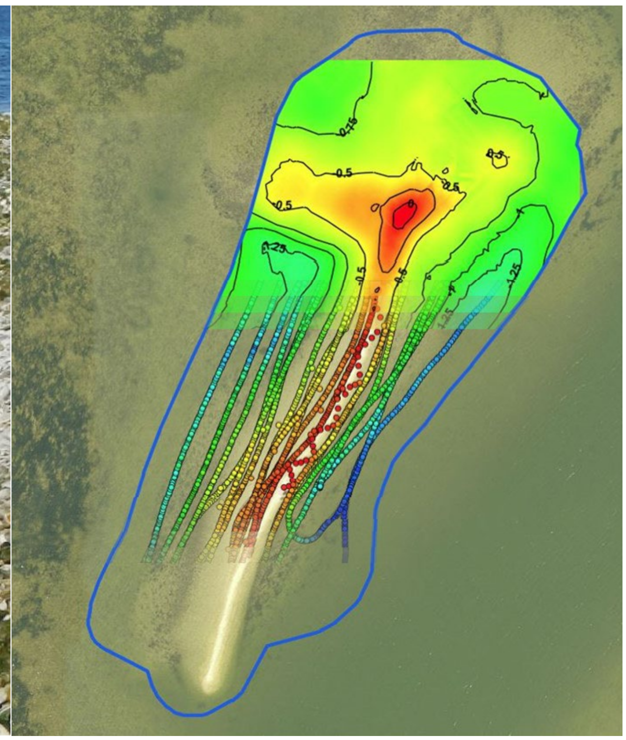
Florida Oyster Recovery Science Guidance Series:
001 - Oyster Habitat Mapping



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Cover images: Oyster habitat mapping in Lee County, Florida. E. Milbrandt and A.J. Martignette, Sanibel-Captiva Conservation Foundation.

Oyster habitat mapping is a dynamic field with rapidly advancing technology. This document will receive periodic updates to keep pace with the state of the science and recommended practices. Reader feedback on ways to improve this document's utility to the oyster recovery science community is welcomed. Direct suggestions to Corey.Anderson@MyFWC.com

Summary of the Florida Oyster Recovery Science Working Group

The FORS Working Group represents a wide diversity of organizations from natural resource agencies, academic institutions, NGOs, and businesses. The group shares the following vision: Florida's oyster populations and habitats are thriving and providing ecosystem services; oyster fisheries are sustainable and growing; and oysters are effectively managed through plans that are science-based, adaptable to changing conditions, and coordinated through partnerships among community stakeholders. To attain that vision, FORS Working Group's mission is to: 1) nurture a community of resource professionals that fosters the comparability of science-based metrics, methods, and models used to recover and manage Florida's oyster habitats and fisheries, 2) develop science-based guidance products, 3) support status and trend assessments, 4) work to eliminate barriers to oyster recovery, and 5) share information with the broader community.

This document takes a step toward accomplishing a goal of the FORS Working Group to develop science-based guidance to inform oyster recovery and management of Florida's oyster habitat and fisheries by fostering comparability among metrics, methods, and models. Achieving this goal relative to oyster mapping in Florida has led to compiling, comparing, and providing technical guidance on existing and new mapping metrics and methods.

Sharing the work of the Florida Oyster Recovery Science (FORS) Working Group with such a broad range of partners will ensure transparency and comparability in data collection as work towards oyster recovery continues.

Authors and Contributors

This document was created by the FORS Working Group mapping subcommittee, which is comprised of members from State and Federal resource management entities, universities and non-profit organizations. The subcommittee (authors) and external reviewers, are as follows:

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Contents

Any software or hardware referenced is not necessarily endorsed by the authors or their organizations.

Executive Summary

Given the dramatic declines in oyster habitat (Beck et al. 2011), spatial extent and biomass (zu Ermgassen et al. 2012), and the economic and environmental value of these species, the need to preserve and restore oyster reefs is paramount. Preservation requires consistent monitoring and restoration involves identifying degraded reefs on a large spatial scale. Successful restoration projects depend on accurately identifying areas most suitable for re-establishing reefs. Utilizing the latest mapping techniques offers the greatest chance for restoration success by providing the highest resolution data possible for a given project, leading to a more informed use of human and financial resources. This document provides guidance to help users navigate oyster reef mapping technology to facilitate comparability in data collection and maximize oyster conservation and recovery on a broad scale. We first outline applications of mapping data, including oyster ecosystem research, monitoring, and restoration and enhancement. Using mapping, we can correlate oyster locations with habitat variables and take repeated physical measurements of reefs or surrounding areas. This information can be implemented in models to project areas of extent, estimate population sizes, or locate suitable restoration sites. We expand upon two- and three-dimensional methods that can be used to collect these data in both intertidal and subtidal oyster habitats. For intertidal oyster mapping, we highlight basic two-dimensional methods such as ground-based perimeter walks and digitization and/or classification of remotely sensed data, and more contemporary three-dimensional methods including Light Detection and Ranging (LiDAR), laser scanning, Structure from Motion (SfM), and Down-imaging sonar. For subtidal oyster mapping, we discuss two-dimensional methods such as poling and probing (in conjunction with a GPS) and acoustic sonar, and three-dimensional methods including depth finders (paired with sonar) and multibeam sonar. We provide a decision support tree to help users select the best mapping method for intertidal mapping given a desired spatial scale, dimensionality (2D or 3D), cost, and resolution. We supply an additional decision support tree to guide selection of a subtidal oyster mapping method given the depth of the reef, desired dimensionality (2D or 3D), and data product required (extent, relief, and rugosity). We discuss the data metrics that can be obtained using the aforementioned methods in both subtidal and intertidal habitats and provide extensive summary tables on each method. These tables include best applications, metrics derived, limitations, cost estimates, and expert commentary on ease of use and other notable considerations. We address ground-truthing methods including poling, tonging, and skin or SCUBA diving to assess mapping products for accuracy and quality assurance and quality control (QA/QC). Finally, we briefly address data processing and analysis methods. Detailed data processing workflows along with accompanying screen images for some methods are included in the Appendix.

Introduction

Mapping oysters (primarily Eastern oyster, *Crassostrea virginica* in Florida) can provide an understanding of habitat spatial extent and can be used to document changes over time. Some mapping techniques can be used to assess status of the target communities. Mapping can be conducted at scales from square meters to hectares, for intertidal and subtidal habitats, and for a number of applications (monitoring, research, restoration). Mapping of oyster habitats in Florida has a long history starting in Apalachicola Bay and surrounding areas to support Florida's oyster fishery (Swift 1897). Mapping to aid in management of oyster resources has since expanded from oyster fishery-related goals to those related to ecosystem health (other fisheries supported by oyster habitats, water quality, biodiversity, and resiliency). Mapping technology has also advanced from the early days in which locations of reefs were identified by poling and probing to use of aerial surveys, high resolution GPS, sonar and laser-based technology. Some of these techniques are established and well-known (e.g., acoustic mapping), whereas others are new and less familiar (e.g., photogrammetry). The most appropriate mapping technique will depend on several factors including size of the target area, tidal variability, location, depth, proximity to surrounding habitats and mapping goal (Radabaugh et al. 2019). Further considerations are financial, legal, and logistical constraints and available technical expertise.

The overarching goal of this document is to provide information that will help users select the most appropriate technology and data analysis for oyster mapping appropriate for their objectives, funding, and technical expertise. Contents of this document include information and summary flowcharts that guide users through technique selection and workflows for processing remote-sensing data using a geographic information system (GIS). The target audience for this information includes those responsible for managing, studying and/or conserving oyster ecosystems, but this document may also help inform mapping of other coastal habitats.

Applications of Mapping

Oyster Resource Mapping

Mapping is a broad term that can encompass spatial representations of different geological categories (e.g., rock, sand), biotopes or habitats (e.g., coral reefs, seagrasses), distributions of biological assemblages (e.g., coral-sponge communities, oyster beds), or other spatially explicit elements (e.g., archaeological artefacts, underwater hazards). Mapping can apply to non-structural ecosystem components such as environmental conditions (temperature, salinity, oxygen) or biological distributions (phytoplankton, zooplankton). Different types of mapping use different tools, which vary in expense, technical complexity, and data products. Early seafloor maps were created by dropping lead weights on marked lines to measure depth over a network of locations (sounding). Today this task is accomplished more efficiently using sophisticated sonar (sound navigation and ranging) instruments. The choice of mapping tools has increased significantly over time, providing practitioners with a potentially confusing array of options.

Mapping the component habitats of an ecosystem is fundamental to understanding the distributions of biological communities in the system and is a prerequisite to spatial research and management. For example, benthic sessile species such as corals, sponges, and oysters, require hard substrate for settlement, and a moderate current to deliver food and oxygen, and remove waste and sediment. Seafloor maps that show bathymetry and geology allow scientists to identify suitable habitats for their target objectives (e.g., distribution mapping, restoration planning, monitoring). Data on species distributions relative to habitat type or geological feature can provide insight into drivers of observed distributions. The greater the resolution of the mapping data, the better we can correlate biological observations to understand the influence of small-scale habitat variation on their associated communities. Overlaying geological maps with other types of mapped data such as temperature, salinity, organic material (food), etc., can further refine our understanding of the habitat requirements for selected species or communities. Extrapolation of known species distributions relative to estuarine substrates can generate estimates of population size over areas too vast to manually count.

Oyster Mapping as a Monitoring Tool

Mapping of oyster resources can be incorporated into monitoring programs, and ideally would include repeated surveys to track key metrics that are indicative of habitat condition. To employ mapping technology as a monitoring tool, consideration should be given to the desired temporal interval of mapping. For example, monitoring for 1 to 7 years following an oyster habitat restoration/enhancement project is recommended. Common practice is to monitor pre-construction, within 3 months of post-construction, and minimally for 1-2 years post-construction (Baggett et al. 2014, Radabaugh et al. 2019). In addition, obtaining monitoring data for 4-7 years post-construction and after events that can alter reef area (e.g., hurricanes) is preferred. For example, oyster reefs in Florida estuaries monitored under the Comprehensive Everglades Restoration Plan's Restoration, Coordination and Verification program (CERP RECOVER) have a target mapping frequency of every 5 years to monitor long-term changes in oyster reef area and substrate type (Dial-Cordy and Associates Inc. 2011). Due to cost and effort, however, repeated mapping at the ecosystem level has not been typically performed. In most Florida estuaries, oyster reef mapping efforts have only initially been completed for a system, or in some cases repeated only once from a previous effort (see Radabaugh et al. 2019 for descriptions of oyster mapping efforts throughout Florida). Regardless, initial mapping can serve as a baseline for future, repeated efforts to determine how reefs change over time at the ecosystem level.

Oyster reef extent, area, height, and condition are among the most useful data that can be regularly collected using mapping techniques (Baggett et al. 2014). The chosen metrics will influence selection of mapping methods and technology (Table 1). Other metrics of interest include percent cover of reef substrate (and corresponding non-reef substrate and types), datum-referenced oyster habitat elevation, shoreline loss or gain (position and elevation), and influence of oyster reefs on adjacent habitats (e.g., marsh, mangroves, shoals, seagrass). With more sophisticated techniques, three-dimensional (3D) measurements such as reef complexity, rugosity, topography, and vertical growth can be monitored, although these are technically more challenging. While this document provides guidance for methods appropriate for mapping oyster habitat, mapping methods can also be utilized in standardized monitoring programs (e.g., Garvis et al. 2020) and for assessment of restoration outcomes (e.g., Hogan and Reidenbach 2019). For Florida-specific oyster habitat monitoring guidance the reader is referred to a forthcoming volume of this publication series (Birch et al., In Press).

Table 1. Oyster habitat mapping metrics user guide.

