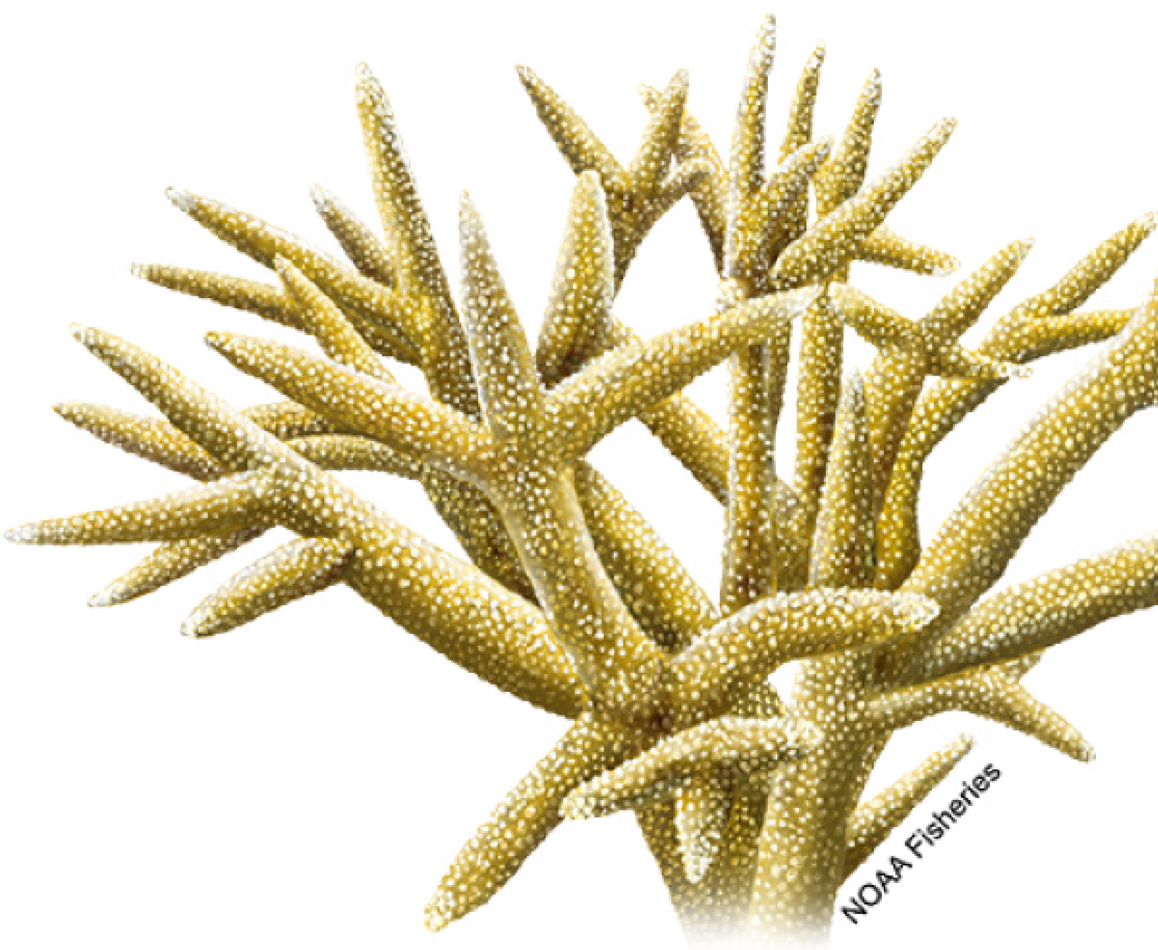
BIOLOGY: INTEGRATING CORE TO ESSENTIAL VARIABLES (Bio-ICE)

TASK TEAM REPORT FOR HARD CORALS



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INTRODUCTION

The Interagency Ocean Observation Committee (IOOC) is chartered by the White House Office of Science and Technology Policy (OSTP) Subcommittee on Ocean Science and Technology (SOST). The purpose of the IOOC is to advise, assist, and make recommendations to the SOST on matters related to ocean observations via task teams such as the Biology - Integrating Core to Essential Variables (Bio-ICE) task team. The goal of the Bio-ICE task team is to advance the integration of biological observations from local, regional, and federal sources using best practices to inform national needs and ultimately feed seamlessly into the Global Ocean Observing System (GOOS), as appropriate. To accomplish this goal, and for the first time at the U.S. federal government level, a subgroup of the Bio-ICE task team focused on tropical, shallow-water (0-30 m) hard corals to identify commonalities between the U.S. Integrated Ocean Observing System (IOOS) core biological variable[1] of "coral species and abundance," the GOOS Essential Ocean Variable[2] (EOV) "hard coral cover and composition," the Group on Earth Observations Biological Observation Network (GEO BON) Essential Biodiversity Variables[3] (EBVs), and the Global Climate Observing System (GCOS) Essential Climate Variables[4] (ECVs) (Figure 1). The EOV data allows production of EBVs such as time series of maps of genetic composition, species populations, etc. Recognizing the complementarity of the different essential variable frameworks helps to promote best practices in observing and information management to facilitate data interoperability (Figure 1).

The task team was charged with identifying where there are synergies in terms of spatial and temporal observing requirements and existing observation infrastructure and data delivery, including best practices and standard operating procedures. The task team also made suggestions to improve pathways for data flow for observations of these variables from Regional Associations of the U.S. IOOS, other nonfederal partners, and federal sources. The focus of the task team was on identifying and implementing best practices surrounding standardized data collection and data delivery to make continued progress toward adhering to the Findability, Accessibility, Interoperability, and Reuse (FAIR) and Collective benefit, Authority to control, Responsibility, and Ethics (CARE) data principles.

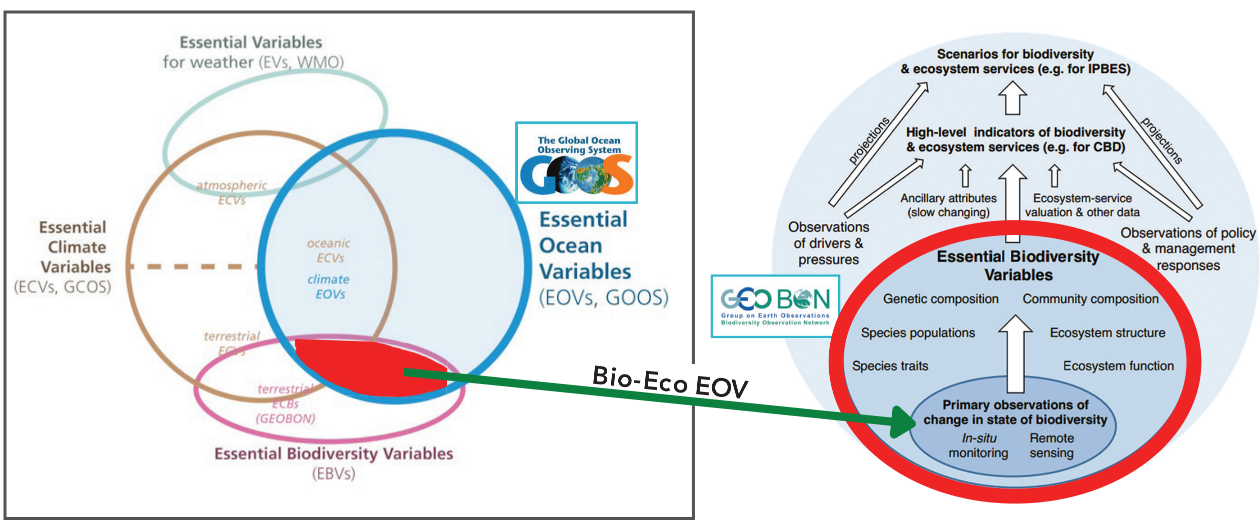


FIGURE 1: Illustration of the relationship between Essential Ocean Variables (Task Team for an Integrated Framework for Sustained Ocean Observing, 2012) and Essential Biodiversity Variables (Pereira et al. 2013). The Venn diagram (left) shows the overlap between different essential variable frameworks (from IFSOO 2012). The observations collected under the Biology and Ecosystems EOV are the fundamental building blocks to construct the (right) Essential Biodiversity Variables (EBVs) as proposed by the Group on Earth Observations Biodiversity Observation Network (GEO BON) in Pereira et al. 2013. The task team was primarily focused on the area highlighted in red where EOVs, EBVs, and ECVs overlap for hard coral data.

1 https://www.iooc.us/task-teams/core-ioos-variables/
2 https://www.goosocean.org/index.php?option=com_content&view=article&id=14&Itemid=114
3 https://geobon.org/ebvs/what-are-ebvs/
4 https://public.wmo.int/en/programmes/global-climate-observing-system/essential-climate-variables

Hard corals, also known as scleractinian corals, were selected as a focus of the task team due to the multitude of data being collected at the U.S. federal level using various methodologies. Hard corals are usually tropical, long-lived organisms that play a crucial role in maintaining healthy coastal and ocean ecosystems and are the foundation of coral reefs. Healthy coral reefs are among the most biologically diverse, culturally significant, and economically valuable ecosystems on Earth. They provide billions of dollars in food, jobs, recreational opportunities, coastal protection, and other important goods and services to people around the world. Thus, understanding hard coral abundance and distribution is an essential starting point to evaluate their role in these critical ocean ecosystems. Furthermore, hard corals are sensitive to a multitude of stressors and their abundance and condition have been declining for several decades due to a myriad of factors, including the compounded stresses caused by human activities like pollution and unmanaged use of resources at a time of rapid global climate change. For these reasons and more, hard corals are included among the key variables to monitor in ocean observing systems, spanning from IOOS to GOOS. As of 2022, the IOOS core variable for hard corals is "coral species and abundance," while the GOOS EOV for hard corals is "hard coral cover and composition". The task team submitted a proposal to align the IOOS "coral species and abundance" variable to match the EOV phrasing "hard coral cover and composition," which IOOS is considering at present. If accepted, the change would reconcile terminology differences for this key ocean observing variable between the IOOS and GOOS frameworks to increase consistency at the global scale.

