doi: 10.25923/sedd-8w68

Summary Report: Workshop Report for Approaches to Mapping, Ground-Truthing, and Predictive Habitat Modeling of the Distribution and Abundance of Mesophotic and Deep Benthic Communities

Mapping, Ground-Truthing, and Predictive Habitat Modeling Project

Authors

Stacey L. Harter[1], Avery B. Paxton[2], Arliss J. Winship[3], Sarah D. Hile[3], J. Christopher Taylor[2], Matthew Poti[2], and Charles Menza[2]

[1] NOAA, National Marine Fisheries Service, Southeast Fisheries Science Center
[2] NOAA, National Ocean Service, National Centers for Coastal Ocean Science
[3] CSS, Inc., under contract to NOAA, National Ocean Service, National Centers for Coastal Ocean Science

December 2022

DWH MDBC Summary Report 2022-02

Suggested Citation

Harter, S. L., Paxton, A. B., Winship, A. J., Hile, S. D., Taylor, J. C., Poti, M., and Menza, C. (2022). Workshop report for approaches to mapping, ground-truthing, and predictive habitat modeling of the distribution and abundance of mesophotic and deep benthic communities. National Oceanic and Atmospheric Administration. DWH MDBC Summary Report 2022-02.
https://doi.org/10.25923/sedd-8w68

Acknowledgments

Thanks to Frank Parker and Hannah Brown (contractor) from the NOAA RESTORE Science Program for their support in planning and facilitating the workshop. Special thanks to Derek Sowers, Lieutenant Jennifer Kraus, Garrett Mitchell, Daniel Sternlicht, Sean Kelly, Greg Packard, Jason Chaytor, Bryan Costa, Scott Gallager, Isabel Romero, Abigail Powell, and Thomas Oliver for presenting information for topic discussions for the workshop. Many thanks also to the participants for their contributions and insights both to the overall workshop and focus group discussions. The report was reviewed by MDBC Technical Team. CSS, Inc. employees were supported under NOAA Contract No. EA133C17BA0062 and EA133C17BA0049.

For more information on MDBC Restoration, please visit:

https://coastalscience.noaa.gov/project/scientific-support-for-mesophotic-and-deep-benthic-community-restoration-in-the-gulf-of-mexico/

and

https://www.fisheries.noaa.gov/southeast/habitat-conservation/mesophotic-and-deep-benthic-communities-restoration

Disclaimer

Mention of trade names or commercial products does not constitute endorsement or recommendation for their use by the United States government.

Deepwater Horizon **Mesophotic and Deep Benthic Communities Restoration**

This report is part of the NOAA Mesophotic and Deep Benthic Communities (MDBC) Series of publications that share the results of work conducted by the *Deepwater Horizon* MDBC restoration projects.

The 2010 *Deepwater Horizon* oil spill was an unprecedented event. Approximately 3.2 million barrels of oil were released into the deep ocean over nearly three months. The plume of oil moved throughout the water column, formed surface slicks that cumulatively covered an area the size of Virginia, and washed oil onto at least 1,300 miles of shoreline habitats. More than 770 square miles (2,000 square kilometers) of deep benthic habitat were injured by the oil spill, including areas surrounding the *Deepwater Horizon* wellhead and parts of the Pinnacles Trend mesophotic reef complex, located at the edge of the continental shelf.

Under the Oil Pollution Act, state and federal natural resource trustees conducted a Natural Resource Damage Assessment (NRDA). The Trustees assessed damages, quantifying the unprecedented injuries to natural resources and lost services. They also developed a programmatic restoration plan to restore injured resources and compensate the public for lost services.

In April 2016, a settlement was finalized that included up to $8.8 billion in funding for the *Deepwater Horizon* Trustees to restore the natural resource injuries caused by the oil spill as described in their programmatic restoration plan, Final Programmatic Damage Assessment and Restoration Plan and Final Programmatic Environmental Impact Statement. The *Deepwater Horizon* Open Ocean Trustee Implementation Group is responsible for restoring natural resources and their services within the Open Ocean Restoration Area that were injured by the oil spill. The Open Ocean Trustees include NOAA, U.S. Department of the Interior, U.S. Environmental Protection Agency, and U.S. Department of Agriculture.

In 2019, the Open Ocean Trustee Implementation Group committed more than $126 million to implement four restoration projects to address the injury to MDBC. The MDBC projects are: Mapping, Ground-Truthing, and Predictive Habitat Modeling; Habitat Assessment and Evaluation; Coral Propagation Technique Development; and Active Management and Protection. NOAA and the Department of the Interior are implementing the projects, in cooperation with a range of partners, over eight years.

Together, the projects take a phased approach to meet the challenges involved in restoring deep-sea habitats. Challenges to restoration include a limited scientific understanding of these communities, limited experience with restoration at the depths at which these communities occur, and remote locations that limit accessibility.

More information about *Deepwater Horizon* restoration and the MDBC restoration projects is available at: www.gulfspillrestoration.noaa.gov.

Table of Contents

List of Figures

List of Tables

Commonly Used Acronyms

AUV: autonomous underwater vehicle
CMECS: Coastal and Marine Ecological Classification Standard
DWH: Deepwater Horizon
GOM: Gulf of Mexico
MBES: multibeam echosounder
MDBC: Mesophotic and Deep Benthic Communities
MGM: Mapping, Ground-truthing, and Predictive Habitat Modeling
NCCOS: National Centers for Coastal Ocean Science
NOAA: National Oceanic and Atmospheric Administration
ROV: remotely operated vehicle
SAS: synthetic aperture sonar
USBL: ultra-short baseline
USGS: U.S. Geological Survey

Definition of Terms

Mesophotic and Deep Benthic Communities (MDBC)
MDBC are an interacting group of benthic species, including fish, mobile and sessile invertebrates and benthic infauna, that grow within mesophotic and deepwater benthic habitats. Some taxa, such as mesophotic corals, create biogenic habitats and are both a taxonomic unit of the community and define the habitat. In the context of the Deepwater Horizon Programmatic Damage Assessment and Restoration Plan, MDBC are defined as a restoration type.

MDBC Habitats
Areas on the seafloor inhabited and/or associated with the MDBC. The MDBC habitats include mesophotic reefs, deep-sea corals, soft-bottom habitats and non-natural substrates (e.g., oil and gas structures, artificial reefs) located on the seafloor. The MDBC habitats may be characterized by geomorphological forms, substrates or biological cover depending on data availability.

Mesophotic Benthic Habitats
Areas on the seafloor that exist in the depth zone where light levels are low and are inhabited by an interacting group of benthic species. Mesophotic habitats are typically found at depths ranging from approximately 100 feet (30 m) and extending to over 500 feet (approximately 150 m) in tropical and subtropical regions (Puglise et al., 2009; Hourigan et al., 2015; Sulak and Dixon, 2015; Deepwater Horizon Natural Resource Damage Assessment Trustees, 2016). For the purpose of these MDBC projects, work in mesophotic habitats will generally focus on biological communities existing between approximately 165 feet (50 m) and 980 feet (300 m) deep. The use of 980 feet (300 m) as the lower limit of this zone is consistent with other regulatory regimes (Minerals Management Service, 2009). This depth range has also been referred to as the "twilight zone" (Pyle, 1996; Kahng et al., 2010). The dominant communities providing structural habitat among mesophotic benthic habitats comprise coral, sponge and algal species.

Deep or Deepwater Benthic Habitats
Areas on the seafloor that exist in the depth zone where light is not present and are inhabited by an interacting group of benthic species. For the purpose of this MDBC project, work in deep benthic habitats will generally focus on depths deeper than 980 feet (300 m) deep.

Seafloor Mapping
Seafloor mapping refers to the process of using remote sensing to survey and derive depth, shape, texture, reflectivity, and backscatter of the seafloor. In the context of this project, mapping is generally used to refer to seafloor mapping, including in the project title. Data from seafloor mapping form the basis in predictive habitat modeling to interpret, classify, and characterize the geomorphological forms, substrates, and benthic biological cover used to define MDBC habitats. We do not include the bottom layers of the water column in the definition of seafloor mapping. For this project, seafloor mapping activities would be undertaken using surface (i.e., ship, autonomous surface vehicle), subsurface (i.e., remotely operated vehicle, autonomous underwater vehicle, human-occupied vehicle, technical diving), and towed sensors, and could also include electromagnetic or laser scanning. Mapping operations will collect high-resolution data to document the distribution and abundance of MDBC habitats and improve existing habitat suitability models (Open Ocean Trustee Implementation Group, 2019, Section 4.4.6.1).

Ground-truthing
The process of collecting in-situ observations to validate the accuracy of MDBC habitat model predictions and information documenting the abundance and distribution of MDBC habitats (Open Ocean Trustee Implementation Group, 2019, Section 4.4.6.1). The specific collection methods and types of data to collect will be determined during the planning phase of this project.

Predictive Habitat Modeling
The process of predicting MDBC habitats from remotely sensed information, including seafloor mapping data, and in-situ MDBC observations. For this project, predictive habitat modeling will focus on producing refined northern Gulf of Mexico regional-scale models for mesophotic and deepwater coral species (Open Ocean Trustee Implementation Group, 2019, Section 4.4.6.1). MDBC habitats may be defined by geomorphological forms, substrates or biological cover depending on data availability.

Model Validation
The process of comparing predictive habitat model predictions to independent data and quantifying how well the predictions match those data through established statistical performance measures and tests. Ideally, data used for validation should be new data collected in a statistically robust manner designed specifically for the purpose of validating a model's predictions. Model validation provides an assessment of model reliability.

Prioritization of Mapping Requirements
The process of engaging data users across MDBC projects as well as subject matter experts, resource management agencies, and other organizations (both internal and external to the Deepwater Horizon Natural Resource Damage Assessment) to develop prioritization criteria, and identify and prioritize spatial gaps in derived products that characterize the seafloor for the MDBC portfolio. The goal of the prioritization will be to recommend locations where derived products are needed and to inform plans for future collaborative field work during the implementation phase of this project. This will support the Deepwater Horizon Natural Resource Damage Assessment and the MDBC portfolio as approved in the Open Ocean Trustee Implementation Group Final Restoration Plan 2/Environmental Assessment: Fish, Sea Turtles, Marine Mammals, and Mesophotic and Deep Benthic Communities (Open Ocean Trustee Implementation Group, 2019).

Inventory
For the purposes of this report, refers to a collection of seafloor mapping, ground-truthing and predictive habitat modeling data, literature, metadata, and derived products.

Mapping Requirements
Defines the intended use or application of the seafloor mapping and ground-truthing data. Requirements are provided by the data users and includes information on the estimated size or extent of features to be mapped, or expected level of uncertainty in measurements, qualities or quantities of features on the seabed. Requirements often have a dimension, scale or extent for reference (e.g., defining hard vs. soft bottom, delineating habitat classes at defined taxonomic resolution, identifying and locating individuals of key taxa, etc.)

Specifications or Survey Specifications

The data specifications are determined by mapping and ground-truthing experts and include considerations of resolution and precision to achieve requirements. The specifications help guide the experts to sensors, platforms and optimal survey designs to achieve the desired resolution. A survey specification may achieve many requirements.

Executive Summary

Successful restoration of mesophotic and deep benthic communities (MDBC) impacted by the Deepwater Horizon oil spill requires knowledge on the distribution, abundance, and status of these communities. Only a small fraction of mesophotic and deep benthic habitats in the Gulf of Mexico (GOM) have been surveyed using mapping and ground-truthing methods. Furthermore, existing predictive habitat models that characterize the distribution and abundance of MDBC need to be validated. Knowledge of MDBC habitat requires coordinated mapping and ground-truthing campaigns, whose data feed into predictive habitat models that guide further investigation and restoration activities.