Metric	Subtidal Methods	Intertidal Methods	Data Type
Reef Area	Tape measure; sonar, poling; with RTK-GPS	Photogrammetry (UAS, satellite, aerial); LiDAR, transect tape, RTK-GPS	Direct measure
Reef Height	Tape measure; sonar, poling; with RTK-GPS	Photogrammetry (UAS); LiDAR; structure from motion, RTK-GPS, laser level	Direct measure
Reef Condition			
• Rugosity / Structural Complexity	Sonar; ground-truthing, chain method	Photogrammetry (UAS); LiDAR; structure from motion, chain method	Direct measure, resolution limited by equipment. LiDAR: modeled with DEM
• Oyster Distribution (continuous or clumpy)	Sonar; ground-truthing, underwater video	Photogrammetry (UAS, satellite); ground-truthing; LiDAR	Direct measure
• Oyster Density	Ground-truthing, underwater video	Photogrammetry (UAS, satellite); ground-truthing	Direct measure
• Size – Frequency Distribution	Ground-truthing, underwater video	Ground-truthing	Direct measure

The tools, techniques and sampling frequency employed in a standardized monitoring program are dictated by costs, personnel expertise, ease of use, and data processing time (see Tables 4-7). Information from these tables was acquired by the authors from published literature, consultation with mapping professionals and direct experience. The spatial extent of the area to be mapped can determine what capabilities are required (e.g., personnel, vessel, or aerial vehicle requirements) because of considerations such as distance, access, or flight time. Habitat type (e.g., intertidal vs subtidal), and the ability to distinguish changes over time, will also influence choice of method(s). Monitoring changes in habitat 3D structure, especially at larger scales, may require use of multiple methods. Advances in mapping technology allow monitoring of habitat metrics at landscape to system scales, whereas traditional, manual methods are limited to much smaller patch or reef scales. However, most mapping methods do not collect biological data such as live or dead oyster density, size distribution, predator density, etc. Therefore, ground-truthing using traditional manual methods is still often necessary to verify mapping results. More detailed discussion of how mapping technology and methods are applied to habitat types and ground-truthing of those results will be covered in ensuing sections of this document.

Oyster Resource Restoration and Enhancement

Mapping for restoration/enhancement planning can utilize many types of spatial data that shed light on the suitability of an area for siting new reefs, restoring existing habitat, or evaluating the success of a restoration project. Effects of natural or anthropogenic perturbations on ecosystems are often evaluated using the before-after-control-impact (BACI) approach (Conquest, 2000). This technique compares before and after status of the 'impacted' site and compares these data with an unimpacted control site. Such studies may incorporate mapping data, particularly for assessment of restoration efforts.

In addition to collecting physical data (reef area, height, substrate type, etc.), creating maps for planning involves integrating other types of spatial data to create a multilayered product that can be used to identify optimal project locations. These data may include oyster density and demographics, incidence of disease or predators, oyster food levels, environmental conditions and areas that are contraindicated (e.g., navigation channels, seagrass beds).

Prior to mapping for planning, it is important to establish the boundaries of the target area so the type and resolution of available data can be identified. The spatial data layers can be numerically represented to identify optimal areas by incorporating them into a habitat suitability model (HSM) or habitat suitability index (HSI). Several different methods have been used to generate HSMs (Conquest 2000, Pollack et al. 2012, Puckett et al. 2018, Theuerkauf et al. 2019); these vary in complexity and type of data input, so available resources should be considered when selecting the model to use. Estuarine areas are highly dynamic systems with high short-term (hours to days) and medium-term (weeks to years) temporal and spatial variability. While the HSM and HSI outputs are useful tools, they must be interpreted with caution as the conditions in any given area will vary over time. As with any desktop-based effort, habitat suitability models benefit from calibration using field-based data and refinement may be appropriate following an evaluation of pilot restoration projects that use such models to provide predictions of success.

Oyster Habitat Suitability Modeling

The value of each HSM will depend on the quality and type of data available for the established target area. There are several types of HSMs ranging from simple to complex forms. A relatively easy to use HSM is described as follows: The first step is to list all the types of data that could be included (Table 2). Each of these potential factors should be evaluated for relevancy, quality,

Table 2. Spatial factors that could be included in a Habitat Suitability Model (not exhaustive). The asterisk (*) indicates parameters that can be obtained and/or directly measured through mapping methods and technology.

Factors	Example Metric
Contemporary oyster reefs	Location, area, height (* for all)
Historical oyster reefs	Location, area, height (* for all)
Substrate type	Mud, sand, shell, rock, reef (also informative on sedimentation and/or burial of hard substrates)
Elevation	Reference (+ or –) to 0.0 (feet or meters) North American Vertical Datum 1988 (NAVD 88) or Mean Sea Level (MSL)*
Water depth	Feet or meters*
Temperature	Summer maximum
Dissolved oxygen (DO)	Seasonal variation in recent time, spatial variation at depth, and minimum concentrations
Salinity	Seasonal maximum and minimum
Water flow	Current speed
Chlorophyll *a*	Concentration
Recruitment	Recent location and density of spat
Disease	Intensity and prevalence
Predators	Density of each species
Managed areas	Management of uplands and submerged lands adjacent to site*
Shoreline type	Natural or altered lands adjacent to site*
Counter-indicated areas	Known persistent seagrass, navigation channels, aquaculture leases and access areas, military restricted areas (* for all)

and sufficiency of spatial references. For instance, there may be relevant and high-quality data available for a particular factor, but the spatial extent of the data may not cover the entire HSM area. In such cases, the data should not be included as the relative ranking of the HSM areas would be compromised. Similarly, the temporal extent of the data should be evaluated to determine if it provides a fair representation of the site conditions.

Consideration should be given to the number of factors to include and whether the factors should be weighted differently. Including too many factors could dilute the influence of those most important. Conversely, identifying the most important factors can be challenging. Selecting between 5 to 10 significantly uncorrelated factors is a reasonable approach. Live oyster reef presence is one of the best indicators of habitat quality; locations of historic or recent live oyster populations may also indicate suitable habitats if environmental and other conditions are ideal for oyster survival. For select Florida estuaries, historical oyster location information dating back over 100 years may be obtained from documents (e.g., Baird, 1883) or, for more recent locations, from the local ecological knowledge of fishers. The duration of time over which live oysters have been sustained at a location may also be considered a good indicator of suitable conditions, especially when oysters are known to have been present for multiple decades. For an overview on approaches identifying and integrating critical data for oyster suitability modeling please see LaPeyre, et al. 2021.

Once factors are evaluated and selected for inclusion in an HSM, the next step is determining how to characterize these factors. Some factors are more easily characterized (reef area, height) as they are relatively stable. Other factors that may be critical to oyster survivability (e.g., salinity, dissolved oxygen (DO), chlorophyll, water flows) have high spatiotemporal variability. Deciding how to spatially characterize this information is important. It is generally recognized that oysters need DO concentrations of 2 to 3 mg/l to thrive (Chesapeake Bay Program, 2022). While they can survive DO concentrations less than this for short periods of time (e.g., overnight), such conditions cause stress in oysters and can result in sublethal to lethal effects (Patterson et al., 2014; Breitburg et al., 2015). Identifying where minimum DO concentrations occur is a better metric to use in an HSM for oysters than average DO concentrations.

The next step is to spatially symbolize the selected factors in raster format (cells of a predefined size, as small as practical to obtain the highest model resolution). This is most easily done with a geospatial information program such as ArcGIS or with open-source programs such as QGIS and R. Individual factor scores in each raster cell are then standardized from 0 to 1 by dividing all raster scores by the highest raster score (Table 3). The final step is to sum all factor scores in each raster cell and divide by the maximum of the summed scores as illustrated in the following simple model formula:

$$\textit{Final Score} = (\textit{Factor}_1 + \textit{Factor}_2 + \ldots + \textit{Factor}_n) \,/\, \textit{Maximum Score}$$

The initial HSM outputs should be reviewed by persons with knowledge of the system and refined as necessary. This HSM is relatively simple so results can be easily updated as new information becomes available. Models have been completed for several Florida estuaries including Pensacola Bay (Johnson et al., 2020), Tampa Bay (TBEP, n.d.), and Charlotte Harbor (Boswell et al., 2012).

Table 3. Example Habitat Suitability Index scoring matrix.

	Factor 1 Raw Score	Factor 1 Standardized Score	Factor 2 Raw Score	Factor 2 Standardized Score	Factor n Raw Score	Factor n Standardized Score	Summed Standardized Factor Scores	Standardized Final Score
Raster 1	50	0.63	1.3	0.45	12	1.00	2.08	0.80
Raster 2	75	0.94	2.9	1.00	8	0.67	2.60	1.00
Raster n	80	1.00	0.5	0.17	5	0.42	1.59	0.61

Mapping Methods

Mapping methods for oysters range from low-tech field surveys to high-tech remote sensing. Selection of a method or combination of methods to use should be dependent on the spatial and temporal scales of the mapping effort, the type of oyster habitat being mapped, and any chosen metrics for monitoring which can be collected during the mapping. Oyster mapping in Florida is typically conducted specific to discrete estuary habitat surveys or restoration/enhancement projects. The main factor influencing mapping method selection is whether oysters are subtidal or intertidal. Subtidal methods require acoustic sensing methods (sonar) while intertidal oysters can be mapped aerially during appropriately low tides. Map information may be collected in 2D (x-y) that depict areal extent or 3D (x-y-z), which adds surface relief to extent. An overview of oyster metrics and the corresponding range of mapping methods are shown in Table 1. Data collection methods in 2D and 3D for subtidal and intertidal oysters are detailed in the following sections and in Tables 4 (Sonar), 5 (LiDAR), and 6 (Other methods). Direct observation and verification methods examples are provided in Table 7.

Intertidal habitats

Two-dimensional methods

Ground-based Surveying

Traditional field-based mapping methods involve the use of global positioning systems (GPS) to delineate reef footprints by walking the perimeter of a reef, while recording GPS coordinates at regular intervals or continuously (for example, every 1 m) which can be uploaded into GIS software. Modern systems incorporate real-time kinematic (RTK) technology that can provide sub-meter to centimeter level accuracy allowing precise measurement of reef metrics over time. Reef area can be calculated from the mapped footprint with monitoring to detect changes in reef position and area over time. In comparison, low-cost GPS instruments are only capable of 1-meter resolution at best. Both, however, are affected by weather conditions at the time of data collection (see below). RTK-GPS is widely used to map and monitor oyster habitats, as well as other coastal habitats. This method of ground-based field measurement is useful for small-scale mapping. It is perhaps one of the only feasible methods for mapping oysters on vertical surfaces such as seawall, pilings, mangrove roots, or when oysters form aprons concealed beneath overhanging branches. As a manual method, ground-based mapping is time- and labor-intensive, preventing monitoring at large scales. Employment of this method is difficult or impossible in remote areas. Additionally, instrument accuracy may be reduced in remote areas (for instance, if further than 12 km from the nearest reference base station when using the Florida Department of Transportation Permanent Reference Network), or where cellular signal is limited or obstructed (i.e., when using cellular RTK). Accuracy may also be affected by field conditions (e.g., cloud cover), especially for vertical data. It is also primarily limited to intertidal habitats at low tides where reef edges can be visibly observed. Subsequent monitoring trips at higher tides can also lead to errors in delineation. Definition of what constitutes a reef edge must be determined pre-survey and stated in resulting mapping products and reports. For example, Baggett et al. (2014), define reef edge as a continuous line of shell cover ≥ 25%. Other monitoring methods define reef edge as shell cover or live oyster density is ≥ 10% (Walters et al. 2015). Regardless, this method can be particularly cost-effective at smaller scales.

Remote Sensing

Remote sensing techniques are useful to map and monitor oyster reef habitats at larger geographic scales. Orthorectified aerial photos and satellite imagery, analyzed by a mapping technician or GIS software, has been used to detect large-scale historical changes in reef habitats (e.g., Garvis et al. 2015, Grizzle et al. 2002, Grizzle et al. 2018, Nieuwhof et al. 2015). These methods have not only allowed detection and delineation of reef habitats and areas, but also determination of reef condition (living vs. dead margins and reefs, reef color related to oyster densities), based on visual or spectral characteristics. Image classifications were verified by field ground-truthing. From studies such as these, continued monitoring of reef positions and areas can be made by repeating these methods for future years, providing valuable information on long-term changes of reef habitats over bay scales. Technology costs for remote sensing methods become cost effective at medium (11-100) to large (>100) hectare scales.

Photogrammetry is the primary method of obtaining 2D intertidal oyster maps and may be accessed from some no-cost or commercial sources or collected *ad hoc*. Imagery at sub-meter resolution is now more widely available from a variety of free web applications (e.g., Google Earth, USGS Earth Explorer, and NOAA Digital Coast) and paid service providers. Effective use of this approach at finer scales can be limited by the resolution of available images. On-demand map information can be collected by manned aircraft or unmanned aerial systems (UAS), also known as drones. These are useful tools to economically map oysters over small (0-10) to medium (11-100) and large (>100) hectare scales and have the added benefit of being collected at any desired temporal interval. Ridge and Johnston (2020) provide a review of marine ecosystem applications for UAS.

