Drone-based image analysis workflows for measuring structural and demographic characteristics of intertidal oyster reefs

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Research Reserve System
Science Collaborative

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I. Introduction and Objectives

Oysters and the reefs that they form present unique management challenges as one of very few ecosystem engineers that are directly subjected to harvest. Harvest not only removes individuals from the population, but also removes shell and three-dimensional reef structure, thereby limiting settlement habitat for oyster larvae, reducing habitat value for reef-dwelling organisms, and often reducing the resilience of reefs to additional stressors (e.g., sedimentation, anoxia). Indeed, following more than a century of harvest, in combination with disease and poor water quality, oyster reefs have been labeled one of the most imperiled marine habitats on earth. To better manage and restore oyster reefs, resource managers and restoration practitioners have expressed a need for novel approaches to better monitor and assess the resource.

Oyster reefs are primarily managed by state agencies to sustain fisheries; however, the importance of regulating (e.g., nutrient remediation, shoreline stabilization) and supporting (e.g., nursery habitat) ecosystem services are increasingly gaining recognition. Along the south Atlantic bight of the United States (i.e., North Carolina to Florida), the focal geography of this project, *Crassostrea virginica* oyster reefs occur primarily in the intertidal. Oyster resource managers and restoration practitioners from NC to FL (primary end users of this project) often rely on the mapping (e.g., boat-based surveys or remote sensing) and monitoring (e.g, *in situ* quadrat sampling) of intertidal reefs to inform management decisions, such as fishery closures, and where to "plant" shell or other alternative materials to provide recruitment substrate for oyster reef restoration and habitat enhancement efforts. However, these methods can be time-consuming, labor intensive, destructive to the reef, and limited by spatial scale (e.g., m^2 quadrats) or resolution (e.g., satellite pixel size).

Both resource managers, applied researchers, and National Estuarine Research Reserve (NERR) staff end users in the region have expressed a need for *rapid, standardized,* and *quantitative measures to assess reef structural and demographic characteristics* for monitoring, managing and restoring the resource in both habitat and fishery contexts. For our purposes, we are defining structural and demographic characteristics as two-dimensional (e.g., footprint) and three-dimensional (e.g., rugosity) physical metrics and metrics such as oyster density, all of which provide information on reef 'condition'.

In this project, we evaluated Uncrewed Aircraft Systems (UAS) as a tool for providing quantitative measures of intertidal eastern oyster reef structural and demographic metrics and changes to reefs in response to natural and anthropogenic factors. We developed and implemented an integrated collaborative and technical process with oyster resource manager end users from the Florida Fish and Wildlife Conservation Commission, Georgia Department of

Natural Resources, South Carolina Department of Natural Resources, and North Carolina Division of Marine Fisheries, as well as end users from all five NERRs in the southeastern U.S. (North Carolina, North Inlet-Winyah Bay, ACE Basin, Sapelo Island, and GTM Reserves). End users prioritized the following metrics: 1) reef height and elevation, 2) rugosity, 3) reef footprint and area, 4) shell substrate and oyster percent cover, 5) shell volumetric change, and 6) oyster density and size structure.

Detailed image analysis workflows for each priority metric are presented in this document. The workflows were developed following drone-based surveys of multiple reef types (e.g., fringe vs patch reefs) and management regimes (e.g., open vs closed to harvest). The drones used in surveys were equipped with stock red, green, blue scale sensors flown at an altitude generating a ground sampling distance of ~ 1cm/pixel. Imagery was processed using structure from motion photogrammetry software. The resulting orthomosaics and/or digital elevation models are generally required as inputs for each workflow. Workflows were developed using ArcGIS Pro and Microsoft Excel. This document is targeted at entry-level UAS users with UAS training and required certifications (e.g., FAA Part 107 certificate) that are interested in exploring UAS as a tool for monitoring intertidal reefs. The document does not include image acquisition or processing guidance. These workflows are selected from many potential metrics and are examples of approaches that are likely to be generally useful for managers and restoration practitioners. Users are encouraged to refine, adapt or otherwise use these workflows as starting points to develop useful approaches for particular needs or programs.

II. Oyster Reef Elevation and Elevation Change Workflow

__Workflow lead and contact__: Brandon Puckett (brandon.puckett@noaa.gov)

Overview

1. Pre-checks
2. Extracting Elevations from DSM for Groundpoints
3. Calculating Model Accuracy and Conduct Regression Analysis
4. Adjusting DSM and Displaying Point Accuracy in ArcPro
5. Calculating elevation change limit of detection (need two DSMs in a time series)

1. Pre-checks

- Before beginning any analyses, it's a good idea to conduct a few simple pre-checks:
    - Check the alignment of the outputs generated from imagery processing, particularly if comparing orthomosaics and digital elevation models over time.
        - To add orthomosaics to a project, right click on ‘Folders’ in the catalog pane → add folder connection and then navigate to the location where your orthomosaics are located. Right click on each orthomosaic file and select ‘add to new map’ or ‘add to current map’.
        - Use the ‘swipe’ tool in the Raster Layer pane to make sure both orthomosaics are aligned. Swipe horizontally and vertically and cue on marsh shorelines, ground control points, landing pads or any other stationary objects in both orthomosaics. If there are offsets between orthomosaics between pre- and post-excavation orthomosaics, then it's likely an error with ground control points (i.e., coordinate may have been entered incorrectly for a GCP for one image set).
- Coordinate system check
    - In the contents pane, right click on each raster, select properties → source → select the spatial reference dropdown. Ensure the projected coordinate system is NAD 1983 (2011) UTM Zone XX (where XX is the appropriate zone for your location). Linear units should be in meters. The vertical coordinate system should be NAVD88 in meters. Repeat for each orthomosaic.

2. Extracting Elevations from DSM for Groundpoints

Determine ArcGIS project structure–Prior to starting, decide whether all sampled reefs will be housed in the same ArcGIS project (*e.g.,* each reef will have a separate Map tab), or if each ArcGIS project will house an individual reef. *Note, your decision will affect the naming convention of the final exported ArcGIS project(s) specified at the end of the workflow.*

1. ADD DSM to the current map (as above) or Drag/Drop DSM into the contents pane. May need to wait for "Calculating Statistics" to finish
2. Under the Map tab at the top, Add data, navigate to file with RTK survey data (.csv).
    a. CHECK the RTK file to make sure elevations from ground control points (GCPs), RTK points taken on top of pvc quadrats, checkpoints, benchmarks, VRS/RTN stations, and groundpoints taken in water are NOT included for vertical accuracy assessment of digital surface models (DSMs). RTK data collected from haphazard shots throughout the reefs, shots along the rugosity chain(s), and shots along axial reef profiles can all be used as groundpoints for this exercise.
3. Right click .csv file → Create Points from Table (note: older versions of ArcPro may use 'display x/y')→ choose "XY Table to Point" → make sure the coordinate system is correct (make sure coordinate system matches the DSM) → assign "x field" to Easting, "y field" to Northing, and "z field" to Elevation columns
4. Under "Analysis" tab, click the geoprocessing toolbox
5. Type in "Extract values to points" and double click that tool to use.
    a. For input point features, find the groundpoint data that was added in step 3.
    b. For input raster, use the DEM of interest.
    c. Make sure to keep the output point feature unchanged except for the last bit after ".gdb\". Anything after the ".gdb\" will be the name of the point feature once the tool finishes.
    d. If you prefer not to change anything, you can always change the name of the point file after it is done running/shows up in the contents section.
    e. Click Run
6. Under the geoprocessing toolbox, type in "Table to excel".
7. Select the point file you just created using the "extract values to points" tool.
    a. To output the excel file, find the folder/path you'd like to save under and give the file a unique name.
    b. Click Run.

Repeat the steps above for each dataset in a time series at a given reef.

3. Calculating Model Accuracy and Conduct Regression Analysis

8. Open the excel file created in the "extract values to points/table to excel" (hereafter referred to as EVTP; step 7).
9. Create a new column next to the "RASTERVALU" column named "Diff".
    a. The base value should be nonexistent
10. In the first row under Diff, calculate the value of the difference between the measured RTK elevation and DSM RASTERVALU (=elevation-rastervalu).
11. Apply the excel formula to all points in the file (double click on the right bottom corner of the cell).
12. Create another column which will be the Diff^2 (i.e., squared error).
    a. The cell formula should look like "=G2^2" where cell G2 contains the Diff value.
13. Make sure this is applied to every point as well.
14. At the bottom of the spreadsheet, use the "=count" formula and count the number of elevation points.
15. To calculate the model vertical accuracy, we'll calculate the root mean squared error (RMSE), which is the square root of the sum of squares error divided by the number of elevation points:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N} (Predicted_i - Actual_i)^2}{N}}$$

    a. The formula in excel would look like "=sqrt(sum(H2:H87)/J88)" where sum(H2:H87) is the sum of squares (sum of Diff^2 column) and J88 is the count or number of elevation point.
16. The RMSE provides an estimate of model vertical accuracy in meters. This estimate of accuracy is in addition to the estimate derived from image processing software when using checkpoints.
17. Multiply by the RMSE value by 100 to convert RMSE to units from meters to cm.
18. For the regression analysis, plot RTK measured elevation ("elevation") vs DSM predicted elevation ("rastervalu"). Right click on the points, select "add trendline", choose linear, and check boxes for "display equation on chart" and "display R-squared value on chart". Ideally, the slope is ~1 and y-intercept is ~0 (see example in Figure 1).
19. Run a regression analysis in excel by clicking on the data tab data analysis regression (note, you will need the analysis toolpak in excel to do this. To add the toolpak, click on File options add-ins. In the table of Inactive Application Add-Ins, click on "Go…" at the bottom of the window next to Manage Excel Add-Ins. Then check the box for Analysis ToolPak, and click "OK"). Input Y range = DSM elevations ("rastervalu"), input X

range = RTK elevations ("elevation"). Also, a good idea to check the box for 'residual plots'. Select output range (which cell you want output started on), otherwise a new tab will be created for the regression output.

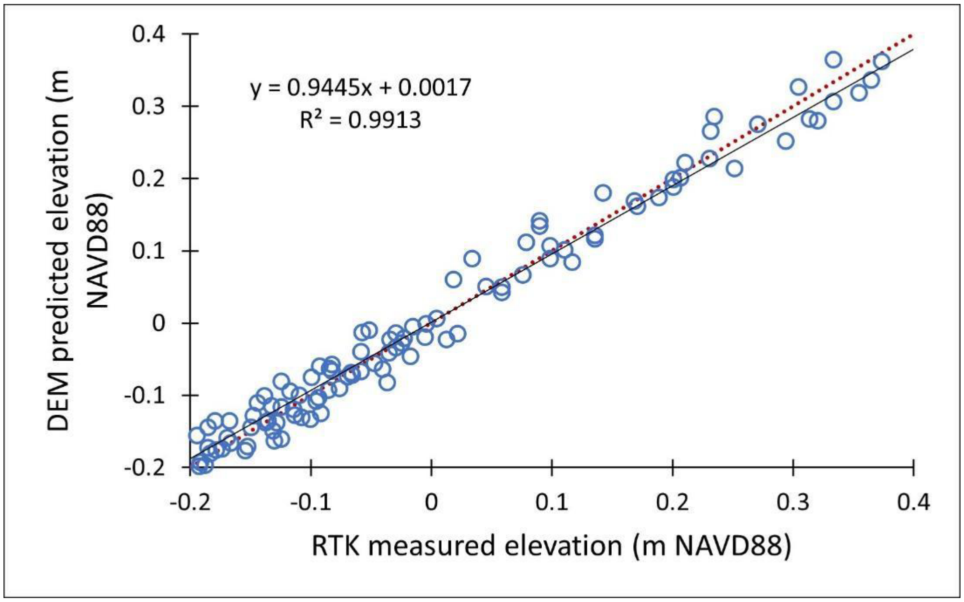


Figure 1. Example observed vs predicted elevation plot. The red dashed line is the 1:1 line.

20. Plot the RTK measured elevation vs DSM error ("Diff") and look for bias (see examples in Figure 2). Are all the errors positive? Negative? Hopefully not, otherwise the DSM has a systematic (non-random) bias in it such that the DSM is always below or always above the in-situ RTK ground points. Errors consistent along all observed elevations?

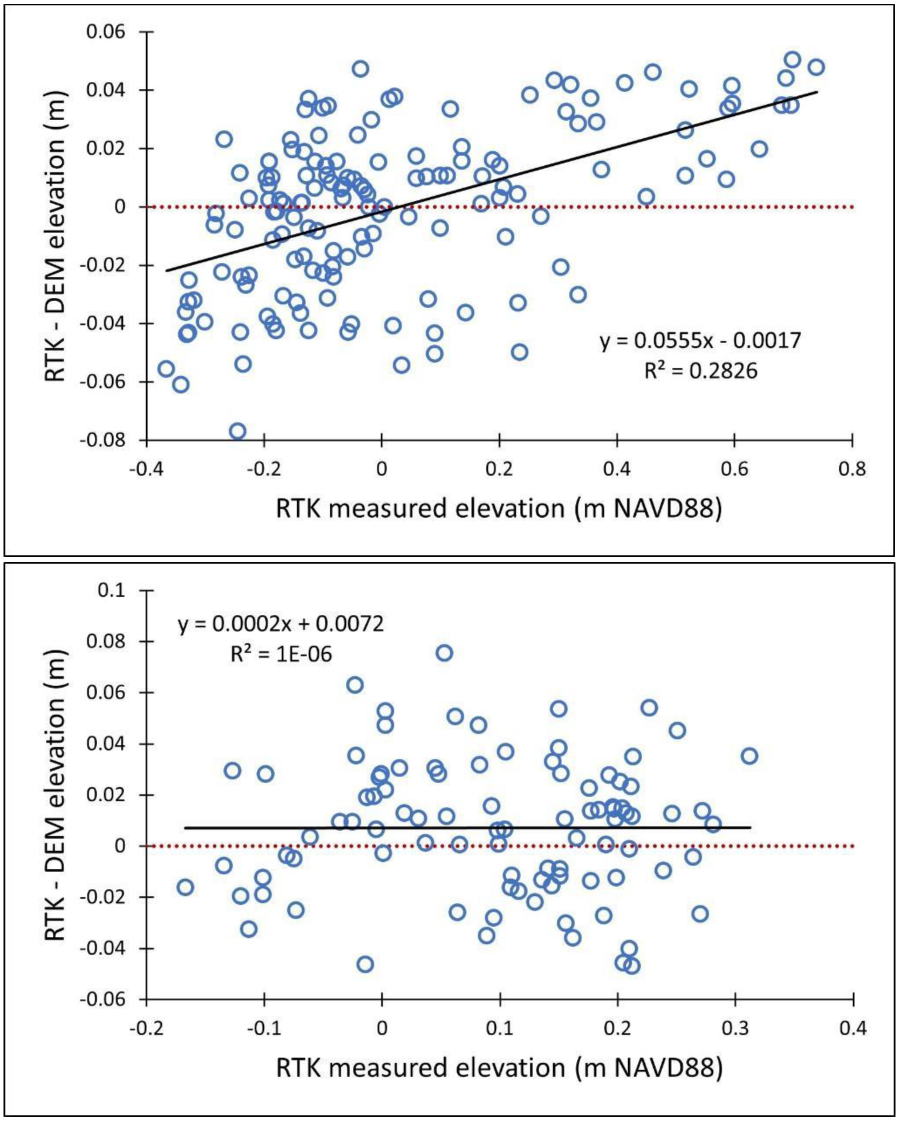


Figure 2. Example DSM error plots. Notice bias in error in top panel whereby errors are generally negative at low RTK measured elevations and generally positive at high RTK measured elevations (i.e., overpredicting elevations at low elevations and underpredicting at high elevations). In contrast, the bottom panel has minimal bias with DSM error distributed ~ equally across RTK measured elevations. As detailed below, correcting model error for examples like the top panel will likely require both a slope and y-intercept adjustment of the DSM, whereas correcting model error for examples like the bottom panel may only require a y-intercept adjustment of the DSM.

21. Calculate RMSE for two additional scenarios: 1) with DSM (“rastervalu”) elevations adjusted by the y-intercept of the regression only and 2) with DSM (“rastervalu”) elevations adjusted by the slope and y-intercept of the regression. Insert 6 columns.

Name them rastervalu_yint_correct, diff_yint_correct, diff^2_yint_correct, rastervalu_slope_yint_correct, diff_slope_yint_correct, diff^2_slope_yint_correct.

22. To calculate values for the rastervalu_yint_correct column, subtract the y-intercept from the original DSM elevations (rastervalu-(y-intercept)). Use the Intercept value (coefficient) reported in the Regression table (step 19). Then follow steps 10-17 to calculate the RMSE for the y-intercept adjusted DSM.
    a. Generate new versions of Figures 1 and 2 (steps 18 and 20).
23. To calculate values for the rastervalu_slope_yint_correct column, subtract the y-intercept from the original DSM elevation (rastervalu) and divide the difference by the slope (=(rastervalu – (y-intercept))/slope). Use the slope and intercept value reported in the Regression table (step 19). Then follow steps 10-17 to calculate the RMSE for the slope and y-intercept adjusted DSM.
    a. Generate new versions of Figures 1 and 2 (steps 18 and 20)
24. Compare RMSE and DSM error plots (e.g., figure 2) for the original DSM, y-intercept adjusted DSM, and slope and y-intercept adjusted DSM. The 'best' scenario hopefully generates a detrended DSM error plot (e.g., bottom panel of figure 2) and the lowest RMSE. Note, there may be instances where the RMSE is similar among scenarios (i.e., within 0.5cm). In that case, choose the best option based on the DSM error plot. This 'best' scenario will be used to adjust the DSM raster in ArcPro and to calculate elevation and volumetric change limits of detection.
25. Save the excel file (.xlsx).

4. Adjusting DSM and Displaying Point Accuracy in ArcPro

26. Return to your ArcPro project with DSM and extract values to points layers in the contents and displayed on the map.
27. Under "Analysis" tab, click the geoprocessing toolbox, type in 'raster calculator'
28. If adjusting the DSM by y-intercept only (based on step 24)…
    a. double click the DSM in the raster box, double click the subtraction sign "-" in the tools box, type "(" in the expression box, enter in the y-intercept from step 19), type ")" in the expression box. The formula should look something like this: "tm_100ft_rgb_post_dsm_cs.tif" - (**0.001652811**) where 0.001652811 is the y-intercept.
    b. Name the output raster as desired (with e.g., yint_corrected at end of file name).
    c. Click Run
29. If adjusting the DSM by slope and y-intercept (based on step 24)…
    a. in the expression box, type "(", double click the DSM in the raster box, double click the subtraction sign "-" in the tools box, type "(" in the expression box, enter in the y-intercept from step 19), type ")" in the expression box, type ")",

double click the division sign "/" in the tools box, enter in the slope from step 19. The formula should look something like this: ("tm_100ft_rgb_post_dsm_cs.tif" - (**0.001652811**))/**0.944468743** where 0.001652811 is the y-intercept and 0.944468743 is the slope.

  b. Name the output raster as desired (with e.g., slope_yint_corrected at end of file name).
  c. Click Run

30. Under "Analysis" tab, click the geoprocessing toolbox
31. Type in "Extract values to points" and double click that tool to use.
    a. For input point features, find the groundpoint data that was added in step 3.
    b. For input raster, use the adjusted DSM created in step 28 or 29.
    c. Make sure to keep the output point feature unchanged except for the last bit after ".gdb\". Anything after the ".gdb\" will be the name of the point feature once the tool finishes.
    d. If you prefer not to change anything, you can always change the name of the point file after it is done running/shows up in the contents section.
    e. Click Run
32. Under the geoprocessing toolbox, type in "Table to excel".
33. Select the point file you just created using the "extract values to points" tool.
    a. For the output excel file, find the folder/path you'd like to save under and give the file a unique name.
    b. Click Run
    c. Open the excel file and check to make sure the corrected DSM elevations (RASTERVALU) match with what you calculated for rastervalu_yint_correct (step 22) or rastervalu_slope_yint_correct (step 23).
34. Right click the point file created in the "extract values to points" (step 31), select "Attribute Table"
35. Select "Add", to create a new field to calculate the difference between RTK measured elevations and DSM corrected elevations. Type in the new field name (i.e., Diff_Corr), hit tab to move to the next column and put the same thing for the "Alias".
    a. Tab again to select the "Data Type".
    b. Make sure the data type is **"Double"**.
    c. Finally click the "number format" column and click the 3 dots (…) that appear in the right side. A window with the Number Format Category will appear.
    d. Click the drop-down arrow and choose "Numeric" for Category and leave everything else as is.
    e. Click OK.
    f. Exit the table and be sure to save all changes when prompted.

36. Now you'll have a newly added blank column (with null values).
37. Click "Calculate", make sure the newly created field name (i.e., Diff_Corr) is selected.
38. Click in the white box with fields and then double click "elevation" under fields, then click the subtraction sign, and finish by double clicking "rastervalu" so that the formula reads "$feature.Elevation - $feature.RASTERVALU".
39. Click Apply and then OK.
40. Right click the EVTP point file and click "Symbology".
    a. Change primary symbology to "Graduated Colors", and change the field to whatever field name you added in step 35.
    b. Change the number of classes to however many you need/want, as well as adjust the values/limits for each class as needed.
    c. Symbol size/shape/color can also be changed by clicking on the symbol itself.
    d. Look for any spatial biases–are all the largest residuals around the edges? Are negative residuals spatially clustered, etc?
41. Exporting ArcGIS project (.ppkx)
    - Exported elevation projects are located at the following path: \imagery_analysis_arcgis_packages\xxx\elevation (where xxx = reserve initials)
    a. Share tab → Project (left side).
        - Start packaging = "Save package to file".
        - Item details = change the file location and name, as appropriate.
            1. If the projects are **reef-specific**, save the files as: **xxx_zz_mmddyy_elevation.ppkx**, where xxx = reserve initials, zz = reef initials, mmddyy = date sampled (*e.g.,* noc_mm_071423_elevation.ppkx).
            2. If the projects are **workflow-specific**, and contain all reefs, save the file as: **xxx_allreefs_yyyy_elevation.ppkx**, where xxx = reserve initials, yyyy = year sampled (*e.g.,* noc_allreefs_2023_elevation.ppkx).
            3. For the **experimental reefs**, save the files in one of the two formats listed above, and **add '_experiment.ppkx' at the end** of the name *(e.g.,* noc_mm_030824_elevation_experiment.ppkx).
        - Select the checkbox for "Share outside of organization". <u>Make sure all other checkboxes are unselected.</u>

5. Calculating elevation change limit of detection

-Note: limit of detection calculations require two DSMs in a time series.

42. Elevation change limit of detection calculation based on: Lane et al. 2003 and applied in James et al. 2017 and Dale et al. 2020.

a. Formula for elevation change limit of detection (LoD) when comparing two DSMs: $LoD_{elev} = t * \sqrt{(RMSE\ of\ DSM1^2 + RMSE\ of\ DSM2^2)}$
   i. where t is the t distribution value at a desired level of confidence (i.e., at 95% confidence, t = 1.96) and RMSE of DSM1 and DSM2 are the root mean squared errors of the pre- and post-excavation DSMs, respectively.

43. Open the 'workflow_elevation_database' template or the experiment version if entering data from the manipulative experiment (\imagery_data_spreadsheets). Enter the required data in the 'RMSE' and 'yint_slope values' tabs based on outputs generated in above sections of the workflow. Column header definitions are defined in the 'metadata' tab.
   a. Note, the data templates have an example from one reef in North Carolina. Delete this entry after entering your data and copying the formulas.
   b. In columns I and J of the 'elevation limit of detection' tab, re-enter the 'best' DSM adjustment determined in step 24 used for each DSM in the time series (e.g., pre- and post-excavation DSMs, respectively). For the experiment, where three DSMs were generated, enter the best DSM adjustment for the shell addition DSM in column K.
   c. In column K (or L for the experiment), enter a value of 1 for each row containing data. The 1 represents the t distribution value associated with 68% confidence.
   d. In column L (or M for the experiment), calculate elevation change LoD.
      i. The excel formula for calculating LoD_{elev} for pre vs post excavation based on 'best' DSM using y-intercept and slope adjustment is: =$K3*SQRT(RMSE!M3^2+RMSE!P3^2).
      ii. Repeat the calculation, making sure to reference the correct RMSE based on the 'best' DSM adjustment for the remaining reefs in your dataset.
      iii. Note, for the experiment, an additional column of LoD calculations is necessary to account for the post-excavation vs shell addition DSMs. The format of the excel formula is the same as above with different RMSE's referenced.
   e. In column N (or O and P for the experiment), convert LoD calculations to meters by dividing LoD values in column L (or columns M and N for the experiment) by 100.

III. Oyster Reef Rugosity Workflow

Workflow lead and contact: Gary Sundin (SundinG@dnr.sc.gov)

Overview

1. Introduction
2. Prepare data
3. Create lines from RTK data
4. Combine rasters (optional)
5. Add line surface information
6. Calculate GIS line rugosity
7. Create rugosity polygons
8. Add polygon surface information
9. Calculate polygon rugosity
10. Data management and final output

1. Introduction

Rugosity is an index of surface roughness or complexity. Whether it's a line or an area, rugosity refers to the surface deviation from a perfectly smooth form.

1.1 Profile Rugosity (Line):

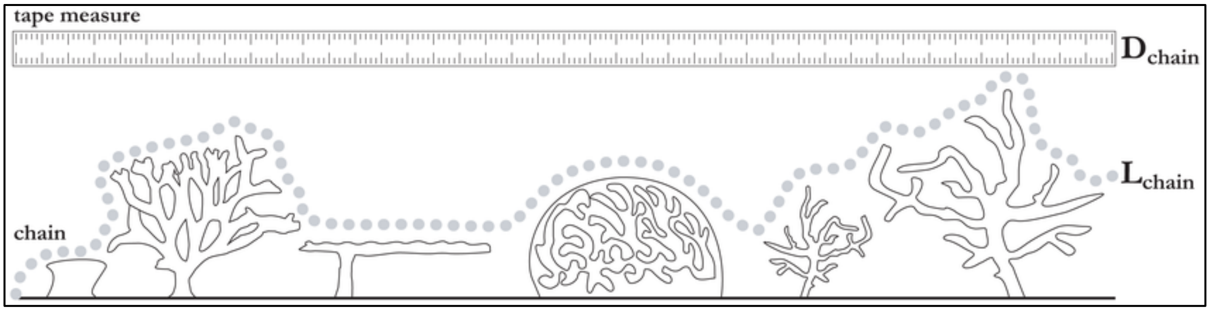
When considering a line (or profile), simple rugosity is quantified as the ratio of the length of the real surface to the length of its ideal linear form. Larger values are relatively rougher than lower values, and a perfectly smooth surface has a simple rugosity value of "1".

1.2 Area Rugosity (Surface):

For three-dimensional data, the rugosity of a surface is calculated as the ratio between the contoured surface area and the ideal planar area.

Basic rugosity = L/D

Where L = profile distance, and D = straight-line distance



This workflow explains how to use ground-based RTK point data and UAV-generated raster elevation data to calculate GIS-based rugosity values for lines and polygons.

Input files needed:

- Corrected DSM(s) for area(s) where rugosity data were collected
- Table of **RTK point data** for endpoints of lines where field rugosity data were collected
- Table of in situ rugosity results data and key metadata (**xxx_raw_data_rugosity**, where xxx = three letter reserve abbreviation)

Data templates (.csv format)

- **xxx_raw_data_rugosity**: base file with key metadata and field-based rugosity measurements for joining to final GIS output (this template has already been populated) (*e.g.,* ace_raw_data_rugosity)
- **workflow_input_rtk_rugosity**: point dataset of endpoints of lines where rugosity data were collected in the field
- **workflow_rugosity_database**: final output containing key metadata, field-based rugosity results, and GIS-based rugosity results

Note, all of these templates can be found at the following paths: \in-situ_data_spreadsheets or \imagery_data_spreadsheets

2. Prepare data

2.1 Determine Project Structure

Prior to starting, decide whether all sampled reefs will be housed in the same ArcGIS project (e.g., each reef will have a separate Map tab), or if each ArcGIS project will house an individual reef. *Note, your decision will affect the naming convention of the final exported ArcGIS project(s), specified at the end of the workflow.*

2.2 Tabular Data Structure

Base data is line level data; each line is the line between a pair of RTK rugosity line endpoints. For this workflow each record must share a LineID value that matches a pair of endpoints in the RTK point file. The example provided below is based upon the data template titled: **xxx_raw_data_rugosity** (*e.g.,* ace_raw_data_rugosity). A copy of each Reserve's data can be found at \in-situ_data_spreadsheets. The file contains key metadata as well as field-based rugosity results for each rugosity measurement. A column has also been added to this table with LineID values to be used in this workflow (reserve initials + RTK rugosity point names). Please download this template (already populated for all reserves) from \in-situ_data_spreadsheets. Be sure to use the unique LineID in this file throughout the workflow.

This data structure will facilitate summaries or analyses among groups (*e.g.,* sites, reef types, etc.) and between GIS and field-based methods.

	A	B	C	D	E	F	G	H	I	J	K	L
1	**Site**	**Reef_coord_**	**Reef_coord_e**	**Date**	**Reef_name**	**Reef_abbreviation**	**Reef_type**	**Harvest_status**	**Project_name**	**FieldRugosity_level**	**FieldRugosity_slope**	**LineID**
2	ACE	3609750.78	565760.5976	#########	Closed_R1	co	Patch	Closed	ACE_rugosity	1.11875	1.11875	s1_1_1
3	ACE	3609750.78	565760.5976	#########	Closed_R1	co	Patch	Closed	ACE_rugosity	1.826530612	1.808080808	s1_1_2
4	ACE	3609750.78	565760.5976	#########	Closed_R1	co	Patch	Closed	ACE_rugosity	1.826530612	1.808080808	s1_1_3
5	ACE	3609721.38	565797.9366	#########	Closed_R2	ct	Patch	Closed	ACE_rugosity	2.057471264	2.011235955	s1_2_1
6	ACE	3609721.38	565797.9366	#########	Closed_R2	ct	Patch	Closed	ACE_rugosity	1.754901961	1.737864078	s1_2_2
7	ACE	3609721.38	565797.9366	#########	Closed_R2	ct	Patch	Closed	ACE_rugosity	2.156626506	2.156626506	s1_2_3
8	ACE	3609703.33	565817.7023	#########	Closed_R3	cr	Patch	Closed	ACE_rugosity	2.081395349	2.057471264	s1_3_1
9	ACE	3609703.33	565817.7023	#########	Closed_R3	cr	Patch	Closed	ACE_rugosity	2.209876543	1.967032967	s1_3_2
10	ACE	3609703.33	565817.7023	#########	Closed_R3	cr	Patch	Closed	ACE_rugosity	2.324675325	2.209876543	s1_3_3
11	ACE	3609305.66	567238.3307	#########	Open_R1	oo	Patch	Open	ACE_rugosity	2.156626506	2.209876543	s2_1_1
12	ACE	3609305.66	567238.3307	#########	Open_R1	oo	Patch	Open	ACE_rugosity	2.294871795	2.355263158	s2_1_2
13	ACE	3609305.66	567238.3307	#########	Open_R1	oo	Patch	Open	ACE_rugosity	2.209876543	2.265822785	s2_1_3
14	ACE	3609278.69	567253.4171	#########	Open_R2	ot	Patch/Fringe	Open	ACE_rugosity	2.632352941	2.753846154	s2_2_1
15	ACE	3609278.69	567253.4171	#########	Open_R2	ot	Patch/Fringe	Open	ACE_rugosity	2.355263158	2.386666667	s2_2_2

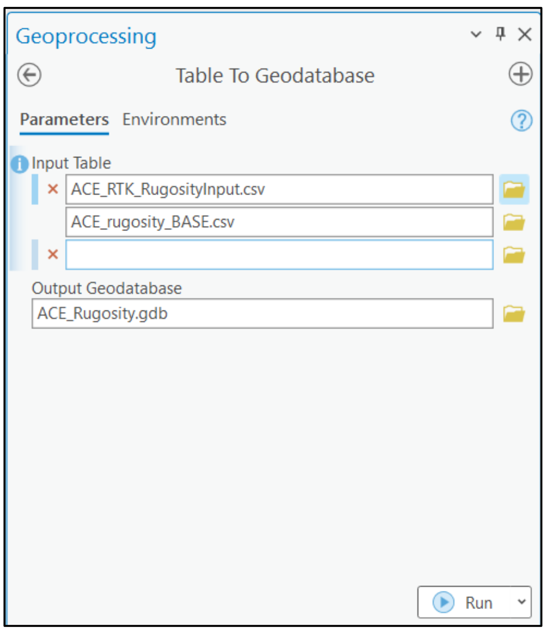
RTK data is point level data and should be structured in pairs, with each pair sharing a **common identifier** and representing the endpoints of a single line. Instructions are provided for starting with a .csv file containing LineID, PointID, easting, northing, and elevation data for each point. Note that the **LineID** is unique to each **PAIR**, where each pair represents the endpoints of the line where field-based rugosity was measured. Please use the same unique LineID that is found in the xxx_raw_data_rugosity template. The example provided below is based upon the data template titled: **workflow_input_rtk_rugosity**. This workflow assumes that a geodatabase (.gdb) has been created and will be used throughout the process.

LineID	PointID	Easting	Northing	Elevation
s1_1_1	s1_1_1_1	565765.1	3609757	0.101
s1_1_1	s1_1_1_2	565765.3	3609756	0.117
s1_1_2	s1_1_2_1	565760.3	3609754	-0.042
s1_1_2	s1_1_2_2	565760.8	3609753	0.09
s1_1_3	s1_1_3_1	565760.5	3609746	0.197
s1_1_3	s1_1_3_2	565760.2	3609747	0.236
s1_2_1	s1_2_1_1	565799.4	3609723	-0.251
s1_2_1	s1_2_1_2	565798.8	3609723	-0.258
s1_2_2	s1_2_2_1	565798.9	3609720	-0.099
s1_2_2	s1_2_2_2	565798.2	3609720	-0.06
s1_2_3	s1_2_3_1	565797.4	3609721	0.175

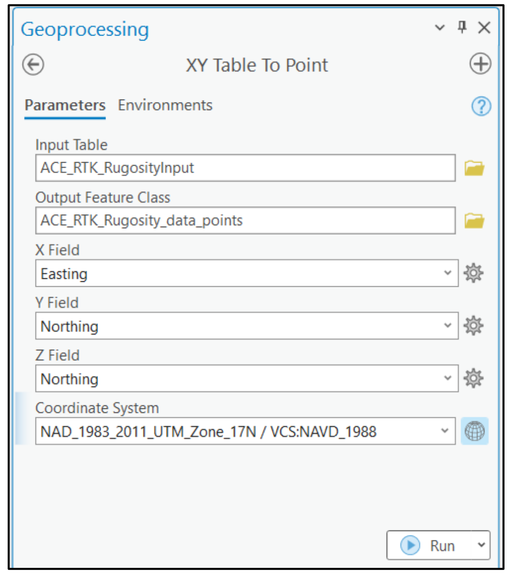
2.3 Import Tables

When the tabular data are in the correct format, import the tables into a geodatabase. If using an .xlsx (excel) file, copy the data to a new workbook and save as a .csv file.

- Search for the "**Table to Geodatabase**" tool
- For the "Input Table" field, add your RTK point data and (if using) xxx_raw_data_rugosity table. These can be imported singly or at the same time.



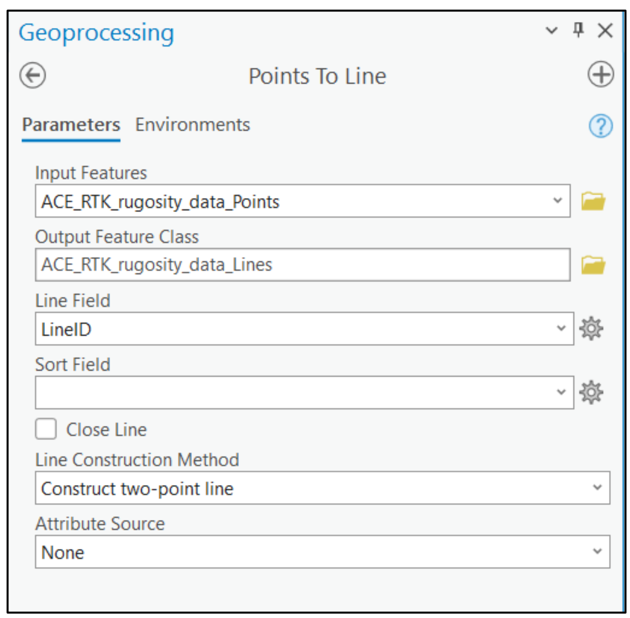
3. Create lines from RTK data



3.1 Convert RTK data table to GIS data

- Search for "**XY Table to Point**" tool
- Input table = .csv rugosity file with RTK coordinates
- Output feature class = converted file with coordinates displayed
- X Field = "Easting" column with X coordinates in .csv
- Y Field = "Northing" column with Y coordinates in .csv
- Z field = "Elevation" column with Z coordinates in .csv
- Coordinate system = click and drag (or select from dropdown menu) a DEM/ortho/other file with coordinate system of interest (e.g., NAD 1983 2011 UTM Zone xxN, NAVD88)

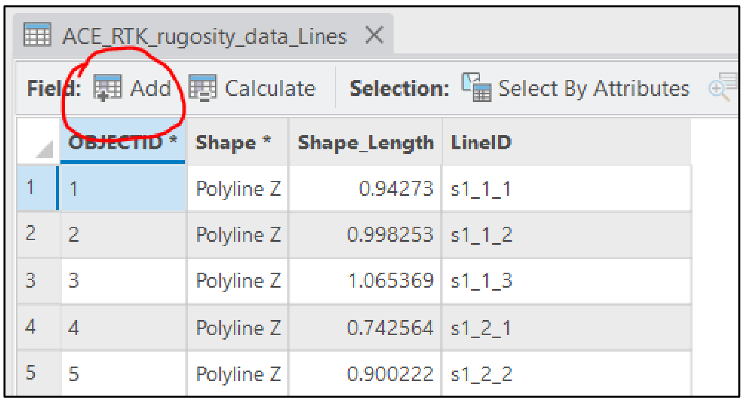
3.2.A Automatic method (preferred). This method can be used if rugosity points are in pairs that have a common identifier as described in the Data Preparation section. If manual digitizing of lines is preferred, skip to 2.2B for that alternative.



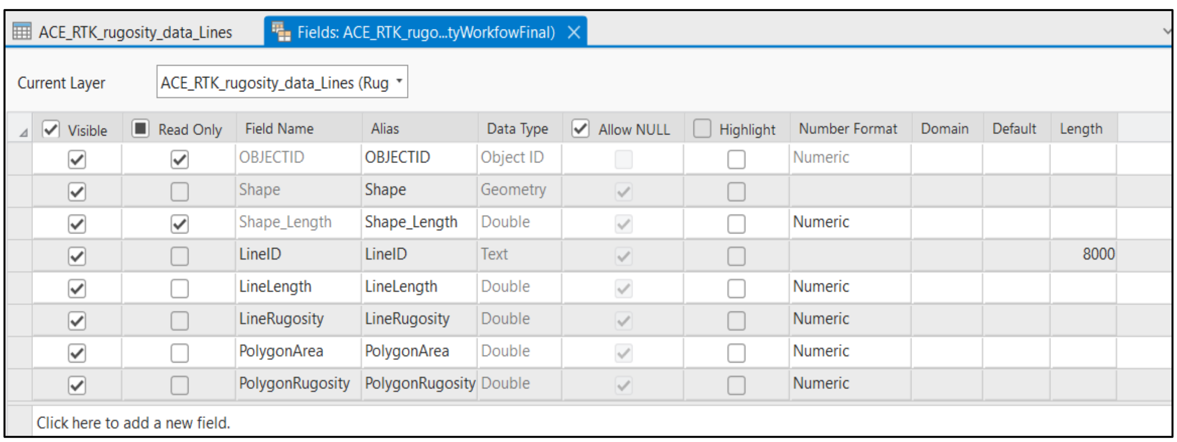
- Search for the "**Points to Line**" tool
- Input: RTK rugosity point file
- Output: Line file to location of choice
- Line Field: enter the common identifier field
- Sort Field—can be left blank
- Close line – leave unchecked
- Line Construction Method: construct two-point line
- Attribute source: none
- Environments: Output has Z values: Enabled (not shown)

3.2.A.1 The “**Points to Line**” tool output contains only the LineID and several automatically generated fields.

- With line feature attribute table open, use the “Add” button to add 4 fields for LineLength, LineRugosity, PolygonArea, and PolygonRugosity, each Double data types.
- Save the changes.