We convened a workshop series with subject matter experts to present on, discuss, and address gaps in criteria for sensor selection, standards for operations, and best practices to help develop a coordinated mapping, ground-truthing, and modeling approach. The workshop series occurred in December 2021 and consisted of three coordinated sessions for mapping, ground-truthing, and modeling that collectively reviewed the state of the science, identified information gaps, and defined suggested approaches.

Seafloor mapping presentations and discussions focused on approaches for using ship-based sonar and autonomous underwater vehicles (AUVs) to meet data requirements. Mapping will occur over multiple years, platforms, and sensors, so approaches for maintaining data consistency should be implemented. While ship-based sonar will primarily fill regional and mesoscale data needs, microscale data are best collected with AUVs incorporating the latest processing and decision-making “engines” and sensors that may offer the ability to image fan-like corals and fine-scale habitats.

Ground-truthing presentations and discussions examined tools and techniques for data collection and analysis. Georeferenced sediment sampling employing multicoring and sediment image profiling approaches can provide key information on substrate and geology. Visual imagery can quantify abundance and distribution of MDBC, and laser and stereo imaging approaches can measure organisms. Some subject matter experts suggested intensive surveys of focal areas (e.g., growth/taxonomic resolution) and more dispersed sampling effort across broadscale regions (e.g., geoforms or substrates). Image analysis should harness artificial intelligence and machine learning to automate processes, and help evolve the Coastal and Marine Ecological Classification Standard (CMECS) classification schemes for MDBC.

Seafloor maps and ground-truthing observations will provide inputs for predictive modeling to characterize spatial distributions of MDBC and associated habitat. Discussions during the modeling workshop session indicated that a range of modeling techniques may be appropriate but that each technique has its own advantages, limitations, and types of outputs. A common theme was that useful models rely on good data, so the collection of input data should be designed with modeling in mind, including appropriate spatial sampling, important predictor variables at relevant scales, and high spatial and temporal data resolution. Modeling should be conducted with the data needed rather than settling for the data in existence. With respect to model outputs, discussions emphasized the need to fully account for uncertainty in model predictions and the need to validate model predictions with new independent data collected for that purpose.

The workshops emphasized the importance of coordinated mapping and ground-truthing to provide critical data to predictive habitat modeling. However, individual data products from mapping and ground-truthing will also provide important data to guide habitat assessments and support restoration activities. Contributions from these workshop sessions will be incorporated into the implementation plans and subsequent field missions and studies that will serve to fill data gaps using the latest sensors, methods, interpretation techniques and modeling approaches.

1. Introduction

The 2010 *Deepwater Horizon* (DWH) oil spill released approximately 3.2 million barrels of oil into the Gulf of Mexico (GOM), injuring an estimated 2,000 km^2 (770 mi^2) area of deep-sea benthic habitat, including associated mesophotic and deep benthic communities (MDBC). The full extent of damage to MDBC from the DWH oil spill remains unknown, and knowledge gaps regarding MDBC distribution create significant challenges for restoring MDBC communities and achieving restoration goals prescribed by the *Deepwater Horizon* Oil Spill: Final Programmatic Damage Assessment and Restoration Plan and Final Programmatic Environmental Impact Statement (Deepwater Horizon Natural Resource Damage Assessment Trustees, 2016).

Successful restoration of MDBC impacted by the DWH oil spill requires knowledge of the distribution, abundance, and status of these communities and associated habitats. An estimated 30,000 square miles of seabed may have qualities that are suitable for settlement and growth of MDBC. Only small fractions of the mesophotic and deep benthic habitats of the GOM have been surveyed with modern methods to validate predictive habitat models which characterize the distribution and abundance of MDBC. The lack of modern, high-resolution seafloor maps, ground-truthing observations and predictive habitat models represents one of the foremost challenges to implementing restoration of MDBC following injury by the DWH oil spill. The Mapping, Ground-truthing, and Predictive Habitat Modeling (MGM) project seeks to fill this gap in understanding of the distribution and abundance of MDBC.

Mapping, as defined here, is the remote sensing of shape and texture of the seafloor. Ground-truthing provides the direct visual observations or sampling of a quality or quantity of the seabed. Predictive habitat models use functional and statistical relationships to extend observations of seabed qualities and quantities by predictions over larger areas. These three components are combined in a cyclical process (Figure 1.1) to develop and refine predictive habitat maps to achieve project requirements (Figure 1.2). Predictive models are also used to guide subsequent ground-truthing to assess the accuracy of model predictions, and to guide mapping and ground-truthing and new model development at finer spatial scales (Figure 1.1). The mapping, ground-truthing, and modeling cycle provides a framework to develop maps of geology, bottom type, and biological cover and distribution and abundance of mesophotic and deep benthic communities across a range of spatial extents and map resolutions.

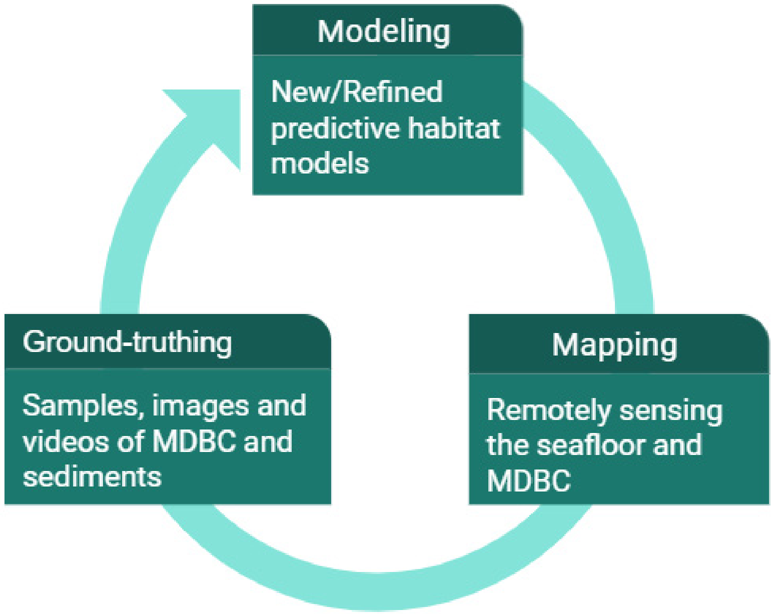

Figure 1.1. Cyclical schematic of seafloor mapping, ground-truthing, and predictive habitat modeling.

We identified key requirements to characterize the distribution and abundance of MDBC to guide activities and objectives for restoration and management through specific projects including habitat assessment and evaluation, coral propagation techniques, and active management (Figure 1.2). The requirements address needs for regional (kilometer) to microscale (sub-meter) extents and resolutions for maps that describe qualities or quantities of MDBC. Large topographic features such as ridges, pinnacles and reefs can be defined from coarse resolution models. Characterizing sediment types or differentiating hard consolidated versus soft sediments may require finer resolution maps, ground-truthing, and predictive habitat modeling. Identifying and locating aggregations of corals or characterizations of coral communities will require the finest resolution maps, ground-truthing, and modeling.

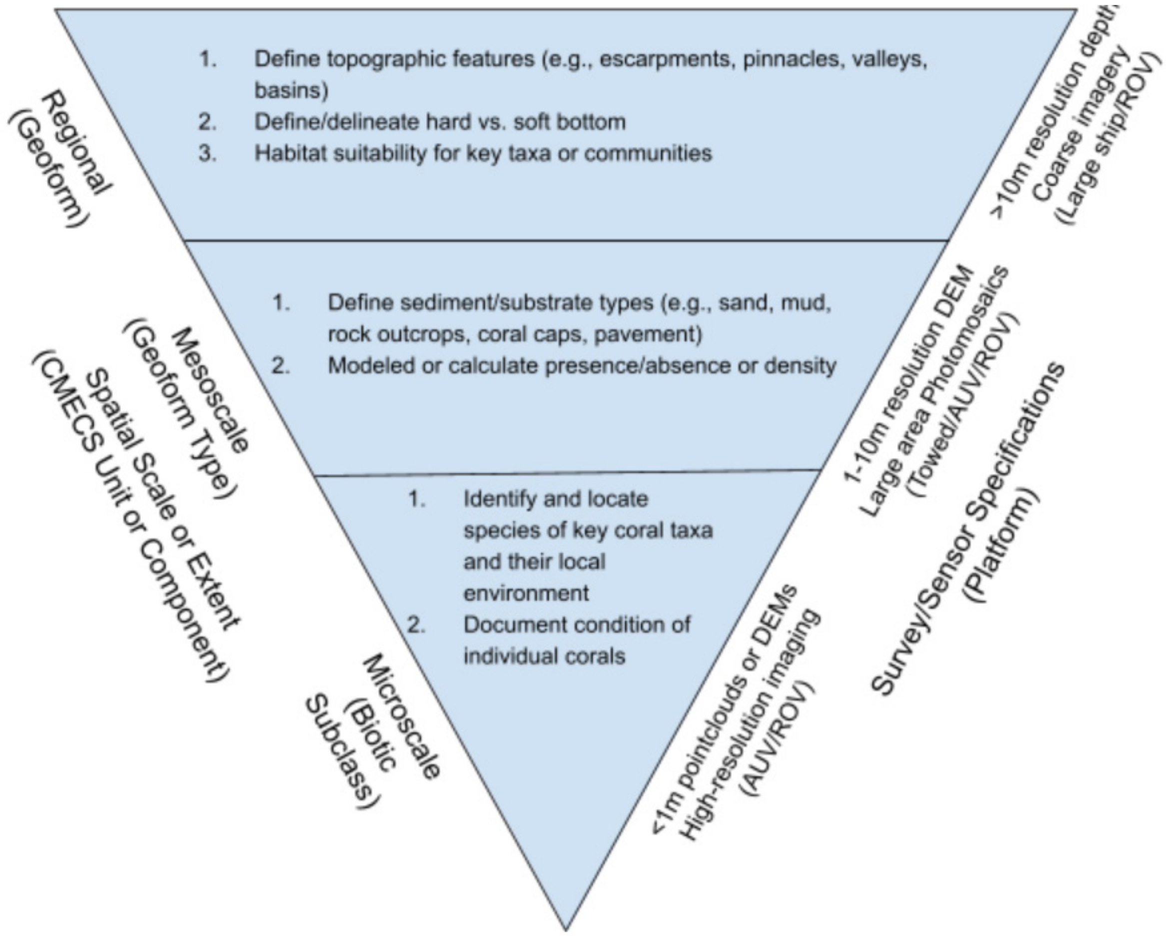

Figure 1.2. Mapping, ground-truthing, and modeling data and product requirements.

In December 2021, we convened a workshop series for subject matter experts (Appendix A) to discuss and address criteria for sensor selection, standards for operations, and best practices for conducting mapping, ground-truthing and predictive habitat modeling. The goal of the workshop was to identify the most appropriate survey platforms and sensors, as well as analysis, interpretation, and classification best practices, that will meet the requirements for characterizing the distribution and abundance of MDBC. The workshop included three coordinated sessions for mapping, ground-truthing, and modeling that collectively reviewed the state of the science, identified information gaps and defined best practices for mapping, ground-truthing and predictive habitat modeling (Appendix B). The workshop built upon outcomes from a MDBC mapping prioritization exercise that identified and ranked mapping, ground-truthing, and modeling needs and requirements, and workshop outcomes will be used to guide implementation of restoration activities.

