Spatially-referenced estimates of seagrass depth of colonization

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1 Introduction

Issues related to excessive nutrient pollution have motivated a substantial amount of research to understand and address impacts on coastal waters. Eutrophication, defined as an increase in the rate of supply of organic matter to an ecosystem (Nixon 1995), is primarily caused by anthropegenic inputs of limiting nutrients that exceed background concentrations of receiving waters. Adverse impacts on aquatic resources are well-documented and have included increased occurrence in the frequency and severity of harmful algal blooms (Cloern 1996), reduction of dissolved oxygen necessary to support heterotrophic organisms (Justíc et al. 1987, Diaz and Rosenberg 2008), and loss of ecosystem functioning through food web simplification (Tewfik et al. 2007). Although management activities have been successful in mitigating or reversing eutrophication impacts (e.g., Greening and Janicki 2006), the evaluation of response endpoints remains an important topic given that ecosystem changes in relation to different nutrient regimes are not fully understood nor anticipated (Duarte et al. 2009). The most appropriate indicators of ecosystem response may be those that exhibit clear biological linkages with water quality changes, such that the potential effects of management actions can be unambiguously characterized through known cause and effect pathways. Critical management decisions may be forced by tentative assessments, political or societal pressures, or qualitative criteria in the absence of empirical methods to identify adequate indicators of ecosytem response (Duarte et al. 2009).

The ecosystem services provided by seagrasses as well as their sensitivity to water quality changes has contributed to their proliferation as biological response endpoints for eutrophication. Seagrasses are ecosystem engineers (Jones et al. 1994, Koch 2001) that serve a structural and functional role in altering aquatic habitat often through different feedback mechanisms with other ecosystem components. For example, seagrass beds create habitat for juvenile fish and crabs by reducing wave action and stabilizing sediment (Williams and Heck 2001, Hughes et al. 2009). Seagrasses also respond to changes in water clarity through direct physiological linkages with light availability. In short, increased nutrient loading contributes to reductions in water clarity through increased algal concentrations, inhibiting the growth of seagrass through light limitation (Duarte 1995). Empirical relationships between nutrient loading, water clarity, light requirements, and the maximum depth of seagrass colonization have been identified (Duarte 1991, Kenworthy and Fonseca 1996, Choice et al. 2014), such that quantitative standards have been developed to maintain light regimes sufficient for seagrass growth targets (Steward et al. 2005). Conversely, seagrass depth limits have formed the basis of quantititative criteria for nutrient load targets (Janicki and Wade 1996). Contrasted with numeric standards for nutrients and phytoplankon, seagrass-based criteria may be more practical for developing water quality standards given that seagrasses are integrative of system-wide conditions over time and less variable with changes in nutrient regimes (Duarte 1995).

The development of numeric criteria and standards for coastal waters has been a management priority within the United States (USEPA (US Environmental Protection Agency) 1998) and internationally (WFD 2000). Numerous agencies and management programs have developed a variety of techniques for estimating seagrass depth limits as a basis for establishing numeric criteria, either as restoration targets or for identifying critical load limits. Such efforts have been useful for site-specific approaches where the analysis needs are driven by a particular management or research context (e.g., Iverson and Bittaker 1986, Hale et al. 2004). However, a lack of standardization among methods has prevented broad-scale comparisons between regions and has even contributed to discrepancies between measures of depth limits based on the chosen technique. For example, seagrass depth limits based on in situ techniques can vary with the sampling device (Spears et al. 2009). Despite the availability of data, techniques for estimating seagrass depth of colonization using remotely sensed data have not been extensively developed. Such techniques have the potential to facilitate broad-scale comparisons between regions given the spatial coverage and annual availability of many products. For example, recent analyses by Hagy, In review have shown that standardized techniques from seagrass coverage maps and bathymetric data can be used to compare growth patterns over time among different coastal regions of Florida. Such methods show promise, although further development to improve the spatial resolution of the analysis are needed. Specifically, methods for estimating seagrass depth limits should be reproducible for broad-scale comparisons, while also maintaining flexibility for site-specific estimates depending on management needs.

Reproducible and empirical approaches can be developed to provide more consistent estimates of seagrass depth limits for restoration targets or criteria development. We describe a method for estimating seagrass depth of colonization using information-rich datasets to create a spatially explicit and repeatable estimate. In particular, methods described in Hagy, In review are improved upon by creating a flexible and repeatable technique for estimating seagrass depth limits from coverage maps and bathymetric data. The specific objectives are to 1) describe the method for estimating seagrass depth limits within a relevant spatial context, 2) apply the technique to four distinct regions of Florida to illustrate improved clarity of description, and 3) develop a spatially coherent relationship between depth limits and water clarity for the case studies. Overall, these methods are expected to inform the development of water quality criteria based on empirical relationships of seagrass depth limits with water clarity over time. The method is applied to data from Florida although the technique is transferable to other regions with comparable data.