At the U.S. federal agency level, hard coral cover and composition data are collected for a variety of management purposes including, but not limited to the following: determining status and trends; determining coral resilience to climate change and other stressors; informing coral reef restoration initiatives; and informing coastal hazard risk mitigations. There are various sub-variables[5] that are commonly associated with the collection of hard coral cover and composition data, including, but not limited to the following:

- Live hard coral cover and areal extent
- Coral diversity (species, genera)
- Coral condition and health (diseases, bleaching, partial or full mortality)
- Total habitable substrate (structural complexity)
- Coral size classes (recruits/juvenile/adult corals, size class distribution)

Additionally, there are various EBVs and ECVs that may be important to collect to complement data on hard coral cover and composition including, but not limited to the following:

- Temperature
- Salinity
- Turbidity
- pH
- Total alkalinity
- Dissolved Inorganic Carbon
- Herbivory and other reef fish EOVs

While various EBVs and ECVs were discussed and considered by the task team, the primary focus was on reconciling hard coral cover data collection by the participating federal agencies and regional partners. The task team selected three common methods to capture hard coral cover as case studies to better understand data flow from identification of management requirements, data collection, data management, and applications to satisfy the management requirements. These case studies included identifying barriers to data collection and data archiving. The task team then developed recommendations for improvement and standardization of data collection and archival at the national level.

5 https://docs.google.com/document/d/1GcfLBiSWCaIgcP5ifCNmoYdu29ClGjqTQWw6uE7ZVrw/edit

In the U.S. federal government, many authorizations direct various agencies to collect information on hard coral cover, including, but not limited to the Coral Reef Conservation Act, the Endangered Species Act, the Magnuson-Stevens Fishery Conservation and Management Act, the Coastal Zone Management Act, the National Marine Sanctuaries Act, the Clean Water Act, the Beaches Environmental Assessment and Coastal Health Act, and many others. These authorizations, along with agency missions and regulatory authorities, frame the monitoring objectives and methodologies for EOVs and associated EBVs/ECVs to generate federal coral reef datasets. Monitoring is required for accurate, up-to-date information on status and trends of hard coral cover and composition to inform appropriate management and/or conservation measures. Despite much information on hard coral cover and composition being publicly available on various agency websites and data products, the availability and accessibility of these data for delivery of information to managers and to the broader ocean observing community remains inconsistent. Combining the different datasets from the various federal programs to produce routine integrated national coral reef assessments, or to contribute to international assessments and EOV databases, is a major challenge. Such interoperability is an important emerging goal of all agencies involved in the collection of information intended for science-based management purposes.

This report focuses on the participating task team agencies collecting hard coral cover data using three common methodologies and highlights synergies in data flow pathways. It points out where improvements need to be made with respect to data accessibility and standardization to enable interoperability. Lastly, this report identifies the challenges associated with each methodology to deliver the EOV of hard coral cover and composition and concludes with recommendations to improve information management and interoperability at a national scale.

U.S. FEDERAL PROGRAMS, COLLECTION RANGES, AND PROCESSES

The list of programs and brief descriptions below are not inclusive of all federal and state/territorial programs collecting hard coral cover data and associated sub-variables. Rather, the groups listed here reflect only those groups that participated on this task team; therefore, this should not be considered an exhaustive list of programs generating U.S. coral cover data.

NOAA's National Coral Reef Monitoring Program

NOAA's National Coral Reef Monitoring Program (*NCRMP*[6]) is funded by NOAA's Coral Reef Conservation Program to collect coral reef monitoring data in every U.S. state, territory, and commonwealth that has shallow-water tropical coral reefs. In the Pacific, these jurisdictions are Hawai'i and the Northwest Hawaiian Islands, Guam, the Northern Mariana Islands, American Samoa, and the Pacific Remote Islands. Each Pacific jurisdiction is monitored once every three years. In the Atlantic, the jurisdictions are Florida, Puerto Rico, the U.S. Virgin Islands, and Flower Garden Banks (Gulf of Mexico). Each Atlantic jurisdiction is monitored every other year (NOAA Coral Program 2021). Generally, Atlantic jurisdictions are surveyed from May to September (with some sampling occasionally extending into the Fall). Pacific jurisdiction data are generally collected from April to September.

NCRMP surveying is limited to 30m depth and the survey design is stratified random with several hundreds of sites per jurisdiction per year. The utility of the data is designed to be optimized at the jurisdiction or sub-jurisdiction scale. For example, data from the U.S. Virgin Islands can be reported out at the U.S. Virgin Islands level (jurisdiction level), as well as at the sub-jurisdiction levels of St. Thomas and St. John or St. Croix. However, because of the stratified random sampling design where sites (defined as GPS locations) are not the same year to year, reporting at the site level is not advised. NCRMP is inclusive of areas both inside and outside of marine protected areas in each jurisdiction.

Methods for collecting hard coral cover data and supporting sub-variables vary slightly between basins (Atlantic or Pacific), but are identical within basins; i.e., identical for all of the Atlantic/Caribbean/Gulf of Mexico jurisdictions and identical for all of the Pacific jurisdictions. The Atlantic jurisdictions collect hard coral cover data using *in situ* transect methodology, and the Pacific jurisdictions collect hard coral cover data using photomosaic methodology.

Although methods vary slightly between basins, the data are statistically comparable across all U.S. coral reef areas. NCRMP data are available from 2013 to the present. The Coral Reef Conservation Program also has data from 2001-2012 from a precursor program to NCRMP. All NCRMP data are free and open access on NOAA's *National Centers for Environmental Information Coral Reef Information System (NCEI CoRIS)*[7].

NOAA's Office of National Marine Sanctuaries

NOAA's Office of National Marine Sanctuaries (ONMS) and partners manage 15 national marine sanctuaries and two marine national monuments throughout the U.S., four of which are tropical and have warm shallow water coral reefs. Those sanctuaries include: Flower Garden Banks National Marine Sanctuary (FGBNMS; Gulf of Mexico), Florida Keys National Marine Sanctuary (FKNMS), National Marine Sanctuary of American Samoa (NMSAS), and Papahānaumokuākea Marine National Monument (PMNM; Northwestern Hawaiian Islands). Although NOAA's NCRMP surveys within these areas and surrounding regions using a stratified random sampling design, each sanctuary also has its own monitoring programs separate from NCRMP to facilitate site-specific management. In general, sanctuary monitoring programs utilize a fixed-site monitoring design. Each sanctuary has slightly different methods and sampling designs for collecting hard coral cover data and supporting sub-variables to address specific management needs. While some datasets are uploaded to publicly accessible NOAA repositories, others are stored on internal

6 https://www.coris.noaa.gov/monitoring/welcome.html
7 https://www.coris.noaa.gov/monitoring/biological.html

servers and available upon request. ONMS is developing procedures for improving public access to its data. Summary data reports are available for *FGBNMS*[8] and *PMNM*[9] on their respective websites. These reports have generally excluded data collected in the sanctuaries from external partners (e.g., Coral Reef Evaluation and Monitoring Project (CREMP) in Florida and NOAA NCRMP more broadly); however, there are initiatives in place to maximize synergies in the future.

NMSAS[10]**:** Five fixed sites are monitored annually in the austral summer (November–April). This program is currently in the process of being implemented, so data are only available beginning in 2020. Each fixed site has 10 stations, selected using a stratified random design at moderate depths. Photo quadrats are taken once per meter along a 30 m transect, then analyzed using Coral Point Count with Excel extensions (CPCe) or CoralNet. Photogrammetry is also used to document a 3x20 m area along each transect described above. Data collected include coral demographic data (abundance, size structure, condition), recorded *in situ* within 2.5x1 m quadrats along each transect, and structural complexity (from photogrammetry).

FKNMS[11]**:** 30+ fixed sites are monitored via CREMP annually in June–October (sites are mostly fore-reef Special Protected Areas with a few mid-channel and nearshore sites). Two deep and two shallow permanent quadrats are monitored per site, and a larger belt transect survey extends from permanent quadrats. Data are available from 1995 to the present and include coral demographic data (abundance, size structure). Florida Fish and Wildlife Conservation Commission's *Disturbance Response Monitoring*[12] program surveys and NCRMP surveys are also used by FKNMS.

FGBNMS[13]**:** Random photo transects (16 per bank [East and West] within one hectare permanent study sites) and repetitive photo quadrats (n = 50 per bank) are collected annually in the summer months (July–August). Data are available from 1989–present and include coral demographic data (recruitment, density, colony size), other benthic cover (algae, sponges, etc.), repetitive photostations to assess individual colony change, sea urchin (*Diadema antillarum*) and lobster density, and water quality (salinity, temperature, turbidity, nutrients).

PMNM[14]**:** Originally PMNM used similar protocols to NCRMP in the off-years when NCRMP did not survey the PMNM, i.e., photo quadrats and CoralNet analysis, though monitoring has been irregular since 2017. The monument is presently looking to reinvigorate the program and move to new photogrammetry survey protocols. Data are available from 2000–present and currently include coral colony health surveys (species, size, condition) and structural complexity (from photogrammetry).

National Park Service's South Florida and Caribbean - Inventory and Monitoring Program

The NPS manages five parks that have coral reefs in *South Florida and the Caribbean*[15]. Those parks include: Biscayne National Park and Dry Tortugas National Park in Florida, and Buck Island Reef National Monument, Virgin Islands National Park, and Salt River Bay National Historical Park and Ecological Preserve in the U.S. Virgin Islands. Benthic surveys are conducted annually, but can also be supplemented when necessary for episodic monitoring due to coral disease, bleaching, hurricanes, etc. The South Florida and Caribbean - Inventory and Monitoring group uses several different designs, which are specified by the targeted site in the park and its size. Data are collected on 2x10 m belt transects and include: rugosity, bleaching (four levels), coral species lists, coral colony counts, a coral disease assessment (disease type, species affected, and lesion size), and *Diadema antillarum* counts. Note that rugosity is collected on a 5-year rotation or after an episodic event (e.g., hurricane); the other variables are collected annually. A digital surface complexity photogrammetry pilot study is underway in the Dry Tortugas and Virgin Islands National Park in partnership with the Pacific Network and the University of Hawai'i.

8 https://flowergarden.noaa.gov/science/sciencereports.html
9 https://www.papahanaumokuakea.gov/new-library/reports/
10 https://americansamoa.noaa.gov/
11 https://floridakeys.noaa.gov/
12 https://myfwc.com/research/habitat/coral/drm/
13 https://flowergarden.noaa.gov/
14 https://www.papahanaumokuakea.gov/
15 https://www.nps.gov/im/sfcn/index.htm

Florida:

- Biscayne National Park: since 2004, data typically collected Aug – Oct
- Dry Tortugas National Park: since 2004, data typically collected Jun - Jul

United States Virgin Islands:

- Buck Island Reef National Monument: since 2000, data typically collected Feb - Apr
- Salt River Bay National Historical Park and Ecological Preserve: since 2012, data typically collected Mar - Apr
- Virgin Islands National Park: since 1999, data collected year-round

National Park Service's Pacific Island Network - Inventory and Monitoring Program

Four parks within the *Pacific Island Network (PACN)*[16] conduct coral reef monitoring. They are: Kalaupapa National Historical Park (Hawai'i), Kaloko-Honokōhau National Historical Park (Hawai'i), the National Park of American Samoa, and the War in the Pacific National Historical Park (Guam).