2. Seafloor Mapping

2.1. Background

At the regional scale, remotely sensed maps of the shape and texture of the seabed often form the first base maps for projects. They help delineate large topographic features or identify areas of slope or roughness that might indicate seabeds that are suitable for mesophotic and deep benthic communities. Mapping sensors such as sonars can be deployed from large survey vessels, autonomous underwater vehicles (AUVs) or towed bodies. Mesoscale mapping at finer resolution may detect seabed substrates that support MDBCs or be indicative of structure forming invertebrates. The mapping sessions focused on two areas: 1) best practices for ship-based multibeam echosounder surveys, specifically addressing combining data from past and current surveys, assessing data quality, and methods for standardizing multibeam backscatter, and 2) evaluating sensors for use in AUV surveys.

2.2. Ship-based Sonar Data and Processing

Mapping the depths of the seafloor is the core mission for updating nautical charts, and robust industry standards exist for defining sensor acquisition parameters and requirements for data quality, however these data have demonstrated implications for understanding ecological communities. Multibeam sonars are often integrated with oceanographic vessels to conduct surveys over broad spatial extents. However, the resolution of ship-based sonars is dependent on water column depth which may preclude product application at mesoscale and microscale applications.

Ship-based sonars are a valuable tool for locating, identifying, and mapping the distribution of sediment types suitable for resource development or extraction, or to locate geological formations and sources of hydrocarbons. In many instances, the techniques developed by industry for data products may exceed nautical charting standards in terms of resolution of bathymetry. In addition, the acoustic backscatter response from multibeam echosounders can be processed to extract additional seabed properties.

This session of the workshop aimed to identify capabilities and limits in mapping seabed habitats using ship-based sonars and understand best practices for collecting and interpreting multibeam backscatter. The session began with presentations by three speakers to provide an introduction and overview to selected methods in compiling and interpreting multibeam survey data for habitat mapping, and methods to standardize acquisition and processing of multibeam acoustic backscatter.

Derek Sowers with NOAA’s Office of Ocean Exploration and Research (OER), presented on his synthesis of existing and new multibeam sonar data to characterize and classify seafloor features and geoforms around deep ocean canyons and indicators of biological communities on the outer continental shelf. He discussed areas of high slope, peaks and ridges as being primary features for supporting deep benthic communities and demonstrated that automated terrain segmentation methods could repeatedly and successfully classify seafloor geomorphology from bathymetric data that may be suitable to scale-up for identifying cold water coral habitats across the GOM.

Lieutenant Jennifer Kraus (NOAA National Centers for Coastal Ocean Science [NCCOS]) presented on procedures used on NOAA’s hydrographic survey vessels that normalizes backscatter between survey launches for a nautical charting project. The vessels conduct a survey over a common reference area on the seabed and “tune” the backscatter in post-processing to achieve comparable responses to produce consistent backscatter surfaces into a larger mosaic. The process is repeated at each geographical setting, or if environmental conditions change.

Garrett Mitchell (Fergo) summarized research and protocols used by Fugro to standardize the acquisition of backscatter, especially for deep multibeam surveys. The purpose of these procedures is to optimize data quality across a range of depths and vessels for detecting water column gas seeps and seafloor indicators of geological formations and sources of hydrocarbons. The process uses correction factors within files specific to the sonar manufacturer. Several survey lines, using the range of expected sonar settings, are conducted over a seabed reference area to estimate parameters that correct for changes in qualities of the sectors in the multibeam and ping characteristics such as pulse length or shape.

After the presentations, facilitated group discussions among the participants focused on the following questions:

What are the tradeoffs in optimizing data acquisition for multibeam bathymetry and backscatter?

- Bathymetry can provide an indication of vertical relief and slope, whereas backscatter can help identify hard versus soft substrates, yielding additional information on seafloor composition.
- In flat areas of the seafloor, backscatter can identify seafloor composition, whereas bathymetry cannot. In high relief areas of seafloor, however, backscatter is less consistent, but bathymetry can be used to quantify vertical relief.
- It may be helpful to consider tradeoffs between bathymetry and backscatter as related to MDBC. For example, key questions include - is bathymetry or roughness more important to quantify for MDBC prediction, and is quantifying the slope versus identifying drop-offs more important for MDBC prediction?
- MDBC presence often correlates with hard substrate occurrence, and backscatter can detect hard substrates. MDBC are also associated with low relief features, so perhaps bathymetry is less important than backscatter in predicting MDBC occurrence.
- Be aware that sometimes collecting the best quality bathymetry can yield poor quality backscatter.
- More overlap between survey lines is required to optimize backscatter data but this reduces mapping speed and efficiency relative to bathymetry-driven survey lines.
- Consider investing in calibration to maximize data quality.

What are the best practices for assessing quality and combining data for bathymetry and backscatter from past surveys?

- Best practices for assessing data quality from past surveys:
    - Several software applications exist that can help assess data quality from past surveys. BRESS (Bathymetric and Reflectivity-based Segments) can be used to segment seafloor mapping data by analyzing colocated digital elevation models and backscatter mosaics. StormFix helps identify and reduce the presence of artifacts in backscatter mosaics and can

also be used to check data quality. Both BRESS and StormFix are available from https://www.hydroffice.org/.

  - When assessing quality and preparing to combine previous surveys, it is necessary to know whether the absorption coefficient was applied during raw data collection (e.g., already accounted for in .raw file) or whether the absorption coefficient correction should be applied during post-processing.
  - For the backscatter coefficient, it is necessary to know how the SVP (sound velocity profile) was observed (e.g., XBT [expendable bathythermograph]; CTD [conductivity, temperature, and depth instrument]; etc.).
  - Data assessment should include examination of the BScorr (backscatter correction) file to ensure that it was entered correctly. Some have encountered issues if the BScorr file was entered incorrectly, necessitating the elimination of an entire channel and resulting in a single-sided mosaic.
- Best practices for combining data from past surveys:
  - Combining bathymetry from multiple surveys is easier than combining backscatter. This is largely because backscatter surveys must be combined on a survey-by-survey basis rather than using a more automated approach. If it is necessary to combine bathymetry and backscatter data for a particular region, it is ideal if the bathymetry and backscatter data were collected together.
  - The spatial resolution of data is an important consideration when combining datasets. Coarser resolution may be appropriate for planning fine-resolution surveys. It is generally not acceptable to resample data to a finer resolution than appropriate for the survey instrument due to potential biases in interpolation methods. Also, recognize that older data are likely to have a coarser resolution and more artifacts than newer data so can present resolution discrepancies if combined.
  - Metadata contain relevant details for combining data, such as how (or whether) SVPs were conducted.
  - If combining bathymetry data, only combine cleaned data that have been subject to quality control and cleaning to remove noise and artifacts. It is often best to create a new bathymetry grid to facilitate data combination. Similarly, only cleaned backscatter data should be combined, and if there is a bad sounding for bathymetry then it is likely also bad for backscatter.
  - When combining backscatter data, it is best to work with the raw data rather than a processed grid or RGB image. If only a processed grid is available, however, then aerial photography tools that use methods, such as histogram matching, and treat the image as a grid can facilitate image combination but are not ideal.
  - Since backscatter is highly frequency dependent, it is not acceptable to merge low and high frequency backscatter products together like a picture. Instead, backscatter surveys from different survey vessels or vehicles should be considered as their own surveys and not be mosaiced together into one dataset.
  - Combining data using normalization techniques is an option but cannot be done across different frequencies.

- Other considerations include using backscatter reference areas, exporting GSF (generic sensor format) files with bathymetry edits incorporated instead of using raw files, applying status dB offsets to match various launches, and investing in calibration because of the value added for interpretation despite the time cost.
- For the MDBC project, there will be multi-resolution data (e.g., ship sonar vs AUV sonar), so combining or merging data will be tricky and will require careful consideration.

Which methods exist for standardizing multibeam backscatter, and which can be operationalized most effectively?

- Select and use one or more seafloor reference sites covering depths where different vessels and sonar settings will be compared and normalized.
  - Ideas for site selection include those used already by NOAA's Office of Coast Survey (OCS), private industry, or the Multibeam Advisory Committee, or potentially sites near major ports that MDBC-project vessels would embark from.
  - Reference sites would need to be surveyed by at least two vessels.
  - Logistics of creating and using reference sites should be considered. Participants suggested areas of homogenous seabed and relatively flat topography.
  - Reference site information should be readily available on all MDBC missions and calibration protocols should be easy to implement.
  - The site and protocol information should also be shared with researchers collecting data in the GOM to facilitate data sharing. Standardized logs should be developed for tracking, especially between operators and between vessels.
- The University-National Oceanographic Laboratory System (UNOLS) fleet is undergoing multibeam standardization protocols that include and may be a helpful resource when making similar decisions for the MDBC portfolio. Offices within NOAA have also pursued standardization protocols.
- Entities have developed internal tools to estimate parameters to calibrate or standardize acquisition settings (see G. Mitchell presentation summary above) or provided as a service by the manufacturer.

2.3. AUV acoustic and optical imaging

While ship-based sonar can effectively meet regional-scale mapping requirements, such as defining topographic features or identifying hard versus soft substrate, and can also meet mesoscale mapping requirements like defining substrate type, ship-based sonar cannot easily provide microscale remote sensing observations and will be difficult to provide mesoscale requirements in deeper water. This presents challenges when attempting to detect aggregations of key MDBC taxa over large spatial scales, as some of these biota are not typically habitat-forming or mound-associated. Instead, MDBC often include one "rope" or two dimensional "fan" structures that rise from the seafloor and cannot be easily detected with ship-based sonar, or using other standard technologies.

Outfitting mapping and imaging sensors on AUVs, however, presents a possible avenue for overcoming challenges of microscale mapping and detection. In particular, technologies applied in defense and industry can likely be harnessed to map and detect MDBC. These technologies include advanced sensors like synthetic-aperture sonar (SAS) and laser-line scanners that can be coupled with improved on-vehicle data processing and autonomous decision making.

This session of the workshop aimed to identify the latest approaches to mapping seabed features with AUVs and to understand capabilities and limitations in using different styles of AUVs for mapping. The session began with presentations by several speakers that provided an introduction to SAS imaging from AUVs and collecting photomosaics and point clouds from AUVs.

Daniel Sternlicht from the Naval Surface Warfare Center provided an overview of SAS and applications for seafloor mapping. SAS offers key advantages compared to other seafloor mapping techniques because it can generate high-resolution images comparable to high-frequency systems but with a much better range potential. SAS is a mature technology that has facilitated advancements in seabed change detection, environmental characterization, multi-modal and sub-bottom sensing, and automated scene perception. While primarily used in industry, it can be applied to seafloor mapping to support MDBC restoration activities because it can conduct high-resolution mapping and imaging at rapid survey rates that can be employed for temporal monitoring of habitat and associated biota and segmentation or characterization of seabed regions.

Sean Kelly from the National Deep Submergence Facility and Greg Packard from Ocean Systems Laboratory at Woods Hole Oceanographic Institute (WHOI) summarized underwater vehicle capabilities, including payload options, endurance and depth, and navigation and tracking. The presentation highlighted the differences between torpedo or linear vehicles versus hover or bottom-tracking vehicles. Briefly, torpedo vehicles are faster and better for surveys of large areas, and can operate at relatively high altitude from the seabed. Bottom tracking or hover vehicles are relatively slow, but suited for detailed imaging of seabed features, especially in high-relief or even vertical structure. Both vehicles can carry similar sensor payloads such as swath sonar mapping systems, video or still imaging systems, and other environmental sensors.