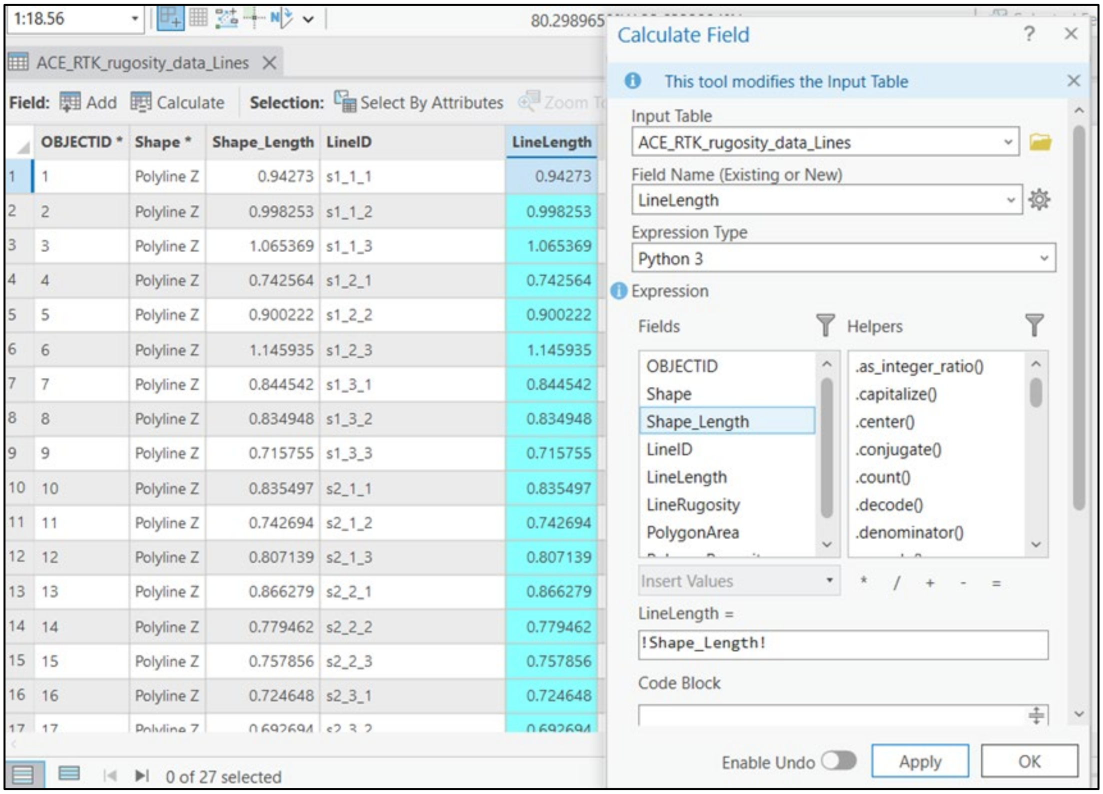
	OBJECTID *	Shape *	Shape_Length	LineID
1	1	Polyline Z	0.94273	s1_1_1
2	2	Polyline Z	0.998253	s1_1_2
3	3	Polyline Z	1.065369	s1_1_3
4	4	Polyline Z	0.742564	s1_2_1
5	5	Polyline Z	0.900222	s1_2_2



Visible	Read Only	Field Name	Alias	Data Type	Allow NULL	Highlight	Number Format	Domain	Default	Length
☑	☑	OBJECTID	OBJECTID	Object ID	☐	☐	Numeric			
☑	☐	Shape	Shape	Geometry	☑	☐				
☑	☑	Shape_Length	Shape_Length	Double	☑	☐	Numeric			
☑	☐	LineID	LineID	Text	☑	☐				8000
☑	☐	LineLength	LineLength	Double	☑	☐	Numeric			
☑	☐	LineRugosity	LineRugosity	Double	☑	☐	Numeric			
☑	☐	PolygonArea	PolygonArea	Double	☑	☐	Numeric			
☑	☐	PolygonRugosity	PolygonRugosity	Double	☑	☐	Numeric			

3.2.A.2 Right click on the “LineLength” field header and select “Calculate Field”

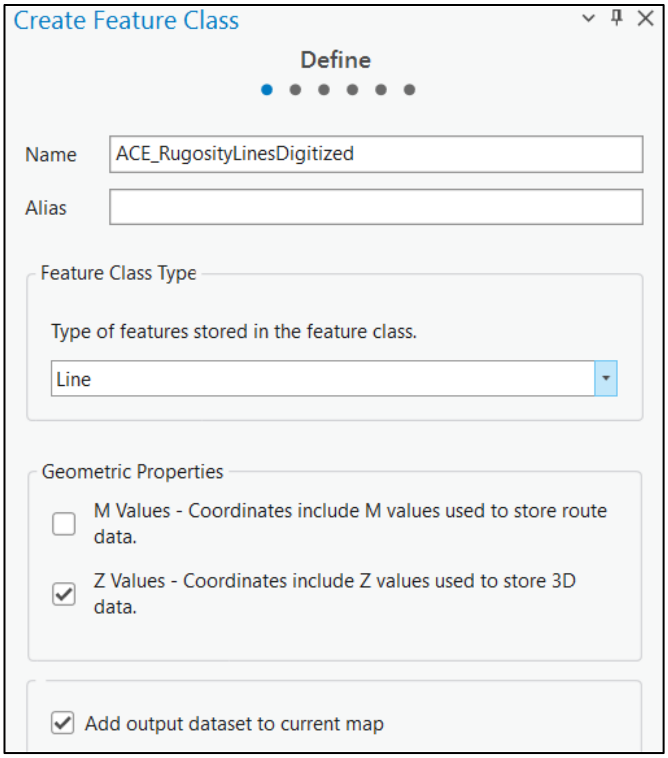
- Leave “Input Table”, “Field Name”, and “Expression Type” as default.
- To fill in the calculation field, double click on “Shape_Length” (surface length) under fields, and Apply
- This step simply copies the auto-generated length field into a permanent location where it will not be altered in subsequent steps.
- Close the calculate field dialogue box

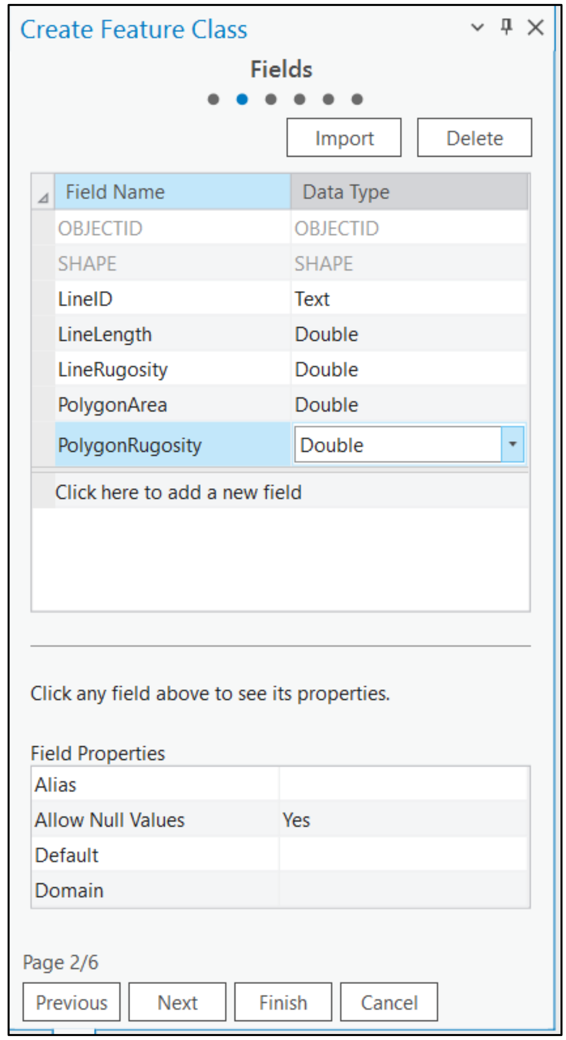


3.2B Digitize lines from the points (**if using Step2A, skip this step and proceed to Step 3**)

3.2.B.1 Create an empty line feature class in your geodatabase to digitize lines into

- Right click on the geodatabase (ending in .gdb) and select New > Feature Class
- Apply an appropriate name
- Feature class type = 'Line'
- In Geometric Properties select to enable "Z values" and leave "Add output…" checked
- Click Next
- In "Fields" menu, add fields for LineID (Text), LineLength (Double), LineRugosity (Double), PolygonArea (Double), and PolyRugosity (Double)

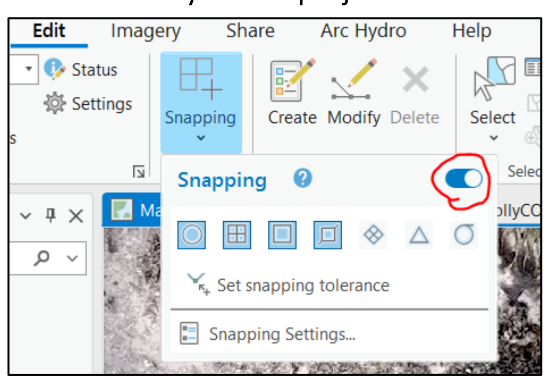




- Click Next
- Set the current horizontal (XY) and vertical (Z)
- Click Next
- Leave “Tolerance” and “Resolution” and “Storage Configuration” settings at default
- Select “Finish” and blank line feature should automatically add to project

3.2.B.2 Set or verify snapping tolerance

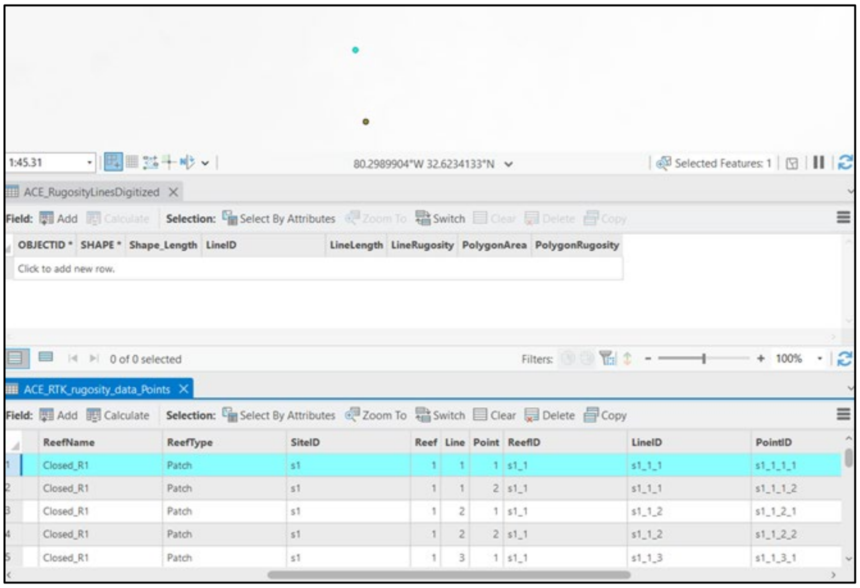
- From “Edit” tab, in the snapping group, make sure snapping is turned on
- Choose “Snapping Settings” and check that the general XY tolerance is set to something like 10 pixels

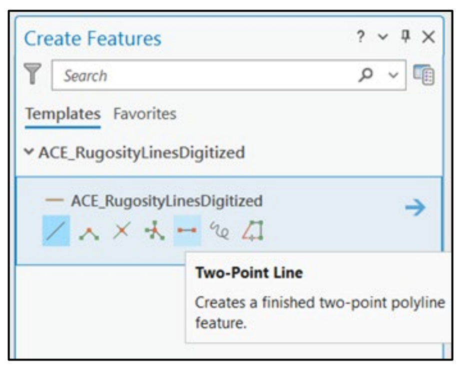


- Having snapping turned on will make it easy to select rugosity points to create the lines

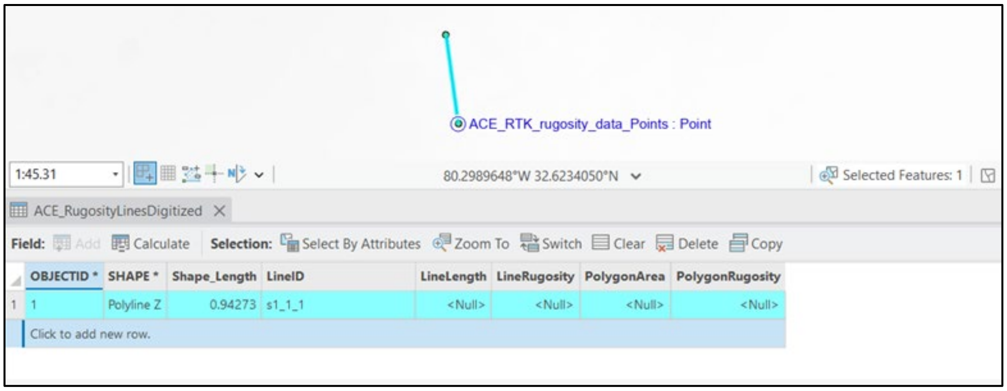
3.2.B.3 Digitize lines

- It is a good idea to have the point feature containing the RTK point data and the blank line file both open so they can be viewed together (for example, stacked)

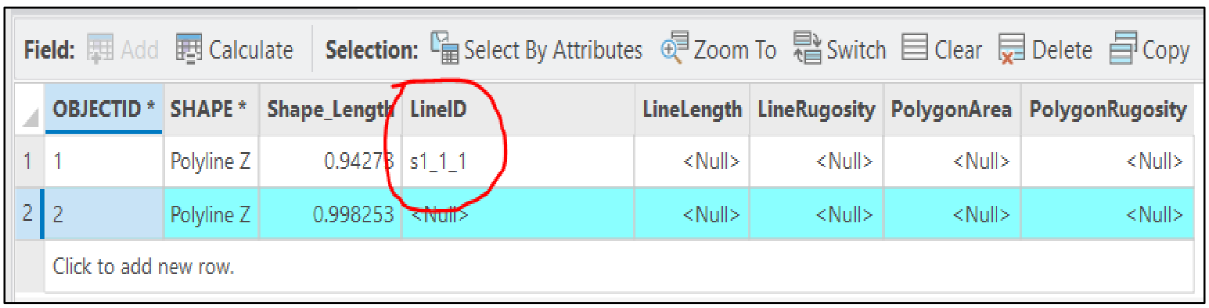




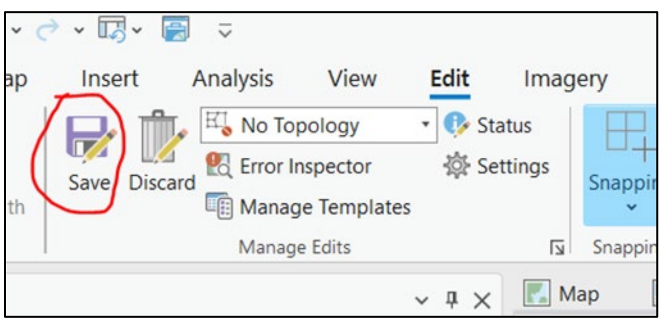
- The blank line file must be turned on in the Contents pane.
- On the “Edit” tab, in the “Features” group, select the “Create” option to open the “Create Features” panel
- On the “Create Features” panel choose the rugosity line feature and the “**Two-Point Line**” tool
- Use the Points file to identify and track the lines as you make them. You can double click on a point to center it in your view
- Hover over a point to select it; after a circle appears around the point click to select; hover over the second point and repeat to complete a 2-point line. The line will appear in your line feature



- Manually type in the correct LineID, based on points used to create it



- Periodically save your work by clicking the save icon on the "Edit" ribbon menu
- Complete for all rugosity lines

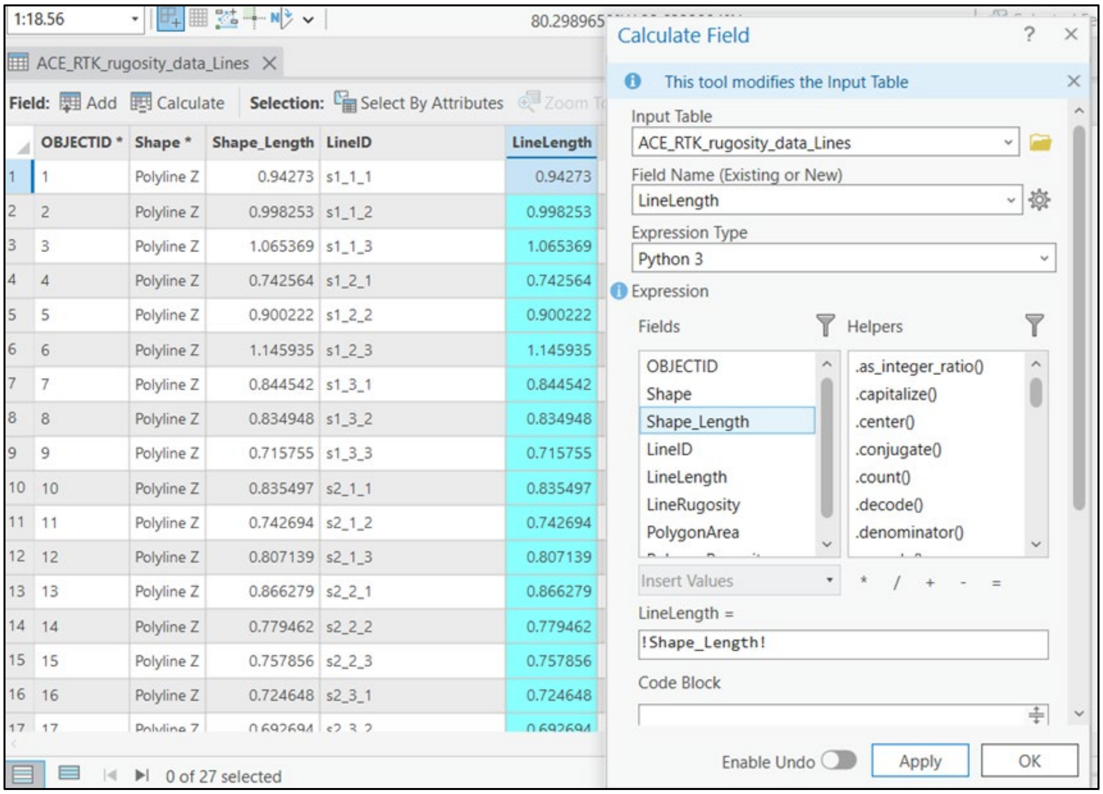


- When complete, make sure all edits are saved and all selections are cleared

3.2.B.4 Populate the LineLength Field

- Right click on the "LineLength" field header and select "Calculate Field"
- Leave "Input Table", "Field Name", and "Expression Type" as default

- To fill in the calculation field, double click on “Shape_Length” (surface length) under Fields, and Apply
- This step simply copies the auto-generated length field into a permanent location where it will not be altered in subsequent steps



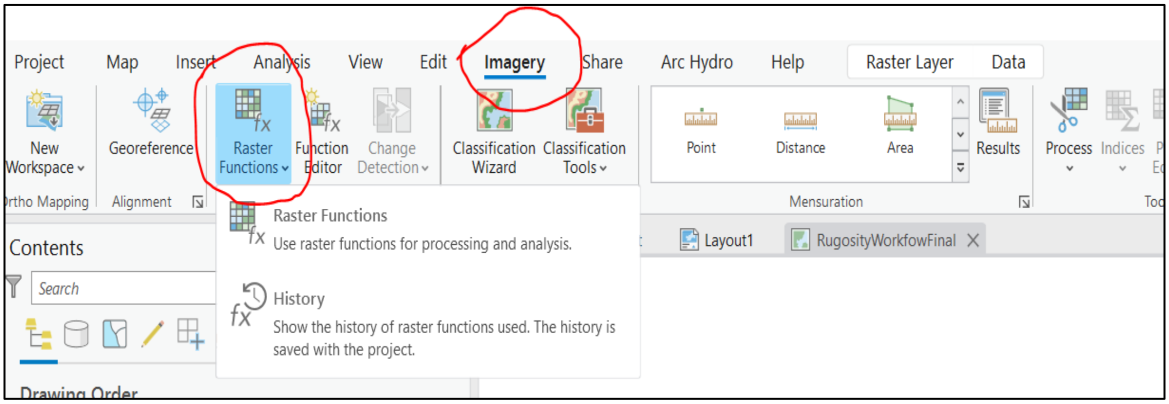
4. Combine rasters (optional)

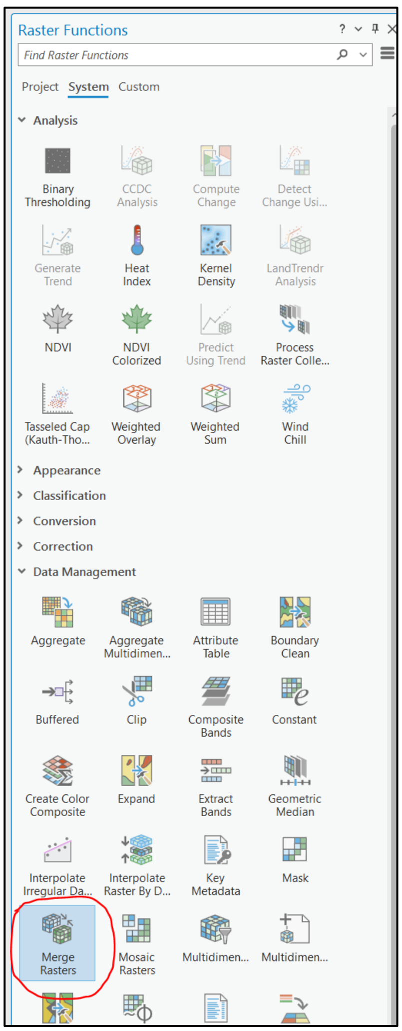
This method can be used to combine the DEMs from several sites so rugosity can be calculated for multiple sites at the same time. This can be skipped if rugosity is calculated separately for each site but is very convenient for calculating values across multiple sites. This method uses a raster function and will not change the individual rasters.

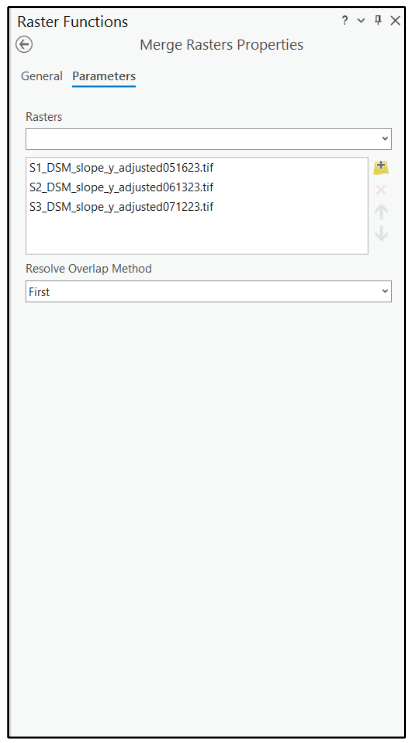
4.1 Apply raster function

- Add corrected rasters to your project
- From the “Imagery” menu, choose “Raster Functions” to open raster function pane
- From “Data Management” group, select “Merge Rasters”
- In dialogue box, add rasters

- Leave Resolve Overlap set to “first” and Output Layer Type as “Raster Layer”
- Select “Create New Layer”
- The merged raster layer is added to the project



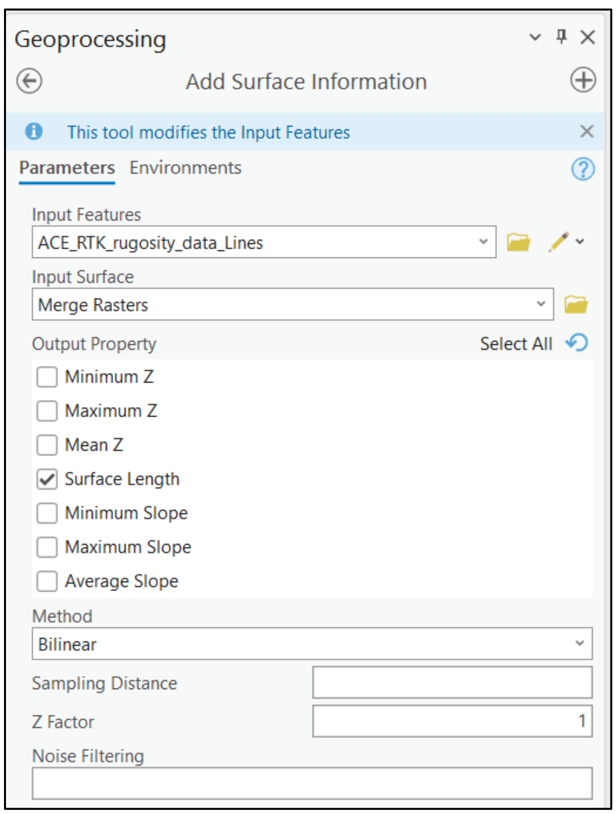




5. Add line surface information

5.1 In Geoprocessing pane, search for "**Add Surface Information**" tool

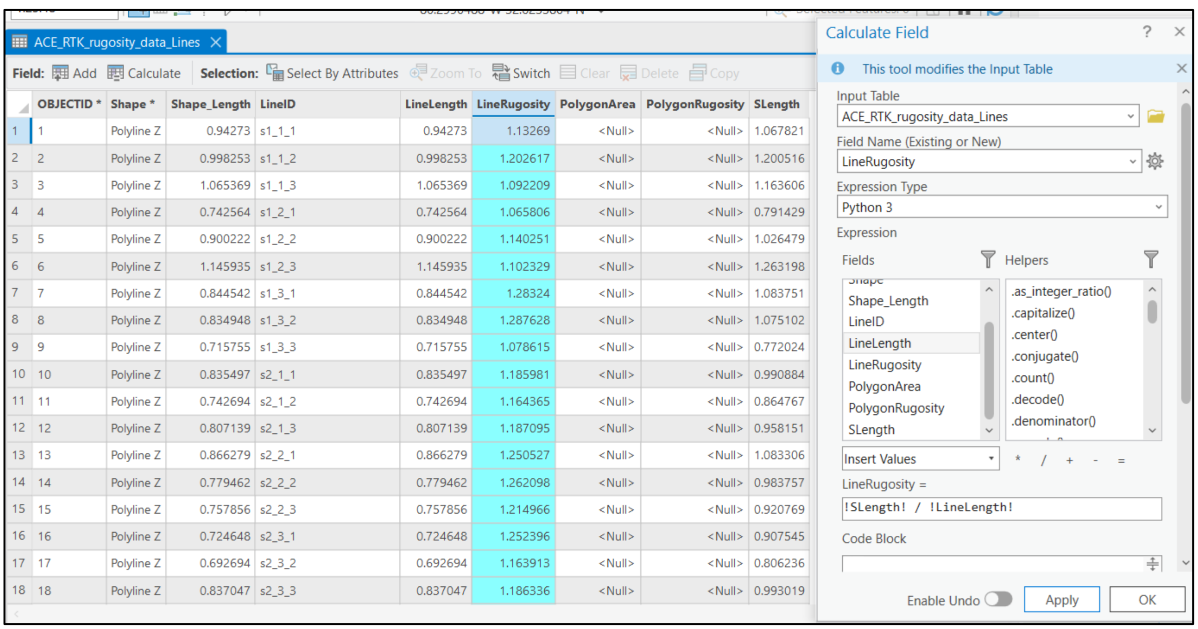
- Add rugosity line file as the Input Features
- Add elevation raster for the Input Surface. This will be either for a single site or a combined raster for multiple sites. Example is for the merged raster described in optional step 3.
- Select Surface Length
- Leave Method default as Bilinear, and Noise Filtering blank
- Sampling distance can remain blank to use the actual pixel cell size, or a value can be chosen. It is recommended, as in this example, that it is left blank, to use actual raster cell size.
- Before running tool, clear any selections. If any records are selected in the line file, the tool will only calculate for that selected record.
- A field called "**SLength**" will be added to the line file and populated with the surface length.



6. Calculate GIS line rugosity

6.1 Recall: rugosity = L/D

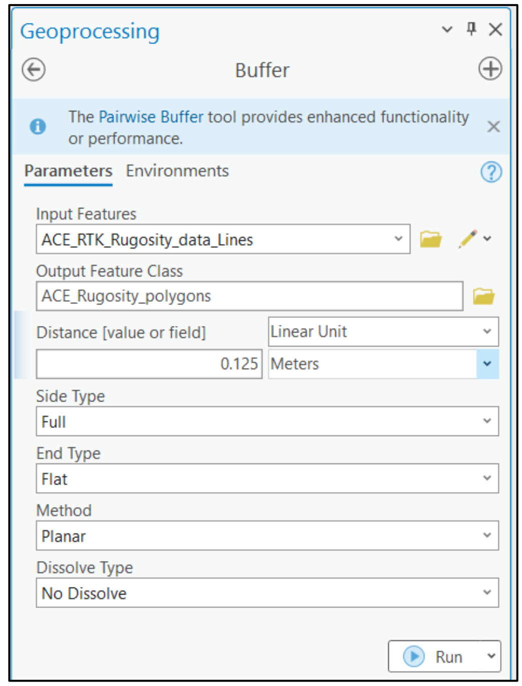
- In the line feature class attribute table, field names, L = “SLength” and D = “LineLength” (calculated in a previous steps)
- In attribute table, right-click on the column heading for “LineRugosity” to highlight column and choose “Calculate Field” from the dialog box
- In the calculate field dialog box leave the “Input Table” and “Field Name” and “Expression Type” as default.
- Delete any pre-existing entries in the calculation field
- To fill in the calculation field, double click on “SLength” (surface length) under fields, then select “/” (divide by), then double click “LineLength” (planar length).
- Click “Apply” to calculate rugosity.



7. Create rugosity polygons

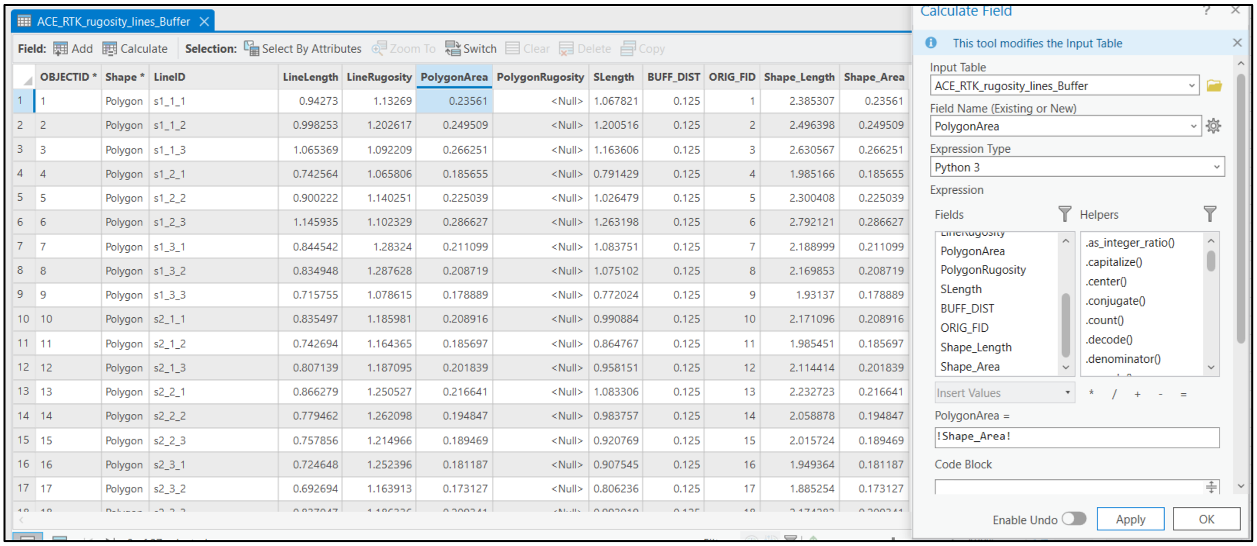
7.1 Create Buffer

- Make sure all edits are saved and all selections are cleared
- In Geoprocessing Panel, search for "Buffer" tool. There are several options—be sure to choose the tool simply called "Buffer" (not Buffer 3D, Graphic Buffer, Create Buffer, etc.).
- For input features, use the rugosity lines previously created.
- Give the output a name/location
- Enter 0.125 for the distance and select "Meters" as the "Linear Unit"
- Set "Side Type" as Full, "End Type" as Flat, "Method' as Planar and "Dissolve Type" as No Dissolve
- Run tool
- Result will be a new feature consisting of small rectangles around the rugosity lines and an attribute table containing all the previous fields PLUS additional fields including "Shape_Area".

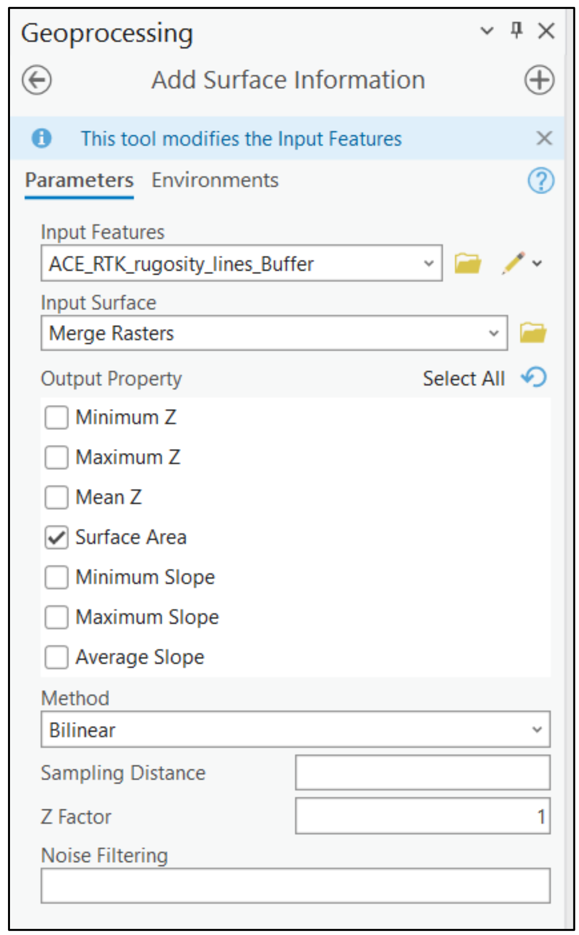


7.2 Populate PolygonArea field

- In the Buffer feature attribute table, save any edits and clear any selections
- Right click on the "PolygonArea" field header and select "Calculate Field"
- Leave "Input Table", "Field Name", and "Expression Type" as default
- Delete any pre-existing entries in the calculation field
- To fill in the calculation field, double click on "Shape_Area" (planar surface area) under fields, and Apply
- This step simply copies the auto-generated length field into a permanent location where it will not be altered in subsequent steps
- Close dialogue box



8. Add polygon surface information



8.1 From Geoprocessing Pane, search for "Add Surface Information" tool.

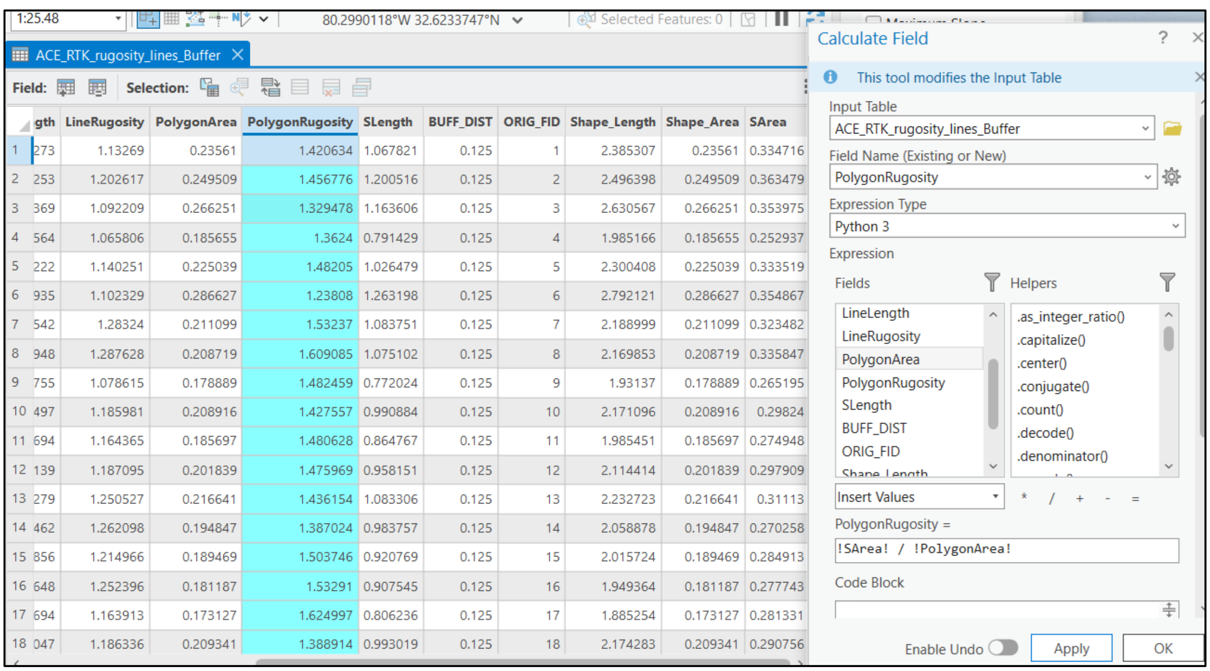
- Add rugosity buffer polygon file as the Input Features
- Add elevation raster for the Input Surface. This will be either for a single site or combined raster for multiple sites. Example is for the merged raster described in optional step 3.
- Select Surface Area
- Leave Method default as Bilinear, and Noise Filtering blank
- Sampling distance can remain blank to use the actual pixel cell size, or a value can be chosen. It is recommended, as in this example, that it is left blank, to use actual raster cell size.
- Before running tool, clear any selections. If any records are selected in the polygon file, the tool will only calculate for that selected record.

- A field called “SArea” will be added to the polygon file and populated with the surface area

9. Calculate polygon rugosity

9.1 Save any edits and clear any selections

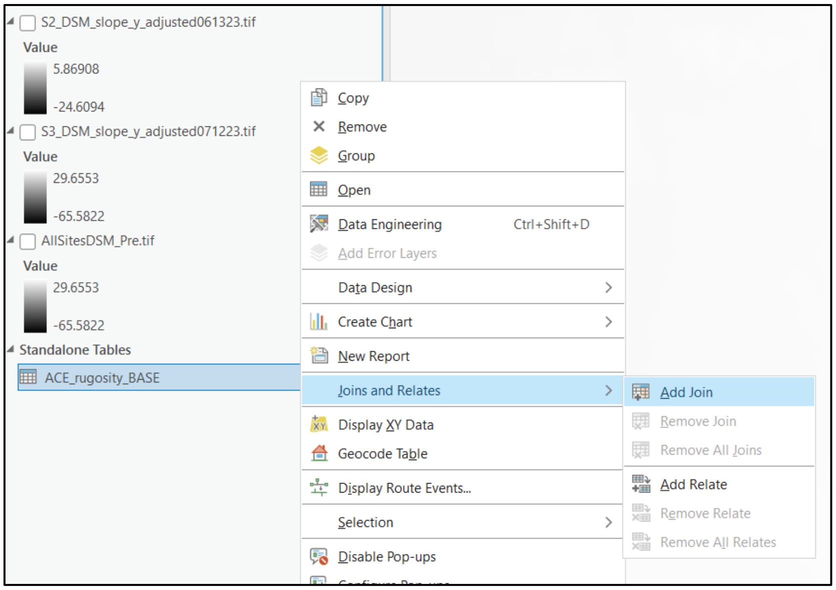
- In polygon file attribute table, right-click on the column heading for “PolygonRugosity” to highlight column and choose “Calculate Field” from the dialog box.
- In the calculate field dialog box leave the “Input Table” and “Field Name” and “Expression Type” as default.
- To fill in the calculation field, double click on “SArea” (profile surface area) under Fields, then select “/” (divide by), then double click “PolygonArea” (planar area).
- Click “Apply” to calculate rugosity.



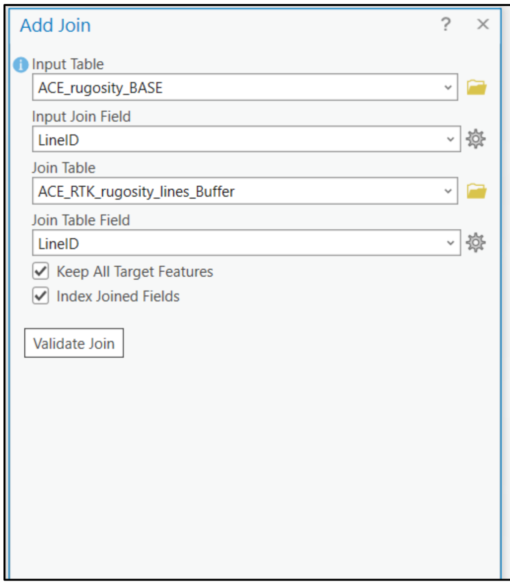
10. Data management and final output

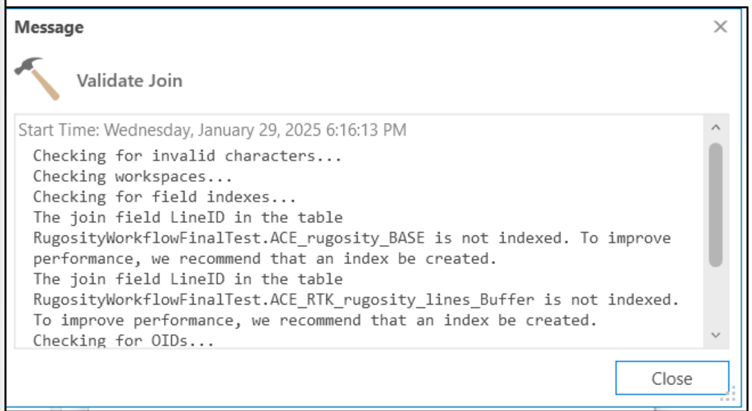
10.1 Joining tables

- Save any edits and clear any selections.
- Make sure **xxx_raw_data_rugosity** is available in the geodatabase (imported Step 1.1) and add to project so it is visible in Contents pane.
- Right click on the file in the Contents Pane, select “Joins and Relates” and “Add Join”



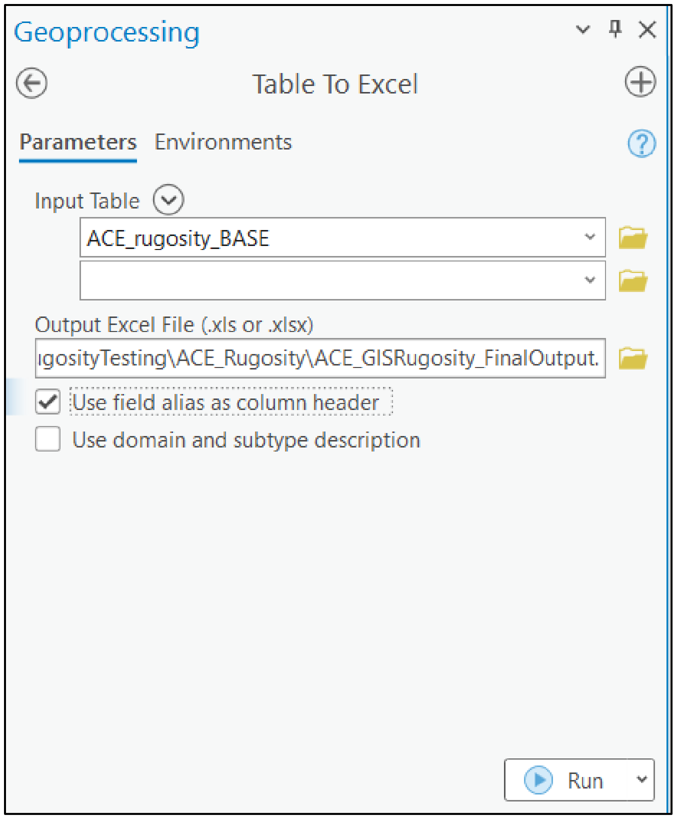
- On the join dialog box, as the Join Table, select the results table which is the **Polygon buffer** created in the steps above.
- Select “LineID” as the input join field and the same field should automatically populate for the join table.
- Choose “Index Joined Fields”.
- It is a good idea to “Validate Join” which will create a message indicating if there are any errors. If not, close this message.
- Select “OK”.