- Data are collected annually and are meant to be representative of an entire park area.
- According to the *protocol narrative*[17] (Brown et al. 2011), data are collected between 10-20 m at the reef slope because biodiversity is greatest there and park patrons do not swim in this area, which limits disturbance to some metrics collected.
- Sampling is randomized using ArcGIS.
- Photo quadrats are taken at 1 m intervals and 50 computer-generated points are identified per quadrat.
- The sampling season consists of three-month periods. June-August for Guam and Hawai'i; November-January for American Samoa.
- Coral bleaching and disease are monitored by proportion or incidence and causes/diagnoses are not determined.
- Coral recruitment assays are conducted.
- Coral growth studies are done on 10 *Pocillopora eydouxi* colonies per permanent transect; tracking colony fate and estimated percent partial mortality are optional depending on park resources.
- 50% of sites are revisited every year (a split panel design).

U.S. Geological Survey

The U.S. Geological Survey (USGS) *Coastal and Marine Hazards and Resources Program*[18] has conducted random surveys for hard coral cover and associated sub-variables since the 1970s up to 40 m depth in all states, territories, and commonwealths with coral reefs. Most USGS data are collected as initial baseline data for a specific National Park, Wildlife Refuge, U.S. Coral Reef Task Force priority study area, or National Marine Sanctuary priority study area, or as geospatial data for numerical modeling activities. The USGS collects an extensive amount of related sub-variables such as water temperature, salinity, turbidity, calcification, coral growth rates, coral geochemistry, water geochemistry, etc., that were not focused on during this task team. Starting in the 2010s, the USGS produces elevation change maps and seafloor stability data on select coral reefs areas that characterize change in seafloor habitats since the 1930s and been conducting georeferenced Structure-from-Motion surveys up to 10 m depth periodically or by request, i.e., to inform the NOAA *Mission Iconic Reefs Project*[19].

16 https://www.nps.gov/im/pacn/index.htm
17 https://irma.nps.gov/DataStore/DownloadFile/427176
18 https://www.usgs.gov/programs/coastal-and-marine-hazards-and-resources-program/science/coral-reefs
19 https://www.fisheries.noaa.gov/southeast/habitat-conservation/restoring-seven-iconic-reefs-mission-recover-coral-reefs-florida-keys

U.S. Environmental Protection Agency

The U.S. Environmental Protection Agency (EPA) develops methods, tools, and technical approaches to support the use of reliable, robust biological and ecological data to assess coral reef condition and to develop and implement protective water quality standards by state, tribal, and territorial water quality management programs consistent with the U.S. Clean Water Act (33 USC § 1251 et seq. 1972). The EPA partners with these jurisdictions and other federal agencies to help prevent and mitigate negative impacts on coral reefs from stressors and threats from land-based sources of pollution and conduct targeted coral reef condition assessments that address specific regional areas and topics of interest.

The EPA *Office of Research and Development (ORD)*[20] has developed regional probabilistic random surveys for hard coral cover and associated sub-variables. A tessellated approach selects irregularly bounded polygons enclosing areas with mapped reef resources for condition assessments. Separately, targeted station selection has been used to test conditions in response to human disturbance gradients in the U.S. Virgin Islands. To date, these targeted surveys have been one-time-only in the following years and regions: 2007 in St. Croix, USVI; 2009 in St. John/St. Thomas, USVI; 2010 in Puerto Rico; 2010 in the Flower Garden Banks; and 2011 in Puerto Rico. These surveys have been largely limited to 12 m depth and a maximum distance of three miles offshore. All surveys collected hard coral demographic data (species (Scleractinian and Hydrozoa *Milleporids*); colony size (maximum height and diameter), structure (morphological shape), density, and condition (presence of six specific coral diseases; full and partial bleaching, and pigment paling for early bleaching; percent colony surface with live tissue); and prominent species and reef surface structural complexity (chain length rugosity method) using *in-situ* transect methodology in 25-15 m transect lengths. The data are freely available at *EPA's official open data catalog*[21].

The Florida Keys National Marine Sanctuary and Protection Act (P.L. 101-605) designated over 2,800 square nautical miles of coastal waters as the FKNMS. The Act required the EPA and the state of Florida to implement a Water Quality Protection Program in collaboration with NOAA. The EPA ORD conducted CREMP sampling for coral disease and condition monitoring in the Florida Keys reef tract including reefs in Biscayne National Monument (NPS), FKNMS (NOAA) (contiguous stations from east to west boundaries, including marine protected areas and sanctuary protected areas), Newgrounds reef area, Dry Tortugas National Park (NPS), and the Tortugas Ecological Preserve (NOAA) from 1997 to 2005. Coral demographic surveys were conducted by divers *in situ*, biannually in spring or early summer (May or June) and late summer or early autumn (August or September) from 1997 to 1999, and annually thereafter. All surveys collected hard coral demographic data (species (Scleractinian and Hydrozoa *Milleporids*), colony size (maximum height and diameter), density, and early coral condition indicators. Additionally, the presence of specific coral diseases described in the literature up to the time of surveys (ranged from 6 to 13), percent colony that was fully or partially bleached white tissue, pigment paling to represent onset of bleaching, and percent colony surface with live tissue were also collected. Water quality and scanning radiometer measurements were made at selected stations to represent multiple coral stations to extrapolate potential exposure. These data reside with EPA ORD.

National Aeronautics and Space Administration

The National Aeronautics and Space Administration (NASA) has used satellite and airborne remote sensing, and *in situ* sampling of hard coral cover and associated sub-variables across the world (project-specific) since the early 2000s. *In situ* coral cover is usually estimated utilizing video or photo transects. These field data are critical to validate satellite and airborne data products. With the availability of higher spatial resolution satellite and airborne imagery, details of coral structure and composition have been improved, enabling the remote classification of a higher percentage of reefs worldwide. More recently,

20 https://www.epa.gov/aboutepa/about-office-research-and-development-ord
21 https://edg.epa.gov/metadata/catalog/main/home.page

NASA's *Laboratory for Advanced Sensing*[22] has been employing a fluid lensing technique to collect coral cover and related sub-variables at very high resolution in two and three dimensions. Examples of NASA-funded projects that have assessed coral reef cover include the *Global Millennium Coral Reef Map*[23] (now distributed by the U.N. Environment Programme World Conservation Monitoring Centre and NASA Goddard, and legacy products also through the Institute for Marine Remote Sensing, University of South Florida) and the *Coral Reef Airborne Laboratory (CORAL)*[24], the former employing Landsat imagery and the latter utilizing airborne imagery from the Portable Remote Imaging SpectroMeter (PRISM). NASA has also conducted specific field campaigns which have captured important events such as the 2005 Caribbean coral bleaching event in Puerto Rico and the U.S. Virgin Islands.

Puerto Rico Coral Reef Monitoring Program

The Puerto Rico Coral Reef Monitoring Program (PRCRMP) is not a federally run coral monitoring program, but rather a territorial monitoring program in Puerto Rico, funded by a NOAA Coral Reef Conservation Program cooperative agreement. PRCRMP is managed by the Puerto Rico Department of Natural and Environmental Resources. PRCRMP uses a mixed multifactorial design with fixed permanent transects at about 42 stations. The 42 stations are monitored every two years since 2016, i.e., 21 sites per year, every other year. The program collects hard coral cover data by species and other benthic biological variables using 10 m-long chain transects with five replicates per site. Percent cover is estimated as the proportion of chain links that cover each benthic category or species to the total number of chain links over a 10 m linear distance. Therefore, at each sampling station, with five 10 m transect replicates, a linear distance of 50 meters is surveyed. The 42 stations are distributed across the west, southwest, south, southeast, east, northeast, and north insular shelf platforms of Puerto Rico, although most stations are in the west and southwest regions. Sites are between 2-30 m in depth, and data are available from 1999 to the present. The *data*[25] are free and open access at NOAA's NCEI and are also in the Ocean Biodiversity Information System (OBIS) using Darwin Core Standards (DwC).

Pacific Islands Ocean Observing System

Pacific Islands Ocean Observing System (PacIOOS) does not conduct independent coral monitoring efforts but works in collaboration with local and regional monitoring programs to host coral cover data from the U.S. Pacific Islands. The data hosted by PacIOOS are regional subsets of NCRMP data pulled from NOAA NCEI and the Pacific Islands Fisheries Science Center *ERDDAP*[26] web services. *Datasets*[27] are standardized into DwC format and *submitted*[28] into OBIS and the Marine Biodiversity Observation Network (MBON). PacIOOS currently hosts a species distribution model of the percent cover for the six dominant coral species around the main Hawaiian Islands. The model is based on data collected between the years 2000 to 2009 by multiple monitoring programs including the University of Hawai'i, the NPS, and NOAA's Pacific Islands Fisheries Science Center. Survey methods included *in situ* diver observations and interpreted photo-quadrats of the shallow seafloor (0 to 30 m depth) around the eight main Hawaiian Islands.

22 https://www.nasa.gov/ames/las
23 https://data.unep-wcmc.org/datasets/1
24 https://coral.jpl.nasa.gov/
25 https://www1.usgs.gov/obis-usa/ipt/resource?r=prcrmp_database
26 https://coastwatch.pfeg.noaa.gov/erddap/index.html
27 https://obis.org/dataset/fca3b113-b145-446c-a23c-3188090e43af
28 https://obis.org/dataset/518c8422-0a94-4926-9e7a-42aaf70002f4

HARD CORAL COVER AS AN EOV

Caveats to Consider When Using U.S. Federal Coral Cover and Associated Sub-variable Data

In many of the U.S. federal agencies' data collections detailed above, even if the EOV of hard coral cover is collected using the same methodology (e.g., transect), the resulting data may not be statistically interoperable (e.g., comparable), depending on many factors including the sampling design and the sampling season. The task team underscores that several factors must be considered when assessing different hard coral cover data from different programs, and those factors should be clearly stated in the metadata associated with the dataset. When thinking about using a single hard coral cover dataset and/or potentially comparing two or more datasets, the data analyst should be able to easily determine:

- The monitoring design used to collect the data (e.g., fixed vs. stratified random site selection).
- The exact date and time of day the data were collected. This is particularly relevant if a sub-variable of interest is coral condition. For example, if the data analyst wants to understand coral bleaching prevalence, the time of year is important: If one wanted to assess how bleaching affected a certain region in a certain year, but the only data were collected in the spring as opposed to the summer/fall bleaching season, that dataset will be very limited in its ability to provide insight on the true severity of bleaching prevalence.
  - It is also critically important that the metadata describe the format used for:
    - Location of the survey (How are degrees and minutes coded? Are latitudes and longitudes in a 360 degree reference mode, or positive/negative?)
    - Date/time of the survey (Month first or day first? Year format? Time format?)
    - Units of measurement of each variable collected (e.g., percent for cover, per square meter for area extent, etc.)
- The frequency of surveying (e.g., monthly, annually, biannually, triannually, etc.) is of particular importance in remote areas which may have less data available than others.