2 *Methods*

Development of a spatially-referenced approach to estimate seagrass depth of {acro:doc} colonization (DoC) relied extensively on data and partially on methods described in Hagy, In review. The following is a summary of locations and data sources, methods and rationale for incorporating spatial information in seagrass DoC estimates, and evaluation of the approach including relationships with water clarity.

2.1 Locations and data sources

Four unique locations were chosen for the analysis: Choctowatchee Bay (Panhandle), Big Bend region (northeast Gulf of Mexico), Tampa Bay (central Gulf Coast of Florida), and Indian River Lagoon (east coast) (Table 1 and Fig. 1). These locations represent different geographic regions in the state, in addition to readily available data and observed gradients in water clarity that likely contributed to hetereogeneity in seagrass growth patterns. For example, the Big Bend region was chosen based on location near an outflow of the Steinhatchee River where higher concentrations of dissolved organic matter are observed. Seagrasses near the outflow were observed to grow at shallower depths as compared to locations far from the river source. Coastal regions and estuaries in Florida are divided into individual spatial units based on a segmentation scheme developed by US Environmental Protection Agency (EPA) for the development of {acro:EPA} numeric nutrient criteria. One segment from each geographic location was used for the analysis to evaluate estimates of seagrass DoC. The segments included numbers 0303 (Choctowatchee Bay), 0820 (Big Bend region), 0902 (Tampa Bay), and 1502 (Indian River Lagoon), where the first two digits indicate the estuary and the last two digits indicate the segment within the estuary.

Data used to estimate seagrass DoC were primarily obtained from publically available {acro:GIS} Geographic Information System (GIS) products. At the most generic level, spatially-referenced information describing seagrass aerial coverage combined with co-located bathymetric depth information were used to estimate DoC. These data products are available in coastal regions of Florida through the US Geological Survey, Florida Department of Environmental Protection, and watershed management districts. Data are generally more available in larger estuaries that are of specific management concern, e.g., Tampa Bay, Indian River Lagoon. For example, seagrass coverage data are available from 1950 (Tampa Bay) to present day (multiple estuaries), with more recent products available at annual or biennial intervals. Seagrass coverage maps are less frequent in areas with lower population densities (e.g., Big Bend region) or where seagrass is naturally absent (northeast Florida). Seagrass maps were produced using photo-interpretations of aerial images to categorize coverage as absent, discontinuous (patchy), or continuous. For this analysis, we considered seagrass coverage as being only present (continuous and patchy) or absent since the former did not represent unequivocal categories between regions.

Seagrass coverage maps were combined with bathymetric depth layers to characterize location and depth of growth in each location. Bathymetric depth layers for each location were obtained from the National Oceanic and Atmospheric Administration's (NOAA) National Geophysical Data Center as either Digital Elevation Models (DEMs) or raw sounding data from {acro:DEM} hydroacoustic surveys. Tampa Bay data provided by the Tampa Bay National Estuary Program are described in Tyler et al. (2007). Bathymetic data for the Indian River Lagoon were obtained from the St. John's Water Management District (Coastal Planning and Engineering 1997). NOAA products were referenced to mean lower low water, whereas Tampa Bay data were referenced to the North American Vertical Datum of 1988 and the Indian River Lagoon data were referenced to mean sea level. Depth layers were combined with seagrass coverage layers using standard union techniques of raster and vector layers in ArcMap 10.1 (Environmental Systems Research Institute 2012). To reduce computation time, depth layers were first masked using a 1 km buffer of the seagrass coverage layer. The final layer used for analysis was a point layer with attributes describing location (latitude, longitude, segment), depth (m), and seagrass (present, absent). Additional details describing the data are available in Hagy, In review.

2.2 Segment-based estimates of seagrass depth of colonization

Methods in Hagy, In review describe an approach for estimating seagrass DoC at individual coastal segments. Seagrass depth data described above are used to estimate maximum (Z_{cMax}) and median ($Z_{c50\%}$) seagrass DoC, where the maximum depth is defined as the deepest depth at which a "significant" coverage of seagrasses occured in a segment and the median depth is defined as the median depth occurring at the deep water edge. The seagrass depth points are grouped into bins and the proportion of points within each depth bin that contain seagrass are quantified. Both seagrass DoC estimates are obtained from a plot of proportion of points occupied at each depth bin. In general, the plot is characterized by a decreasing trend such that the proportion of occupied points by depth bin decreases and eventually flattens with increasing depth. A regression is fit on this descending portion of the curve such that the intercept point on the x-axis is considered the maximum depth of colonization. The median portion of this curve is considered the median depth of the deepwater edge of seagrass.

