# Technical Report

## Increasing agency confidence in eelgrass maps used for project review and ocean planning

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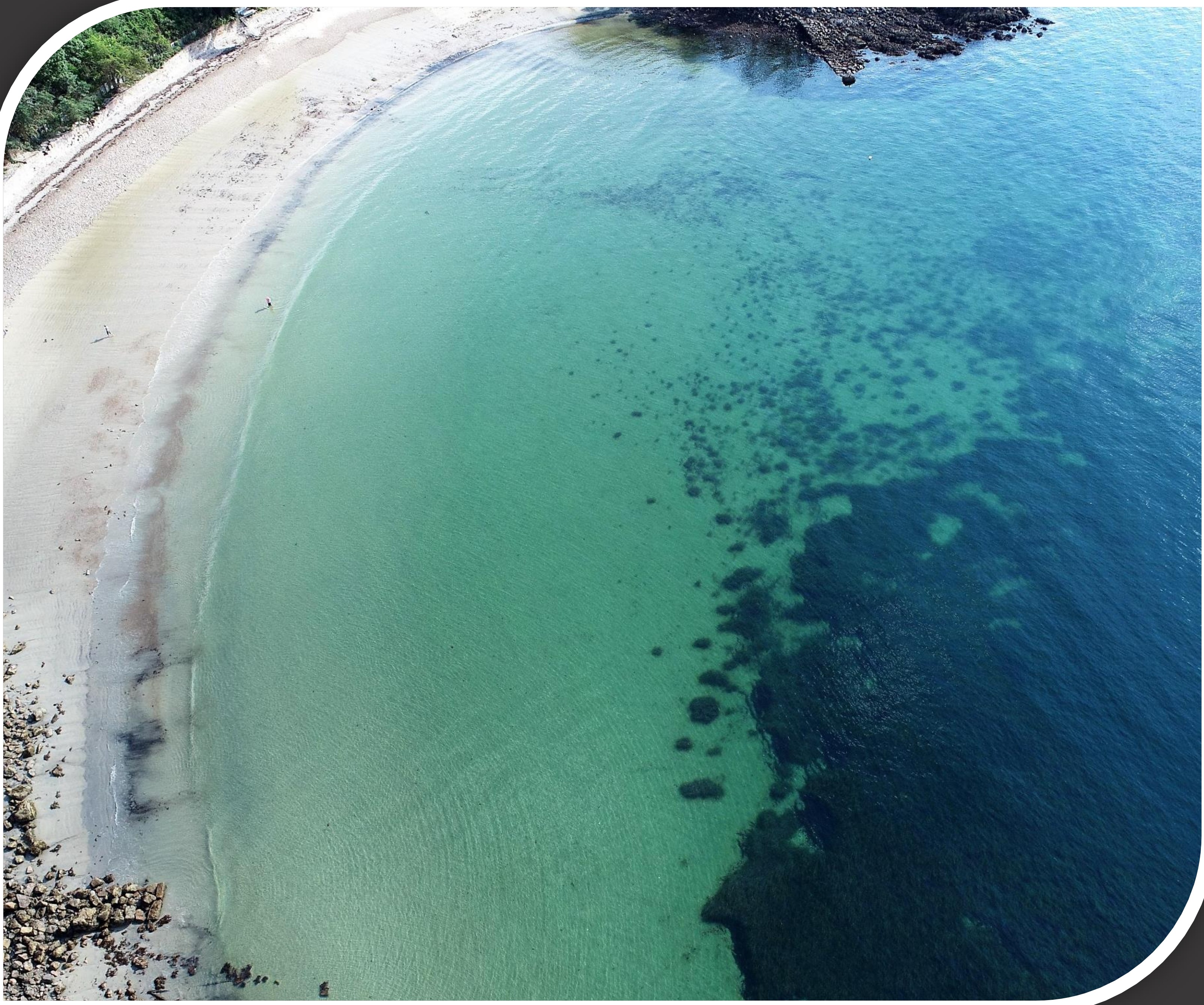

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# ABSTRACT

Remote sensing imagery is heavily relied upon where eelgrass maps are needed for tracking trends, project siting and permitting, government waterbody assessments, and restoration planning. However, there is a low degree of confidence in the exact location of the shallow and deep edges derived from remote sensing imagery, thus risking inadequate resource protection. In this study, semi-synchronous drone, airplane, satellite and side scan sonar missions were conducted alongside SCUBA diver and photo ground-truthing surveys at five Massachusetts eelgrass meadows. Maps derived from each remote sensing survey were compared to diver and photo ground-truthing results to (1) determine if and how much eelgrass was missed by each method, (2) assess the effects of eelgrass percent cover, canopy height and meadow patchiness on survey performance, and (3) make management recommendations regarding the use of remote sensing data for eelgrass mapping. Results showed that all remote sensing methods under-mapped eelgrass, especially at the deep edge, and map accuracy generally decreased with decreasing imagery resolution. Eelgrass percent cover, canopy height and meadow patchiness all influenced remote survey performance to varying degrees.

# INTRODUCTION

Eelgrass (*Zostera marina)* meadows provide multiple ecosystem benefits in estuarine systems: they support biodiversity, attenuate wave energy, stabilize and oxygenate sediments, sequester carbon and nutrients, and filter the water column. Eelgrass meadows and patches create important coastal habitat, providing shelter and forage for many commercially important marine fish species. The Massachusetts Department of Environmental Protection (DEP) uses eelgrass extent and condition as an aquatic health indicator under CWA §305(b) and 303(d). Eelgrass is also acutely sensitive to anthropogenic and environmental stressors such as water quality impairment, physical damage, turbidity and rising sea temperatures, and as a result, meadow density and extent can vary considerably from year to year.

In Massachusetts, local, state, regional, and federal agencies and entities rely heavily on mapping data derived from remote sensing for their assessments. Municipal Conservation Commissions, DEP, Office of Coastal Zone Management (CZM), Division of Marine Fisheries (DMF), the U.S. Environmental Protection Agency (EPA), U.S. Army Corps of Engineers (USACE), NOAA (specifically for Essential Fish Habitat consultations) and others use maps provided primarily by DEP through their fixed wing manned aerial photography surveys. These flights cover a subset of the Massachusetts coast each year, providing nearly coast-wide maps approximately every five years. This Eelgrass Mapping Project[1] has the greatest coverage and longest time series of any efforts to track eelgrass extent in Massachusetts and is therefore the most heavily utilized source of mapping data. However, as the DEP eelgrass survey only provides updates every five years, and the imagery is captured at a 1:20,000 scale, it is not well-suited for tracking detailed seasonal or inter-annual patterns within eelgrass meadows, especially in patchy dynamic meadows or in estuaries with poor water clarity. This makes it difficult to accurately measure changes in eelgrass extent and assess possible causes in a timely manner.

To supplement data from DEP's aerial program, various entities carry out *ad hoc* mapping efforts for their own purposes: DMF and academic researchers conduct side scan sonar surveys and SCUBA surveys, EPA Region 1 compiles high-resolution imagery acquired from satellites, and area academic institutions use consumer-grade unmanned aerial vehicles (drones). Several nonprofit watershed groups use underwater cameras, snorkelers, and GPS to map and track changing conditions in local meadows and whole embayments. Even with this supplemental information in hand, managers have a difficult time condensing and analyzing mapping data collected with different methods due to varying unknown detection capabilities. Comparing data collected using different methods is challenging when it comes to application for management purposes, especially when confidence in the methods varies. In the absence of additional resources for routine statewide eelgrass mapping using higher resolution methods (e.g., side scan sonar, drones, or diver surveys), or to increase the frequency of fixed wing aerial photography surveys, it is important to develop means to integrate data derived from these methods into habitat maps that can be used with confidence.

With new information generated through this project, we are able to: 1) assess the detection capabilities of four remote eelgrass mapping techniques as compared to diver surveys; 2) rank the methods by their ability to accurately detect sparse eelgrass and the meadow edge; 3) establish a process for integrating eelgrass maps derived from the various techniques (e.g. by determining appropriate buffers); 4) generate map products showing updated eelgrass estimates; and 5) make management and future survey recommendations.

# METHODS

The project was guided by the input from a Steering Committee, consisting of partners from various agencies, nonprofits and academic entities involved in data acquisition and analysis; and a technical Advisory Committee made up of New England-based eelgrass and remote sensing experts. The Committees ensured the project utilized appropriate timing, field site selection processes, survey methods, and data analysis procedures.

## Study Locations

Five sites were selected for this study (Figure 1, Table 1). Site selection was constrained by DEP's planned aerial survey area for 2022 (from Marshfield, MA to Rockport, MA), presence of known persistent eelgrass meadows, and accessibility (e.g., nearby boat launch for boat-based survey, nearby public lands from which to operate drones). Meadows known to have very sparse, patchy cover throughout were avoided where possible. All sites contained eelgrass with a shallow edge at approximately 0-2 feet (ft) Mean Lower Low Water (MLLW) and a deep edge at approximately 6-15 ft MLLW, based on the most recent DEP eelgrass layers (Table 1). The most recent layers were from 2016 for all sites with the exception of Curlew Beach, Nahant which was last mapped in 2012.

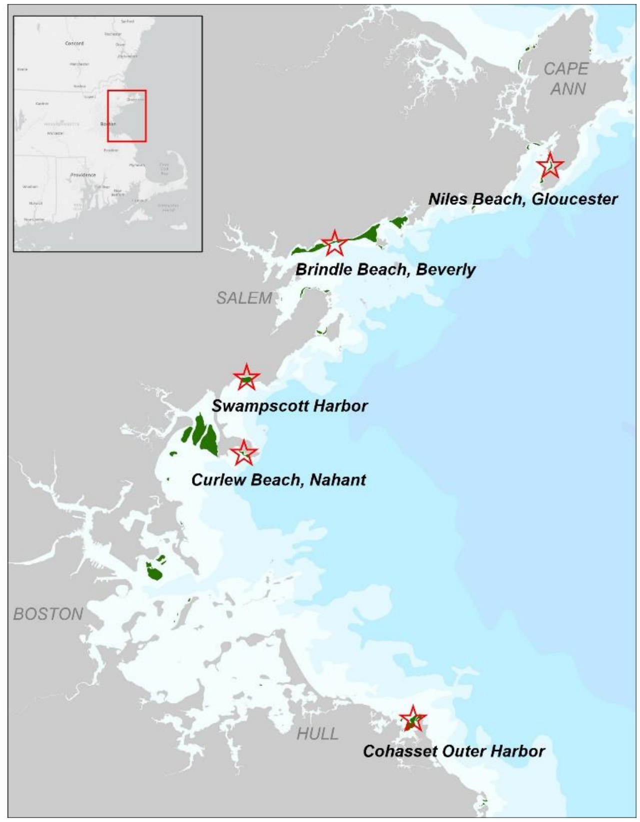



Figure 1. Map of study sites (stars) showing DEP 1995 eelgrass (green).

Table 1. Study site information. Approximate depths at shallow and deep edges are based on the most recent DEP eelgrass layer and the NOAA nautical chart.

| Site | Approximate site center Lat/Long | Approximate MLLW Depth (ft) at shallow edge | Approximate MLLW Depth (ft) at deep edge |
|---|---|---|---|
| Niles Beach, Gloucester | 42.59613<br>-70.65648 | 1 | 14 |
| Brindle Beach, Beverly | 42.54943<br>-70.83571 | 1 | 15 |
| Swampscott Harbor, Swampscott | 42.46385<br>-70.91119 | 2 | 7 |
| Curlew Beach, Nahant | 42.41932<br>-70.91693 | 0 | 11 |
| Cohasset Outer Harbor, Cohasset | 42.25427<br>-70.77691 | 0 | 6 |

## Data Acquisition

A total of 25 data acquisition missions took place over a six-week period from 6/5/22 to 7/13/22, with the majority of those (86%) taking place within a three-week period (Table 2). A three-week window was targeted to minimize the effects of meadow expansion over time during peak growing season. Methods specific to each survey type are described below.

Table 2. 2022 mission dates by survey method and town.

| | Gloucester | Beverly | Swampscott | Nahant | Cohasset |
|---|---|---|---|---|---|
| Satellite | 6/5 | 6/21 | 6/21 | 6/21 | 7/1 |
| Airplane | 7/1 | 7/1 | 7/1 | 7/1 | 7/1 |
| Side Scan Sonar & Drop camera | 6/30 | 6/30 | 6/24 | 6/24 | 6/22 |
| Drone | 7/13 | 6/11 | 6/15 | 6/15 | 7/1 |
| Diver | 6/21 | 6/23 | 6/30 | 6/24 | 6/28 |

### Satellite imagery

Satellite imagery was obtained by securing approval from NASA to utilize their Commercial Smallsat Data Acquisition (CSDA) Program, which grants federally funded projects access to 3 meter (m) resolution imagery from Planet's Super Dove (instrument ID "PSB.SD") platforms free of charge. The PSB.SD platform includes hundreds of small shoebox-sized satellites, orbiting in a constellation at roughly 400 kilometer (km) altitude that provides near-daily overpasses of every location across the globe, collecting spectral imagery with eight bands (Table 3)[2]. The platform produces imagery tiles approximately 32.5 x 19.6 $km^2$ in size.