After the presentations, facilitated group discussions among the participants focused on the following questions:

What are the benefits and limitations in using alternative sonars like synthetic aperture sonar on AUVs for mapping biological communities?

- SAS is particularly well-suited for seafloor habitat change detection because it can provide fine-resolution imagery over broader seafloor areas compared to more mainstream sonar seafloor mapping approaches.
- SAS-derived data products are large and often require advanced onboard vehicle data processing harnessing machine learning or deep learning. Power consumption for SAS is also high and can present a challenge for seafloor mapping applications; this challenge can be overcome with appropriate planning.
- SAS may be able to detect soft corals that are often part of MDBC. SAS typically has a lower frequency than typical side-scan sonar so there is a possibility that soft corals may appear “transparent” using SAS. It could be worthwhile to examine the response of surface targets (e.g.,

different coral species) to different SAS imaging frequencies. Soft coral imaging might be complicated since soft corals may move (e.g., with water current). An interesting SAS survey approach is to use a circular survey design to image an object in 360 degrees, and this could be applicable to imaging MDBC fauna.

- SAS coregistry can be complicated since passes around objects or the particular areas of the seafloor cannot be precisely repeated, but warping or sift or slam techniques can help to more precisely coregister images.
- SAS processing is typically done using a Raytheon product that was built on code developed 15–20 years ago.

What are the benefits and limitations of using linear versus hover type AUVs to achieve mapping requirements?

- Torpedo vehicles are faster than hover vehicles.
- Torpedo vehicles are better for mapping large areas, whereas hover vehicles are better for mapping finer seafloor features.
- Seafloor slope can dictate which type of AUV is suitable for mapping. Torpedo AUVs can handle 30 to 35 degree bottom slopes; slopes greater than 40 degrees are less suitable for torpedo AUVs but this is also dependent upon vehicle response time. In contrast, hover AUVs are more maneuverable so are more suitable across a range of slopes and areas of high relief.
- Hover AUVs can move closer to the seafloor so are more appropriate for particular sensors that require proximity to the seafloor for best results.
- Torpedo and hover AUVS are not mutually exclusive, but rather can be complementary together to maximize AUV surveys across a range of spatial extents and resolutions.

What are new or existing sensors from other industries that can be considered for AUVs to enhance detection and mapping of MDBC?

- Sensor integration and fusion can enhance detection and mapping of MDBC. On-board processing from one sensor can trigger data acquisition or adaptive missions to investigate targets.
- Advancements in sensor capabilities and on-vehicle processing can improve MDBC mapping. Specifically, improved autonomy and dynamic path planning can enable vehicles to make real-time decisions to revise survey lines to target particular habitat types, revisit features of interest that meet prescribed criteria (e.g., feature size), or more. While some high-level AUV engines are defense classified, others are available publicly.
- Other developments include the integration of eDNA sampling devices and hyperspectral sensors (measures chemicals such as hydrocarbons to help locate features like seep), as well as the advances in multispectral imaging systems and use of temporal gating to remove water-column backscatter to improve use of artificial lighting.

2.4. Summary

Mapping presentations and discussions focused on approaches for using ship-based sonar and AUVs to meet regional, meso-, and micro-scale MGM data requirements. Because the multi-year MDBC mapping campaign will span a variety of platforms and sensors, maintaining consistency in data products, especially for bathymetry and backscatter, is going to be challenging. Approaches to improve consistency in mapping products include developing and following standardized data acquisition and data tracking protocols. For example, the survey teams must record sensor parameters, such as pulse length, frequency, and offsets and establish a network of calibration or reference sites that can be visited multiple times by the survey fleet. While ship-based sonar will serve as the mapping "workhorse" filling regional and mesoscale data needs, microscale data are best filled by AUVs outfitted with fine-scale mapping and imaging sensors. Torpedo- and hover-style AUVs are suitable for different terrains (e.g., hover best for high-relief) and survey designs. Both AUV styles can incorporate improved "engines" that facilitate on-vehicle data processing and autonomous survey path decisions aimed towards improving efficiency for mapping MDBC. AUV sensors, including SAS and laser line scanners, may offer the ability to image soft, fan-like corals and detect fine-scale habitats to identify organisms or aggregations of organisms. Consistency in mapping protocols will allow for repeated mapping campaigns that may be able to track changes over time. By following the discussed approaches to mapping, the highest quality maps from remote sensing tools maps will be provided. These mapping products will feed into the MGM cycle, guiding ground-truthing observations used to produce predictive habitat maps.

3. Ground-truthing

3.1. Background

Once an area has been remotely sensed, ground-truthing can provide visual and analytical characterization of information to document abundance and distribution of MDBC, substrate, and geology. Ground-truthing data can be collected from imagery using a variety of sensors on a variety of platforms or from biological and sediment samples. Approaches to collecting and analyzing ground-truthing data depend on the data or product requirements. For instance, to define substrate type or calculate density of MDBC species, large area photomosaics with a resolution of 1–10 m could be created using a towed camera, remotely operated vehicle (ROV), or AUV. In order to document the condition of individual corals, however, high resolution (<1 m) imagery would be needed using an ROV or AUV.

3.2. Suggested Tools and Techniques for Collecting Ground-truthing Data

The goal of this session of the workshop was to discuss suggested requirements, tools, and techniques for collecting ground-truthing data via imagery and sediment sampling. The session began with presentations by three speakers to provide an overview of some of the tools and techniques that can be used for collecting ground-truthing data.

Jason Chaytor with U.S. Geological Survey (USGS) gave a presentation on methods available for sediment sampling. When deciding on what sediment collection tool to use, there are several factors to consider such as whether the purpose of the sampling is geological vs biological and what qualitative vs quantitative information is to be derived. The depth of the desired sample will also affect tool choice. For example, surficial seafloor sampling will collect the upper few cm of seafloor sediment as well as the sediment-water interface and can be accomplished using a grab sampler. Sub-seafloor sampling can be divided into two depth categories. For the upper 50 cm of seafloor sediment, a wide variety of tools are available such as box cores, push cores performed by an ROV or human-occupied vehicle, multicore, or monocore. When wanting to get deeper samples (down to meters or kilometers of sediment), suitable platforms are less available, but a vibracore, gravity core, or piston core could be used. It is also good practice to conduct observation techniques with sample collection to characterize the sub-seafloor. Examples would include sediment profile imagers and geoacoustic profiling transducers.

Bryan Costa with NOAA NCCOS gave a presentation on sampling design for developing benthic habitat maps. Habitat maps show spatial distribution of physical structure and biological cover types on the seafloor and ground-truthing is a critical link for creating these maps. Ground-truthing sampling design for habitat mapping falls into two broad categories; training and validation. Ground-truthing sites for training will often be created using a random sampling approach since little is known about the area. Ground-truthing sites for validation can be used as an independent dataset to assess performance of model predictions and accuracy. A random stratified sampling design is usually used in this case to sample error appropriately. Once ground-truthing data is collected, the steps for processing the imagery include: color correction, georeferencing, mosaicking, and annotation. Decisions on ground-truthing data collection should be guided by anticipated data use, map requirements such as positional accuracy and imagery resolution, and project limitations.

Scott Gallager with WHOI and CoastalOceanVision, Inc. gave a presentation on imaging the seafloor for characterization and habitat modeling. Two imaging systems were discussed; HabCam and HARIM. HabCam is a towed system with paired stereo imaging systems. HARIM is an imaging module that sits on front of a REMUS 600 AUV. Because HARIM and HabCam images partially overlap, they can be mosaicked, allowing for analysis of spatial patterns at all scales. One of the challenges is how to deal with the large volume of images being collected. Their workflow involves several real-time automated processes completed at sea including: color correction, substrate classification which can be put into the Coastal and Marine Ecological Classification Standard (CMECS), and geomorphology. Real time processing on the vehicle can be used to make decisions about navigation and where to sample. By integrating environmental variables and biological distributions together, one could look at how events change distributions of communities.

Following the presentations, there was group discussion among the participants on the following questions:

Are there tools other than photos, videos, biological and sediment samples that are useful for ground-truthing?

- eDNA
- Passive acoustics
- Chemical sensors to detect seeps and vents
- Ground-truthing localized current measurements that an organism would experience is particularly important for filter feeders.
- Active acoustics to look at water column organisms and food supply.
- Other related comments:
    - It is useful to add sensors to gears you are deploying such as adding CTD and oxygen sensors to your imagery platform.
    - Structure for motion and photogrammetry of images will provide more information than just presence/absence or habitat classification.
    - Long term observations or temporally repeated surveys are important especially for dynamic environments.
    - Precision and accuracy are directly related to the resulting derived products.

What are the sample requirements for sediment samples? How deep? How many replicates? Standard methods? Differences between mesophotic and deep? Differences between near coral and soft sediment?

- The appropriate sampling density needs to be determined beforehand.
- Sampling regime will depend on how dynamic the environment is.
- Depth of sediment sampling depends on the study and the question being addressed. To compare with previous DWH data, 20 cm samples should be taken. From a geologic perspective, however, the deeper the sample, the better. To simply validate remote sensing multibeam data, a shallower sample would be acceptable.

- Multicoring was suggested by several as a preferred method of sampling. It can collect multiple cores at one time that can be used by chemists, microbiologists, etc. They also save the water-sediment interface which contains valuable information.

What are the pros and cons of sediment profile imaging? Would you suggest this technique for MDBC restoration work? Why or why not?

- There was general consensus that this would be a method to incorporate into our ground-truthing protocol for MDBC work.
- It takes rapid samples and is fairly easy to process.
- There is work currently being done to couple sediment profile imaging with spectral cameras to get chemical composition, PAHs (polycyclic aromatic hydrocarbons) and more.
- It is important to know which habitat and topographic setting you're collecting your sample in. Visual tools and analyses of sediments for contaminants and benthic communities are valuable.
- It is usually good practice to couple sediment profile imaging with physical samples. A stratified sampling design based on specific topographic features would be valuable.

Given the difficulty of obtaining mesophotic sediment samples, what are the best techniques to use in these habitats?

- There is often a lot of biological cover that you don't want to destroy so precision of targeting a particular patch is key.
- A multicore is not the gear to use near a coral system as it cannot handle the hard surface.
- It is becoming more common to use precision coring capabilities. Ultra-short baseline (USBL) and camera systems allow you to put ship-deployed sampling packages precisely where you want to sample. For example, cameras on boxcore or multicorer.
- Gear loss is a risk when sampling near structural habitat.

What are the imagery requirements for ROV and AUV? How high off bottom should images be taken? Periodicity of images? Minimum camera specifications? Orientation of images: oblique vs nadir shots vs lateral view from hovering AUV/ROV? Pros/cons? Are video AND stills required? Should one be focused on over the other?

- There was general consensus for keeping an ROV approximately 1–1.5 m off bottom, but it may be challenging to keep an AUV that close to the seafloor. An AUV will more likely be 3–5 m off bottom.
- When creating photomosaics, 60% overlap of images is common. An area of 100 m^2 will produce approximately 2000–4000 photos.
- Scale/lasers that have been calibrated should be included in images. Four lasers are better than two, green is better than red. Stereo cameras can also be used for measuring. Stereo cameras in oblique view have been found to be more effective than lasers as lasers can lose themselves in the distance.
- Forward and down looking cameras are important. Oblique versus nadir camera orientation depends on the seafloor orientation. Oblique view is good for taxon identification, but percent

cover is easier to calculate with nadir. Two camera systems incorporating both views that are somewhat synced are becoming more popular.