Existing Synergies Between Programs and Agencies

The existence of multiple coral reef datasets containing comparable EOVs, EBVs, and ECVs collected from a wide range of governmental, non-governmental, and academic institutions creates a unique opportunity to leverage information that can fill data gaps, develop meta-analyses, and build models. Federal agencies and partners are working together to create and utilize datasets and collect comparable indicators to help meet monitoring and assessment needs at federal, state, territorial, tribal, and local levels. In addition, federal agencies have collaborated on research leveraging long-term datasets to create models, meta-analyses, and monitoring recommendations. While there are many existing synergistic projects, the task team emphasizes that U.S. federal agencies should seek to increase interagency partnerships on hard coral cover data collection.

In an effort to identify synergies between federal coral reef datasets, EPA has invested in research comparing the monitoring plans and associated methods from three long-term *in situ* federal coral reef monitoring programs: EPA's National Coastal Condition Assessment's Pacific Island Coral Reef Flat Survey, NOAA's NCRMP, and NPS' Inventory and Monitoring Program. This research is aimed at highlighting ways to leverage existing federal datasets to fill gaps in monitoring schemes at national, regional, state, and territorial levels (Brucker et al. in prep). In addition to the forthcoming Brucker report, the task team identified several non-exhaustive examples of current synergistic activities and products between federal agencies collecting hard coral cover data and associated sub-variables, below.

- PacIOOS nearshore sensors monitor coastal water conditions to help provide early indications of potentially polluted run-off from storm drainage, sewage spills, and soil erosion from land-based waterways that lead directly into the ocean. PacIOOS owns and maintains sensors at nine sites across the U.S. Pacific Islands that collect salinity, turbidity, Chlorophyll-*a*, pH, sensor depth, oxygen concentration, and percent saturation.
- The Biological Condition Gradient (BCG) is a conceptual, scientific framework for interpreting biological response to anthropogenic stress. The framework is based on common patterns of biological response to stressors that have been observed by aquatic scientists across the United States (*U.S. EPA 2016*[29]). It supports consistent interpretation of biological conditions independent of the specific method used to collect data, the type of waterbody being assessed, or the location of the waterbody. Numeric BCG models for both fish and benthic macroinvertebrate assemblages were recently completed for assessment of coral reef condition in the waters off the coast of Puerto Rico and the U.S. Virgin Islands (U.S. EPA 2021). The models provide a practical framework for federal and territorial programs to share data, guide development of their monitoring programs, develop biological criteria, and communicate assessment results on coral reef condition.
  - The narrative BCG model for benthic coral reef systems described in Santavy et al. (in review), adapted the general BCG framework into narrative rules for Caribbean coral reefs. The data for the benthic BCG narrative rules were collected by the EPA from the south coast of Puerto Rico in 2010 and 2011 and included Scleractinian coral condition and abundance, sponge, and gorgonian metrics. It was determined that, while the EPA datasets were sufficient to aid experts in developing the narrative BCG rules, they lacked sufficient quantitative measurements of benthic coverage that were needed to develop a robust numeric BCG model. Therefore, numeric BCG rules for each level built upon the narrative BCG model by incorporating metrics obtained from NOAA's NCRMP 2013-2015 Puerto Rico and U.S. Virgin Islands biological surveys (Santavy et al. (2022)).
  - A team from the Caribbean Coral Reef Research Institute (CCRI), University of the Virgin Islands, the Puerto Rico Department of Natural and Environmental Resources, and the U.S. Virgin Islands Department of Planning & Natural Resources have begun exploring a pilot for how to use the BCG model as a framework to coordinate coral monitoring programs, synthesize meaningful information on the condition of coral reefs, and enable data sharing and assessment results. The foundation for this pilot at the territorial scale builds on the partnership between NOAA NCRMP and EPA coral reef research program in sharing data and methods instrumental in the development of the coral reef BCG model. The goal of this pilot is to use NCRMP (benthic and fish) data, PRCRMP (coral and fish) data, and U.S. Virgin Islands territorial coral reef monitoring program (fish) data to run the BCG model at targeted sites where the results of the model will be tested against field (direct sampling) and historical environmental/stressors data publicly available in various sources such as the Caribbean Coastal Ocean Observing System (waves), NASA (rainfall), NOAA (hurricanes, habitat maps, turbidity, temperature, degree heating weeks), Puerto Rico Department of Natural and Environmental Resource (fishing pressure), and various universities (population pressure, productivity, pollution).
- The USGS has developed new Structure-from-Motion (SfM) technology for collection of georeferenced, high-resolution (less than 1 cm horizontal and vertical resolution) underwater imagery and elevation data. USGS is collaborating with NOAA FKNMS and its partnering institutions to apply this technology to the NOAA *Mission: Iconic Reefs* project, one of the world's largest coral reef restoration projects. The Structure-from-Motion Quantitative Underwater Imaging Device with 5 cameras (SQUID-5) is towed behind a boat allowing for rapid collection of data over large geographic areas with highly accurate locational information. The three-dimensional orthomosaic imagery and digital elevation models created from these data are currently being used to support seafloor elevation, structure, and habitat change work to inform coastal hazards and coral reef restoration work along the Florida Reef Tract. Additionally, baseline SQUID-5 georeferenced SfM imagery and digital elevation models support co-registration of diver-based SfM data collected by the broader research and monitoring community for repeat assessments of restoration progress and success.

29 https://www.epa.gov/sites/production/files/2016-02/documents/bcg-practioners-guide-report.pdf

Selected Methodologies to Collect the Hard Coral Cover EOV

The task team selected three overarching methodologies to focus on that broadly encompass major ways that U.S. member agencies of the task team collect hard coral cover data. These three methodologies are not exhaustive, but represent the most common ways the task team believes most U.S. federal coral cover data are currently being collected, and the pros and cons of each with respect to data collection, data processing, data archiving, and data sharing. The three methodologies that will be described in this document include: 1.) direct diver-based measurements made visually, 2.) underwater *(in situ)* imagery, and 3.) above-water (*ex situ*) imagery. The task team seeks to convey that there are various pros and cons to each method depending on a program or agency's resources and management needs, so the team did not make recommendations as to which of the three methods is optimal, but rather seeks to convey that the data derived from the three methods should ultimately be formatted and archived in the same way to increase interoperability and reusability.

Direct diver-based measurements made visually

FIGURE 2. A scientist lays a transect over a thicket of the hard coral *Acropora palmata* in Puerto Rico. Photo credit: M. Figuerola.

Direct diver-based visual measurements to collect hard coral cover data are the most common and the most simple of the three methods discussed in this document and can include *in situ* transects, line point-intercept, and other strategies. The data collector must be proficient in SCUBA and hard coral identification.

The pros of this method include:

- Transects are a fundamental sampling strategy in ecology to evaluate gradients and variability in organism abundance, density, and taxa across an area.
- Levels of detail can be added or removed as needed to meet specific agency and/or management goals.
- Nearly identical transects can be repeated in subsequent visits.
- Observers can make real-time decisions during dives, allowing for adaptive sampling.
- Identification of multiple taxa (e.g., corals, other invertebrates, algae) is possible in real-time.
- The data collector has direct observation of the *in situ* habitat.
- Capturing EBVs relating to species-level identification, juvenile corals and coral recruits, and cryptic reef fauna are easier via direct, *in situ* observation.
- Capturing EBVs relating to coral condition (e.g., bleaching and disease) are easier via direct, *in situ* observation.
- Useful for ground-truthing measurements captured via imagery.
- Little-to-no post-processing of data is required after a dive is complete.

The cons of this method include:

- Operations can be physically challenging (e.g., long dive times, inherent dangers of diving, weather can make operations difficult or impossible).
- Operations can be expensive (e.g., boat time, person-hours, field equipment).
- Limited in spatial scale.

- Potentially more opportunity for human error in data collection/entry.
- Requires technical expertise for species identification.
- Observations may be difficult to compare if there is a divergence of methods and approaches to record data and/or metadata.

Underwater (in situ) imagery

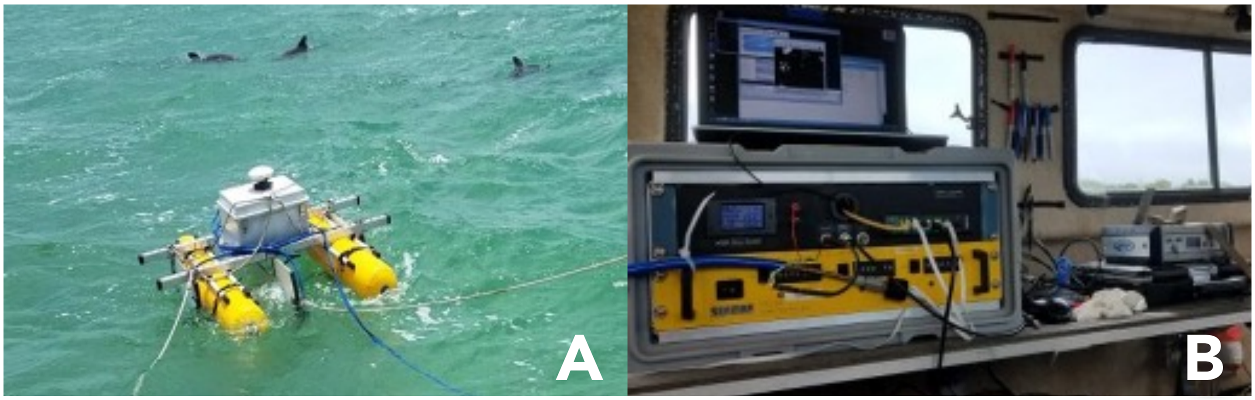
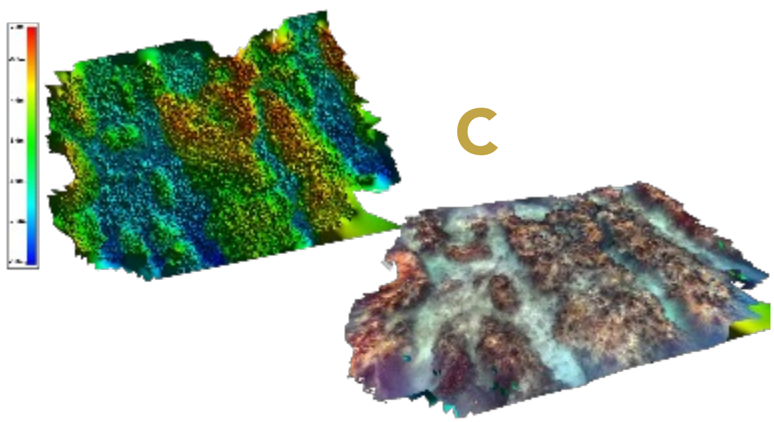


FIGURE 3. Structure-from-Motion Quantitative Underwater Imaging Device with five cameras (SQUID-5) is a surface-towed camera system that combines high-resolution imagery with highly accurate positioning information to create georeferenced three-dimensional orthomosaic and seafloor elevation maps. A.) SQUID-5 camera system and B.) Data acquisition technology deployed from a research vessel. C.) Examples of seafloor bathymetry (top left, 5.3 mm horizontal and 2 mm vertical resolution) and corresponding orthomosaic imagery (bottom right, 3mm resolution) collected from a 40x40 m section of coral reef. Photo and image credits: USGS.



