain strong partnerships with federal, state/territory, and academic partners.
- collect scientifically sound, geographically comprehensive biological, climate, and socioeconomic data in U.S. coral reef areas.
- deliver high-quality data, data products, and tools to the coral reef conservation community.
- provide context for interpreting results of localized monitoring.
- provide periodic assessments of the status and trends of the nation's coral reef ecosystems.
- contribute to the advancement of NOAA's Coral Program Strategic Plan as a cross-cutting function.
- contribute to local capacity-building through its engagement of jurisdictional entities and private-public partnerships involved in NCRMP data collection.

While the program is not a stand-alone pillar in the Coral Program's most recent strategic plan (NOAA Coral Program 2018), it is integral to assessing progress towards long-term conservation goals:

- Corals: By 2040, resilient, genetically diverse, reproductively viable populations of key coral species have been restored or preserved to maintain ecosystem function in key reef sites.
- Fisheries Taxa: By 2040, 100 percent of key coral reef fisheries taxa have stable or increasing abundance and average size in U.S. waters.
- Water Quality: By 2040, 100 percent of key watersheds have stable or improved water quality.
- Coral Recruitment Habitat: By 2040, at least 40 percent of the consolidated substrate at key reef sites remains free of sediment and macroalgal cover and hosts conditions that support recruitment.

The monitoring program is also making important contributions to the advancement of the four pillars (climate, fisheries, pollution, and restoration) in the aforementioned strategic plan. Of note, this monitoring data is used to help the Coral Program meet the following targets:

- Target C1.3: By 2022, NOAA is collecting data and providing technical assistance to support the jurisdictions to integrate modeling and monitoring efforts, including status and trends monitoring, response monitoring, effectiveness monitoring, and reassessments of climate vulnerability.
- Target F1.1: By 2022, the Coral Program's fish monitoring data can be statistically compared with data from at least five partners' monitoring programs and shared in a way that managers would use.
- Target F1.2: By 2024, 75 percent of key MPAs have baseline and performance assessments completed.

- Target F1.3: By 2026, 75 percent of key coral reef fisheries taxa have completed stock or population assessments that inform current stock or population status and provide quantitative management advice.
- Target L1.3: By 2024, the efficacy of key erosion and sediment control practices and stormwater management practices to reduce sediments or nutrients is quantified.

Implementation

National Coral Reef Monitoring Program (NCRMP) implementation began in fiscal year (FY) 2013 with six implementation teams (Biological-Atlantic, Biological-Pacific, Climate-*in situ*-Atlantic, Climate-*in situ*-Pacific*,* Climate-Satellite, and Socioeconomic) conducting field work and remote sensing activities, developing methods and protocols, and engaging with partners and stakeholders to refine NCRMP operations and analyses. Major accomplishments between FY13-FY21 include, but are not limited to:

- Completion of the first full cycle (all seven inhabited jurisdictions) of NCRMP socioeconomic surveys.
- Seven NCRMP cruises in the Pacific Islands states and territories to collect NCRMP biological and climate data (2013-2019) *Note no cruises in 2020 and 2021 due to the COVID-19 global pandemic.
- Nine years of NCRMP missions in the Atlantic/Caribbean/Gulf of Mexico territories to collect NCRMP biological and climate data (2013-2021) *Note that some small-boat-based missions did occur during the COVID-19 global pandemic due to partner efforts.
- Completion of the first NCRMP Data Summary Report for managers (2018).
- Completion of five NCRMP Pacific jurisdiction status reports for policy makers and the public (2018).
- Completion of five NCRMP Atlantic jurisdiction status reports for policy makers and the public (2020).
- Completion of the NCRMP National status report for policy makers and the public (2020).

Specific details of NCRMP activities have evolved during the first nine years (FY13-21) as new methods, protocols, and data management tools were evaluated and new partners across the U.S. were engaged. In the future, as new technologies become available and as resources and partnerships change, NCRMP implementation may continue to adaptively change as well.

Biological Monitoring

NCRMP monitoring of coral reef ecosystems focuses on status and changes in the benthic community, with emphasis on the reef-building corals and on the assemblages of reef fishes that utilize the coral reef environment. Reef calcifiers (such as corals, crustose coralline algae, calcified macroalgae, and foraminifera), gorgonians, and certain sponges provide architectural complexity and critical structure for reef fishes and other benthic organisms that comprise coral reef diversity. Reef fish populations can be depleted by human activities such as fishing, and by habitat degradation from factors such as land-based sources of pollution and climate change impacts. NCRMP biological monitoring is intended to address a broad range of needs for NOAA and for the wider management and science community while staying within the required funding constraints. For example, data collection and analysis can inform the efficacy of management and restoration strategies and implemented policies in achieving their targeted objectives.

For the benthic component, priority is given to scleractinian coral population structure and benthic cover. For coral species that are listed or may be listed under the *U.S. Endangered Species Act* (ESA 2002), NCRMP can contribute presence/absence data; however, fulfilling the additional requirements for monitoring and status assessment under ESA is outside the current scope of NCRMP. For the fish component, not all taxa are equally targeted. For some groups of fishes— cryptic, nocturnal, schooling pelagic and semi-pelagic species (e.g., scad)—NCRMP records data when they are encountered during surveys, but survey designs are not optimized for these species. While NCRMP recognizes that species-specific coral reef fish information is highly useful for jurisdictional and federal fisheries management, achieving species-specific population information, especially for rare or patchily distributed species, may require more intense sampling than is feasible within NCRMP alone.

Survey Design

The overall NCRMP survey design is optimized for the scale of the NCRMP reporting units (typically island or sub-island scale; Table 2), rather than providing comprehensive information at single site or small-scale local spatial scales. The target domain for NCRMP includes reef habitats down to 30 meters within the Coral Program's geographic priority coral reef areas. NCRMP has adopted the general principle of geographically comprehensive monitoring, i.e., that the broad goal is spreading sampling effort widely across reefs within each jurisdiction, rather than focusing effort at "representative" stations, given concerns that identifying such stations is an inherently subjective and unreliable process (Rodgers et al. 2010). The most appropriate means to ensure that biological survey data are representative of the target domain is to randomize site locations within that domain. Data quality is generally optimized (e.g., variance minimized) by stratification of the target domain. Depending on the quality and extent of available bathymetry and habitat, NCRMP stratifies using combinations of depth (e.g., shallow, medium, deep), reef zone (forereef, backreef, etc.), habitat type (e.g., spur and groove, colonized pavement), and management zone (e.g., MPA, no-take area). Thus, optimum stratification is specific to reporting units. Within the NCRMP stratified random design for biological monitoring, development and subsequent fine-tuning of stratification schemes is led by the NCRMP biological monitoring implementation teams (including NOAA scientists and external partners) in each jurisdiction.