As with RTK-GPS, accurate mapping and monitoring via remote sensing is limited to intertidal habitats, and available images might not all be at optimal tidal exposures to allow repetitively accurate delineations of the same reefs. From the imagery, reefs are manually delineated, which can be time consuming particularly when a new system is mapped. Once initially delineated, subsequent mapping will likely be more readily expedient, allowing this technique to be used for monitoring for reef changes at multi-year increments. To continue accurate delineation of reef changes and consistent visual interpretation of map images, consistency of staff involved in data evaluation and training of new staff is important. Automated detection methods have been developed (Schill et al. 2006, Ridge et al. 2020) but may not be widely available to all practitioners at this time. Imagery analyses have been primarily limited to tracking reef position/footprint and area. Grizzle et al. (2018) attempted to correlate satellite imagery with another “universal metric”, oyster density (Baggett et al. 2014). Image color corresponded well with direct measurements of oyster density and shell weight. Although restricted to general classifications, this does point to the potential for imagery to monitor and evaluate an important metric of oyster reef health at wider geographic scales. Imagery can also be used to analyze other associated metrics such as shoreline loss or gain or changes in adjacent habitats (such as marsh, mangroves, or seagrass, shoals). At this time, however, photo and satellite imagery are mainly used to monitor physical changes in intertidal habitats, but not oyster health. Methods for mapping intertidal and subtidal reefs differ as do methods for mapping in two dimensions (2D) or three dimensions (3D). The type of mapping method selected will depend on the metric(s) of interest and the habitat type. Subtidal oyster reef mapping is largely restricted to sonar-based methods because water clarity may be poor or currents may be rapid in these habitats, making them unsuitable for applying other methods. In contrast, there are more methods available for intertidal oyster mapping, especially when conducted at a low tide when oysters are exposed. Both subtidal and intertidal reefs can be measured to determine areal extent (a 2D metric), height (a 3D metric) and rugosity (a 3D metric). Decision support trees in Figures 1 and 2 provide a tool for users to determine the metrics and methods to use for specific mapping projects. Georeferenced side-scan sonar is a common method of obtaining 2D areal extent maps of subtidal oyster reefs. Many collection platforms also provide 3D information or can be outfitted with additional hardware to do so. Current 3D data collection technologies (e.g., multibeam sonar, LiDAR, structure from motion) provide enhanced resolution over 2D methods. Decision support trees in Figures 1 and 2 provide a tool for users to determine the metrics and methods to use for specific intertidal or subtidal mapping projects, respectively.

Three dimensional methods

As mentioned previously, metrics of reef complexity (reef height and rugosity/topography) are important in assessing oyster reef condition. High vertical relief is associated with better reef health (Lenihan et al. 1999). Tidal position and reef elevations also influence survival, growth, and reef health (Bartol et al. 1999, Ridge et al. 2015). RTK-GPS systems measure elevations with centimeter-level accuracy, allowing multiple elevation measurements across an individual reef and thereby capturing reef surface heterogeneity with positional data. Changes in average reef height as well as topography can be monitored over time in select reef locations. Ground-based monitoring methods (laser-level surveying, reef height above substrate, RTK-GPS, chain method for rugosity; Baggett et al. 2014, McCormick 1994, Walters et al. 2015,) effectively capture precise changes in these metrics. However, these techniques are labor-intensive, limiting the geographic scale in which they can be used. Advances in mapping technologies allow for capturing high-resolution changes in reef complexity at broader scales. Details in some of these techniques will be described in later portions of this document, but their applications to monitoring are covered in this section.

LiDAR/Laser Scanning

Aerial LiDAR has been used to assess vertical height, elevation, and morphology of oyster reefs (Schill et al. 2006). Vertical elevations can be challenging to resolve, however. Recent advances in instrumentation allow for mounting on unoccupied aircraft systems (UAS) and lower altitude flights, improving resolution of complex features, such as oyster clusters (Windle et al. 2019). However, instrumentation and expertise costs are high, precluding common adoption of this method for widespread monitoring. Other logistical limitations may be required pilot licensing for users in professional applications and locations with potentially restricted air space due to proximity to airports, military facilities, certain publicly managed lands, or other sensitive areas.

Other applications of LiDAR include terrestrially based systems (laser scanners) that allow for precise vertical measurements. The data output is essentially a 3D photo. Used in conjunction with RTK-GPS, geo-referenced 2D and 3D measurements (e.g., reef area and heights) can be collected over the same reef structure(s), enabling mapping of not only reef area, but also vertical changes across that area. Terrestrial LiDAR has been used to characterize fine-scale growth and complexity in oyster reef patches. Digital elevation models (DEM) referenced to NAVD88 elevation allow determination of Optimal Growth Zones for intertidal oysters (20–40% exposure), which could inform assessments of existing reef condition and design of constructed oyster habitats (Rodriguez et al. 2014, Ridge et al. 2015). Again, limitations on using this technique for regular monitoring include costs associated with instruments, processing software, and expertise in operation and analyses. Both aerial and LiDAR techniques are limited to intertidal habitats as well. Although short-range terrestrial LiDAR can rapidly and accurately scan a swath of habitat (e.g., a shoreline) at scales of 10s–100s of m^2 (Large and Heritage 2009), it is still geographically limited and not amenable to measurement on bay-wide scales. It does enable a non-invasive method of assessing changes in reef complexity and condition over discrete intertidal reefs. Precise elevational changes in oyster reefs, shorelines and other adjacent habitats can also be monitored with this method. Manned aircraft or UAS may also collect multiple types of data concurrently, allowing post-collection overlay of orthoimages on 3D surfaces generated using LiDAR or Structure from Motion points (defined below). Fixed wing and multi-rotor UAS were used successfully to map 2D and 3D oyster reef features in North Carolina on scales ranging from 30–300 m^2 (Windle et al. 2019).

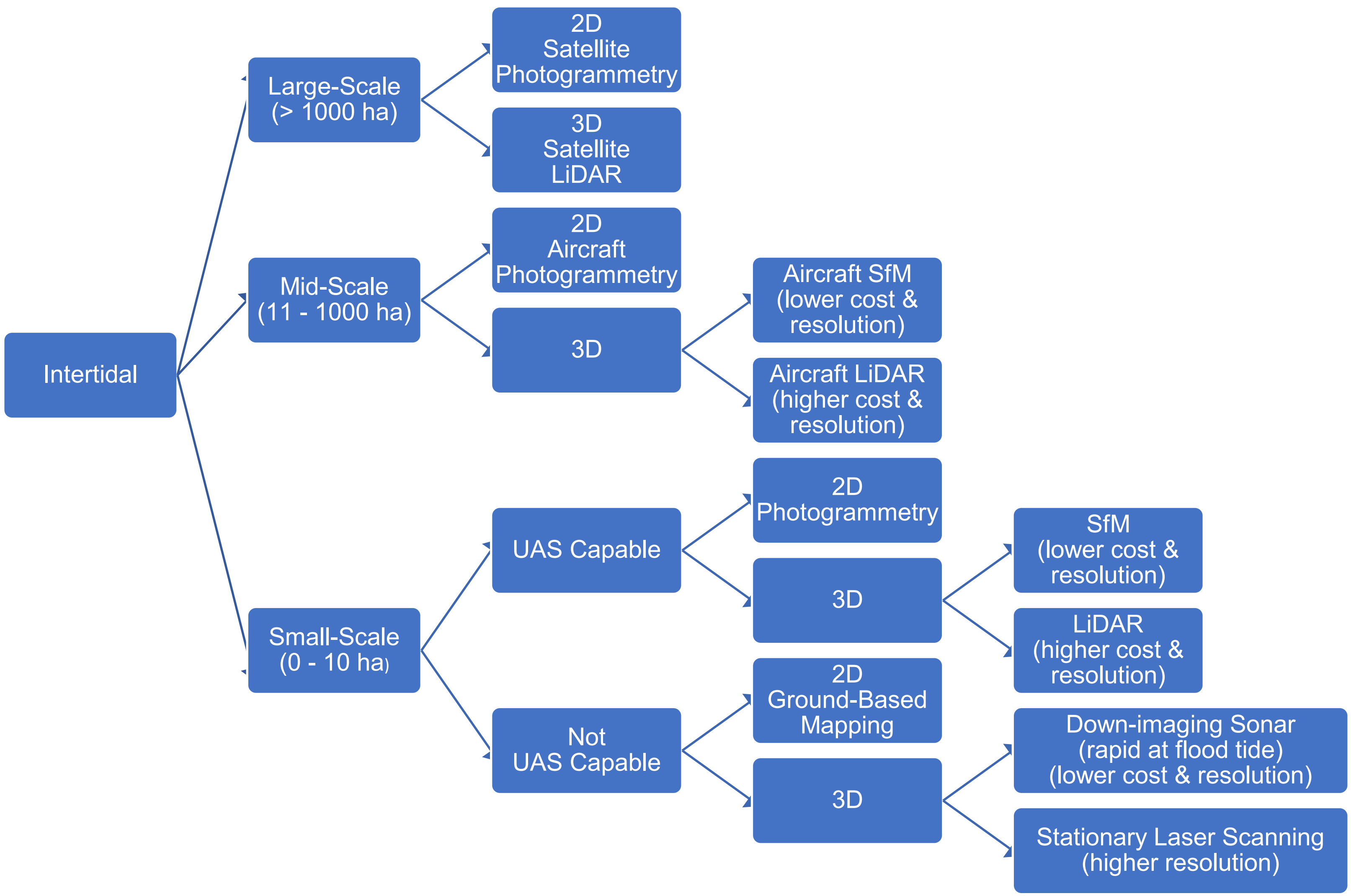
Structure from Motion (SfM)

Newer techniques utilize both aerial ortho-rectified and UAS imagery to produce digital surface models (DSM) that can detect both changes in 2D footprint and 3D reef heights or elevations (Windle et al. 2019). As a UAS technique, imagery can be produced on-demand during optimal tide conditions, an advantage over relying on image databases. 3D images and generated DSM are created from SfM processing of tiled images. Although not an exact DSM, true elevations are obtained from exposed land and intertidal surfaces. Detecting changes in reef footprint, area, and reef elevations is possible using this technique. As this method is less expensive, more frequent monitoring trips are possible. As with other previously described methods, mapping and monitoring is limited to intertidal reefs. However, adjacent shorelines and other existing and/or future planned habitat restoration/enhancement sites can be monitored with this technique as well. Geographic scales measured can be greater than shoreline or reef scales, but more time-consuming for bay-wide scales, compared to analyses of coarse scale aerial photo or satellite imagery.

Down-Imaging Sonar

It may also be possible to map intertidal reefs using sonar if surveys are conducted during the highest tides possible (see Figure 1). This approach may be used to survey intertidal oyster reefs at flood tide using shallow draft manned or unmanned vessels mounted with sonar and GPS where other methods (i.e., motorboat with sonar tow fish) are infeasible due to draft. High-resolution elevation and position points are obtained with RTK-GPS linked to a fish-finder-style sonar unit and transducer attached to a shallow-draft vessel, e.g., a kayak (Milbrandt and Martignette, 2017). The RTK-GPS is preferred for higher accuracy 2D mapping and 3D mapping. The system may be connected to a marine battery for power. Built-in sonar mapping software records location in the horizontal plane and GPS-linked sonar returns in the vertical plane. Bathymetry data points are imported to a GIS, where DSM and contour maps can be generated. Shallow depths over intertidal habitat, however, may still preclude vessel access. Instruments may also require a minimum operating depth (typically 0.6-1.0 m) for effective performance and accuracy. Operating sonar in depths shallower than the minimum recommended by the equipment’s manufacturer may result in inaccurate imagery due to the transducer being too close to the reef surface, distorting sonar returns.

Figure 1. Decision support tree for intertidal oyster mapping method selection.