10.2 Exporting tables

- Input is the joined table created in the previous step.
- Search for “Table to Excel” tool.
- For “Input Table” select the results table
- Check the “Use field alias as column header” box to simplify field headers (optional)
- Choose a location and run tool
- An excel spreadsheet is created
- Alternatively, the table can be selected and copied directly to a spreadsheet



10.3 Final data manipulation

- If the **workflow_input_rtk_rugosity** template and the **xxx_raw_data_rugosity** template were used to configure data for the previous steps, then the output data will be easy to configure for entry into the **workflow_rugosity_database** spreadsheet.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	
1	OBJECTID	Site	ɛf_coord_north	ef_coord_easti	Date	Reef_name	_abbrevi	Reef_type	Harvest_status	Project_name	ɛldRugosity_le	ldRugosity_slc	LineID	OBJECTID	
2	1	ACE	3609750.775	565760.5976	###########	Closed_R1	co	Patch	Closed	ACE_rugosity	1.11875	1.11875	s1_1_1	1	s1
3	2	ACE	3609750.775	565760.5976	###########	Closed_R1	co	Patch	Closed	ACE_rugosity	1.826530612	1.808080808	s1_1_2	2	s1
4	3	ACE	3609750.775	565760.5976	###########	Closed_R1	co	Patch	Closed	ACE_rugosity	1.826530612	1.808080808	s1_1_3	3	s1
5	4	ACE	3609721.383	565797.9366	###########	Closed_R2	ct	Patch	Closed	ACE_rugosity	2.057471264	2.011235955	s1_2_1	4	s1
6	5	ACE	3609721.383	565797.9366	###########	Closed_R2	ct	Patch	Closed	ACE_rugosity	1.754901961	1.737864078	s1_2_2	5	s1
7	6	ACE	3609721.383	565797.9366	###########	Closed_R2	ct	Patch	Closed	ACE_rugosity	2.156626506	2.156626506	s1_2_3	6	s1
8	7	ACE	3609703.328	565817.7023	###########	Closed_R3	cr	Patch	Closed	ACE_rugosity	2.081395349	2.057471264	s1_3_1	7	s1
9	8	ACE	3609703.328	565817.7023	###########	Closed_R3	cr	Patch	Closed	ACE_rugosity	2.209876543	1.967032967	s1_3_2	8	s1
10	9	ACE	3609703.328	565817.7023	###########	Closed_R3	cr	Patch	Closed	ACE_rugosity	2.324675325	2.209876543	s1_3_3	9	s1
11	10	ACE	3609305.663	567238.3307	###########	Open_R1	oo	Patch	Open	ACE_rugosity	2.156626506	2.209876543	s2_1_1	10	s2
12	11	ACE	3609305.663	567238.3307	###########	Open_R1	oo	Patch	Open	ACE_rugosity	2.294871795	2.355263158	s2_1_2	11	s2
13	12	ACE	3609305.663	567238.3307	###########	Open_R1	oo	Patch	Open	ACE_rugosity	2.209876543	2.265822785	s2_1_3	12	s2
14	13	ACE	3609278.693	567253.4171	###########	Open_R2	ot	Patch/Fringe	Open	ACE_rugosity	2.632352941	2.753846154	s2_2_1	13	s2
15	14	ACE	3609278.693	567253.4171	###########	Open_R2	ot	Patch/Fringe	Open	ACE_rugosity	2.355263158	2.386666667	s2_2_2	14	s2
16	15	ACE	3609278.693	567253.4171	###########	Open_R2	ot	Patch/Fringe	Open	ACE_rugosity	2.182926829	2.294871795	s2_2_3	15	s2
17	16	ACE	3609267.433	567277.3199	###########	Open_R3	or	Fringe	Open	ACE_rugosity	2.355263158	2.294871795	s2_3_1	16	s2
18	17	ACE	3609267.433	567277.3199	###########	Open_R3	or	Fringe	Open	ACE_rugosity	2.418918919	2.418918919	s2_3_2	17	s2
19	18	ACE	3609267.433	567277.3199	###########	Open_R3	or	Fringe	Open	ACE_rugosity	2.209876543	2.182926829	s2_3_3	18	s2
20	19	ACE	3609960.803	566553.5064	###########	Culture_R1	uo	Patch	Culture	ACE_rugosity	1.217687075	1.234482759	s3_1_1	19	s3
21	20	ACE	3609960.803	566553.5064	###########	Culture_R1	uo	Patch	Culture	ACE_rugosity	1.52991453	1.443548387	s3_1_2	20	s3
22	21	ACE	3609960.803	566553.5064	###########	Culture_R1	uo	Patch	Culture	ACE_rugosity	1.455284553	1.387596899	s3_1_3	21	s3
23	22	ACE	3609978.165	566561.5799	###########	Culture_R2	ut	Patch	Culture	ACE_rugosity	1.376923077	1.356060606	s3_2_1	22	s3
24	23	ACE	3609978.165	566561.5799	###########	Culture_R2	ut	Patch	Culture	ACE_rugosity	1.704761905	1.721153846	s3_2_2	23	s3
25	24	ACE	3609978.165	566561.5799	###########	Culture_R2	ut	Patch	Culture	ACE_rugosity	1.269503546	1.278571429	s3_2_3	24	s3
26	25	ACE	3609967.417	566582.6799	###########	Culture_R3	ur	Patch	Culture	ACE_rugosity	1.504201681	1.672897196	s3_3_1	25	s3
27	26	ACE	3609967.417	566582.6799	###########	Culture_R3	ur	Patch	Culture	ACE_rugosity	1.316176471	1.387596899	s3_3_2	26	s3
28	27	ACE	3609967.417	566582.6799	###########	Culture_R3	ur	Patch	Culture	ACE_rugosity	1.772277228	1.826530612	s3_3_3	27	s3

- The following column headings from the Base table should not change and can be copied directly into the results template
    - Site
    - Reef_coord_northing
    - Reef_coord_easting
    - Date
    - Reef_name
    - Reef_abbreviation
    - Reef_type
    - Harvest_status
    - Project_name
    - FieldRugosity_level
    - FieldRugosity_slope

- The following column headers in the output table (left) can be copied into the corresponding results template (right) as shown below
    - LineLength = GIS_Planar_LineLength
    - SLength = GIS_LineProfile_length
    - LineRugosity = GIS_LineRugosity
    - PolygonArea = GIS_Planar_PolygonArea
    - Sarea = GIS_3D_Area
    - PolygonRugosity = GIS_PolygonRugosity

- Alternatively, the output table can be modified by removing the non-used headers (e.g. OBJECTID, LineID, Shape_Length, Shape_Area, etc.), and renaming, adding, and relocating the appropriate columns as needed.

10.4 Exporting ArcGIS project (.ppkx)

- Exported rugosity projects are located at the following path: \imagery_analysis_arcgis_packages\xxx\rugosity (where xxx = reserve initials)
- Share tab → Project (left side)
    - Start packaging = "Save package to file"
    - Item details = change the file location and name, as appropriate
    - Select the checkbox for "Share outside of organization". Make sure all other checkboxes are unselected

        If the projects are **reef-specific**, save the files as:
        xxx_zz_mmddyy_rugosity.ppkx, where xxx = reserve initials, zz = reef

initials, mmddyy = date sampled (*e.g.,* noc_nr_061323_rugosity.ppkx).

If the projects are **workflow-specific**, and contain all reefs, save the file as: **xxx_allreefs_yyyy_rugosity.ppkx**, where xxx = reserve initials, yyyy = year sampled (*e.g.,* noc_allreefs_2023_rugosity.ppkx).

For the **experimental reefs**, save the files in one of the two formats listed above, and **add '_experiment.ppkx' at the end** of the name (*e.g.,* noc_nr_030724_rugosity_experiment.ppkx).

IV. Oyster Reef Footprint Classification and Assessment Workflow

Workflow lead and contact: Dan Bowling (djbowlin@ncsu.edu)

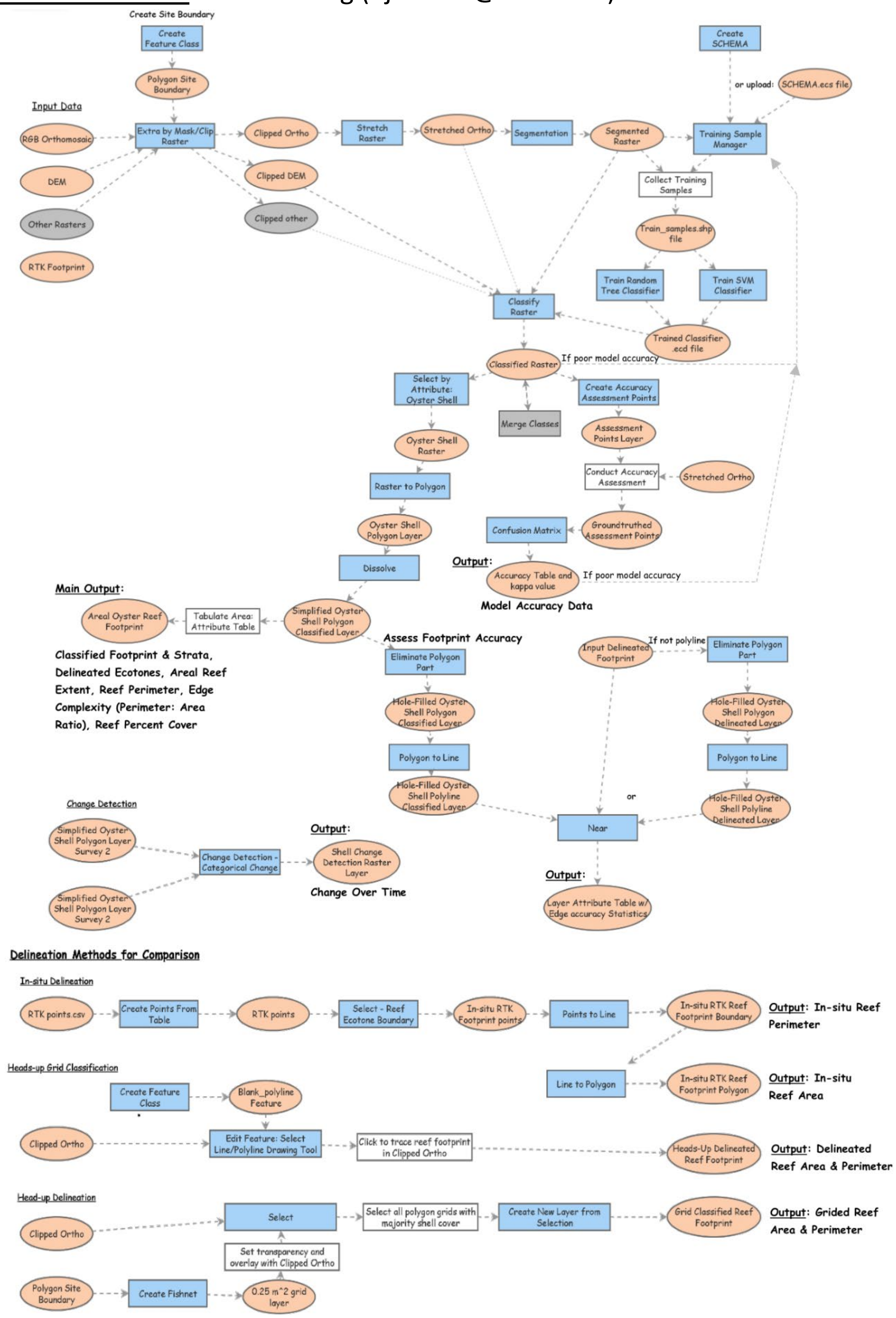


Figure 1. Workflow of Supervised Classification for oyster reef footprint.

Overview

1. Determine project structure
2. Start up (GIS Basics)
3. Heads-up delineation (Traditional approach 1)
4. Heads-up grid classification (Traditional approach 2, optional)
5. Machine learning, supervised classification
6. Accuracy assessment
7. Classification to footprint
8. Areal footprint compare
9. Assessing delineated footprint boundary accuracy
10. Sharing and uploading projects
11. Appendices
12. Digital reef classification & footprint assessment cliff notes

1. Determine Project Structure

Prior to starting, decide whether all sampled reefs will be housed in the same ArcGIS project (*e.g.,* each reef will have a separate Map tab), or if each ArcGIS project will house an individual reef. *Note, your decision will affect the naming convention of the final exported ArcGIS project(s) specified at the end of the workflow.*

2. Start Up (GIS Basics)

Create a project folder to house your project, associated files, and ArcGIS Pro database

- This is a good time to create a "Data Inputs" folder and add copies of the original study site orthomosaics, corrected DEMs/DSMs (hereafter referred to as DSMs), and other associated layers/files (these can later be moved into a geodatabase as preferred). See Appendix 1.0 for further information on creating an ArcGIS Geodatabase.

Open ArcGIS Pro and create new project, referencing project folder (Appendix 1.0)
Click Add Data and add all project layers.

Minimum Data Requirement: Study site RGB orthomosaic

Data for Improved Results: Corrected DSMs of good quality, RTK boundary delineated reef footprints are recommended to improve raster classification accuracy.

Optional Data: Multispectral, NDVI, texture/roughness raster layers (e.g., Vector Ruggedness Measures, Terrain Ruggedness Index; see Oyster Percent Cover and Oyster Density workflow sections for details on creating these layers), or layers from previous surveys for comparison.

- Select YES to build pyramids and calculate statistics for all layers if requested.

Corrected and quality DSMs are recommended for each project, follow step-by-step guide in Oyster Reef Elevation and Elevation Change Workflow. [**Optional**: RTK GCP and Checkpoint points can be added to verify layer accuracy and that the project is working with the corrected DSM. This can be done by adding a the RTK.csv file, right clicking on the newly added table in the Contents pane, select "Create Points From Table", click "XY Table To Point", enter an appropriate name for RTK data, set X to Easting, Y to Northing, and Z to Elevation (this can be checked for accuracy by selecting the table and opening from the Contents pane). Make sure the coordinate system matches the ortho! Once added, make sure the points are properly aligned with GCPs and Checkpoints and the DMS with the ortho.]

Add in situ RTK collected footprint points as *.csv* file (again check coordinate system)

- Add .csv file
- Right click on .csv data in the Contents pane
- Select "Create Points From Table"
- Click "XY Table To Point"
- Enter an appropriate name for RTK data, set X to Easting, Y to Northing, and Z to Elevation
- These points will be used later to create an in-situ reef ecotone layer (or multiple layers if field sampling delineated reef-water ecotone/boundary, subtidal shell extent ecotone/boundary, marsh ecotone/boundary, etc.). [If this was not done in the field, there will be the option to do this digitally during the workflow]
- Be sure to hide this layer during Heads-Up Delineation to avoid biasing results.

Fill database fields A-I for Site Information in the workflow_footprint_database available at the following path: \imagery_data_spreadsheets

2.1 – Set Site Boundary

Next all layers will be clipped to the Site Boundary Layer to help standardize outputs and analysis (this is also a good time to see if future flight paths, or GCP placement needs to be adjusted).

Site boundaries can be set based on the needs of each End User. For example, if priorities are to monitor several strata (e.g., reef, marsh, mud flat, submerged aquatic vegetation, etc.) or at a broader landscape scale it may be beneficial to just clip the margins of the aerial data (Option 1, Figure 2). Be aware, however, that larger sites may produce lower classification accuracies and kappa values due to confusion from additional strata (classes in your machine learning schema), strata with similar spectral characteristics, water confusion and glare, and image artifacts.

End Users most interested in one stratum (i.e., Oyster Reefs) and willing to accept the tradeoff of reduced map area for higher classification accuracy and kappa values should opt to set a smaller and more selective site boundary (Option 2, Figure 3). This approach may better serve those using study sites as indices or proxies for reef "condition".

Option 1. Analysis Tools Create Feature Class (Data Management Tools)

Feature Class Location: Select project geodatabase

Feature Class Name: Site_Boundary_Layer

Geometry Type: Polygon

Coordinate System: Set to site ortho layer

*Leave remaining options as default

*Click Run

*On the ribbon, click Edit, Create icon, select Site_Boundary_Layer and preferred drawing tool and create a feature to represent the site boundary

*Once created, this feature can be modified by clicking the Modify icon on the ribbon

*Click Save under the Edit tab once finished with edits.

Click the Geoprocessing tab or analysis tab on the ribbon, then Tools. Search Clip Raster (Data Management Tools). [Note: This will clip to whatever shape you created for your site boundary. If you are wanting a closer or irregular shape boundary, skip to option 2 below.]

Input Raster: Select each input layer (i.e., ortho, DSM of the site)

[Note: This can be the color-balanced ortho or a raw reflectance map, depending on available outputs]

Output Extent: Boundary_Layer

Output Raster Dataset: "Name_of_layer"_Clip (be sure to check output locations are within geodatabase)

Check "Use Input Features for Clipping Geometry"

NoData Value: 255 (This could also be 256 in some versions, or a completely different value for DSMs/additional layers. This can be checked via a data query in the null data region in the map frame.)

*Click Run

*Repeat with all data input layers (i.e., DSM, etc.) for standardization of the study area and assessment

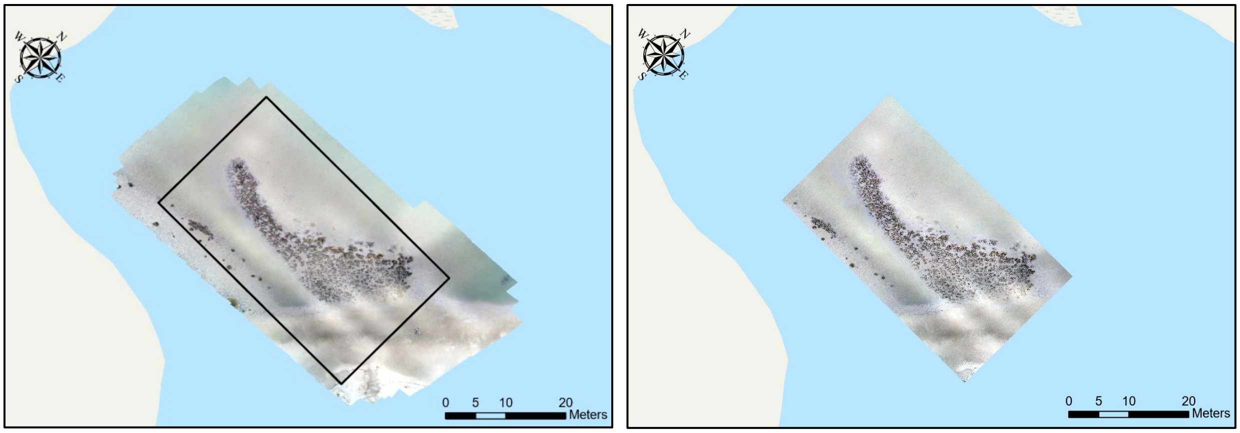
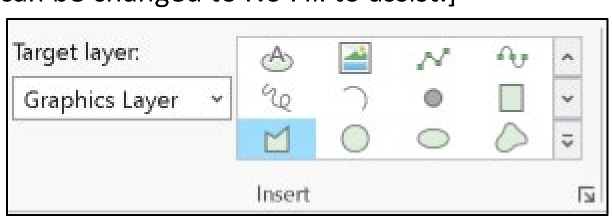


Figure 2a, b. Raw study site orthomosaic raster and created study site boundary areas (left panel) and the resulting clipped layer, allowing for spatiotemporal standardization of each study area (right panel).

Option 2. More closely delineates the oyster reef using the same steps in option 1 above and selecting a more appropriate drawing tool for quick delineation (Polygon, Lasso, or Freehand Line). Others may prefer the flexibility offered by using the Add Graphics Layer tool.
This close boundary delineation approach can be quick and crude for efficiency as the supervised learning steps will more accurately define the oyster reef footprint. For best classification results, be sure to remove excess water and habitat areas not needed in oyster reef classification. Be mindful to include some degree of buffer, capturing areas that may serve as future oyster habitat as reefs recruit, expand, or migrate. The initial area defined as the site boundary should be saved and applied to all future surveys for spatiotemporal standardization in analysis.

Use Create Feature Class as above in Option 1 or use:
Map tab Add Graphics Layer
*A graphics layer will be added to your Map Contents panel
*Select in Contents panel, Click Graphics tab and in the Insert group chose a feature drawing tool (Polygon, Lasso, or Freehand Line is recommended) [Note: If Lasso or Freehand Line is used, the Feature to Polygon tool will need to be used prior to applying a mask for the intended area. Also, fill color for the Polygon drawing tool can be changed to No Fill to assist.]



*Once drawn, Tool Graphics to Feature (Conversion Tools) can be used

Input Graphics: Select Graphics Layer

Graphics Type: Select Polygon

Output Feature Class: Navigate to project geodatabase and name Boundary_Layer

Analysis ⍰ Tools ⍰ Graphics to Features (Conversion Tools)

***Note: If you are creating a polygon around separate patch reefs, make sure they are connected with a thin line between them; disconnected polygons may pose problems later in the workflow.**

Analysis ⍰ Tools ⍰ Extract by Mask

Input raster: Select site data layers (Ortho, DSM, etc.)

Input raster or feature mask: Select newly created graphics feature

Output raster: Name appropriately and save for future use [NC_MiddleMarsh_ortho_bound]

Extraction Area: Inside

(This method will reduce the negative space and null data areas in subsequent data layers)

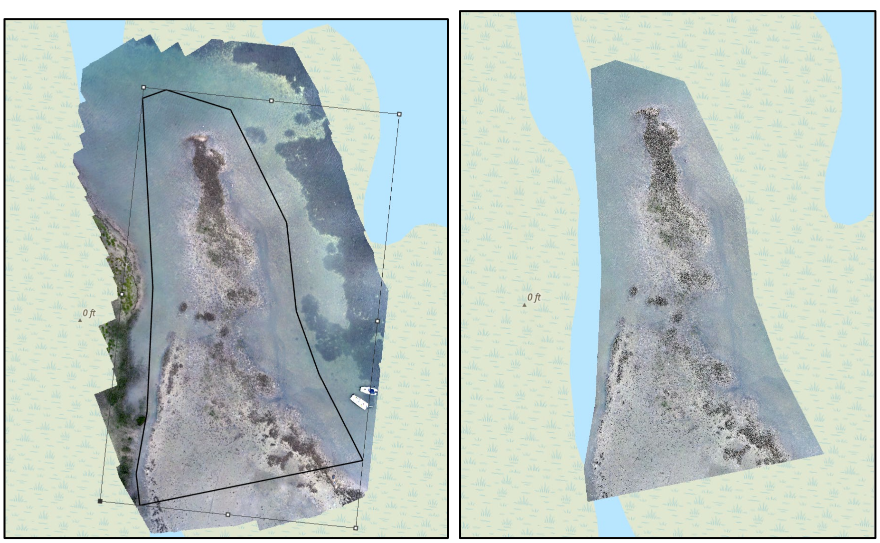


Figure 3a, b. Raw study site orthomosaic raster and created study site boundary areas (left panel) and the resulting clipped layer, allowing for spatiotemporal standardization of each study area (right panel).

Fill workflow_footprint_database fields J-L for Boundary Information (Clipped_Y/N, Boundary_Size)

2.2 – Stretch Raster

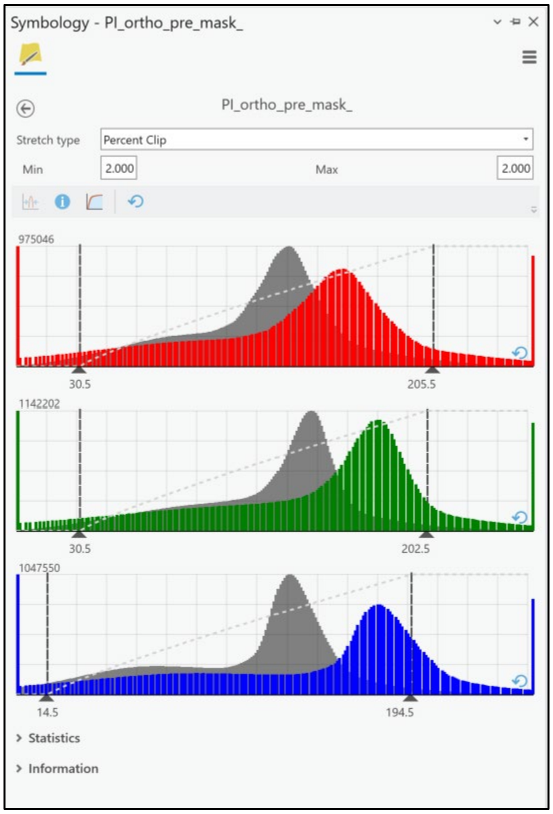
Select the clipped raster ortho layer from the Contents.

Click the Raster Layer tab on the ribbon and select the Stretch Type icon.

Stretch Type: Percent Clip

Min: 2.0

Max: 2.0



Under the Enhancement tab, adjust Layer Brightness, Layer Contrast, and Gamma (adjust last and only if needed, typical value for gamma should be 0.7-1.8 to achieve good white balance).

- The goal should be to make the oyster reef/shell areas as prominent as possible.
- Tip: The standardized balance that was found to best accentuate reefs was brightness 10, contrast 10, gamma 1.0, however this will strongly depend and vary based on initial image products and environmental conditions during surveying.

(Note: Raster stretching tools can also be accessed via the layer's symbology - right click the raster layer on the contents pane ⍰ select "symbology" ⍰ set the min and max below. **More info on the Stretch Raster Function can be found at:** https://desktop.arcgis.com/en/arcmap/latest/manage-data/raster-and-images/stretch-function.htm)

Fill workflow_footprint_database fields M-T (Raster Enhancement notes and StartUp_Time_min) and make sure fields A-T are entered.

2.3 – RTK In-situ Delineation

In this step RTK data that was collected in the field will be used to create an in-situ reef ecotone layer (or multiple layers for reef-water boundary, subtidal shell extent boundary, marsh boundary, etc.). Toggle on the site ortho and overlay this layer with the RTK point layer. Use the select tool to select all the points of each desired category (the Shift key can be held down to add to selection and the Control key can be used to remove points from selection). Separate reef areas and patch reefs will need to be broken down into sub-reef areas and run through the following steps.

Once all points are selected for a boundary type, right click the RTK layer in the Contents pane Selection Make Layer From Selected Features

Use the Points to Line tool with the RTK collected data on footprint from the field.

Line Field: leave blank

Sort Field: leave blank

Select "Closed Line Option"

Select "Construct Continuous Line"

*Click Run

Next use the Feature to Polygon tool

Input: previous output

Name output appropriately to signify this is the RTK footprint of the study site

*Click Run

Optional: The Merge tool can be used to combine polygon layers.

Note: If there are points missing in areas, use the Create New Feature tool, followed by Merge tool to fill in data gaps. Similarly, if the following steps do not generate an accurate layer, some points may need to be de-select for clarity or the RTK points can simply be used as a guide to create an accurate layer using the Create New Feature tool.

2.4. RTK Delineated Metrics

Right click on the created footprint feature in the Contents pane and open the feature's attribute table. Click "Add" next to Field: just above the attribute table, enter Shape_Perimeter for Field Name and Alias, set Data Type to Double and Number Format to Numeric. Click the Save icon on the ribbon (repeat this process for Shape_Area if it does not already exist). To calculate the parameter, right click on the column heading, and select "Calculate Geometry".

Field: Shape_Perimeter

Property: Perimeter length (geodesic)

Length Unit: Meters
Coordinate System: Select the same as the ortho
*Click “Ok”
*For large areas, be sure that the Shape_Area is using the Area (geodesic)

Values of Interest:
Footprint area: Found in Field Shape_Area
Footprint perimeter: Found in Shape_Perimeter

Fill workflow_footprint_database fields U-W (RTK Delineation).

3. Heads-Up Delineation (Traditional Approach 1)

This section will focus on creating a footprint layer from the study site orthomosaic using a heads-up or on-screen digitizing approach to trace the reef footprint. Prior to machine learning tools, this approach was a traditional standard for extracting area and perimeter estimates and it will serve as a comparative metric for future machine learning classification results. At sites where in-situ RTK delineation was not collected, this step would be recommended.
To get started, navigate to the toolbox to create a new feature class in your geodatabase that we will use to create a digital delineation of the reef footprint. This can also be accomplished using the Add New Graphics tool and initial steps listed above in create boundary option 2 (section 1.1). Users should consider delineating total footprint (including what is invisible in water), exposed footprint, or both as separate features.

Analysis Tools Create Feature Class (Data Management Tools)
Feature Class Location: Select project geodatabase
Feature Class Name: [Site ID]_HU_Delin_[User Initials]
Geometry Type: Polygon
Coordinate System: Set to site ortho layer
*Leave remaining options as default
*Click Run
*On the ribbon, click Edit, Create icon, select the newly created feature in the Create Features pane and preferred drawing tool (polygon recommended) and create a feature to represent the site boundary
*Click along the perimeter edge of the reefs, keeping each point around one meter or less apart to standardize the approach and match the resolution of in-situ RTK data
*Vertices can be deleted by hovering the cursor over a point until it changes appearance, right clicking, and selecting delete

*Click  to finish and click the Save button the top of the ribbon when complete

*Large, shell devoid areas can be cut out from larger footprint by creating a separate feature for these areas and using the clip tool to remove them from the larger footprint.

*Once created, this feature can be modified by clicking the Modify icon on the ribbon

Delineated Metrics

Right click on the created footprint feature in the Contents pane and open the feature's attribute table. Click "Add" next to Field: just above the attribute table, enter Shape_Perimeter for Field Name and Alias, set Data Type to Double and Number Format to Numeric. Click the Save icon on the ribbon (repeat this process for Shape_Area if it does not already exist). To calculate the parameter, right click on the column heading, and select "Calculate Geometry".

Field: Shape_Perimeter

Property: Perimeter length (geodesic)

Length Unit: Meters

Coordinate System: Select the same as the ortho

*Click "Ok"

*For large areas, be sure that the Shape_Area is using the Area (geodesic)

Values of Interest:

Footprint area: Found in Field Shape_Area

Footprint perimeter: Found in Shape_Perimeter

Fill workflow_footprint_database fields X-Z (Heads-Up Delineation).

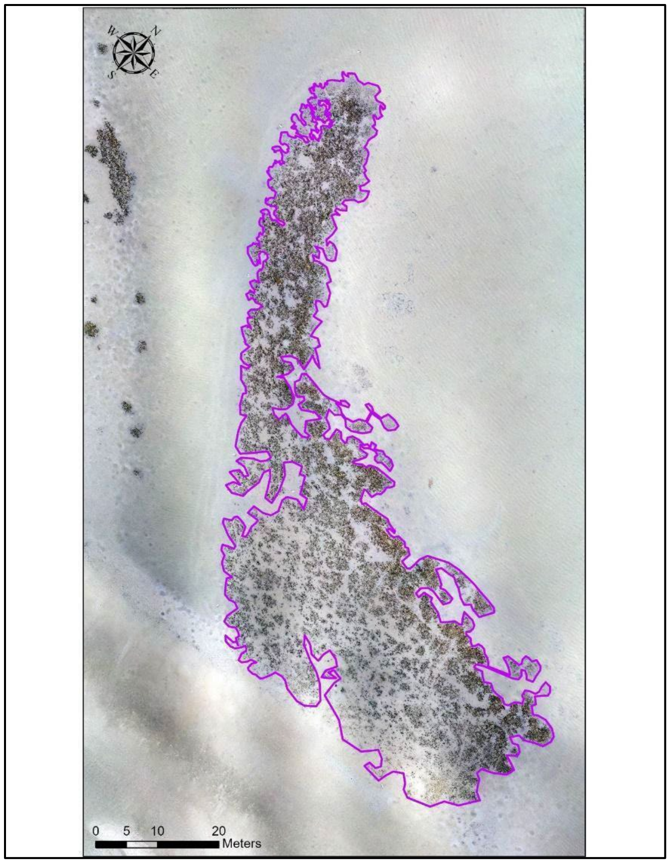


Figure 4. Town Marsh Lagoon, 2022 – Heads Up, linear delineated footprint

Alternative Delineation Method (Optional):
Use Spatial Analyst Raster Reclassify geoprocessing tool.
Change to Integer Type
Use Raster to Polygon tool
Perimeter/boundary created
Reference: How To: Create Polygons from a Raster Dataset Based on the Reclassified Value (esri.com)

4. Heads-Up Grid Classification (Traditional Approach 2, Optional)

Heads-up grid classification is an optional on-screen digitizing method that provides a more standardized and higher resolution and accuracy of reef footprint and reef level percent cover. To get started, in the Contents pane toggle on the orthomosaic layer and overlay the Boundary Layer. Under the Map tab on the ribbon, use the Measure Icon to measure the latitude and longitude distance (m) of the Boundary Layer (if the site Boundary Layer is not rectangular, a new rectangular graphic layer will need to be created, or the extent can be used of that feature). Note these measurements and zoom into the corner points to be as accurate as possible. Note down the measurements as these will be used in the next tool.

- Search Toolbox for Create Fishnet tool

  Output Feature Class: "sitename_year_grid" (save to correct geodatabase)
  Template Extent: Boundary_Layer (or Graphics Layer if a new one was used, this should be the same clipped study site)
  Number of Rows: number will be Lat. distance/.25 (round to nearest whole)
  Number of Columns: number will be Long. distance/.25 (round to nearest whole)
  Uncheck Create Label Points
  Geometry Type: Polygon

  - Leave all remaining fields blank
  - This will produce a grid with 0.0625 m^2 cells (if a lower resolution is desired the number used to divide the distances accordingly; for example, a denominator of 1 will produce a grid with 1 m^2 cells)

-Select the grid output in the Contents pane, select Feature Layer tab on the ribbon, adjust the Transparency to user preference and Layer Blend to Color Dodge (or preference) to allow easy viewing of the ortho and a faint hint of the grid.
-With the grid layer still selected in the Contents pane click the Map tab, then Select icon (chose selection method of choice – Lasso recommended).
-Begin selecting grid cells that contain 50% or more of shell, by left clicking while holding down shift. Areas can continue to be added as long as the Shift key is held. Areas can be unselected by holding down the Ctrl key and left clicking. Important, be sure to save progress often in case selection is lost. Reopening a save point will restore selected areas.
-Once a significant area of shell has been selected, an interim layer can be made by right clicking on the grid layer in the Contents pane, going to Selection Create Layer From Selected Features.
-Symbology of layer selections can be adjusted (i.e., with a fill color) to assist in continued delineation and classification.
-Once the study site has been fully classified, any selected layers can be combined into a single layer using the Merge tool (Data Management Tools; Merge (Data Management)—ArcGIS Pro | Documentation).

Optional: If time is a limiting factor for creating this footprint layer from scratch, use RTK polygon or heads up delineated polygon of the footprint to guide selection and extract exact area of interest from fishnet. (Map tab Select by location Apply, then export selections to obtain only targeted reef area grids, finally tabulate using these new layers). ***Be aware that this shortcut does have strong potential to bias the layer and overestimate footprint. Time is still needed to go back through and de-select grids that were incorrectly selected.***

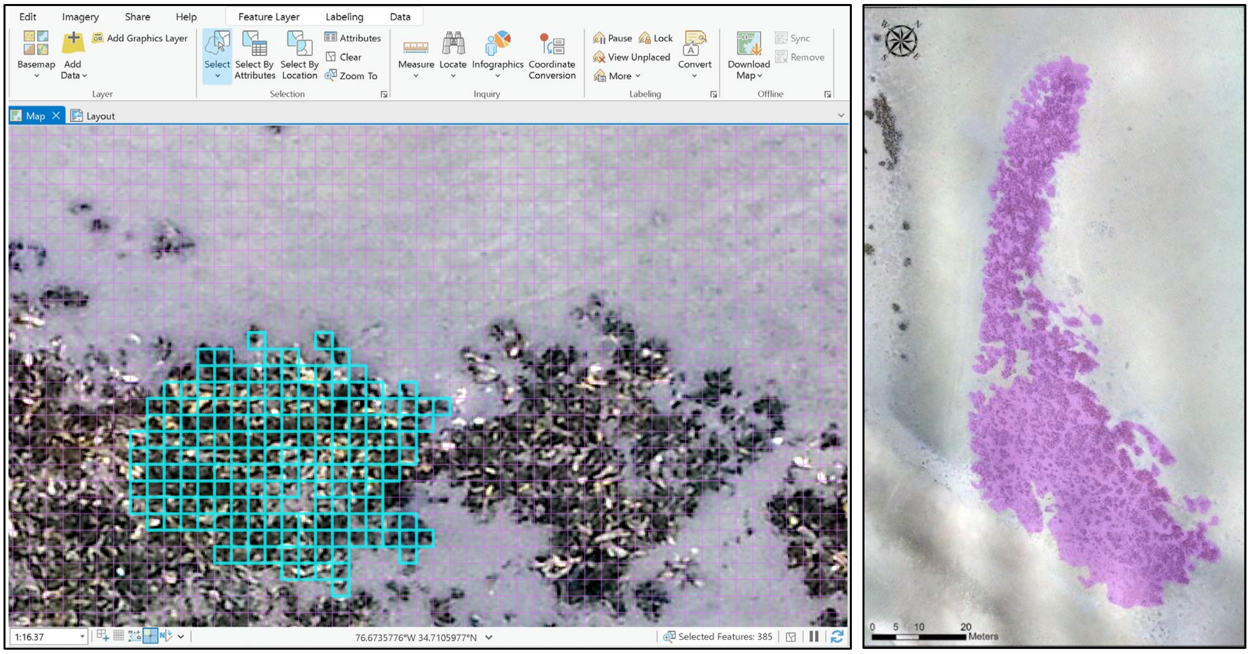


Figure 5a, b. Town Marsh Lagoon, 2022 – Grided (0.25m x 0.25m) footprint area (5a is zoomed in to show the process of selecting the individual grids in order to create the layer for oyster reef footprint seen in 5b).

Grid Classification Metrics

Currently, the classified grid layer of the footprint consists of hundreds to thousands of unique polyshape files and these need to be combined.

Dissolve Polygon Features to make Simplified Polygon Feature Layer
Analysis Tab ⍰ Tools ⍰ Dissolve (Data Management Tools)

Input Features: select gridded footprint layer
Output Feature Class: name final footprint layer (ex. “MM23_Grid_Footprint_DB”)
Check “Create multipart features” only
* Click Run

Right click on the created final footprint feature in the Contents pane and open the feature’s attribute table. Click “Add” next to Field: just above the attribute table, enter Shape_Perimeter for Field Name and Alias, set Data Type to Double and Number Format to Numeric. Click the Save icon on the ribbon (repeat this process for Shape_Area if it does not already exist). To calculate the parameter, right click on the column heading, and select “Calculate Geometry”.

Field: Shape_Perimeter
Property: Perimeter length (geodesic)
Length Unit: Meters

Coordinate System: Select the same as the ortho
*Click "Ok"
*For large areas, be sure that the Shape_Area is using the Area (geodesic)

Values of Interest:
Footprint area: Found in Field Shape_Area
Footprint perimeter: Found in Shape_Perimeter

Fill workflow_footprint_database fields AA-AC (Grid Classification).

5. Machine Learning, Supervised Classification

5.1 – Segmentation

Select your stretched orthomosaic layer (created in section 1.2), click the Imagery tab on the ribbon, click the Classification Tools icon, and select Segmentation. Segmentation parameter selection is recommended as one of the following (Figure 6).

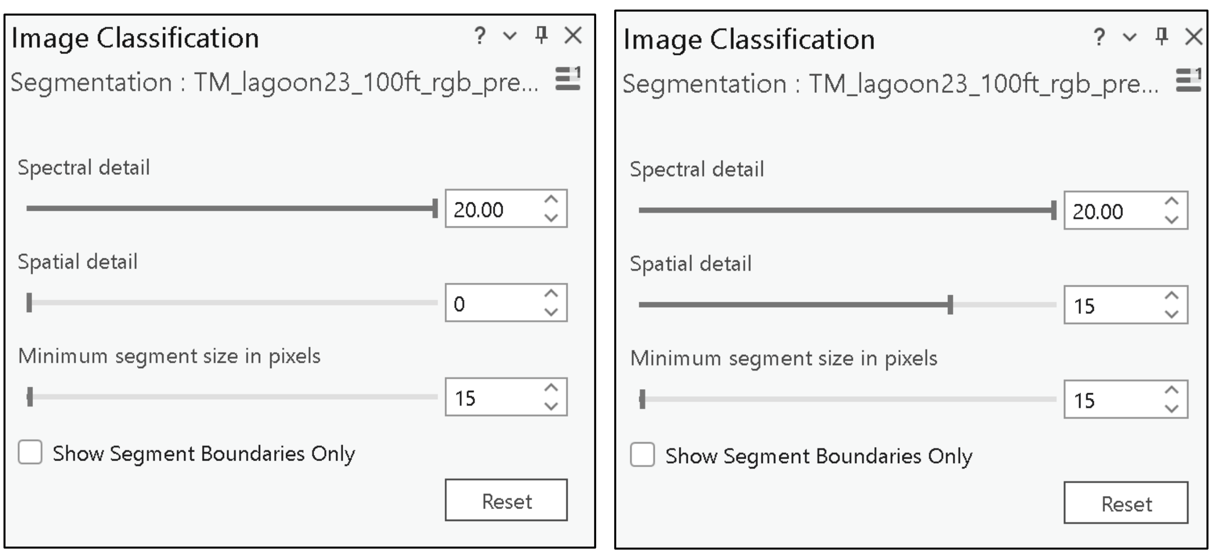


Figure 6a, b. Two optional parameter setting combinations that have been tested and should be considered based on the resolution/image quality of the RGB raster. Higher resolutions and quality orthomosaics should have more confidence in selecting option 1 (Figure 6a). When finer spatial detail can be used, it can promote accuracy of the machine learning algorithms. In cases of fuzzy clarity or a high degree of spectral variation within a class or objects of interest, the extra detail is unhelpful and can result in more inaccuracies. In these instances, option 2 (Figure 6b) with a higher spatial detail spec should be preferred. Option 2 will also help mitigate cases of glare and wave confusion when there is the possibility of such a challenge.