Resulting data have value at several scales:

1. Jurisdictional Scale (e.g., Guam, Puerto Rico)**:** This is the highest level of reporting. NCRMP annual data reports are developed per jurisdiction. Jurisdictions generally include at least several hundred kilometers of coastline where reefs are found, and typically encompass large variations in anthropogenic pressure and reef condition. Therefore, although NCRMP data are reported at a jurisdictional scale, NCRMP monitoring designs also generate useful data at smaller, more ecologically similar, and more management-relevant scales.

2. Sub-Jurisdiction (reporting unit) Scale (e.g., Florida Keys within Florida, or by island within the Main Hawaiian Islands, see Table 2)**:** Sub-jurisdictions are regions within jurisdictions, which are generally the minimum reporting units for NCRMP data, i.e., they are spatial units that are small enough to have ecological and management-relevant meaning, but large enough that NCRMP can sample each reporting unit with sufficient levels of replication to generate acceptable levels of data quality (e.g., coefficient of variation within target limits).

3. Site Scale (limited use): Individual “sites” are randomized survey locations sampled by a team of divers, generally during a single dive. Single sites may be sub-sampled (e.g., there may be replicate surveys, transects, quadrats, or other measures at a single site). Site-level data are estimated values that typically represent less than an hour’s effort over a few hundred square meters. While it might be meaningful to represent site-level data in plots of data from multiple sites (e.g., bubble plots), survey data generally have limited value at the site scale, and are pooled at higher scales to become useful for broad-scale monitoring purposes.

Collecting biota and habitat data from the same sample sites greatly increases the scope for interpreting fish and benthic survey data. Climate theme water samples are also co-located with fish and benthic sites to allow for analysis at higher spatial scales. A critical question for NCRMP is the amount of effort necessary to generate meaningful and useful coral reef monitoring data at the scale of a national program. As a basis for estimating necessary effort (replication), NCRMP uses precision (measured as the coefficient of variation [CV = SE/mean]) as the core measure of data quality. CV is a useful measure of data quality because it is a scale and unit independent measure, and because it can be directly related to confidence intervals (for other than very small samples, the 95% confidence interval is ~± 2 CV). Values of CV vary depending on the parameter of interest, survey method, inherent variability of the sample area, level of survey effort, optimization of the survey design, and observers’ experience, skill, and training.

Table 2: Geographic Reporting Units for Biological and Climate Monitoring. Sub-jurisdictions within the ten Coral Program priority geographic areas constitute the minimum reporting units for NCRMP biological and climate monitoring.

Jurisdiction	**Sub-reporting Regions**
Florida	Southeast Florida
	The Florida Keys
	The Dry Tortugas
Puerto Rico	No sub-jurisdiction reporting units
U.S. Virgin Islands	St. Thomas and St. John
	St Croix
Flower Garden Banks	East and West Bank
American Sāmoa	Tutuila

Jurisdiction	Sub-reporting Regions
	Ofu and Olosega
	Ta‘ū
	Swains
	Rose Atoll
Main Hawaiian Islands	O‘ahu
	Kaua‘i
	Kaho‘olawe
	Maui
	Lāna‘i
	Hawai‘i
	Ni‘ihau and Lehua
Northwestern Hawaiian Islands	Pearl and Hermes Atoll
	Kure Atoll
	Lisianski
	French Frigate Shoals
Mariana Archipelago (Guam and the Commonwealth of the Northern Mariana Islands)	Guam
	Rota

Jurisdiction	Sub-reporting Regions
	Tinian and Aguijan
	Saipan
	Sarigan, Guguan and Alamagan
	Pagan
	Agrihan
	Asuncion
	Maug
	Urracas
Pacific Remote Island Areas	Johnston Atoll
	Wake Atoll
	Howland
	Baker
	Jarvis
	Palmyra Atoll
	Kingman Atoll

Coral and Benthos Monitoring

Coral abundance, size structure, condition, and diversity:

NCRMP provides data on coral population demographics and space utilization of selected coral species relative to their geographical and environmental range. For example, the relative proportion of small and large colonies for a particular species (i.e., size-frequency distribution) reflects the population structure, where effective juvenile recruitment (surveyed in the Pacific only), colony longevity, and the most frequent colony size indicate the relative impact of total and partial mortality (Bak and Meesters 1998), as well as physical forcing factors (Gove et al. 2013). Colony size-frequency distributions have been used to assess the impacts of bleaching, predation, and tropical cyclones (Done and Potts 1992; Mumby 1999; Gove et al. 2013), and may be particularly useful for assessing success of juvenile corals. Size-frequency distributions should change in predictable ways as reefs degrade (Bak and Meesters 1999), and populations in marginal habitats tend to have lower abundance and consequently larger coefficients of variation (Vermeij and Bak 2000). Species size-frequency distribution characteristics can be quantified mathematically (skewness, mode, coefficient of variation, etc.), allowing detection of change over time and comparison of different populations, provided sampling effort generates robust distributions. Coral population structure (size-frequency and colony density) is derived from *in situ* coral demographic surveys along belt transects that systematically assess a predetermined and replicable reef area (e.g., Smith et al. 2011).

Over the last three decades, mass coral bleaching and disease outbreaks have resulted in global reductions in coral reef diversity and resilience. Assessments of coral condition that include coral bleaching and disease are indicators of coral health and can help identify possible causes of changes in benthic community structure. Bleaching and disease are generally estimated via colony prevalence (i.e., percent of population abundance exhibiting a particular condition), which depends on reliable counts (occurrences) of individual colonies within their respective taxonomic units (species/genera), and standardized descriptions of the health condition of the individual colonies (disease/non-diseased, bleached/non-bleached). In the Atlantic/Caribbean, coral colonies in belt transects are scored for partial mortality (old and recent), bleaching (partial, total, paling, absent) and disease (present/absent). In the Pacific, coral colonies in belt transects are scored for partial mortality (old, recent), recent mortality cause (e.g., predation, disease), bleaching (extent, severity), and disease (by type, extent).