Subtidal habitats

Subtidal oyster habitats are more challenging to map than those in the intertidal zone, particularly because estuarine water visibility is generally poor. In such conditions, reef extent is not visible using aerial systems. Although direct measurement from a vessel using poling and probing in conjunction with GPS may be useful for small-scale, or even larger-scale mapping (Ibis Environmental, Inc. 2004), especially in clear water, oftentimes sub-optimal water clarity, surface conditions (i.e., waves and currents), and minimum depth requirements for vessels make accurate and comprehensive mapping in this manner very difficult. Subtidal oyster mapping with sonar may be limited by depth for reasons of vessel navigability and by the physical restrictions of the technology itself. For example, multibeam sonar may require a depth of at least 3 meters, while some side-scan systems can operate in as little as 0.6 meters (FDEP 2021). In waters less than 1 m in depth, down-imaging sonar may be the most effective approach (see Figure 2). With all sonar systems, different wave frequencies are optimal for different depth ranges, and the data must be checked for errors, so some expertise is necessary when using these systems. To effectively classify, map and monitor intertidal and subtidal reefs within an estuarine system, a dual approach of intertidal methods (RTK-GPS or aerial image analyses) and sonar mapping of subtidal habitats is likely needed.

Two-dimensional methods

Side-scan Sonar

Side-scan sonar technology largely overcomes these difficulties and is now widely used in 2D mapping of oyster reefs. Vessel-deployed acoustic sonar allows wide spatial coverage of a water body. Sonar may be mounted on a vessel or on a smaller towed or autonomous vehicle; these systems are relatively inexpensive and readily available, although poor marine conditions (e.g., rough seas, erratic boat motion, increased turbidity, stratified water column) can still compromise data quality. Care must also be made in vessel operation to minimize turns which can distort images and give inaccurate reef extents. Sonar data outputs are 2D, providing an image of the seafloor. Instrumentation generally integrates GPS positions so imagery can be uploaded into GIS software for analyses. Sonar-based imagery can also detect variations in bottom hardness (brighter areas indicate hard-bottom habitat), so some limited information on habitat condition can be derived. Automated seabed classification is possible using software that can be ‘trained’ to identify different habitat types from sonar data (Allen et al. 2005); however, training and data processing can be time consuming. Accuracy assessment via direct ground-truthing is still necessary to verify bottom classifications. Once accuracy between imagery and ground-truthing is established, sonar can be used to capture data when in-water work is precluded by environmental conditions (water temperature, clarity, depth, etc.), or personnel limitations. Monitoring to detect changes in reef footprint, area, and bottom type can be performed on a multi-year frequency to detect changes over time. As mentioned earlier, interpretation of images for this purpose will rely on consistency among staff and trainings of new staff to accurately delineate reef-level changes.

Three-dimensional methods

Multibeam Sonar

Depth finders deployed concurrently with sonar instruments can be used to determine reef heights and topography, although accurate height measurements may be limited for low relief reefs (Baggett et al. 2014). Multibeam sonar systems are generally vessel-mounted and transmit an array of acoustic “beams” that are reflected off the seafloor. Multibeam systems generate two types of data: backscatter and depth across a fan-shaped swath below the vessel as it moves forward. Multibeam data generates 3D geo-referenced bathymetric maps of the sea floor, and the backscatter data can be used to identify different habitat types. Multibeam systems are similar in many ways to the side-scan sonar systems but are more expensive because multiple sensors are used concurrently. With some multibeam systems acoustic profiling may be added as one of the “beams”. Acoustic profiling can detect sub-bottom characteristics, allowing identification of historic reefs that have changed over time due to burial from sedimentation or movement of edges due to currents or waves. These data can provide additional insight into how reefs change, information which visual methods cannot provide. It should also be noted that LiDAR technology advancements may allow subtidal use soon.

Figure 2. Decision support tree for subtidal oyster mapping method selection.

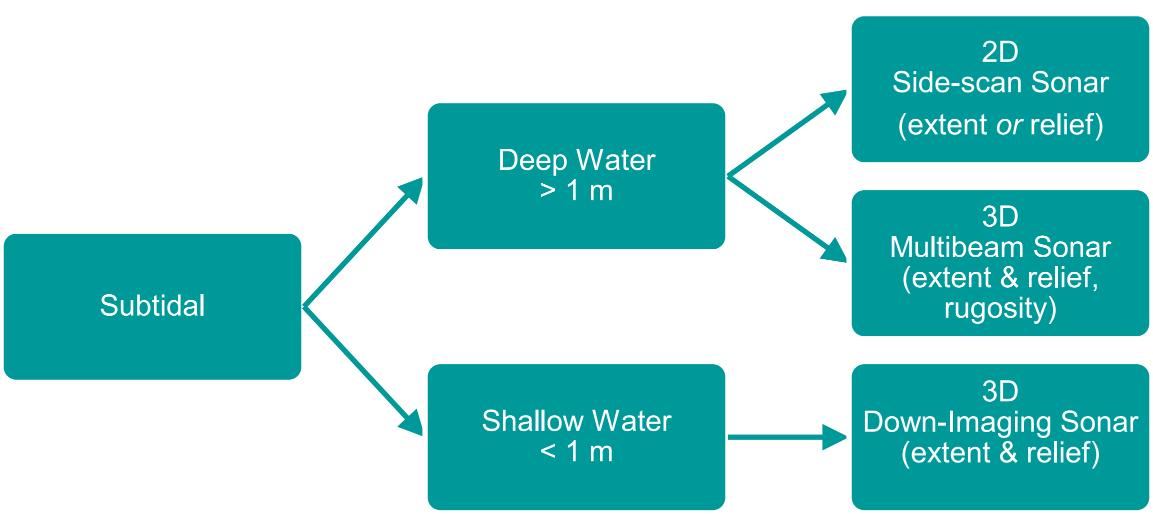


Table 4. Sonar-based oyster mapping method user guide.

Method	Best Application	Possible Uses	Limitations	Cost	Ease of Use	Resolution and Notes
Side-scan sonar	Subtidal reef mapping	Reef height Reef area	Applicable in waters at least 0.8 m deep.	Dependent on sonar swath spacing and whether processing is included. $4,700/km^2 (76 m spacing of lines for surveying. Contracted post-processing can double or triple costs).	Requires software skill for accurate post-processing.	Preferred for “cleaner” sonar swath edge than multibeam in moderate-depth waters.
Down-imaging sonar	Subtidal or intertidal reef mapping	Reef height Reef area	Metrics modeled through GIS.	$16,000 (Sonar plotter, transducer, mounting hardware, battery and housing, RTK-GPS, GNSS receiver, and antenna rod. Additional costs of boat or kayak, GIS license, field time, and processing not accounted for.)	Requires GIS skill for accurate post-processing.	GPS accuracy +/- 10 cm horizontal. Sonar accuracy +/- 8 cm vertical.
Multibeam sonar	Subtidal reef mapping, substrate type	Reef height Reef area Substrate type	Requires intensive effort in shallow waters; Requires knowledge for accurate post-processing.	Unmanned surface vessels $2,000/day. Up to 5.2 km^2 of surveying per day.	Post-processing can be challenging & technically intensive.	
Sub-bottom profiling	Subtidal, sub-bottom hard bottom mapping	Detection of buried hard substrate	Vertical profile x-section. Only useful to detect buried hard bottom (e.g., remnant reef).	$600/day including post-processing time. 32 km of track per day on average.	Best when operator owns the equipment. Rental costs are unpredictable & escalate when weather delays operations.	This is an add-on tool to complement sonar imaging. Provides information on what is buried beneath the near surface.

Table 5. LiDAR-based oyster mapping method user guide.

Method	Best Application	Possible Uses	Limitations	Cost	Ease of Use	Resolution and Notes
LiDAR - UAS (Unmanned Aircraft System, "drone")	Intertidal reef mapping	Reef height Reef area	Cost prohibitive for large areas. Field logistics (weather). UAS prohibitions may exist in some areas.	Sensor hardware - \$75,000 – \$100,000. Software license \$40,000 – \$45,000/year. Contracted: \$300/ flight, (processing models, photo mosaics, and travel).	Requires experienced pilot & data processor. Open-source software exists, and processing can be done in GIS.	Sub-cm resolution.
LiDAR - Satellite acquired	Intertidal reef mapping	Reef height Reef area	Lower resolution, or cost for high-resolution, unable to map under mangrove. Poor water penetration.	Global Ecosystem Dynamics Investigation (GEDI) and NASA IceSat-2 LiDAR data are available free.	Many digital models have been developed. Uncommon to task satellites with custom data collection.	Resolution GEDI- 25 m up to 1 km; IceSat2- as high as 0.7 m, but varies with cloud cover and reflectivity
LiDAR - Planes	Intertidal reef mapping	Reef height Reef area	Cost for high-resolution. Unable to map under mangroves. Poor water penetration. Flight logistics (weather, tide).	\$215 – \$300 per km^2 (\$0.87-\$1.21 per acre). Variable based on area & resolution. Larger areas have lower per-unit cost	Many contractors available that can customize flight times/locations; contractors are able to process data.	Resolution varies by contractor/ equipment used, but can be as high as 1 cm.
LiDAR - Bathymetric	Subtidal reef mapping	Reef height, Reef area, Reef rugosity.	Aerial, surface, and subsurface technologies exist.	Bathymetric LiDAR is much more expensive than conventional LiDAR (Dewberry 2017).	Possibly difficult to compare data with other methods if not aerial.	Highest vertical resolution currently available is +/- 0.25 m.
Stationary 3D Laser Scanning	Intertidal reef mapping	Georeferenced reef height, Reef area, Reef rugosity.	Intertidal only, limited to small areas (line of sight).	Hardware cost approximately \$20,000 and up.	High-resolution. Low startup cost. Useful where UAS disallowed.	Resolution as high as 1 mm. See charts in Massot-Campos & Oliver-Codina (2015).

Table 6. Photogrammetry-based oyster mapping method user guide.

Method	Best Application	Possible Uses	Limitations	Cost	Ease of Use	Resolution and Notes
Photogrammetry - UAS	Intertidal reef mapping. small to intermediate project areas	Reef area	Field conditions (tide & weather). Ground-truthing may be necessary to ensure detailed habitat classification.	\$700 - \$30,000 hardware purchase price.	DIY analysis carried out with relative ease in GIS (ArcGIS, R, etc.). Contracted image processing more costly.	Altitude-dependent resolution but can reach a minimum of 0.5 cm; reduction in area surveyed with higher resolution and lower altitude.
Photogrammetry - Satellite imagery	Intertidal reef mapping; large project areas	Reef area	Best images captured during low tides. Can be difficult to differentiate live and dead extent of reef.	Ranging from free (open source) for 30 – 80 m resolution (depending on bands and satellite source) to \$17.50/ km^2 for 30-cm resolution (WorldView 3 panchromatic).	DIY analysis carried out with relative ease in GIS (ArcGIS, R, etc.). More costly for image processing by contractor.	Open-source data (LANDSAT) provides 30 m resolution.
Photogrammetry - Aerial orthoimagery	Intertidal reef mapping; large project areas	Reef area	Best images captured during low tides. Can be difficult to differentiate live and dead extent of reef. Time consuming.	\$5,000 (rough flight estimate; Fitzpatrick 2016). Image digital scanning (USGS) \$30.00/frame + \$5.00 order fee.	Imagery collection by contractor or agency. DIY analysis carried out with relative ease in GIS, R, etc. More costly for image processing by contractor.	Resolution capabilities dependent on the imagery used and allowable flight altitudes.
Structure from Motion (SfM)	Mapping reef height and possibly rugosity	Reef area Reef height Can use to measure “clumpiness”.	Logistically limited intertidal or clear water subtidal. Photography-based, needs multiple-angles (consecutive images taken in rapid succession).	Dependent on aerial imagery used (see UAS and orthoimagery), UAS being most cost effective for repeated use of large area sampling).	Combination of imagery requirements and UAS flight requirements. Becoming easier with some free open-source software available.	Resolution capabilities dependent on the imagery used. Possible to apply to subtidal but labor intensive. Highly detailed; may be useful on small scales.

Table 7. Other oyster mapping method user guide.