- Videos and stills are both important. Videos provide a broader perspective and stills are easier to use for identification purposes. Sometimes, video is essential to verify a species identification based on behavioral observations. Broad scale video is important for characterizing the habitat.
- It is useful to identify the end products to determine imagery requirements. For example, if you are measuring coral growth, this requires a precisely taken photo with correct lighting, no movement, etc.
- Physical sampling will often be required by most taxonomists to help with identifications. Physical samples will also preserve associates which are largely unaccounted for when analyzing imagery.
- Consistent lighting and color balancing are just as important as resolution.
- Higher resolution will greatly expand the data storage and management requirements. The full data life cycle and associated costs should be considered.
- There is a dichotomy in need. Focal areas in supremely high intensity and broadscale regions in less intensity with a broader view of the habitat and less focus on growth/taxonomic resolution.

What precision is needed for bottom images/measurements and geographic positioning and what techniques are available for automating georeferencing of images?

- Precision may depend on the habitat. In diverse areas, more frequent photos may be warranted whereas more uniform areas may require less frequent images.
- Precision also depends on the study question being addressed.
- Automated georeferencing has been accomplished using simple techniques including Access database joins. Also, National Marine Electronics Association (NMEA) strings have been used to bring into ESRI ArcMap.
- Ground-truthing precision should match the underlying bathymetry map.
- Commonwealth Scientific and Industrial Research Organization (CSIRO) has made a tool for real time quality control matching USBL to video and images for georeferencing.
- Markers are essential especially when revisiting sites or individual corals. They are a better tool than relying on USBLs.
- NOAA Ocean Exploration on NOAA ship *Okeanos Explorer* unifies positioning and imagery using timestamps integrated in Ocean Networks Canada SeaTubeV3.
- Positional accuracy is limited by USBL accuracy, which has more uncertainty with greater depths.
- There is often a tradeoff between sample size and precision.
- Image subsampling - Most of the time it is a logistical choice to pick less images to analyze or a semi-independence decision to avoid counting the same individual twice. It also depends on over ground speed as well. Most camera systems should have USBL (sub 10-m horizontal positioning).

3.3. Suggested Techniques for Analysis of Ground-truthing Data

The goal of this session of the workshop was to discuss analysis or interpretation of ground-truthing data. This includes discussion on available options for image annotation and classification techniques, habitat classification schemes, machine learning options, and best practices for analyzing sediment samples.

Isabel Romero with the University of South Florida gave a presentation on analyzing sediment samples and using organic chemicals as indicators of ecosystem change and recovery. Samples can either be collected from the water column to analyze sinking/suspended sediment or from the seafloor. Chemical markers from the sediment can be analyzed using gas chromatography to determine spatial and temporal trends, impacts to systems, and system processes. These outcomes can be used to assist in restoration by establishing recovery trajectories and establishing new health baselines. These tools were used in two prior studies: 1) determining the fate of contaminated sediments deposited by the DWH oil spill and 2) determining how quickly the offshore ecosystem will recover following the DWH oil spill.

Abigail Powell with NOAA Northwest Fisheries Science Center gave a presentation on image annotation tools and machine learning. There are a number of available annotation tools that all have varying user interfaces and tools to support annotations for different metrics. There are a number of things to consider when choosing the annotation tool appropriate for a study: 1) consider the study aim (e.g., counts, length measurements, percent cover, etc.), 2) consider the deployment system (video or digital stills), 3) web-based or desktop, 4) off the shelf or custom, 5) data quantity and project timeframe, and 6) are prior annotations available which is important for machine learning. CoralNet and VIAME were examples given that have machine learning capabilities. Summary suggestions included: 1) use existing annotation tools if possible, 2) machine learning tools range from assisted annotation to developing your own detectors, and 3) spend time planning the workflow if using machine learning.

Thomas Oliver with NOAA Pacific Islands Fishery Science Center gave a presentation on using CoralNet to characterize reef communities and track coral colonies. CoralNet is an online repository and software for point classification of benthic features. It randomly places points and uses computer vision algorithms for fully- or semi-automated classification of points into benthic cover categories. Their team is working on transforming imagery into coral reef metrics. Metrics include: benthic cover, structural complexity, coral density and diversity, colony size, colony condition. They have a well-characterized and operational technique to annotate photos at the photoquad scale (approximately 1 m^2) for benthic cover estimates and an in-development technique to push image annotations into large area photomosaics (approximately 100 m^2). This will allow measurements of growth, mortality, and recruitment over time. They currently have a program called PICOGRAM that is working to repeat annotations of photomosaics to conduct coral demographic modeling.

Following the presentations, there was group discussion among the participants on the following questions:

What are the available options for image annotation and classification techniques and standards? What are the pros/cons of each?

- Several participants used and suggested VIAME for video analysis because of the machine learning capabilities it has. Having a predetermined species list and knowing the level of identification is key.
- FathomNet is currently in development and uses deepsea images with annotations to support machine learning.
- One of the biggest limitations for choosing an annotation tool is finding programs that are fed-ramped approved. If they are not already approved, the process takes several years. CoralNet, VIAME, and SeaTube (which is used by the NOAA Ship *Okeanos Explorer*) are all widely used in NOAA and should be approved softwares.
- One strength of SeaTube is that it can be used in real time as well as for post-processing. It can also sync sensor data from the ROV to observations and allows you to search for particular annotations and view just those video clips.
- CPCe was not suggested for use in analyzing digital stills.
- Having the data in a structured format that would allow use in models is helpful.

What are the available habitat classification schemes? Which ones do you suggest and why? How do existing classification schemes align with CMECS?

- It would be helpful to look at studies that have already been completed in the area to see what annotation tools and classification schema have been used.
- Given our lack of knowledge of many deep-sea coral ecosystems, most classification exercises are fairly site or project specific. We may not know what classification schemes apply to particular systems (i.e., sponge-reef system).
- CMECS can be effective for describing communities, but not individual organisms.
- The Monterey Bay Aquarium Research Institute (MBARI) media management system works similarly to link video, photos, position, and auxiliary information.
- The Marine Geological and Biological Habitat Mapping (GeoHab) website has a number of different models being built to assess habitat and are working to demonstrate how the best models align with CMECS.
- The MDBC project could help evolve CMECS and be useful for this type of application.
- We may never have a universal habitat classification scheme.
- Habitats are classified based on the components. If you have identified components and rules you can aggregate them in to 'habitats' or communities.

What are available techniques for measuring or counting organisms using stereo imaging or photogrammetry?

- There is a general trend of transitioning from lasers to stereo imaging as there is a difference of an order of meters between the two.
- A technique that hasn't been fully explored is light field imaging (plenoptic imaging).

- Lasers are typically standard on ROVs and the higher tech stereo cameras are often not available on many vehicles.
- Structure for motion has its place, but needs high quality imaging and image distribution planning. Georeferencing is often lacking in subsea structure for motion.
- Stereo cameras have to be calibrated regularly.
- Software that has stereo analysis capabilities include: EventMeasure, OneTwoRedBlue, Sebastes, Tator.
- Some of the habitats at the deep sites include planar octocorals, so downlooking images/video will not work. Straight on imagery will have to be used to measure those corals and having a physical marker for scale and repeated sampling over time is critical as a USBL at these depths will not be reliable.

What are the options for machine learning tools for image analysis? Are those options developed enough to be used for this project?

- A program known as Diverse Counterfactual Explanations (DiCE) is a pre-built deep learning module that can handle any type of imagery. It takes a lot to train a deep learning algorithm and requires a diverse set of habitat classes and a good diversity of organisms in different orientations and colors.
- Diversity vs specificity of the target is important. CoralNet and VIAME can have a human element, too.
- There is a large overlap of annotation/analysis, which usually is using inference, or trained models, and the tools used to train models. Some tools (e.g., VIAME) include training routines built in, but many other software can run routines trained in industry standard machine learning frameworks such as TensorFlow and PyTorch.
- Computer power can help speed up training.
- Getting enough examples of rare organisms can be tricky.
- Having the ability to extract annotations and use different machine learning softwares would be extremely valuable which is the goal of the FathomNet project.

What do you suggest as best practices for analyzing sediment samples?

- High resolution sampling is important. There are ways to get a tremendous amount of information from small sample sizes. For instance, a vast number of chemical markers can be examined in a small sample.
- Collaborating with benthic community ecologists is key to comparing results across disciplines.
- Consider the array of different variables for extraction. Pigments, food supplies can be interesting fodder for environmental characterization.
- Consider which standardized variables from sediment to examine across the projects.
- Chemical analysis can also be conducted on the animals themselves. Since organisms have different metabolism and characteristics, this allows you to pair how animals living in this environment have been affected. It is important to describe chemical markers and contaminants, too.

- For analysis of the benthic community vs chemicals (and other parameters), it works better to have separate cores (multicores are very helpful for this) to avoid contamination.

3.4. Summary

Ground-truthing will be an important component of the MGM cycle. Remote sensing data can be used to select locations for more detailed visual and analytical characterization of information to document abundance and distribution of MDBC, substrate, and geology. Ground-truthing data can then feed into models to characterize the spatial distribution of MDBC habitat. This workshop elicited expert advice about the suggested tools and techniques for collecting and analyzing ground-truthing data. The advice received is summarized in what follows.

For sediment sample collection, multicoring and sediment profile imaging were both suggested. It is also becoming more common to include real time vision cameras or USBLs for precise positioning from ship-based cores. For sediment sample analysis, high resolution sampling is important as a small sample can provide a great deal of information. Considering the variables to be examined is important and collaborating with benthic ecologists is useful to compare results across disciplines.

For the collection of imagery, requirements and geographical positional accuracy should be determined by the end products. Oblique vs nadir camera orientation, videos and digital still images are all important and provide different information. Positional accuracy is often limited by USBL but should at least match the underlying bathymetry map. There is a dichotomy in need. One suggestion was to examine focal areas in supremely high intensity and broadscale regions in less intensity with a broader view of the habitat and less focus on growth/taxonomic resolution. For analyzing imagery, there are many options for image annotation but study goals and objectives should be considered when deciding on a platform. Machine learning will be an important part of the MDBC project but time needs to be dedicated to planning the workflow for incorporating it. When considering habitat classification schemes, the MDBC project could help evolve CMECS. Finally, when it comes to measuring organisms, there is a general trend of transitioning from lasers to stereo imaging, however not all vehicles will have the higher tech gear available.

4. Predictive habitat modeling

4.1. Background

Predictive habitat models, as defined for the purposes of this project, are models that predict MDBC habitat from relationships defined or estimated between environmental predictor variables and direct observations of MDBC habitat. Predictive habitat models leverage comprehensive environmental data to translate spatially sparse habitat observations into comprehensive maps of habitat distributions (Figure 4.1). Predictions of MDBC habitat may include physical substrates and features or biota that themselves provide habitat for other organisms, such as deep-sea corals. While there are many other techniques for modeling habitat and species distributions (e.g., interpolation, unsupervised classification), those techniques are not being considered for the predictive habitat modeling component of this project.