Diversity measures, combining species richness and evenness, are often used to characterize parts of coral reef ecosystems, but traditional observations do not easily capture the full range of taxonomic diversity on a reef or genotypic diversity within a species. At present, coarse richness and diversity measures for fish and corals and some sampling of cryptic diversity form the basis of NCRMP diversity assessments.

The NCRMP Benthic team (particularly in the Pacific) is exploring innovative technologies to monitor benthic communities more efficiently. One approach gaining traction in the coral reef sciences is a branch of photogrammetry known as Structure from Motion (SfM), which generates three-dimensional reconstructions of a scene from overlapping images. In a recent study, Couch et al. (2021) quantitatively compared data generated from *in situ* surveys to SfM-derived metrics for assessing coral demography to evaluate whether NCRMP can maintain continuity in our long-term data sets if the program transitions to SfM survey methods. The NCRMP Benthic team in the Atlantic is considering and evaluating a future transition to image-based benthic data collection as well, but has not begun any piloting for NCRMP purposes to date.

Benthic cover:

Benthic cover data represent the proportion of biotic and abiotic elements occupying the benthos. Each of these elements is quantified to a predetermined level of taxonomic or functional resolution. Typically, the type of substrate (e.g., hard bottom, rubble, sand) is also represented. Many coral reefs have a small percentage of cover by scleractinian corals, and other benthic components may be more important to characterizing benthic communities and habitat. Percent cover of non-coral benthos, especially for different functional groups of algae, including turfs, macroalgae and crustose coralline algae and other invertebrates (gorgonians and sponges), is the focus in this sampling approach. Changes in benthic cover can reflect the integrated effects of a set of environmental and disturbance regimes that characterize each reef system (Rogers et al. 1994; Jokiel et al. 2005; Gove et al. 2013). Where the total percent of live coral is very low (generally ≤ 10%), it becomes more difficult to detect changes in abundance or composition of the community. For context, all the Atlantic jurisdictions excluding the Flower Garden Banks have less than 10% coral cover as of the 2018/2019 data collection.

NCRMP derives estimates of benthic cover at sites co-located with benthic and fish survey sites. In the Atlantic/Caribbean, a diver-based line point intercept (LPI) method is used to quantify benthic cover. This approach involves tallying the benthic elements that fall under specified intervals along transects of predetermined length (e.g., Smith et al. 2011, NOAA 2021). In the Pacific, benthic cover is derived from point counts on sequential photo quadrat images of the benthos acquired along belt transects. Images are analyzed in the widely used machine-learning software, CoralNet (coralnet.ucsd.edu; Beijbom et al. 2015). Human annotators use the semi-automated annotation mode to identify/classify benthic features where CoralNet returns a 75% certainty, and the remainder of the points are manually annotated.

Benthic key species and rugosity:

“Key” benthic species are those that can have profound ecological effects on reef communities (*e.g.*, the Indo-Pacific corallivorous crown-of-thorns-starfish *Acanthaster planci*; the Atlantic/Caribbean sea urchin *Diadema antillarum*). In the Pacific, COTS predation scars, prevalence, and size are estimated from transect, colony-level surveys. In the Atlantic/Caribbean, fine-scale benthic transects capture density and distribution data of long-spined sea urchin *Diadema antillarum,* queen conch *Aliger gigas,* and Caribbean spiny lobster *Panulirus argus*. The presence and abundance of ESA-listed coral species are also recorded. In the Atlantic/Caribbean, these include *Acropora cervicornis, A. palmata, Dendrogyra cylindrus, Mycetophyllia ferox, Orbicella annularis, O. faveolata, and O. franksi.*

Rugosity is a measure of the topographic complexity and the three-dimensionality of the coral reef (i.e., reef structural complexity, physical relief). Rugosity is currently quantified in the Atlantic using small-scale *in situ* methods, in which divers measure the height of the seafloor along transect intervals (NOAA 2021). The increasing availability of high-resolution geo-rectified bathymetry from habitat mapping (e.g., collected via LiDAR or multibeam sonar) allows for computer-based calculations of structural complexity at multiple spatial scales from meters to much larger. In the Pacific, NCRMP is testing Structure-from-Motion photogrammetry methods to extract high-resolution structural complexity metrics such as rugosity, substrate height, fractal dimension, and slope across StRS and climate stations (60-100m^2/site). Coarse-scale rugosity data (Brandt et al. 2009) is visually estimated, and useful as an explanatory variable for fish at co-located sites; fine-scale rugosity data from digital imagery are collected at the climate Class III stations.

Reef Fish Monitoring

Fish abundance, size structure, and diversity:

NCRMP fish surveys gather data on the number and size of reef fishes within sample units at the lowest feasible taxonomic resolution (typically species level). This abundance data can be converted to a range of diversity indicators, including richness per sample unit, as well as calculated diversity and evenness measures. Similarly, information on size and numbers allows for the calculation of density and biomass per taxon or functional group, with biomass estimated using species-specific length-to-weight conversion parameters available from a range of published and Web-based sources (e.g., FishBase 2000; Kulbicki et al. 2005). The working group set a minimum data quality of CV of 20% (i.e., 95% CI of 40%) for the biomass of four fish groupings: all herbivorous fishes, all piscivorous fishes, all reef fishes combined, and parrotfishes. That level of data quality scales to a minimum CV of ≤ 10% at the jurisdictional level.

Teams in both basins currently use stationary point count (SPC) fish survey methods (Bohnsack and Bannerot 1986; Ault et al. 2006; Smith et al. 2006; Brandt et al. 2009; Richards et al. 2011; Williams et al. 2011). This survey method provides the abundance, size, and species of reef fishes. Survey design and methods were chosen to optimize use of these data in stock assessments.