Table 3. SuperDove bands and corresponding wavelengths

| Band | Name | Wavelengths (nm) |
|---|---|---|
| 1 | Coastal Blue | 431-452 |
| 2 | Blue | 465-515 |
| 3 | Green I | 513-549 |
| 4 | Green II | 547-583 |
| 5 | Yellow | 600-620 |
| 6 | Red | 650-680 |
| 7 | Red Edge | 697-713 |
| 8 | NIR | 845-885 |

The web-based Planet Explorer data viewer tool was used to query the archive[3]. Because the SuperDoves that cover coastal Massachusetts pass over at nearly the same time every day (around 11 am EDT at the time of study), specific days can be targeted to take advantage of optimal tidal conditions. Tide charts were consulted to identify days and times when low tides co-occurred with satellite image capture[4]. After selecting the preferred dates, additional query filters were used in the Planet Explorer data viewer tool including cloud cover, targeting < 20% cover over the image area, and off-nadir angle, targeting < 30 degrees off nadir (i.e., not directly downward looking, but within +/- 30 degrees). Returned imagery results were assessed within the tool for completeness (e.g., no dropped tiles over the study sites) and usability (e.g., no radiometric abnormalities, no cloud cover over the study sites, and no wave chop at study sites). Usable images were downloaded in Red-Green-Blue (RGB). While the target was to obtain imagery acquired on the same day across all sites, spotty cloud cover and glare reflecting off waves at two of the sites made it necessary to use imagery from different overpass days (Table 2).

### Airplane imagery

A fixed wing manned aerial survey was coordinated with DEP as part of their existing survey program, which has used airplanes to collect aerial imagery over eelgrass beds across coastal Massachusetts since the early 1990s. DEP segments the coastline into four survey areas, and each year a different area is flown and assessed for eelgrass. Every 4-5 years, an updated state-wide eelgrass layer is released via MassGIS[5]. Image collection follows established DEP and NOAA Coastal Change Analysis Program protocols, targeting two hours on either side of low tide, sun angle 30-50°, and little to no wind, waves, cloud cover or turbidity. Weather forecasts, aviation reports, tide charts and solar position calculators were used in flight planning[6,7,8]. Imagery was collected at a scale of 1:20,000 with +/- 3 m ground position accuracy and 0.25 m pixel resolution, in four bands: Red, Green, Blue, and Infrared. The survey acquired 144 image tiles over a 433 square mile area. A Federal Geographic Data Committee (FGDC) compliant metadata record was generated. RGB imagery was mosaicked and georeferenced by the flight contractor using a GIS and provided in 8-bit and 16-bit formats; the latter was used in this analysis.

### Drone imagery

Drone missions were planned, managed and carried out by Federal Aviation Administration (FAA) licensed pilots using DroneDeploy proprietary software and a consumer-grade DJI Phantom 4 Pro V2 drone. Flight planning included checking airspace restrictions[9], securing access to launch areas, and ensuring suitable environmental conditions. Missions targeted a one hour window on either side of low tide, sun angle 15-30˚, cloud cover < 10 %, wind < 10 km/h, wave height < 0.5 m, low turbidity, and recent calm weather[10,11,12]. Flight missions were flown at 80 m altitude, with ≥ 50% side and front image overlap, and image tiles were orthomosaicked in DroneDeploy software with 2.5 centimeter (cm) pixel resolution. Ground control points were not incorporated into this project given the challenging nature of deployment and retrieval in the subtidal environment. Instead, horizontal accuracy was visually checked for agreement by comparing the location of the coastline, built infrastructure, and emergent features in the water visible in the drone imagery against 2021 USGS Color Orthoimagery of known positional accuracy (15 cm). All flights were documented with a metadata flight log.

## Side scan sonar imagery

A consumer-grade Humminbird HELIX9 side scan sonar system was used to generate benthic imagery at all sites. Missions were performed in a “mow the lawn” pattern either parallel or perpendicular to shore, depending on the shape of the coastline and any safety hazards (e.g., mooring fields, piers, etc.). Imagery swaths were set to 160 ft in width (i.e., 80 ft to left and right of the sonar unit), and swaths were evenly spaced such that ≥ 50% coverage was achieved over the footprint of the study site. The three diver transect locations at each site were surveyed at a higher coverage, with each transect area surveyed both parallel and perpendicular to shore, and each swath overlapping the adjacent swath by ≥ 25%, totaling ≥ 200% imagery coverage. The use of two opposing patterns improves eelgrass visibility in the event it is laying down in the current or casting shadows in the imagery, issues that are especially problematic in low-density edge areas.

GPS position of each image tile was collected internally in the Humminbird unit using its built-in geolocation functionality. Individual side scan imagery tiles were processed, slant-corrected and mosaicked together using proprietary SonarTRX software. The resulting mosaics had approximately 30 cm pixel resolution. The horizontal accuracy of sonar imagery was not assessed as part of this project, rather, the equipment was checked by the contractor by imaging an underwater target of known dimensions from different angles and approaches. The equipment used for this study was within the accuracy tolerance defined by the contractor.

## Drop frame ground-truthing

Using a SplashCam underwater camera mounted to a 0.25 $m^2$ quadrat drop frame, eelgrass presence, percent cover, sediment type and algae presence were field verified at each site along the track of each diver transect. At least 30 stations were randomly sampled within 25 m to either side of each transect. At each of the stations, without anchoring the boat, the drop frame was lowered to the seafloor, imagery was assessed in real-time, and an underwater photo was captured for additional QA/QC in the lab. Eelgrass percent cover was determined visually on-screen using bins of size 10 (e.g., 0%, 1-10%, 11-20%, 21-30%)(Fig 2). A total of 515 drop frame stations were sampled across all sites.

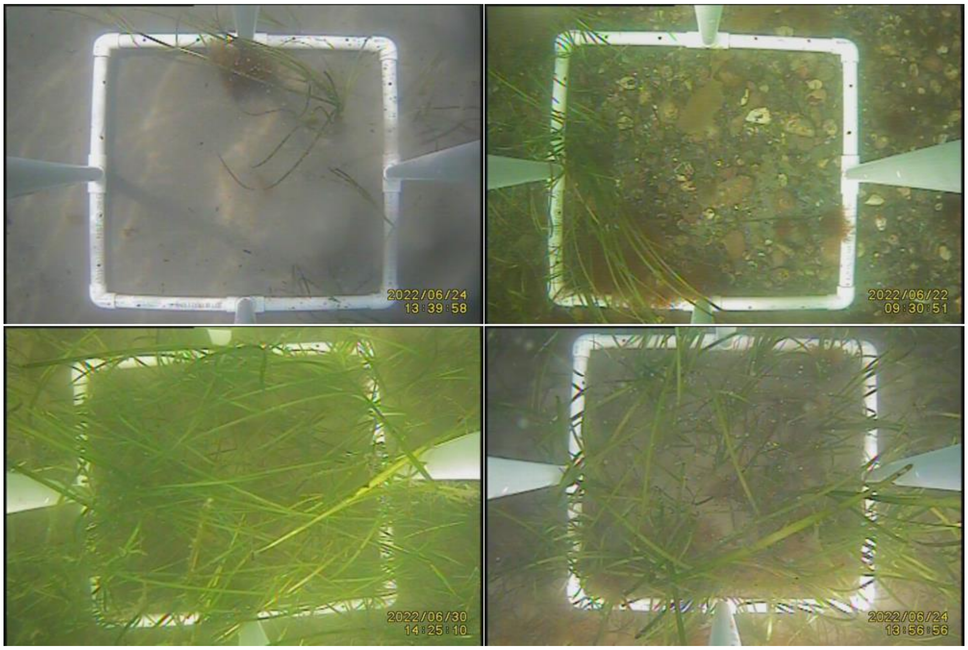


Figure 2. Examples of drop frame photos, showing eelgrass of different percent cover bins. Clockwise from top left: 1-10%, 11-20%, 61-70%, 81-90%.

## Diver surveys

SCUBA divers conducted transect surveys at pre-selected near-edge locations, beginning in the dense part of the meadow and extending perpendicular to shore until divers located the last shoot along the transect. At each site, two transects were placed along the meadow's shallow edge and one along the deep; a total of 15 transects were conducted. Transect starting locations were determined by viewing 2021 USGS Color Orthoimagery and the most recent DEP eelgrass maps for each site in ArcGIS Pro, and using the layers to identify the dense and continuous meadow edge. A draft starting point was placed in this edge area, and a transect was drawn using the ArcGIS Pro Draw tool with a Perpendicular constraint to draw the transect perpendicular to the CZM Coastline layer[13]; all GIS work was done in projection NAD1983 (2011) State Plane Massachusetts Mainland FIPS 2001 (Meters). The starting point was then fine-tuned prior to the start of dive work by deploying the SplashCam underwater camera with a live video feed to the surface and towing it along the approximate transect location to ensure proper siting, with the goal being a transect across the gradient from dense to sparse eelgrass. Ideally, transects were targeted to be completed within one 60- to 75-minute-long dive, which was estimated to be able to cover a 100-150 m transect. Transect distance and bearing were calculated using the ArcGIS Pro Measure tool. To account for magnetic declination, the true bearing from the GIS output was converted to magnetic bearing for use by divers by subtracting the approximate declination for Massachusetts[14] (14.3°) from the true bearing. In the field, the final starting point was moved closer to or farther from shore along the transect to meet the targets above. After finalizing the transect starting point, a drop buoy connected to a small anchor was deployed at the starting point, and two divers used a transect reel to lay the transect tape along the pre-defined bearing perpendicular to shore (or perpendicular from shore, for the deep edge transect) until locating the last eelgrass shoot observed along the transect within a swath 2 m to either side of the transect tape. Divers confirmed the last shoot location by swimming an additional 20 m beyond in search of other shoots (Fig 3). A drop buoy was placed at the last shoot location, and coordinates were collected at both buoys using a marine GPS aboard the boat with < 3 m accuracy. The subsurface buoy line was kept taught during coordinate collection to reduce effects of current on buoy location. With the transect laid, divers then sampled thirteen 0.25 $m^2$ quadrats evenly spaced along the transect. One quadrat per transect was sampled by both divers to provide a QA/QC evaluation of diver observations. Within each quadrat, divers recorded eelgrass percent cover using bins of size 10 (e.g., 0%, 1-10%), canopy height (cm), eelgrass distribution type, and algae species present, and collected an underwater photograph of the quadrat. Eelgrass distribution type was a novel metric developed for this project to indicate the degree of meadow contiguity or patchiness. Options were < 1 m, 1-5 m, and > 5 m, where the distances represent how far apart individual patches or shoots were in the vicinity of each quadrat. A total of 194 quadrats were sampled across all sites and transects.

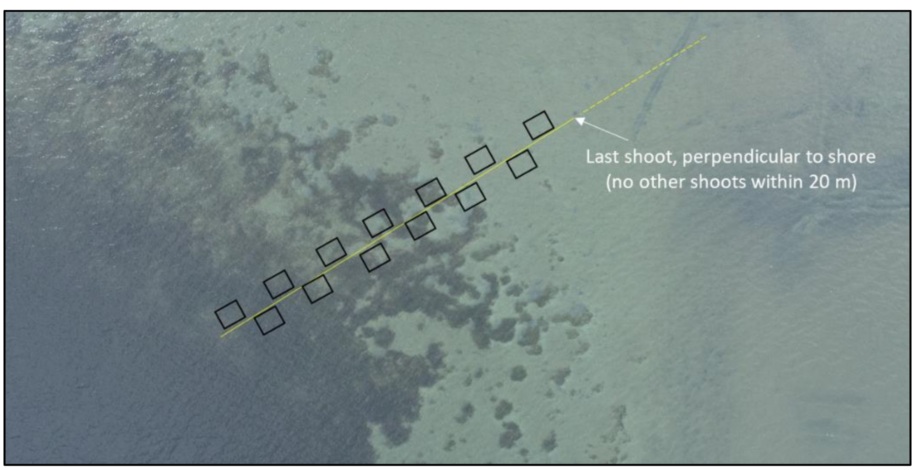



Figure 3. Hypothetical transect layout traversing the gradient from dense meadow to edge, with twelve quadrats. Diagram shown on drone imagery.