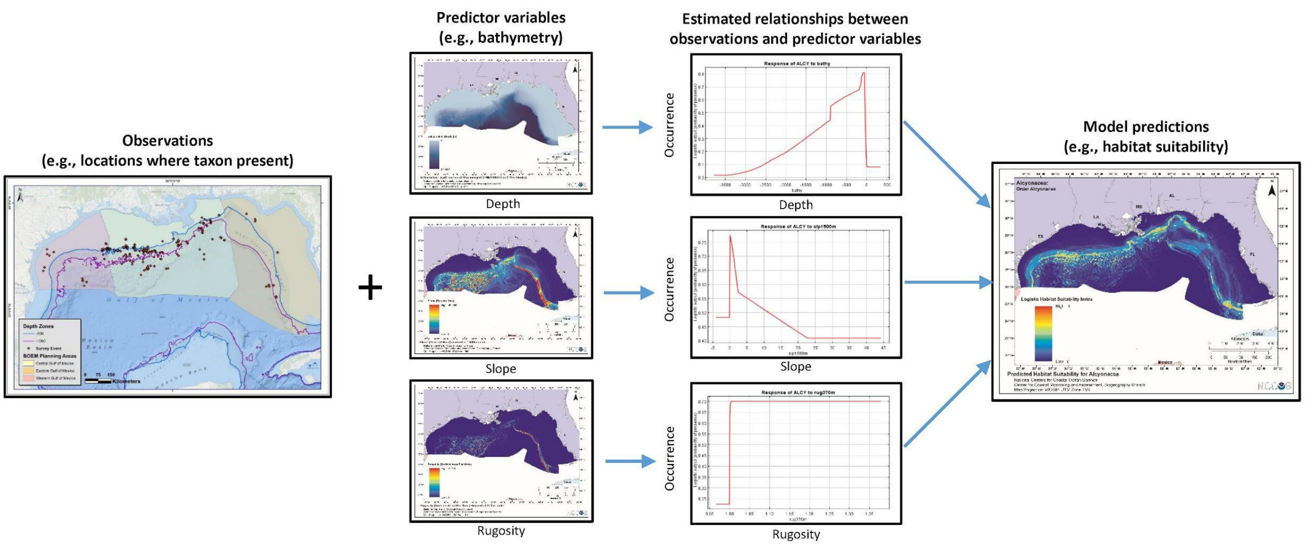

Figure 4.1. Schematic of predictive habitat modeling process. The example shown is a predictive model of the spatial distribution of a biological taxon, but predictive models can also be developed for less specific biological variables (e.g., biological cover) or physical habitat characteristics (e.g., to predict the spatial distribution of a habitat class). Results shown are from Kinlan et al. (2013).

Many predictive models of MDBC habitat have been developed for the Gulf of Mexico, and a large proportion of those models (12 in total) have been inventoried as part of the MGM Data Inventory and Analysis (Paxton et al., In prep.). The predictions from those models vary in spatial extent, ranging from global models that include the Gulf of Mexico to regional models that cover a large part of the Gulf to models of more localized areas. The majority of the models are species distribution models for deep-sea corals of varying taxonomic resolution, from individual species to higher levels like families or even orders. There are also four models of the distribution of habitat, two of which focus on seeps; the other habitat models include predictions of hard versus soft substrate and predictions of multiple habitat categories. The predicted quantity varies across the models in the inventory, but the majority of models make predictions of habitat suitability–a relative measure of where species or habitats are more or less likely to be found. There are also models that predict absolute measures of the probability of occurrence of species or habitats, as well as models of the most likely habitat type in a given location. Regarding the statistical modeling frameworks used, all but three models employed MaxEnt (maximum entropy), while the others used boosted regression trees, random forests, a nearest neighbors learner, or occupancy. Regarding spatial resolution, approximately half of the model datasets are relatively high resolution predictions on the scale of about 10 m or less, a few have a resolution on the scale of hundreds of meters, and a couple have a resolution on the scale of kilometers. The higher resolution models tend to correspond to the more localized models while the coarsest predictions correspond to the global models.

The MGM project has a set of 'requirements' of predictive habitat models to serve the various MDBC projects and stakeholder interests. Requirements are essentially the information that users want models to provide to them. These requirements were elicited through a series of meetings with personnel from the different MDBC projects and through a spatial prioritization exercise (Kendall et al., 2022). Some of the key requirements are:

1. Model uses ranging from guiding exploration to targeting high-density coral aggregations for specimen collection and planting
2. Local and regional models
3. Models for species and habitat types
4. Incorporation of important predictor variables
5. Model validation (existing and new models)
6. Meaningful measures of reliability and uncertainty
7. Model outputs that are interpretable and accessible

The purpose of this part of the workshop was to determine the predictive habitat modeling approaches and techniques that would best achieve these modeling requirements, taking into account the inventory of existing models. Workshop invitees spanned the globe and represented a selection of researchers, modelers, and managers who have firsthand experience with developing or using predictive models of MDBC habitat. The format of the modeling workshop component was a series of four discussion sessions addressing different aspects of predictive habitat modeling and focusing on a series of predefined questions. In contrast to the seafloor mapping and ground-truthing workshop components, there were no presentations from workshop invitees.

4.2. Techniques for Modeling Distribution and Abundance

A range of techniques has been used for predictive modeling of mesophotic and deep benthic habitat in the past, and the modeling requirements of this project are varied. The purpose of this discussion topic was to consider which techniques are best suited to achieving the different modeling requirements.

Which predictive modeling techniques have you found best suited to developing: 1) regional models for exploration? 2) local models to identify high-density aggregations?

- Ensembles of models (i.e., using a range of model types) can be useful for several reasons including: 1) avoids criticism of particular modeling techniques, and 2) can exhibit improved performance and predictive ability by balancing advantages and disadvantages of individual modeling techniques.

- Ensembles tend to treat the individual member models as interchangeable in the sense that all of the models predict the same quantity; however, different management applications require predictions of different quantities, so a suite of models that predict different quantities should also be considered; e.g., a multi-species model to estimate spatial distributions and richness for some species along with a demographic-based distribution model(s) for individual species with more available data like dispersal rates, population connectivity, recruitment rates, size, and growth rates.
- For regional models, predictions that do not tightly fit the observed data are better because those predictions generalize more effectively.
- The usefulness of global models will depend on the similarity of environmental niches for taxa of interest between the Gulf of Mexico and elsewhere (e.g., other parts of the North Atlantic).
- Presence-absence data and models have advantages over presence-only and presence-background models.
    - Presence-only models often assume comprehensive, unbiased sampling; biased sampling can cause bias in model predictions.
    - However, there is concern about false absences when inferring and using absence data, especially with deep-sea data.
    - Predicted absence can be enforced on the basis of independent information about where a taxon is absent (e.g., deep-sea coral taxa that are restricted to hard substrates).
    - The reliability of absence data can depend on taxonomic resolution; e.g., documented absences of entire communities or habitat types are typically more certain than documented absences of individual species.
    - Occupancy and N-mixture models, along with appropriate sampling, allow one to account for imperfect detection and false absences.
- Choice of predictor variables and datasets is at least as important as the choice of modeling technique; these data provide the foundation for a predictive habitat model.
    - Multibeam echosounder (MBES) data (bathymetry data and derivatives) are very useful for creating local scale models.
    - Topographic variables at multiple scales can be useful; e.g., large features like valleys versus local slope and aspect.
    - When data on oceanographic variables (e.g., water temperature and current) are available they may be more useful than depth.
    - Backscatter can be a source of informative predictor variables, although for regional models there may be a trade-off between using backscatter variables and the time required to develop a suitable backscatter dataset.
    - Local predictions from regional models can be inaccurate when such models are developed using global data sources (e.g., bathymetry).

Which predictive modeling techniques have you found best suited for: 1) modeling species distributions? 2) physical habitat distributions?

- Models of physical habitats are usually derived from detailed bathymetry and substrate data (MBES with backscatter, sediment samples) and typically employ classification and segmentation techniques; spatial terms can be modeled with techniques such as regression kriging.
- Species distribution models tend to be on a wider scale and commonly employ techniques such as generalized additive models, mixed-effects models, random forests, etc.
- While habitat modeling more typically uses mapping techniques, species distribution modeling techniques can be applied to physical habitat and have been previously.
- Models of species distributions can predict different quantities (e.g., occurrence, density, size, biomass), and depending on data availability these should all be considered, although some quantities may not be informative for some species (e.g., probability of occurrence of common widespread species); the best technique may depend on the quantity being predicted.
- It can be useful to model the distributions of multiple species jointly in a single model, perhaps even jointly modeling habitat characteristics.
- Many modeling techniques are potentially useful; there is no single best technique; each technique entails detailed considerations.
- It is important to estimate uncertainty in model predictions; e.g., for physical habitat models one can estimate the probability that the predicted habitat class is correct.
- Predictions of species distributions entail multiple aspects of uncertainty; e.g., spatial uncertainty, temporal uncertainty (variability and change over time).
- Mechanistic models may better allow one to predict changes in species distributions over time than correlative models.

4.3. Data Requirements and Sampling Design

Predictive habitat models rely on biological and environmental data. The purpose of this discussion topic was to consider aspects of data collection and recording that would facilitate modeling requirements and to consider which environmental predictor variables are important to include.

How should data collection be designed spatially to provide appropriate sampling for input to models?

- Allocation of sampling effort has been a big challenge for deep sea studies, and it is related to the extent and resolution of the model.
- There may be a tradeoff between the spatial extent of sampling and the level of detail that can be recorded; e.g., fewer, longer ROV transects versus more drop camera observations.
- More, shorter camera tows have been useful for modeling in shallow and deep waters, but there are logistical challenges when it takes a long time for the camera to reach the seafloor, which necessitates planning to efficiently sample all environmental gradients with limited bottom time.

- Sampling bias can be minimized by not focusing all sampling in certain areas or only in types of areas that are typically sampled; e.g., also sample areas where a target species or habitat is less likely to be found.
- A K-nearest neighbor approach can be used to calculate parametric isolation and identify feature space where observational data are lacking.
- However, replicate samples from the same site in different surveys can be helpful for estimating uncertainty.
- Stratified random sampling designs can be useful (e.g., see Anderson et al., 2016 and Foster et al., 2017).
- Strata can be informed by previous sampling and independent habitat classifications; backscatter intensity free of artifacts and other geophysical data (MBES, side scan sonar, seismic) can be useful for informing sample design and focusing limited survey resources; e.g., focus on transitional areas between different substrate types.
- When surveys have multiple objectives, planning and the development of protocols are required; e.g., ROV height(s) and locations and frequencies of zooms.
- Different sampling designs may be appropriate for different modeling objectives; e.g., broadscale survey for terrain analysis versus stratified random sampling to select localized areas of interest for detailed sampling.
- The scale of the model and the scale of biological and habitat observations should be considered when designing sampling.
- The model grid should also be considered when designing sampling so that samples are distributed appropriately across multiple grid cells.
- The use of sampling bias grids in presence-only/background modeling is more frequent now; e.g., general extractions from OBIS (Ocean Biodiversity Information System) and GBIF (Global Biodiversity Information Facility) to represent sampling effort.

How should biological and habitat data be recorded to facilitate input to models?

- Aim to record the most and highest-resolution information possible; one can always simplify or reduce the information afterward if needed; record counts and densities during camera surveys, and record biomass and abundance when collecting direct samples.
- Standardize recorded data so that data can be aggregated across surveys, studies, etc.; standardization facilitates coherent data products that can be used and interpreted by multiple teams (databases, application programming interfaces, R packages).
- NOAA's OER is developing standardized data recording protocols and tools for annotation of video from ROVs; OER has worked with Ocean Networks Canada to implement SeaTube, a web-based annotation tool (https://data.oceannetworks.ca/SeaTubeV3?resourceTypeId=600&resourceId=449); standardized annotation catalogs reference established sources such as CMECS and OBIS; data are time- and position-stamped to facilitate modeling; expert review of video can be costly.
- It is important to record data quality to allow for data filtering prior to modeling.

How should sampling effort be recorded to facilitate input to models?

- The number of samples in a grid cell can influence the likelihood of detection, so that should be accounted for when modeling.

What important predictor variables should be included in models?