Key fish taxa:

“Key taxa” for this purpose are representative coral reef fisheries taxa that are particularly vulnerable to overfishing, ecologically important to coral reef health, good indicators for status of other fisheries species or ecosystem health, and are lacking key life history or population status information needed for management. They are a subset of jurisdictions' priority species/taxa that the Coral Program will use to track progress towards achieving stated targets within Fisheries Pillar strategies in the strategic plan (NOAA Coral Program 2018). These include:

AS, CNMI, GU, HI, PR, USVI: Parrotfish Family/Subfamily (Scaridae/Scarinae)
AS, CNMI, GU, HI, PR, USVI: Surgeonfish Family (Acanthuridae)
FL, PR, USVI: *Lachnolaimus maximus*
FL, PR, USVI: *Lutjanus griseus*

NCRMP sampling generally captures sufficient observations of key taxa and other commercially important families (snappers, groupers, triggerfish, etc.) for abundance indices or other fisheries management uses. Although not designed for this targeted purpose, NCRMP sampling may also capture observations of rare and/or vulnerable species (e.g., sharks, large-bodied parrotfish [*Bolbometopon muricatum, Scarus guacamaia*, *S. coeruleus*, etc.], large groupers, etc.), including those that are ESA-listed. These fishery-independent observations can be especially informative regarding the presence of such species in locations not targeted by other survey efforts.

Climate Monitoring

Rising ocean temperatures and ocean acidification are having profound influences on the nation's coral reef ecosystems. By altering the fundamental physical and chemical environment within which coral reef organisms reside, long- term changes in climate will likely affect vital physiological and ecological processes and ecological functions of coral reefs. Increases in ocean temperatures have already negatively impacted coral reefs globally through widespread mass coral bleaching, enhanced disease outbreaks, and resultant mortality (Williams and Bunkley-Williams 1990; Wilkinson and Souter 2008; Eakin et al. 2009; Eakin et al. 2010). Corals that survive the increasing number of severe, long-lasting, and/or repeat stress events are usually immunocompromised and have impaired reproduction and growth for years after the heat stress subsides. Furthermore, a mounting number of studies suggest that ocean acidification, the process in which rising levels of atmospheric CO_2 absorb into sea surface waters and change the ocean's chemistry, could significantly impact coral reef ecosystems over the next several decades (Langdon and Atkinson 2005; Kleypas et al. 2006; Hoegh-Guldberg et al. 2007; Ricke et al. 2013).

Status and trends in ocean temperature (thermal stress) and carbonate chemistry (ocean acidification) were chosen as NCRMP core indicators based on the expectation that changes over time in these two indicators will cause the most significant synoptic impacts to coral reef ecosystems and their ability to deliver essential ecosystem goods and services at regional, national, and global scales. Monitoring these parameters is achieved through a synthesis of remotely-sensed, moored, and discrete observations that provide regional sea surface temperature patterns, *in situ* vertical thermal structure, and carbonate chemistry observations. These observations are supplemented with targeted and repeated ecological observations at key climate and ocean acidification monitoring sites. Collectively, these thermal stress and ocean acidification monitoring observations provide information essential to tracking the impacts of climate change within the nation's coral reef ecosystems, and serve as critical validation datasets to ongoing climate and ocean acidification risk/vulnerability modeling both within and external to NOAA.

Thermal stress:

Ocean temperatures have increased globally over the last century and have directly resulted in the loss of significant coral reef resources (Parry et al. 2007). Globally, thermal stress events in coral reef areas are becoming increasingly common and more severe (Baker et al. 2008; Eakin et al. 2009; Strong et al. 2009; Hughes et al. 2018; Hughes et al. 2018; Eakin et al. 2019; Leggat et al. 2019;) and have directly resulted in mass coral bleaching and mortality (Wilkinson 2000; Eakin et al. 2010). Anomalously warm summer (and winter) temperatures have also been correlated with more frequent and severe coral disease outbreaks (Bruno et al. 2007; Heron et al. 2010). Within coral reef environments, water temperatures exhibit spatial and temporal variability through complex and dynamic physical oceanographic processes (e.g., Leichter et al. 1996), including surface heat and buoyancy fluxes, and current-topographic interactions (Gove et al. 2006; Leichter et al. 2012). Analyses of existing time-series data comparing surface and subsurface *in situ* temperatures from around the U.S. Pacific reveals that most reef systems are characterized by a highly complex and variable thermal structure, both within island-reef systems (Gove et al. 2006) and across regional scales, on diurnal to interannual time scales.

Sea surface temperature (SST) is a simple observation that is common to most existing *in situ* coral reef observing platforms and available through satellite remote-sensing. However, temperature at the sea surface alone can be insufficient to discern the full thermal complexities that coral reefs at depth are exposed to. Conversely subsurface temperature variability can rarely be captured solely with surface observations (Venegas et al. 2019). Understanding this variance is important in identifying potential localized bleaching refugia that may be important to coral reef resilience to climate change (Karnauskas and Cohen 2012). Elucidation of thermal structure confers insight into water movement patterns that directly influence the physical and chemical environment of coral reefs.

Satellite-based observations serve as the primary means of monitoring, in near real-time, predicting, and providing estimates of surface heat stress for all the nation's coral reefs. Data from NOAA and partner operational geostationary and polar-orbiting satellites, when blended together, provide an accurate measure of SST, from which Coral Reef Watch's operational daily global 5km satellite coral bleaching heat stress monitoring products (including SST Anomaly, Coral Bleaching HotSpot, Degree Heating Week, Single-Day and 7-Day Maximum Bleaching Alert Area, and SST Trend) and the daily 5 km satellite Regional Virtual Stations systemeks) are derived (Liu et al. 2006; NOAA Coral Reef Watch 2011; Liu et al. 2013; Heron et al. 2016; Liu et al. 2017; Skirving et al. 2020). These products provide near real-time updates of changes in the coral reef environment that can lead to bleaching, disease, and other impacts (Liu et al. 2006; NOAA Coral Reef Watch 2011; Liu et al. 2013; Heron et al. 2016; Liu et al. 2017; Skirving et al. 2020). Vertical thermal structure is monitored using *in situ* subsurface temperature recorders deployed at representative sites at three to four depths in each of the sub-jurisdictions where NCRMP biological monitoring will occur.