Method	Best Application	Possible Uses	Limitations	Cost	Ease of Use	Notes
Probing/Polling	Presence/absence of exposed or buried hard substrate	Quality Control of subtidal methods	Staff-intensive Time-consuming Requires vessel & accurate GPS	Not available	Easy, but may require vessel	Useful for QA/QC ground-truthing other indirect measurement methods
In-water measurements	Intertidal reef mapping. Small areas with firm enough substrate to walk	Accurate area measurements for individual reef area measurements over time	Staff-intensive Time-consuming Requires accurate GPS	$13,500 for sub-decimeter RTK-GPS, GNSS receiver, and rod.		Useful for QA/QC ground-truthing other indirect measurement methods
Underwater video	Subtidal reefs	Ground-truthing subtidal reef presence and quality	Limited visibility impairs the method. Video review can be time-consuming	Approximately $5,200 for hardware (Grizzle et al. 2008)	Fairly low-tech, but requires a vessel	
Historical documents	Historical locations Historical abundance	Anecdotal measurement of past conditions	Approximate information based on maps or harvest volumes.	Not available		Difficult to interpret and translate to contemporary data.

Data Products

Decision support trees in Figures 1 and 2 provide a tool for users to determine the metrics and methods to use for specific mapping projects, whether the goal is to characterize intertidal or subtidal habitats. Mapping surveys may generate large amounts of data which require processing through software to be interpreted. Processing is achieved through freeware, paid software, or a combination of both. Map data may be processed for quality control in an application-specific software and exported to a GIS for measurement and to combine it with other map data, or processed directly within a GIS, depending on the file type generated during data collection (see Appendix for examples). Turnkey mapping services are offered commercially and by some non-profit research organizations. Map data collection and analysis can also be conducted in-house with purchased, leased, or rented hardware and subscription-based software. Remotely sensed imagery collected by satellite or fixed-wing aircraft is available commercially but is impacted by cloud cover and may not have been performed at optimal tide levels to capture the full extent of intertidal habitats.

Ground-Truthing & Data QA/QC

As described above, there are many remote-sensing methods that do not involve direct visual or hands-on contact with the reef systems. The only way to know if the interpretation of bottom-type and reef is accurate is by ground-truthing the areas remotely mapped. This can be done through several methods including poling, tonging, skin or SCUBA diving, underwater video recording, and land-or boat-based field assessment. Poling involves probing the bottom with a pole from a boat. Through poling, one can establish whether the bottom is soft mud, sandy mud, sand or has oyster shell present. It is even possible to detect reef structure below shallow sediments with this method depending on operator skill. Typically, poling is conducted concurrently with sonar scans of the bottom to reduce cost/boat operating hours. Resolution of the poling data depends on how frequently the bottom is probed. GPS coordinates of the poling data are recorded along with the poling results and can assist with interpretation of the sonar scanning results. Tonging involves the physical collection of a sample of reef material using tongs, two long-pole rakes connected by a hinge and commonly used to harvest oysters. Tonging is also conducted from the side of a boat and has the added advantage of producing quantitative information on the reef condition as well as bottom type information. Tonging, where allowed, is a useful method for quantitatively assessing reef location and condition and involves physically collecting a sample from the bottom with oyster tongs and bringing the sample onto the boat. If oysters and/or oyster shell are present, these samples can be processed (e.g., weighed, measured, counted and condition of oysters and/or bottom type described). As with tonging, scuba and land-based field assessment are useful for ground-truthing remotely sensed data, and for quantitatively characterizing oyster reef conditions and spatial extent. Because of the direct impacts to reef structure via the removal of material, tonging is not performed concurrently with remote sensing techniques, and only after mapping to verify reef substrate and reef condition. Because it is a destructive sampling method, tonging is not preferred as a frequently performed ground-truthing method. Non-destructive ground-truthing methods such as diver surveys should be performed as much as possible vs. fishery-derived destructive methods (Lenihan and Peterson 2004). Underwater video may be used in place of diver-surveys when conditions are unfavorable or unsafe, but visibility is still adequate to interpret oyster presence on recordings. Video cameras may be pole-mounted and lowered from a vessel to “spot-check” oyster presence or may be towed from a vessel to cover a larger survey area. Video review can be time consuming, and poor underwater visibility may limit its usefulness.

Data Processing

Software which can set routes to maximize coverage and minimize duplication of effort is available for UAS for planning field surveys and is built into some mid-range and advanced sonar/fish finder combination systems. Survey routes can be set up on desktop computers (recommended) or in the field. Successful and efficient mapping “plans the survey and surveys the plan”. Establishing a survey route ahead of the survey, whether using a computer and transferring the information, or directly in a survey unit itself, is recommended because it helps with obtaining the most usable data. For example, trying to establish a sonar survey route while on a boat in inclement weather can lead to data gaps or distortion as the boat turns and rolls. For aerial mapping georeferenced ground control points are recommended to be set up as part of the survey. Survey tracks with a high degree of data overlap (approximately 75%) avoid the need to interpolate. The data collection method and survey scheme should match the mapping objective though: some system-wide surveys are intentionally conducted more cost-effectively without overlap to sample an estuarine system and interpolated using GIS models (e.g., Grizzle et al. 2021).

Some post-data-collection processing software is open-source and available for free while others, typically with greater capabilities, require a paid license. Georeferenced and georectified images obtained from down or side-scan sonar units can be exported from post-processing software and further analyzed in GIS software to calculate reef areal extent. Point cloud data (e.g., 3D data collected using LiDAR, Structure from Motion, laser scanning, or multibeam sonar) may be analyzed in GIS software to develop DEM depicting bare surface elevations or DSM depicting surface elevations with objects on it. Oyster clumps and reefs can be manually or automatically selected from the surfaces and analyzed for extent, relief, and rugosity. 2D relief data from side-scan sonar can be analyzed within sonar software by manually measuring shadows cast by freestanding subtidal oyster reefs. 2D extent imagery from side-scan sonar may be imported to GIS and measured manually, as can 2D orthoimagery. 2D relief data points collected with down-imaging sonar may be input to GIS and oyster reef height and extent interpolated to create a DEM/DSM. Information from direct measurements must be manually put into GIS for analysis.

Conclusion and Recommendations

This document serves as an overview of methods and technology that have been currently used to map oyster resources in the state of Florida. Our goal is to provide guidance on the range of mapping methods, their applications to mapping intertidal and subtidal habitats, and obtaining 2D and 3D reef metrics. Although the information provided herein is current at the time of writing, we expect that technology will evolve and improve to enhance mapping resolution and metrics, ease of use, data visualization and analyses. We also expect that fundamental principles in appropriately applying new technologies, such as matching mapping methods to habitat setting, and user(s) goals and objectives, and the need for ground-truthing will remain. As these technologies evolve, the guidance contained in this document will be regularly revised and updated to reflect these advances and assist users. The goal of this guidance document is to promote consistent and improved applications of mapping technologies resulting in recovery and effective management of Florida's oyster resources.

The authors echo mapping-specific recommendations of Radabaugh et al. (2019) in order to promote methodological consistency across oyster maps and improve their utility for resource assessment and management.

- Whenever possible fill oyster map knowledge gaps by targeting previously unmapped areas and by regularly updating existing maps (e.g., at 5–7-year intervals).
- Map all types of oysters including subtidal, intertidal, those on hardened shorelines, and on mangrove roots.
- Differentiation between live and dead extent on oyster reefs when mapping, including dead fringes and unconsolidated substrate areas.

We also recommend further research and development into mapping methods with the goal of standardizing map data collection techniques and improving the utility of and comparability between methods.

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Appendix

Data Processing Workflows

Side-scan Sonar

Side-scan sonar data can be stored in a variety of platform-specific file types such as DAT, SON, IDX. SLG, SL2, JSF, or XTF. DAT files or SON and IDX files are some of the more commonly encountered types. DAT files contain basic sonar information and settings as well as time and position data (note: time and position refer only to the first sonar ping). SON files contain the sonar echograms (8-bit) and IDX files (one per SON file) contain records of consecutive pings in the corresponding SON file. Various software programs can be used to view and process sonar data, including ReefMaster 2.0, SonarTRX, Chesapeake SonarWiz, and EdgeTech Discover. Below is an example of the data processing steps involved in using the ReefMaster software with Bottom Composition Upgrade and using ArcGIS Pro to measure oyster reef extent:

Sonar track files are imported to a new Workspace project. The Track SideScan tool is used to clean up data noise and remove the track center line (blind spot). Track files can be combined to create reef Mosaics (Figure A1). Track files can also be combined to create Map Projects that can be exported to ArcGIS Pro as a Shapefile.

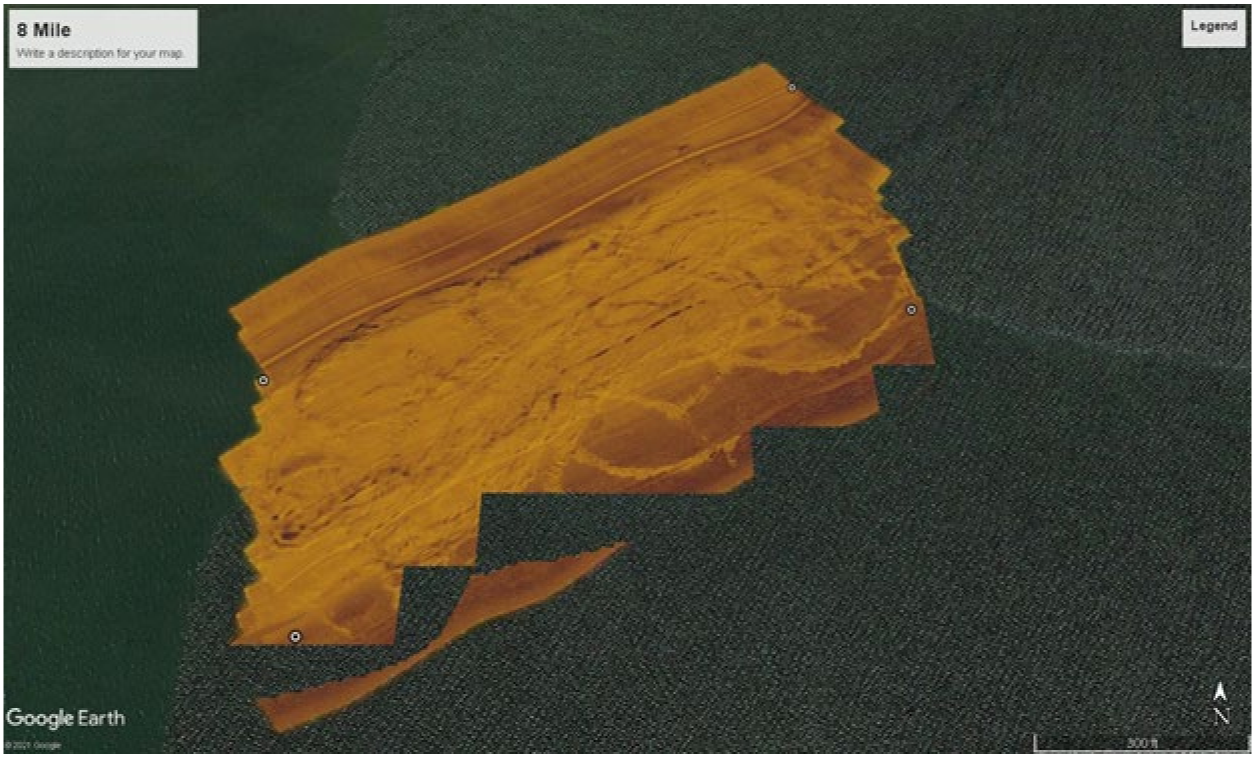

Figure A1. Example of a mosaic created in Reefmaster 2.0.

Reefmaster 2.0 has multiple add-ons that can be purchased to further analyze side-scan sonar files: bottom composition, volumes and areas, and an additional mosaic add-on. The bottom composition module creates hardness maps from sonar log files roughness (E1), hardness (E2) and peak signal layers. Hardness maps can be exported as contours or iso-areas in Shapefile, KML and Navico AT5 formats. Hardness shapefiles that were exported from Reefmaster 2.0 can be trimmed to their respective reef boundaries, and symbology can be modified to display the different levels of hardness using, for example, ArcGIS Pro (Figure A2).