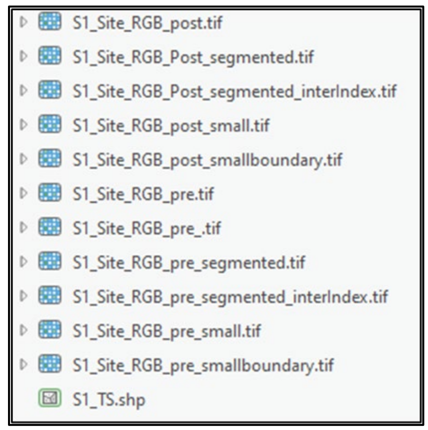
Spectral detail: 20.00

Spatial detail: 0 (Other versions may have to select 1 here)
Minimum segment size in pixels: 15 (Again, this depends on your layer resolution, adjust accordingly and further experimentation is welcome. For instance, a larger setting of 20, 30, or more may be helpful to combat glare and a high degree of color variation in shell areas.)
Output Dataset: (adjust to meaningful name, example: "middlemarsh_06_23_ortho_segment")
* Click 'Run'

Fill workflow_footprint_database fields AD-AI for Segmentation (Spectral_Detail, Spatial_Detail, Min_Seg_Size, Time)

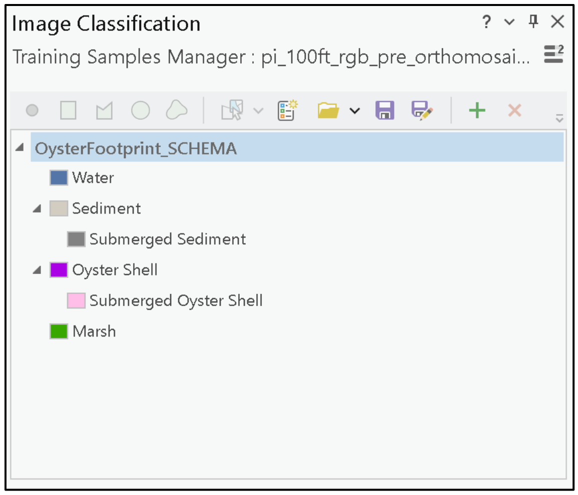
5.1.1 – Troubleshooting

The segmented raster output will also contain an 'interindex.tif' file. The index file contains the segmented raster information with associated attribute table. Keep the segmented raster and index raster files together. If they are separated, then any future use of the raster will produce a geoprocessing error due to a broken path.



5.2 – Training Samples

Select segmented layer in the Contents pane, click Imagery tab on the ribbon, click Classification Tools, scroll down to select Training Samples Manager.
In the GIS project folder create a new folder ("Training_Data")
Download and add OysterFootprint_SCHEMA.ecs to the folder or create a unique project schema (Appendix 3.0). Add schema to Image Classification Training Samples Manager by clicking the down arrow next to the file folder and browse to the existing schema. Locate .ecs file within the project folder and add.



Schema can be adjusted, or new class/sub-class added, by right clicking on the level needed within the schema and selecting "Add New Class":
Unique values must be set for the Value field. At a minimum, we will classify OYSTER SHELL, WATER, and SEDIMENT. Feel free to add additional classes and subclasses as needed and desired for your specific sites. In the OysterFootprint_SCHEMA.ecs file the Current Name and Values included are:

- Oyster Shell: 1
  - Submerged Oyster Shell: 2
  - Vegetated Oyster Shell: 3
  - Exposed Dark/Wet Oyster Shell: 4
  - Exposed Light/Dry Oyster Shell: 5
  - Shell Rake: 6
- Water: 10
- SAV: 20
- Sediment: 30
  - Submerged Sediment: 35
- Marsh: 40

Schema Defined:

Oyster Shell (parent class) – all detected and exposed oyster shell, both live oyster and dead oyster as substrate. Subclasses include Submerged Oyster Shell (shell has a different spectral characteristic due to submergence in water at time image acquisition), Vegetated Oyster Shell (shell with algal growth that may otherwise be miss-classified), Exposed Dark/Wet Oyster Shell (shell that is has not been exposed as long at time of image acquisition and therefore bearing a darker spectral characteristic; also typically more indicative of live oysters as they retain water in doing so have a darker relative signature), Exposed Light/Dry Oyster Shell (shell that is still intertidal, but has been exposed long enough to bear a lighter signature; dead shell tends to dry faster than live individuals so this may warrant and additional sub-class if interested in teasing out live oysters here), Shell Rake (dead and typically mounded shell that appear bleach white due to extended sun exposure; these areas are not available to juvenile oysters as settlement substrate).

Water (parent class) – any submerged area where the bottom remains undefinable without certainty or likely to be misclassified by machine learning. If water is present across a broad spectral range, consider creating sub-class if numerous samples of each area produce poor results and clipping the water extent is not preferred.

SAV (parent class) – submerged aquatic vegetation (e.g., sea grass)

Sediment (parent class) – exposed sediment at the study site at the time of survey. Subclass included submerged sediment as it typically appears spectrally different from exposed sediment. As the case with Water, add additional subclasses for sediment, especially exposed as needed. For example, mud will appear different from sand.

Marsh (parent class) – marsh grass areas

(These unique values were selected to standardize the approach across sites. Parent class level strata were staggered by ~10 units to allow for the addition of sub-class schema where warranted. Remember classes should exist to help the computer correctly classify. For instance, water may be used best to represent deep areas or muddy water areas where the bottom is not clearly depicted and shallow water areas where the bottom can be seen, reserved for submerged sediment classification. Establishing and following a clear definition for each is important both in training sample creation and again later in Accuracy Assessment.)

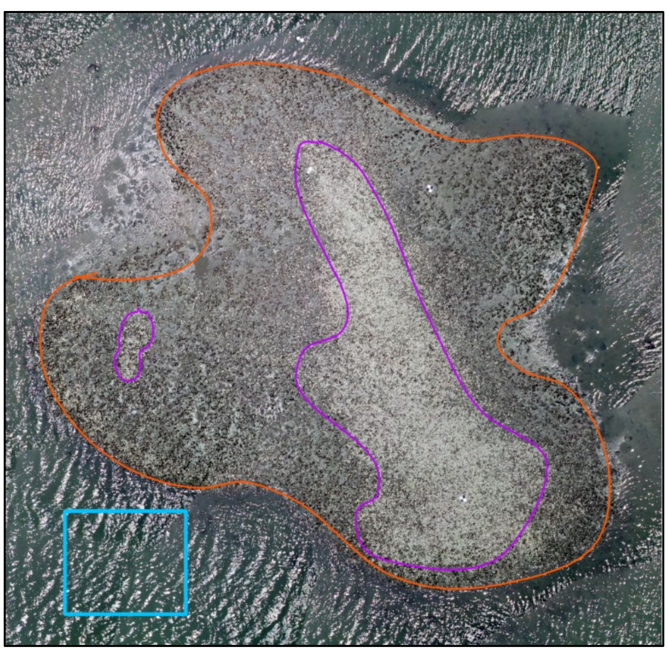


Figure 7 – Example of a study site where it would be beneficial to collect training samples for both Exposed Dark/Wet Oyster Shell (orange delineated area) and Exposed Light/Dry Oyster Shell (purple delineated area). This is also a case where water with waves and glare can be better classified by including larger training samples (such as blue quadrat) to include glare and wave spectral and segment characteristics.

Remove any unneeded classes based on the study site, select save as to save schema changes to a new file name (i.e., keep the original version unmodified).
Begin training sample selection by clicking on class of interest and then desired drawing tool (rectangle or polygon is recommended).

- Take the time to collect quality training samples for each class, make sure to collect samples from different areas, of various sizes and dimensions (i.e., not just rectangles), and cover the spectral diversity of each class. Also be sure to grab samples from various elevations when relevant (see Appendix 3 for additional information).
    - Zoom in and out with the mouse wheel and hold down ‘c’ key to move around/pan the map while searching for locations to create new training samples.
    - Additional suggestions: Shell and Sediment samples should be mainly small and spectrally ‘pure’ samples, but some added benefit can be gained by including a few slightly larger (still relatively ‘pure’) samples to include segmentation node details as features to guide classifications. Water with lots of glare or waves/ripples can be best dealt with using larger samples that include glare and wave features.
- The number of samples needed for each class will depend on the spectral variation expressed in each class and within each ortho/segmented layer. (Recommendation: for prevalent and varied classes aim for a minimum of 20 samples)
- It is recommended to toggle on/off the segment layer to use the ortho to assist with placing training sample polygons for improved quality of training material.
- Samples should be as targeted as possible and poor samples should be removed using the  icon.
- If desired, stable areas can be targeted to use the same training sample polygon areas across orthomosaic/segmented raster layers for multiple time periods to improve efficiency (If using sample polygon locations from another time period, be sure to check the validity of the polygon placement to ensure quality training data).
- Save training samples as a shapefile (this can be used for other surveys at this site)
- Merge all samples into like classes by selecting each sample and clicking the merge icon . Samples can be unmerged by clicking .
- Once merged, it is a good idea to check that sample collection number and percent distribution is representative of the general percent cover of each class (i.e., strata) within the site boundary.
- Save final training samples within the project folder (Recommended to create a Training_Data folder to house all of the unique training files).

5.3 – Train Classifier

Search Tools for Train Random Trees Classifier (Spatial Analyst Tools) and select:

Input Raster: Clipped and segmented ortho layer

Input Training Sample File: Select saved polygon training sample shapefile

Leave Dimension Value Field Blank

Output Classifier Definition File: sitename_year_segment_RT.ecd

(Note: This Must be saved in the project's training folder and not in the geodatabase)

Additional Input Raster: Select corresponding DSM or ortho if DSM does not produce good results (Note: if available, you could also use any of the Multispectral, NDVI, Texture rasters)

(Important: If using the DSM in the classifier, it must be used in the classification of the raster and vice versa to avoid an error. It is also recommended to make a note of any additional layer used by referencing it in the output naming scheme. Using DSM as an additional raster layer can deliver slightly better classification results, but this appears to be dependent on the quality of the DSM and the lack of artifacts/inaccuracies. It is possible to apply a DSM from a previous sample period if it is still relevant to the imagery being analyzed).

Max Number of Trees: 50

Max Tree Depth: 30

Max Number of Samples: 0 (Setting to 0 should allow for the algorithm to use as many as deemed necessary; if issues result then use default)

Segment Attributes: Select All

- Click Run

Search Tools Classify Raster (Spatial Analysis Tools) and select:

Input Raster: Select corresponding segmented layer

Input Classifier Definition File: Use output from Train Classifier tool

Output Classified Raster: sitename_year_classified (Recommended to save in training data folder)

Additional Input Raster: DSM/RGB/Multispectral layer (optional - if used note it in the naming scheme of the output classified raster)

- **Use of quality DSM typically improves classification accuracy, if multiple accurate DSMs exist for a site, select the one with the fewest artifacts (even layers from previous years could be applied).**
- Click Run

Inspect classified raster output. If the classification seems reasonable, move on to accuracy assessment. If the classification seems unreasonable, move to section 4.3.1 below.
In cases where the resulting classes, or sub-classes, are not of interest in the final map product, the Merge Classes tool should be used to simplify the map layer.

Click Imagery Tab → Classification Tools → Merge Classes

Under Classification Schema navigate to your .ecs file and load.

Under the New Class column new drop-down options should be available to select alternative classes to merge the old classes into new designations. Save output dataset with 'merged' somewhere in the file name.

*Click Run

Fill workflow_footprint_database fields AJ-AX for Training and Classifying. Actual processing times can be obtained in the View Geoprocessing, under Recent, hold cursor over a used tool and click Open History.

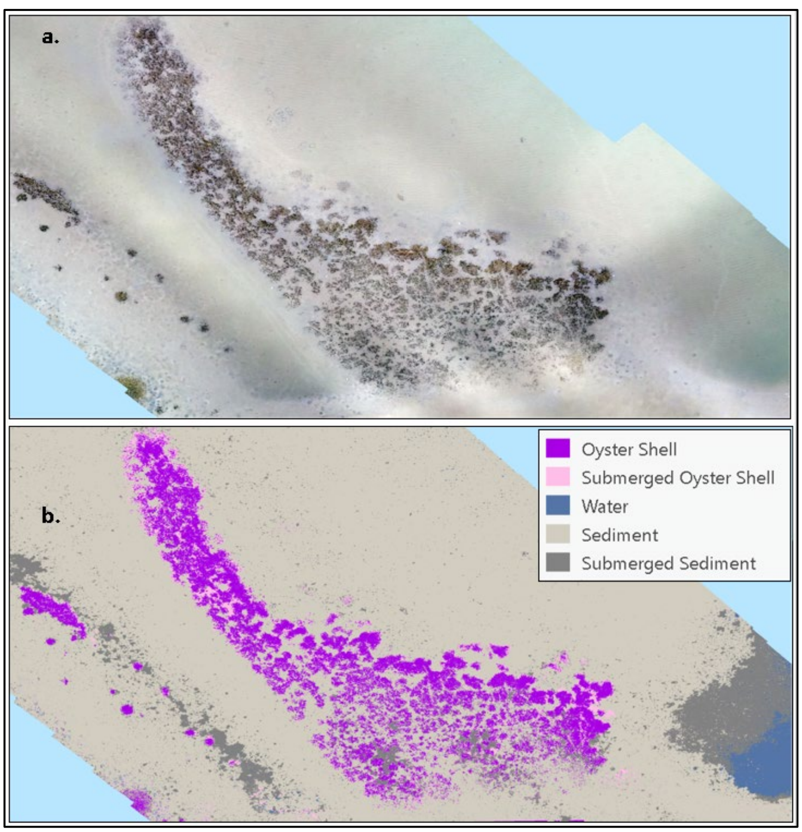


Figure 8a, b. Town Marsh Lagoon study site within the Rachel Carson Reserve displayed in an orthomosaic layer (UAS aerial imagery obtained from Drone the Oyster Science Collaborative;

top) and the resulting classified layer using current Machine Learning model with a Random Trees classifier (bottom).

5.3.1 – Troubleshooting

1. If DSM or additional layer was used and inaccuracies are falling around artifacts in those layers (a typically case is in DSMs where the corresponding ortho contains a lot of water glare), the Classify Raster tool can be re-run with only the RGB and segmented raster layer (often with good performance).
2. Alternatively, Support Vector Machine can be utilized as a classifier (this can take longer for larger sites, but yield improvements when Random Tree fails)
   - Search tools for Train Support Vector Machine (Spatial Analysis Tools) and select:
     Input Raster: Clipped and segmented ortho layer
     Input Training Sample File: Select saved polygon training sample shapefile
     Output Classifier Definition File: Sitename_year_SVM
     Additional Input Raster: Select corresponding RBG/ DSM/Multispectral layer (Optional - if used note it in the naming scheme of the output classified raster)
     Max Number of Samples: 0
     Segment Attributes: Select All
     - Click Run
3. Should classification remain insufficient, investigate where the output is failing and return to the Training Sample Manager to adjust polygon samples (look for some that may be poor and driving confusion) and add additional training samples to specific classes and map areas that are underperforming.
4. If classification is still insufficient and there is an abundance of glare in the water, try reducing the size of the Site Boundary (created at the beginning of the workflow) to clip out as much water as possible.

6. Accuracy Assessment

Before you start the Accuracy Assessment, inspect the classified output layer to see if any negative area, null data, or extraneous classified area was created during the classification process. If so, the tool Extract by Mask (Spatial Analyst Tools) will need to be used again with the site boundary as the masking area to remove the unwanted areas. If this is not done, the random assessment points can populate in these areas as well.

Search toolbox for Create Accuracy Assessment Points and select:

Input Raster: select classified raster layer
Leave Dimension Value Field Blank
Output Accuracy Assessment Points: AA_“ClassifiedLayerName”

Target Field: Classified

Number of Random Points: N (see box below for suggestion)

Sampling Strategy: Stratified Random

- Click Run

Number of Accuracy Assessment Points (N)

N = Number of Parent Classes of Interest x 100 x Hectares

*If you are not concerned with the accuracy of a class, do not include it in the total count for Number of Parent Classes of Interest, unless a class of interest is inaccurately being classified where this class persists. For instance, if you are not interested in SAV, this class can be excluded if oyster is not being miss classified for SAV.

*Consider add an additional 100 points to the total N for each class of interest that comprises less than 10% coverage of the study area to insure adequate assessment.

*If classes of interest are highly clumped heterogeneously across the study site, consider adding an additional 100 points (this need could always be re-evaluated after inspecting initial assessment point distribution across the site imagery).

*Subtract 100 points if willing to sacrifice time for accuracy.

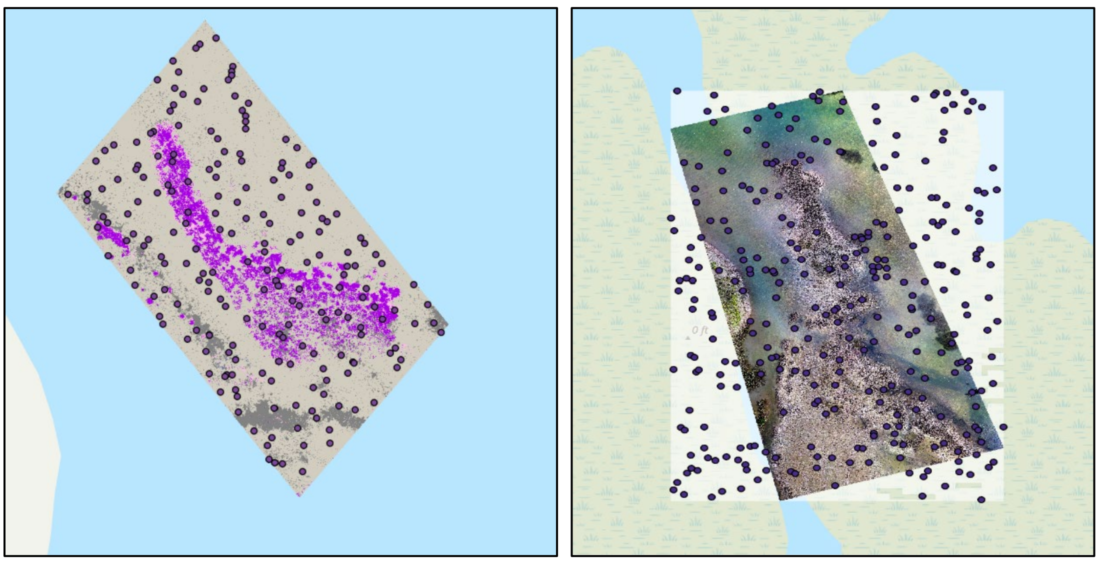


Figure 9a, b. Site with accuracy assessment points distributed via random stratification within the study site boundary to measure classification error and output layer accuracy (left figure). A case where the points are incorrectly distributed, and the Extract by Mask tool is needed to remove data null areas first (right figure).

- Open attribute table from output
- In the Contents pane toggle to corresponding ortho layer
- Right click on the “Classified” header column and select Hide to reduce bias.
- Begin by selecting each row in the attribute table to highlight and focus on the assessment point.

- Under the “Grndtruth” column begin editing each cell for each point by identifying the correct strata class and entering in the corresponding field value (i.e., 1 for oyster shell, 10 for water, etc.), remembering to zoom in on the orthomosaic as needed (use Crl+ to Zoom to).
- Save edits
- Search tools for Compute Confusion Matrix (Spatial Analyst Tools)
- Run with the updated accuracy point shapefile as the input (make sure none of the rows in the accuracy assessment point attribute table are ‘select’ or the option ‘Use the selected records’ under the Input Raster is turned off)
- View Confusion Matrix table from the Contents pane (this table should be output at the bottom of the Contents pane).
    - The diagonal represents correctly classified, the off-diagonal cells represent misclassified points
    - P_accuracy (producer’s accuracy): proportion of the area for each class that was correctly classified
    - U_accuracy (user accuracy): proportion of the actual area of each class that was classified correctly
    - Intersection of P_accuracy & U_accuracy in the matrix is the overall accuracy of the classified map

  (For more information on how to read a confusion matrix, see Appendix 5)

Error should be randomly distributed, and accuracy should be **greater than 75%**, with expected Kappa values: 0.61 – 0.80 Substantial agreement; 0.81 – 0.90 Strong agreement; >0.90 Near perfect agreement. Much lower values should suggest a revision to the training sample step to adjust the training sample library (either add more samples in areas that performed poorly, improve the quality of samples, improve the number of samples, or remove bad samples) before moving forward in the workflow.

Do not rely on the accuracy assessment and kappa values alone. Such evaluations are extremely helpful, but can be susceptible to bias and fallacies. Also make sure that one or two accuracies are not strongly skewing the results. If this is the case, consider merging classes into more meaningful groups. For instance, if the classes were Marsh, Sediment (submerged and exposed), Oyster Reef (submerged and exposed), SAV, and Water it would be recommended to reduce to Marsh, Sediment, Oyster, and Water, or even as far as Non-Oyster and Oyster to most accuracy assess the classes most important to the objective (see example supporting Tables 2-5 in Appendix). Merging classes will update the stored class values, but a new confusion matrix will need to run with updated points. It can be helpful here to copy the groundtruth data column into excel and use find and replace to update these points. Once updated, they can be pasted back to the updated confusion matrix. The Update Accuracy Assessment Points tool (Spatial Analyst Tools) should be used to update points previously classified with a raster layer. Be sure to look at the classification outputs and compare them with the study site imagery to get an End User perspective of the model's performance.

Fill workflow_footprint_database fields AY-BF for Accuracy Assessment

Repeat with other classifications if multiple orthomosaics were run (e.g., rasters from different sample time periods) or the model was run with alternative settings or machine learning algorithms (i.e., SVM) to find the best output.

Search Toolbox for Update Accuracy Assessment Points

Input Raster: select next classified layer for assessment

Input Accuracy Assessment Points: select previously used points

Output Accuracy Assessment points: AA_"ClassifiedLayerName"

Target Field: Classified

- Click Run

- Groundtruth points should remain the same and already be entered.

- Alternatively, the Update Accuracy Assessment Points tool can be used to resample raster values at the same previously created random points. This can be useful in collecting classified point data from the next classified layer up for evaluation or quickly filling the groundtruth data column with information from a previously hand-defined layer.

6.1 Accuracy Assessment Troubleshooting

The output confusion matrix table will be in table format. The format of the table is determined by the output location and path. By default, the output will be a geodatabase table. If the path is not in a geodatabase, specify a .dbf extension to save it in dBASE format.

7. Classification to footprint

7.1 Select Strata of Interest

Click Select by Attribute under the Map tab

Input Rows: select the classified layer of interest containing the footprint

Selection Type: New selection

Where: 'Classvalue' 'is equal to' '1' (this should be the class value of interest since 1 is the class value for oyster shell)

*Click 'Apply'

If there are undesired areas incorrectly classified outside of the reef footprint, this or the next step is the time to de-select these areas (the lasso tool can be helpful here) and creating an intermediate layer from selected features to create a corrected classified layer.

7.2 Convert Raster to Polygon Features

Analysis Tab Tools Raster to Polygon Tool

Input raster: select the classified layer of interest containing the footprint
Turn on the "Use the selected records" option to include current selection
Field: Value
Output polygon features: give appropriate name (e.g., Shack_reef_FPpolygons)
Check Simplify polygons
*Click Run

7.3 Dissolve Polygon Features to make Simplified Polygon Feature Layer

Analysis Tab Tools Dissolve (Data Management Tools)

Input Features: select the output layer created in with the Raster to Polygon Tool
Output Feature Class: name final footprint layer (ex. "Shack_Footprint_RTClassified")
Check 'Create multipart features' only
*Click Run

If several footprint features remain after the dissolve, use the Merge tool to combine into a single feature.

7.4 Supervised Learning Classification Metrics

Right click on the created final footprint feature in the Contents pane and open the feature's attribute table. Click 'Add' next to Field: just above the attribute table, enter Shape_Perimeter for Field Name and Alias, set Data Type to Double and Number Format to Numeric. Click the Save icon on the ribbon (repeat this process for Shape_Area if it does not already exist). To calculate the parameter, right click on the column heading, and select 'Calculate Geometry'.

Field: Shape_Perimeter
Property: Perimeter length (geodesic)
Length Unit: Meters
Coordinate System: Select the same as the orthook
*Click "Ok"
*For large areas, be sure that the Shape_Area is using the Area (geodesic)

Values of Interest:

Footprint area: Found in Field Shape_Area
Footprint perimeter: Found in Shape_Perimeter

Fill workflow_footprint_database fields BL-BP (Grid Classification).

8. Areal Footprint Compare

Resulting footprints from the various approaches can be compared by adding the polygon shapefile data layers of each. In addition to displaying and comparing each approach or time period's resulting layer, the total area and perimeters can be viewed in the respective attribute tables as well as in the Reef_Footprint_Database.

8.1 – **Percent Cover / Patchiness**

This can be calculated at the reef scale by dividing the total area of oyster within a delineated area by the area of that delineated area. For the most accurate assessment of this metric, use the reef area extent that is created in section 8.3 (below).

Reef Patchiness = [Area of Oyster reef in Delineated Area] / [Delineated Area]

Note: The selected classified area may need to be clipped using the Extract by Mask tool (Spatial Analysis Tool) with the chosen delineated area as the feature mask data.

Fill workflow_footprint_database fields BQ (where applicable)

8.2 – **Change Detection**

To evaluate how a site may be changing over time, classified feature layers can be compared spatiotemporally. One approach is to create an overlay map of the various footprints with transparency added to each layer of interest (Figure 10). [A layer's transparency can be adjusted by selecting that layer in the Contents pane → clicking Feature Layer or Raster Layer tab → Adjusting the Transparency setting]

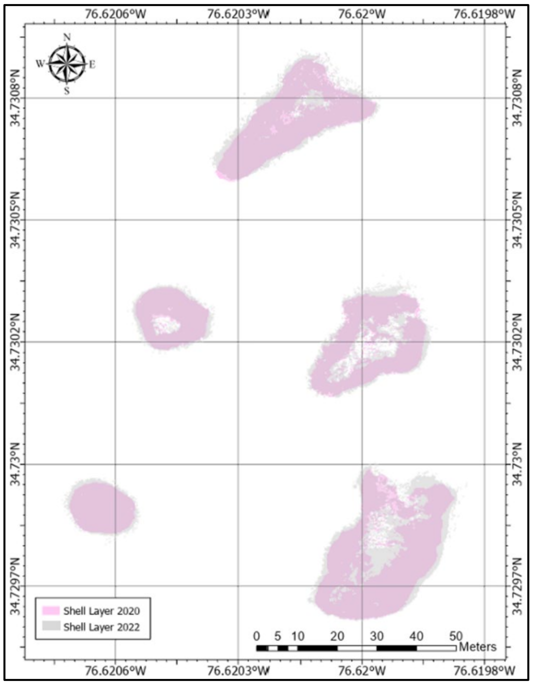


Figure 10. Change in reef areal footprint at Hollowing Reef, North River, NC illustrates the capabilities of UAS to define oyster reef areas and detect areal change from delineated orthomosaic layers. This study site was classified with 367.7 m^2, or 23.3% more reef area in 2022 than in 2020, suggesting reef accretion. Heads-up delineation and classification were utilized to define the 2020 and 2022 shell layers (spatial resolution of 25x25 cm).

A more detailed analysis can be conducted using the Change Detection tool (Figure 11). This tool allows users to detect areas of loss, gain, and stability across two rasters or data layers.

Change Detection Method: Categorical Change (For those with longer time series, Time Series Change could be worth running as well; [Change Detection Wizard—ArcGIS Pro | Documentation])

From Raster: select initial raster

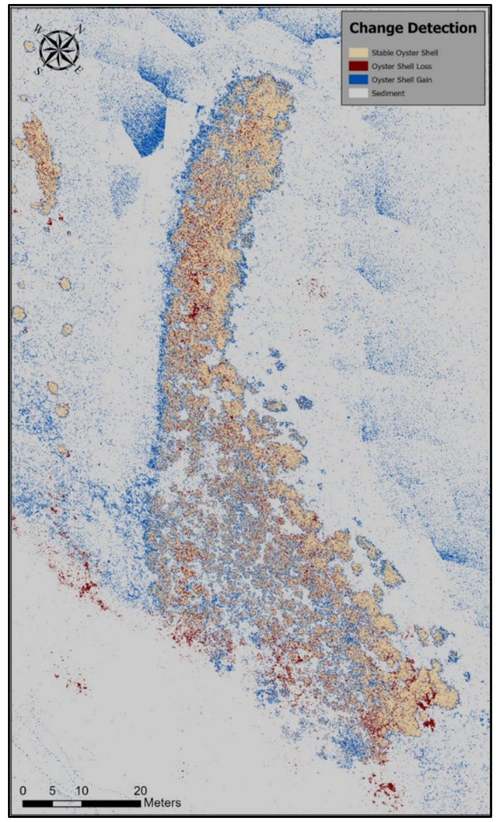
To Raster: select newest raster

Field names: can be used if your raster contains multiple fields still and interest is only in one.

Processing Extent: at a minimum this should be set at the extent of your smallest raster. This is another instance where setting an appropriate site boundary is useful and can again be used. However, best accuracy and results will occur using a delineated extent or a raster that under when heavier masking. For example, you can see numerous artifacts that remain off the reef in Figure 11 that if left in the analysis will skew the results. The extract by Mask tool can also be applied after running the Change Detection tool to remove these inaccuracies.

The output layers will provide counts for stable, gained, losses for each class. The counts can be viewed in the attribute table and area can be calculated by creating a new area field.

Figure 11. Change detection map of Town Marsh Lagoon from Fall 2022 to Summer 2023 showing 794 m of stable shell area, 402 m of shell area change/anomalies, and 7806 m area of stable sediment. Future runs will work to reduce anomalies and improve estimate accuracy.



9. Assessing Delineated Footprint Boundary Accuracy

9.1. Add RTK Points to Map.

At sites where footprint was RTK delineated in the field, RTK points should be used to assess delineated and classified footprint edge accuracy. If they have not been uploaded already, go to Catalog, and add the *.csv* file containing the RTK footprint/boundary points to the project. This can be accomplished either by: (a) adding a table or (b) selecting 'XY data' (under the add data dropdown) and creating a shapefile.

*Be sure to set X to Easting, Y to Northing, and Z to Elevation (again, check that the coordinate system matches the orthomosaic raster).

- Once added, points may need to be binned into their corresponding feature type/ecotone (i.e., footprint, reef-water boundary, subtidal shell extent, reef-marsh boundary, reef axis, profile, etc.)
- Open the attribute table and select all the points of each desired feature type
- Right click on the feature class in the Contents pane, click Selection Make Layer from Selected Features
- Rename the newly created feature class to the correct category (i.e., oysters), labeling 'RTK' as appropriate.

9.2. Generating Digital RTK (optional).

Note: For sites that were not RTK delineated in the field, digital check points can be created either independently from the RGB orthomosaic (Option 1) or from the Heads-up delineation (Option 2). [Some may be interested in doing this anyway to compare RTK footprint points to the RGB ortho image to note any difference or discrepancy. For those interested in assessing this, be sure to pair the new point placement with RTK points. Later the two-point shapefiles will be selected in the Near tool for comparison.]

Option 1: Create independent checkpoints from RGB ortho

Analysis → Tools → Create Feature Class (Data Management Tools)

Feature Class Location: select project geodatabase

Feature Class Name: Digital_FootprintCheckpts

Geometry Type: Multipoint

Coordinate System: set to site ortho layer

- Leave remaining options as default

*Click Run

- Toggle on the appropriate ortho layer.
- On the ribbon, click Edit, Create icon, select Digital_FootprintCheckpts and begin clicking on the ortho layer along the footprint eco-tone/reef edge to create the footprint boundary. It is recommended to aim for ~1m point placement if possible.
- Poorly placed points can be deleted by right clicking on a point and selecting delete vertex. Clicking the button will delete all newly created points. Once point placement is completed, select the button to save as the updated layer in the Contents panel.
- Once created, this feature can be modified by clicking the Modify icon on the ribbon

Option 2: If RTK points were not collected in the field for the site, the geoprocessing tool "Generate Points Along Lines" can be used with any other delineated footprint layer that has been converted to a polyline or polygon shape file.

Geoprocessing ⍰ Select tools ⍰ Generate Points Along Lines (Data Management Tools)

Input Features: select chosen delineated footprint feature

Output Feature Class: name accordingly (example: random_footprint_pts)

Point Placement: By distance

Distance: 1 Meter

* Click Run

Note: Check the Contents panel for all the site's digital delineated polygon and polyline shapefiles.
If not there, upload these features to the project (these should have been created in previous steps: outputs from Head's-up Delineation, Grid Delineation, Supervised Learning Classification).

9.3. Preparing Footprint Polygon Features
Footprint polygon features will need to be augmented for an accurate edge assessment, percent cover, and full footprint extent (this is especially true with patchy footprints as polygon holes and patchiness will result in incorrect features registering as the nearest feature).

9.3.1. Using the polygon footprint layer derived from the classified raster follow the steps below:

Geoprocessing Tools → Eliminate Polygon Part (Data Management Tools)
Input Features: select classified polygon layer
Output Feature Class: "name of classified polygon layer_filled"(extension .shp)
Condition: Area
Area: input a value in square meters larger than the reef footprint itself
*Check "Eliminate contained parts only"

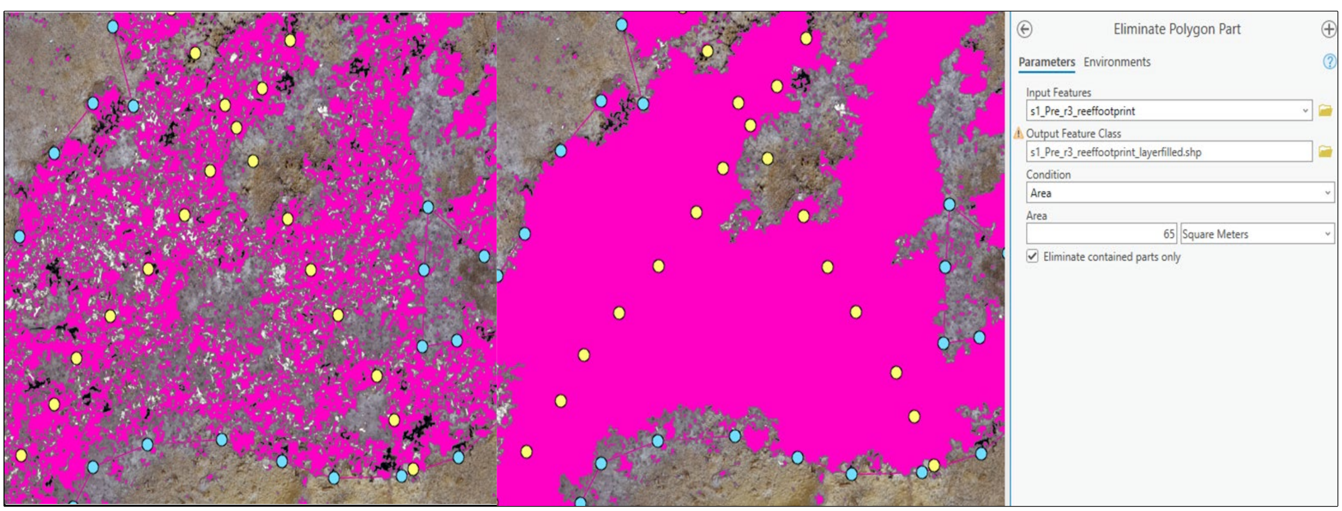


Figure 12: Example of a classified reef polygon footprint layer prior to augmentation--eliminating polygon part (left); polygon footprint after processing augmentation. Yellow circles indicate the reef axis ground-truth points and blue circles the reef RTK points.

Geoprocessing Tools → Polygon to Line (Data Management Tools)

Input Features: select output from Eliminate Polygon Part tool

Output Features: “name of classified polygon layer_line”

*Check “Identify and store polygon neighboring information.”

Repeat with all final footprint polygon shapefile layers.

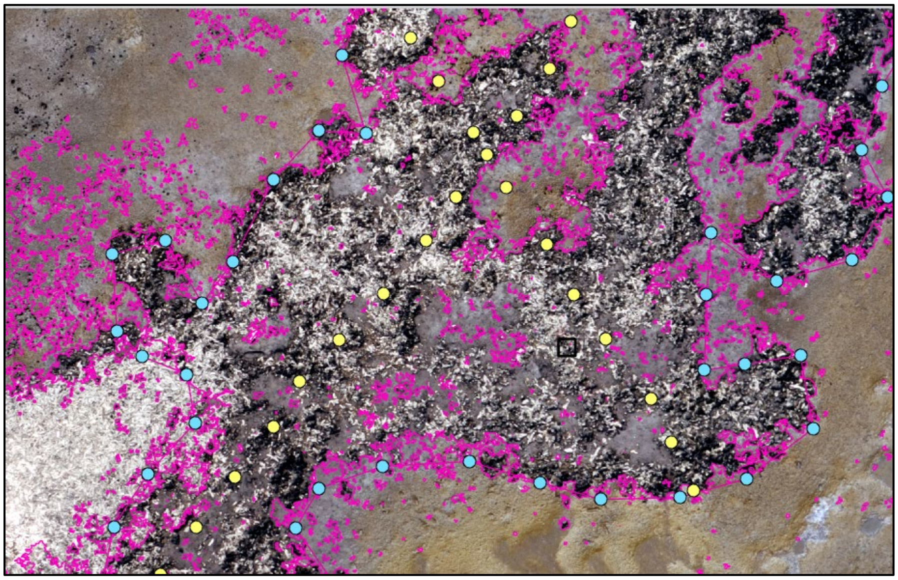


Figure 13: Classified reef line footprint layer (pink) post processing “eliminate polygon part” and “Polygon to line” geoprocessing tool. Yellow circles indicate the reef axis ground-truth points and blue circles the reef RTK points.

9.4. Footprint Boundary Accuracy

Geoprocessing Tools → Analysis Tools → Near (Analysis Tools); [Near (Analysis)—ArcGIS Pro | Documentation]

Input Features: select shapefile with RTK footprint of interest

Near Features: select the computer-based delineation layer (Heads-up, Grid, Classifications)

Method: Geodesic

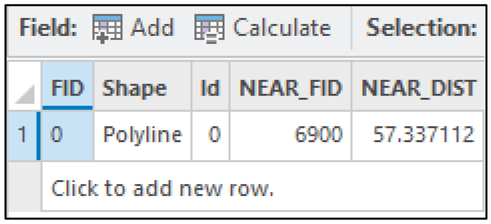
Field Names: Leave the same or update field names accordingly

Distance Unit: Meters

*Click Run

Repeat with all layers as needed.

**The output is a computed distance between the RTK footprint line layer and the NEAR feature added (i.e., classified footprint line). This is added to the RTK footprint line layer attribute table.



	FID	Shape	Id	NEAR_FID	NEAR_DIST
1	0	Polyline	0	6900	57.337112
	Click to add new row.				

9.5. Viewing Results

Open attribute table of each layer selected for as the “Near Feature” in the Near tool
* Right-click on the column and select “Statistics”
* View mean and standard deviation for statistical analysis of RTK measured and digitally delineated reef footprint edge.
* Graphs and tables can be exported and saved.

Fill workflow_footprint_database fields BG-BK (where applicable)

10. Sharing and Uploading Projects

10.1 Exporting ArcGIS project (.ppkx)

- Exported footprint projects are located at the following path:
\imagery_analysis_arcgis_packages\xxx\footprint (where xxx = reserve initials)

Share tab → Project (left side).

- Start packaging = “Save package to file”.
- Item details = change the file location and name, as appropriate.
    1. If the projects are **reef-specific**, save the files as: **xxx_zz_mmddyy_footprint.ppkx**, where xxx = reserve initials, zz = reef initials, mmddyy = date sampled (*e.g.,* noc_mm_071423_footprint.ppkx).
    2. If the projects are **workflow-specific**, and contain all reefs, save the file as: **xxx_allreefs_yyyy_footprint.ppkx**, where xxx = reserve initials, yyyy = year sampled (*e.g.,* noc_allreefs_2023_footprint.ppkx).
    3. For the **experimental reefs**, save the files in one of the two formats listed above, and **add ‘_experiment.ppkx’ at the end** of the name *(e.g.,* noc_mm_030824_footprint_experiment.ppkx).

- Select the checkbox for “Share outside of organization”. Make sure all other checkboxes are unselected.

11. Appendices

11.1 Creating an ArcGIS Pro Database

Create a project folder to house your project, associated files, and ArcGIS Pro database

- This is a good time to create a “Data Inputs” folder and add copies of the original study site orthomosaics, DSMs, and other associated layers/files (these can later be moved into a geodatabase as preferred).
- See the linking for further information on ArcGIS Pro geodatabases (What is a geodatabase?—ArcGIS Pro | Documentation) and assistance in creating an ArcPro database (Create a file geodatabase—ArcGIS Pro | Documentation).

Open ArcGIS Pro and select the map icon under New Project

- Name new project accordingly
- Under Location, navigate to the newly created project folder
- Uncheck create a new folder for this project (this should have already been created in the previous step)

11.2 Importing RTKs points and Creating Layer

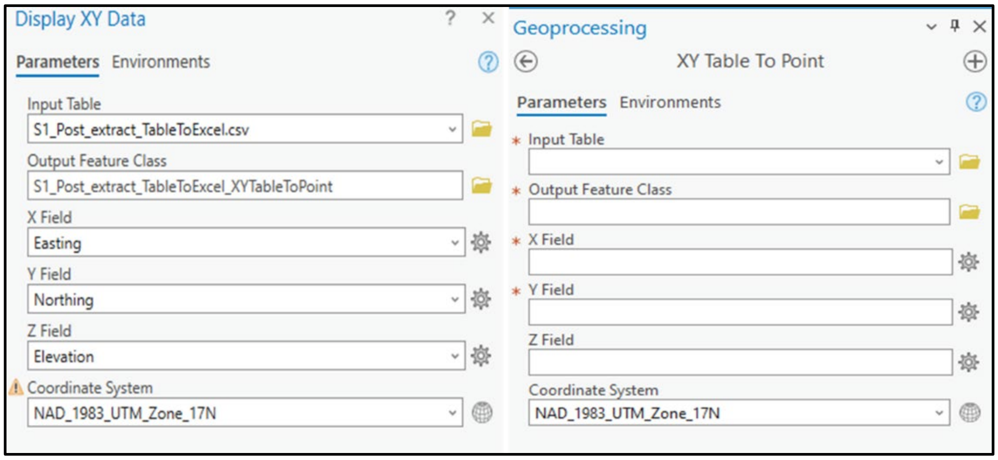
Transform RTK points to point layer

Under the Map tab,
Select add data,
navigate to the data file (.csv) located in the computer folder. If RTK data is stored in Excel file, make sure the file is saved as a .cvs from Excel.