Ocean acidification:

The persistence of coral reefs under continued ocean acidification remains a primary concern as an increasing number of studies have measured reduced rates of calcification for many species of reef-building organisms (e.g., Leclercq et al. 2002; Marubini et al. 2003; Ohde and Hossain 2004; Langdon and Atkinson 2005; Anthony et al. 2008). Ocean acidification may also increase dissolution of reef sediments that often contain appreciable amounts of more soluble carbonate minerals (Morse et al. 2006), and may enhance bioerosion of corals and reef frameworks (Tribollet et al. 2009; Wisshak et al. 2012). Bioerosion and dissolution of reef carbonates may outpace carbonate production in some reef habitats by 2030 (Yates and Halley 2006; Ricke et al. 2013). Furthermore, present-day coral reefs that exist in upwelling zones where water chemistry is analogous to future conditions (i.e., a tripling of atmospheric CO_2) are poorly cemented and highly bio-eroded (Manzello et al. 2008). Such effects would likely compromise reef framework integrity and resilience in the face of other acute and chronic stresses, such as coral bleaching, diseases, potential increases in storm intensity, and rising sea level (e.g., Silverman et al. 2009). Other modes of expected impact include a potential lowering of the thermal thresholds for bleaching (Anthony et al. 2008) and impairment of early life stages of corals including reduced fertilization success, reduced larval settlement, and reduced growth and survival rates of newly settled corals (Cohen and Holcomb 2009; Albright et al. 2010; Morita et al. 2010; Suwa et al. 2010). Direct impacts of ocean acidification on coral growth and fitness, in combination with largely unknown potential impacts on non-calcareous competing functional groups, may profoundly affect the basic ecological interactions structuring coral reef ecosystems.

Ecological impacts:

Understanding ecological responses of marine ecosystems is needed to serve as the basis for testing the validity of climate model predictions and experimentally-derived assumptions about the impacts of climate change and ocean acidification on the natural environment. To date, most climate change research targeting biological impacts has focused on laboratory response experiments rather than examining these impacts *in situ*. The Coral Program's partnership with the NOAA Ocean Acidification Program provides an opportunity to sustain long-term *in situ* monitoring of ecological responses to climate change, and allows investigation of the relationships between biological response variables (calcification and bioerosion rates) to both physical and chemical processes.

Climate stations:

The NCRMP climate monitoring strategy includes fine temporal-resolution monitoring with moored instruments at fixed time-series sites in both the U.S. Atlantic/Caribbean and Pacific basins, complemented by broadly-distributed water sampling surveys nested within the NCRMP biological surveys within each of the sub-jurisdictions. There are four classes of NCRMP climate stations (Table 3): Class 0 represents water sampling conducted at a subset of the random stratified sites monitored by the biological teams; Classes I, II, and III represent fixed sites exhibiting an increasingly comprehensive suite of observations at fewer locations.

Table 3: Summary of the Parameters and Instrumentation Deployed at Each Type (Class) of NCRMP Climate Monitoring Station

		Class 0 random	Class I fixed	Class II fixed	Class II+ fixed	Class III fixed
Parameters	**Physical environment:**					
	Temperature	•	•	•	•	•
	Salinity	•	ǂ	ǂ	•	•
	Dissolved Oxygen (DO)				•	•
	Photosynthetically Active Radiation (PAR)				•	•
	Water velocity				ǂ	•
	Rugosity				•	•
	Carbonate chemistry:					
	Dissolved Inorganic Carbon (DIC) and Total Alkalinity (TA)	•	ǂ	ǂ	•	•
	pH				•	•
	pCO_2					•
	Ecological Impacts:					
	Coral growth rates				•	•
	Carbonate accretion rates			•	•	•
	Bioerosion rates			†	•	•
Instrumentation/ Surveys	**STR:** Subsurface temperature recorder		•	•	•	•
	Diel suite: SeaFET pH sensor, ADCP, CTD, DO sensor, PAR sensor, automated water samplers				•	•
	MAPCO2: Moored Autonomous pCO_2 buoy					•
	CAUs: Calcification Accretion Units			•	•	•
	BMUs: Bioerosion Monitoring Units			†	•	•
	SfM: Structure-from-Motion (landscape mosaic)			ǂ	•	•
	Carbonate budget assessment				†	†

•Atlantic/Caribbean and Pacific
†Atlantic/Caribbean only
ǂPacific only

Vertical thermal structure:

Observations at Class I stations provide the widest distribution of fixed sites measuring change in vertical thermal structure (for understanding thermal stress) within NCRMP. Near-surface (1 m) temperatures are the uppermost of the vertical temperature profiles, and other monitoring platforms such as the Class III buoys contain SST recorders. Subsurface temperature recorders (STR) are attached to the reef substrate at 3-4 depths in locations (primary exposures of seas and currents) around most islands or atolls in the jurisdictions. Island size and proximity are evaluated for instrumentation requirements (i.e., small islands and islands within close proximity may require less instrumentation, while large islands, island chains, or mainland areas may require more). Each STR array is deployed for 2-3 years, after which they are recovered, data downloaded, and processed. Where feasible, STRs are deployed at the site of previous monitoring efforts, thereby extending existing long-term temperature records and providing validation to remotely-sensed products.

Carbonate chemistry:

Discrete carbonate chemistry water sampling at a subset of the stratified random biological monitoring sites (Class 0 stations) provides important linkages needed to establish broad-scale spatial and temporal relationships between key biological indicators (e.g., coral cover and benthic composition) and the corresponding climate observations (thermal stress and aragonite saturation state) at regional and sub-jurisdictional scales. Carbonate chemistry water samples are collected according to best practices (Dickson et al. 2007) in concert with subsurface temperature and salinity measurements. All collected samples are processed for dissolved inorganic carbon (DIC), total alkalinity (TA), and spectrophotometric pH (Atlantic only). These spatially distributed water samples are complemented by fine-temporal-resolution observations of key physical and chemical indicators at the fixed climate change and ocean acidification monitoring sites (Class I, II, and III).