- Chemical variables are important for understanding the distributions of MDBC habitat and biota.
- Carbon export could be an important predictor variable.
- Models should include predictor variables that are meaningful from an organismal perspective; e.g., temperature, salinity, food supply.
- Predictor variables that reflect impacts, such as fishing effort, can improve model performance when there are good supporting data.
- The model spatial resolution may partially dictate the usefulness of predictor variables; e.g., multibeam bathymetry data are typically the only predictor data with very fine spatial resolution in the deep-sea.
- Temporal variation in predictor variables, such as seasonality of production, is important to consider but is often overlooked due to a lack of data.
- An important decision is how many predictor variables to include; one common approach is to reduce the number of variables (i.e., model complexity) so that the model is more ecologically interpretable and may provide a better understanding of mechanistic relationships between predictors and the distribution of MDBC habitat.
- The number of predictors can potentially be reduced by using geomorphic features as surrogates for certain variables.

4.4. Validation and Assessment of Uncertainty

One of the key modeling requirements is that predictions of MDBC habitat be validated, whether from existing or new models. The purpose of this discussion topic was to consider techniques and data that would best allow for validation of predictive habitat models.

What statistical frameworks are best suited to validating models (existing and new)?

- An important first step in model validation is to identify the quantity to be validated (e.g., biomass, diversity, etc.).
- It is also important to distinguish between validation of estimated distributions and validation of temporally forecasted changes in distributions; the latter are best validated through experiments to evaluate the accuracy of predicted impacts in terms of both direction and magnitude.
- Statistics can give some indication of prediction uncertainty and model reliability, but the best test of accuracy is new observations that were not included when fitting the model.
- Data resampling techniques like (spatial) cross-validation can emulate validation with new data; however, spatial cross-validation can underestimate model performance (Wadoux et al., 2021).

- The performance of a model is best assessed in the context of its application to management; it can be more useful to evaluate model performance in terms of a management risk assessment or loss function rather than in terms of statistical goodness of fit to data; stakeholders can help define the loss function.
- It is critical to have clear measures of model prediction uncertainty that can be communicated to and understood by decision makers.
- Coverage of environmental space by the biological data can be a useful measure of model uncertainty and reliability, particularly for communicating uncertainty to stakeholders.

What are the implications of using existing opportunistic data to validate models?

- When historical imagery exists, it could be processed and used for validation.
- Existing opportunistic data are likely subject to a similar spatial sampling bias/structure as the data models are fitted to; many existing data are biased toward shallow depths (e.g., US Atlantic sediment sampling and biological trawl surveys) and might not be in areas where model validation is most needed.
- Opportunistic data can be heterogeneous and of varying quality.
- Unless the validation data are from a completely different source (e.g., different sampling gear), there is limited value to techniques such as cross-validation.
- The best approach to validation is to design a validation survey and collect new data across prediction categories to evaluate prediction accuracy.

How should new data collection be designed spatially to validate models?

- Validation of positive and negative predictions should be considered, conceptually like a confusion matrix; e.g., predictions of presence and absence.
- Validation data should capture absences within a given organism's or habitat's depth range (i.e., where an organism or habitat could/should be but is not); absence data outside of that depth range are of limited value.
- Model predictions themselves should be used to design validation data collection; e.g., to sample presences and meaningful absences.
- Uncertainty in model predictions should also be considered when designing validation data collection; e.g., sample areas of low, medium, and high model uncertainty.
- Some useful references regarding validation survey design include Anderson et al. (2016), Foster et al. (2017), and Stephenson et al. (2021).

What are some cost-effective methods for collecting validation data?

- Visual samples can be cost-effective depending on factors such as water depth; e.g., ROVs, drop cameras, towed cameras, AUVs.
- Visual sampling can be subject to depth limitations because of cabling; deeper than 1000 m requires fiber optics or other expensive equipment.

- Drop camera, towed camera, and AUV surveys can be more efficient at covering large areas than ROV surveys.
- Towed cameras allow for relatively efficient sampling by conducting short transects spaced apart without having to bring the camera to the surface in between.
- Depending on the type (torpedo or hover), AUVs may be better suited for flatter seafloor terrain than rugged terrain (e.g., canyons), and there may be challenges with AUVs getting close enough to the seabed; the SeaBED bottom tracking AUV can collect good imagery data; AUVs can provide good bathymetry data (MBES).
- The KATFISH active synthetic aperture sonar tow vehicle (https://krakenrobotics.com/products/towed-vehicles) can provide high resolution seafloor imagery and bathymetry data over large areas.
- Trawl data can be very useful, for example biomass samples, but the sampling method is destructive; also, positional accuracy of trawl data can be limiting.
- The sampling technology chosen can have implications for the best survey design (Foster et al., 2014).
- It is important to have accurate locations associated with validation data; e.g., USBL technology in combination with an ROV.
- It is important to collect the same type of observation data that the model was fitted to; e.g., should not validate trawl data with video data.
- Given the expense of ROV surveys, it is efficient when multiple data types can be collected at the same time; e.g., imagery, specimens, environmental data, sediment samples.
- Validation of some types of model predictions (e.g., effects of impacts) may require different data types such as size and growth.

4.5. Model Products for Management

Natural resource managers are one of the key stakeholder groups that will use the predictive habitat modeling products from this project. The purpose of this discussion topic was to consider ways that those products can be made accessible, interpretable, and effectively used by managers and other stakeholders.

What model products are most useful to managers and stakeholders?

- Useful products are openly accessible, downloadable, and have good metadata.
- Different stakeholder groups may need different products, although some products may be more widely useable than others; e.g., a spatially-explicit life cycle model can inform how various stressors and impacts affect populations.
- Some information needed by managers and stakeholders is relatively straightforward: habitat suitability, probability of occurrence, abundance, and diversity; this information can help define areas for conservation.
- Predictions of habitat suitability can be challenging to interpret.

- The locations of dense populations of corals or sponges is of great interest to managers, but there are not enough models predicting this quantity.
- Managers are often interested in broad areas, so data products should be consistent and interpretable across large areas.
- It is important to convey limitations of models and uncertainties in their predictions to avoid their misinterpretation and misuse; admitting up front that all models have shortcomings can help focus conversations with stakeholders on ways that a model is useful.

What aspects of existing models have limited their utility?

- Low spatial resolution can limit model utility.
- Difficulty with interpretation can also limit model utility.
- Believability is important for model utility; acknowledging model limitations and uncertainties facilitates moving toward model usefulness.
- Contextual information can aid with model utility; e.g., usefulness of predictions could be limited without an understanding of how predictions may change as a result of future impacts and management actions; if model predictions are provided without an interpretive frame, users will apply their own, which can lead to disagreement and limit utility.

How can model reliability and uncertainty be best characterized for ease of interpretation?

- Maps of spatial model uncertainty can be useful; e.g., heatmap of model uncertainty or heatmap of model predictions with transparency indicating model uncertainty.
- Written disclaimers about model uncertainty may be more likely to be ignored.
- Depictions of spatially gridded data density can indicate spatial bias in data and sampling of environmental space.
- Maps indicating consistency in model predictions across data resamples (e.g., bootstrapping, cross-validation) can be useful.
- The MeshAtlantic project (https://keep.eu/projects/395/Mapping-Atlantic-Area-seabed--EN) considered how to characterize uncertainty and developed an online visualization tool.
- It can be useful to present multiple different forms of maps and tables to convey model uncertainty; decision support tools can be used to combine these visualizations and allow managers to choose and weight different measures of uncertainty.
- Reliability is a function of all model aspects including input data and model outputs.
- It is important to address uncertainty in environmental predictor and biological input datasets; e.g., taxonomic uncertainty.
- Peer review can serve as a form of reliability, although it can be a lengthy process; setting peer review as a standard early on can help focus later stakeholder discussions on scientific questions rather than on the quality of the work.
- An ICES working group on deep sea ecology is currently developing a benchmarking process for what qualifies as a suitable model (International Council for the Exploration of the Sea, 2021); Kenchington et al. (2019) report on a different workshop that considered standards for deep sea species distribution modeling for management and conservation.

What formats and platforms are most accessible to managers and stakeholders?

- ESRI ArcGIS Online provides easily accessible tools; users can add their own layers to these tools.
- Providing scientific data (model output) as well as simplified versions of model outputs (web mapping tools, ESRI ArcGIS StoryMaps) allows for a wider range of users.
- Guided data discovery hubs can help in terms of accessibility; e.g., Gulf TREE (http://www.gulftree.org).
- SeaSketch is another useful licensed online collaborative mapping tool (https://www.seasketch.org/home.html).
- It would be good to serve model products in existing ocean observing and regional data portals for the Gulf of Mexico when possible (e.g., IOOS, GCOOS).

4.6. Summary

Predictive habitat modeling will play a synthetic role in the MDBC MGM project, taking seafloor mapping data and ground-truthing data as input and producing model outputs that characterize the spatial distributions of mesophotic and deep benthic community habitat. Model outputs will serve the entire MDBC portfolio and its wide range of requirements. This workshop elicited expert advice about the techniques and data that would best achieve those requirements. The advice received is summarized in what follows.

Each modeling technique has advantages, limitations, and types of outputs. A range of techniques should be considered, especially when management requirements vary. The value of models is critically dependent on good input data. Predictive habitat models should include relevant environmental predictor variables at an appropriate spatial resolution. Collection of data for the purpose of modeling should be designed with that purpose in mind, considering aspects of sampling such as coverage, stratification, randomization, and replication. Data should be recorded at the highest possible resolution (spatial, taxonomic, etc.) in a standardized format to facilitate modeling flexibility and integration. All model predictions entail uncertainty, and a full accounting of that uncertainty is desirable. Model predictions should be validated, ideally with independent data collected for the express purpose of validation. Sampling design for validation has many of the same considerations as sampling design for modeling. In order for models to be useful to managers and other stakeholders, model outputs should be interpretable, easily understood, at a scale matching management needs, openly accessible, downloadable, and have good metadata. It is also important to communicate model uncertainty and reliability to users. A range of model outputs, including simplified versions, will reach the broadest audience.

5. Conclusion

Seafloor mapping, ground-truthing, and predictive habitat modeling are key interdependent activities that will inform restoration of MDBC in the GOM. Multiple products are required from each activity reflecting multiple restoration objectives and tasks over different spatial extents and spatial resolutions. This workshop aimed to identify the mapping, ground-truthing, and modeling data and techniques that would best achieve the product requirements. More than 50 subject matter experts from around the world attended the workshop, relating their expertise and experience and providing crucial advice about best practices.

The conclusions drawn from the workshop presentations and discussions reported here will guide seafloor mapping, ground-truthing, and predictive habitat modeling activities to restore MDBC in the GOM. Specifically, the data and approaches identified will be considered during the development of project management plans and annual work plans which will guide field operations and analyses for each activity from 2022–2026.

Literature Cited

Anderson, O.F., J.M. Guinotte, A.A. Rowden, M.R. Clark, S. Mormede, A.J. Davies, and D.A. Bowden. 2016. Field validation of habitat suitability models for vulnerable marine ecosystems in the South Pacific Ocean: Implications for the use of broad-scale models in fisheries management. Ocean & Coastal Management 120:110-126.

Deepwater Horizon Natural Resource Damage Assessment Trustees. 2016. Deepwater Horizon oil spill: Final Programmatic Damage Assessment and Restoration Plan and Final Programmatic Environmental Impact Statement. Online: http://www.gulfspillrestoration.noaa.gov/restoration-planning/gulf-plan (Accessed 10 November 2022)

Foster, S.D., G.R. Hosack, N.A. Hill, N.S. Barrett, and V.L. Lucieer. 2014. Choosing between strategies for designing surveys: autonomous underwater vehicles. Methods in Ecology and Evolution 5:287-297.