## Data Analysis

Imagery and field data underwent a thorough Quality Assurance/Quality Control (QA/QC) process to ensure the targets in the Quality Assurance Project Plan (QAPP)[15] were met and that all datasets were usable. Corrective actions were taken as needed, including resampling a diver transect that was placed incorrectly the first time, and extending the sampling window to access satellite imagery from days where solar glare and/or wind-driven waves did not obscure the imagery. When a complete and quality assured dataset was ready for each site (Fig 4, more in Appendix A), photointerpretation and geospatial analysis were carried out.

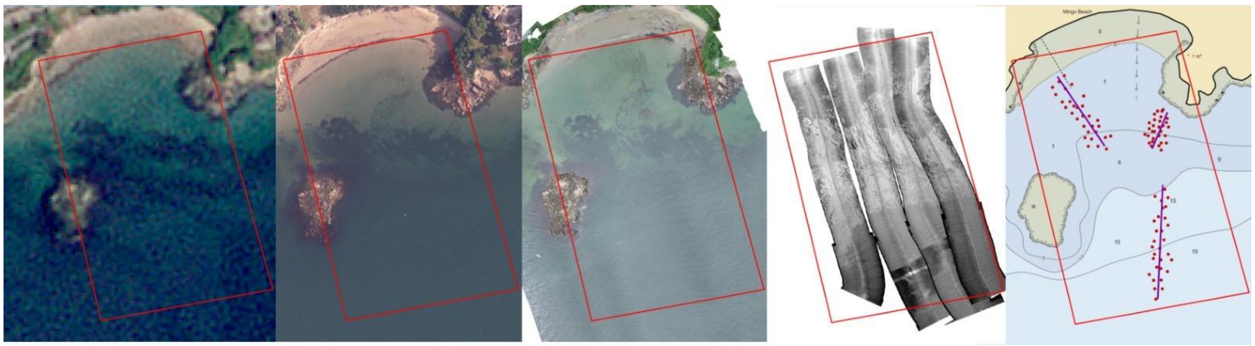


Figure 4. The complete dataset for Beverly includes (from left to right): satellite imagery, airplane imagery, drone imagery, side scan sonar imagery, diver transect data (purple lines) and photo ground-truthing samples (red circles) within the study area (red box).

## Photointerpretation

Trained project partners provided unbiased interpretation of the imagery, with four academic and/or nongovernmental partner organizations each assigned to one of four data sources: satellite, airplane, drone, and side scan sonar imagery. Partners were trained during several sessions, with training modules on the principles of remote sensing, remote sensing applications for eelgrass mapping, fundamentals of eelgrass signature and environmental variables that can affect it, hands-on experience delineating eelgrass, and practice using the various ArcGIS Pro tools to manipulate imagery and create polygons. Partners received detailed instructions on applying a Heads-Up digitizing approach, where the interpreter's attention was up on the screen while they manually traced the eelgrass signature visible in the underlying imagery. Interpreters were given a set of rules to follow during interpretation, including requirements for map scale, minimum mapping unit, polygon smoothing, and color manipulations (Table 4). Partners passed a skill evaluation prior to receiving their dataset. They were provided with the imagery for all five sites from their assigned survey method, NOAA bathymetry layer, and a shapefile showing the study areas to be interpreted. Ground-truthing data were not provided to avoid bias. For example, regarding bias: all interpreters would need to receive the same ground-truthing points to ensure none have advantages over the others, however points that confirm eelgrass presence may be obvious detections in one remote dataset (e.g., in a drone image with higher resolution and more detail), but may lead the interpreter of a different dataset (e.g., satellite) to include the point in their polygon even if they can't see eelgrass in the imagery. Interpreters were instructed to not view any other data sources that might bias their interpretation. At each partner organization, two scientists interpreted the imagery separately, and then worked together to compare results and agree upon a final eelgrass delineation.

Table 4. Rules for photointerpretation by method

| | **Satellite** | **Airplane** | **Drone** | **Side Scan Sonar** |
|---|---|---|---|---|
| On-screen spatial scale restrictions for image exploration | none | none | none | none |
| On-screen spatial scale restrictions for drawing eelgrass polygon | 1:2000 | 1:1000 | 1:500 | 1:500 |
| Spectral restrictions for image exploration | none | none | none | none |
| Spectral settings for drawing eelgrass polygons | Natural Color, but stretches can be applied | Natural Color, but stretches can be applied | Natural Color, but stretches can be applied | Black and white |
| Minimum mapping unit (for inclusion/exclusion of patches) | None – include all visible | None – include all visible | None – include all visible | None – include all visible |
| Maximum distance threshold (between patches, to be bridged together along the edge boundary) *i.e., line smoothing* | 10 m | 10 m | 10 m | 10 m |

While the intent was to exclusively use the results from the newly trained interpreters, an expert interpretation was deemed necessary across all sites and survey methods. This project change was incorporated upon review of the newly trained interpretations, which revealed some inconsistencies in executing the photointerpretation rules and differences in skill level across interpreters. The study authors felt a comparison of experience level would be a valuable and informative addition. Due to lack of experts available for-hire, study author Carr performed the interpretations, minimizing bias to the greatest extent possible by: 1. Drawing polygons only where eelgrass was visible in the imagery (e.g., even if having knowledge of additional eelgrass areas); 2. Working through imagery in order from low to high resolution; and 3. Interpreting imagery from one survey method every other week to force a lag time between interpretations at the same site.

This resulted in two separate photointerpretation datasets for analysis: one conducted by trained partners, and one conducted by an expert interpreter; with each dataset containing one eelgrass polygon per survey method and site. Expert and newly trained interpretations were compared by looking at differences in edge error and meadow area.

### Drop frame ground-truthing data

Drop frame data were quality assured in the lab by comparing a subset of the field sheet records against digital photo files to ensure correct assignment of percent cover bins. All data passed the evaluation without revision.

The digitized field data were imported into ArcGIS Pro as a point layer, where each point contained coordinates, site name, transect location, eelgrass percent cover, algae presence, and notes. Percent cover bins were converted to bin midpoints (e.g., 1-10% bin converted to 5.5%) to achieve numerical format. The presence of algae was qualitatively assessed by examining points that contained eelgrass only, algae only, or an eelgrass-algae mix relative to the interpreted polygons. Drop frame data were used for accuracy assessment as described below.

### Diver Survey data

Diver quadrat data were quality assured by comparing measurements at the same sampling location across the two divers responsible for data collection. One such “QC quadrat” was sampled at each of the 15 diver transects. All diver data passed the evaluation without revision.

The start and end locations of each transect, as recorded on a marine GPS unit, were imported into ArcGIS Pro and converted to a point layer. A line representing the diver transect was drawn between the start and endpoints of each transect using the *Points to Line* tool. Approximate quadrat locations were placed on the line using the *Generate Points Along Line* tool, placing 13 quadrats evenly spaced with the first occurring at the start of the transect (0 m) and the remaining 12 quadrat locations distributed evenly over the remainder of the transect using the *Point Placement by Percentage* setting in the tool. Each quadrat location was then manually adjusted along the transect, as needed, to reflect the actual transect meter marking recorded in the field data for each quadrat. Diver data were used to assess accuracy, edge error, and effects of canopy height, patchiness and percent cover as described below.

### Edge Error

The distance between the interpreted eelgrass polygons for each survey type and the diver-measured last shoot is considered the Edge Error, or the distance of eelgrass missed by the survey method along each transect. This distance was calculated using the ArcGIS Pro *Erase* tool by removing the portion of the diver transect lines that fell within the interpreted polygons and calculating the length of the remaining fragments. Edge error was compared by site, depth (shallow vs deep) and survey method using pivot tables in Excel (Microsoft 365).

### Accuracy Assessment

Data from drop frame ground-truthing and diver surveys were used as reference points to assess the accuracy of the photo-interpreted eelgrass polygons at each site and for each survey method. The analysis workflow involved using ArcGIS Pro tools to spatially join and assess the ground-truthing points against the interpreted polygons. All polygons from all survey methods were merged into one feature layer, and the ground-truthing points and diver quadrat sampling points were joined to the new merged polygon feature using the *Spatial Join* tool.

Eelgrass presence/absence at each diver and ground-truthing point (n = 701) was assessed relative to the point's location inside or outside the interpreted eelgrass polygons. The proportion of points with eelgrass cover > 0% that fell within the eelgrass polygons for a given survey type are the measure of accuracy for that survey, where the number of correctly interpreted reference points was divided by the total number of reference points and multiplied by 100. Accuracy was further assessed by site and percent cover bin, using pivot tables in Excel.

### Effects of Canopy Height and Patchiness

The diver-collected data on canopy height and distribution type (i.e., patchiness) were assessed at quadrat locations inside and outside of the interpreted polygons. The *Join* tool was used to spatially combine the diver quadrat location data to the interpreted polygons. Then, quadrat data could be analyzed based on what measured characteristics tended to fall inside or outside of the interpreted polygon for each survey type. Canopy height was analyzed to determine what height values tended to be mapped or missed, and distribution type was analyzed to determine what levels of patchiness tended to be mapped or missed.

## Results

### Photointerpretation

Imagery was successfully acquired via satellite, airplane, drone and side scan sonar per the protocols described in the QAPP, and imagery passed QA/QC review. Expert and newly trained interpretations generated eelgrass polygons for each survey method at each site (Fig 5, Beverly example). Imagery and expert photointerpretation results can be found in Appendix A.

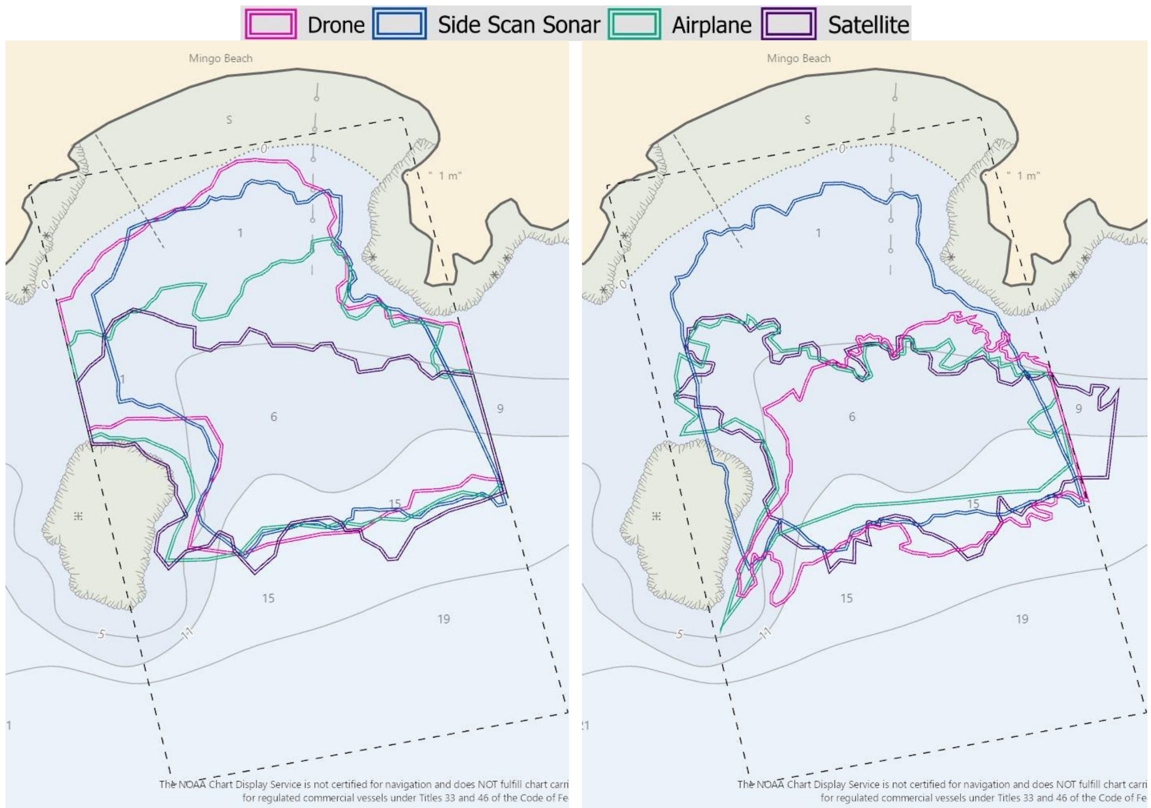



Figure 5. Expert (left) and newly-trained (right) photointerpretation results at Beverly Bridle Beach, showing all survey methods.