Considerable spatial heterogeneity in the observed seagrass growth patterns suggests that a segment-wide estimate of seagrass DoC may be inadequate for fully characterizing growth patterns, particularly for the examples in the current analysis. Fig. 2 illustrates spatial variation in seagrass distribution for a location in the Big Bend region of Florida. Using methods in Hagy, In review, the estimate for median seagrass DoC for the segment is over- and under-estimated for different areas of the segment. In particular, DoC is greatly over-estimated at the outflow of the Steinhatchee where high concentrations of dissolved organic matter naturally limit seagrass growth. This example suggests that estimates of DoC may be needed at finer spatial scales to provide a more robust determination of restoration targets and nutrient criteria.

2.3 Estimating seagrass depth of colonization using spatial information

The approach used to estimate seagrass DoC with spatial information has several key differences with the original method. As before, seagrass DoC estimates are based on empirical measures of the frequency occurrence of seagrass by increasing depth. The first difference is that maximum DoC is estimated from a logistic growth curve fit through the data, in addition to a simple linear regression in the previous example. Second, a third measure describing the depth at which seagrass were most commonly located was defined, in addition to median and maximum depth of growth. The third and most important difference is that the estimates are assigned to discrete locations, using either a grid of points or as a single location of interest. Methods and implications of these differences are described below.

The spatially-referenced approach for estimating DoC begins by creating a grid of evenly-spaced points within the segment. The same process for estimating DoC is used for each point. Alternatively, a single location of interest can be chosen rather than a grid-based design. Seagrass depth data (i.e., merged bathymetric and seagrass coverage data) that occur within a set radius from the chosen locations are selected for estimating seagrass DoC values. The estimate for each location is quantified from a plot of the proportion of bathymetric soundings that contain seagrass at each depth bin (Fig. 4a). Although the chosen radius for selecting depth points is problem-specific, the minimum radius must sample a sufficient number of points for estimating DoC. In general, an appropriate radius will produce a plot that indicates a decrease in the proportion of points that are occupied by seagrass with increasing depth.

A curve is fit to the sampled depth points using non-linear regression to characterize the reduction in seagrass as a function of depth. Specifically, a decreasing logistic growth curve is fit to the plot to create a monotonic and asymptotic function of the sample data. The curve is fit by minimizing the residual sums-of-squares with the Gauss-Newton algorithm (Bates and Chambers 1992) and user-supplied starting parameters that are an approximate estimate of the curve characteristics. The model has the following form:

$$Proportion = \frac{\alpha}{1 + \mathrm{e}^{(\beta - Depth)/\gamma}} \qquad (1)$$

{eqn:prop}

where the proportion of points occupied by seagrass at each depth is defined by a logistic curve with an asymptote α, a midpoint inflection β, and a scale parameter γ. Starting values α, β, and γ were estimated empirically from the observed data.

Finally, a simple linear curve is fit through the inflection point (β) of the logistic curve to estimate depth of colonization (Fig. 4c). The inflection point is the depth at which seagrass are decreasing at a maximum rate and is used as the slope of the linear curve. Three measures describing seagrass growth characteristics are obtained. The maximum depth of seagrass colonization, DOC_{max}, is the x-axis intercept of the linear curve. The depth of maximum seagrass occupancy, SG_{max} is the location where the linear curve intercepts the asymptote of the logistic growth curve. The median depth of seagrass colonization, DOC_{med}, is the depth halfway between SG_{max} and DOC_{max}. DOC_{med} was typically but not always the inflection point of the logistic growth curve. Functionally, each measure has specific ecological significance. The median and maximum depth estimates describe the growth limitations of seagrasses as a function of water clarity, whereas the maximum occupancy depth is considered the depth were most seagrasses were encountered in the sample. Median and maximum depth estimates differ in that the former describes the median depth of the deep water edge, whereas the latter describes a nominal characterization of maximum depth independent of outliers.