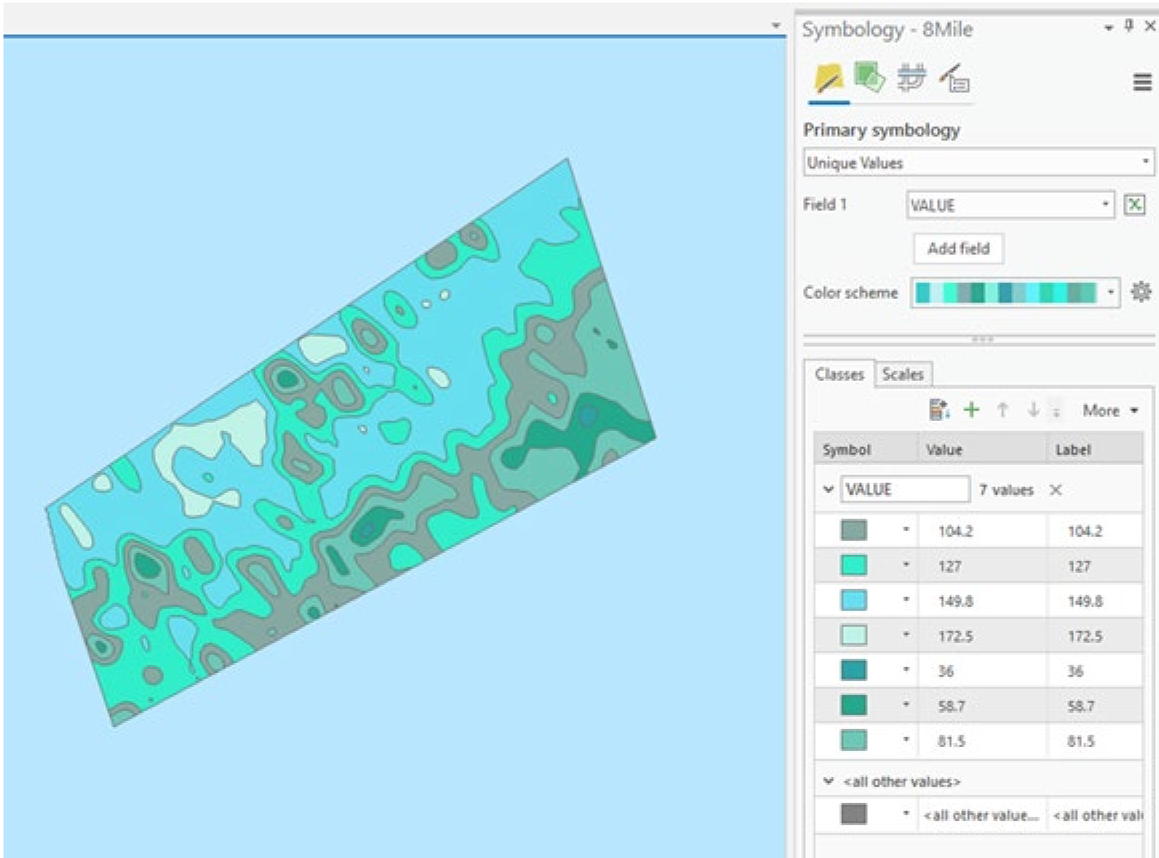

Figure A2. Example of hardness map in ArcGIS Pro.

Symbology can be further altered to make measuring reef area easier. Typically, the top four highest values in the symbology chart are considered oyster reef and/or cultch material. Changing the hardness areas to be measured to the same color will facilitate measuring area in ArcGIS Pro (Figure A3). Zoom in rather close to the selected areas to ensure all the individual polygons are accurately outlined.

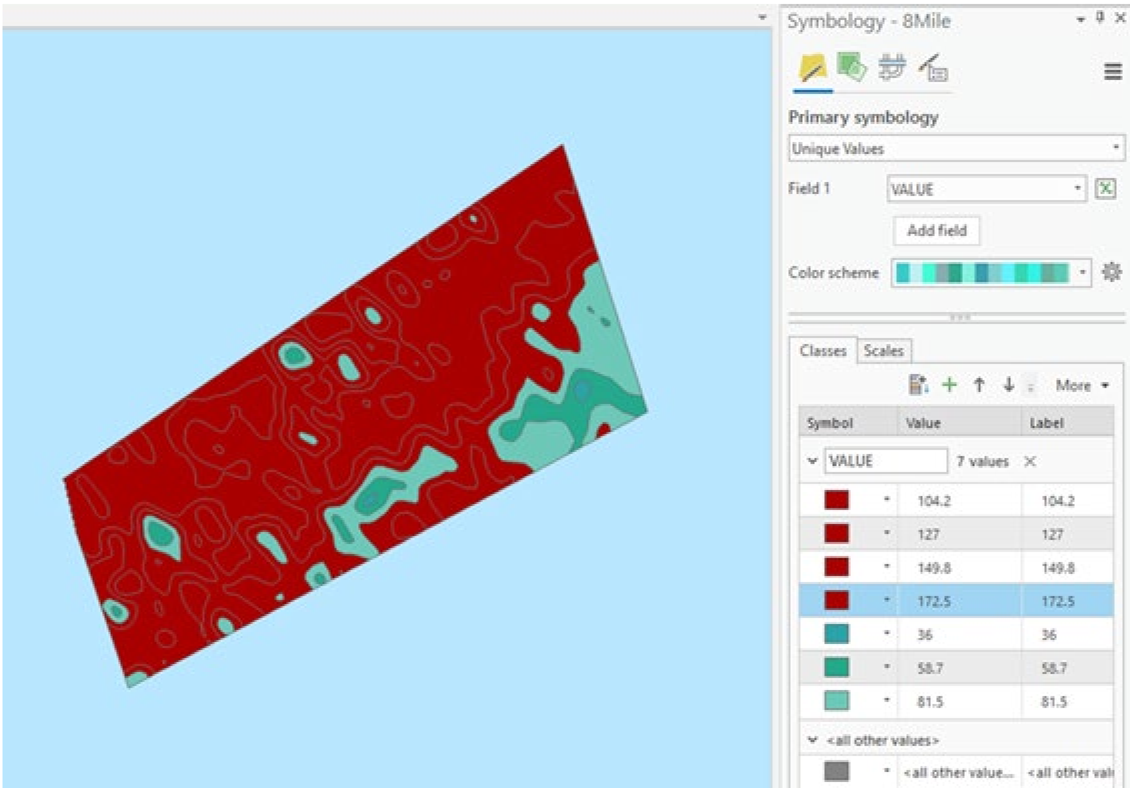

Figure A3. Example of hardness map in ArcGIS Pro where symbology has been changed to measure reef area. Red depicts scanned reef or cultch from Figure A2, with green shades representing softer substrates.

Light Detection and Ranging (LiDAR)

Raw LiDAR data are stored in LAS (LASer) files, which combine GPS, inertial measurement unit (IMU), and laser pulse range data to form X, Y, and Z point clouds. For more information on the LAS file type as well as the information a LAS file can include, refer to American Society for Photogrammetry and Remote Sensing (2013). LAS files can be viewed and edited with various paid (e.g., ESRI, Global Mapper) and open-source software (e.g., CloudCompare, R). This is an example of a raw, unfiltered point cloud of Gomez Key, Florida in ESRI ArcScene:

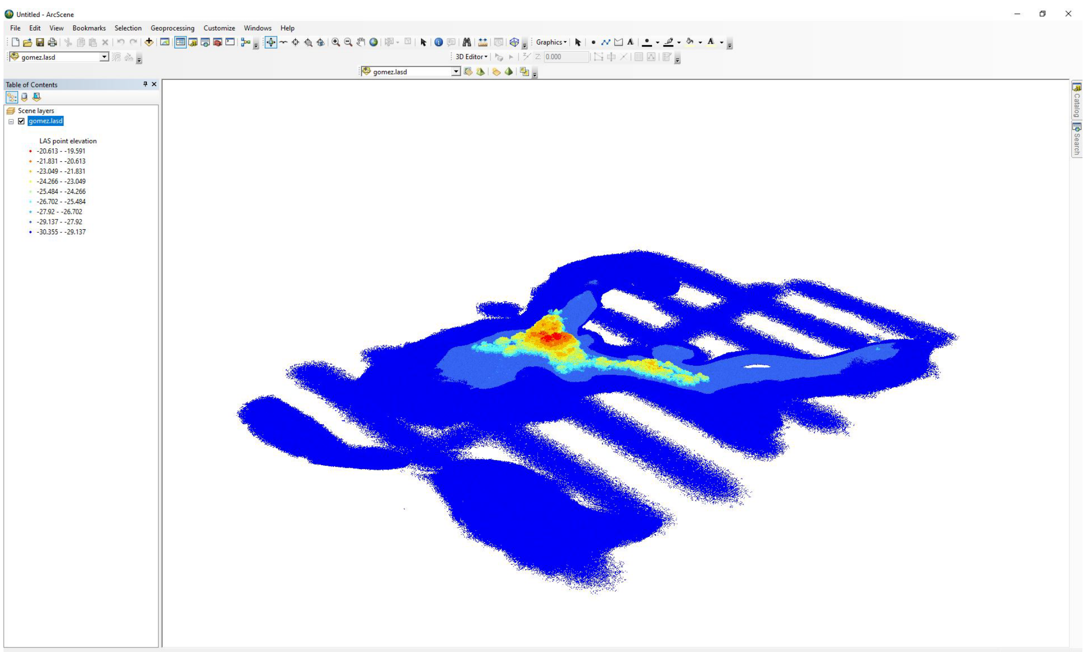

Figure A4. Example of LiDAR x, y, z point cloud image.

LiDAR point clouds are initially filtered to ensure correct classification of ground vs. non-ground readings. Correct classification is crucial for creating DEM (bare earth) and DSM (includes objects such as buildings and trees). We can filter the point cloud to only show ground readings:

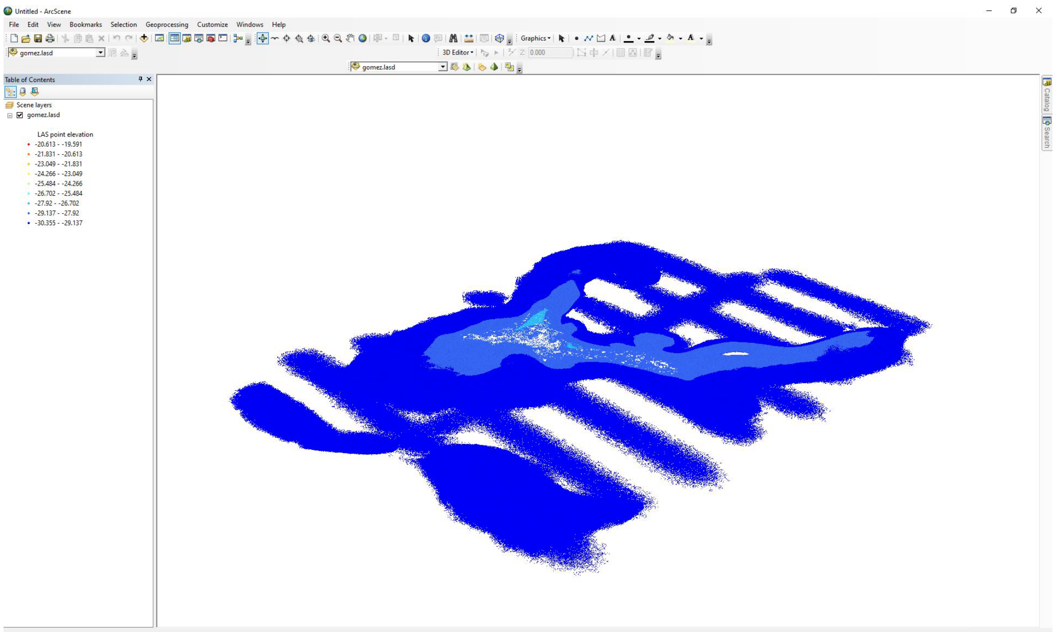

Figure A5. Example of filtered and corrected LiDAR point cloud image.