## Edge error and effects of interpreter experience

False negatives were assessed, where eelgrass was not mapped by the photointerpreter even though it was present. For the expert interpreter at the shallow edge, error was lowest for drone imagery – about 11 m, and increased with decreasing image resolution, up to 38 m for satellite imagery (Fig 6). Some survey types (drone, airplane) had close to zero error at the shallow edge, as noted with the deviation bars that approach zero.  At the deep edge, error varied by data type but ranged from 72 - 101 m. Noting the standard deviation bars, all methods had errors at the deep edge upwards of 120 m. Surprisingly, the sonar deep edge error was nearly as high as that of other methods, which was unanticipated given that the strength of sonar in remote sensing is that it is unaffected by water clarity. This supports that edge dynamics and density are just as influential as water clarity when using remote sensing methods. Variability in edge locations among sites is displayed Appendix A, and shown relative to the last shoot along the diver transect in Appendix B.

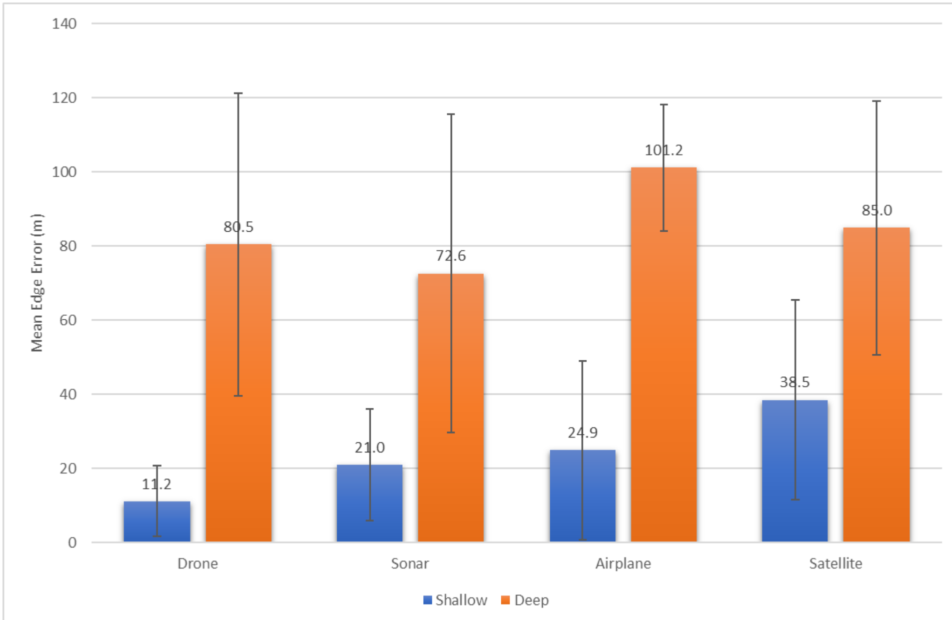


Figure 6. Mean edge error by survey type and edge depth, where eelgrass was not mapped by the expert interpreter though it should have been (false negative).

Newly trained interpreter results also showed higher edge error along the deep edge (Fig 7). However, the magnitude of edge error differed greatly from that of the expert interpretation. Assuming that the expert interpretation is more "correct," the higher edge errors might indicate lower confidence in newly trained interpreters in mapping patchy edge areas, and a tendency to not include these areas in the eelgrass polygons. In terms of eelgrass acreage mapped, across all survey methods combined, newly-trained interpreters mapped 378 acres of eelgrass compared to 481 mapped by an expert (27.3% higher).

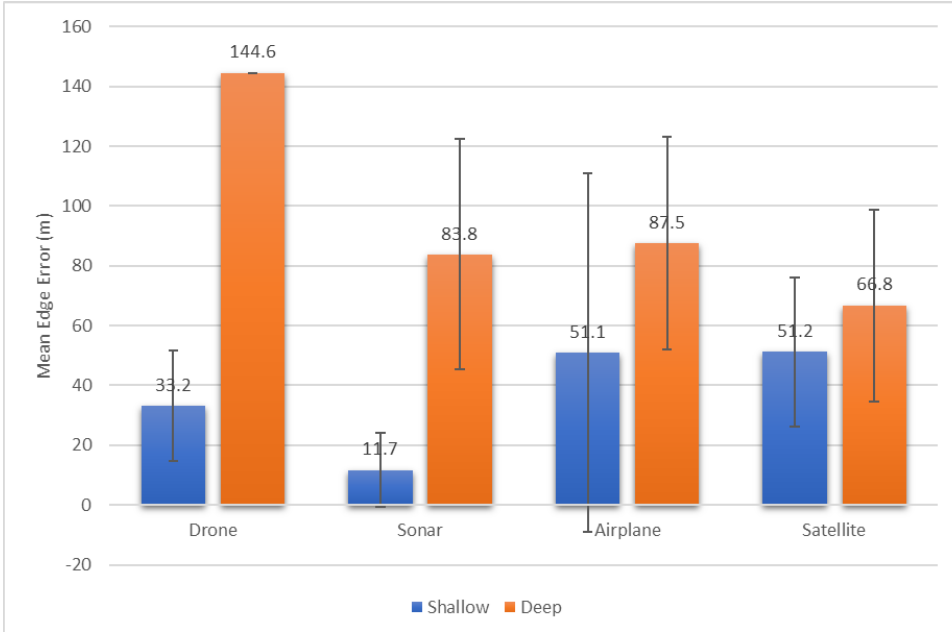
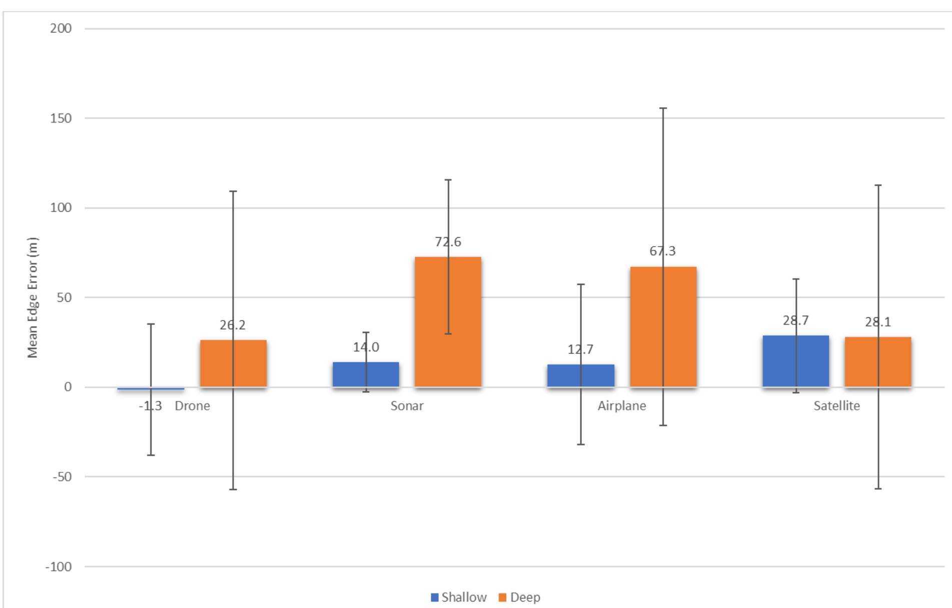



Figure 7. Mean edge error by survey type and edge depth, where eelgrass was not mapped by the newly trained interpreter though it should have been (false negative). Note: drone results are based on only two sites where complete datasets that passed QA/QC were available.

When false positives (i.e., overestimates due to signature confusion from algae, rocks, etc.) are also incorporated, the results are more difficult to interpret due to very wide error bars (Fig 8). However, false positives do drive edge errors down across all survey types and edge depths. This effect would likely be mitigated by allowing interpreters access to ground-truthing data, as would typically be the case in real-world photointerpretation work.



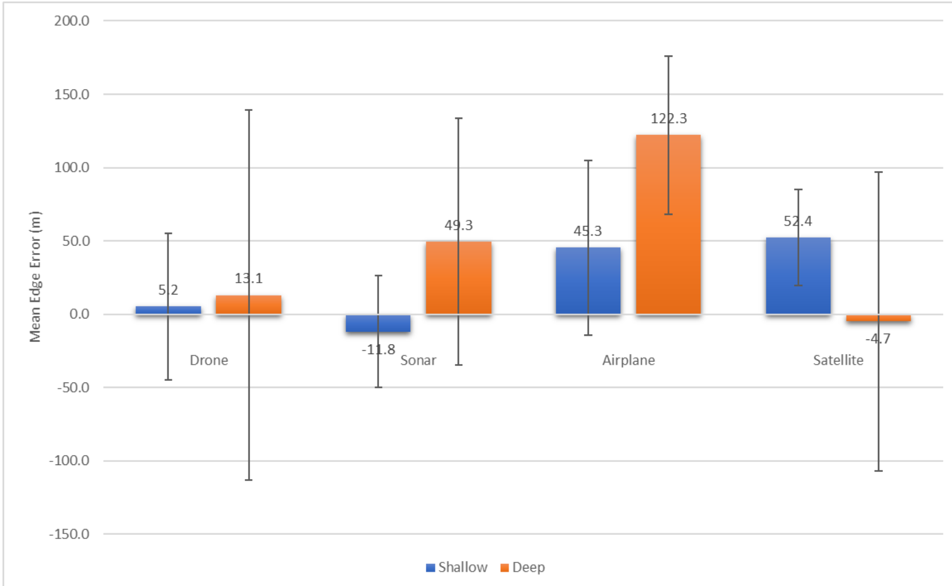



Figure 8. Mean edge error including false negatives and positives in expert interpretations (top) and newly trained interpretations (bottom).

Some survey methods achieved better agreement between expert and newly trained interpretations than others: drone and sonar interpretations were < 20% different between expert and newly trained interpreters; while the expert mapped 94% more eelgrass in airplane imagery and 52% more in satellite imagery. Site specific conditions strongly influenced agreement between expert and newly trained interpretations, especially where algae was prevalent, and where meadows had an expansive low density edge. Providing interpreters with ground-truthing data likely would have improved agreement, but would have introduced significant bias as described previously. Eelgrass maps from newly trained interpreters were not used in the remainder of the analyses due to incomplete data sets (e.g., drone interpretations from two sites did not pass QA/QC).

## Accuracy Assessment

The ability to accurately detect eelgrass varied by remote sensing method. Accuracy ranged from 76-89% and corresponded with image resolution, with drone performing best followed by sonar, airplane and satellite (Table 5). Accuracy at the shallow edge was greater than at the deep edge across all survey types with the exception of satellite, where accuracy was the same at both depths.

Table 5. Accuracy assessment results. Within each column, accuracy is ranked from high to low using dark to light cell shading.

| | **Overall** | **Shallow Edge** | **Deep Edge** |
|---|---|---|---|
| Drone | 89% | 89% | 86% |
| Sonar | 84% | 91% | 63% |
| Airplane | 77% | 83% | 59% |
| Satellite | 76% | 76% | 76% |

Accuracy was also influenced by percent cover. The 1-10% cover bin was the most problematic for all survey types (Table 6, Appendix B). Accuracy was reduced in percent cover bins up to 40% across all survey types and in even higher bins for satellite imagery (Table 6). Within the 1-10% bin, accuracy again tracked with image resolution. However, there was a high degree of site variability within these averages. Table 7 shows that some sites performed better than others in the 1-10% cover bin, which is likely due to varying site conditions. Gloucester performed very well across all surveys, and in this location the edge is abrupt near the low tide line where waves break on the beach. In contrast, Beverly has an expansive area of low-density patchy eelgrass, and more opportunity for mapping error in the lowest cover bins (Fig 9, Appendix B).

Table 6. Accuracy assessment results by survey type and percent cover. Within each column, accuracy is ranked from high to low using dark to light cell shading.

| | **1-10** | **11-20** | **21-30** | **31-40** | **41-50** | **51-60** | **61-70** | **71-80** | **81-90** | **91-100** |
|---|---|---|---|---|---|---|---|---|---|---|
| Drone | 79% | 92% | 96% | 91% | 100% | 100% | 100% | 96% | 100% | 100% |
| Sonar | 68% | 97% | 89% | 96% | 100% | 100% | 100% | 96% | 100% | 100% |
| Airplane | 56% | 92% | 89% | 91% | 100% | 100% | 100% | 88% | 100% | 100% |
| Satellite | 60% | 85% | 85% | 87% | 93% | 91% | 100% | 85% | 80% | 100% |

Table 7. Accuracy assessment results for the 1-10% cover bin, by survey type and site. Within each column, accuracy is ranked from high to low using dark to light cell shading.

| | **Drone** | **Sonar** | **Airplane** | **Satellite** |
|---|---|---|---|---|
| Gloucester | 86% | 90% | 86% | 90% |
| Beverly | 64% | 59% | 50% | 18% |
| Swampscott | 78% | 52% | 4% | 78% |
| Nahant | 68% | 59% | 45% | 23% |
| Cohasset | 94% | 78% | 91% | 78% |

Figure 9. Airplane imagery from Gloucester Niles Beach (left) and Beverly Brindle Beach (right), showing abrupt versus sprawling edge characteristics.