1. Display data

   On the Contents pane,
   Right click the newly added table,
   select → display x/y→ assign “x field” to Easting, “y field” to Northing, and “z field” to elevation columns
2. Table to point

   Under “Analysis” tab,
   click the geoprocessing toolbox
   Select “XY table to point”

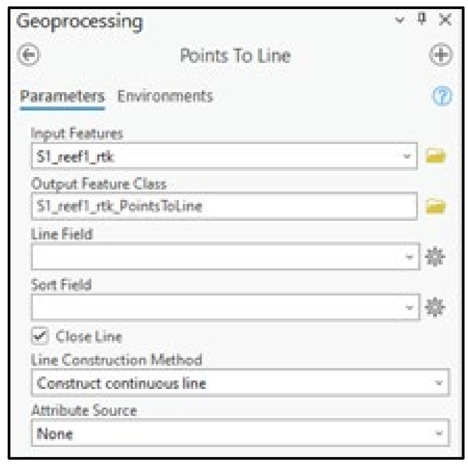


3. Creating boundary as a polygon from RTK point data

To create the individual reef-specific boundaries use the processed RTK point layer to snap line segments that build the boundary of each reef to the RTK points.

In the geoprocessing toolbox search: “points to line”

Input features: the individual reef RTK point
Output feature class: the name for the new RTK line (boundary) file
Check the box for ‘close the line’
Select ‘construct continuous line’ from the Line Construction dropdown menu
Attribute source: none



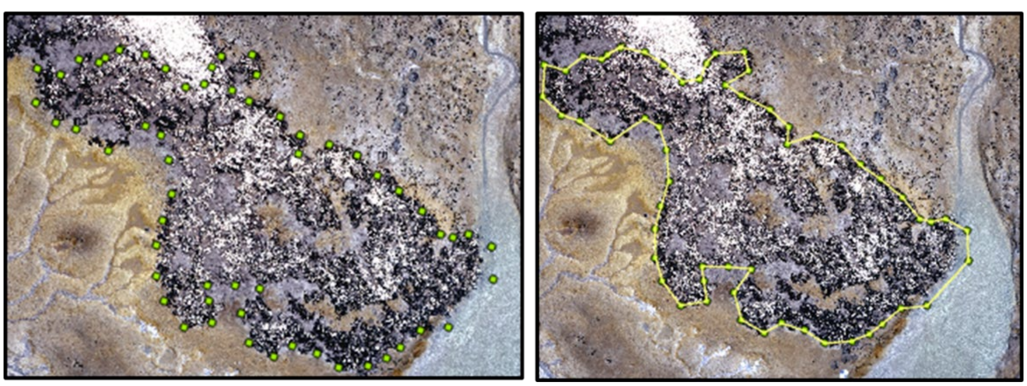


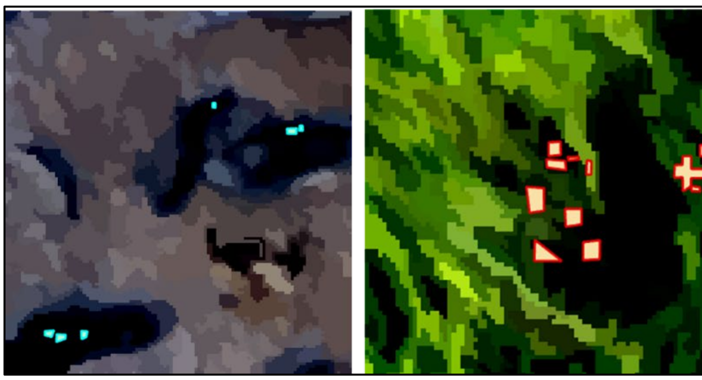
Figure S1. SCDNR Sample reef 1 (site1) RTK points (left); output of reef 1 RTK points snapped as a line feature class (right) after geoprocessing.

11.3 Creating Unique Project Schema and Training Samples

A classification schema determines the number and types of classes to use for supervised classification. Schemas can be hierarchical, meaning there can be classes within subclasses. When creating the training samples, it is important to consider:

- **(a)** The quality of the training samples before running the classification
- **(b)** The proportionality of the training samples across the different classes
- **(c)** Capturing spectrally pure pixel-level samples — meaning, no overlapping pixels in different categories and unimodal color histograms per class.

*It may be helpful to create a table of the different color pixels presented in the segmented image to distinguish the classes (refer to Figures S2 and S3 for examples). Doing this can define the classes and subclasses more accurately to avoid confusion or color overlap that may confuse the image classification algorithm.



Class	# Samples	Pixels (%)
ShellSubstra	31	7.89
Vegetation	31	2.85
Sediment	41	11.05
SubSedimen	60	35.62
DarkSedimer	28	4.94
Water	39	10.80
LiveReefs	137	26.85

Figure S2. Example of training sample polygons for dark sediment pixels on mud areas (left) and in vegetation (right).

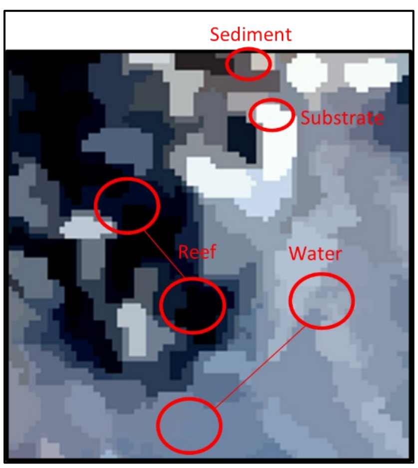


Figure S3. Overview of pixel distinction for multiple classes captured as unique training samples.

Schema	Oyster Reef	Substrate	Rakes	Sediment	Submerged sediment	Dark Sediments	Dry Sediments	Marsh	Water
Class Value	1	5	6	30	35	38	39	40	50
Sample Pixels									
Description	Live oysters and clusters, typically dark due to retaining water longer than surrounding substrates. Spectral characteristics will vary strongly with time of exposure and may warrant additional subclass strata.	Hard substrate or habitable shell material, within the tidal frame. Often it dries faster and appears brighter and whiter when not covered in mud.	Dead shell washed ashore, often older and sun bleached. These areas are non-viable for settlement as they persist above mean water levels.	Sediment areas that are free of water. Drying sediments may also present a broad spectrum.	Dark brown sediments, typically muddy areas, captured on the UAV imagery that appear visibly wet or marginally submerged.	Spots of dark sediment areas typically associated with footprints or sediment patches not submerged, but remaining wet. These pixel areas are often confused with that of oyster during classification.	Dry sediment that appears grey or light.	Marsh habitat areas with shoreline vegetation present at the study site.	Water areas where benthos are not clearly discernible. This can be applied in deeper water areas or water with high turbidity. Subclass strata may need to represent the varied spectral characteristics of the parent class.

Figure S4. A sample table of the pixel color variations identified in the imagery that were used as guidance to create the schema and training samples.

11.4 Guidance on Selecting Support Vector Machine (SVM) or Random Tree (RT)

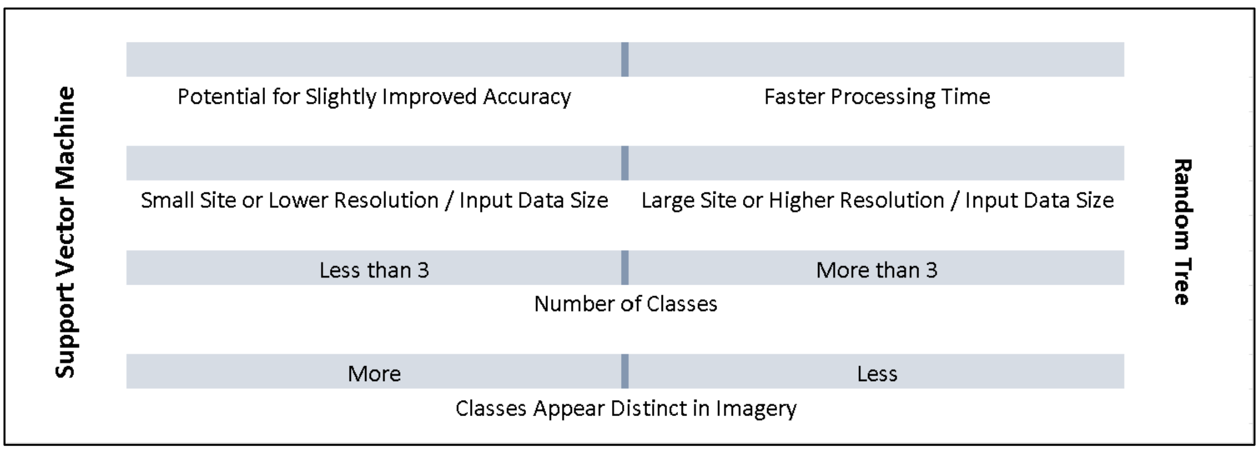


Figure S5. Factors of consideration and guidance on selecting SVM vs RT.

11.5 How to read a Confusion Matrix

- Each cell dictates the number of points that were correctly or incorrectly identified. The graphic below (Figure S6) gives a good description of how each cell(s) is classified. In the case of the oyster reef footprint, imagine that the purple squares make up the two cells outside the diagonal line, not just one.
- You can modify the confusion matrix to show how specific classifications compare to the rest (Figure S7).
  - For example, you can isolate the Underwater Shell class and compare its accuracy to the rest of the classes, since this class usually has the most trouble.

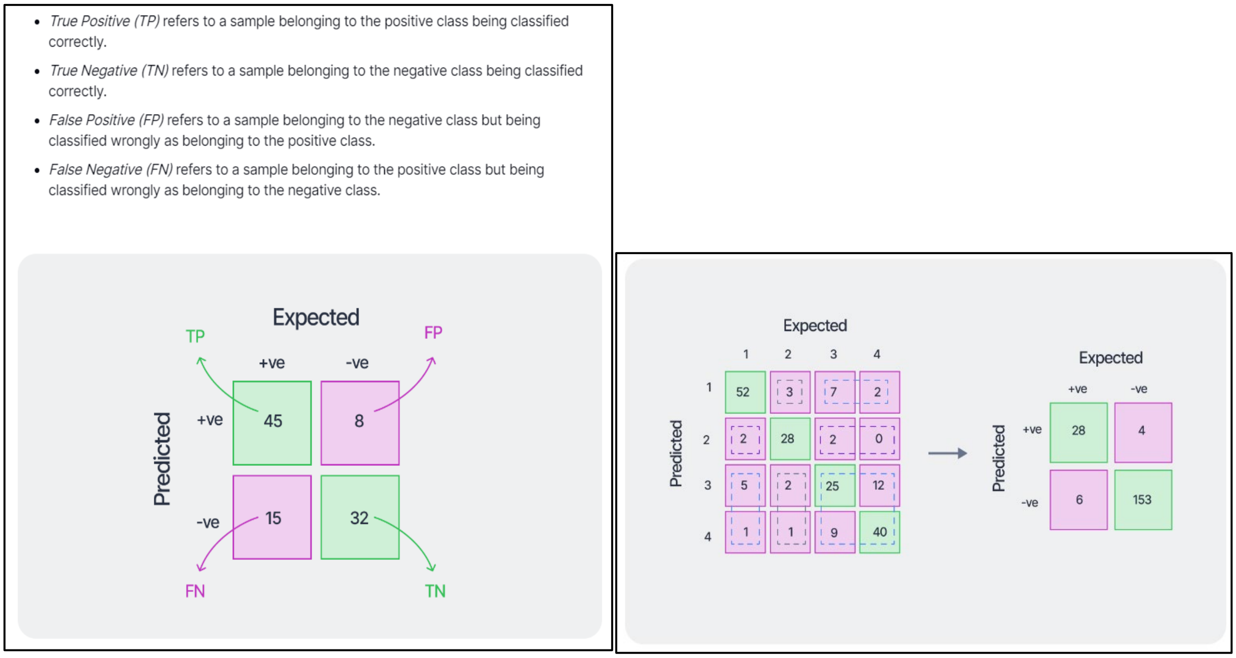


Figure S6 and S7. A step-by-step guide to reading and comprehending a confusion matrix.

11.6 Composite Bands and Ruggedness Layers

In cases where surveys result in additional data layers (i.e., multispect, ruggedness layer, etc.) the Composite Band tool can be used to stitch these individual layers together for use along with the RGB ortho so that End Users are not limited to selecting/making use, of only one additional data layer. **On average, ruggedness layers, such as Terrain Ruggedness (TRI) or Vector Ruggedness Measure (VRM), improved classification accuracy when classification remained poor from RGB and/or DSM layers alone. More detailed instructions on creating TRI and VRM layers can be found in the Oyster Percent Cover and Oyster Density workflow sections.**

11.7 Seed Points for Training Samples

The Seed Points tool is a great way to guide where training samples are created especially for End Users who are interested in creating train samples around their groundtruth areas.
[Generate Training Samples From Seed Points (Spatial Analyst)—ArcGIS Pro | Documentation]

Supporting Tables

Accuracy Assessment Result Examples and explanations for handling classes

Table 1. Unmerged Classes – Fine Resolution Confusion Matrix.

ClassValue	C_1	C_2	C_10	C_30	C_35	Total	U_Accuracy	Kappa
C_1	38	5	0	2	0	45	0.844444	0
C_2	4	8	0	2	0	14	0.571429	0
C_10	0	0	1	8	1	10	0.1	0
C_30	2	1	0	395	0	398	0.992462	0
C_35	0	0	0	6	36	42	0.857143	0
Total	44	14	1	413	37	509	0	0
P_Accuracy	0.863636	0.571429	1	0.956416	0.972973	0	0.939096	0
Kappa	0	0	0	0	0	0	0	0.826541

Confusion matrix summarizing classification accuracy assessment for the Town Marsh Lagoon study site, North Carolina (2022). Individual habitat strata include C_1 = exposed oyster shell; C_2 = submerged oyster shell; C_10 = water; C_30 = exposed sediment; C_35 = submerged sediment. This classification achieved an overall accuracy of 93.91% and a Kappa coefficient of 0.827, indicating strong model agreement beyond chance. Oyster shell (C_1) exhibited strong performance with a User's Accuracy of 84.4% and Producer's Accuracy of 86.4%, while other classes such as sediment (C_30) and water (C_10) also showed high accuracy.

This example provides a detailed view of classification performance at a fine resolution. While valuable for assessing subclass behavior (e.g., exposed vs. submerged habitats), such granularity may increase observed confusion due to visual or spectral similarity. These distinctions are crucial when ecological processes differ between subclasses, but they may also lower apparent accuracy despite solid model performance.

Table 2. Grouped Classes – Simplified Confusion Matrix.

ClassValue	C_1	C_10	C_30	Total	U_Accuracy	Kappa
C_1	55	0	3	58	0.948276	0
C_10	0	1	0	1	1	0
C_30	4	9	437	450	0.971111	0
Total	59	10	440	509	0	0
P_Accuracy	0.932203	0.1	0.993182	0	0.968566	0
Kappa	0	0	0	0	0	0.858731

Confusion matrix showing classification accuracy after grouping similar classes at the same site and survey period (Town Marsh Lagoon, NC, 2022). Grouped strata include: C_1 = all oyster shell (exposed and submerged); C_10 = water; C_30 = all sediment (exposed and submerged). The model achieved an overall accuracy of 96.86% and a Kappa coefficient of 0.859, indicating excellent agreement beyond chance. For the grouped oyster class, User's Accuracy reached 94.8%, and Producer's Accuracy was 93.2%, reflecting minimal misclassification and robust model performance across habitat types.

This example illustrates the benefits of intelligently grouping classes: it improves clarity, minimizes within-group confusion (e.g., between exposed and submerged shell), and aligns with ecological management goals focused on broader habitat categories. However, while accuracy metrics are improved, fine-scale differences are masked — making this approach best suited for applications prioritizing general habitat detection over detailed habitat structure.

Table 3. Grouped Classes – Oversimplified Confusion Matrix.

ClassValue	C_1	C_10	C_30	Total	U_Accuracy	Kappa
C_1	17	5	3	25	0.68	0
C_10	0	60	14	74	0.810811	0
C_30	1	27	73	101	0.722772	0
Total	18	92	90	200	0	0
P_Accuracy	0.944444	0.652174	0.811111	0	0.75	0
Kappa	0	0	0	0	0	0.577203

Confusion matrix showing classification accuracy for grouped habitat classes at the Town Marsh Lagoon study site, North Carolina, surveyed in 2023. Grouped classes include C_1 = all oyster shell (exposed and submerged); C_10 = water; C_30 = all sediment (exposed and submerged). The model achieved an overall accuracy of 75.0% and a Kappa coefficient of 0.577, indicating moderate agreement beyond chance and a decline in performance relative to the 2022 grouped model. Image quality was notably affected by sun glare during the 2023 survey, contributing to classification challenges. The User's Accuracy for the oyster class was 68.0%, and the Producer's Accuracy was 94.4%, suggesting that while most true oyster pixels were detected, a substantial number of false positives reduced classification reliability from a user perspective.

This example highlights some of the limitations of grouping when classification performance is lower overall. Although grouping helped capture broad habitat trends, it also obscured specific sources of confusion and error. For example, this was particularly the case between sediment and water, where misclassifications were more frequent (e.g., 27 water-labeled pixels incorrectly classified as sediment). Ungrouping would be more informative in addressing poor/inadequate samples and retraining the model or simply removing underperforming strata if of less importance. These patterns suggest a clear need to retrain the model using an improved and balanced training dataset, especially for underrepresented or frequently confused classes such as water. Additionally, the classification would benefit from more randomly distributed assessment points to better capture water and sediment zones, to reduce sampling bias, capture misclassification trends in transitional or low-contrast areas, and increase confidence in oyster reef accuracy values. This case, compared to the 2022 examples, demonstrates that grouping alone cannot compensate for broader issues in image quality, training representativeness, or class confusion. However, even with a lower performance, the model is still acceptable, and the grouped approach provides a useful high-level habitat overview.

Table 4. Binary Classification – Oyster Reef vs. Not Oyster Reef.

ClassValue	C_0	C_1	Total	U_Accuracy	Kappa
C_0	174	1	175	0.994286	0
C_1	8	17	25	0.68	0
Total	182	18	200	0	0
P_Accuracy	0.956044	0.944444	0	0.955	0
Kappa	0	0	0	0	0.766234

Confusion matrix summarizing binary classification accuracy at the Town Marsh Lagoon study site, North Carolina, surveyed in 2023. Classes were grouped into: C_1 = oyster reef (exposed + submerged shell), C_0 = non-oyster reef (water + all sediment types).

The model achieved a high overall accuracy of 95.5% and a Kappa coefficient of 0.766, reflecting strong agreement beyond chance for a binary classification. The User's Accuracy for oyster was 68.0%, while Producer's Accuracy was 94.4%, indicating that most true oyster areas were detected, but many predicted oyster pixels were false positives. In contrast, the not-oyster class showed excellent performance (User's Accuracy = 99.4%, Producer's Accuracy = 95.6%).

This example illustrates both the strengths and limitations of extreme class grouping. Binary classification simplifies interpretation, improves overall accuracy, and aligns well with management objectives focused on oyster presence or absence (e.g., restoration planning or regulatory thresholds). However, it also masks internal confusion within the non-oyster class (such as between sediment and water) and highlights the model's tendency to overpredict oyster habitat. This overprediction likely stems from glare in imagery, along with generalization issues or class imbalance in the training data, particularly in complex areas like patchy reefs or habitat edges. To address this, retraining the model with more representative oyster samples and expanding the spatial distribution of validation points—especially across transitional or visually ambiguous zones—could reduce false positives and improve the model's reliability across diverse spectral conditions.

Compared to the more detailed 2023 grouped classification (Table 3), this binary approach yields cleaner metrics and is suitable for coarse-scale decision-making — but it should be paired with finer-scale validation when spatial accuracy of oyster habitat is paramount.

12. Digital Reef Classification & Footprint Assessment Cliff Notes

WORKFLOW

1. TRANSFORM RTK POINTS
   - Display Northing, Easting and Elevation fields
   - Extract points from table
   - Create site boundary

   Display XY Data

2. ORTHOMOSAICS/ RASTER PROCESSING
   - Extract raster areas
   - Mask 'no-data' values
   - Enhance/stretch raster
   - Create composites (optional)

   Raster Functions

   Raster Functions
   Use raster functions for processing and analysis.

3. SEGMENTATION
   - Set segmentation parameters
   - Run geoprocessing tool
   - Add support raster (optional)

4. SCHEMA & TRAINING SAMPLES
   - Develop schema
   - Create training samples
   - Evaluate training samples

5. MODEL TRAINING
   - Train classifier definition file
   - Algorithm (SVM or RT) settings
   - Add supporting raster files

6. CLASSIFY RASTER
   - Set classifier type
   - Set segment attributes
   - Train classifier
   - Classify imagery

7. ACCURACY ASSESSMENT
   - Create Stratified random points
   - Update points
   - Compute confusion matrix

8. FOOTPRINT ANALYSIS
   - Raster to polygon
   - Dissolve
   - Calculate area

INPUTS

ArcGIS Pro geodatabase/ project folder

RTK GNSS points (csv)

Ortho reflectance rasters (.tif)
Digital surface models

OUTPUTS

RTK points

Site boundary

Masked + enhanced raster(s) (.tif)

Segmented raster(s) (.tif)

schema file (.ecs)

Training samples

Classified raster image (.tif)

Confusion matrix table (.dbf)

Classified polygon areas

V. Oyster Percent Cover Workflow

Workflow lead and contact: Allix North (allix.north@floridadep.gov)

Overview

1. Prepare map project
2. Set up the data template spreadsheet
3. Create/orient quadrats
4. Calculate total oyster percent cover
5. Calculate focal statistics
6. Calculate TRI
7. Combine and extract oyster class
8. Tabulate TRI areas for each quadrat
9. Set up Excel worksheet
10. Adjust values to proportion of quadrat size
11. Calculate cumulative sum of each quadrat
12. Run Solver tool & calculate thresholds
13. Create vertical oyster, cultch, and sediment layers
14. Export arcgis project
15. Appendix (formulas; TRI manual method; VRM process)

Input files needed

The following files will be used, from the Oyster Reef Elevation and Elevation Change Workflow:

- **Corrected clipped pre-excavation DSM** (This will be the same DSM used to create your Classified Raster; RMSE corrected and clipped to same extent used in other workflows)
    - *Note, for experimental reefs, you will follow the workflow using the pre-harvest DSM, and then again using the post-harvest DSM if percent cover data were collected in-situ before and after harvesting.*
- **Table to Point RTK data** for in-situ quadrats OR developed polygon quadrats
- **RGB orthomosaic** (for visual ground-truth reference)

And from the Oyster Reef Footprint workflow:

- **Classified Raster** (the final classified raster output containing all classes); the goal is to capture live oyster and shell for this processing. Note, the classes and code values used to classify oysters, shell and sediment in the footprint workflow.
- **Simplified Polygon Feature Layer** of intertidal oysters only (created in Section 6 of the footprint workflow using the Dissolve tool).

1. Preparing the map project

1.1. Prior to starting, decide whether all sampled reefs will be housed in the same ArcGIS project (*e.g.,* each reef will have a separate Map tab), or if each ArcGIS project will house an individual reef.

Note, your decision will affect the naming convention of the final exported ArcGIS project(s), specified at the end of the workflow.

1.2. Add corrected DSM created in the Oyster Reef Elevation and Elevation Change Workflow.

1.3. Add the RTK Point data for all percent cover quadrats.

Note, some reserves may have recorded all 4 quadrat corners, while others may have only recorded the center point and one corner. If you did not create these points in the DSM Workflow, then follow these steps:

1.4. Under Map tab at the top, add data, navigate to quadrat point file (.csv).

1.5. Right click .csv file → Create Points from Table (note, older versions of ArcGIS Pro may use 'display x/y') → choose "XY Table to Point" → Make sure the coordinate system is right (choose the DSM you just brought in to check) → Assign "x field" to Easting, "y field" to Northing, and "z field" to Elevation columns and ignore the warning message if one pops up, which means there were empty cells it did not include.

1.6. Add the Classified Raster and the Simplified Polygon Feature Layer of intertidal oysters only created in the Oyster Reef Footprint Workflow.

2. Setting up the data template spreadsheet

2.1. Open the data template ("workflow_percent_cover_database.xlsx") from \imagery_data_spreadsheets.

2.2. In columns A-H, fill in the site/reef metadata, which can be copied and pasted from the in-situ data template.

Note, make sure to create the same number of rows as there are percent cover quadrats (e.g., if percent cover data was collected in 3 quadrats at Reef 1, there will be three rows of data in the spreadsheet for said reef).

2.3. In column I, copy the names of each quadrat from the in-situ data template, and in column J, fill in the name of your ArcGIS project.

3. Creating/Orienting quadrats

If using 4-corner points:

3.1. Load quadrat point file containing center and corner points collected in the field.

3.2. Go to Geoprocessing Tools, search for and open ‘Create Feature Class’.

-<u>Feature Class Name</u> → per_cov_quads
-<u>Geometry Type</u> → Polygon
<u>-Coordinate System</u> → Select from dropdown menu a -DSM/orthomosaic/other file with the coordinate system of interest (*e.g.,* -NAD 1983 2011 UTM Zone 18N, NAVD88).
-<u>Leave the remaining variables unchanged.</u>
<u>-Click Run.</u>

3.3. Go to the Edit tab (top ribbon), select “Create” and choose the polygon feature class just created under the “Create Features” window on the right side.

3.4. Also in the Edit tab, set the xy snapping tolerance[1] to 10 pixels by opening the Snapping Settings.

3.5. Once finding the points associated with the first percent cover quadrat, right click on one of the quadrat corner points and choose “Snap to feature” → “Vertex”.

Make sure no PVC is included in the polygon if quadrats were left on the reef during the drone flights.

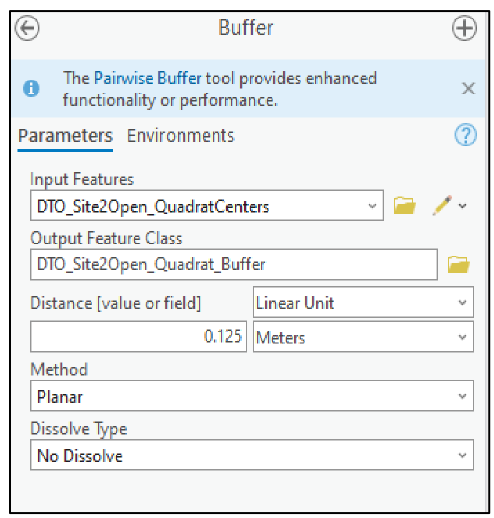
3.6. Repeat this snapping process for each corner of the plot, and double click the last corner to close the polygon.

If using center point and one corner point:

3.7. Select one point from each quadrat point. The center point works best to complete the steps.

3.8. Create a buffer around a point feature in ArcGIS Pro. The Buffer tool creates a circular polygon buffer by default when used on a point feature. The circular buffer can be used as a base to create a square buffer.

3.9. Go to Geoprocessing Tools, search for and open ‘Buffer’.



<u>Input Feature</u> → “quadrats table to point file”
<u>Output Feature Class</u> → quadrats_Buffer.shp

[1] Use snapping—ArcGIS Pro | Documentation

Distance → should be set to half the distance of one side of the quadrat size (in meters) using linear units (*e.g.,* if quadrat size is 0.25m^2 then distance = 0.125m).
Leave the remaining variables unchanged.
Click Run.

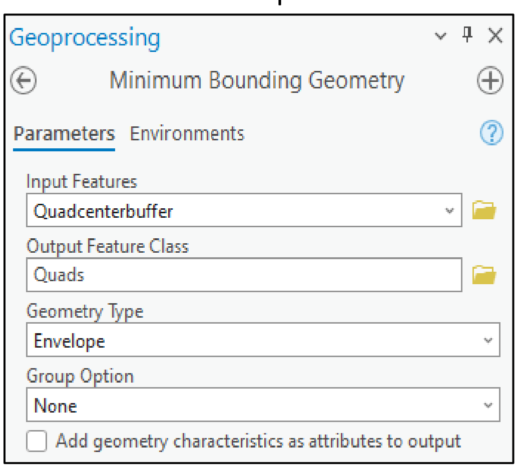
As an example, if the quadrat area = 0.25m^2, then the radius is half that distance or = 0.125m (distance linear unit on each side of the center point). To create the polygon using the buffer tool, we use that radius distance to extend from the center point.

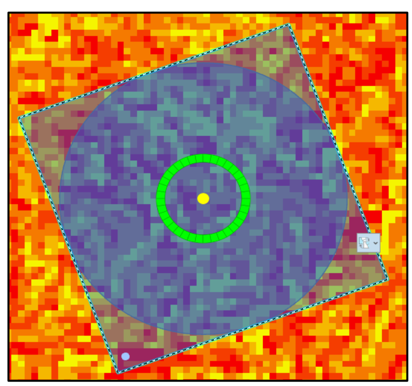
3.10. Go to Geoprocessing Tools, search for and open 'Minimum Bounding Geometry'. Create a square envelope for the buffer in the next steps. The newly created shape will be the quadrats.

-Input Features → Quadrats_Buffer.shp
-Output Feature Class → Quadrats_polygon.shp
-Geometry Type → Envelope. (Using envelope will ensure the quadrat polygon we create captures the full extent of the buffer area---like an envelope)
-Group Option → None
-Click Run.

3.11. Once the quadrat polygons are created, adjust location and orientation to match the corners of the actual quadrat points taken in the field.

3.12. Use the Edit tab and select "move" from the Tools (OR Feature → modify) to rotate the quadrats in the direction of the corner point.





Note, do not adjust size, only move and rotate to orient the polygon to match the orientation of the quadrat points.

Naming the quadrat polygons:

3.13. Right click on the layer and open the attribute table.

-Field → Add
-Field Name → Plot_name
-Alias → Plot_name
-Data Type → Text

3.14. Click Save on the top ribbon and close the "Fields" tab.

3.15. Go to the Edit tab, click Edit, and select Attributes button.

3.15.1. In the panel that opens on the right, rename the "Plot_name" field created in the previous step; make sure the name matches whichever quadrat you are working on (*e.g.,* if you created the polygon around the RTK coordinates for quadrat 1, then the plot_name field would be labeled as "percov_1").

3.15.2. Repeat this step for each plot, going in order of what the plots were named (percent cover quad 1 first, percent cover quad 2 second, etc.).

3.15.3. Save edits and click "Edit" in the top ribbon to end the editing process.

3.15.4. Each polygon quadrat should now have a name assigned to it.

4. Calculating total oyster percent cover

4.1. Go to Geoprocessing Tools, search for and open 'Summarize Within' (Analysis Tool).

-Input Polygons → quadrat polygons created in step 3
-Input Summary Features → Simplified Polygon Feature Layer of only intertidal oysters (created in section 6 of the Footprint workflow)
-Output Feature Class → intertidal_total_oyster_cover
Check the boxes for "Keep all input polygons" and "Add summary attributes"
-Shape Unit → Square meters
-Click Run.

4.2. Go to Geoprocessing Tools, search for and open 'Table to Excel'.

-Input Table → table created with Summarize Within tool
Make sure to toggle off the "Use selected records" button
-Output Excel File → intertidal_total_oyster_cover_table
-Leave "Use field alias as column header" and "Use domain and subtype description" boxes unchecked.
-Click Run.

4.3. Open the exported Excel spreadsheet and add a new column to the right of the existing columns, labeled "oyster_coverage".

4.3.1. In this new column, type the formula: = (sum_Area_SQUAREMETERS) / (Shape_Area) (*e.g.,* E2 / D2).

4.3.2. Drag this formula to populate cells for all quadrats.

4.3.3. All values should be less than or equal to 1, since 1 represents a percent cover of 100%.

4.4. In column R of the data template, copy and paste the values from the "oyster_coverage" column that was calculated in Excel (one row per quadrat).

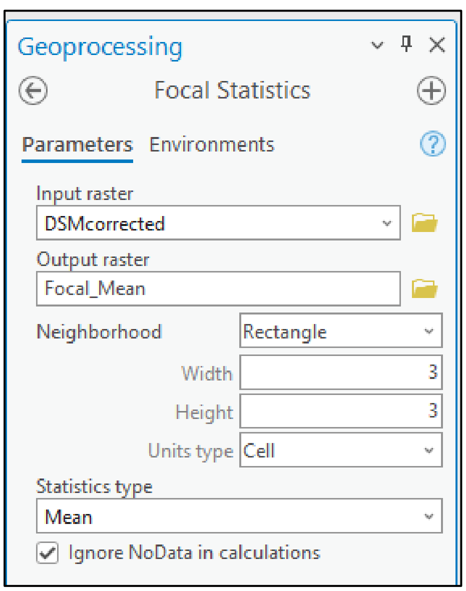
Note, make sure the order of quadrat polygons in both tables matches before copying and pasting the data.

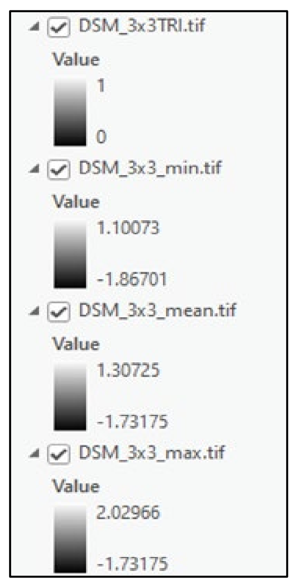
4.5. In column Q of the data template, enter the formula "= 1 – column R" (*e.g.,* 1 – R2). This is the percent cover of anything other than oyster (*e.g.,* sediment, marsh vegetation). Columns Q and R should add up to 1.

5. Focal Statistics

5.1. Go to Geoprocessing Tools, search for and open 'Focal Statistics'.

-Input Raster → Corrected clipped pre-extraction DSM
-Set Neighborhood → Rectangle, width = 3, height = 3, Units type = Cell
-Statistic type → Mean
-Output Raster → Focal_Mean
-Click Run.





5.2. Repeat step 5.1 two more times changing the statistic Type to "Min" and "Max"

Note, this will give you three outputs total (Mean, Min, and Max elevation for each 3x3 neighborhood). Make sure to change the output raster name for each output.

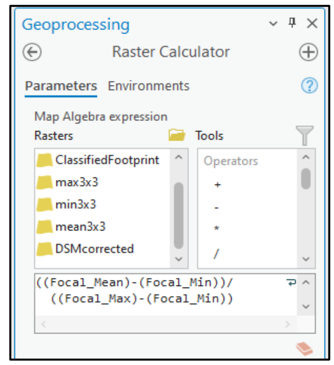
5.3. In column K of the data template spreadsheet, enter the neighborhood size (*e.g.,* 3x3). This value will be the same for all quadrats.

6. Calculate Terrain Ruggedness Index (TRI)

6.1. Go to Geoprocessing Tools, search for and open ‘Raster Calculator’.

Using the three focal statistic outputs you created in the previous step calculate TRI. To calculate, set the parentheses in order and for each space double click the raster file. It should appear on the raster calculator window as part of the formula.

<u>-Formula</u> → ((Focal_Mean)-(Focal_Min))/((Focal_Max)-(Focal_Min))
<u>-Output Raster</u> → TRI
<u>-Click Run.</u>



`

Output TRI Raster has a TRI range varying from 0 to a max value (typically 1).

6.2. Go to Geoprocessing Tools, search for and open ‘Raster Calculator’.

<u>-Formula</u> → Input TRI * 100
<u>-Output Raster</u> → TRI_100
<u>-Click Run.</u>

6.3. Go to Geoprocessing Tools, search for and open 'Int’ (this creates an Integer Raster).

<u>-Input Raster</u> → TRI_100
<u>-Output Raster</u> → TRI_Int
<u>-Click Run.</u>

6.4. In column L of the data template spreadsheet, enter in the range of values in the TRI integer raster created in the previous step. This range will be the same for all quadrats.

Progress check: 6 outputs

DEM 3x3 mean.tif
DEM 3x3 min.tif
DEM 3x3 max.tif
DEM 3x3 TRI.tif
DEM 3x3 TRI_x100.tif
DEM 3x3 TRI_100Integer.tif

7. Combine rasters and extract oyster class

Combine (a) the raster of the classified reef with (b) the TRI_100integer raster to continue with the following steps.

Combining the two products mentioned above will result in another raster that merges the oyster class_value of the Classified Raster with the TRI integer value for each cell in the image neighborhood.

7.1. Combine TRI and classified raster: (include all intertidal oysters –including exposed oysters-- that were captured during the footprint classification process). Remember, we are using the final classified raster output created from the footprint workflow.

7.2. Go to Geoprocessing Tools, search for and open 'Combine'.

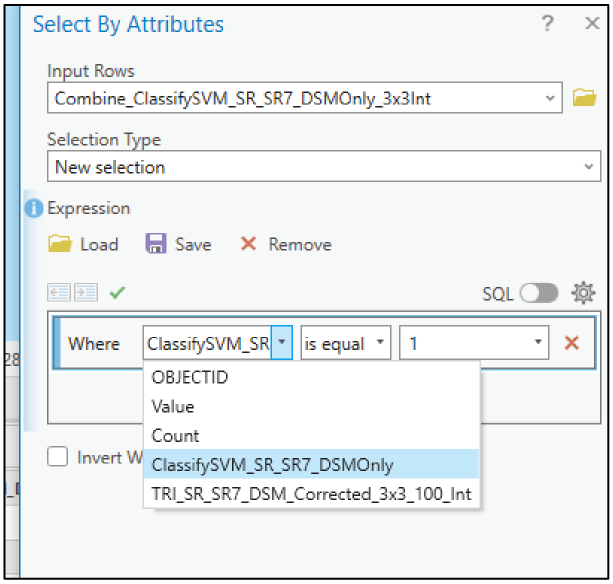
-Input Rasters → Classified Raster from Footprint workflow and TRI_Int
-Output Raster → Classified_TRI_Combine
-Click Run.

7.3. Go to Map Tab and select "Select by Attribute" to select the classified oyster values. (*e.g.,* oyster Class_Value = 1) from the output created above (Classified_TRI_Combine).

-Input row → combined raster
-Selection Type → New
-Expression → where Classified Raster Row in your new table "is equal to" class code for Oyster
-Click apply

Note, if completing this step for the experiment, make sure to use the classified raster from the correct footprint workflow (either pre-excavation or post-excavation).

In the image below the classified raster is "Classify_SR_SR7_DSMOnly_3x3int" and the Class Code for Oyster is "1"

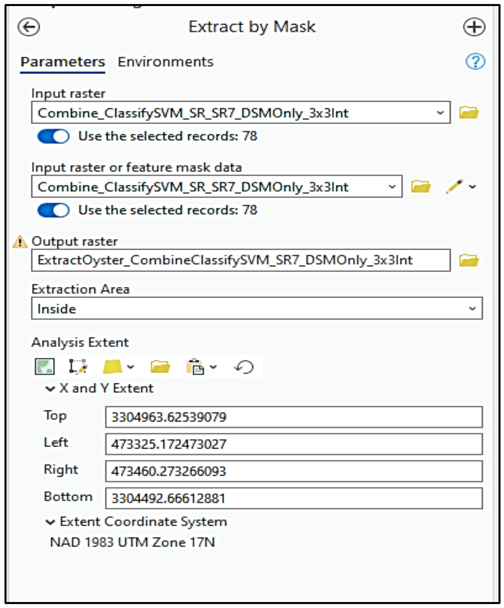


7.4. Go to Geoprocessing Tools, search for and open 'Extract by Mask'.

-Input Raster → Classified_TRI_Combine
-Keep the toggle checked for "Use the selected records".
-Input raster or feature mask data → Classified_TRI_Combine
-Output Raster → Extract_Oyster_Classified_TRI_Combine
-Extraction Area → Inside
-Analysis Extent → Extent of Layer (third tab over)
Select drop down and select the Classified_TRI_Combine layer.
-Click Run.

7.5. In column M in the data template, enter the range of values in this newly created TRI raster for live oysters only.

Note, the scale bar in the contents pane might show a max value greater than 100. Make sure to open the attribute table and check that the range of TRI values does not exceed 100.