From these filtered point clouds, we can create end-user raster products. Here is an example of a digital elevation model created by filtering out non-ground returns and running the LAS Dataset to Raster tool in ArcScene or ArcMap:

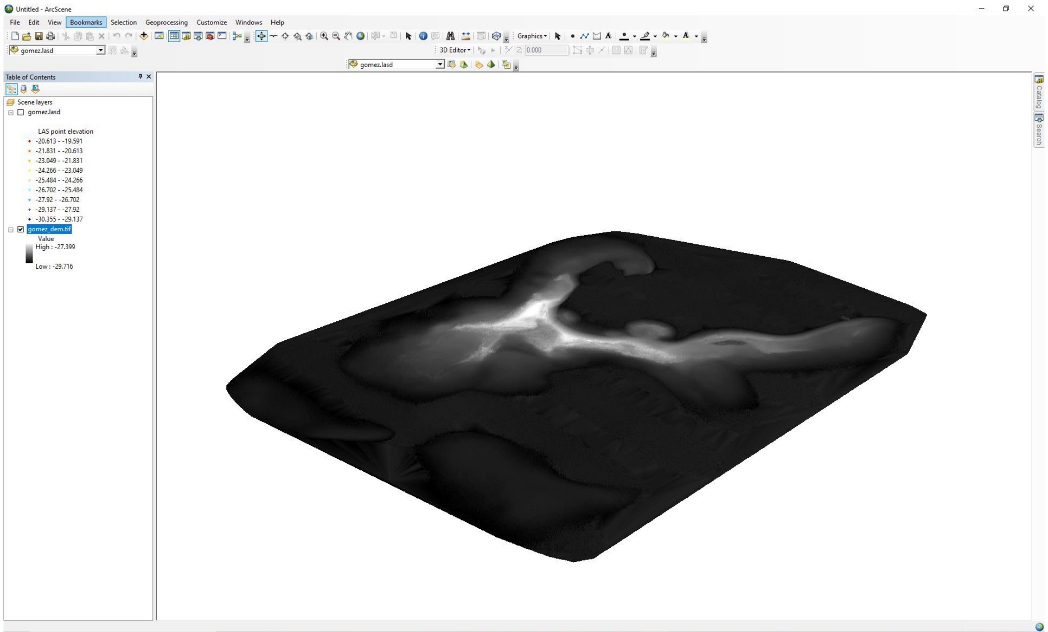

Figure A6. Example of filtered digital elevation model.

Using all the returns we can construct a DSM:

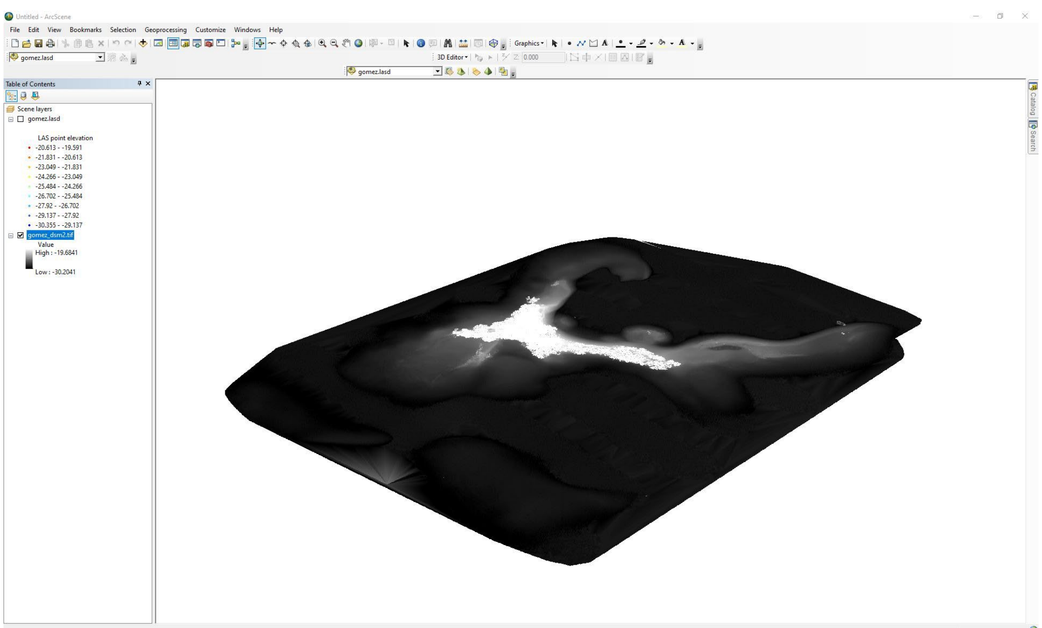

Figure A7. Example DSM.

We can visualize the three-dimensional surface in ArcScene:

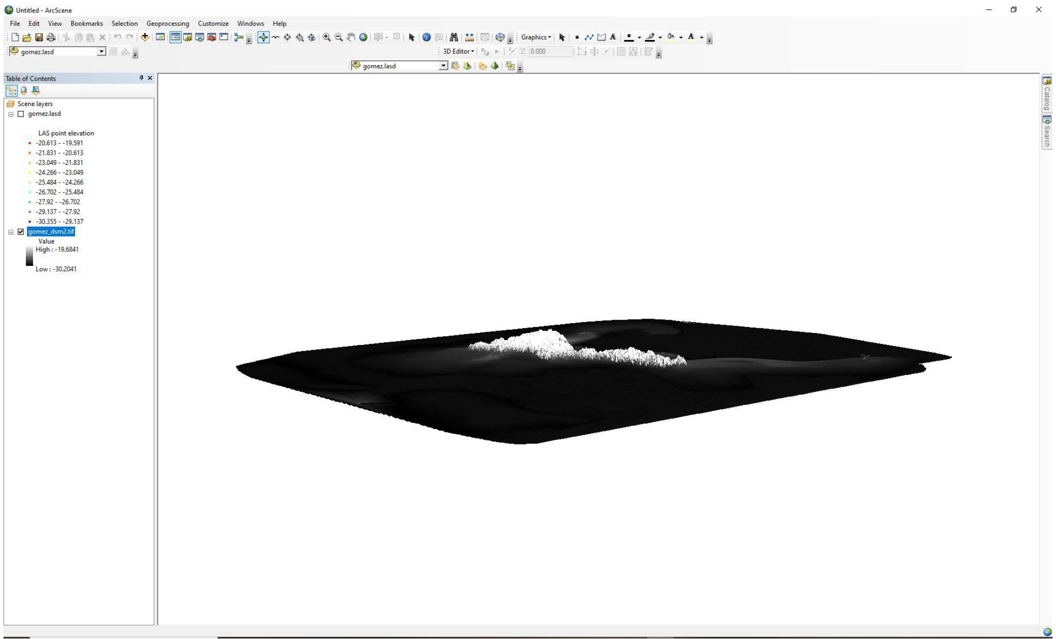

Figure A8. Example of 3-D surface.

And we can drape high-resolution aerial imagery over the surface:

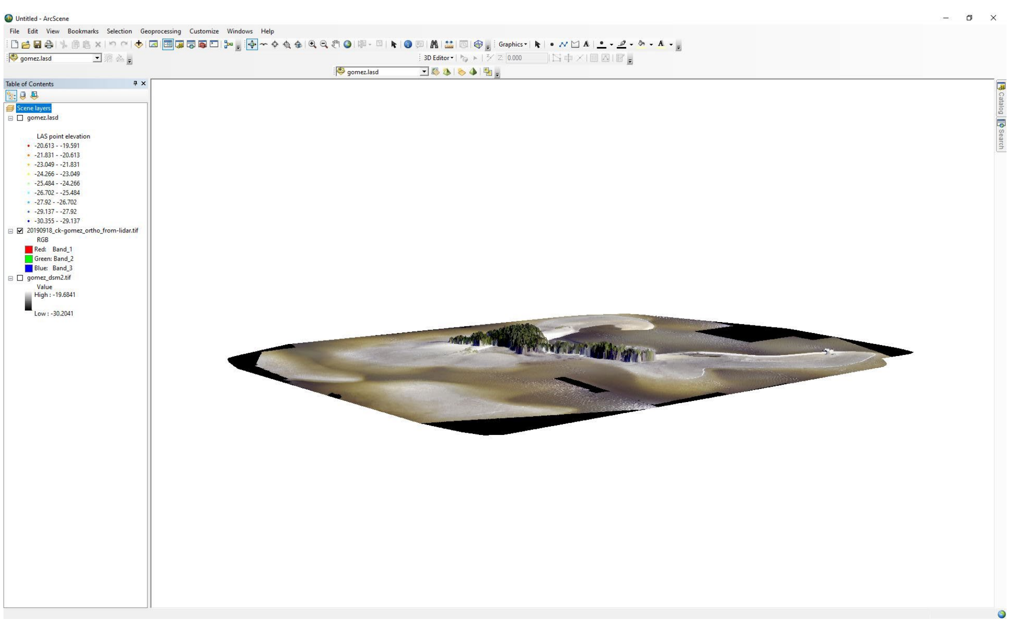

Figure A9. Aerial imagery overlaying DSM.

We can zoom in to more closely examine or analyze areas of interest, in this case an oyster reef:

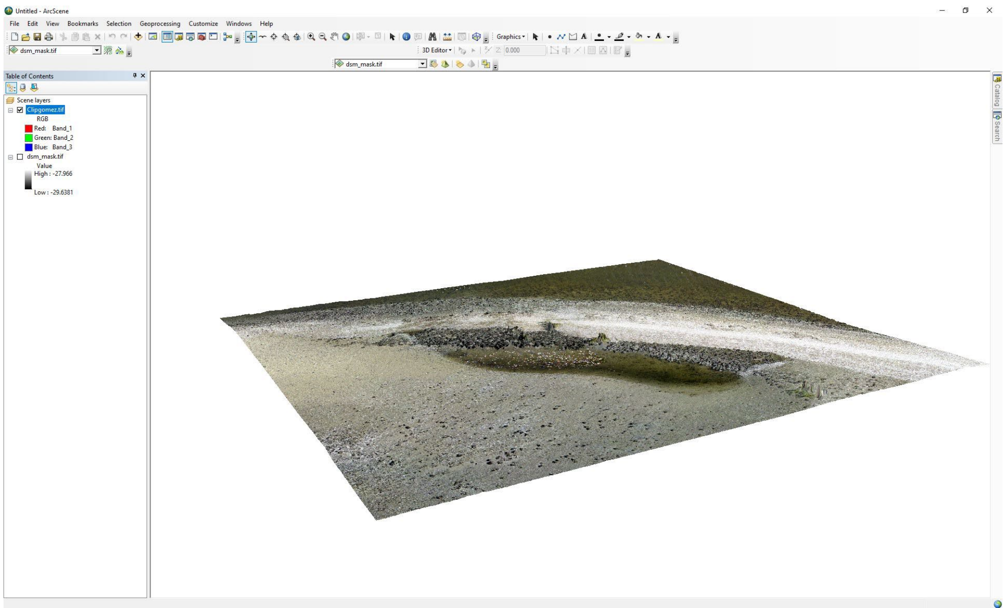

Figure A10. Zoomed-in perspective of oyster reef from aerial imagery and DSM.

And we can adjust the vertical exaggeration to emphasize or understate certain features. In this case we are exaggerating the oysters:

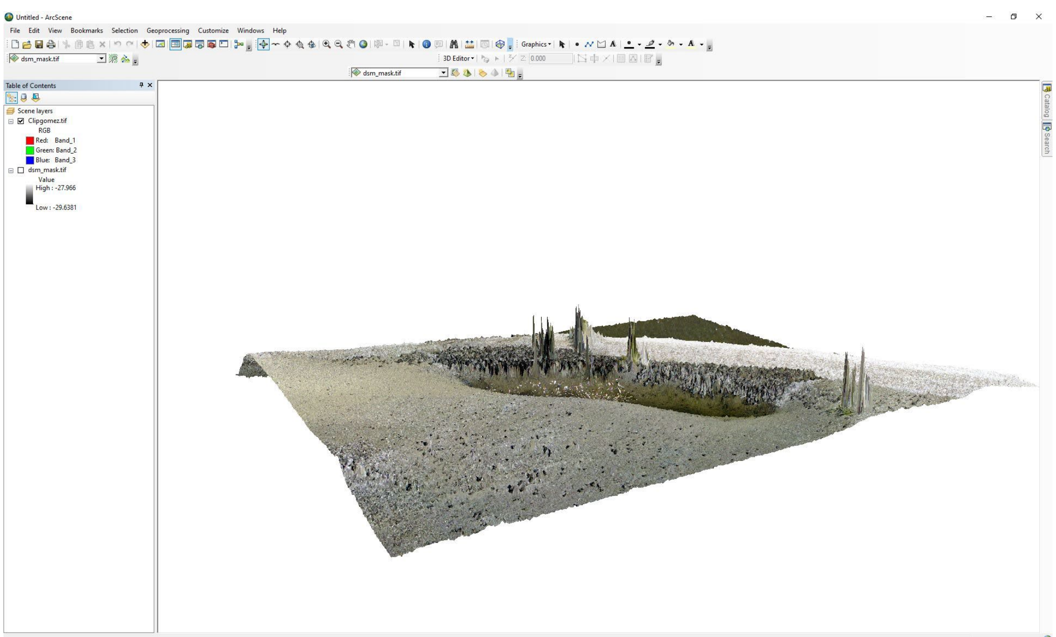

Figure A11. Vertically exaggerated image showing changes in oyster reef topography.