Underwater imagery can be acquired using a variety of camera-based systems that can be operated manually by SCUBA divers or integrated into automated data collection systems. Data collectors must be proficient in operation of imagery collection systems and technology for post-processing of data (Figure 3).

The pros of this method include:

- Encompasses many ways of deployment: diver-based, surface-towed, autonomous underwater vehicle (AUV), and more, that can be combined.
- Can be combined with automated collection of supporting data (e.g., GPS, bathymetry) for accurate georeferencing, characterization of habitat structure, and co-registration of non-georeference, repeat imagery data (e.g., diver-based SfM data).
- Allows for a more perpetual archive of data for future analyses (e.g., a user can go back and re-do analyses or conduct new analyses of the imagery years later).
- Allows for the ability to cover more area than traditional transect methods.
- Allows for evolution of technology as it advances.
- Many codes for analysis are open access, facilitating ease of collaboration across institutions.

The cons of this method include:

- Requires substantial post-processing.
- Requires technical expertise for identification, particularly for small, cryptic species.
- Requires potential technical expertise in artificial intelligence (AI) and/or machine learning (ML)
- May require high performance computing.
- Certain data types may have very large storage files (10+ TB data/year).
- Data transfer – without the cloud – can be a limitation with certain data types.
- Some instrumentation and/or software is expensive and may be inaccessible for some groups depending on funding.
- Tethered (e.g., towed imaging sled) and non-tethered (e.g., AUV) instrumentation could be subject to loss in the field.

Above water (ex situ) imagery

FIGURE 4. Top Left: Part of the Florida Keys as imaged by the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) on the Terra satellite. Image Credit: US/Japan ASTER Science Team. Top Right: Natural color image of the island of St. John (U.S. Virgin Islands) captured by the Advanced Land Imager (ALI) on NASA's Earth Observing-1 (EO-1) satellite. Image Credit: NASA EO-1 Team. Bottom Left: Unoccupied Autonomous Vehicle (UAV) flying the Multispectral Imaging, Detection, and Active Reflectance (MiDAR) instrument over a reef in Guam. MiDAR is a next-generation remote sensing instrument developed for providing simultaneous high-frame, high signal-to-noise ratio (SNR) multispectral imaging with hyperspectral potential. Bottom Right: UAV collecting high resolution imagery (video and photos) over a coral reef in La Parguera, Puerto Rico. Drone photos credit: Dr. Ved Chirayath.

Above water, suborbital (Figure 4) and satellite imagery provides the advantage of data collection over practically any place on Earth. As such, it is particularly useful for obtaining information from remote places where diver-based or *in situ* underwater imagery collection is either extremely hard to obtain or expensive. The spatial resolution and geographic coverage of the imagery and spectral resolution will depend on the sensor used, whether satellite- or airborne-based. Independently, the amount of data collected usually requires advanced post-processing.

The pros of this method include:

- Allows for the ability to capture a big-picture overview for major bottom type classes (i.e., coral vs. sand or algae) in shallow areas at the reef or platform level.
- Particularly useful for remote areas with limited accessibility where satellite or airborne data may be the only data source available.
- Allows for a higher temporal resolution (days to months depending on the platform) to follow particular events (i.e., coral bleaching events).
- Extensive area coverage is possible from the local (e.g., hundreds of meters to 1 km) to the global scale (e.g., thousands of km).
- Allows for the collection of complementary parameters (e.g., water quality) at diverse scales.

The cons of this method include:

- Requires ground-truthing close or during the platform (satellite, aircraft) overflight for validation of the remotely sensed data. This is particularly important when assessing water-quality parameters in coastal waters.
- Characterization of bottom features with remotely sensed data relies on very clear waters and is limited by depth; usually only top 20 m or less.
- Availability of remotely sensed optical data is limited by cloud cover.
- Coarse resolution image data may be affected by mixed pixels (land/sea) near the shoreline.
- Spatial resolution is limited and does not allow for benthic taxa ID (species, genera).
- Cannot capture important EBVs such as recruitment or identification of other invertebrates at present.
- Depends on substantial spectral differences between benthic components which is not usually the case. The use of multispectral imagery is limited for benthic characterization due to the reduced number of spectral bands.
- May require advanced water column removal techniques (i.e., fluid lensing, algorithms) for proper characterization of benthos.
- Requires substantial post-processing.
- Large files (giga- to terabytes depending on image size/resolutions) may require large data storage capabilities either physically or in the cloud.
- Costs associated with image acquisition, particularly for airborne missions, can be prohibitive, especially for small entities like NGOs and others.

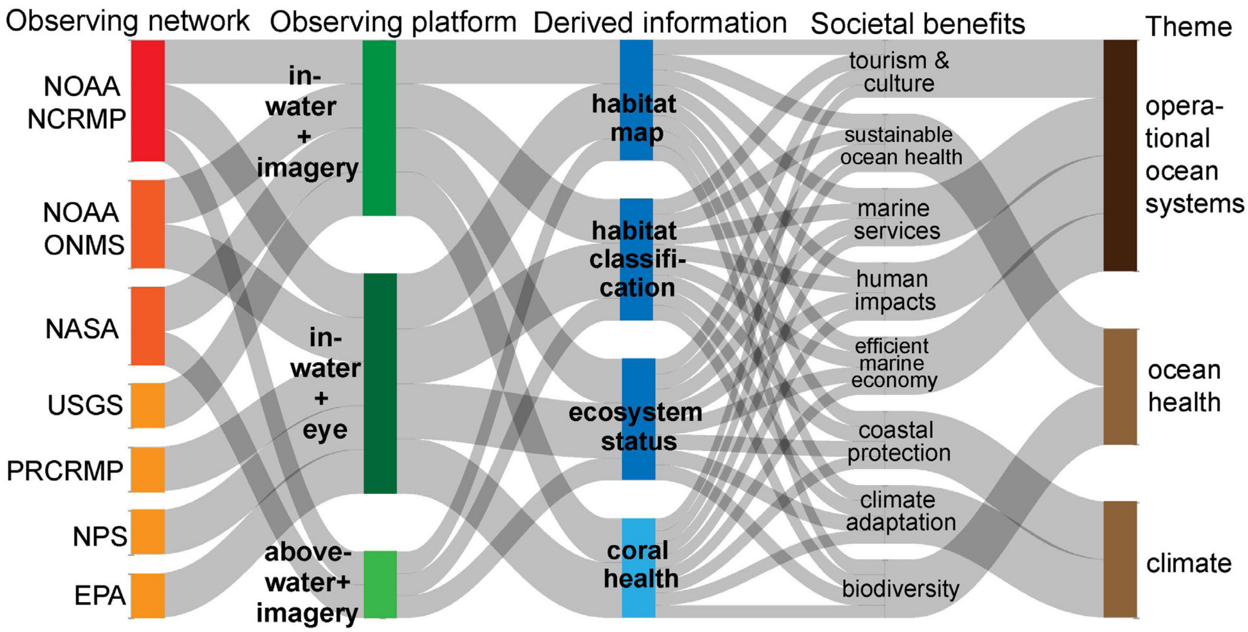


FIGURE 5: Sankey diagram depicting how the U.S. governmental agencies included in this task team measure coral cover, as well as how the acquired data are leveraged to 1) increase our understanding of coral reefs and 2) provide services and resources that benefit stakeholders.

Spatial and Temporal Considerations Within the Methodologies

Although the task team member agencies and regional groups may employ different approaches to assess coral cover, in virtually all cases the scientific and societal goals are broadly similar (Figure 5): to gain a better understanding of coral reefs through habitat classification, mapping, and characterizing both ecosystem status and, in a subset of instances, the health of the corals themselves (and perhaps other reef inhabitants). This is not to say, however, that each observing network is comprehensively modeling coral reef condition and resilience via all existing technologies at their current disposal during each research and monitoring initiative. Instead, using current survey and sampling methodologies for coral reef assessment (see Figure 6 for a non-exhaustive list), researchers must typically decide whether to prioritize resolution of the data with respect to both the temporal scale of the data and in terms of the number of parameters measured or their spatial extent. Whereas certain measurements are small in the spatial context (e.g., coral core samples; not discussed further herein), they can provide data that span many years. In contrast, environmental DNA (eDNA) surveys (not discussed further herein) can be carried out at global scales, yet only reveal a snapshot of the biota in the seawater at the time of sampling. Coral cover can be measured at both small (e.g., within-reef; blue bubble in Figure 6) and large (e.g., cross ocean basins; yellow bubble in Figure 6) spatial scales, with the level of resolution of the survey method ultimately dictating the extent of the temporal inferences that can be derived from the data. As technologies continue to improve, we may soon possess the capacity to observe reefs at global scales in which changes can be observed over potentially minute-hour timescales (i.e., near-real-time) such that the hypothetical spatio-temporal "space" in Figure 6 would be covered in entirety.