Foster, S.D., G.R. Hosack, E. Lawrence, R. Przeslawski, P. Hedge, M.J. Caley, N.S. Barrett, A. Williams, J. Li, T. Lynch, J.M. Dambacher, H.P.A. Sweatman, and K.R. Hayes. 2017. Spatially balanced designs that incorporate legacy sites. Methods in Ecology and Evolution 8:1433-1442.

Hourigan, T.F., P.J. Etnoyer, R.P. McGuinn, C. Whitmire, D.S. Dorfman, M. Dornback, S. Cross, and D. Sallis. 2015. An Introduction to NOAA's National Database for Deep Sea Corals and Sponges. NOAA Technical Memorandum NOS NCCOS 191. Silver Spring, MD. 27 pp.

International Council for the Exploration of the Sea. 2021. Workshop on the Use of Predictive Habitat Models in ICES Advice (WKPHM). ICES Scientific Reports 3:67. 100 pp. doi: http://doi.org/10.17895/ices.pub.8213

Kahng, S.E., J.R. Garcia-Sais, H.L. Spalding, E. Brokovich, D. Wagner, E. Weil, L. Hinderstein, R.J. Toonen. 2010. Community ecology of mesophotic coral reef systems. Coral Reefs 29:255-275.

Kenchington, E., O. Callery, F. Davidson, A. Grehan, T. Morato, J. Appiott, A. Davis, P. Dunstan, C. Du Preez, J. Finney, J.M. González-Irusta, K. Howell, A. Knudby, M. Lacharité, J. Lee, F.J. Murillo, L. Beazley, J.M. Roberts, M. Roberts, C. Rooper, A. Rowden, E. Rubidge, R. Stanley, D. Stirling, K.R. Tanaka, J. Vanhatalo, B. Weigel, S. Woolley, and C. Yesson. 2019. Use of species distribution modeling in the deep sea. Canadian Technical Report of Fisheries and Aquatic Sciences 3296. Dartmouth, NS, Canada. 76 pp.

Kendall, M.S., B.L. Williams, K. Buja, and D. Dorfman. 2022. Priority Areas Suggested by Stakeholders for Restoration and Protection of Mesophotic and Deep Benthic Communities Injured by the Deepwater Horizon Oil Spill. NOAA Technical Memorandum DWH MBDC 001. Silver Spring, MD. 28 pp. doi: https://doi.org/10.25923/61r3-gk12

Kinlan, B.P., M. Poti, P. Etnoyer, L. Siceloff, C. Jenkins, D. Dorfman, and C. Caldow. 2013. Digital data: Predictive models of deep-sea coral habitat suitability in the U.S. Gulf of Mexico. Downloadable digital data package. NOAA National Ocean Service, National Centers for Coastal Ocean Science, Center for Coastal Monitoring and Assessment, Biogeography Branch. Online: https://coastalscience.noaa.gov/project/deep-coral-habitat-modeling-atlantic-gulf-mexico/ (Accessed 10 November 2022)

Minerals Management Service. 2009. Notice To Lessees No. 2009-G39 Biologically-Sensitive Underwater Features and Areas. Effective Date: January 27, 2010 Expiration Date: January 26, 2015. New Orleans, LA. Online: https://www.bsee.gov/sites/bsee.gov/files/notices-to-lessees-ntl/notices-to-lessees/09-g39.pdf (Accessed 10 November 2022)

Open Ocean Trustee Implementation Group. 2019. Deepwater Horizon Oil Spill Natural Resource Damage Assessment, Open Ocean Trustee Implementation Group, Final Restoration Plan 2/ Environmental Assessment: Fish, Sea Turtles, Marine Mammals, and Mesophotic and Deep Benthic Communities.

Paxton, A. B., Herting, J., Winship, A. J., Ebert, E., Sautter, W., Kraus, J., Hile, S. D., Howell, J., Dorfman, D., Flounders, S., Poti, M., Coyne, M., Formel, S., Shukla, A., Taylor, J. C., Benson, K., Harter, S. L., Battista, T., and Menza, C. (2023). Comprehensive Inventory of Seafloor Mapping, Ground-truthing, and Predictive Habitat Modeling Datasets to Support Deepwater Horizon Mesophotic and Deep Benthic Communities. National Oceanic and Atmospheric Administration. DWH MDBC Data Report 2023-02. https://doi.org/10.25923/ptv8-vb15

Puglise, K.A., L.M. Hinderstein, J.C.A. Marr, M.J. Dowgiallo, and F.A. Martinez. 2009. Mesophotic Coral Ecosystems Research Strategy: International Workshop to Prioritize Research and Management Needs for Mesophotic Coral Ecosystems, Jupiter, Florida, 12-15 July 2008. NOAA Technical Memorandum NOS NCCOS 98 and OAR OER 2. Silver Spring, MD. 24 pp.

Pyle, R.I. 1996. The twilight zone. Natural History 105:59-62.

Stephenson, F., A.A. Rowden, O.F. Anderson, C.R. Pitcher, M.H. Pinkerton, G. Petersen, and D.A. Bowden. 2021. Presence-only habitat suitability models for vulnerable marine ecosystem indicator taxa in the South Pacific have reached their predictive limit. ICES Journal of Marine Science 78:2830-2843.

Sulak, K. J. and P.M. Dixon. 2015. Change in Gulf of Mexico mesophotic reef fish community structure across the time threshold of the Deepwater Horizon oil spill event in 2010: Mesophotic reef fish community impacts of the DWH oil spill. DWH Deepwater Benthic NRDA Technical Working Group Report. Montgomery, AL.

Wadoux, A.M.J.-C., G.B.M. Heuvelink, S. de Bruin, and D.J. Brus. 2021. Spatial cross-validation is not the right way to evaluate map accuracy. Ecological Modelling 457: 109692.

Appendices

Appendix A: Workshop Attendees

Table A.1. List of workshop attendees.

Name	Organization
Abigail Powell	NOAA
Alex Ilich	University of South Florida
Amanda Demopoulos	USGS
Anand Hiroji	University of Southern Mississippi
Andrew Davies	University of Rhode Island
Andy David	NOAA
Anna Downie	Center for Environment, Fisheries and Aquaculture Science
Arliss Winship	NOAA Affiliate
Ashley Rowden	National Institute of Water and Atmospheric Research; Victoria University of Wellington
Asmita Shukla	NOAA Affiliate
Avery Paxton	NOAA
Benjamin Woodward	CVisionAI
Brian Andrews	NOAA
Bryan Costa	NOAA
Candice Untiedt	Commonwealth Scientific and Industrial Research Organization
Charles Menza	NOAA
Charles Paull	Monterey Bay Aquarium Research Institute
Chris Taylor	NOAA
Curt Whitmire	NOAA
Daniel Sternlicht	Naval Surface Warfare Center
David Millar	Fugro
David Shea	Kraken
Derek Sowers	NOAA Affiliate
Edward Sweeney	NOAA Affiliate
Erik Cordes	Temple University
Erik Ebert	NOAA Affiliate
Frank Parker	NOAA
Franzis Althaus	Commonwealth Scientific and Industrial Research Organization
Garrett Mitchell	Fugro
Greg Packard	Woods Hole Oceanographic Institution
Hannah Brown	NOAA Affiliate
Isabel C. Romero	University of South Florida
Jacob Howell	NOAA Affiliate
James Thorson	NOAA

Jason Chaytor	USGS
Jeff Condiotty	Kongsberg
Jeffery Leirness	NOAA Affiliate
Jennifer Kraus	NOAA
John Runyan	Naval Oceanographic Office
Jordan Rees	Kraken
Kerry Howell	University of Plymouth
Kristopher Benson	NOAA
Kylie Maguire	Southern Cross University
Lauren Szathmary	Research Planning Inc.
Leonardo Macelloni	University of Southern Mississippi
Lindsay Gee	Ocean Exploration Trust
Madalyn Newman	NOAA
Marissa Nuttall	NOAA Affiliate
Mark Amend	Kongsberg
Mark Mueller	Bureau of Ocean Energy Management
Martha Nizinski	NOAA
Matthew Poti	NOAA
Megan Cromwell	NOAA
Meredith Westington	NOAA
Michael Coyne	NOAA Affiliate
Mike Rasser	Bureau of Ocean Energy Management
Patrick Duff	US Naval Research Laboratory Stennis
Paul Montagna	Texas A&M University Corpus Christi; Harte Research Institute
Philip Hall	NOAA
Randy Clark	NOAA
Rob Downs	NOAA
Ryan Gasbarro	Temple University
Samuel Georgian	Marine Conservation Institute
Sandra Brooke	Florida State University
Sarah Hile	NOAA Affiliate
Scott Gallager	Woods Hole Oceanographic Institution
Scott Jones	NOAA Affiliate
Sean Keenan	Florida Fish and Wildlife Research Institute
Sean Kelley	Woods Hole Oceanographic Institution
Shannon Hoy	NOAA Affiliate
Stacey Harter	NOAA
Stephanie Farrington	NOAA Affiliate
Stephen Formel	NOAA
Steve Intelmann	NOAA

Taylor Runyan Lee	US Naval Research Laboratory
Ted Switzer	Florida Fish and Wildlife Research Institute
Thomas Oliver	NOAA
Tom Hourigan	NOAA
Travis Sterne	USGS
Warren Wood	US Naval Research Laboratory
William Mowitt	NOAA

Appendix B: Workshop Agenda

Day 1 (Modeling) Dec 7, 2-5pm Eastern

Introduction	
2:00-2:15	Welcome, Agenda
2:15-2:25	Presentation: MDBC MGM project
2:25-2:40	Presentation: MGM predictive habitat modeling - requirements and inventory
Plenary Discussion	
2:40-3:10	Techniques for modeling distribution and abundance
3:10-3:20	BREAK
Plenary Discussion continued	
3:20-3:50	Data requirements and sampling design
3:50-4:20	Validation and assessment of uncertainty
4:20-4:50	Model products for management
Conclusion	
4:50-5:00	Summary and next steps

Day 2 (Mapping) Dec 8, 1-5pm Eastern

1:00-1:30	Welcome, Agenda *Mapping* project introduction and background
Topic 1: Mapping - Ship-based sonar data and data processing for mapping MDBC	
1:30-2:30	Presentations on Topic 1
2:30-3:00	Group Discussion: Best practices & methods for data collection
3:00-3:15	Break
Topic 2: Mapping - AUV acoustic and optical imaging for mapping MDBC	
3:15-3:45	Presentations on Topic 2
3:45-4:45	Group Discussion: AUV methods for mapping MDBC
4:45-5:00	Summary and next steps

Day 3 (Ground-truthing) Dec 9, 1-5pm Eastern

1:00-1:25	Welcome, Agenda *Ground-truthing* project introduction and background, Intro to Topic 1
Topic 1: Data Collection - Imagery requirements, precision of images & positioning, techniques for automating georeferencing images	
1:25-2:05	Presentations on Topic 1
2:05-3:00	Group Discussion: Best practices & methods for data collection
3:00-3:15	Break

Topic 2: Image/Sample Interpretation - Annotation and classification techniques and standards, AI/ML tools	
3:15-3:20	Intro to Topic 2
3:20-3:55	Presentations on Topic 2
3:55-4:45	Group Discussion: Best practices and methods for image/sample interpretation
4:45-5:00	Summary and next steps

DEPARTMENT OF COMMERCE
UNITED STATES OF AMERICA

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NOAA
U.S. DEPARTMENT OF COMMERCE