Digitizing visible reefs using aerial or satellite imagery

There are myriad resources for both free and paid aerial (UAS or plane-based) and satellite imagery. The most current free high resolution aerial imagery for Florida is available through the Florida Department of Transportation (FDOT, https://www.fdot.gov/gis/aerialmain.shtm) and free satellite imagery (varying satellites, schedules, and resolution) can be found on USGS EarthExplorer (https://earthexplorer.usgs.gov/). Once the imagery has been downloaded, reefs can be manually digitized in any GIS program. It is important to digitize reefs in the projected coordinate system that best fits your area of interest for locational accuracy and area calculations.

First, select your area of interest (and satellite platform if applicable):

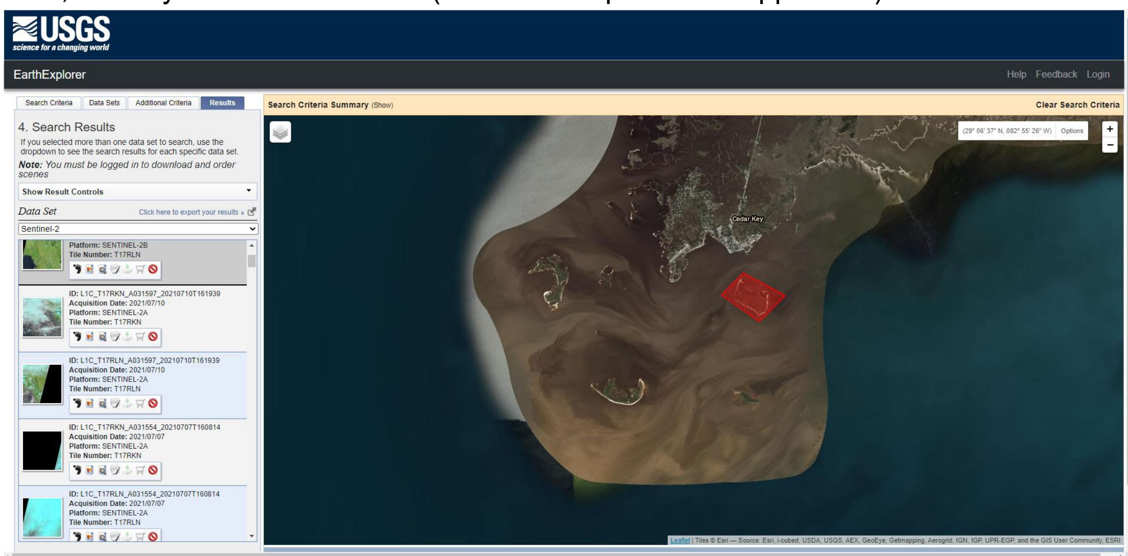

Figure A12. Example aerial image from USGS EarthExplorer.

Preview the scene and download imagery:

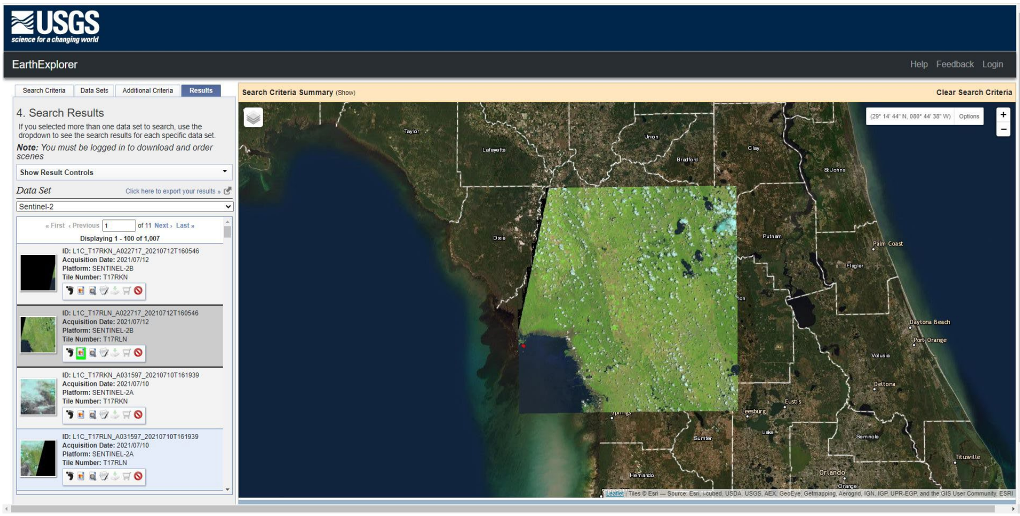

Figure A13. Imagery preview from USGS EarthExplorer site.

Bring imagery (FDOT aerial imagery shown) into GIS, create an empty feature class in the projected coordinate system most appropriate for your area of interest, and manually digitize reef polygons:

Figure A14. Aerial image showing digitized outline of areas of interest.

Digitized reefs can be ground-truthed to ensure accurate boundaries and note reef status.

Structure from Motion

Structure from Motion (SfM) is a stereo-based photogrammetric approach to deriving topographic information of geographic features and/or regions. It is less expensive, easier to use and more detailed (depending on size of survey area and altitude) when compared to certain LiDAR methodologies (Johnson et al. 2014). However, use of imagery limits SfM's ability to penetrate vegetation and obtain ground topography, unlike with LiDAR (Johnson et al. 2014). The following workflow provides generalized stepwise process to obtain topographic data using structure from motion algorithms and applications.

*Regarding imagery collection and sampling: Establishing spatially referenced ground control points (GCPs) are necessary for quality georeferencing and obtaining accurate feature geometries. Additionally, overlapping imagery is needed to properly align key features spatially. The percent of overlap between imagery depends on the key environmental factors such wind effects on UAS during collection. Espriella et al. (2020) recommend 80% front overlap and 75% side overlap to properly identify key points over water. Greater overlap in imagery may potentially lead to a high-density point cloud and a more detailed topographic model (Dandois et al. 2015). Further, flight height should be considered as it will directly affect the details of the resulting models. These details should all be considered in tandem during the fieldwork planning process to ensure the models produced closely reflect the natural state of the habitats surveyed. While implementing GCPs is not discussed in this workflow, the references provided below discuss these topics and provide appropriate use of GCPs.

1. Identify/introduce input images and associated spatial information to the application/program.

    a. RAW image files are recommended, as JPEG can introduce unwarranted noise (Shervais 2015).

2. Select desired coordinate system and projection.

3. Spatially align photos.

    a. Be sure there is appropriate overlap in collected imagery here. Overlap is also necessary during the application of feature identification algorithms (see next step).

4. Apply an extraction algorithm to define feature descriptors or vectors within each image.

    a. The algorithm determines and extracts "key points" from images to aid in feature matching (Westoby et al. 2012).

    b. Feature tables are then matched across all images, relating all combinations of descriptors using brute force feature matching or model-fitting algorithms, among other techniques.

c. Three-dimensional structure is established by employing multi-view geometry (MVG) techniques, effectively recovering structure from camera motion, or differing perspectives of a scene.

d. Using the structure and camera models previously established (previous step), as well as 2D data features, correspondence, and a triangulation algorithm, a 3D point cloud and then DSM (left) are then created. Additionally, an orthomosaic is generated from the original input imagery (right).

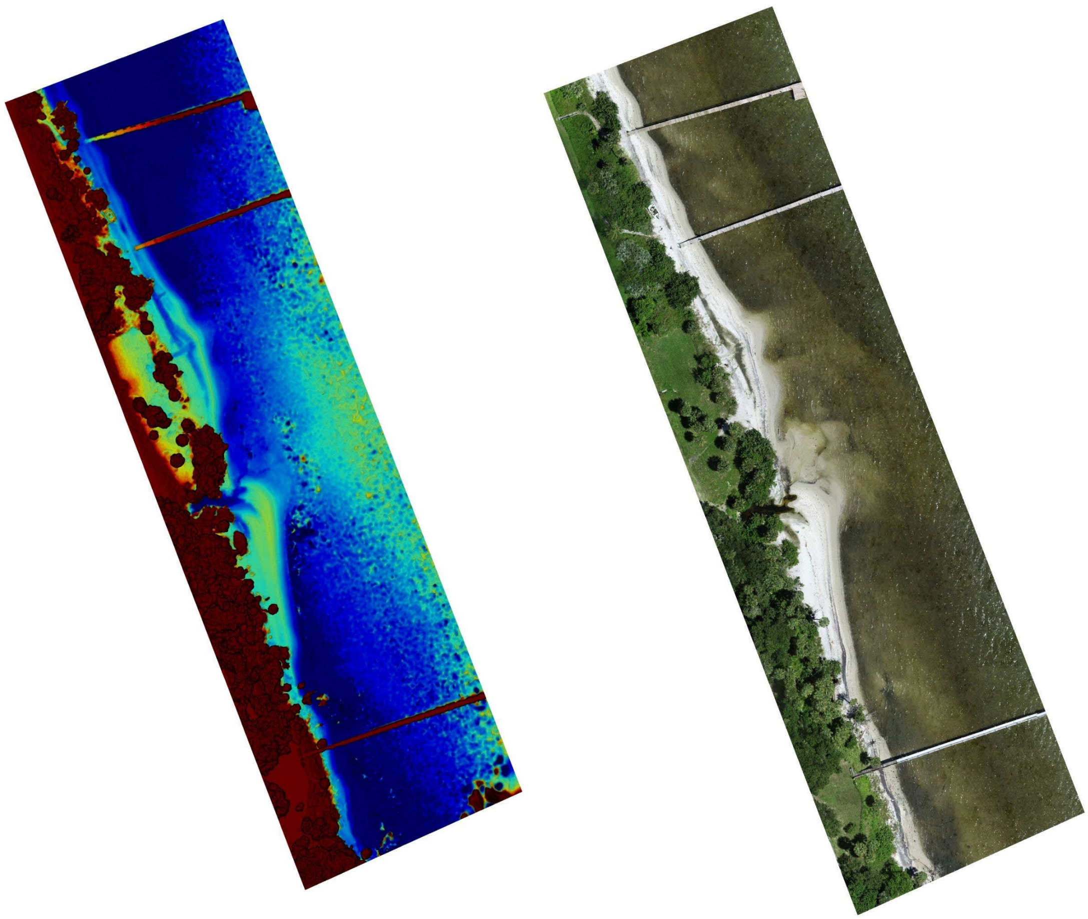

Figure A15. Digital Surface Model image (left) and original orthomosaic image. Images courtesy of Mark Clark (University of Florida).

e. Common algorithms used, but not limited to:

i. Scale-invariant feature transformation (SIFT; Lowe 2004)

ii. Speeded-up robust features (SURF; Bay et al. 2008)

iii. DAISY, a fast local descriptor for dense matching (Engin et al. 2008)

iv. Rotation invariant feature transformation (RIFT; Lazebnik et al. 2005)

v. Gradient location orientation histogram (GLOH; Mikolajczyk 2005)

5. Finally, the orthomosaic can be draped over DSM for detailed visualization of data in a dynamic viewer, such as ArcPro. There, any necessary manipulations or vetting of data can occur.

   a. If ground control points are included in sampling, they can be digitized in this step to assess the degree of difference between the true and model elevations.

Currently, there are several commercial (C) and open-source (OS) application/software available for SfM, the most widely used being Agisoft Metashape (formerly Photoscan Pro; C), Pix4D mapper (C), Bundler (OS; available on GitHub), OpenMVG (OS), and Meshroom (OS), among others. Software-specific workflows or workflow comparisons may be found in Johnson et al. (2014), Rossi et al. (2012), and Shervais (2015).