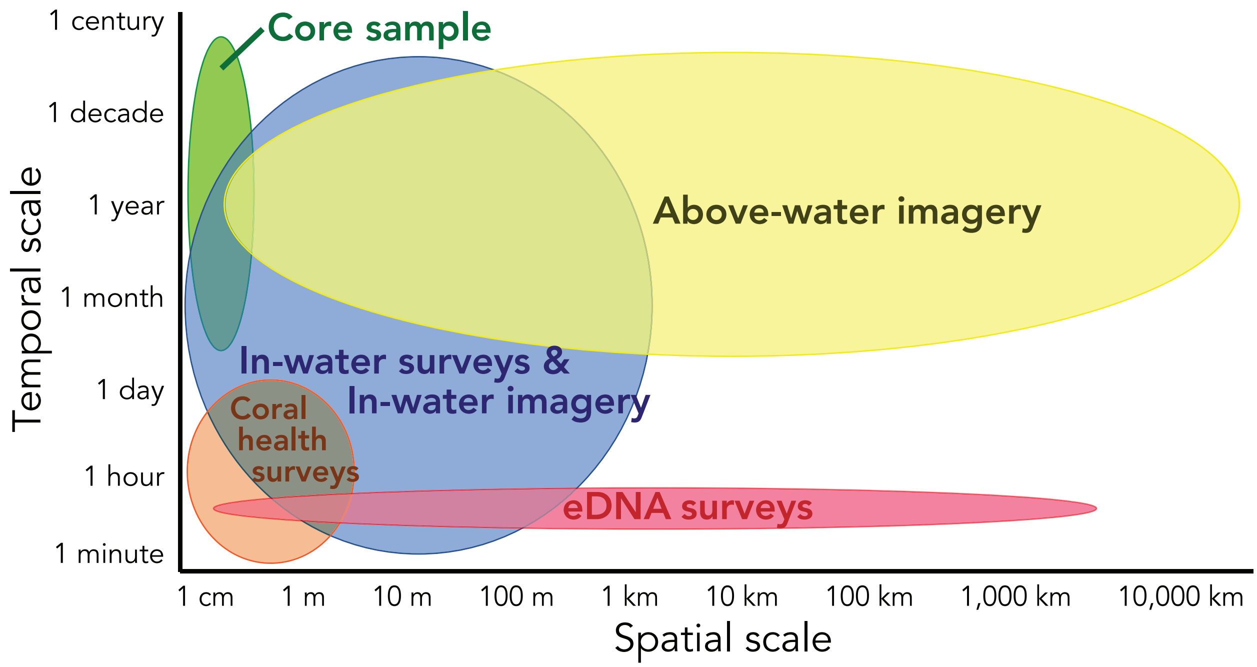


FIGURE 6: Diagram depicting spatial scales of coral reef ecosystem assessment using several currently utilized methodologies (X axis) versus the temporal data captured by the approaches (Y axis).

Observation Infrastructure and Data Delivery

Over the last six years, access to hard coral cover data has increased across the community as FAIR principles have been adopted by scientists. While access to hard coral data has increased, the interoperability of these data between different agencies and programs remains a challenge due to differences in statistical design and/or data formatting that make utilization of the data difficult without a significant investment in time to transform content to follow a similar data structure. As there is a need to understand the hard coral cover EOV and the associated EBVs and ECVs at a global scale, it is critical to be able to share data and metadata across multiple agencies in an efficient manner. This section highlights some of the challenges the task team observes regarding using data collected by various U.S. federal agencies along with recommendations on how to address these issues to make the data more interoperable. There are two major categories of challenges the task team identified. The first are challenges with general data and metadata accessibility and discoverability which are discussed in greater depth than this report allows in Benson et al. (2021). The second are challenges with disparate data formats preventing data usability and interoperability. As part of the contribution of this sub-task team to improve these efforts, the team developed a data flow diagram that promotes these qualities (see Figure 8).

With respect to the first challenge of data discoverability and accessibility, many U.S. federal agencies have made their hard coral cover data publicly available online, but this does not necessarily mean that data users are able to easily aggregate data between sources when trying to answer regional or national questions on the status of coral reef ecosystems. Data accessibility has generally increased within the federal government since the 2013 OSTP memorandum Increasing Access to the Results of Federally Funded Scientific Research, also known as *Public Access to Research Results (PARR)*[30] requirements. However, to be able to quickly download and merge multiple datasets across programs without significant post-processing remains a challenge due to data formatting inconsistencies.

30 https://www.ngdc.noaa.gov/parr.html

With respect to access to best practices for data collection and methodology, the Ocean Best Practices Systems (OBPS)[31] is a global, sustained system comprising technological solutions and community approaches to enhance management of methods as well as support the development of ocean best practices. A main component of OBPS is an open-access and sustained digital repository of community best practices in all ocean-related sciences and applications. Wider use of this repository may be useful for U.S. federal agencies to upload their coral cover collection methodologies to in one centralized location that may alleviate discoverability issues related to methodology.

The second challenge of data interoperability is more complex. In addition to issues one would expect when trying to use multiple datasets collected using different methodology, data users may also be presented with the challenges of needing to adjust data to correct for differences in coordinate systems between datasets, differences in date formats and time zones, and/or differences in use of species names, among other barriers. All of these issues add to the complexity of regional- to national-scale data analyses and can make answering questions for managers in a timely manner quite challenging. Below, the task team outlines how interoperable the data generated from each of the three case study methods are across agencies, followed by a brief analysis of how well the coral variables are currently being implemented, and finally, the task team's recommendations to improve these challenges.

31 https://www.oceanbestpractices.org/repository/

DISCUSSION

How Interoperable Are the Variables Across Agencies by Method?

Direct diver-based measurements made visually

- Sampling design drives the degree of interoperability within this method, and many U.S. programs are not currently interoperable, with some exceptions.
- NCRMP and NPS monitoring programs have high interoperability within NPS areas in both the Atlantic and Pacific regions. Data from the two programs can complement each other and may be used together to increase annual resolution.
  - For example, in the U.S. Virgin Islands, NCRMP's index period spans from May to September and NPS' index period occurs during the months of September-October and January-April. The difference in sampling months between the programs provides a range of seasonality.
  - In American Samoa, NCRMP's index period is April-September and NPS' index period is November-January. The difference in sampling months between the programs provides a range of seasonality.
  - In Guam and Hawai'i, NCRMP and NPS monitoring programs have index periods that overlap by three months (June-August). The overlap in sampling can be used to increase overall sample size.
- EPA uses both NCRMP and NPS monitoring data for the BCG model (detailed in section 3.0), in the U.S. Caribbean.
- There is a currently funded NOAA project in place to increase data interoperability between NCRMP and the FGBNMS monitoring programs.

Underwater (in situ) imagery

- Co-registration is a challenge with respect to geolocating underwater data, which can be more of a challenge than the processing of the image itself.
- Appropriate metadata are also a barrier with respect to camera corrections. There is a strong need for metadata on the camera itself and geolocation of the site. However, assuming the metadata associated with a raw image is clear, a raw image is the most interoperable type of data in the context of this task team.
- Processing of imagery depends on the software used, but most software can receive raw imagery. Different scientists have their favorite software(s).
- Regarding underwater imagery methods, outwardly sharing derived data from the underwater imagery is often a barrier. For example, some scientists will not share derived data before it is published, but sharing the raw data (the raw image) is generally easier.
- Data derived from raw imagery can be just as disparate as in the direct, diver-based visual method. In other words, the sampling design behind the image collection impacts how the data derived from the image can be compared between programs and agencies.

Above-water (ex situ) *imagery*

- There are a lot of challenges associated with correcting for turbidity, reflectivity, and refractivity extrapolations when comparing *ex-situ* imagery.
- Spatial resolution can be widely variable from dataset to dataset.
  - For example, NASA looks at broad categories of resolution (i.e., seagrass vs. coral vs. sand), which would not necessarily be interoperable with an agency looking for higher resolution categories for different management needs like seafloor mapping or coral restoration.
- Water quality sub-variable parameters, (e.g., Chlorophyll a, light, etc.) are generally well-understood and interoperable by a variety of partners across programs and agencies.

How Well Are the Variables Currently Being Implemented, From Observation to Information Delivery, to Meet Requirements?

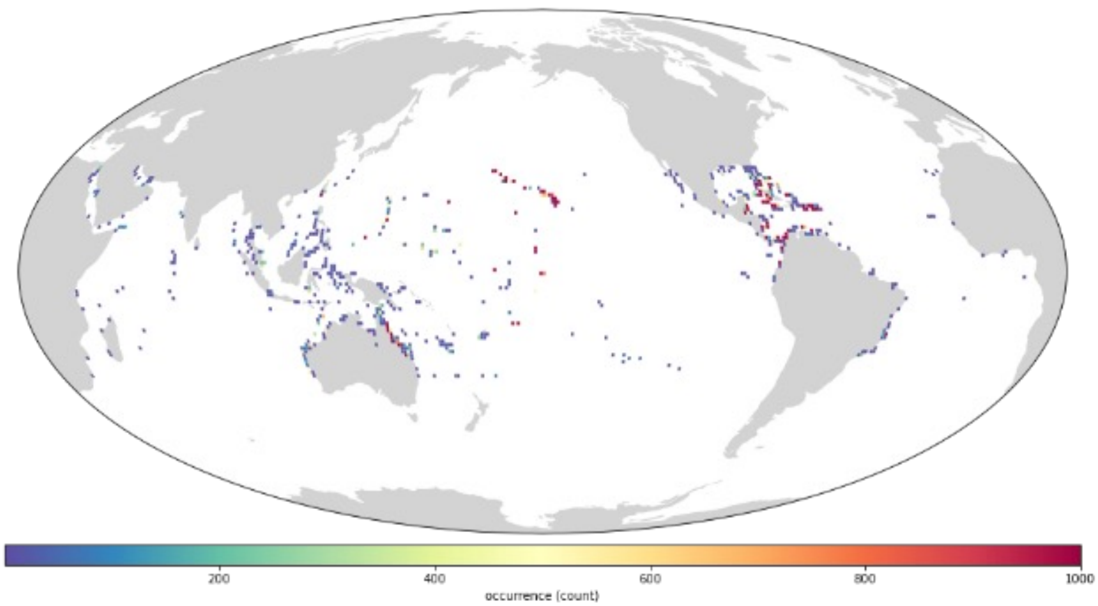
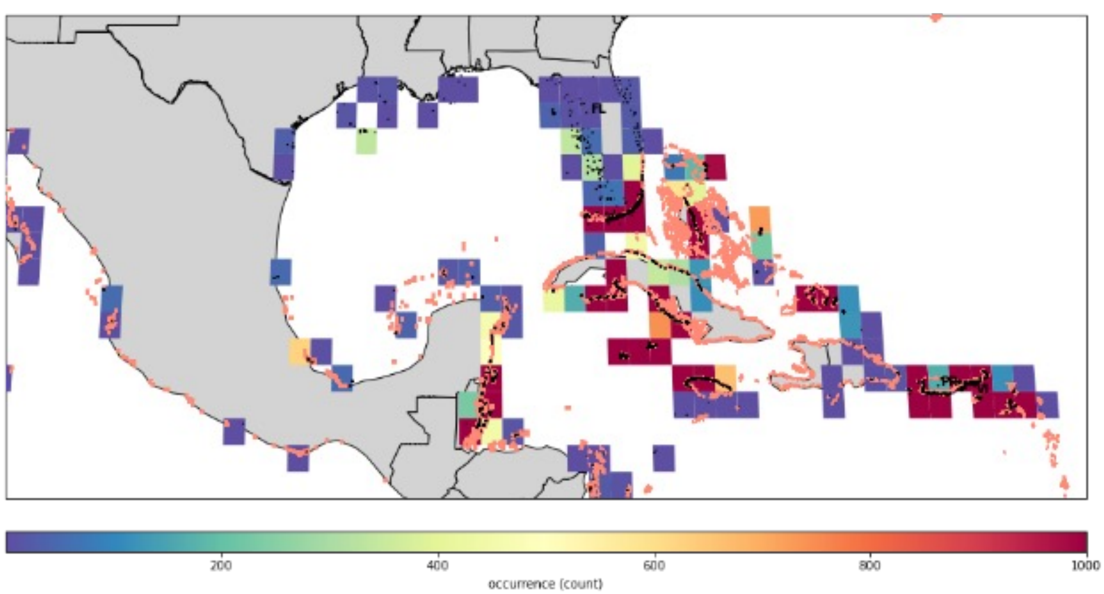


FIGURE 7A (ABOVE): Density of occurrences for *Scleractinia* from the Ocean Biodiversity Information System (OBIS) binned to 1° cells with depth between 0-30 m and latitude between 30°N and 30°S. This figure does not include occurrences where depth was missing in the occurrence data shared to OBIS.