Estimates for each of the three DoC measures are obtained only if specific criteria are met. These criteria were implemented as a safety measure that ensures a sufficient amount and appropriate quality of data are used. First, estimates are provided only if a sufficient number of seagrass depth points are present within the radius of the grid point to estimate a logistic growth curve. This criteria applies to the sample size as well as the number of points with seagrass in the sample. That is, the curve cannot be estimated for small samples or if an insufficient number of points contain seagrass regardless of sample size. Second, estimates are provided only if an inflection point is present on the logistic curve within the range of the sampled depth data. This criteria may apply under two scenarios where the curve is estimated but a trend is not adequately described by the sampled data. That is, a curve may be estimated that describes only the initial decrease in points occupied as a function of depth but the observed points do not occur at depths deeper than the predicted inflection point. The opposite scenario may occur when a curve is estimated but only the deeper locations beyond the inflection point are present in the sample. Finally, the estimate for SG_{max} is set to zero if the linear curve through the inflection point intercepts the asympote at x-axis values less than zero. The estimate for DOC_{med} is also shifted to the depth value halfway between SG_{max} and DOC_{max}.

All estimates were obtained using custom-made functions in program R that were based on the `nls` and `SSlogis` functions to fit a nonlinear least squares using a self-starting logistic growth model (Bates and Chambers 1992, R Development Core Team 2014). All seagrass depth shapefiles were imported and processed in R using functions in the `rgeos` and `sp` packages (Bivand et al. 2008, Bivand and Rundel 2014).

2.4 Comparison with segment-based approach and sensitivity analysis

Spatially-referenced estimates for seagrass DoC were obtained for each of the four segments described above. Segment-wide estimates obtained using methods in Hagy, In review were used as a basis of comparison such that departures from these values were evidence of spatial heterogeneity in seagrass growth patterns within each segment. A sampling grid of locations for estimating each of the three depth values in Fig. 4 was created for each segment. The grid is masked by the segment boundaries to remove locations that did not occur on the water, whereas seagrass depth points used to estimate DoC extended beyond the segment boundaries. Initial spacing between sample points was chosen arbitrarily as 0.02 decimal degrees, which is approximately 2 km at 30 degrees N latitude. The sampling radius around each sampling location in the grid was also chosen as 0.02 decimal degrees to allow for complete coverage of seagrass within the segment while also minimizing redundancy of information described by each location. In other words, radii were set such that the seagrass depth points sampled by each grid location were only partially overlapped by those sampled by neighboring points.

The ability to characterize heterogeneity in seagrass growth patterns using the grid-based approach can be informed by evaluating the level of confidence associated with DoC estimates. Confidence intervals for non-linear regression can be estimated using a Monte Carlo simulation approach that considers the variance and covariance between the model parameters and the depth measurements (Hilborn and Mangel 1997). For simplicity, we assume that the observation uncertainty associated with the depth measurements is zero such that the variability associated with parameter estimates is considered the primary source of uncertainty. A 95% confidence interval for each DoC estimates was constructed by repeated sampling of a multivariate normal distribution followed by prediction of the proportion of points occupied by seagrass as in eq. (1). The sampling distribution assumes:

$$x \sim N(\mu, \Sigma) \tag{2}$$

where x is a predictor variable used in eq. (1) that follows a multivariate normal distribution with mean μ, and variance-covariance matrix Σ. The mean values are set at the depth value corresponding to the inflection point on the logistic curve and the predicted model parameters (i.e., α, β, and γ), whereas Σ is the variance-covariance matrix of the model parameters and depth, with the latter being zero. A large number of samples ($n = 10000$) were drawn from the distrubution to characterize the uncertainty. The 2.5th and 97.5th quantile values of the sample were considered bounds on the 95% confidence interval.

The uncertainty associated with the DoC estimates were based on the upper and lower limits of the estimated inflection point on the logistic growth curve. This approach was used because uncertainty in the inflection point is directly related to uncertainty in each of the DoC estimates that are based on the linear curve fit through the inflection point. Specifically, linear curves were fit through the upper and lower estimates of the inflection point to identify upper and lower limits for the estimates of SG_{max}, DOC_{med}, and DOC_{max}. These values were compared with the initial estimates from the linear curve that was fit through the predicted logistic curve (i.e., Fig. 4c). This approach provided an indication of uncertainty for individual estimates for a set radius. Uncertainty estimates were obtained for each DoC estimate for the grids in each segment.

2.5 Developing a spatially coherent relationship of water clarity with depth of colonization

Potentially useful information can be obtained from the seagrass depth estimates for each segment by evaluating the relationship with water clarity through space and time. In particular, increased resolution of seagrass depth estimates compared with multiple measures of water clarity can potentially improve the ability to empirically describe light requirements leading to the development of numeric criteria. Secchi measurements provide a precise estimate of water clarity and have been obtained at numerous locations described in the Florida Department of Environmental Protection's Impaired Impaired Waters Rule (IWR) database. All available secchi {acro:IWR} data for each of the four segments were obtained from the IWR database, update number 40. Prior to analyses, all secchi data were screened to exclude observations that were coded with any flags indicating that the value was lower than the maximum depth of the observation point. Secchi data were also compared with bathymetric data to verify unflagged values were not missed by initial screening.