Progress check: 2 outputs

Combined_classified _3x3TRI_int_raster.tif
Combined_classifiedliveoysterextract__3x3TRI_int_raster.tif

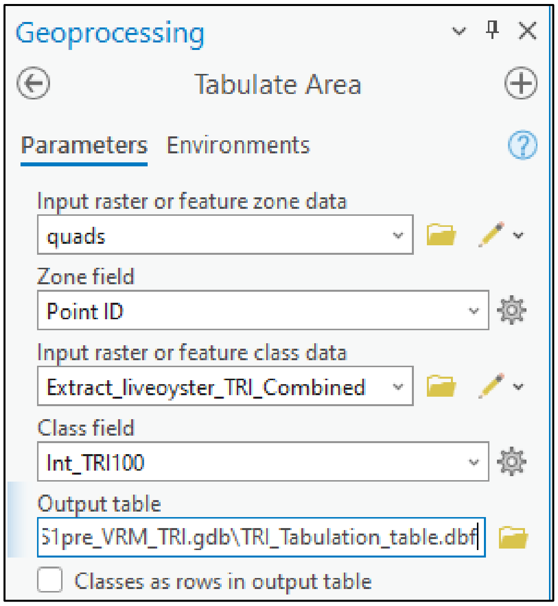
8. Tabulate Area

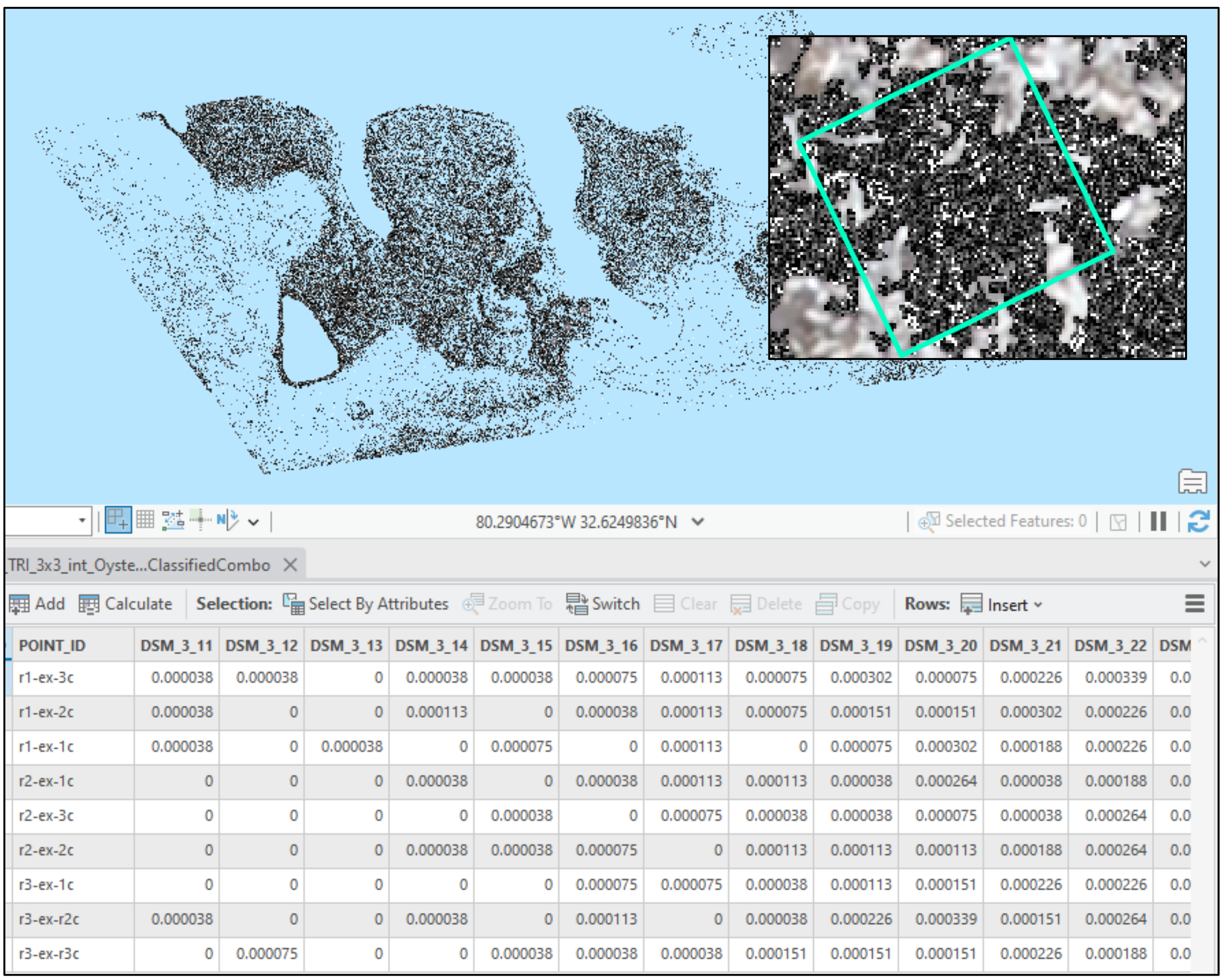
8.1. Go to Geoprocessing Tools, search for and open 'Tabulate Area'.

<u>-Input raster or feature zone data</u> → Quadrat_polygons
<u>-Zone Field</u> → Attribute field that contains quadrat name

Note, if a numeric new field was created to label the quadrats (e.g., 1, 2, 3), make sure to choose "long" for data type and "numeric".

<u>-Input raster or feature class data</u> → Extract_Oyster_Classified_TRI_Combine
<u>-Class field</u> → Attribute field that contains the TRI data (in example below that is called 'Int_TRI100')
<u>-Output Table</u> → TRI_Tabulation_table.dbf
Leave the processing cell size as the default.
<u>-Click Run.</u>





POINT_ID	DSM_3_11	DSM_3_12	DSM_3_13	DSM_3_14	DSM_3_15	DSM_3_16	DSM_3_17	DSM_3_18	DSM_3_19	DSM_3_20	DSM_3_21	DSM_3_22	DSM
r1-ex-3c	0.000038	0.000038	0	0.000038	0.000038	0.000075	0.000113	0.000075	0.000302	0.000075	0.000226	0.000339	0.0
r1-ex-2c	0.000038	0	0	0.000113	0	0.000038	0.000113	0.000075	0.000151	0.000151	0.000302	0.000226	0.0
r1-ex-1c	0.000038	0	0.000038	0	0.000075	0	0.000113	0	0.000075	0.000302	0.000188	0.000226	0.0
r2-ex-1c	0	0	0	0.000038	0	0.000038	0.000113	0.000113	0.000038	0.000264	0.000038	0.000188	0.0
r2-ex-3c	0	0	0	0	0.000038	0	0.000075	0.000038	0.000038	0.000075	0.000038	0.000264	0.0
r2-ex-2c	0	0	0	0.000038	0.000038	0.000075	0	0.000113	0.000113	0.000113	0.000188	0.000264	0.0
r3-ex-1c	0	0	0	0	0	0.000075	0.000075	0.000038	0.000113	0.000151	0.000226	0.000226	0.0
r3-ex-r2c	0.000038	0	0	0.000038	0	0.000113	0	0.000038	0.000226	0.000339	0.000151	0.000264	0.0
r3-ex-r3c	0	0.000075	0	0	0.000038	0.000038	0.000038	0.000151	0.000151	0.000151	0.000226	0.000188	0.0

8.2. Go to Geoprocessing Tools, search for and open ‘Table to Excel’.

<u>-Input Table</u> → TRI_Tabulation_table.dbf
<u>-Output Excel File</u> → TRI_Tabulation_table.xls

Note, the range of TRI values generated at each reef may differ from this example. As a result, the cells selected for your formulas will differ from the examples provided in the steps below, which are just for illustrative purposes.

Progress check: 3 outputs

Quadrat_polygons.shp
TRI_Tabulation_table.dbf
TRI_Tabulation_table.xls

9. Set-up Excel workbook

9.1. Open the excel file generated above.

9.2. Import your estimated in-situ percent cover data (as a decimal) for 3d/live oysters. Make sure you enter percent cover values associated with the correct quadrat for each site.

9.3. Set the in-situ percent cover data and the TRI estimated values side by side to mirror each other in a row format.

	Estimated 3D/liveoyster *(shell and oyster) tabulated area*									
Insitu_per_cov	POINT_ID	INT_T_13	INT_T_14	INT_T_15	INT_T_16	INT_T_17	INT_T_18	INT_T_19	INT_T_20	INT_T_21
0.911183773	rf1-q1-ct	3.2E-05	3.18E-05	0	3.18E-05	0	6.36E-05	0	6.36E-05	0.000127
0.802902398	rf1-q2-ct	0	0	3.18E-05	0	0	0	0	6.36E-05	3.18E-05
0.662719381	rf1-q3-ct	0	0	0	0	0	9.54E-05	0	0	0
1	rf2-q1-ct	3.2E-05	0	0	3.18E-05	0	3.18E-05	9.54E-05	6.36E-05	0
0.897771835	rf2-q2-ct	0	0	0	0	0	6.36E-05	3.18E-05	0	0
0.808460102	rf2-q3-ct	0	0	0	6.36E-05	0	0	0	3.18E-05	0
0.940298634	rf3-q1-ct	0	3.18E-05	0	0	0	0	0	0	6.36E-05
0.973259894	rf3-q2-ct	3.2E-05	0	3.18E-05	0	3.18E-05	0	9.54E-05	3.18E-05	6.36E-05
0.705604654	rf3-q3-ct	0	0	0	0	6.36E-05	3.18E-05	9.54E-05	3.18E-05	3.18E-05

POINT_ID	INT_T_13	INT_T_14	INT_T_15	INT_T_16	INT_T_17	INT_T_18
rf1-q1-ct	3.2E-05	3.18E-05	0	3.18E-05	0	6.36E-05
rf1-q2-ct	0	0	3.18E-05	0	0	0
rf1-q3-ct	0	0	0	0	0	9.54E-05
rf2-q1-ct	3.2E-05	0	0	3.18E-05	0	3.18E-05
rf2-q2-ct	0	0	0	0	0	6.36E-05

In the figure above, the top row is the TRI value identifier (red), and each cell (blue) is the tabulated 3d/live oyster area value for each quadrat in that specific TRI threshold.

10. Adjust tabulated values table

10.1. Table cell values. In this section, we standardize the tabulated area values (cell values) to a proportion relative to the quadrat size, so that all quadrats together sum up to 1 or 100%. This will allow us to compare the areas for each TRI cell equally.

10.2. Below the original table from step 9, copy the table formatting and paste on the same sheet below the original table. The new table's cells should remain blank. These blank cells will be filled with values after the quadrat size adjustment is made.

	3T	BU	BV	BW	BX	BY	BZ	CA
1								
2	_T_80	INT_T_81	INT_T_82	INT_T_83	INT_T_84	INT_T_86	INT_T_88	rowsum
3	0	0	6.36E-05	0	0	0	0	0.061552
4	4E-05	3.18E-05	3.18E-05	3.18E-05	0	0	0	0.054585
5	3E-05	0	0	3.18E-05	0	0	0	0.059643
6	)0223	3.18E-05	0	0	0	0	3.18E-05	0.042784
7	3E-05	6.36E-05	6.36E-05	3.18E-05	0	0	0	0.052359
8	0	0	0	0	0	0	0	0.04571
9	3E-05	6.36E-05	6.36E-05	0	6.36E-05	0	0	0.05888
10	0	0	0	0	3.18E-05	3.18E-05	0	0.02971
11	3E-05	3.18E-05	0	3.18E-05	0	3.18E-05	0	0.059484

Each cell in the quadrat row represents an area of 3D shell/live oysters identified within the TRI threshold indicated.

10.3. Create a new column in the first table and label it "rowsum". Type "=sum(select quadrat row)" to calculate the total row sum area.

10.4. Repeat step 10.3 for all quadrats.

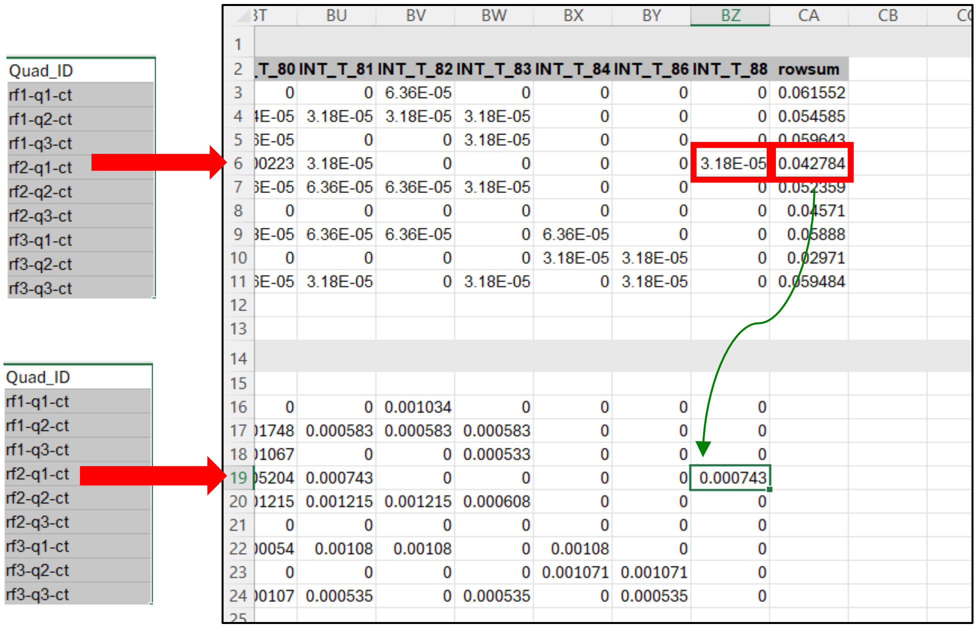
10.5. In the empty formatted table, look for the equivalent quadrat cell and type the formula "=(select cell value) / (select quadrat row sum)".

Note, the rowsum total should be equal to 1, if it isn't, double check calculations.

Table formulas

Rowsum = sum(select quadrat row)

Proportion-adjusted cell value = (Cell area value) / (total row rum area)



Quad_ID		BT	BU	BV	BW	BX	BY	BZ	CA
	1								
Quad_ID	2	_T_80	INT_T_81	INT_T_82	INT_T_83	INT_T_84	INT_T_86	INT_T_88	rowsum
rf1-q1-ct	3	0	0	6.36E-05	0	0	0	0	0.061552
rf1-q2-ct	4	4E-05	3.18E-05	3.18E-05	3.18E-05	0	0	0	0.054585
rf1-q3-ct	5	5E-05	0	0	3.18E-05	0	0	0	0.059643
rf2-q1-ct	6	00223	3.18E-05	0	0	0	0	3.18E-05	0.042784
rf2-q2-ct	7	5E-05	6.36E-05	6.36E-05	3.18E-05	0	0	0	0.052359
rf2-q3-ct	8	0	0	0	0	0	0	0	0.04571
rf3-q1-ct	9	3E-05	6.36E-05	6.36E-05	0	6.36E-05	0	0	0.05888
rf3-q2-ct	10	0	0	0	0	3.18E-05	3.18E-05	0	0.02971
rf3-q3-ct	11	5E-05	3.18E-05	0	3.18E-05	0	3.18E-05	0	0.059484
	12								
	13								
	14								
Quad_ID	15								
rf1-q1-ct	16	0	0	0.001034	0	0	0	0	
rf1-q2-ct	17	01748	0.000583	0.000583	0.000583	0	0	0	
rf1-q3-ct	18	01067	0	0	0.000533	0	0	0	
rf2-q1-ct	19	05204	0.000743	0	0	0	0	0.000743	
rf2-q2-ct	20	01215	0.001215	0.001215	0.000608	0	0	0	
rf2-q3-ct	21	0	0	0	0	0	0	0	
rf3-q1-ct	22	00054	0.00108	0.00108	0	0.00108	0	0	
rf3-q2-ct	23	0	0	0	0	0.001071	0.001071	0	
rf3-q3-ct	24	00107	0.000535	0	0.000535	0	0.000535	0	

10.5.1. In the figure above, Row 6 (quadrat rf2-q1-ct) has a total row sum of 0.042784. At TRI threshold of TRI-88 (BZ6) the area of 3D shell/ live oysters present = 3.18E-05.

3.18E-05 **/** 0.042784 = 0.000743

The formula adjusted the cell area to a proportion for BZ19 (in quadrat rf2-q1-ct). This means that the proportion of 3d shell/ live oysters identified for this quadrat is about 0.0743% for a TRI-88 threshold.

10.6. After completing the quadrat value adjustments, copy the table formatting again (including the column headers). Scroll down at least one row and paste the copied data below that second table. At this point, there should be three identically labeled tables where the third is blank to be filled later with the cumulative sum calculations.

Tabulated Estimated 3D/liveoyster *(shell and oyster)*

Quad_ID	INT_T_13	INT_T_14	INT_T_15	INT_T_16	INT_T_17	INT_T_18	INT_T_19	INT_T_20	INT_T_21	INT_T_22	INT_T_23	INT_T_24	INT_T_25	INT_T_26	INT_T_27
rf1-q1-ct	3E-05	3.2E-05	0	3.2E-05	0	6.4E-05	0	6.4E-05	0.00013	3.2E-05	0.00019	6.4E-05	0.00019	0.00029	0.00025
rf1-q2-ct	0	0	3.2E-05	0	0	0	0	6.4E-05	3.2E-05	3.2E-05	9.5E-05	3.2E-05	0.00013	0.00025	9.5E-05
rf1-q3-ct	0	0	0	0	0	9.5E-05	0	0	0	3.2E-05	0	0.00016	0.00019	0.00022	0.00016
rf2-q1-ct	3E-05	0	0	3.2E-05	0	3.2E-05	9.5E-05	6.4E-05	0	3.2E-05	3.2E-05	0.00019	0.00013	0.00016	0.00022
rf2-q2-ct	0	0	0	0	0	6.4E-05	3.2E-05	0	0	0	6.4E-05	6.4E-05	9.5E-05	9.5E-05	0.00019
rf2-q3-ct	0	0	0	6.4E-05	0	0	0	3.2E-05	0	6.4E-05	0	3.2E-05	0.00013	0.00016	0.00013
rf3-q1-ct	0	3.2E-05	0	0	0	0	0	0	6.4E-05	0	0.00016	6.4E-05	9.5E-05	0.00022	0.00022
rf3-q2-ct	3E-05	0	3.2E-05	0	3.2E-05	0	9.5E-05	3.2E-05	6.4E-05	6.4E-05	0.00022	0.00019	0.00016	0.00022	0.00025
rf3-q3-ct	0	0	0	0	6.4E-05	3.2E-05	9.5E-05	3.2E-05	3.2E-05	9.5E-05	9.5E-05	0.00032	0.00016	0.00013	0.00029

Tabulated area Adjusted

Quad_ID															
rf1-q1-ct	0.0005	0.00052	0	0.00052	0	0.00103	0	0.00103	0.00207	0.00052	0.0031	0.00103	0.0031	0.00465	0.00413
rf1-q2-ct	0	0	0.00058	0	0	0	0	0.00117	0.00058	0.00058	0.00175	0.00058	0.00233	0.00466	0.00175
rf1-q3-ct	0	0	0	0	0	0.0016	0	0	0	0.00053	0	0.00267	0.0032	0.00373	0.00267
rf2-q1-ct	0.0007	0	0	0.00074	0	0.00074	0.00223	0.00149	0	0.00074	0.00074	0.00446	0.00297	0.00372	0.0052
rf2-q2-ct	0	0	0	0	0	0.00122	0.00061	0	0	0	0.00122	0.00122	0.00182	0.00182	0.00365
rf2-q3-ct	0	0	0	0.00139	0	0	0	0.0007	0	0.00139	0	0.0007	0.00278	0.00348	0.00278
rf3-q1-ct	0	0.00054	0	0	0	0	0	0	0.00108	0	0.0027	0.00108	0.00162	0.00378	0.00378
rf3-q2-ct	0.0011	0	0.00107	0	0.00107	0	0.00321	0.00107	0.00214	0.00214	0.00749	0.00642	0.00535	0.00749	0.00857
rf3-q3-ct	0	0	0	0	0.00107	0.00053	0.0016	0.00053	0.00053	0.0016	0.0016	0.00535	0.00267	0.00214	0.00481

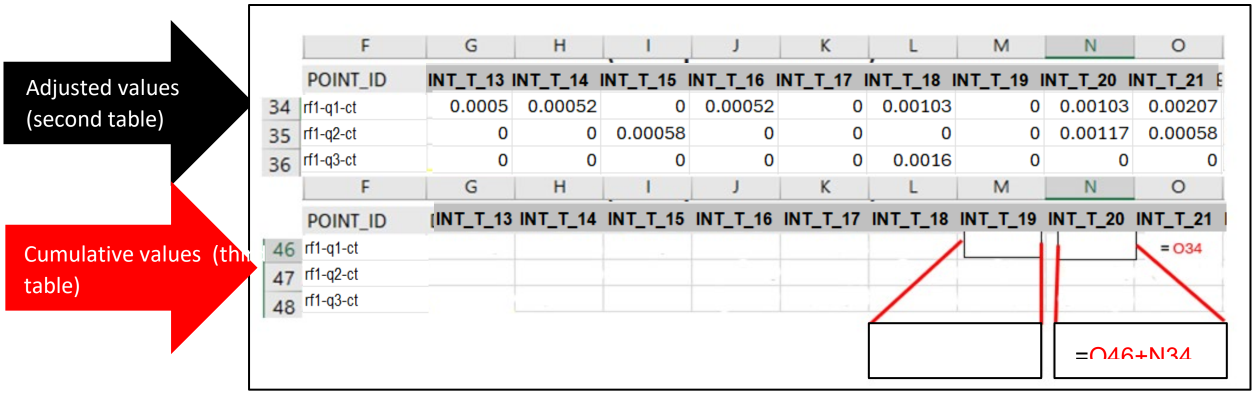
Cummulative % Table

Quad_ID	INT_T_13	INT_T_14	INT_T_15	INT_T_16	INT_T_17	INT_T_18	INT_T_19	INT_T_20	INT_T_21	INT_T_22	INT_T_23	INT_T_24	INT_T_25	INT_T_26	INT_T_27
rf1-q1-ct															
rf1-q2-ct															
rf1-q3-ct															
rf2-q1-ct															
rf2-q2-ct															
rf2-q3-ct															
rf3-q1-ct															
rf3-q2-ct															
rf3-q3-ct															

11.Calculate the cumulative percentage

11.1. To calculate the cumulative sum for each quadrat, work from right to left across the row. Add each number in the sequence to the sum of the previous cell on the right. Continue summing up this way until you reach the leftmost cell (the first value).

11.1.1. Use the following table below to follow the process.



11.1.2. Scroll along the top row to the last column header (the end of the TRI values). In this example, the end is column O.

11.1.3. To populate the third table, begin at the end of column O. Starting with quadrat rf1-q1-ct (row 46) cell O46. Used the formula "= (select cell #)", where cell# corresponds to adjusted value from the same quadrat cell in the second table. Essentially, O46 = the same value as O34.

11.1.4. Drag that formula down column O to apply to other row of quadrats below it.

11.1.5. In the cell to the left of O46 (the next leftmost cell) or N46 follow this convention "= cell> + cell #". Where *cell>* is the value of the previous rightmost cell (O46) and cell# is the adjusted equivalent to N46 on the second table (N34).

11.1.6. Drag that formula down for all the remaining rows where you have quadrat data.

11.1.7. Repeat for all quadrats.

N46 value = O46 + N34 value

M46 value = N46 cumulative value + M34 value

L46 value = M46 cumulative value + L34

K46 = L46 cumulative value + K34 and so on….

11.2. Once the entire quadrat (or row) is completed, the leftmost value should have a cell value of 0.9999 or 1 or really close to 1. If it doesn't, the calculations might be off.

cummulative									
Quad_ID	INT_T_13	INT_T_14	INT_T_15	INT_T_16	INT_T_17	INT_T_18	INT_T_19	INT_T_20	INT_T_21
rf1-q1-ct	1	0.99948	0.99896	0.99896	0.99844	0.99844	0.99741	0.99741	0.99638
rf1-q2-ct	1	1.00001	1.00001	0.99942	0.99942	0.99942	0.99942	0.99942	0.99826
rf1-q3-ct	1	1	1	1	1	1	0.9984	0.9984	0.9984
rf2-q1-ct	1	0.99926	0.99926	0.99926	0.99851	0.99851	0.99777	0.99554	0.99405
rf2-q2-ct	1	1	1	1	1	1	0.99878	0.99818	0.99818
rf2-q3-ct	1	1	1	1	0.99861	0.99861	0.99861	0.99861	0.99791
rf3-q1-ct	1	1	0.99946	0.99946	0.99946	0.99946	0.99946	0.99946	0.99946
rf3-q2-ct	1	0.99893	0.99893	0.99786	0.99786	0.99679	0.99679	0.99358	0.99251
rf3-q3-ct	1	1	1	1	1	0.99893	0.9984	0.99679	0.99626

11.3. Now continue setting up the final table with the remainder of formulas needed for analysis.

11.4. Add 2 new columns next to insitu_per_cov on the left-hand side of the table and name them: ***est_per_cov*** (calculates a TRI-based percent cover estimate from drone products), and ***sq_err*** (calculates the difference squared between in-situ and estimated percent cover values).

Insitu_per_cov	est_per_cov	sq_err								
			Quad_ID	INT_T_13	INT_T_14	INT_T_15	INT_T_16	INT_T_17	INT_T_18	INT_T_19
0.911183773	0.821182974	0.008100	rf1-q1-ct	0.99999	0.999476	0.99896	0.99896	0.998443	0.998443	0.997409
0.802902398	0.851402869	0.002352	rf1-q2-ct	1.00001	1.000005	1.000005	0.999422	0.999422	0.999422	0.999422
0.662719381	0.856	0.037357	rf1-q3-ct	1	1	1	1	1	1	0.9984
1	0.855018587	0.021020	rf2-q1-ct	1	0.999257	0.999257	0.999257	0.998513	0.998513	0.99777
0.897771835	0.865127582	0.001066	rf2-q2-ct	1	1	1	1	1	1	0.998785
0.808460102	0.848990953	0.001643	rf2-q3-ct	1	1	1	1	0.998608	0.998608	0.998608
0.940298634	0.840626688	0.009934	rf3-q1-ct	1	1	0.99946	0.99946	0.99946	0.99946	0.99946
0.973259894	0.781584582	0.036739	rf3-q2-ct	1	0.998929	0.998929	0.997859	0.997859	0.996788	0.996788
0.705604654	0.805882353	0.010056	rf3-q3-ct	1	1	1	1	1	0.99893	0.998396

11.5. On the sq_err column add a new field on the cell below the final quadrat row. Label it ***"SSE"***

Insitu_per_cov	est_per_cov	sq_err		
			Quad_ID	INT_T_13
0.911183773	0.821182974	0.008100	rf1-q1-ct	0.99999
0.802902398	0.851402869	0.002352	rf1-q2-ct	1.00001
0.662719381	0.856	0.037357	rf1-q3-ct	1
1	0.855018587	0.021020	rf2-q1-ct	1
0.897771835	0.865127582	0.001066	rf2-q2-ct	1
0.808460102	0.848990953	0.001643	rf2-q3-ct	1
0.940298634	0.840626688	0.009934	rf3-q1-ct	1
0.973259894	0.781584582	0.036739	rf3-q2-ct	1
0.705604654	0.805882353	0.010056	rf3-q3-ct	1
Insituper_cov_avg	est_per_cov_avg	SSE	sum_tri_Select	0
0.855800074	0.836201843	0.128267	1	

11.6. Add a final field label on the cell next to SEE and below the last quadrat label: name it "**sum_tri_select**". This value will be used when running the solver tool and will define the binary output constraints needed.

11.7. For each of the newly added fields, refer to the following formulas (four of them) to calculate values in their respective cells and rows in the third table.

11.8. **Sum_TRI_Select** = sum(binomial range)

11.8.1. To the right of the cell labeled "Sum_TRI_select", add a row of 0's spanning the width of the entire table (*e.g.,* from the first TRI value to the last in the table) (see example below). Replace the first '0' in the row with a '1'. *There can only be a single 1 in the sequence*.

Insitu_per_cov	est_per_cov	sq_err	cummulative													
			Quad_ID	INT_T_13	INT_T_14	INT_T_15	INT_T_16	INT_T_17	INT_T_18	INT_T_19	INT_T_20	INT_T_21	INT_T_22	INT_T_23	INT_T_24	INT_T_25
0.911183773	0.999993119	0.007887	rf1-q1-ct	1	0.99948	0.99896	0.99896	0.99844	0.99844	0.99741	0.99741	0.99638	0.99431	0.99379	0.99069	0.98966
0.802902398	1.000005012	0.038849	rf1-q2-ct	1	1.00001	1.00001	0.99942	0.99942	0.99942	0.99942	0.99942	0.99826	0.99767	0.99709	0.99534	0.99476
0.662719381	1	0.113758	rf1-q3-ct	1	1	1	1	1	1	0.9984	0.9984	0.9984	0.9984	0.99787	0.99787	0.9952
1	1	0.000000	rf2-q1-ct	1	0.99926	0.99926	0.99926	0.99851	0.99851	0.99777	0.99554	0.99405	0.99405	0.99331	0.99257	0.9881
0.897771835	1	0.010451	rf2-q2-ct	1	1	1	1	1	1	0.99878	0.99818	0.99818	0.99818	0.99818	0.99696	0.99575
0.808460102	1	0.036688	rf2-q3-ct	1	1	1	1	0.99861	0.99861	0.99861	0.99861	0.99791	0.99791	0.99652	0.99652	0.99582
0.940298634	1	0.003564	rf3-q1-ct	1	1	0.99946	0.99946	0.99946	0.99946	0.99946	0.99946	0.99946	0.99838	0.99838	0.99568	0.9946
0.973259894	1	0.000715	rf3-q2-ct	1	0.99893	0.99893	0.99786	0.99786	0.99679	0.99679	0.99358	0.99251	0.99036	0.98822	0.98073	0.9743
0.705604654	1	0.086669	rf3-q3-ct	1	1	1	1	1	0.99893	0.9984	0.99679	0.99626	0.99572	0.99412	0.99251	0.98717
Insituper_cov_avg	est_per_cov_avg	SSE	sum_tri_Select	1	0	0	0	0	0	0	0	0	0	0	0	0
0.855800074	0.999999792	0.298581	1													

11.8.2. Sum the binomial row (the newly added row of 0s and 1) in the cell below "sum_tri_select". Use formula "=sum(range)'. This should equal to 1.

Insitu_per_cov	est_per_cov	sq_err	cummulative													
			Quad_ID	INT_T_13	INT_T_14	INT_T_15	INT_T_16	INT_T_17	INT_T_18	INT_T_19	INT_T_20	INT_T_21	INT_T_22	INT_T_23	INT_T_24	INT_T_25
0.911183773	0.999993119	0.007887	rf1-q1-ct	1	0.99948	0.99896	0.99896	0.99844	0.99844	0.99741	0.99741	0.99638	0.99431	0.99379	0.99069	0.98966
0.802902398	1.000005012	0.038849	rf1-q2-ct	1	1.00001	1.00001	0.99942	0.99942	0.99942	0.99942	0.99942	0.99826	0.99767	0.99709	0.99534	0.99476
0.662719381	1	0.113758	rf1-q3-ct	1	1	1	1	1	1	0.9984	0.9984	0.9984	0.9984	0.99787	0.99787	0.9952
1	1	0.000000	rf2-q1-ct	1	0.99926	0.99926	0.99926	0.99851	0.99851	0.99777	0.99554	0.99405	0.99405	0.99331	0.99257	0.9881
0.897771835	1	0.010451	rf2-q2-ct	1	1	1	1	1	1	0.99878	0.99818	0.99818	0.99818	0.99818	0.99696	0.99575
0.808460102	1	0.036688	rf2-q3-ct	1	1	1	1	0.99861	0.99861	0.99861	0.99861	0.99791	0.99791	0.99652	0.99652	0.99582
0.940298634	1	0.003564	rf3-q1-ct	1	1	0.99946	0.99946	0.99946	0.99946	0.99946	0.99946	0.99946	0.99838	0.99838	0.99568	0.9946
0.973259894	1	0.000715	rf3-q2-ct	1	0.99893	0.99893	0.99786	0.99786	0.99679	0.99679	0.99358	0.99251	0.99036	0.98822	0.98073	0.9743
0.705604654	1	0.086669	rf3-q3-ct	1	1	1	1	1	0.99893	0.9984	0.99679	0.99626	0.99572	0.99412	0.99251	0.98717
Insituper_cov_avg	est_per_cov_avg	SSE	sum_tri_Select	1	0	0	0	0	0	0	0	0	0	0	0	0
0.855800074	0.999999792	0.298581														

sum_TRI_select	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
=SUM(F44:CD44)															

11.9. **est_per_cov** = SUMPRODUCT (first array, second array)

11.9.1. The first array in the formula is the entire row of cumulative tabulated area values for a quadrat. Select the entire row of values for that quadrat.

11.9.2. The second array in the formula is the binomial selection of sum_tri_Select (the entire row of 0's and 1).

Note, the “$” embedded before the row entry in the second array. Putting 1 for the second array (part of formula after the comma) will not work. The formula requires an array, and it would give an error if only a single digit number is included.

11.9.3. Drag the formulas down for all the remaining rows (quadrat cells).

Insitu_per_cov	est_per_cov	sq_err	cummulative											
			Quad_ID	INT_T_13	INT_T_14	INT_T_15	INT_T_16	INT_T_17	INT_T_18	INT_T_19	INT_T_20	INT_T_21	INT_T_22	INT_T_23
0.911183773	BZ38)	0.008100	rf1-q1-ct	0.999993	0.99948	0.99896	0.99896	0.99844	0.99844	0.99741	0.99741	0.99638	0.99431	0.99379
0.802902398	0.851402869	0.002352	rf1-q2-ct	1.000005	1.00001	1.00001	0.99942	0.99942	0.99942	0.99942	0.99942	0.99826	0.99767	0.99709
0.662719381	0.856	0.037357	rf1-q3-ct	1	1	1	1	1	1	0.9984	0.9984	0.9984	0.9984	0.99787
1	0.855018587	0.021020	rf2-q1-ct	1	0.99926	0.99926	0.99926	0.99851	0.99851	0.99777	0.99554	0.99405	0.99405	0.99331
0.897771835	0.865127582	0.001066	rf2-q2-ct	1	1	1	1	1	1	0.99878	0.99818	0.99818	0.99818	0.99818
0.808460102	0.848990953	0.001643	rf2-q3-ct	1	1	1	1	0.99861	0.99861	0.99861	0.99861	0.99791	0.99791	0.99652
0.940298634	0.840626688	0.009934	rf3-q1-ct	1	1	0.99946	0.99946	0.99946	0.99946	0.99946	0.99946	0.99946	0.99838	0.99838
0.973259894	0.781584582	0.036739	rf3-q2-ct	1	0.99893	0.99893	0.99786	0.99786	0.99679	0.99679	0.99358	0.99251	0.99036	0.98822
0.705604654	0.805882353	0.010056	rf3-q3-ct	1	1	1	1	1	0.99893	0.9984	0.99679	0.99626	0.99572	0.99412
Insituper_cov_avg	est_per_cov_avg	SSE	sum_tri_Select	0	0	0	0	0	0	0	0	0	0	0
0.855800074	0.836201843	0.128267	1											

11.10. **Sq_err** = ((insitu_percov) – (est_per_cov))^2

11.10.1. Type this formula in the first cell under the “Squared_error” heading. Drag the formula down for all of the remaining rows with quadrat data. In the example below, the sq_err formula for row D53 (quadrat r1-ex-1o) is “=((B53)-(C53))^2”.

	B	C	D	E
	in situ%	est_cov analysis	Squared error	Quadrat
53	0.9112	0.856963607	0.002940	r1-ex-1c
54	0.8029	0.855535095	0.002770	r1-ex-2c
55	0.6627	0.832728275	0.028903	r1-ex-3c
56	1.0000	0.833272996	0.027798	r2-ex-1c
57	0.8978	0.848906989	0.002388	r2-ex-2c
58	0.8085	0.847683826	0.001539	r2-ex-3c
59	0.9403	0.844716295	0.009136	r3-ex-1c
60	0.9733	0.835031705	0.019107	r3-ex-r2c
61	0.7056	0.849666875	0.020754	r3-ex-r3c

11.11. **SSE** = SUM(sq_err column)

11.11.1. SSE (or sum of squared error) calculates the sum of squared errors by summing all the values in the sq_err column. In figure this is equal to SUM (D53:D61).

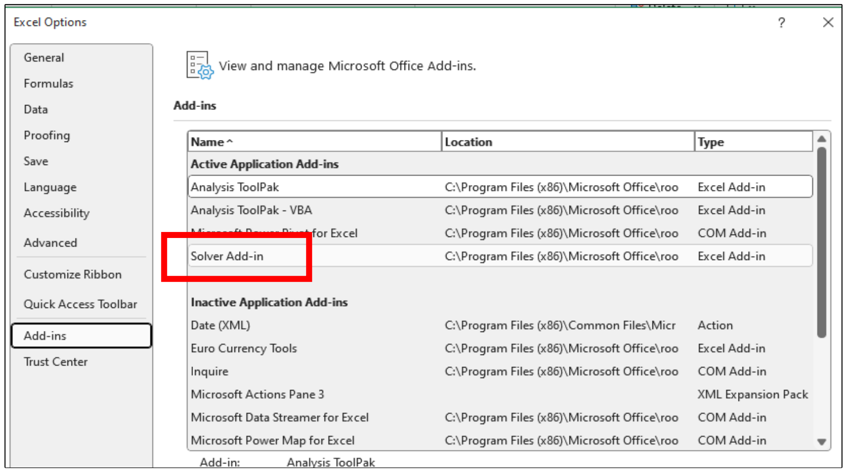
12. Solver tool

The Solver tool will be used to estimate percent cover and minimize the sum of squared errors, and ultimately determine the minimum TRI threshold where 3D shell/live oyster was detected in each quadrat. These estimates will be compared with in-situ percent cover estimates.

12.1. Add the ‘Solver’ data analysis tool as an excel add-in function.

12.1.1. Go to the File tab. Click on Options.

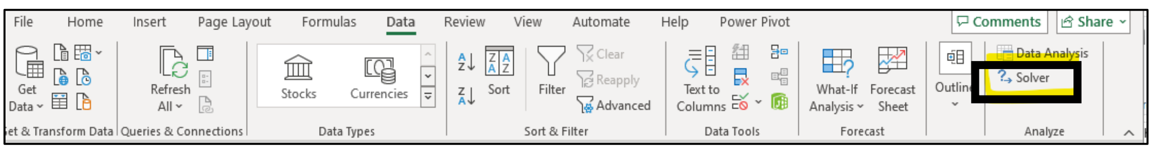
12.1.2. Select Add-ins. Choose Solver Add-in from the Add-ins tab.



12.1.3. Click on Go. The Add-ins window pops up.

12.1.4. Select the Solver Add-in checkbox and click OK.

12.1.5. After you load the Solver Add-in, the Solver command is available in the Analysis group on the Data tab.



12.2. Click the Data tab → Solver (typically to the far right of the Data ribbon in the Analyze section). In the Solver Parameters pop-up, enter the following:

12.2.1. Set Objectives: Select the cell where you calculate the sum of squared errors (SSE).

12.2.2. To: “Min” (we want to minimize the sum of squared errors).

12.2.3. By Changing Variable Cells: Select the row range of 0’s and 1.

12.3. Add first constraint.

12.3.1. Subject to the Constraints: Select the Add button found on the right side of the pop-up window.

12.3.2. While in the constraint pop-up, select the cell where Sum_TRI_select is calculated (*e.g.*, the cell below “sum_TRI_Select”, where the range sum equals 1).

12.3.3. Select the “=” sign from the middle drop-down menu, type “1” for the Constraint, click Add. This constrains the Solver solution such that only one TRI threshold value can be identified in the solution. Press “OK”.

12.4. Add a second constraint.

12.4.1. Subject to the Constraints: Click Add.

12.4.2. In the Add Constraint pop-up, select all the cells with 0's and 1 (the Sum_TRI_select binary range).

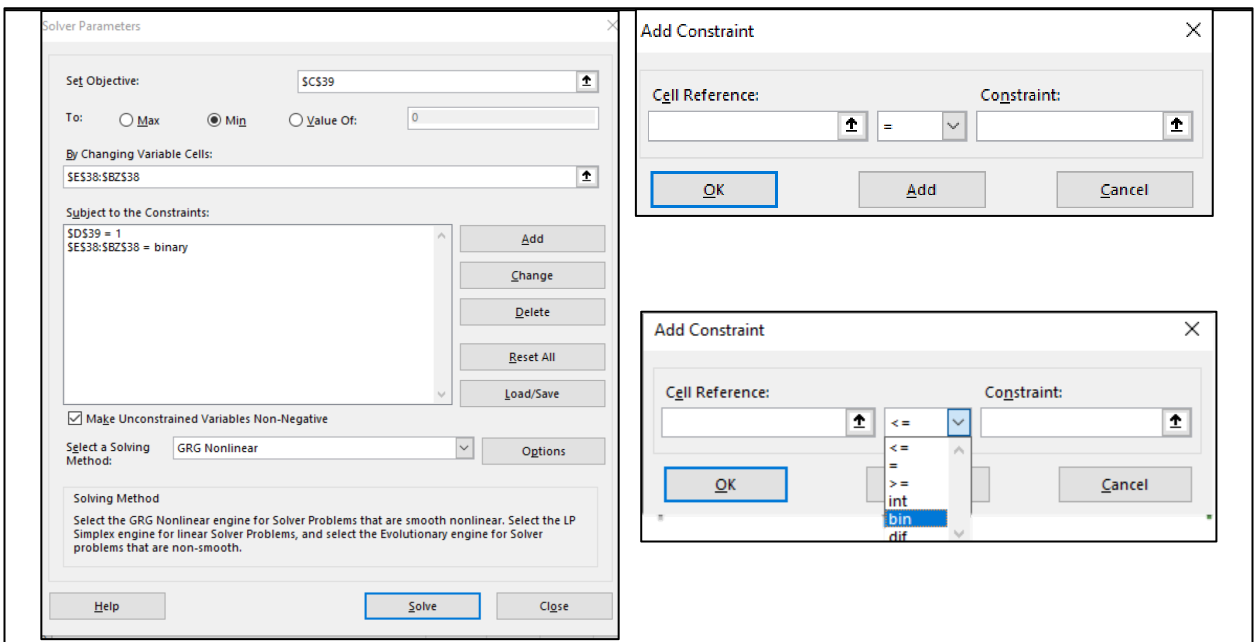
12.4.3. Select "bin" from the middle drop-down menu (for binary), click Add. This constrains the solution such that values in that row must remain binary (0 or 1). Press "OK".

12.5. Check the box for Make Unconstrained Variables Non-Negative.

12.6. Select a Solving Method: GRG Nonlinear.

12.7. Click Solve.

Note, the Solver tool may take a few minutes to run.