## Effects of Patchiness and Canopy Height

Eelgrass distribution affected the likelihood of it being correctly mapped or missed during photointerpretation. Where eelgrass had continuous distribution, or < 1 m separation between shoots or patches as measured by divers, interpreted polygons from all survey methods correctly included 89 - 98% of those survey locations (Fig 10). Sonar performed best in continuous distribution (98% of ground-truthing sites were correctly mapped), followed by satellite (93%), drone (91%), and airplane (89%). In transitional eelgrass, drones performed best (85%) followed by sonar (67%) and airplane and satellite (both 59%). All survey types missed at least half of the ground-truthing points containing patchy eelgrass, with drones performing best (41%), followed by satellite (31%), sonar (23%), and airplane (18%).

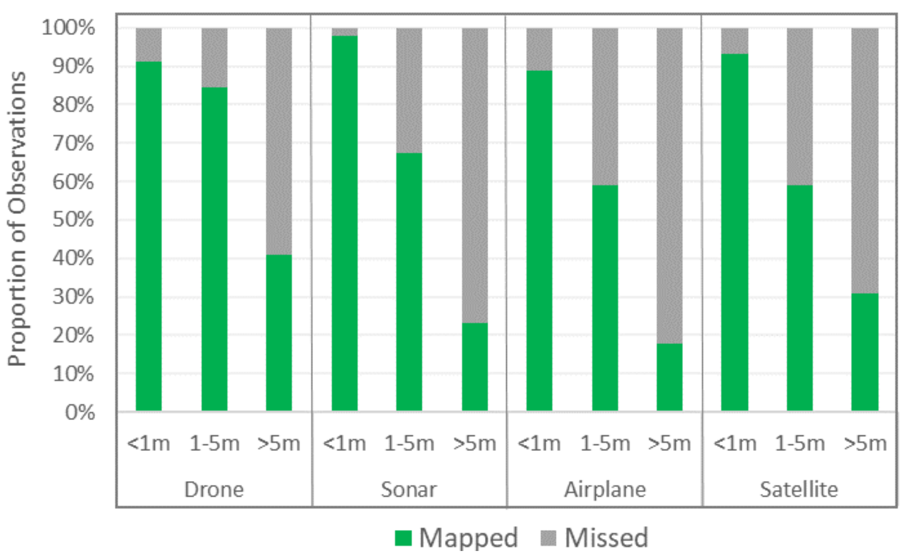



Figure 10. Proportion of observations within each distribution type (i.e., shoots and patches are < 1 m, 1-5 m, > 5 m apart) that were positively mapped or missed by each survey method.

Canopy height affected the likelihood of eelgrass being correctly mapped or missed during photointerpretation. Across all diver quadrat locations and all sites, the mean canopy height of eelgrass that was mapped by each survey method ranged from 49 – 55 cm (Fig 11). Eelgrass with mean canopy height < 21 cm was less likely to be mapped by any method. Drone and sonar were more likely to detect slightly shorter eelgrass (> 17 cm) compared to airplane and satellite (> 21 cm).

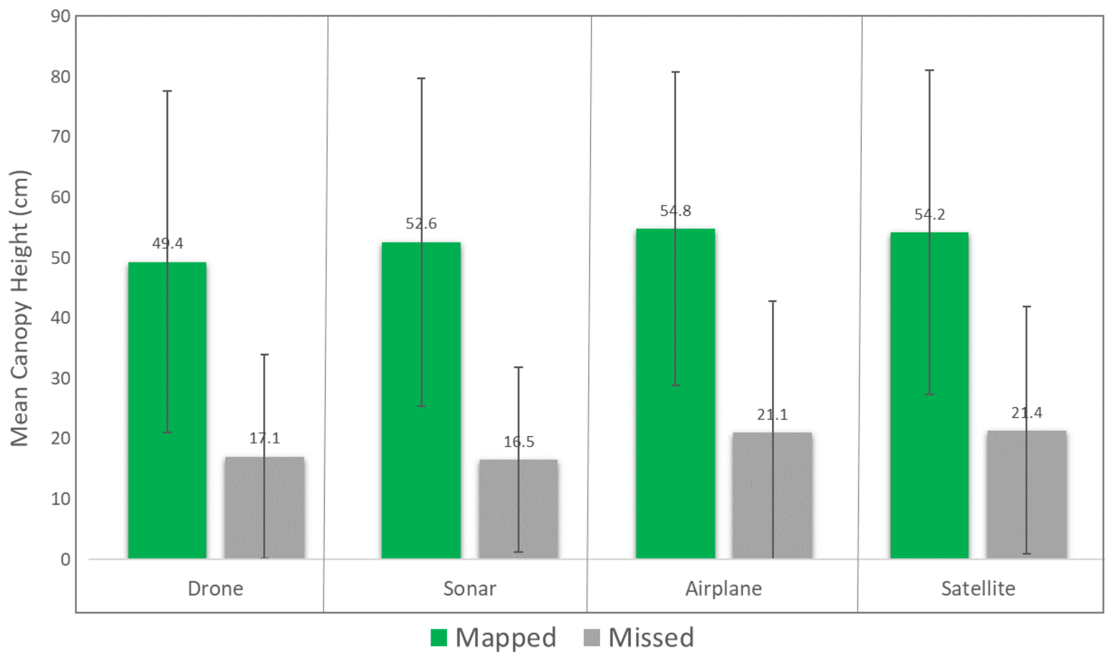



Figure 11. Mean canopy height that was positively mapped or missed by each survey method.

Canopy height, percent cover, and distribution type likely interact to influence detectability. However, investigating the nature of those interactions was not in the scope of this study.

## Discussion & Management Recommendations

Remote sensing continues to be one of the most effective and efficient tools for mapping eelgrass, however it is critical to understand the detection capabilities and accuracies of remote sensing methods to ensure appropriate use of derived data products. In Massachusetts, DEP’s airplane-derived eelgrass maps are used to assess waterbodies for impairments, track statewide eelgrass trends, and to inform permitting of coastal construction projects, dredging activities and aquaculture leases. Often, regulators require additional mapping when eelgrass is at risk of impact, but often the supplemental maps are also derived from remote sensing. While direct human observation via SCUBA or snorkel is considered the “gold standard” in delineating an eelgrass boundary, it is not feasible to deploy human surveyors in a routine manner over a large area. Here and in other states, management buffers are sometimes applied to eelgrass maps to enhance protection from specific impacts. For example, in Massachusetts, aquaculture leases must be 25 ft (7.6 m) from mapped eelgrass to avoid foot and vessel traffic impacts, and dredging activities are often required to remain 100 ft (30.5 m) away to avoid burial from sediment resuspension. This study finds that these and other buffers fall short of protecting the whole meadow, specifically including low density edge areas. It is in such areas where year-to-year variability in eelgrass cover can be expected most, and where new growth can expand in response to sea level rise or other stressors that might influence a shift into shallower or deeper water.

The distance of “missed eelgrass”, or mean edge error, ranged from 11 to 38 m at the shallow edge and 72 to 101 m at the deep edge, with drones having the lowest error followed by sonar, airplane, and satellite (Fig 6). Edge error tracked inversely with image resolution, which the authors expected due to the greater level of spatial detail afforded in higher resolution imagery. Of all the methods, sonar had the lowest edge error at the deep edge but still missed an average of 73 m of eelgrass – surprising, given that sonar provides benthic imagery that is unaffected by water clarity. This suggests that meadow characteristics (e.g., patchiness, height) are just as important as water column characteristics in remote sensing eelgrass mapping, if not moreso.

Overall map accuracy ranged from 76-89% and corresponded with image resolution, with drones performing best followed by sonar, airplane and satellite (Table 5). Accuracy at the shallow edge was greater than at the deep edge across all survey types with the exception of satellites, where surprisingly, depth did not affect accuracy. This study also found that percent cover, canopy height, and patchiness all influenced the likelihood of eelgrass being mapped. Map accuracy was lowest where percent cover was 1-10%, though drones performed best at this coverage followed by sonar, airplane and satellite. Still, all methods had reduced accuracy where eelgrass was < 40 % cover. Canopy height also limited eelgrass detectability, especially when < 21 cm, where most methods failed to detect it. Drone and sonar were able to detect slightly shorter eelgrass than airplane and satellite. All remote methods performed very well where eelgrass was continuous, moderately where it was transitional, and poorly where eelgrass distribution was patchy. Overall, drones performed best in patchy eelgrass.

The results of this study support the modification and augmentation of existing mapping programs, as well as a new management approach when using eelgrass maps derived from remote sensing data. The authors and project Advisory Committee offer the following management recommendations:

1. If map accuracy is a program’s priority, high-resolution imagery sources such as drone and side scan sonar are the most accurate and eelgrass-inclusive mapping tools and can be significantly

enhanced with diver ground-truthing of the edge. However, these methods present implementation challenges at the coast-wide scale and may be more appropriate for site- or embayment-level mapping.

2. If high spatial coverage is a program's priority, imagery acquired from airplane or high-resolution satellites will be more logistically efficient but will miss more eelgrass. In this case, more resources should be allocated toward enhanced ground-truthing of the edge. Integrating routine site- or embayment-level mapping with higher resolution methods at select representative sites would help improve map accuracy by providing another source of ground-truthing data and a correction factor, or adaptive buffer, that could be applied to the lower resolution data products.
3. Regardless of remote sensing survey method used, we recommend a management buffer be applied if precise diver-measured edge surveys are not conducted. The least protective buffers are the mean edge errors for each survey method at each depth (Fig 6)(e.g., 11.2 m buffer at the shallow edge and 80.5 m buffer at the deep edge when using drone imagery). The most protective buffers are the maximum edge error observed, which is approximately 120 m across all survey methods.
4. The mean edge errors can be used to crosswalk disparate remote sensing data products. For example, to integrate eelgrass maps from drone and airplane imagery together at a project site, one could apply an 11 m buffer to the drone-derived shallow edge and a 25 m buffer to the airplane-derived shallow edge. The resulting integration of two eelgrass maps is not likely to be a perfect match but would be more representative of the true meadow edge across both methods.
5. The management buffers should be used to model the edge of the eelgrass bed; it should be assumed that eelgrass of some density exists or can exist within the buffer area. Thus, it may be appropriate to implement additional regulatory buffers from the modeled edge; i.e., for silt-producing construction activities, dredging projects, or aquaculture lease areas proposed adjacent to a meadow.
6. It is important to note that most dive transects had to end between 100 and 140 m in length due to air and swimming limitations. In some cases, divers continued to find single shoots every 10-20 m toward the end of the transect, a pattern presumed to continue until some change occurred (e.g., depth that could no longer support eelgrass of any density; a change to unfavorable sediment). The present study did not have the resources to extend each transect

farther with additional dives, but the true distance to last shoot at these sites is worthy of more study.

7. Along the meadow's expansive edge, eelgrass tends to grow shorter and sparser as bathymetry and wave dynamics change. Eelgrass < 21 cm in canopy height and eelgrass with patchy distribution (shoots or patches > 5 m apart) were often missed by the remote sensing methods studied. Mapping programs should collect canopy height and distribution data during ground-truthing efforts as a useful tool in tracking meadow change and detectability over time. This is especially useful in light of eelgrass meadow losses, which can often be observed as a gradual decline in eelgrass density, contiguity and/or leaf area.
8. This study evaluated the use of 3 m resolution satellite imagery, with which interpreters performed the poorest of all the survey types in terms of overall accuracy but resulted in interpretations very similarly to airplane imagery across all other metrics. It is strongly recommended that the use of sub-meter resolution satellite imagery be further explored. For example, Planet frequently acquires 0.25 m imagery during the target survey window, the same resolution collected by MassDEP's aerial program. Satellite tasking to target specific date, tide, and environmental conditions is another understudied option. Given that MassDEP's imagery performed similarly to satellite, the program might consider integration of or transition to satellite imagery which may be more cost effective and less of a logistical burden.
9. Site-specific conditions greatly influenced the performance of remote sensing imagery for eelgrass mapping. Sites with a high degree of macroalgae, and those with expansive, diffuse patchy edges created the greatest difficulty for interpreters. The optimal survey method for map accuracy in these conditions is the use of SCUBA divers. Given the high degree of site variability, more condition-specific buffers may be desirable but more difficult to implement, since a high degree of survey work needs to be done to accurately characterize site conditions.
10. While weather and environmental conditions were standardized to the greatest extent possible across sites and surveys, some variables may have influenced eelgrass detectability across the datasets. Water clarity and chemistry sampling during each remote sensing mission was outside the scope of the project but would have helped ensure that differences in mapping performance were influenced only by survey method and site.
11. Qualitatively, drop-frame photo ground-truthing performed poorly in detecting low density eelgrass compared to divers (Appendix B). While divers were able to detect the lowest percent cover bins (e.g., 1-10%, 11-20%) photo ground-truthing in the near-vicinity detected nothing.