FIGURE 7B (BELOW): Density of occurrences for *Scleractinia* from OBIS (1° cells, 0 - 30 meters) in the northwestern Caribbean Sea, Gulf of Mexico, and eastern tropical Pacific Ocean. The pink dots represent known distribution of corals from the UNEP WCMC[32], showing that many coral reef locations have no records in OBIS. (This map may be generated with the code found here https://github.com/MathewBiddle/bio_ice/blob/main/create_map_from_OBIS_API.ipynb)



32 Coral reef distribution from the UNEP World Conservation Monitoring Centre (UNEP-WCMC) and the WorldFish Centre, developed in collaboration with WRI (World Resources Institute) and TNC (The Nature Conservancy). Data sources include the Millennium Coral Reef Mapping Project (IMaRS-USF and IRD 2005, IMaRS-USF 2005) and the World Atlas of Coral Reefs (Spalding et al. 2001). See: https://data.unep-wcmc.org/datasets/1

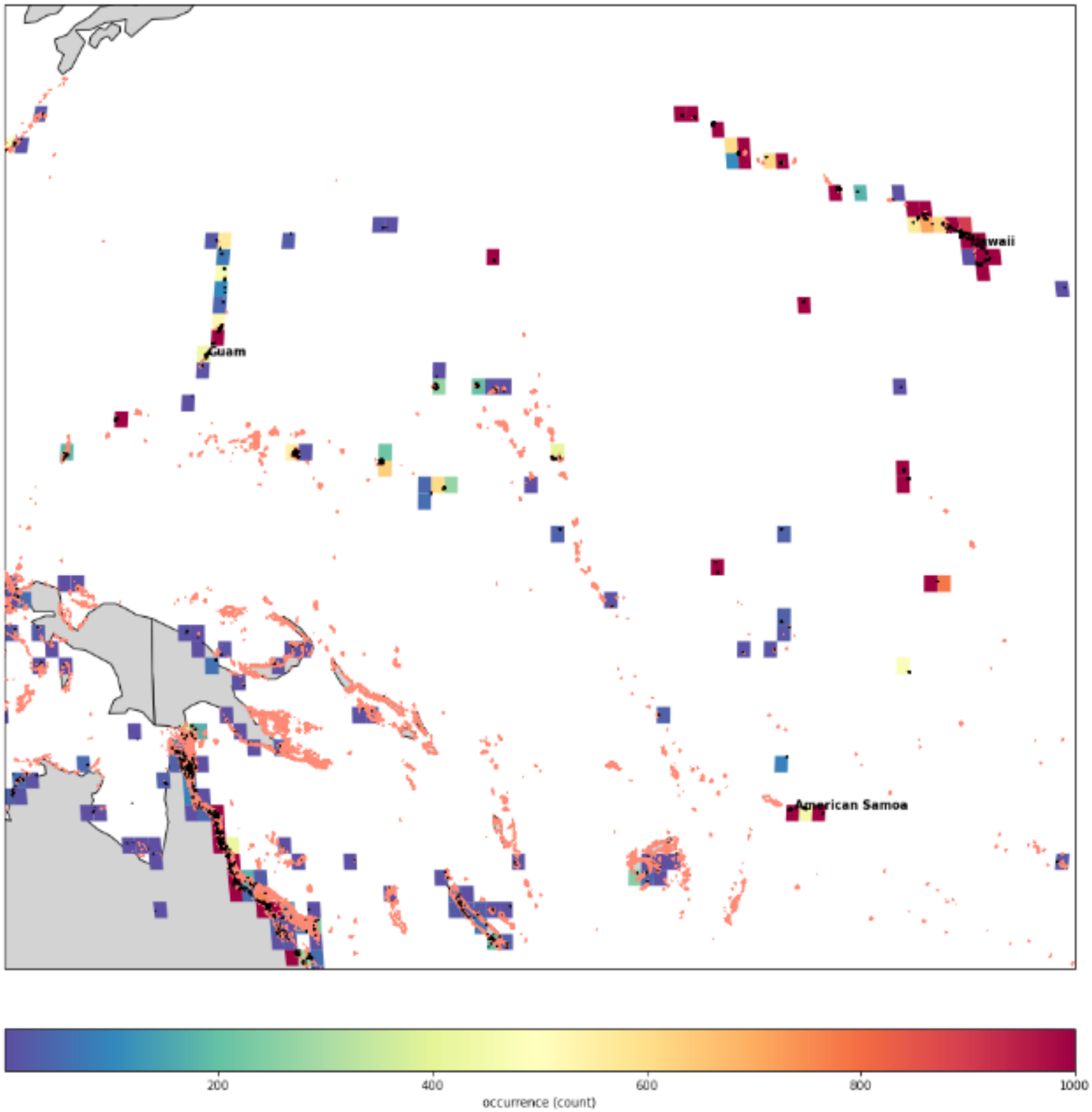


FIGURE 7C (ABOVE): Density of occurrences for *Scleractinia* from OBIS (1° cells, 0-30 m) in the U.S. Pacific Islands including Hawai'i, the Northwest Hawaiian Islands, Guam, the Commonwealth of the Northern Mariana Islands, American Samoa, and the Pacific Remote Island Areas. The pink dots represent known distribution of corals from the UNEP WCMC[33], showing that many coral reef locations have no records in OBIS.

Implementation of the EOV "Hard Coral Cover and Composition" and the slate of associated EBVs and ECVs relies upon data being shared in standardized ways to facilitate reuse and application of these variables to a broad range of stakeholder, policy, and conservation management needs. While each agency is beholden to agency-specific reporting requirements, the data are often not useful beyond the life of the project they pertain to due to the lack of standardization preventing broader reusability.

33 Coral reef distribution from the UNEP World Conservation Monitoring Centre (UNEP-WCMC) and the WorldFish Centre, developed in collaboration with WRI (World Resources Institute) and TNC (The Nature Conservancy). Data sources include the Millennium Coral Reef Mapping Project (IMaRS-USF and IRD 2005, IMaRS-USF 2005) and the World Atlas of Coral Reefs (Spalding et al. 2001). See: https://data.unep-wcmc.org/datasets/1

Given the global nature of the essential variables, scientists and data users need to be able to answer questions at global scales which requires data available at both broad spatial and temporal scales. While progress has been made in data availability for scleractinian corals at global scales (Figure 7), this sub-task team has identified further work is needed to fully understand the extent to which data exist that capture this EOV but are not discoverable in a publicly accessible repository. To answer scientific questions posed in the hard coral cover *EOV specification sheet*[34] such as 1) "What is the current status of coral reefs (extent, diversity, health) and of life on coral reefs?"; 2) "How is life on coral reefs changing?"; 3) "What are the natural and anthropogenic drivers of change on a coral reef?"; and 4) "How does the changing status and trend of coral reefs affect ecosystem function and the provision of ecosystem services and benefits?" data are urgently needed in open-access, aggregated, standardized, and easily manipulated ways, now more than ever due to the myriad of threats facing coral reefs.

NOAA's NCRMP is a good example of a national-scale, long-term monitoring program collecting hard coral cover using similar methods across all U.S. coral reef areas; yet, there are still challenges with integration between different regions. Data collected by investigators from different regions has led to variations in the data structure with dates captured in different formats, time zones, geographic coordinate systems, and using different column headers for the same variables. All of these differences add complexity to integrating data across regions to be able to show the state of U.S. coral reefs. If the data were stored in a consistent format, combining data that utilize the same collection method from different regions would be much easier.

Another challenge to data integration can be inconsistent references to species names. For example, has the data collector referenced the species by scientific name or by common name? Are there typographical errors in the species' scientific names? Has the species name changed during the course of the monitoring program? For example, the Caribbean hard coral *Montastraea faveolata* became known as *Orbicella faveolata* in 2012 (Budd et al. 2012). Small inconsistencies in species names can mean that the same species may be counted as two different species when aggregating data from multiple providers without human quality assurance and control. One way to reduce this type of error is for providers to validate the names of species against a controlled taxonomic list such as the World Register of Marine Species (WoRMS). Use of a taxonomic list helps to increase standardization and the interoperability of data across multiple data providers.

One globally recognized way for providing data standardization is to use the data standard DwC. DwC is a standard glossary of terms used for sharing and integration of biological diversity data (Wieczorek et al. 2012). DwC was originally designed for natural history collection data but has grown in use and applicability with its adoption by global biodiversity data aggregator repositories like the OBIS and the Global Biodiversity Information Facility (GBIF). Further, DwC has been adopted by GOOS (Benson et al., 2021).

Once data are standardized, they can be integrated in global aggregation systems like OBIS and can be easily reused by data analysts all over the world to answer the scientific questions posed above in the specification sheet for hard coral cover and composition. The time it takes to prepare a federal dataset for public access is often extensive, such that after the dataset is released, the data manager may not have the time or resources to release in a format that differs from their agency's guidelines. Therefore, a key to more widespread success with respect to data standardization would be an acknowledgment at the agency levels that data should be standardized from the beginning of the quality assurance and control and archival process using a common format like DwC.