Diel variability in carbonate chemistry can be significant in coral reef environments in response to local oceanographic (e.g. residence time) and/or biological (e.g. reef metabolism) processes. To supplement daytime discrete water sampling and better constrain diel ranges in carbonate chemistry parameters, an oceanographic instrument package is deployed at many of the Class II stations. The instrument package includes automated benthic water samples, a SeaFET pH sensor, Conductivity-Temperature-Depth unit (Pacific only), Acoustic Doppler Current Profiler (Pacific only), Aquadopp current meter (Pacific only), dissolved oxygen (DO) sensor (Pacific only), and photosynthetically active radiation (PAR) sensor. Sensors are programmed to measure seawater parameters every 5-10 minutes, and water samples are collected every 3-4 hours during a one-to-two diel cycle window (24 to 48 hours). Diel ranges in pH and aragonite saturation state are derived post-recovery from DIC/TA analysis of water samples.

The spatiotemporal variability of carbonate chemistry is inherently complex, and a direct function of the interaction between physical forcing (meteorology, oceanography) and diurnally-varying reef metabolism (Manzello 2010a). As such, the near-reef seawater CO_2 system varies with temperature, salinity, tidal state, water mass residence time, light intensity, as well as the benthic community's integrated rates of organic (photosynthesis, respiration) and inorganic (calcification, dissolution) carbon metabolism. The high variability in carbonate chemistry experienced within most reef systems precludes the utility of solely obtaining discrete observations for the purpose of establishing the rate and magnitude of changes in aragonite saturation state (a key indicator of interest with regard to ocean acidification).

Moored Autonomous pCO_2 ($MApCO_2$) buoys deployed at five Class III stations provide autonomous real-time carbon dioxide aqueous partial pressure ($pCO_{2,aq}$), carbon dioxide atmospheric partial pressure ($pCO_{2,atm}$), pH, atmospheric pressure, air temperature, salinity, dissolved oxygen (DO), and relative humidity. Discrete and automated remote sampling conducted at Class III sites are used to devise algorithms to estimate carbonate mineral saturation state from autonomous observations of $pCO_{2,sw}$, salinity, and temperature, and allow for extrapolation of information collected at the Class III monitoring sites to wider areas within the jurisdiction or basin based upon the discrete sampling (Class 0 sites). This approach of fine temporal-resolution time-series sampling nested within broad spatial surveys is similar to that of other NOAA ocean acidification monitoring efforts within coastal environments, providing an internally consistent and logical extension of the NOAA-wide monitoring effort.

Both the thermal (ocean warming) and chemical (ocean acidification) ramifications of global climate change have the potential to push the calcium carbonate budget of coral reefs into a state of net erosion (Manzello et al. 2008; Manzello 2010b). Consequently, the architectural complexity of reefs is likely to continue to deteriorate as it has broadly in the Atlantic/Caribbean (Alvarez-Filip et al. 2009). Thus, it is important to monitor these changes given their potential to impact reef structure. To measure these changes, fine-scale observations of rugosity using side-scan and/or multi-beam sonar provide more habitat characterization information at each Class III station (Costa et al. 2009). High-resolution acoustic data are collected using a small-boat-based multi-beam system to collect fine-scale bathymetry and backscatter and map fine-scale rugosity. These data are post-processed to produce finalized mosaics of the bathymetry, backscatter, and derivative layers (e.g., rugosity, slope, fractals).

Coral growth rates, bioerosion rates, and community structure:

The benthic community directly surrounding each Class II and Class III site is characterized and mapped at the beginning and end of each deployment to measure coral and algal cover and benthic community structure using photo quadrats and image analysis. This is necessary to interpret and eventually model carbonate dynamics given that the community structure of benthic organisms (e.g., proportion and types of calcifiers *vs*. non-calcifiers) exerts a strong influence on the reefal water chemistry (e.g., Gattuso et al. 1997). Coral cores are collected and processed to assess historical extension and calcification rates of massive reef-building corals (primarily *Porites* spp. in the Pacific and the *Orbicella* [formerly *Montastraea*] spp. complex in the Atlantic).

Laboratory experiments have shown that crustose coralline algae (CCA), which are important calcifiers and well-known substrata for successful settlement of coral larvae, are particularly sensitive to ocean acidification (Gherardi and Bosence 2001; Webster et al. 2006; Kuffner et al. 2008). Their abundance, therefore, can be inherently linked to the resilience of coral reefs. As such, it is important to monitor long-term trends in the recruitment potential and accretion of CCA as they provide an index of reef resilience and may be first responders to ocean acidification. Calcification accretion units (CAUs), settling plates onto which CCA recruit, are deployed at the fixed Class II and III monitoring sites to systematically monitor broad-scale spatial patterns of rates of net CCA recruitment and accretion. After recovery, each plate is photographed and the net weight of accumulated calcium carbonate measured. CAU deployments and recoveries, processing, and analysis is repeated at the Class II and Class III fixed sites at 2-3 -year intervals to monitor changes over time.

The formation of reef habitat and its persistence is a function of additive calcification and the subtractive process of erosion. Biological erosion (bioerosion) is a complex process involving a diverse suite of taxa utilizing numerous behaviors and methods of reef substrate removal. Recent evidence suggests that the rate at which many of these taxa erode reef habitat may be accelerated by ocean acidification (e.g., Tribollet et al. 2009; Wisshak et al. 2012). This represents a direct mechanism by which ocean acidification will lead to reef degradation and the loss of ecosystem services. Bioerosion monitoring units (BMUs), blocks of calcium carbonate, are deployed at fixed Class II and III monitoring sites to systematically detect changes in the broad-scale spatial patterns of net reef bioerosion rates. Before deployment, BMUs are scanned using a high-resolution computed tomography (micro-CT) to assess coral block density. After recovery, they are scanned again to quantify the loss of material due to biological, chemical, and physical processes. BMU deployments and recoveries, processing, and analysis are repeated at Class II and Class III sites at two- to three-year intervals to monitor changes over time. Marine biodiversity is predicted to be indirectly impacted by climate change and ocean acidification (Worm et al. 2006; Riebesell 2008) due to alterations in community structure, functionality, relationships among organisms, and the anticipated increases in species extinctions and invasion (Ives and Carpenter 2007; Cheung et al. 2009). Much of the biomass and most of the diversity of coral reef ecosystems lies within the complex architecture of the reef matrix (Ginsburg 1983; Small et al. 1998; Knowlton et al. 2010). This community of organisms is collectively known as the cryptobiota (Macintyre et al. 1982), some of which may be vulnerable to acute direct impacts, such as habitat degradation, and chronic indirect impacts, such as climate change and ocean acidification.