This is attributed to the likelihood of the drop-frame being placed in “just the right spot” where eelgrass is very sparse, whereas divers have a broader context underwater and can record observations over a larger viewing area. Drop-frame photo ground-truthing is therefore not reliable in detecting very low-density eelgrass. Video surveys along a transect may perform better, especially if multiple views are incorporated (e.g., a 360° camera). This is deserving of more study.

12. This study did not investigate the ability of remote sensing methods to detect and map new or previously unmapped meadows – it specifically targeted the edge of known meadows. Given that all of remote sensing methods in this study performed poorly in patchy, low density and shorter areas of the meadow, it can be assumed that mapping programs may consistently miss meadows that are dominated by these characteristics. Thus, diver, video transects, and/or drop-frame ground-truthing surveys should be implemented in places where eelgrass was previously mapped via remote sensing but has since disappeared; or where impacts to highly suitable habitat are proposed.
13. The experience level, rules and tools used by the photointerpreter are all important influences on results. Novice interpreters tended to under-map eelgrass, in some cases displaying a lack of confidence when the meadow transitioned from dense to patchy along the edge. Even though training was standardized, minor variations in the implementation of the rules and “judgement calls” introduced a great deal of variability in results from different interpreters. ArcGIS Pro raster tools, such as the Histogram Stretch feature, helped to draw out the eelgrass signature from the image and were preferred over working with the image in its raw state.
14. Semi-automated and machine learning image analysis tools were not studied in the present project. However, they have potential to reduce manual interpretation errors and increase interpreter efficiency, since computers can differentiate far more color, shape and texture variations than can human eyes. DEP is currently piloting an object-based image analysis (OBIA) workflow that should be compared against a manual interpretation of the same areas to assess accuracy and efficiency of integrating OBIA into the program.

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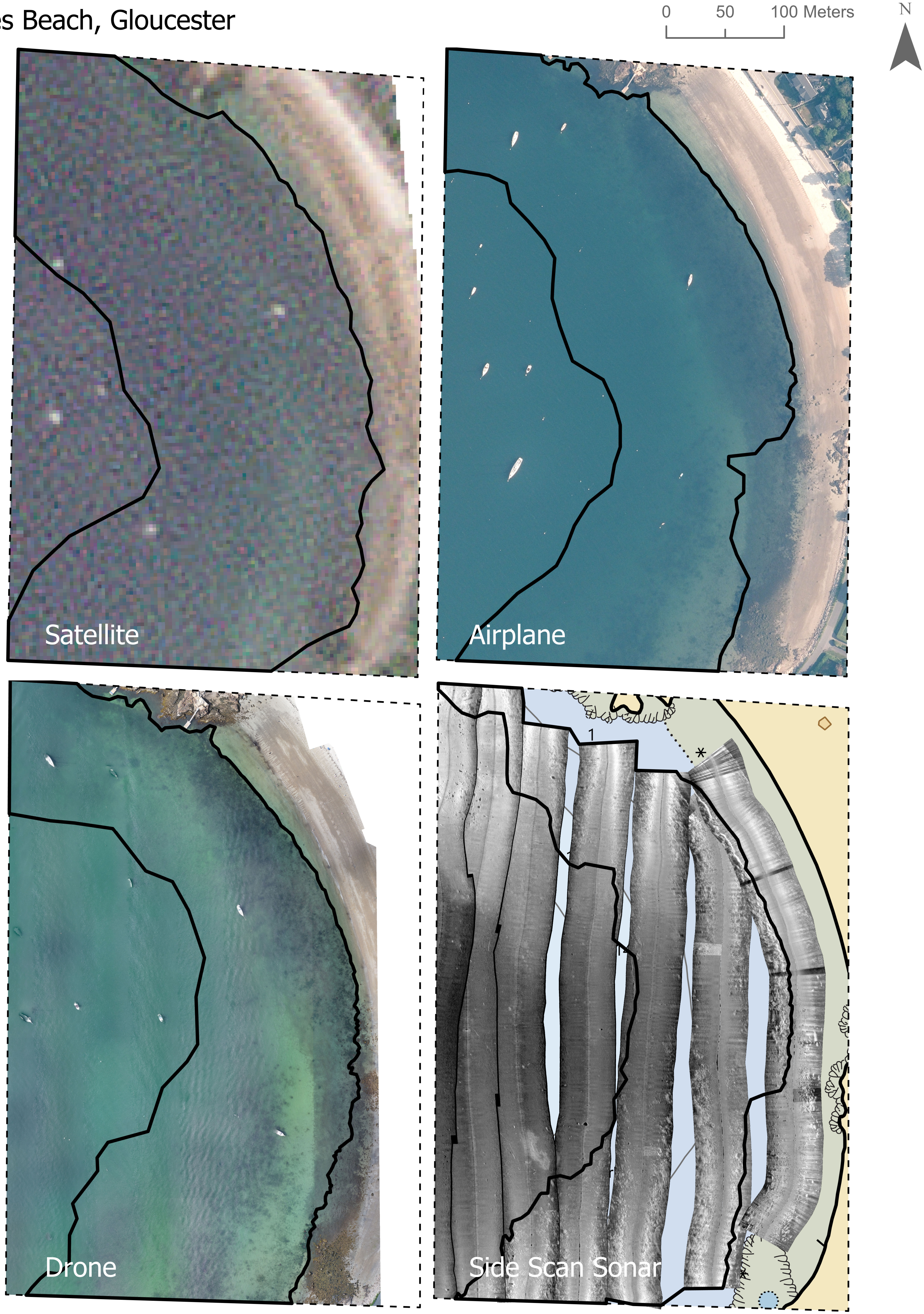
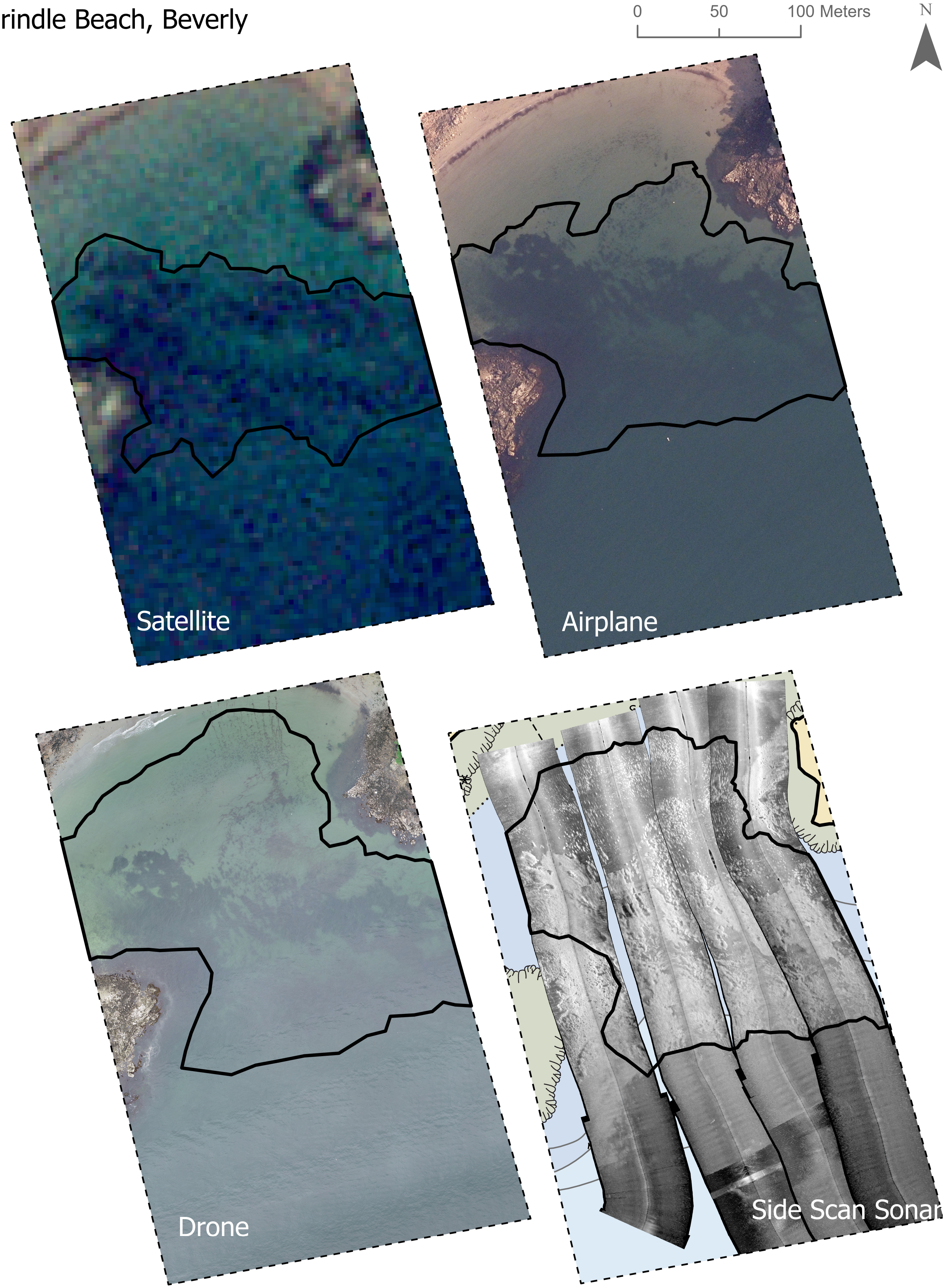
# Appendix A: Imagery with Photointerpretation Maps