34 https://drive.google.com/file/d/1DN3yzP5C58CiwKYCtC7-3af7BKFOS5UH/view?usp=sharing

RECOMMENDATIONS

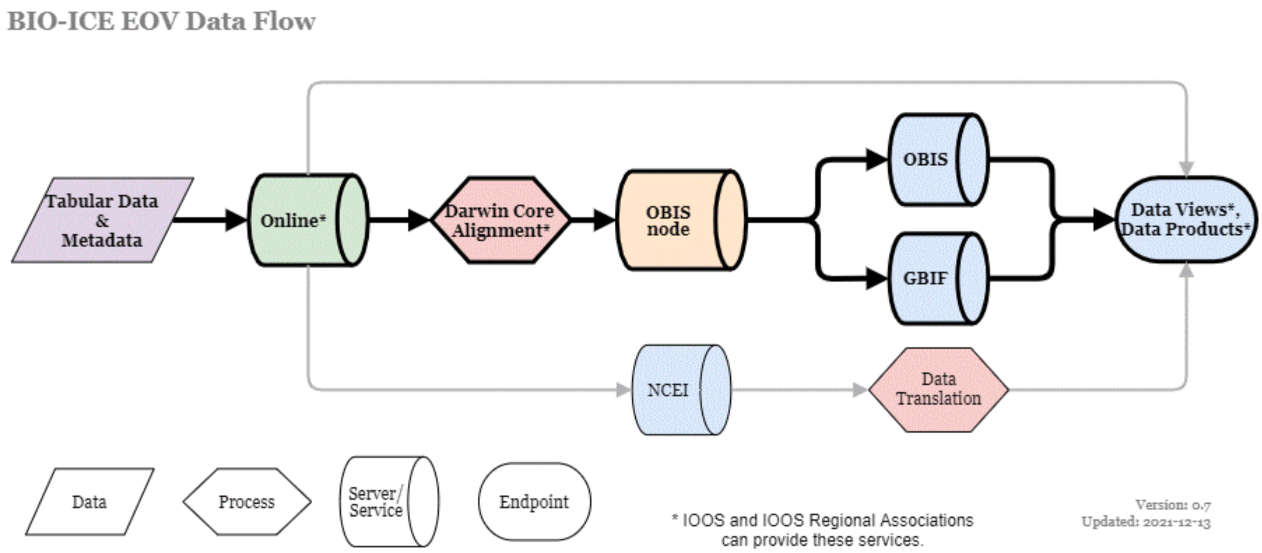


FIGURE 8: Data flow diagram depicting preferred (bolded black lines) and alternate (gray lines) data flows for hard coral observation data to inform hard coral cover and composition visualizations and products. (After Benson et al., 2021)

Optimized Data Workflow

Figure 8 shows the task team's preferred (bolded black lines) data flow for hard coral cover data. The perspective of Figure 8 is from the data originator (the person or group that created the data) and the steps are defined below:

Tabular Data & Metadata - These are the post-collection observations in an electronic format that may have some scientific quality assurance and control already performed.

Online - Data are available through some online platform. This might be through a project or program platform, or through another entity's service (like NCEI's archive services or an IOOS Regional Association website).

DwC Alignment - The process of translating the post-collection observations into a community agreed upon standard. This process can be facilitated by IOOS and the IOOS Regional Associations through their data management capabilities.

OBIS node - Once data are following DwC, they can be included in OBIS nodes (OBIS-USA is recommended), which share the data with global aggregators such as OBIS and GBIF.

OBIS/GBIF - Data made accessible to global aggregators are integrated with other datasets around the world to provide increased interoperability and reusability of observational data.

Data Views/Products - Observations available online can feed into defined data viewer tools and products to communicate status and trends on EOVs. The IOOS Office and Regional Associations can provide these products and views.

NCEI - *(non-preferred as the final or only outcome)* The National Centers for Environmental Information (NCEI) is used as an example in the figure to represent repositories that do not require the data to follow community agreed standards when accepting data into their collection. This path depicts data submitted directly to this type of repository that may or may not follow community agreed upon standards. This path may require the producer of the data viewer tool or data product to perform data translation to make the data ingestible into a platform of choice. Typically, this requires significant effort unique to each dataset, and does not create data that can be easily integrated with other datasets.

Data Translation - *(non-preferred outcome of not using DwC)* When data do not follow agreed upon community standards there is a data translation step needed to make an appropriate data viewer tool or product, and often this does not allow the data to be reused by others.

On the left side of the data flow diagram the preferred pathway begins when a user starts with their tabular data and metadata in the format most useful for the project the data were collected for. The data are then put online in the project-specific format so they are accessible. To improve reuse and interoperability of the data, they are then aligned to the data standard DwC. Once the data are standardized to DwC, they can be included in an OBIS node (OBIS-USA is recommended). The OBIS node then makes the data available to the global aggregators OBIS and GBIF. Once appropriate datasets are aggregated together, data viewers and other data products can be developed to assess hard coral cover data across multiple projects, representing a pathway where data are accessible, discoverable, interoperable, and reusable.

The observation requirements (i.e., what defines the data collected in Tabular Data & Metadata box) are identified by the agency and through groups like IOOS, GOOS, and GEO BON, and feed into the determination of what tabular data and metadata should be collected. Notably, each of the arrows in the diagram represent an iterative process that can bring the process back to an earlier step. The bolded boxes and arrows indicate the preferred process a data provider should strive to achieve. However, alternative pathways that are currently used are also depicted in the diagram. Finally, to reduce the complexity of the diagram, some interagency data flows are not depicted (for example, OBIS-USA submitting data for long-term archiving at NCEI).

Implementation Recommendations

Based on the summary and evaluation report above, the Bio-ICE coral task team makes the following recommendations, below. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of the U.S. Government and its funding sources.

The task team recommends:

- IOOS adopt the GOOS BioEco EOV naming "hard coral cover and composition" for its core variable "coral species and abundance." (Proposal submitted).
- U.S. agencies apply the DwC to percent hard coral cover observations collected or funded by such agencies.
  - > DwC already exists as a global standardized solution, and there is no need to reinvent the wheel for data standardization solutions. General education on DwC and the importance (globally) of data standardization is needed.
- U.S. agencies validate species names against a controlled taxonomic list such as the WoRMS to the extent resources allow.
- U.S. agencies continue to use Federal Geographic Data Committee (FGDC)-endorsed metadata standards to document data collections to ensure that key details to assess interoperability related to methodologies and sampling design are captured in a consistent manner.
- IOOS or another entity establish a hard coral cover data assembly center to facilitate standardization and sharing of hard coral cover data from U.S. agencies.
- U.S. agencies better coordinate pre-sampling regarding methods of data collection and sampling design. If the agencies are in alignment with respect to sampling region and method, they could potentially double data collection, for example pre- and post- bleaching season to assess impacts if the combined agencies have resources for two field seasons. Better coordination would allow for a more complete dataset to be collected. This could be facilitated via a monitoring working group of the U.S. Coral Reef Task Force.

- Submission of hard coral cover collection protocols to the Ocean Best Practices System (OBPS) in the community associated with the Bio-ICE task team.
- Utilizing the *IOOS video and photograph portal*[35] for archiving raw images.

To improve and resolve the issues surrounding interoperability, the federal scientific coral reef scientific community needs to get other similar groups of colleagues talking about data standards such as the SOST Biodiversity Working Group and the U.S. Coral Reef Task Force. The task team is pleased to put forward these recommendations, and next steps include a member agency of the task team, NCRMP, piloting the formatting of several hard coral cover datasets into DwC format in Spring 2022. Previous similar efforts regarding federal data interoperability have not been as successful as intended, potentially as a result of lack of prioritization and accountability. To maximize effectiveness, the IOOC could help campaign and socialize these recommendations within the relevant agencies at multiple levels including data collectors, data managers, and supervisors. An appropriate reference for the general approach that outlines the concrete steps for suggested data flow management is Benson et al. (2021).

35 https://video.ioos.us/

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APPENDIX A: ACRONYM LIST

AI - *Artificial Intelligence*

AUV - *Autonomous Underwater Vehicle*

BCG - *Biological Condition Gradient*

Bio-ICE - *Biology - Integrating Core to Essential variables*

CARE - *Collective benefit, Authority to control, Responsibility, and Ethics*

CoRIS - *Coral Reef Information System*

CREMP - *Coral Reef Evaluation and Monitoring Project*

DwC - *Darwin Core Standard*

EBV - *Essential Biodiversity Variable*

ECV - *Essential Climate Variable*

eDNA - *Environmental Deoxyribonucleic Acid*

EOV - *Essential Ocean Variable*

EPA - *Environmental Protection Agency*

FAIR - *Findability, Accessibility, Interoperability, and Reuse*

FGBNMS - *Flower Garden Banks National Marine Sanctuary*

FKNMS - *Florida Keys National Marine Sanctuary*

GB - *Gigabyte*

GBIF - *Global Biodiversity Information Facility*

GCOS - *Global Climate Observing System*

GEO BON - *Group on Earth Observations Biological Observation Network*

GOOS - *Global Ocean Observing System*

GPS - *Global Positioning System*

IOOC - *Interagency Ocean Observation Committee*

U.S. IOOS - *U.S. Integrated Ocean Observing System*

LiDAR - *Light Detection and Ranging*

MBON - *Marine Biodiversity Observation Network*

MiDAR - *Multispectral Imaging, Detection, and Active Reflectance*

ML - *Machine Learning*

NASA - *National Aeronautics and Space Administration*

NCEI - *National Centers for Environmental Information*

NCRMP - *National Coral Reef Monitoring Program*

NGO - *Non-Governmental Organization*

NMSAS - *National Marine Sanctuary of American Samoa*

NOAA - *National Oceanic and Atmospheric Administration*

NPS - *National Park Service*

OBIS - *Ocean Biodiversity Information System*

ONMS - *Office of National Marine Sanctuaries*

ORD - *Office of Research and Development*

OSTP - *Office of Science and Technology Policy*
PacIOOS - *Pacific Islands Ocean Observing System*
PACN - *National Park Service's Pacific Island Network*
PARR - *Public Access to Research Results*
PMNM - *Papahānaumokuākea Marine National Monument*
PRCRMP - *Puerto Rico Coral Reef Monitoring Program*
SCUBA - *Self Contained Underwater Breathing Apparatus*
SfM - *Structure-from-Motion*
SNR - *Signal-to-noise ratio*
SQUID-5 - *Structure-from-Motion Quantitative Underwater Imaging Device with 5 cameras*
SOST - *Subcommittee on Ocean Science and Technology*
TB - *Terabyte*
UAV - *Unoccupied Autonomous Vehicle*
USCRTF - *United States Coral Reef Task Force*
USGS - *U.S. Geological Survey*
USVI - *United States Virgin Islands*
WoRMS - *World Register of Marine Species*

APPENDIX B

OBPS repository link/upload confirmation

APPENDIX C

Consolidated EOV/EBV Tables

APPENDIX D

Updated hard coral cover EOV *Specification sheet*