Insitu_per_cov	est_per_cov	sq_err	cummulative	INT_T_13	INT_T_14	INT_T_15	INT_T_16	INT_T_17	INT_T_18	INT_T_19	INT_T_20	INT_T_21	INT_T_22	INT_T_23	INT_T_24
			Quad_ID												
0.911183773	0.821182974	0.008100	rf1-q1-ct	0.999993	0.99948	0.99896	0.99896	0.99844	0.99844	0.99741	0.99741	0.99638	0.99431	0.99379	0.99069
0.802902398	0.851402869	0.002352	rf1-q2-ct	1.000005	1.00001	1.00001	0.99942	0.99942	0.99942	0.99942	0.99942	0.99826	0.99767	0.99709	0.99534
0.662719381	0.856	0.037357	rf1-q3-ct	1	1	1	1	1	1	0.9984	0.9984	0.9984	0.9984	0.99787	0.99787
1	0.855018587	0.021020	rf2-q1-ct	1	0.99926	0.99926	0.99926	0.99851	0.99851	0.99777	0.99554	0.99405	0.99405	0.99331	0.99257
0.897771835	0.865127582	0.001066	rf2-q2-ct	1	1	1	1	1	1	0.99878	0.99818	0.99818	0.99818	0.99818	0.99696
0.808460102	0.848990953	0.001643	rf2-q3-ct	1	1	1	1	0.99861	0.99861	0.99861	0.99861	0.99791	0.99791	0.99652	0.99652
0.940298634	0.840626688	0.009934	rf3-q1-ct	1	1	0.99946	0.99946	0.99946	0.99946	0.99946	0.99946	0.99946	0.99838	0.99838	0.99568
0.973259894	0.781584582	0.036739	rf3-q2-ct	1	0.99893	0.99893	0.99786	0.99786	0.99679	0.99679	0.99358	0.99251	0.99036	0.98822	0.98073
0.705604654	0.805882353	0.010056	rf3-q3-ct	1	1	1	1	1	0.99893	0.9984	0.99679	0.99626	0.99572	0.99412	0.99251
Insituper_cov_avg	est_per_cov_avg	SSE	sum_tri_Select	0	0	0	0	0	0	0	0	0	0	0	0
0.855800074	0.836201843	0.128267	1												

12.8. After the Solver tool is finished, locate the Sum_TRI_select binary row.

12.9. Scan that row and find the value of 1 among the 0s. The column where the 1 is located represents the TRI threshold value that Solver determined minimizes the sum of squared errors between in-situ 3D/live oyster cover and TRI-based 3D/live oyster cover.

12.9.1. In column N of the data template, record the TRI threshold value, which will be identical for all quadrats on the reef.

12.9.2. In column O of the data template, copy and paste the values in the cells in the threshold TRI value column (each quadrat will have a different value). After pasting these values, multiply each one of these values by the values in column R (*e.g.,* multiply O2*R2, O3*R3, etc.). The final value represents the percentage of live oysters in each quadrat after taking into account what percentage of the quadrat is covered by oysters versus sediment.

12.9.2.1. The caption of the screenshot below describes an example.

12.9.3. In column P of the data template, enter the formula "= R2 – O2" and drag the formula down for all rows. This formula subtracts the estimated percent cover of live oysters from the estimated total percent cover of oysters to determine the estimated percent cover of cultch.

AA	AB	AC	AD	AE	AF	AG	AH	AI	
INT_T_35	INT_T_36	INT_T_37	INT_T_38	INT_T_39	INT_T_40	INT_T_41	INT_T_42	INT_T_43	INT
0.91007	0.8956	0.87596	0.85943	0.84289	0.82118	0.79689	0.76744	0.73901	0
0.93648	0.92133	0.90385	0.8922	0.87471	0.8514	0.82751	0.80187	0.77215	
0.9408	0.9248	0.9088	0.896	0.87413	0.856	0.8304	0.8032	0.77493	0
0.92268	0.91301	0.89814	0.88104	0.86691	0.85502	0.83494	0.80669	0.77323	0
0.93925	0.92831	0.91738	0.90036	0.88153	0.86513	0.83718	0.80984	0.78676	0
0.9318	0.92136	0.90814	0.89144	0.87543	0.84899	0.82463	0.79471	0.77383	0
0.92869	0.91248	0.90005	0.88439	0.86386	0.84063	0.81578	0.78822	0.76931	0
0.894	0.86831	0.8469	0.82976	0.80407	0.78158	0.76017	0.73019	0.70557	
0.91016	0.89305	0.87594	0.85615	0.82995	0.80588	0.78342	0.7508	0.72299	0
0	0	0	0	0	1	0	0	0	

In this screenshot, the determined TRI threshold is 40, so 40 would be pasted in column M of the data template. Additionally, the values beneath 40, starting with 0.82118 and ending with 0.80588, would be copy and pasted into column N of the data template. Then, these values would be multiplied by each respective value in column Q.

13. Create a vertical oyster, cultch, and sediment layers

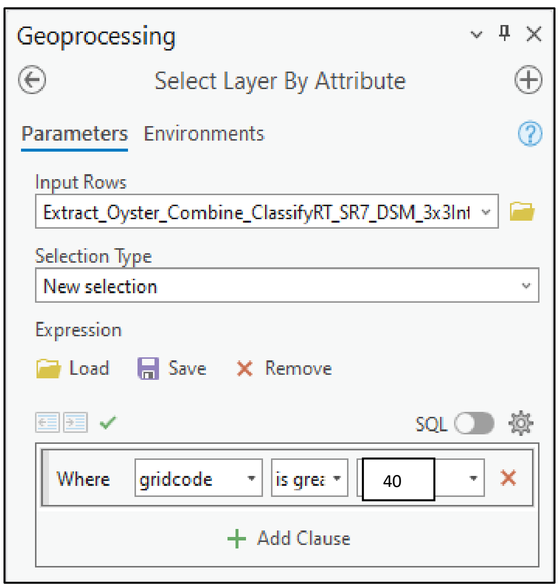
To create the following Feature Class layers for vertical oyster shell, cultch, and sediment, steps 6 and 8 from the Footprint Workflow can be followed (*e.g.,* 'Raster to Polygon', 'Select by Attribute', 'Dissolve', 'Eliminate', and 'Calculate Geometry Attributes'). The only difference is that the TRI layer created above is combined with the Classified Layer in the Footprint Workflow.

13.1. Go to Geoprocessing Tools, search for and open 'Raster to Polygon'.

-Input Raster → Extract_Oyster_Classified_TRI_Combine
-Field → TRI_100Int
-Output → Oyster_Classified_TRI_Polygon

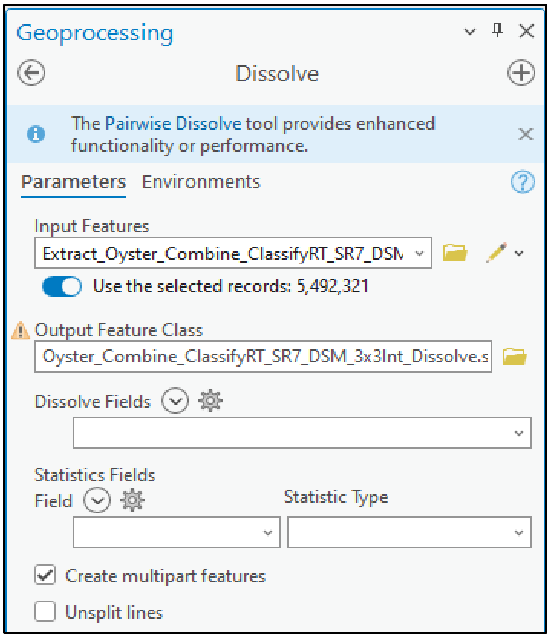
13.2. Go to Geoprocessing Tools, search for and open 'Select Layer By Attribute'.

-Input Rows → Oyster_Classified_TRI_Polygon
-Selection Type → New Selection
-Expression → Where "gridcode" "is greater than or equal to" "TRI value from step 11.9" (*e.g.,*TRI 40)



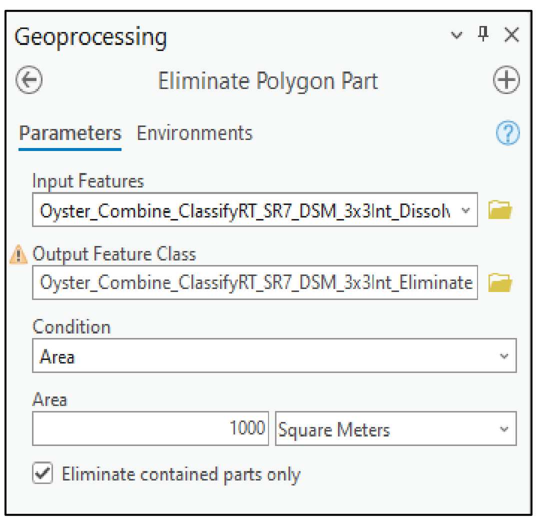
13.3. Go to Geoprocessing Tools, search for and open 'Dissolve'.

Input Features → Oyster_Classified_TRI_Polygon
Make sure "Use the Selected Records" is toggled on
Output Feature Class → VerticalOyster_Classified_Polygon
Make sure "Create multipart features" is checked



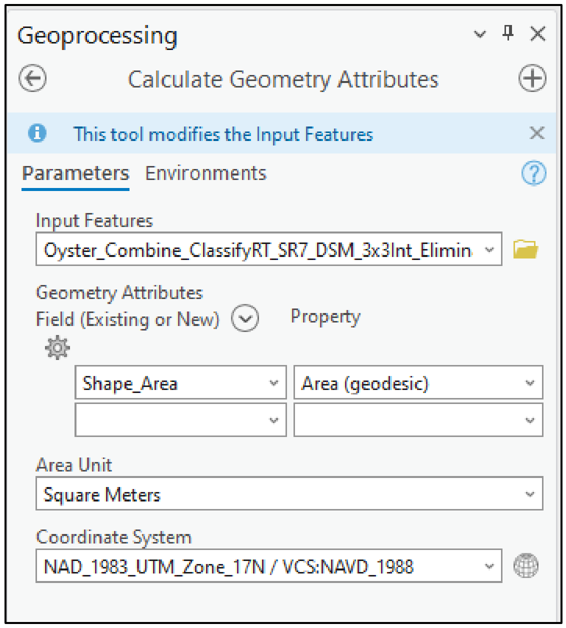
13.4. Go to Geoprocessing Tools, search for and open 'Eliminate Polygon Part'.

<u>Input Features</u> → VerticalOyster_Classified_Polygon
<u>Output Feature Class</u>→ Vertical_Oyster_Polygon
Make sure that <u>"Eliminate contained parts only"</u> is checked



13.5. Go to Geoprocessing Tools, search for and open 'Calculate Geometry Attributes'.

<u>Input Features</u> → Vertical_Oyster_Polygon
<u>Geometry Attributes</u> → Shape_Area, Area (geodesic)
<u>Area Unit</u> → Square Meters
<u>Coordinate System</u> → Use the Coordinates System from the project



13.6. To calculate shell culch, follow steps 13.2 to 13.6. The only change to be made is in step 13.2 where you replace "greater than or equal to" to "less than". This will select all classified oysters below the calculated TRI value for vertical oysters.

13.7. To calculate sediment, follow steps 7.3 and 7.4 to extract sediment by mask from the combined raster. Change the class code to sediment on step 7.3.

Expression → where Classified Raster "is equal to" class code for Sediment.

13.8. To continue calculations for sediment, follow step 13.1, then steps 13.3-13.5 using the extracted raster created in the previous step (skip step 13.2). The order of tools used will be: Raster to Polygon → Dissolve → Eliminate Polygon Part → Calculate Geometry Attributes.

Progress check: 3 outputs

Vertical_oyster_polygon.shp
Cultch_polygon.shp
Sediment_polygon.shp

14. Exporting ArcGIS project (.ppkx)

14.1. Share tab → Project (left side).

14.1.1. Start packaging = “Save project to file”.

14.1.2. Item details = change the file location and name, as appropriate.

- If the projects are **reef-specific**, save the files as: **xxx_zz_mmddyy_percov.ppkx**, where xxx = reserve initials, zz = reef initials, mmddyy = date sampled (e.g., noc_nr_061323_percov.ppkx)
- If the projects are **workflow-specific**, and contain all reefs, save the file as: **xxx_allreefs_yyyy_percov.ppkx**, where xxx = reserve initials, yyyy = year sampled (*e.g.,* noc_allreefs_2023_percov.ppkx).
- For the **experimental reefs**, save the files in one of the two formats listed above, and **add ‘_experiment.ppkx’ at the end** of the name *(e.g.,* noc_nr_030724_percov_experiment.ppkx).

14.1.3. Select the checkbox for “Share outside of organization”. Make sure all other checkboxes are unselected.

15. Appendix

Summary of formulas

TRI = ((Focal_Mean)-(Focal_Min))/((Focal_Max)-(Focal_Min))

est_per_cov = SUMPRODUCT (first array, second array)

Sq_err = ((insitu_percov) – (est_per_cov))^2

SSE =SUM(sq_err column)

Rowsum = sum(select quadrat row)

Adjusted cell value =(Cell area value) / (total row rum area)

TRI Manual method

1. Open the excel file generated in step # 5.
2. Follow the sample table below for reference to complete the following steps.

	A	B	C	D	E	F	G
1	Quad	in-situ_ per_cov	est_per_co v	TRI_22	TRI_23	TRI_24	TRI_25
2	SR7_Q1	0.17		0	0	0	0.00025
3	SR7_Q2	0.31		0	0.00012	0	0
4	SR7_Q3	0.26		0.0001 2	0	0.00025	0

3. Insert two columns after column A and name them in-situ_per_cov and est_per_cov, for in-situ percent cover and estimated percent cover (from drone products).
4. Import your in-situ percent cover data (as a decimal) estimated for 3d/live oysters and make sure you enter percent covers associated with the correct quadrat.
5. Place the equation =sum() into the est_per_cov column.
6. Working from the highest TRI number (far right of the table). Calculate the Sum working right to left in the table for each row until the Sum from the TRI values is close to the in-situ_per_cov value for that row. Highlight the last cell from right to left on the table that gives the sum close to the in-situ number.

B2 =SUM(AQ2:BB2)

	A	B	C	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP	AQ
1	IN-SITU	Analysis	NAME	TRI_50	TRI_51	TRI_52	TRI_53	TRI_54	TRI_55	TRI_56	TRI_57	TRI_58	TRI_59	TRI_60	TRI_61	TRI_62	TRI_63	TRI_64
2	⚠ 00	0.00	Q10M	0.11	0.09	0.08	0.05	0.04	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.00	0.00	0.00
3	0.34	0.36	Q11M	0.09	0.07	0.06	0.05	0.04	0.03	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.00	0.00
4	0.22	0.19	Q12M	0.11	0.09	0.07	0.06	0.04	0.03	0.02	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00
5	0.05	0.05	Q9M	0.09	0.09	0.07	0.06	0.05	0.04	0.02	0.02	0.01	0.01	0.01	0.00	0.00	0.00	0.00
6	0.26	0.28	Q13M	0.10	0.08	0.07	0.05	0.04	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.00	0.00
7	0.05	0.05	Q1M	0.16	0.14	0.09	0.06	0.03	0.03	0.02	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00
8	0.14	0.12	Q2M	0.17	0.12	0.09	0.06	0.03	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.05	0.06	Q3M	0.17	0.12	0.08	0.05	0.02	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	Q4M	0.16	0.12	0.09	0.05	0.03	0.02	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.01	0.01	Q5M	0.16	0.11	0.06	0.04	0.03	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.04	0.04	Q6M	0.13	0.11	0.09	0.05	0.04	0.02	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
13	0.18	0.18	Q7M	0.12	0.12	0.09	0.05	0.04	0.02	0.02	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00
14	0.03	0.03	Q8M	0.10	0.08	0.08	0.06	0.04	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.00	0.00	0.00

7. Now calculate the average TRI value from the highlighted cell place holders. Sum all the TRI numbers then divide by the number of quadrats.
8. Using the example table above. Equation (51+52+53+53+53+54+56+57+58+59+60)/11=55
9. I dropped the two outlier TRI values that have a percent cover of 0%.
10. Using the TRI value from the equation (55 from example) the percent cover vertical oyster layer will be created.

VRM (Vector Ruggedness Measure) Process

To use the VRM tool, you will need to install the ArcHydro toolbox into ArcPro Desktop.

Vector Ruggedness Measure (archydropro) ×

The Vector Ruggedness Measure (VRM) provides a way to measure terrain ruggedness as the variation in three-dimensional orientation of grid cells within a neighborhood. Slope and aspect are captured into a single measure and used to decouple terrain ruggedness from just slope or elevation. The VRM was first proposed by Hobson (1972) in "Surface roughness in topography: quantitative approach" and was later adapted by Sappington et al (2007) in "Quantifying landscape ruggedness for animal habitat analysis: A case study using bighorn sheep in the Mojave Desert."

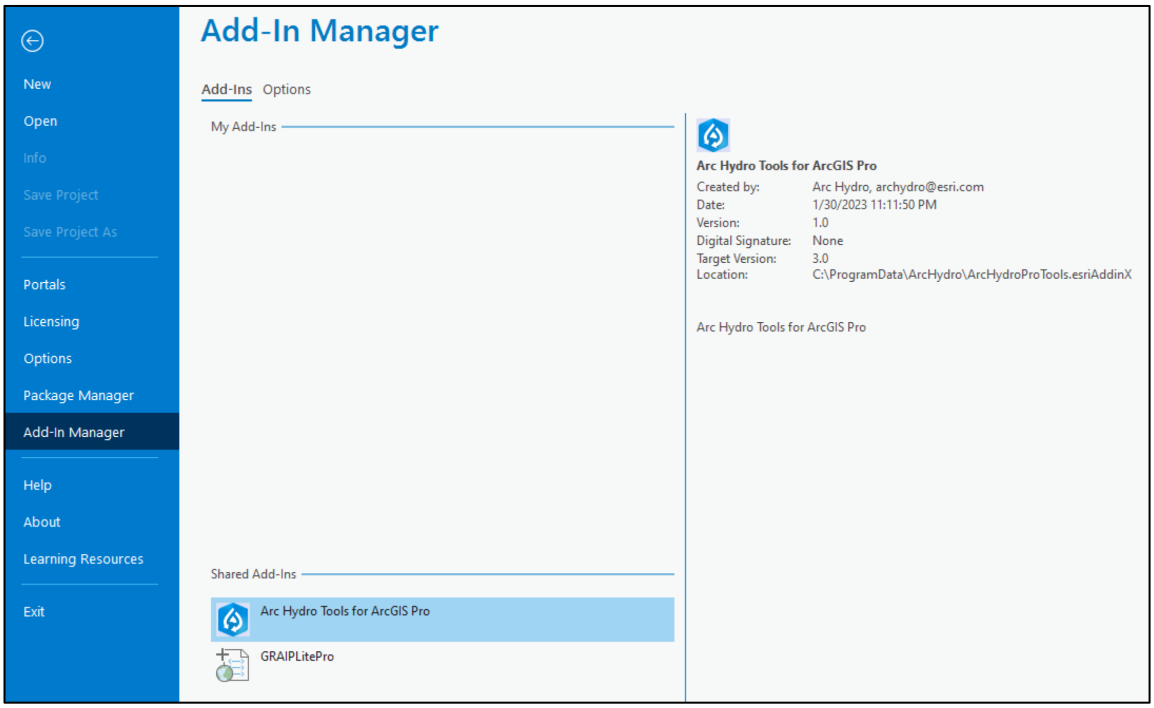
To calculate VRM, elevation cells are decomposed into their x, y, and z components using trigonometric operators on the slope ( ) and aspect ( ) of each cell. Next, a resultant vector over a neighborhood is derived from a rectangular focal operation. A window size (n) chosen by the user determines the number of cells used in the rectangle's neighborhood and is a measure of the landscape for the selected scale. Then, the magnitude of the resultant vector is subtracted from 1, resulting in a dimensionless ruggedness number ranging from 0 (flat) to 1 (most rugged). Typical values for natural terrains range between 0 and .5, with rugged landscapes often defined by values > 0.01 or 0.02.

The code used to run the tool is based off of the ArcGIS geoprocessing workflow developed by Barry Nickel at UC Santa Cruz.

1. Set up the VRM toolbox
   1.1. Download : Arc Hydro Downloads for ArcMap & ArcGIS Pro (esri.com)

1. Launch ArcGIS Pro.
2. Go to Settings > Add-In Manager.
3. On the Options tab, click Add Folder.
4. Browse to the folder where the Add-In previously installed is hosted.
5. Re-open ArcGIS Pro to apply the changes.

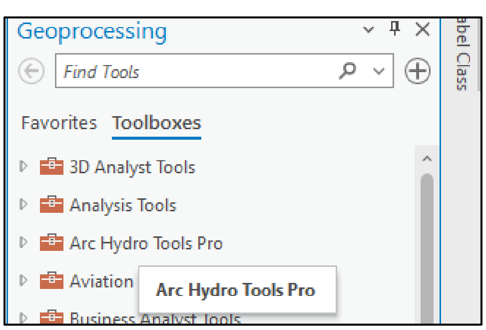
2. To add the downloaded file into ArcGIS Desktop, select “settings” on the main ArcGIS Pro desktop page. Then select, “Add-in Manager”.

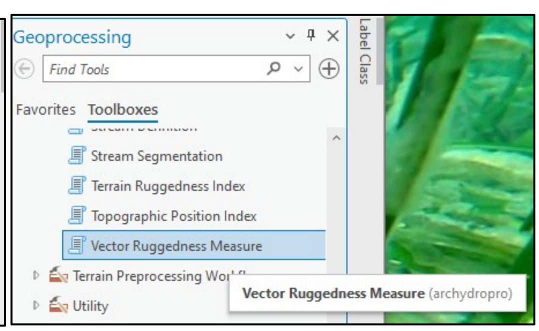


The file is an “.msi” extension file that needs to be added to the software through the add-in Manager”.

2.1. Load the .msi archydro file through the add-in manager. After it is properly installed it should look like the figure above.

3. Open your ArcGIS project and search in the geoprocessing toolbox for “archydro” or VRM to confirm it is there. The tool now exists within the geoprocessing toolbox.

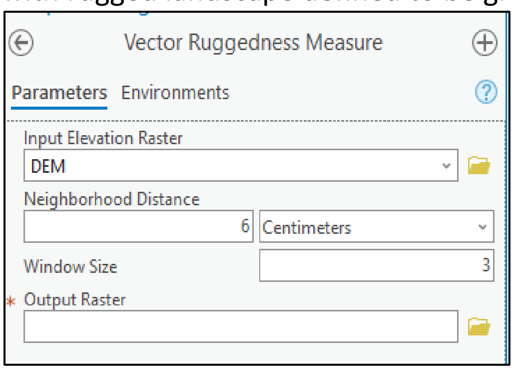




Run the ArcHydro VRM tool for your RMSE adjusted digital surface model (DSM). You are using the same DSM that was used for the TRI process.

4. Open the VRM tool and select the proper parameters.

   Input ⮚ DSM
   Neighborhood distance ⮚ a value preferred for analysis based on the pixel size and image resolution
   Window size ⮚ default is 3 (*Note, a larger window size can be useful but often causes a smoothing effect on the landscape*).
   Output ⮚ VRM raster data set that has a dimensionless ruggedness value between 0 (flat) and 1 (most rugged). Typical values for natural terrains range between 0 and 0.5, with rugged landscape defined to be greater than 0.02.



5. Turn VRM into degrees

   5.1. Go to Geoprocessing Tools, search for and open Raster Calculator and calculate formula: (SquareRoot (“VRM_raster” * 2)) * (57.3)

   -Input → VRM_raster
   -Output Raster → VRM_degrees
   -Click Run.

6. Turn VRM into integer form

   6.1. Go to Geoprocessing Tools, search for and open ‘Int’ (this creates an Integer Raster).

   -Input Raster → VRM_degrees
   -Output Raster → VRM_Int
   -Click Run.

7. Tabulate area following the same process used for TRI.

Progress check: 4 outputs

```
VRM.tif
VRMdegrees.tif
VRMdegrees_INT.tif
Tabulated_VRM.xls
```

VI. Oyster Shell Volumetric Change Workflow

Workflow lead and contact: Camille Elfstrom (camille.steenrod@noaa.gov)

Overview

1. Introduction
2. Preparing data and setting up data template
3. Subtracting DSM rasters
4. Create quadrat polygon layer
5. Clipping raster
6. Incorporating limit of detection values (LoD)
7. Calculating volumetric change at the quadrat-level
8. Finish filling out data template and export ArcGIS project

Introduction

This workflow was developed to detect volumetric change following excavation of oysters from the reef using pre- and post-extraction products (*i.e.,* orthomosaics and Digital Surface Models (DSMs)). Only proceed with this workflow if you have completed the Oyster Reef Elevation and Elevation Change Workflow, and produced corrected pre- and post-extraction DSMs.

This workflow is specific to the quadrat-level, so that it can be compared to volumetric change measured in-situ. If interested, this workflow can also be used at the reef scale. Simply create a polygon feature class of the general reef area, rather than a polygon feature class of the quadrats.

$$\textbf{Volumetric change} = \sum (+LoD_{elev} \geq (\text{Post DSM} - \text{Pre DSM}) \leq -LoD_{elev}) * \text{cell size X} * \text{cell size Y}$$

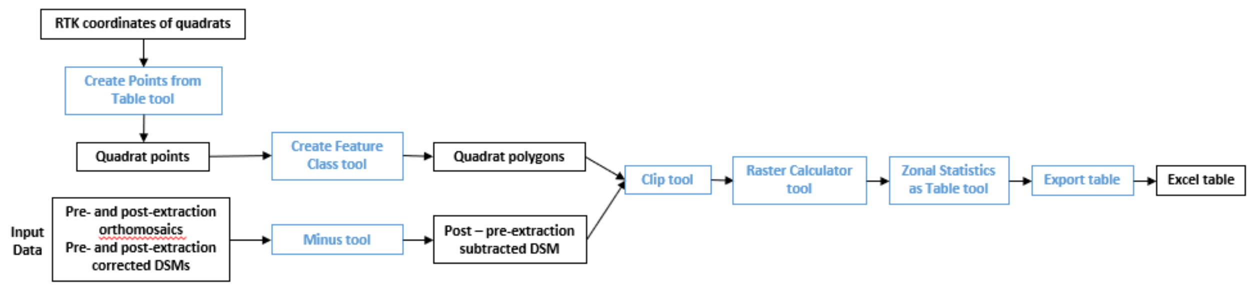
Inputs:

- Corrected DSMs (pre- and post-extraction).
- Orthomosaics (pre- and post-extraction).
- RTK coordinates for quadrat corners.
- Values of volumetric change measured *in situ* (if comparing to GIS-generated values) (\in-situ_data_spreadsheets: “raw_data_density_volume_weight”).
- Values of limit of detection as calculated in Excel spreadsheet (\imagery_data_spreadsheets: “workflow_elevation_database”).

Output:

- Excel spreadsheet with volumetric results for all reefs (\imagery_data_spreadsheets: "workflow_volume_database").

Flow chart overview of workflow:



*General note: If a tool fails, it's possible that the name of the product can only be 9 or 13 characters. Try shortening the name or output location and run the tool again.

****Reminder: Please keep track of how long this workflow takes to complete, as you will record this information in the Excel spreadsheet.**

1. Preparing data and setting up data template

1.1. Setting up volumetric change Excel data template

a. Open the "workflow_volume_database" Excel spreadsheet (\imagery_data_spreadsheets).

→ Row 2 can be deleted; it is example data from North Carolina.

b. In columns A-H, fill in the site/reef metadata, which can be copied and pasted from the in-situ data templates.

→ Column header definitions are defined in the "metadata" tab.

→ Note, make sure to create the same number of rows as there are quadrats (e.g., if six quadrats were excavated at Reef 1, there will be six rows of data in the spreadsheet for said reef).

c. In column I, enter the name of the ArcGIS project.

d. In column J, enter whether the analysis was performed for the harvest or control plot for the experimental reefs, OR put "NA" for non-experimental reefs.

1.2. Determine project structure

a. Prior to starting, decide whether all sampled reefs will be housed in the same ArcGIS project (*e.g.,* each reef will have a separate Map tab), or if each ArcGIS project will house an individual reef. *Note, your decision will affect the naming convention of the final exported ArcGIS project(s), specified at the end of the workflow.*

1.3. Create a new ArcGIS Pro file and add files

a. Open ArcGIS Pro and create a new map (check the box for “Create a folder for this project”).
b. Import .csv file with RTK coordinates for quadrats (xyz data for each point).
c. Import corrected pre- and post-extraction DSMs created using the Oyster Reef Elevation and Elevation Change Workflow.
d. Import pre- and post-excavation orthomosaics.

1.4. Convert RTK coordinates XY data

a. Right click on the .csv file added in the Table of Contents (under “Standalone Tables”) → Create Points from Table → XY Table to Point (Fig. 1).
   - → X Field = column with X coordinates (e.g., easting) in .csv.
   - → Y Field = column with Y coordinates (e.g., northing) in .csv.
   - → Z field = column with Z coordinates (e.g., elevation) in .csv.
   - → Coordinate system = click and drag (or select from dropdown menu) a DSM/orthomosaic/other file with coordinate system of interest (*e.g., NAD 1983 2011 UTM Zone 18N, NAVD88*).

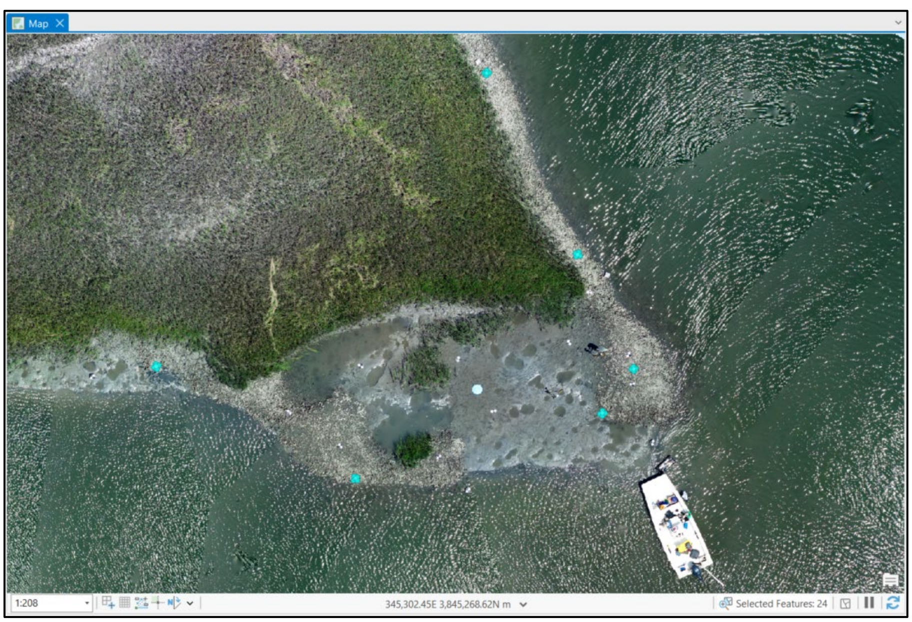


Figure 1. Screenshot of a pre-extraction orthomosaic, with the coordinates of the corners of six RTK quadrats converted to XY data (highlighted in turquoise).

2. Subtracting DSM rasters

2.1. Subtracting post- minus pre-extraction corrected DSMs

a. Analysis tab (top ribbon) → Tools → Minus (Fig. 2).

→ Input before raster surface = Corrected post-extraction DSM.

→ Input after raster surface = Corrected pre-extraction DSM.

→ Output raster = Minus tool results (*e.g., "[reef-initials]_minus_popr"*).

- Note, the difference raster in units of meters.

2.2. Entering data into date template

a. In column K of the template, enter which rasters were subtracted from one another in step 2.1 (*e.g.,* "post_pre" for all non-experimental reefs, and "post_pre" OR "add_post" for experimental reefs).

b. Right click on the clipped "minus" raster product (*e.g., "[reef-initials]_minus_popr_clip"*) layer in ArcGIS → Properties → Source → Raster information → Cell Size X and Cell Size Y.

c. In columns X and Y of the template, record these cell size values (units should be in meters). All quadrats on the reef will have the same cell size X and Y, so copy and paste these values into all quadrat rows.

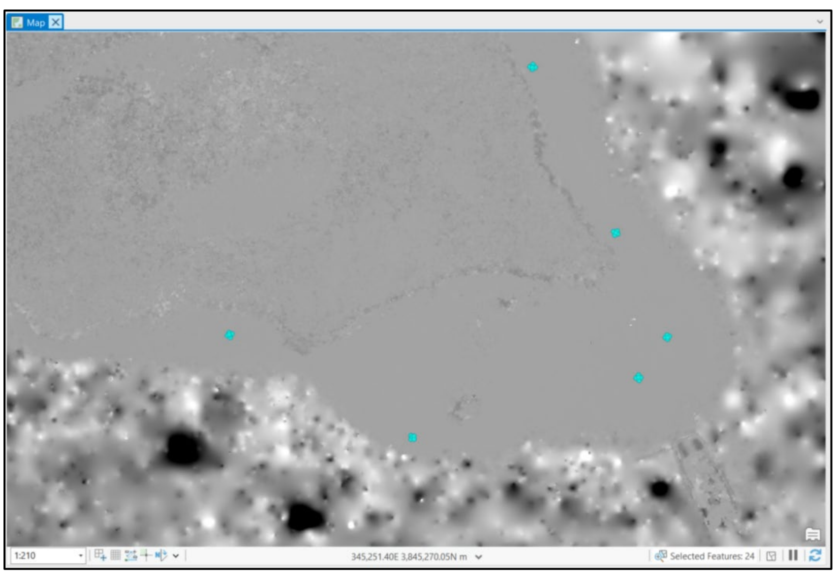


Figure 2. Screenshot of post – pre corrected DSMs using the Minus tool, with the coordinates of the corners of six RTK quadrats (highlighted in turquoise). Note, the difference anomalies (black and white colors) are concentrated over water.

3. Create quadrat polygon layer

3.1. Creating polygon layer feature class for quadrats

a. Analysis tab → Tools → Create Feature Class.

→ Input Parameters

- Feature class name = name of output (*e.g., "[reef-initials]_plot_polygons"*).
- Geometry type = polygon.
- Template dataset = pre- or post-excavation DSM that has the coordinate system of interest.
- Has Z = Same as the template feature class.
- Coordinate system = pre- or post-excavation DSM that has the coordinate system of interest.

b. Left click on the polygon feature class created in the Table of Contents and make sure the box for this layer is checked.

c. Right click on the layer and open the attribute table.

→ Field: Add.

→ Field Name: plot_name.

- Alias: plot_name.
- Data Type: text.

→ Click Save on the top ribbon.

→ Close the "Fields" tab.

d. Edit tab (top ribbon) → Edit → Create → Choose the polygon feature class just created under the "Create Features" window on the right side (*e.g., "[reef-initials]_plot_polygons"*).

e. Right click on the RTK coordinates layer → Open attribute table.

f. Find the points associated with quad 1 and select these points in the attribute table by clicking and dragging the rows of interest (will be highlighted in turquoise when selected) → right click on one of the highlighted rows → click "Zoom to".

g. Right click on one of the quadrat corner points and choose "Snap to feature" → "Vertex".

h. Repeat this snapping process for each corner of the plot.

i. Double click the last corner to close the polygon (Fig. 3).

→ Make sure no PVC is included in the polygon if quadrats were left on the reef during the flights (use BOTH pre- and post-extraction orthomosaics to check).

j. Edit tab → Edit → Attributes.

k. In the panel that opens on the right, rename the “plot_name” field created in the previous step; make sure the name matches whichever quadrat you are working on (*e.g.,* if you created the polygon around the RTK coordinates for quadrat 1, then the plot_name field would be labeled as “quad_1”).

   → Repeat this step for each plot, going in order of what the plots were named (quad 1 first, quad 2 second, etc.).

l. Save edits.

m. Click “Edit” in the top ribbon to end the editing process.

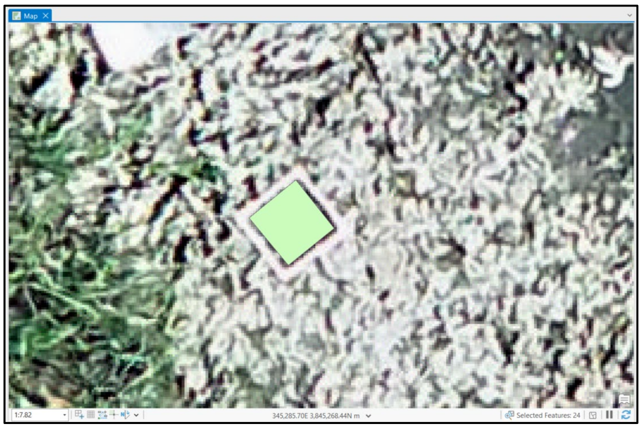


Figure 3. Screenshot of an example quadrat polygon (1/16 m^2). Note that any areas with PVC in the imagery (in this case the PVC quadrat) were excluded when creating the polygon.

4. Clipping raster

4.1. Clipping DSMs to the plot feature class layer

a. Analysis tab → Tools → Clip raster (Fig. 4).

   → Input raster = Minus tool DSM produced in step 3 (*e.g., “[reef-initials]_minus_popr”*).

   → Output raster = quadrat polygon shapefile created in step 4 (*e.g., “[reef-initials]_plot_polygons”*).

   → Check the box for “Use input features for clipping geometry”.

   → Output raster = Clipped post-DSM – pre-DSM (*e.g., “[reef-initials]_minus_popr_clip”*).

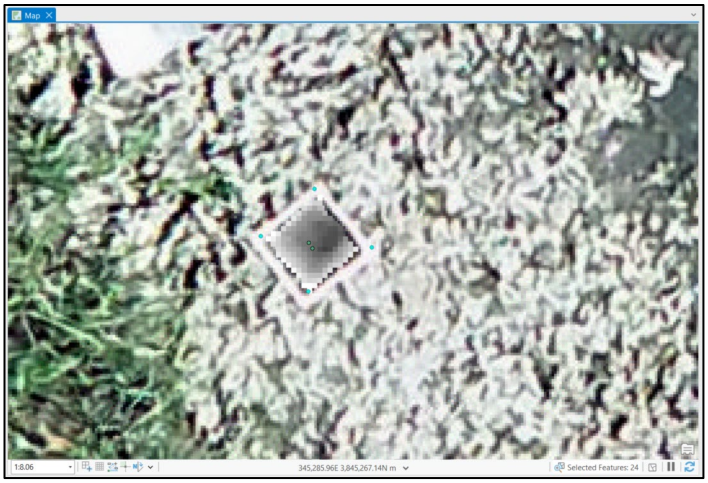


Figure 4. Screenshot of an example of the subtracted raster created in step 2 clipped to the plot-level in step 4.

5. Incorporating limit of detection values (LoD)

5.1. Calculating Elevation Change LoD

a. If you calculated LoD as part of the Oyster Reef Elevation and Elevation Change Workflow, skip to step 7 below.

b. Elevation change limit of detection calculation based on: Lane et al. 2003 and applied in James et al. 2017 and Dale et al. 2020. Formula for elevation change limit of detection (LoD) when comparing two DSMs: $LoD_{elev} = t * \sqrt{(RMSE\ of\ DSM1^2 + RMSE\ of\ DSM2^2)}$

→ where t is the t distribution value at a desired level of confidence (i.e., at 95% confidence, t = 1.96) and RMSE of DSM1 and DSM2 are the root mean squared errors of the pre- and post-excavation DSMs, respectively. We will calculate LoD at 68% confidence using a t value = 1

c. Open the 'workflow_elevation_database' data template (or the experiment version if entering data from the manipulative experiment). Both are available at the following path: \imagery_data_spreadsheets. Enter the required data in the 'RMSE' and 'yint_slope values' tabs based on outputs generated in above sections of the workflow. Column header definitions are defined in the 'metadata' tab.

→ Note, the data templates have an example from one reef in North Carolina. Delete this entry after entering your data and copying the formulas.

d. In columns I and J of the 'elevation limit of detection' tab, re-enter the 'best' DSM adjustment used for each DSM in the time series (e.g., pre- and post-excavation DSMs, respectively). For the experiment, where three DSMs were generated, enter the best DSM adjustment for the shell addition DSM in column K.

e. In column K (or L for the experiment), enter a value of 1 for each row containing data. The 1 represents the t distribution value associated with 68% confidence.

f. In column L (or M for the experiment), calculate elevation change LoD.

g. The excel formula for calculating LoD_{elev} for pre vs post excavation based on 'best' DSM using y-intercept and slope adjustment is: =$K3*SQRT(RMSE!M3^2+RMSE!P3^2).

h. Repeat the calculation, making sure to reference the correct RMSE based on the 'best' DSM adjustment for the remaining reefs in your dataset.

   → Note, for the experiment, an additional column of LoD calculations is necessary to account for the post-excavation vs shell addition DSMs. The format of the excel formula is the same as above with different RMSE's referenced.

i. In column N (or O and P for the experiment), convert LoD calculations to meters by dividing LoD values in column L (or columns M and N for the experiment) by 100. These are the values you will use in step 7 when running the raster calculator.

5.2. Run the Raster Calculator tool

a. Analysis tab → Tools → Raster Calculator (Fig. 5).

   → Map algebra expression = Con("[reef-initials]_minus_popr_clip" <= [negative LoD value from Excel], "[reef-initials]_minus_popr_clip", Con(("[reef-initials]_minus_popr_clip" >= [positive LoD value from Excel]), "[reef-initials]_minus_popr_clip”)).

   - For our purposes, we will use the LoD value associated with a 68% confidence interval. Units should be in meters.
   - For example, if the elevation change LoD for pre- vs post-excavation DSMs is 0.020494523, then the raster calculator formula is *Con("pi_minus_popr_clip" <= -0.020494523, "pi_minus_popr_clip", Con(("pi_minus_popr_clip" >= 0.020494523), "pi_minus_popr_clip")).*

   → Output raster = Subtracted raster with LoD threshold (*e.g., “[reef-initials]_popr_con68”*).

   - Note, the units of the subtracted raster are in meters.

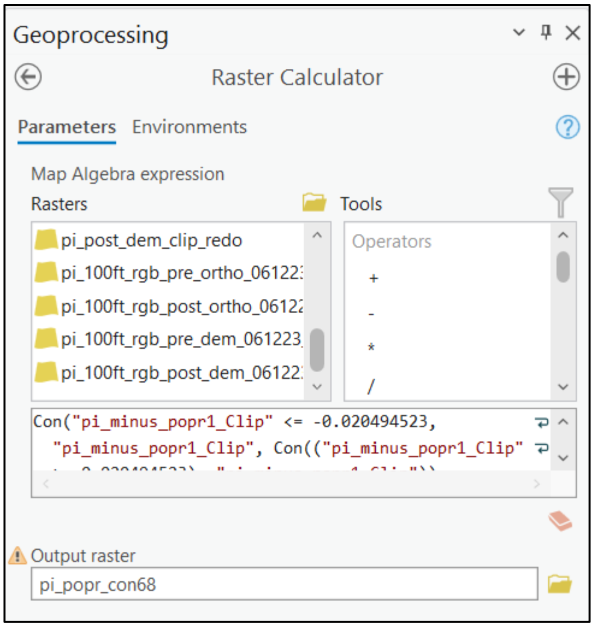


Figure 5. Screenshot of an example of the formula to be used in the raster calculator.

b. Right click on the new layer in Table of Contents → Create chart → Histogram (Fig. 6).