Global coral cover decline has caused a reduction of reef growth. Census-based carbonate budget surveys completed at the six Atlantic class II+ climate monitoring sites constitute a holistic assessment of the current state of net habitat production or erosion at each site. These surveys are based on the Caribbean *ReefBudget* Methodology described by Perry et al. (2012). Briefly, six benthic transect surveys (10 m each) are conducted at each site to quantify benthic cover, as well as ten parrotfish surveys to account for parrotfish erosion rates. Benthic cover, as well as size-frequency data of parrotfish and urchins are used with taxon-specific rates of carbonate alteration to create a single metric for reef persistence at each site. A carbonate budget methodology for the Pacific is currently under development.

Socioeconomic Monitoring

NCRMP uses social science strategically to improve coral reef management by engaging local communities to better assess the social and economic consequences of management policies, interventions, and activities within those communities. Coral reefs contribute significant economic value to the U.S. public, and consideration of the economic value of coral reefs should lead to more effective decision-making that balances development and conservation as well as raising awareness and building public support for the protection of these valuable natural resources (NOAA Coral Program 2013). The Coral Program's *Social Science Strategy* (Loper et al. 2010; Edwards et al. 2016) prioritizes social science activities and information needs to further coral reef management in the jurisdictions. Development of national-level social science indicators, collected through jurisdictional surveys in consultation with local jurisdictional authorities/partners, constitutes two of the top three priorities under the *Social Science Strategy*, with the third calling for an increase in social science capacity within the program.

Including socioeconomic indicators in NCRMP represents a strong step forward for the Coral Program, which recognizes the need to integrate socioeconomic factors with the suite of biophysical indicators. Integration of socioeconomic factors strengthens national monitoring and improves the program's ability to explain how coral reef ecosystems and coral reef management strategies are perceived by the public -- issues of utmost interest to Coral Program partners, resource managers, and policy makers. The socioeconomic component of NCRMP collects and monitors socioeconomic information, including human use of coral reef resources, knowledge, attitudes, and perceptions of coral reefs and coral reef management, and demographics of the populations living in coral reef areas. The overall goal of the socioeconomic monitoring component is to track relevant information regarding each jurisdiction's population, social and economic structure, the benefits of coral reefs and related habitats, the perceived impacts of society on coral reefs, and the impacts of coral management on communities. The Coral Program uses this information to improve coral reef conservation programs at local, regional, and national levels, as well as to inform continuing research and communication products.

The main purpose of the socioeconomic component is to answer the following questions: *What is the status of human knowledge, attitudes, and perceptions regarding coral reefs? And, how are human uses of, interactions with, and dependence on coral reefs changing over time?* The overall approach uses indicators that were developed in consultation with stakeholders, partners and other scientists to answer the questions above. These indicators complement the biophysical indicators and inform management on the social-ecological interactions that occur in coral reef ecosystems. Two streams of data are integrated to inform the indicators for each of the seven inhabited U.S. coral reef jurisdictions: South Florida, the U.S. Virgin Islands (USVI), Puerto Rico, Hawaiʻi, American Sāmoa, Guam, and the Commonwealth of the Northern Mariana Islands (CNMI)[1]. First, residents in each coral jurisdiction are surveyed every seven years. Second, additional socioeconomic data are compiled using secondary data sources, such as the U.S. Census Bureau and local government agencies. Jurisdictional findings are then able to support national metrics. The NCRMP socioeconomic indicators are:

1. Participation in reef activities
2. Perceived resource condition
3. Attitudes toward coral reef management strategies and enforcement
4. Awareness and knowledge of reefs
5. Human population changes near coral reefs
6. Economic impact of coral reef fishing to jurisdiction c
7. Economic impact of dive/snorkel tourism to jurisdiction
8. Community well-being
9. Cultural importance of reefs
10. Participation in behaviors that may improve coral reef health
11. Physical infrastructure
12. Awareness of coral reef rules and regulations
13. Governance

[1]For Florida, this includes Monroe, Miami-Dade, Broward, Palm Beach, and Martin Counties only. For all other states and territories, the entire jurisdiction is included.

Indicators informed by NCRMP resident surveys:

Resident surveys take place in each jurisdiction approximately every seven years. The potential respondent universe for this study is adults, eighteen years or older, who live near, and may use or derive direct or indirect benefits from coral reefs affected by activities related to the Coral Program.

Jurisdictional surveys gather longitudinal information from residents in each of the seven inhabited U.S. coral reef jurisdictions. All surveys use a core set of survey questions that is consistent across all locations. NCRMP works with jurisdictional partners and stakeholders to incorporate jurisdiction-specific items into certain question matrices. If directly related to local management needs, jurisdictions can request the addition of one or two short questions to the core survey.

The socioeconomic monitoring locations within the seven inhabited Coral Program priority geographic areas (analogous to the biological monitoring reporting units) are:

American Sāmoa Islands of Tutuila, Taʻu, Olosega, Ofu, and Aunuʻu
Commonwealth of the Northern Mariana Islands of Saipan, Tinian, and Rota only
Guam Entire island of Guam
Hawaiʻi Islands of Oʻahu, Kauaʻi, Maui, Molokaʻi, Lānaʻi, Hawaiʻi only
Florida Martin, Palm Beach, Broward, Miami-Dade, and Monroe Counties only
Puerto Rico Puerto Rico, Vieques, Culebra Islands
U.S. Virgin Islands St. Croix, St. Thomas, and St. John

The survey data collection is focused on the following indicators:

- Participation in reef activities (including snorkeling, diving, fishing, harvesting)
- Perceived resource condition
- Attitudes toward coral reef management strategies and enforcement
- Awareness and knowledge of coral reefs
- Cultural importance of reefs
- Participation in behaviors that may improve coral reef health
- Awareness of coral reef rules and regulations

Information is collected using the most efficient and effective method in each jurisdiction, including in-person, mail, online, and/or telephone surveys, generally following the Total Design Method as described by Dillman (1978; 2007; 2014). NCRMP strives for statistically representative samples of individuals with a 95% confidence level from each coral reef jurisdiction, and sample size is adjusted to ensure representative coverage of certain demographic characteristics (e.g., age, gender, race). Indicator reporting units are influenced by local management needs, and where feasible, coincide with sub-jurisdictional scales used by NCRMP biological teams. Efforts are made to ensure sufficiently robust sample size to allow for reporting of socioeconomic indicators at appropriate sub-jurisdictional scales.