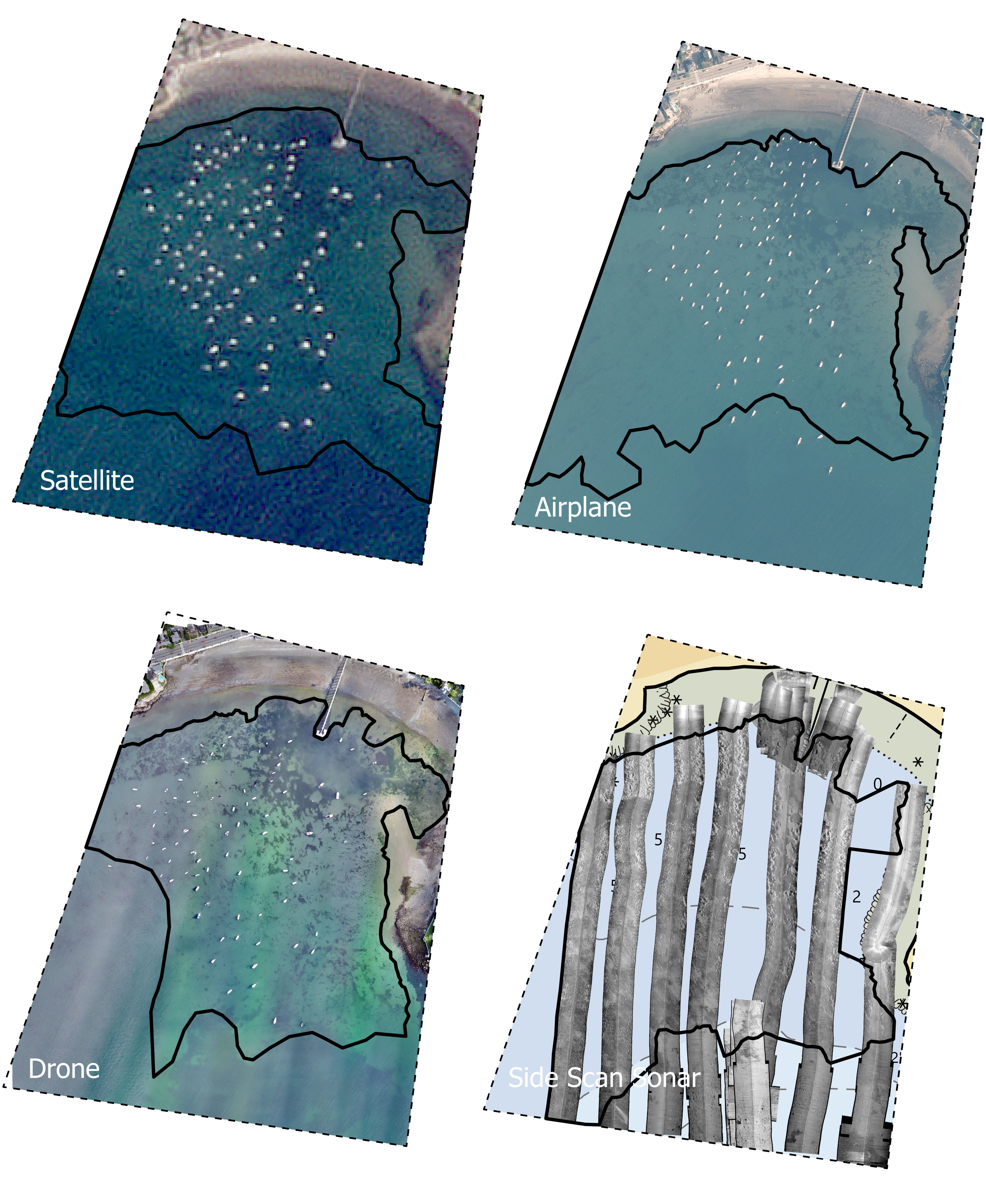
# Niles Beach, Gloucester

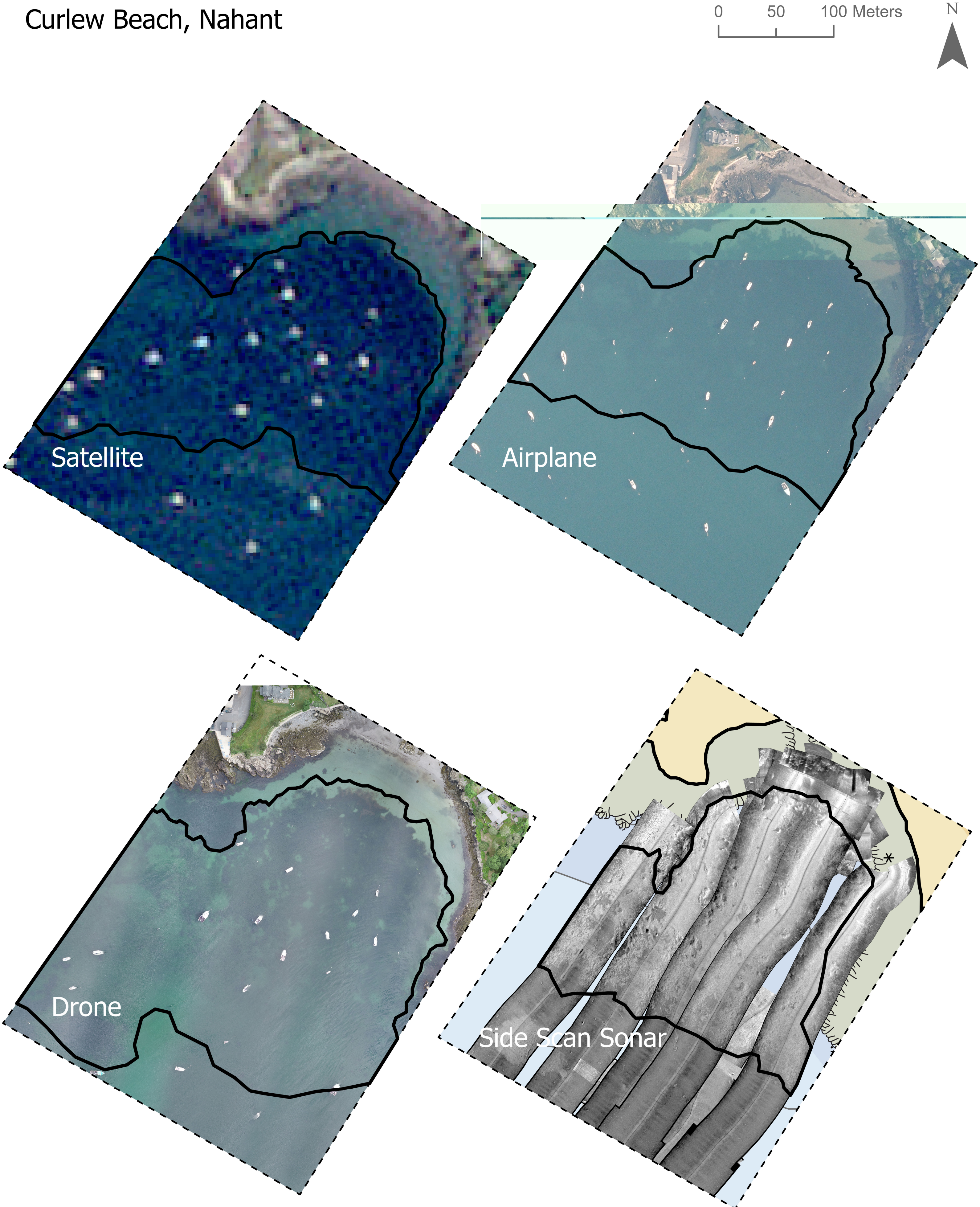


# Brindle Beach, Beverly



## Swampscott Harbor, Swampscott




Curlew Beach, Nahant
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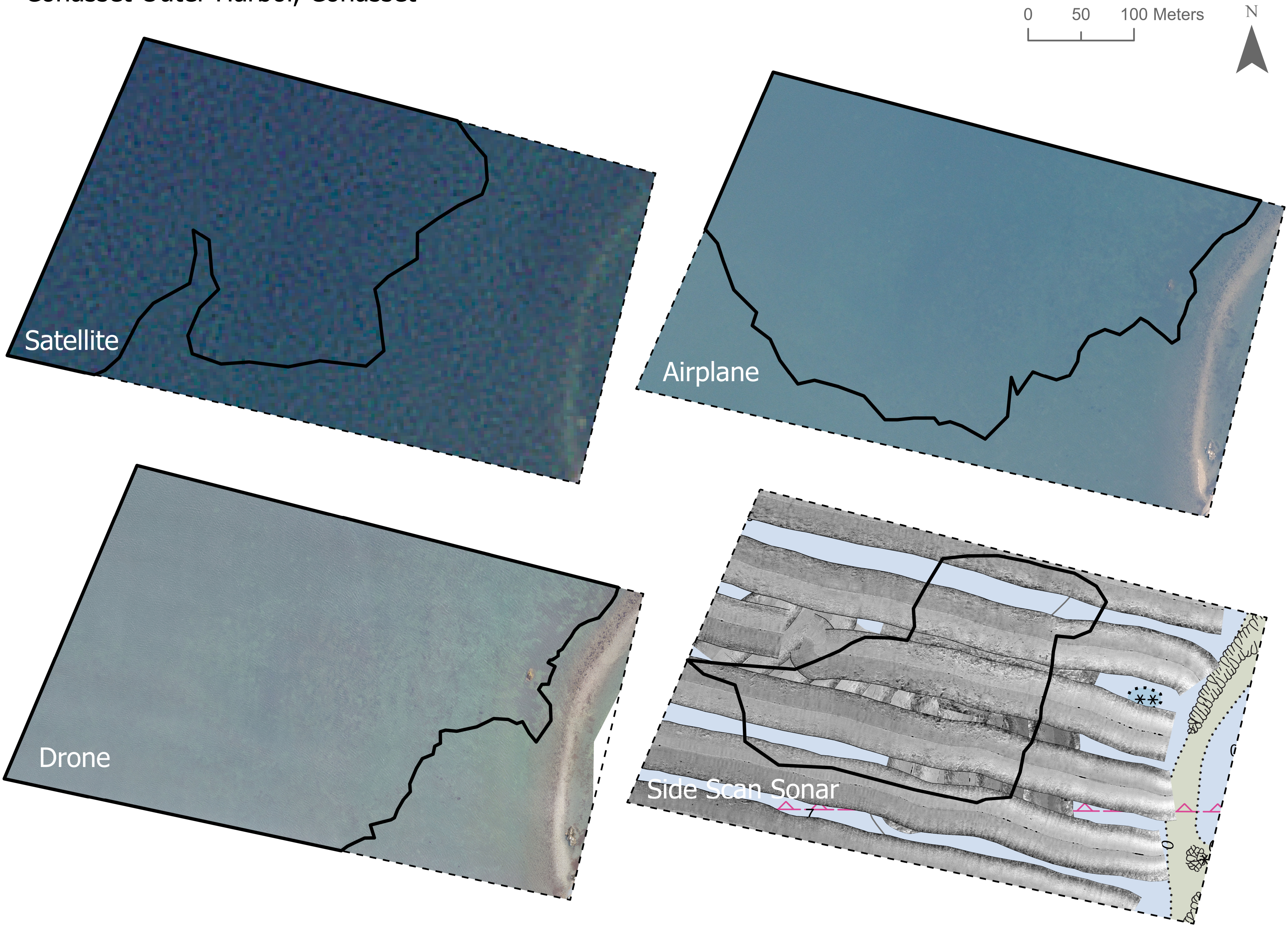
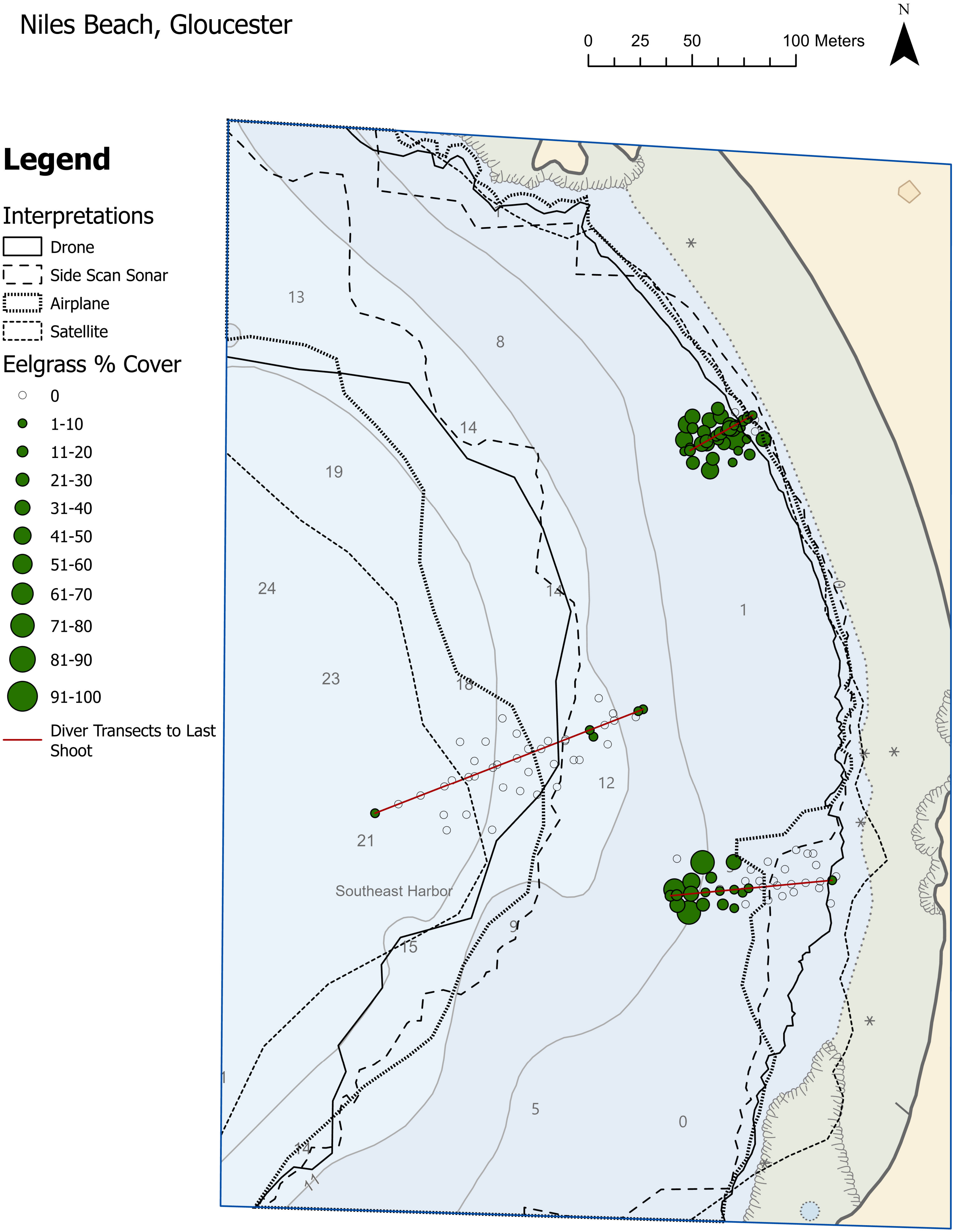
50
100 Meters
N
Satellite
Airplane
Drone
Side Scan Sonar