→ Make sure that there are no cells (i.e., count = 0) between the negative LoD value and positive LoD value.

- Note, ArcGIS automatically generates the range of values in the histogram, so it may appear as though some cells that fall outside of the range are included. In this example, since -0.020 is less than -0.016 and greater than -0.022, a few cells appear to be in the bar labeled -0.016.
- If you want to double check that the tool ran correctly, simply expand the layer in the Table of Contents, and it will show you the minimum and maximum raster cell value.

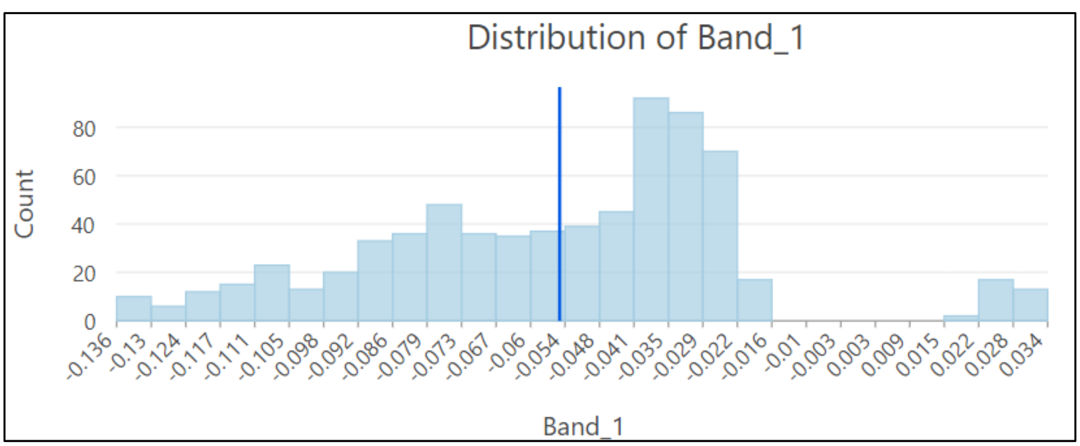


Figure 6. Frequency distribution histogram of cells in newly created raster with 68% confidence interval LoD values only (*i.e.,* cells > 0.020494523 and cells < -0.020494523).

6. Calculating volumetric change at the quadrat-level

6.1. Run the Zonal Statistics as Table tool and export results to Excel

a. Analysis tab → Tools → Zonal Statistics as Table.

→ Input raster = Feature class layer with plot polygons.

→ Zone field = OBJECTID.

→ Input value raster = Minus tool results produced in step 6 (*e.g., "[reef-initials]_popr_con68"*).

→ Output table = Zonal statistics table (*e.g., "[reef-initials]_zonal_plots_con68"*).

→ Leave the other settings as the default options.

→ Note, units in the table are as follows: area = m^2, all other columns in meters.

b. Right click on the table added to the Standalone Tables in the Table of Contents (Fig. 7).

→ Click on the three horizontal bars in the top right corner of the table → Export.

- Input table = Table created using the Zonal Statistics as Table tool (*e.g., "[reef-initials]_zonal_plots_con68"*).
- Output table = Table exported to Excel (e.g., "[reef-initials]_zonal_plots_con68_ExportTable.csv").
  - ⇒ Manually **add .csv** at the end of the name.
  - ⇒ Do **NOT** save the output to the geodatabase (.gbd).

Field: Add Calculate **Selection:** Select By Attributes Zoom To Switch Clear Delete Copy **Rows:** Insert

	OBJEC...	plot_name	ZONE_C...	COUNT	AREA	MIN	MAX	RANGE	MEAN	STD	SUM	MEDIAN	PCT90
1	1	quad 1	1	102	0.032504	-0.090418	-0.023252	0.067166	-0.055937	0.019325	-5.705598	-0.055662	-0.026107
2	2	quad 2	2	138	0.043976	-0.042167	-0.021013	0.021154	-0.032605	0.005269	-4.499504	-0.033534	-0.024162
3	3	quad 3	3	193	0.061503	-0.135468	-0.023326	0.112143	-0.083072	0.025211	-16.032921	-0.083462	-0.046688
4	4	quad 4	4	129	0.041108	-0.136184	0.020518	0.156701	-0.067591	0.031661	-8.719279	-0.064868	-0.028416
5	5	quad 5	5	39	0.012428	-0.038375	0.032281	0.070655	-0.010383	0.026188	-0.404927	-0.0234	0.028541
6	6	quad 6	6	102	0.032504	-0.075948	0.033228	0.109176	-0.034159	0.029519	-3.484175	-0.040753	0.025868

Figure 7. Screenshot of an example zonal statistics table, with data on all six quadrats; row 1 = data for quad 1, etc.

6.2. Calculate volumetric change in Excel

a. Open the exported table in Excel.

b. Copy all cells of data from this spreadsheet, and paste them in columns L-W of the data template spreadsheet under the appropriate headings.

c. In column Z of the data template, add a formula which multiplies the (SUM) * (cell_size_X) * (cell_size_Y) (*e.g., U2 * X2 * Y2*).

→ Note, units are in m^3 (1 m^3 = 1000 Liters).

d. Drag this formula to calculate volumetric change in all rows (*i.e.,* quadrats) of the table (Fig. 8).

→ Note, rows for some quadrats may be missing if no cells exceed the positive and negative LoD threshold. In this case, you can insert a row to add the quadrat and the Sum_x_area value for that quadrat should be equal to 0.

L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
OBJECTID_1	plot_name	COUNT	AREA	MIN	MAX	RANGE	MEAN	STD	SUM	MEDIAN	PCT90	Cell_size_x	Cell_size_y	Sum_x_area
1	quad_1	143	0.04557	-0.09042	0.011898	0.102317	-0.04189	0.027946	-5.98993	-0.04359	-0.00512	0.0178513	0.0178513	-0.001908806
2	quad_2	197	0.062778	-0.04217	0.003173	0.04534	-0.02655	0.010634	-5.22983	-0.02918	-0.0108	0.0178513	0.0178513	-0.001666584
3	quad_3	193	0.061503	-0.13547	-0.02333	0.112143	-0.08307	0.025211	-16.0329	-0.08346	-0.04669	0.0178513	0.0178513	-0.005109194
4	quad_4	147	0.046844	-0.13618	0.020518	0.156701	-0.05912	0.037636	-8.69075	-0.05609	-0.01433	0.0178513	0.0178513	-0.002769473
5	quad_5	147	0.046844	-0.03837	0.032281	0.070655	-0.00272	0.01729	-0.39939	-0.00391	0.019202	0.0178513	0.0178513	-0.000127273
6	quad_6	158	0.05035	-0.07595	0.033228	0.109176	-0.0212	0.030239	-3.34973	-0.02804	0.020112	0.0178513	0.0178513	-0.001067456

Figure 8. Screenshot of the data template with the copied and pasted values from the zonal statistics table for a reef with six quadrats, plus the cell_size_X and cell_size_Y data added, and the Sum_x_area column calculated.

7. Finish filling out data template and export ArcGIS project

7.1. Finish filling out the data template to finish filling in data

a. In column AA and AB, record (in minutes) how long the workflow took to complete, and the last name of the workflow user.

→ Note, time recorded will be reef-specific, not quadrat-specific. Please record the time it took in the first row of data for each reef, and fill the remaining rows associated with that reef with zeros (*e.g.,* if it took 60 minutes to complete the workflow for Reef 1, and there are six quadrats (rows) associated with Reef 1, then fill row 2 with a '60' and rows 3-7 with '0' in column Z).

b. When saving the file, add the reserve's initials at the start of the file name (*e.g.,* "noc_workflow_vol_change_database").

7.2. Exporting ArcGIS project (.ppkx)

a. Share tab → Project (left side) (Fig. 10).

→ Start packaging = "Save package to file".

→ Item details = change the file location and name, as appropriate.

- If the projects are **reef-specific**, save the files as: **xxx_zz_mmddyy_volume.ppkx**, where xxx = reserve initials, zz = reef initials, mmddyy = date sampled (*e.g.,* noc_nr_061323_volume.ppkx).
- If the projects are **workflow-specific**, and contain all reefs, save the file as: **xxx_allreefs_yyyy_volume.ppkx**, where xxx = reserve initials, yyyy = year sampled (*e.g.,* noc_allreefs_2023_volume.ppkx).
- For the **experimental reefs**, save the files in one of the two formats listed above, and **add '_experiment.ppkx' at the end** of the name *(e.g.,* noc_nr_030724_volume_experiment.ppkx).

→ Select the checkbox for "Share outside of organization". Make sure all other checkboxes are unselected.

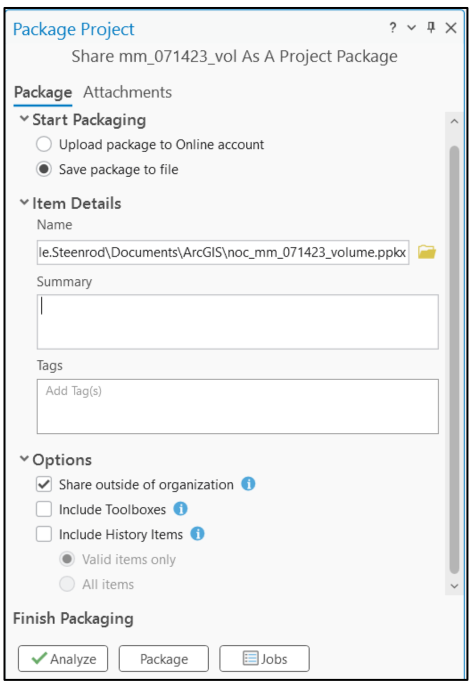


Figure 10. Screenshot of the Project Package window, with the appropriate selections chosen and file name edited to match the instructions listed above.

VII. Oyster Density Workflow

Workflow leads and contacts: Brandon Puckett (brandon.puckett@noaa.gov) and Dan Bowling (djbowlin@ncsu.edu)

Overview

1. Start up
2. Develop density model from site specific variables
3. Extract explanatory variables from rasters
4. Generate density predictions using generalized additive model
5. Generate estimated density map layer
6. Appendix

1. Start up

Determine ArcGIS project structure–Prior to starting, decide whether all sampled reefs will be housed in the same ArcGIS project (*e.g.,* each reef will have a separate Map tab), or if each ArcGIS project will house an individual reef. *Note, your decision will affect the naming convention of the final exported ArcGIS project(s) specified at the end of the workflow.*

Create a project folder to house your density project, dataset, and ArcGIS Pro. It is recommended to have a separate ArcGIS Pro geodatabase for this workflow.

*This is a good time to create a "Data_Inputs" folder and add copies of the original study site orthomosaics, corrected Digital Elevation Models/Digital Surface Models (hereafter referred to as a DSM), and RTK data of corners of quadrats used for in-situ sampling.
Open ArcGIS Pro and create a new project, referencing the project folder created in the previous step ("Create a folder for this project' option can be unchecked as the project folder has already been made). [suggested naming convention: "AbbreviatedSite Name_densityYear_UserInitials", example: pi_density23_DB]

Click Add Data Load:

1) Corrected DEM raster data from before any in-situ excavation
2) Orthomosaic raster data from before any in-situ excavation
3) RTK data (this will be used check the raster data layers and create polygon reef sample areas)

Corrected and quality DSMs are recommended for each project, follow step by step guide in Oyster Reef Elevation and Elevation Change Workflow. [Optional: RTK surveyed ground control points (GCP) and Checkpoint points can be added to verify layer accuracy and that the project is working with the corrected DSM. This can be done by adding a the RTK .csv file, right clicking on the newly added table in the Contents pane, select ‘Create Points From Table’, click ‘XY Table To Point’, enter an appropriate name for RTK data, set X to Easting, Y to Northing, and Z to Elevation (this can be checked for accuracy by selecting the table and opening it from the Contents pane). Make sure the coordinate system matches the ortho! Once added, make sure the points are properly aligned with GCPs and Checkpoints and the DMS with the ortho.]

2. Develop density model from site specific variables

-Display RTK data as points

-*If RTK data is in table or .csv file format:

- Make sure the RTK data has been added to the map’s Contents pane
- Right click on the table data in the Contents pane
- Select ‘Create Points From Table’
- Click ‘XY Table To Point’
- Enter an appropriate name for RTK data, set X to Easting, Y to Northing, and Z to Elevation

-Create Sample Quadrat Polygons

-*Inspect the RTK points that correspond with the excavated sample quadrats

-*Click Analysis Tools Create Feature Class (Data Management Tools)

Feature Class Location: Select project geodatabase

Feature Class Name: Site_quad_polygon

Geometry Type: Polygon

Coordinate System: Set to site DEM layer

*Leave remaining options as default

*Click Run

*Navigate to the project geodatabase in the catalog pane and add the feature class you created to the current map

*On the ribbon, click Edit, Create icon, select Site_quad_polygon

*In the order of the quadrats, zoom all the way into the RTK quadrat corner points tool and create a feature to represent each quadrat

-enable Snapping (within edit ribbon) to automatically “snap” to the RTK points and more easily generate a polygon using the quadrat corners

*Double clicking on the 4th corner of a quadrat will close the feature and allow you to move on the next sample quadrat

*IMPORTANT – be sure to modify the polygons as needed to avoid inaccuracies (i.e., PVC quadrats left on the reef. A fix to this would be adjusting corner points to fall just inside to avoid inaccuracies in digital sampling.)
*Inaccurate or unwanted points can be deleted by hovering the cursor over the point, right clicking, and selecting 'Delete Vertex'
*Created features can be modified by clicking the Modify icon on the ribbon

*Once all sample quadrat polygons have been created, click the  icon and then click the 

icon under the Edit tab once finished with edits.
*Open the quadrat polygon attribute table

-Add column to attribute table, name it 'quadrat_id'

-Specify type as text, add quadrat names in each row (e.g., quadrat_1, quadrat_2, etc)

-Make sure the order of the quadrat name labels are in the same order as the polygons were delineated above.

-Save all Edits

3. Extract explanatory variables from rasters

3.1. Run zonal statistics on the RGB Orthomosaic

-Analysis → Tools → Zonal Statistics as Table (Image or Spatial Analyst Tools)

-Input Raster or Feature Zone Data: Site_quad_polygon

-Zone Field: quadrat_id)

-Input Value Raster: Selected site RGB Orthomosaic

-Make sure this is the pre-excavation RGB orthomosaic

-Output Table: ZonalSt_Site_Year_RGB_Ortho

-*Check 'Ignore NoData in Calculations'

-Statistics Type: All

-Percentile Values: 90

-*Click Run

*Open ZonalSt_Site_Year_Ortho table

-Copy the values from 'Count' to 'Pct90' and paste in columns N to AD of the workflow_density_database.xlsx (\imagery_data_spreadsheets).

-In column AE of the ***_workflow_density_database.xlsx, standardize 'Sum' values in column U of the data template by quadrat area in column O of the data template using the following formula: '=if(U2="", "", U2/O2)'. Drag the formula down for the remaining quadrat (row) entries.

3.2. Iso Cluster unsupervised classification

3.2.1. Clip RGB Orthomosaic to reef polygon

-Generate reef polygon that excludes most water

-Note, this is intended to be a quick, crude outline of the reef

-Analysis → Tools → Create Feature Class (Data Management Tools)

-Feature Class Location: Select project geodatabase

-Feature Class Name: Site_Reef_Boundary_Layer (where 'Site' should be changed to the site abbreviation)

-Geometry Type: Polygon

-Template Datasets: leave blanks

-OID Type: select same as template

-Has M: No

-Has Z: No

-Coordinate System: Set to site orthomosaic layer

-Feature Class Alias: leave blank

-*Click Run

*Select Edit from the ribbon, click the 'Create' icon. In the Create Features pane, select the Site_Reef_Boundary_Layer and select your preferred drawing tool. The Line tool is sufficient given that the boundary is supposed to be a quick outline of the reef. Create a feature to represent the site boundary

*Once created, this feature can be modified by clicking the Modify icon on the ribbon

*Click Save under the Edit tab once finished with edits.

-Clip RGB orthomosaic to reef boundary layer

-Analysis → Tools → Clip Raster (Data Management Tools)

-Input Raster: Selected site RGB Orthomosaic

-Make sure this is the pre-excavation RGB orthomosaic

-Output Extent: Site_Reef_Boundary_Layer

-Output Raster Dataset: Site_RGB_Ortho_Reef_Clip

-Make sure output raster dataset is within the project geodatabase

-Check 'Use Input Features for Clipping Geometry'

-NoData Value: 999

-*Click Run

3.2.2. Generate Iso Cluster unsupervised classification

-Analysis → Tools → Iso Cluster Unsupervised Classification (Spatial Analyst Tools)

-Input raster bands: Site_RGB_Ortho_Reef_Clip

-Number of classes: 3

-Note, the 3 classes correspond to dark, intermediate, and light colored pixels

-Output classified raster: RGB_Ortho_IsoClust_Site_Year

-Make sure this is saved to the appropriate (e.g., site) geodatabase

-Minimum class size: 20

-Sample interval: 20

-Note, minimum class size and sample interval values are based on Windle et al. 2022.

-Output signature file: leave blank (this is an optional input)

-Click Run

-Note values of 1 = dark pixels, 2 = intermediate pixels, and 3= light pixels.

3.2.3. Run zonal statistics on iso cluster raster

-Analysis → Tools → Zonal Statistics as Table (Image or Spatial Analyst Tools)

-Input Raster or Feature Zone Data: Site_quad_polygon

-Zone Field: quadrat_id

-Input Value Raster: RGB_Ortho_IsoClust_Site_Year

-Output Table: ZonalSt_Site_Year_RGB_IsoClust

*Check 'Ignore NoData in Calculations'

-Statistics Type: All

-Percentile Values: 90

-*Click Run

*Open ZonalSt_Site_Year_RGB_IsoClust table

-Copy the values from 'Count' to 'Pct90' and paste in columns AF to AV of the workflow_density_database.xlsx (\imagery_data_spreadsheets).

-In column AW of the workflow_density_database.xlsx, standardize 'Sum' values in column AM of the data template by quadrat area in column AG of the data template using the following formula: '=if(AM2="", "", AM2/AG2)'. Drag the formula down for the remaining quadrat (row) entries.

-In column AX, calculate the count of dark (1) pixels:

'=IF($AP2="", "", IF(AND($AO2=1,$AR2=1),$AF2, IF($AO2=$AR2, 0, IF($AO2=1,$AP2,IF($AR2=1,$AS2,$AF2-SUM($AP2,$AS2))))))'

-In column AY, calculate the count of intermediate (2) pixels:

'=IF($AP2="", "", IF(AND($AO2=2,$AR2=2),$AF2, IF($AP2=$AS2, 0, IF($AO2=2,$AP2,IF($AR2=2,$AS2,$AF2-SUM($AP2,$AS2))))))'

-In column AZ,calculate the count of light (3) pixels:

'=IF($AP2="", "", IF(AND($AO2=3,$AR2=3),$AF2, IF($AP2=$AS2, 0, IF($AO2=3,$AP2,IF($AR2=3,$AS2,$AF2-SUM($AP2,$AS2)))))'

-In column BA, calculate the proportion of dark (1) pixels: '=if(AX2="","", AX2/$AF2)'

-In column BB, calculate the proportion of intermediate (2) pixels: '=if(AY2="", "", AY2/$AF2)'

-In column BC, calculate the proportion of light (3) pixels: '=if(AZ2="", "", AZ2/$AF2)'

-*Drag the formulas down for the remaining quadrat (row) entries.

3.3. Run zonal statistics on the DEM

-Analysis → Tools → Zonal Statistics as Table (Image or Spatial Analyst Tools)

-Input Raster or Feature Zone Data: Site_quad_polygon

-Zone Field: quadrat_id

-Input Value Raster: Selected site corrected DEM

-Make sure this is the pre-excavation AND corrected DEM

-Output Table: ZonalSt_Site_Year_DEM

-*Check 'Ignore NoData in Calculations'

-Statistics Type: All

-Percentile Values: 90

-*Click Run

*Open ZonalSt_Site_Year_DEM table

-Copy the values from 'Count' to 'Pct90' and paste in column BD to BM of the workflow_density_database.xlsx (\imagery_data_spreadsheets).

-In column BN of the ***_workflow_density_database.xlsx, standardize 'Sum' values in column BK of the data template by quadrat area in column BE of the data template using the following formula: '=IF(BK2 = "", "", BK2/BE2)'. Drag the formula down for the remaining quadrat (row) entries.

-In columns BO through BQ, convert minimum, maximum, and mean elevations relative to the mean low water tidal datum. To do so, use NOAA Vertical Data Transformation Tool (VDATUM).

-Select region (Contiguous United States for all of our study sites)

-Horizontal Information: set source and target to reference frame = NAD83(2011), coor. system = projected UTM (Easting, Northing), unit = meter, zone = 18 (noc), 17 (niw, ace, sap, gtm).

-Vertical information: set source to reference frame = NAVD88, unit = meter, select height, check geoid model → GEOID18 (unless you used a different GEOID during RTK surveys of reefs). Set Target to reference frame = MLW, unit = meter, select height, check geoid model → GEOID18 (unless you used a different GEOID during RTK surveys of reefs).

-Point conversion: input northing and easting coordinate of reef (or use the map below), enter height = 0, click 'transform', the output height is the offset between elevations in mNAVD88 and m MLW. Add the output height (keeping the sign of the output height) to minimum, maximum and mean elevations in mNAVD88 to convert to MLW.

-For example at the Pivers Island Reef in NOC, an elevation of 0m NAVD88 = MLW elevation of 0.601m. The offset of 0.601m would be added to minimum, maximum and mean elevations in mNAAVD88 to convert to MLW.

3.4. Terrain Ruggedness Index (TRI)

3.4.1. Clip DEM to reef boundary layer

-Analysis → Tools → Clip Raster (Data Management Tools)

-Input Raster: Selected site corrected DEM

-Make sure this is the pre-excavation AND corrected DEM

-Output Extent: Site_Reef_Boundary_Layer

-Note, this layer is generated in section 3.2.1 above

-Output Raster Dataset: Site_DEM_Reef_Clip

-Make sure output raster dataset is within the project geodatabase

-Check 'Use Input Features for Clipping Geometry'

-NoData Value: 999

-*Click Run

3.4.2. Generate Mean Elevation Raster

-Analysis → Tools → Focal Statistics (Image or Spatial Analyst Tools)

-Input raster: Site_DEM_Reef_Clip

-Output raster: FocalSt_Site_Year_DEM_Mean

-Neighborhood: Rectangle

-Width: 3

-Height: 3

-Units type: Cell

-Statistics type: Mean

-Check 'Ignore NoData in calculations'

-*Click Run

3.4.3. Generate Maximum Elevation Raster

-Analysis → Tools → Focal Statistics (Image or Spatial Analyst Tools)

-Input raster: Site_DEM_Reef_Clip

-Output raster: FocalSt_Site_Year_DEM_Max
-Neighborhood: Rectangle
-Width: 3
-Height: 3
-Units type: Cell
-Statistics type: Maximum
-Check 'Ignore NoData in calculations'
-*Click Run

3.4.4. Create Minimum Elevation Raster

-Analysis → Tools → Focal Statistics (Image or Spatial Analyst Tools)
-Input raster: Site_DEM_Reef_Clip
-Output raster: FocalSt_Site_Year_DEM_Min
-Neighborhood: Rectangle
-Width: 3
-Height: 3
-Units type: Cell
-Statistics type: Minimum
-Check 'Ignore NoData in calculations'
-*Click Run

3.4.5. Generate TRI Raster

-Analysis → Tools → Raster Calculator (Image or Spatial Analyst Tools)
-Map Algebra expression:
('FocalSt_Site_Year_DEM_Mean' – 'FocalSt_Site_Year_DEM_Min') /
('FocalSt_Site_Year_DEM_Max' – 'FocalSt_Site_Year_DEM_Min')

-Output raster: Site_Year_TRI
-*Click Run

3.4.6. Run zonal statistics on TRI raster

-Analysis → Tools → Zonal Statistics as Table (Image or Spatial Analyst Tools)
-Input Raster or Feature Zone Data: Site_quad_polygon
-Zone Field: quadrat_id
-Input Value Raster: Selected site TRI
-Output Table: ZonalSt_Site_Year_TRI
-*Check 'Ignore NoData in Calculations'
-Statistics Type: All

-Percentile Values: 90

-*Click Run

*Open ZonalSt_Site_Year_TRI table

-Copy the values from 'Count' to 'Pct90' and paste in columns BR to CA of the workflow_density_database.xlsx (\imagery_data_spreadsheets).

-In column CB of the workflow_density_database.xlsx, standardize 'Sum' values in column BY of the data template by quadrat area in column BS of the data template using the following formula: '=IF(BY2="", "", BY2/BS2)'. Drag the formula down for the remaining quadrat (row) entries.

3.5. Vector Ruggedness Measure (VRM)

3.5.1. Download and install ArcHydroPro Package (Appendix 1)

3.5.2. Generate VRM Raster

-Analysis → Tools → Vector Ruggedness Measure (archydropro)

-Input Elevation Raster: Site_DEM_Reef_Clip

-Note, this layer is generated in section 3.4.1 above

-Neighborhood Distance: 1 centimeter

-Window Size: 3

-Output Raster: Site_Year_VRM

-Be sure to save in the project geodatabase or the tool will not render a raster data layer

-*Click Run

3.5.3. Run zonal statistics on VRM raster

-Analysis → Tools → Zonal Statistics as Table (Image or Spatial Analyst Tools)

-Input Raster or Feature Zone Data: Site_quad_polygon

-Zone Field: quadrat_id

-Input Value Raster: Site_Year_VRM

-Output Table: ZonalSt_Site_Year_VRM

-*Check 'Ignore NoData in Calculations'

-Statistics Type: All

-Percentile Values: 90

-*Click Run

*Open ZonalSt_Site_Year_VRM table

-Copy the values from 'Count' to 'Pct90' and paste in columns BZ to CI of the workflow_density_database.xlsx (\imagery_data_spreadsheets).

-In column CM of the ***_workflow_density_database.xlsx, standardize 'Sum' values in column CJ of the data template by quadrat area in column CD of the data template using the following formula: '=IF(CJ2="", "", CJ2/CD2)'. Drag the formula down for the remaining quadrat (row) entries.

****Make sure to record the time in minutes it takes to complete a reef or site in column CR of the ***_workflow_density_database.xlsx, being sure to divide that time up among quadrats for a given reef (i.e., if steps 1-3 take 300 minutes and you have 5 quadrats, enter 60 minutes in each row).**

-Export the ArcGIS project (.ppkx)

- -Share tab → Project (left side).
  - -Start packaging = "Save package to file".
  - -Item details = change the file location and name, as appropriate.
    - -If the projects are **reef-specific**, save the files as: **xxx_zz_mmddyy_density.ppkx**, where xxx = reserve initials, zz = reef initials, mmddyy = date sampled (*e.g.,* noc_mm_071423_density.ppkx).
    - -If the projects are **workflow-specific**, and contain all reefs, save the file as: **xxx_allreefs_yyyy_density.ppkx**, where xxx = reserve initials, yyyy = year sampled (*e.g.,* noc_allreefs_2023_density.ppkx).
    - -For the **experimental reefs**, save the files in one of the two formats listed above, and **add '_experiment.ppkx' at the end** of the name *(e.g.,* noc_mm_030824_density_experiment.ppkx).
  - -Select the checkbox for "Share outside of organization". <u>Make sure all other checkboxes are unselected.</u>

****Steps 1.0 through 3.0 will need to be completed for each site (and over time if oysters were counted following removal as part of the experimental manipulation).**

4. Generate density predictions using generalized additive model

-In columns CN of the workflow_density_database.xlsx (where *** is the reserve abbreviation), use the following formula to generate reef easting centroid: '=IF(B2="","",B2)'

- Drag the formula down for the remaining quadrat (row) entries.

-In columns CO of the workflow_density_database.xlsx, use the following formula to generate reef northing centroid: '=IF(C2="","",C2)'

- Drag the formula down for the remaining quadrat (row) entries.

-In columns CP of the workflow_density_database.xlsx, use the following formula to generate reef harvest status (0 = closed, 1 = open): '=IF(H2="","",IF(H2="Closed", 0, 1))'

- Drag the formula down for the remaining quadrat (row) entries.

-In columns CQ of the workflow_density_database.xlsx, use the following formula to generate reef type (0 = patch, 1 = fringe): '=IF(G2="","",IF(G2="Fringe", 1, 0))'

- Drag the formula down for the remaining quadrat (row) entries.

-Statistical modeling to predict oyster density will be done outside of ArcGIS Pro and MS Excel given the modeling complexities associated with the multitude of explanatory variables (and multivariate combinations therein).

-We will adopt a generalized additive modeling (GAM) approach sensu Windle et al. 2022. Model scripts were coded in R (the R script is located: \image_analysis_workflows\GAM_density_predict_validate_in-situ_quad_archive.R).

-The input data is located: \image_analysis_workflows\GAM_density_input_data_archive.xlsx

-GAM predictions for oyster recruit density (< 25mm in length), submarket density (26-74 mm), market density (75+ mm), and total density and associated standard errors will be appended to the workflow_density_database.xlsx (columns CS-CZ). These predictions will be used to compare in-situ density estimates with imagery-based density estimates.

5. Generate estimated density map layer

-Open the ArcPro footprint project for the site and export 1) Reef footprint polygon feature and 2) Site boundary feature into the density project geodatabase.

-Contents pane → Right click on reef footprint polygon → Data → Export Feature

-*Save as a new feature in the density project geodatabase.

-Repeat with site boundary feature

-In the density project, click Add Data and add both the footprint and site boundary

5.1 Create Density Grid

-Analysis → Tools → Create Fishnet (Data Management Tools)

Output Feature Class: SiteYear_density_grid

-Template Extent: Select site boundary

-Check Extent Coordinate System: Make sure it is correct

-Cell Size Width: 0.25

-Cell Size Height: 0.25

-Uncheck 'Create Label Points'

-Geometry Type: Polygon

-*Click Run

5.1.1. Create Label Grids

-Open density grid fishnet layer attribute table
-Click create new field
-Enter: Field Name (‘Grid_Number’), Alias (‘Grid_Number’), Date Type (‘Text’), Allow Null (‘check’); click save

-Right click on header of new field (Grid_Number)
    -Select Calculate Field Tool
    -Input Table: Site_density_grid
    -Field Name: Grid_Number
    -Expression Type: Python
    -Grid_number = !OID!

5.2. Extract explanatory variables for entire reef
5.2.1. Run zonal statistics on RGB Orthomosaic
-Analysis → Tools → Zonal Statistics as Table (Image or Spatial Analyst Tools)
    -Input Raster or Feature Zone Data: SiteYear_density_grid
    -Zone Field: Grid_Number
    -Input Value Raster: Select site RGB Orthomosaic clipped to reef
    -Output Table: ZonalSt_Site_Year_grid_Ortho
    -*Check ‘Ignore NoData in Calculations’
    -Statistics Type: All
    -Percentile Values: 90
    -*Click Run

5.2.2. Run zonal statistics on Iso cluster raster
-Analysis → Tools → Zonal Statistics as Table (Image or Spatial Analyst Tools)
    -Input Raster or Feature Zone Data: SiteYear_density_grid
    -Zone Field: Grid_Number
    -Input Value Raster: Select site Iso Cluster clipped to reef
    -Output Table: ZonalSt_Site_Year_grid_Iso
    -*Check ‘Ignore NoData in Calculations’
    -Statistics Type: All
    -Percentile Values: 90
    -*Click Run

5.2.3. Run zonal statistics on DEM
-Analysis → Tools → Zonal Statistics as Table (Image or Spatial Analyst Tools)
    -Input Raster or Feature Zone Data: SiteYear_density_grid

-Zone Field: Grid_Number
-Input Value Raster: Select site DEM clipped to reef
-Output Table: ZonalSt_Site_Year_grid_DEM
-*Check 'Ignore NoData in Calculations'
-Statistics Type: All
-Percentile Values: 90
-*Click Run

5.2.3. Run zonal statistics on TRI raster

-Analysis → Tools → Zonal Statistics as Table (Image or Spatial Analyst Tools)

-Input Raster or Feature Zone Data: SiteYear_density_grid
-Zone Field: Grid_Number
-Input Value Raster: Select site TRI
-Output Table: ZonalSt_Site_Year_grid_TRI
-*Check 'Ignore NoData in Calculations'
-Statistics Type: All
-Percentile Values: 90
*Click Run

5.2.4. Run zonal statistics on VRM raster

-Analysis → Tools → Zonal Statistics as Table (Image or Spatial Analyst Tools)

-Input Raster or Feature Zone Data: SiteYear_density_grid
-Zone Field: Grid_Number
-Input Value Raster: Select site VRM
-Output Table: ZonalSt_Site_Year_grid_VRM
-*Check 'Ignore NoData in Calculations'
-Statistics Type: All
-Percentile Values: 90
-*Click Run

5.3. Join zonal statistics into one table

-In the contents pane, right click on the SiteYear_density_grid table and select copy.
-Paste the copied table under Standalone Tables in the Contents Pane and rename to SiteYear_density_grid_combined.
-Analysis → Tools → Add Join (Data Management Tools)

-Input Table: SiteYear_density_grid_combined
-Input Field: Grid_Number
-Join Table: ZonalSt_SiteYear_grid_Ortho

-Join Field: Grid_Number
-*Check keep all input records
-*Click "Validate Join" to check
-*Click Run

-Open the SiteYear_density_grid_combined attribute table to check the join was added correctly.

-Repeat step 5.3 using the Add Join Tool for DEM, TRI, ISO, and VRM tables.

5.4. Export combined table

-Analysis → Tools → Table to Excel (Conversion Tools)

-Input Table: SiteYear_density_grid_combined
-Output Excel File: ZonalSt_SiteYear_densitygrid_combined_TableToExcel.xlsx
-*Click Run

5.5. Generate Density Predictions Using Generalized Additive Model

-Follow step 4.0 to generate prediction densities for each reef grid cell.

-The R script for predicting densities for each reef grid cell is located:
\image_analysis_workflows\GAM_density_predict_reef_grid_archive.R

-The input data files are located at the following:

-\image_analysis_workflows\GAM_density_input_data_archive.xlsx
-\image_analysis_workflows\noc_ci_reef_density_pred_archive.xlsx

-Add table with density predictions to ArcGIS project folder.

-In ArcPro, click add data to add ZonalSt_SiteYear_densitygrid_combined_Predicted.xlsx" table to the project.

-The table should now appear in the Contents Pane under "Standalone Tables".

-Analysis → Tools → Add Join (Data Management Tools)

-Input Table: SiteYear_density_grid
-Input Field: Grid_Number
-Join Table: ZonalSt_SiteYear_densitygrid_combined_predicted
-Join Field: Grid_Number
-*Check only 'keep common'
-*Click "Validate Join" to check
-*Click Run
-Open the SiteYear_density_grid attribute table to check that the join was added correctly.

5.6. Create Reef Extent

5.6.1. Add a buffer to reef footprint

-Analysis → Tools → Buffer (Analysis Tools)

-Input Features: SiteYear_classified_Footprint

-Output Feature Class: SiteYear_classified_Footprint_buff_add1m

-Distance [value or field]: Linear Unit

-Distance: 1 Meters

-Side Type: Full

-Method: Geodesic

-Dissolve Type: Dissolve all output feature into a single feature

-*Click Run

-Re-run buffer tool with adjusted buffer distance if buffer is excessive or insufficient.

5.6.2. Fill holes in reef footprint

-Analysis → Tools → Eliminate Polygon Part (Analysis Tools)

-Input Features: SiteYear_classified_Footprint_buff_add1m

-Output Feature Class: SiteYear_classified_Footprint_buff_filled

-Condition: Area

-Area: set to an area size larger than the voids in the site footprint that need to be filled (example 1000 m^2).

-Check eliminate contained parts only

-*Note: This tool can be run again with "Eliminate parts only", Condition: Area, and Area set to small unit (i.e., 1 m^2) to remove small, miss-classified footprint polygon artifacts (typically caused by glare).

5.6.3. Subtract buffer (optional)

-This step can be taken to remove excess or unwanted areas extending well past the reef footprint that are unhelpful in modeling oyster reef density (i.e., water or marsh areas that would be better depicted by the ortho raster layer).

-Analysis → Tools → Buffer (Analysis Tools)

-Input Features: SiteYear_classified_Footprint_buff_filled

-Output Feature Class: SiteYear_classified_Footprint_buff_filled_final

-Distance [value or field]: Linear Unit

-Distance: -0.5 m

-Side Type: Full

-Method: Geodesic

-Dissolve Type: Dissolve all output feature into a single feature

-*Click Run

5.7. Create map of modeled oyster density

-Analysis →Tools → Clip (Analysis Tools)

-Input Features or Dataset: SiteYear_density_grid

-Clip Features: Use the final Site Reef Footprint created in the last step (ex. SiteYear_classified_Footprint_buff_filled_Final)

-Output Features or Dataset: SiteYear_density_Total

-*Click Run

-In the contents pane, right click on SiteYear_density_Total and select symbology (use Classify as primary symbology). Select Total density as the 'Field'. Select desired symbology settings for method, number of classes, and color scheme. See Figure 1 for an example.

5.7.1 Create additional density layers

-In the contents pane, right click on SiteYear_density_Total and select Data → Export features.

-Input Features: SiteYear_density_Total

-Output Feature Class: SiteYear_density_Recruit

-Click Ok

-Repeat step 5.7 to create a map for density of oyster recruits (being sure to symbolize with Recruit density as the 'Field').

-Repeat steps 5.7 and 5.7.1 to create a map for density of submarket and market sized oysters (again, make sure to symbolize by the correct 'Field').

5.7.2. Create complimentary layers to display error associated with density estimates

-In the contents pane, right click on SiteYear_density_Total and select Data → Export features.

-Input Features: SiteYear_density_Total

-Output Feature Class: SiteYear_density_Total_sterror

-Click Ok

-In the contents pane, right click on SiteYear_density_Total_sterror and select symbology (use Classify as primary symbology). Select standard error associated with total density estimates as the 'Field'. Select desired symbology settings for method, number of classes, and color scheme.

-Repeat steps 5.7.2 to create a layer for error associated with density estimates for recruits, submarket, and market sized oysters (making sure to symbolize by the correct 'Field').

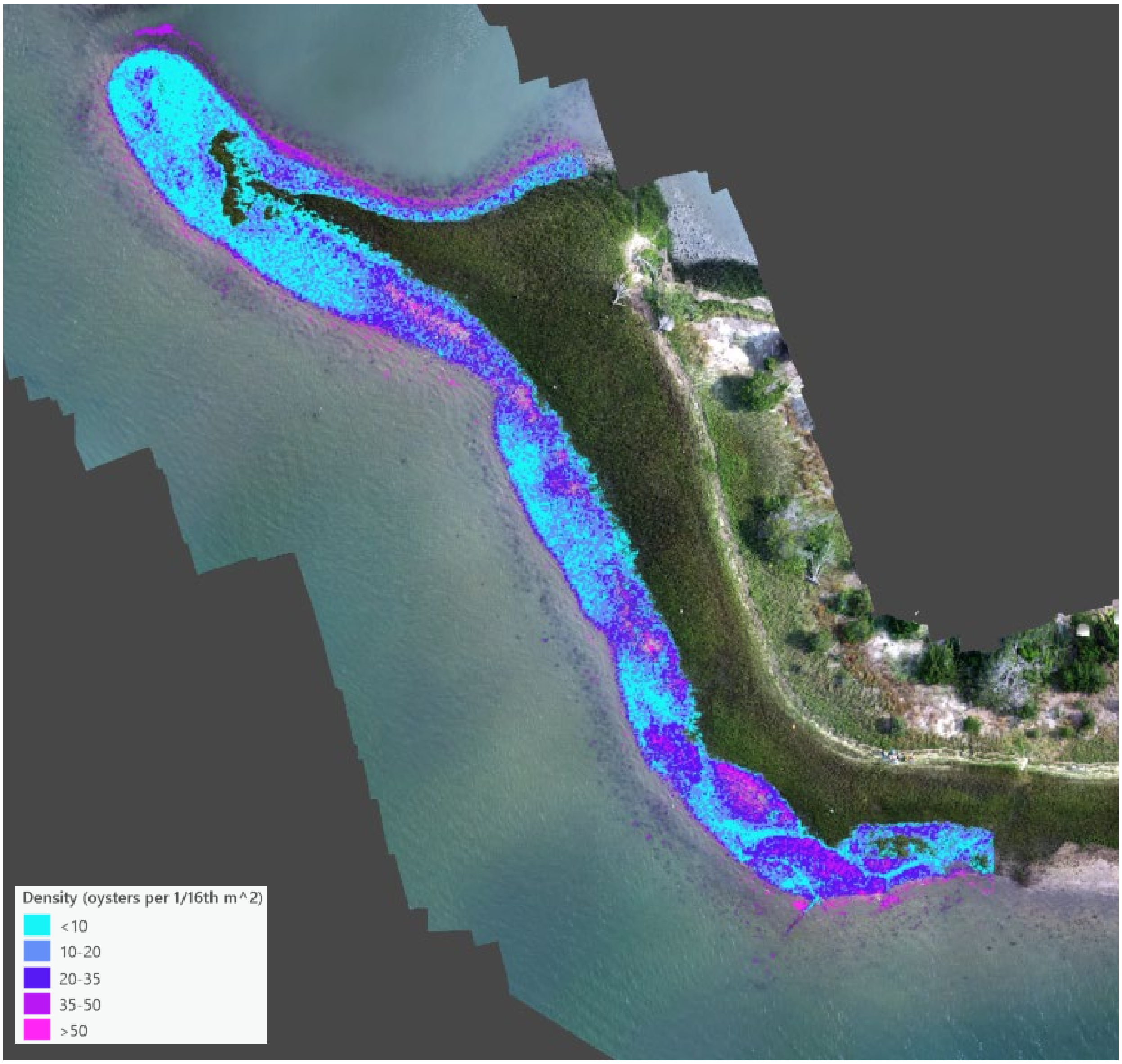


Figure 1. Estimate of total oyster density (oysters per 1/16th m^2) at Pivers Island, NC (2023).

6. Appendix

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