Indicators informed by existing data sources:
The remaining socioeconomic indicators are measured using existing data sources due to restricted survey length and scope. They include:

- Human population changes near coral reefs
- Economic impact of coral reef fishing to jurisdiction
- Economic impact of tourism to jurisdiction
- Community well-being
- Physical Infrastructure
- Governance[2]

[2]Governance will ideally be informed by a separate NCRMP primary data collection that targets coral reef managers; though, it is currently informed by existing socioeconomic data streams.

All socioeconomic data on population estimates, community well-being, and physical infrastructure are compiled and analyzed for each jurisdiction using secondary data sources like the U.S. Census Bureau and local government agencies. Indicators of economic impacts and governance of coral reef resources are tracked through various existing primary and secondary datasets. All sources are subject to change as new datasets emerge. Similarly, the Coral Program is open to the possibility of expanding Program monitoring to directly include the above indicators.

Data Documentation and Reporting

In alignment with FAIR (Findability, Accessibility, Interoperability, and Reusability) principles (see Wilkinson et al. 2016) and the U.S. Open Data Policy, NCRMP data are available for free to the public and the scientific community in the belief that their wide dissemination will lead to greater understanding and new scientific insights. NCRMP standard operating procedures, raw data, and data products are archived at NOAA's National Centers for Environmental Information (NCEI) as well as the NOAA institutional repository. All data are documented using International Organization for Standardization (ISO) compliant metadata to ensure understanding. With a strong commitment to FAIR principles, many single and cross-disciplinary peer-reviewed publications are produced through the sharing of NCRMP data.

NCRMP activities generate a broad range of biological, physical, chemical, and socioeconomic data that are highly valuable to the coral reef conservation community. NCRMP is committed to making data and data products publicly available in a timely and user-friendly format and creating products tailored to a wide variety of audiences. NCRMP data reporting follows data stewardship and dissemination guidelines recommended by the NOAA Environmental Data Management Committee (EDMC). NCRMP technical reports by theme and ocean basin are generally completed within one year of the end of each year's monitoring activities, following quality assurance and control and data synthesis, and report on observations at the jurisdiction level and sub-jurisdiction level where feasible and appropriate. For example, generally a dataset collected in FY21 would be published as a technical report to be released in FY22. These technical reports are generally designed for stakeholders and resource managers and can be used to inform science-based decision making. NCRMP is moving toward the automation of reports using Rmarkdown templates in an effort to streamline the production of analytical reports from this long-term data set to make information more accessible and valuable to managers in the future.

NCRMP data are also used to generate periodic jurisdiction and national-level status reports on the status and trends of U.S. coral reefs pursuant to the Coral Reef Conservation Act. These status reports assimilate and synthesize the data products from NCRMP monitoring activities to tell the story of how the condition of the nation's reefs is changing over time. The primary audience for these reports is intended to be Congress and other high-level decision makers, as well as the general public, and are intended to be used as a communication tool and not as a decision tool for management or restoration efforts. These relatively short documents replace the Coral Program's previous major monitoring reports, e.g., *The State of Coral Reef Ecosystems of the United States and Pacific Freely Associated States* (Waddell and Clarke 2008), in an effort to more clearly and succinctly disseminate status and trends of

U.S. coral reefs as a whole. The format of the jurisdictional and national-level status reports was determined with the assistance of partners at the University of Maryland Center for Environmental Science Integration and Application Network, who specialize in science communication. Indicators were presented by sub-jurisdictional reporting unit, by jurisdiction, as well as rolled up by basin (Pacific and Atlantic), and finally summarized at a national level. Key findings, additional information, and case studies augment the status and trends reporting tools. The first set of Pacific Status reports using the new format was released in 2018; the first set of Atlantic status reports was released in 2020; and the first national summary report was also released in 2020. NCRMP intends to release new status reports for Congress every 5-6 years pending funding availability, and will continue to release ports technical reports by jurisdiction, basin, and theme on a yearly basis.

Acronyms

AS American Sāmoa
BMU Bioerosion Monitoring Unit
CAU Calcification Accretion Unit
CCA Crustose Coralline Algae
CI Confidence Interval
CNMI Commonwealth of the Northern Mariana Islands
CO_2 Carbon Dioxide
CRCP or Coral Program Coral Reef Conservation Program
CV Coefficient of Variation
DIC Dissolved Inorganic Carbon
DO Dissolved Oxygen
ESA Endangered Species Act
FGB Flower Garden Banks
FL Florida
HI Hawaiʻi
ISO International Organization for Standardization
LPI Line Point Intercept
MApCO_2 Moored Autonomous pCO_2 Buoy
MHI Main Hawaiian Islands
MPA Marine Protected Area
NCRMP National Coral Reef Monitoring Plan
NESDIS NOAA National Environmental Satellite, Data, and Information Service
NMFS NOAA National Marine Fisheries Service
NOAA U.S. National Oceanic and Atmospheric Administration
NOS NOAA National Ocean Service
NWHI Northwestern Hawaiian Islands
OAR NOAA Office of Oceanic and Atmospheric Research
$pCO_{2,aq}$ Seawater Carbon Dioxide Partial Pressure
$pCO_{2,atm}$ Atmospheric Carbon Dioxide Partial Pressure
PR Puerto Rico
PRIA Pacific Remote Island Areas
SE Standard Error
SOP Standard Operating Procedure
SPC Stationary Point Count
SST Sea Surface Temperature
STR Subsurface Temperature Recorder
TA Total Alkalinity
U.S. United States of America
USVI U.S. Virgin Islands

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