Cohasset Outer Harbor, Cohasset



# Appendix B: Last Shoot and Eelgrass Percent Cover Maps


Niles Beach, Gloucester
0
25
50
100 Meters
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Legend
Interpretations
Drone
Side Scan Sonar
Airplane
Satellite
Eelgrass % Cover
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1-10
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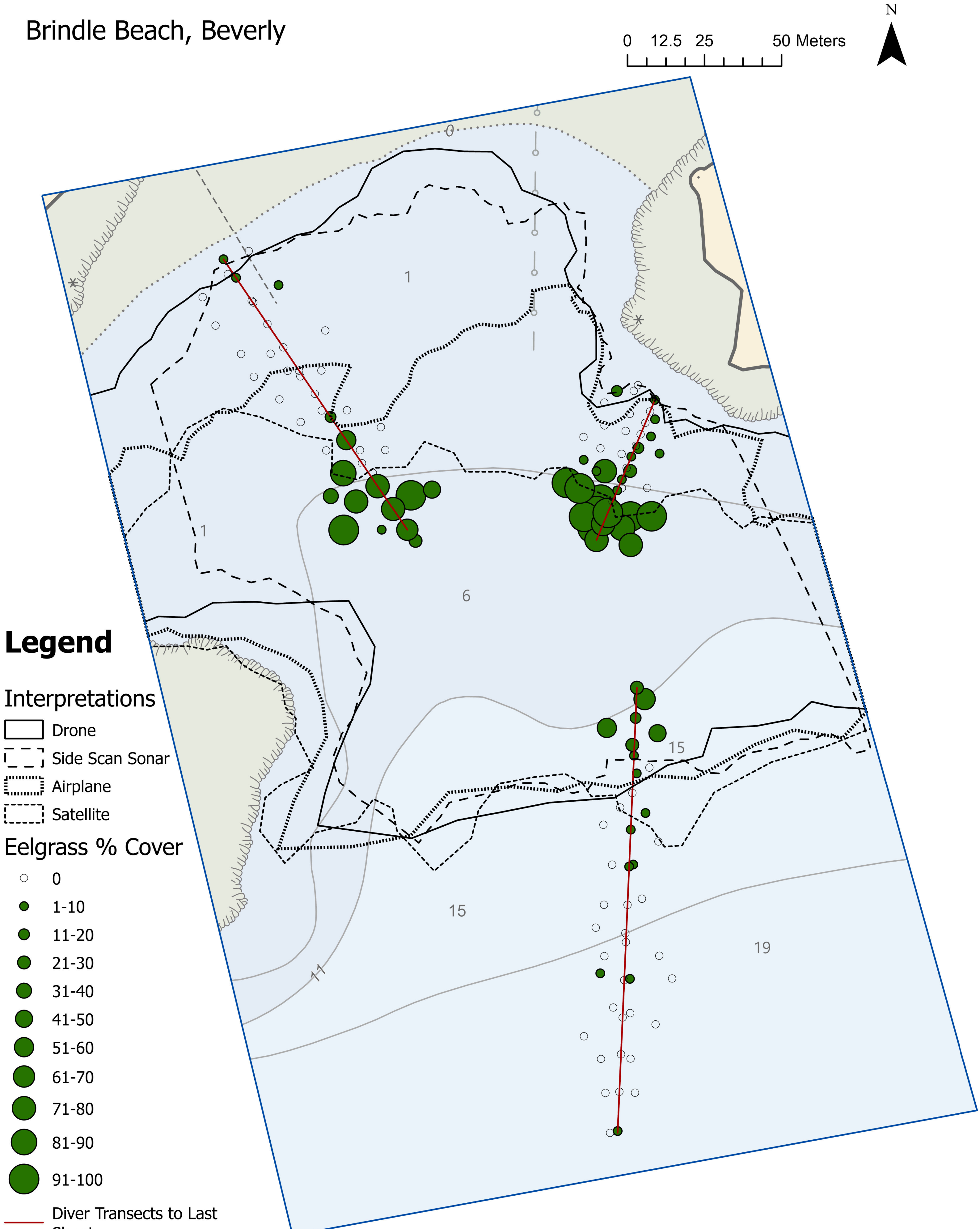
41-50
51-60
61-70
71-80
81-90
91-100
Diver Transects to Last Shoot
Southeast Harbor



Brindle Beach, Beverly
0 12.5 25 50 Meters
N
0
1
1
6
15
15
11
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Legend
Interpretations
Drone
Side Scan Sonar
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Satellite
Eelgrass % Cover
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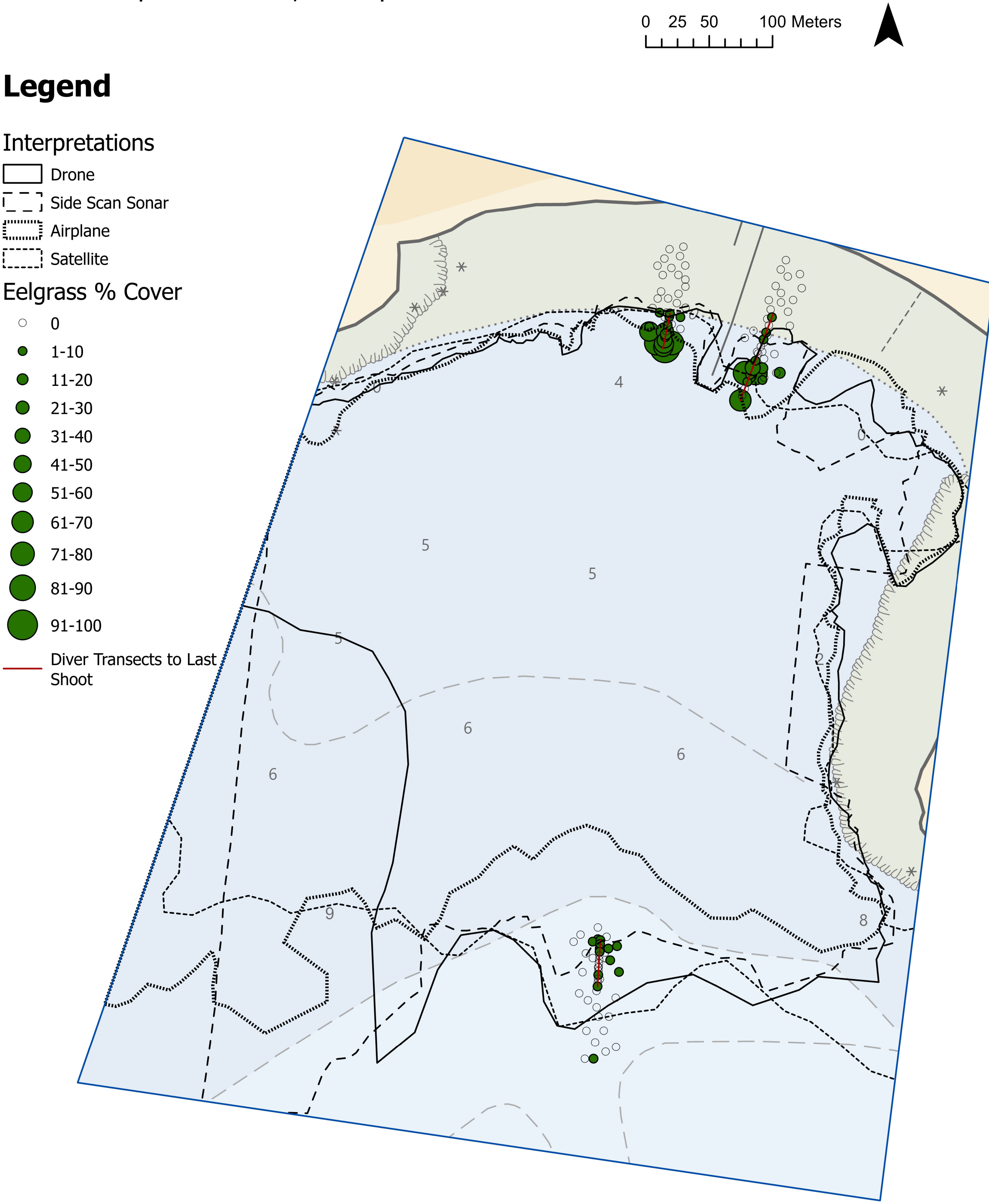
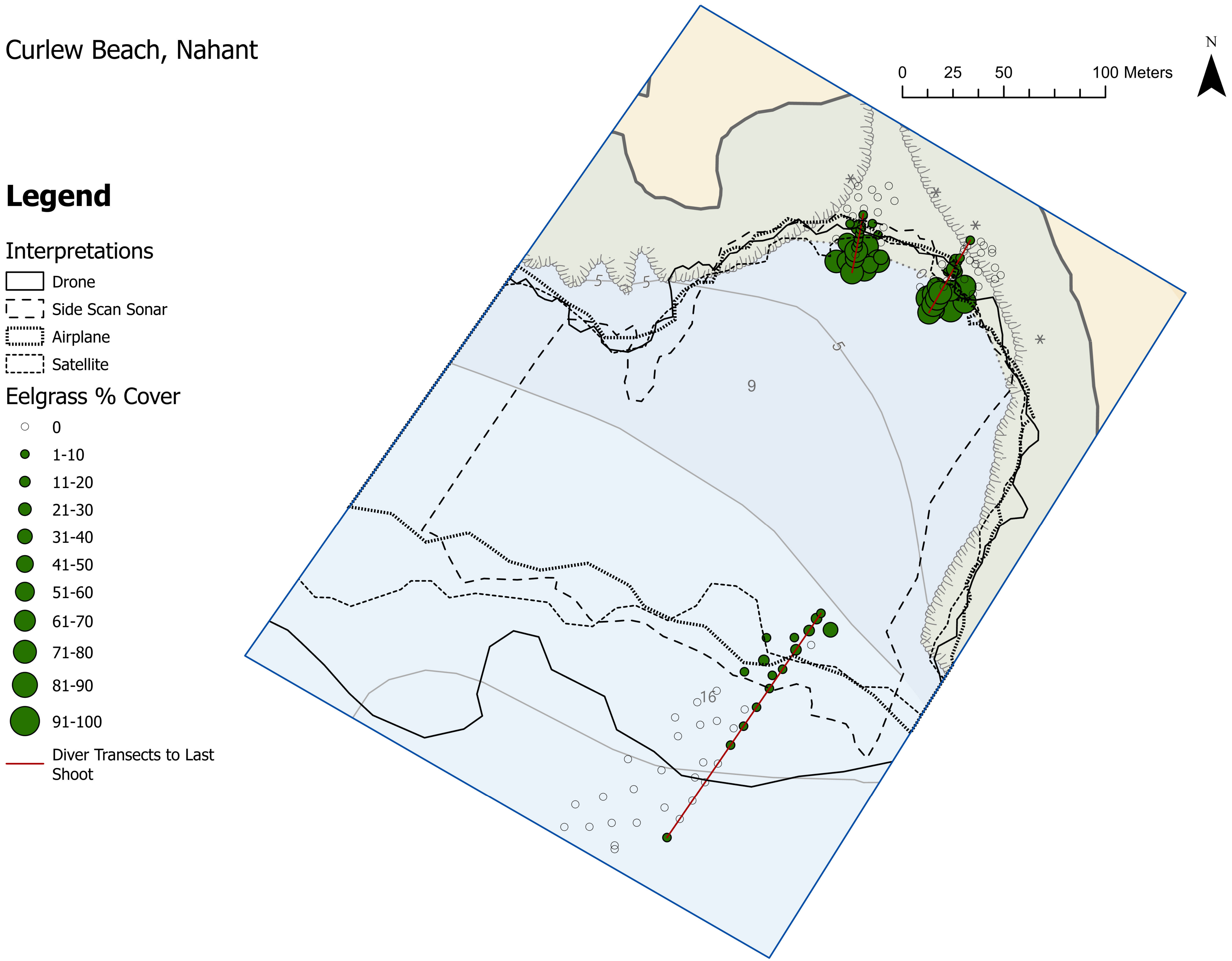
1-10
11-20
21-30
31-40
41-50
51-60
61-70
71-80
81-90
91-100
Diver Transects to Last Shoot

# Swampscott Harbor, Swampscott





Curlew Beach, Nahant
Legend
Interpretations
Drone
Side Scan Sonar
Airplane
Satellite
Eelgrass % Cover
0
1-10
11-20
21-30
31-40
41-50
51-60
61-70
71-80
81-90
91-100
Diver Transects to Last Shoot
0 25 50 100 Meters
N
5
5
5
9
16

## Outer Harbor, Cohasset