The relationship between seagrass depth limits and secchi measurements were explored using empirically estimated light requirements and attenuation equations. The traditional Lambert-Beer equation describes the exponential decrease of light availability with depth:

$$I_z = I_O \cdot \exp\left(-K_d \cdot Z\right) \qquad (3)$$ {eqn:lambe

such that the irradiance of incident light at depth Z (I_Z) can be estimated from the irradiance at the surface (I_O) and a light extinction coefficient (K_d). Minimum seagrass light requirements have also been estimated on average as approximately 11% surface irradiance (Duarte 1991), such that eq. (3) can be described by DOC_{max}:

$$0.11 = \exp\left(-K_d \cdot DOC_{max}\right) \tag{4}$$

A conversion factor is commonly used to estimate the light extinction coefficient from secchi depth Z_d, such that such that $1.44 = K_d \cdot Z_d$ (Holmes 1970). Thus, K_d is replaced with the the conversion factor and the equation is rearranged to describe DOC_{max} as a function of secchi depth Z_d:

$$DOC_{max} = \frac{-\log\left(0.11\right)}{1.44} \cdot Z_d \tag{5}$$

{eqn:sgreg

A regression of seagrass depth estimates against secchi measurement is expected to have a slope corresponding to eq. (5), provided that the current approach for estimating maximum DoC is consistent with previous analyses that have empirically related seagrass depth limits with light requirements. The geographic coordinates for each secchi measurement were used as locations for estimating DOC_{max} in each segment. These estimates were compared with the secchi estimates using linear regression forced through the origin. The slope of the corresonding regression was compared with that in eq. (5) with the assumption that the two would not differ significantly. However, the relationship between the depth estimates and secchi measurements may vary depending on the specific radius around each sample point for estimating DOC_{max}. The effect of radius size on the relationship was also explored.

3 Results

Describe spatial heterogeneity within segments reasons why

Describe why estimates were unavailable in particular areas of each segment

Acknowledge that comparisons with segment wide estimate are specific to grid spacing and radii tha twere used, thus the comparison is only useful for illustrating the presence of heterogeneity within segments, as well as variation between segments. Absolute values will vary with different spacing and radii.

Fig. 5

Table 2

Fig. 6

4 Discussion

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Table 1: Characteristics of coastal segments used to evaluate seagrass depth of colonization estimates. Segments are spatial units defined by US EPA for nutrient criteria development (see Fig. 1). Area and depth values are meters and square kilometers, respectively. Secchi measurements (m) were obtained from the Florida Department of Environmental Protection's Impaired Waters Record, upadate number 40 (IWR40). tab:seg_summ

	Choctawhatchee Bay	Big Bend	Old Tampa Bay	Indian River Lagoon
Segment	0303	0820	0902	1502
Latitude	30.43	29.61	27.94	28.61
Longitude	-86.54	-83.48	-82.62	-80.77
Surface area	59.41	271.37	205.50	228.52
Seagrass area	3.51	203.02	24.48	74.89
Depth (mean)	5.31	1.41	2.56	1.40
Depth (max)	11.90	3.60	10.40	3.70
Secchi (mean)	2.13	1.34	1.34	1.34
Secchi (se)	0.07	0.19	0.01	0.01

Table 2: Summary of seagrass depth estimates (m) for each segment using all grid locations in Fig. 5. Whole segment estimates were obtained from all seagrass depth data for each segment. tab:est_summ

Segment	Whole segment	Mean	St. Err.	Min	Max
0303					
SG_{max}	1.92	1.65	0.24	0.52	2.30
DOC_{med}	2.26	2.01	0.15	1.52	2.46
DOC_{max}	2.60	2.36	0.16	1.90	2.85
0820					
SG_{max}	1.50	1.71	0.43	0.06	3.23
DOC_{med}	2.92	2.07	0.42	0.52	3.46
DOC_{max}	4.34	2.42	0.43	0.69	3.97
0902					
SG_{max}	0.52	0.45	0.15	0.00	1.03
DOC_{med}	0.79	0.82	0.14	0.29	1.59
DOC_{max}	1.07	1.18	0.17	0.59	2.15
1502					
SG_{max}	1.25	1.33	0.11	0.90	2.02
DOC_{med}	1.51	1.50	0.10	0.98	2.08
DOC_{max}	1.77	1.66	0.10	1.06	2.16

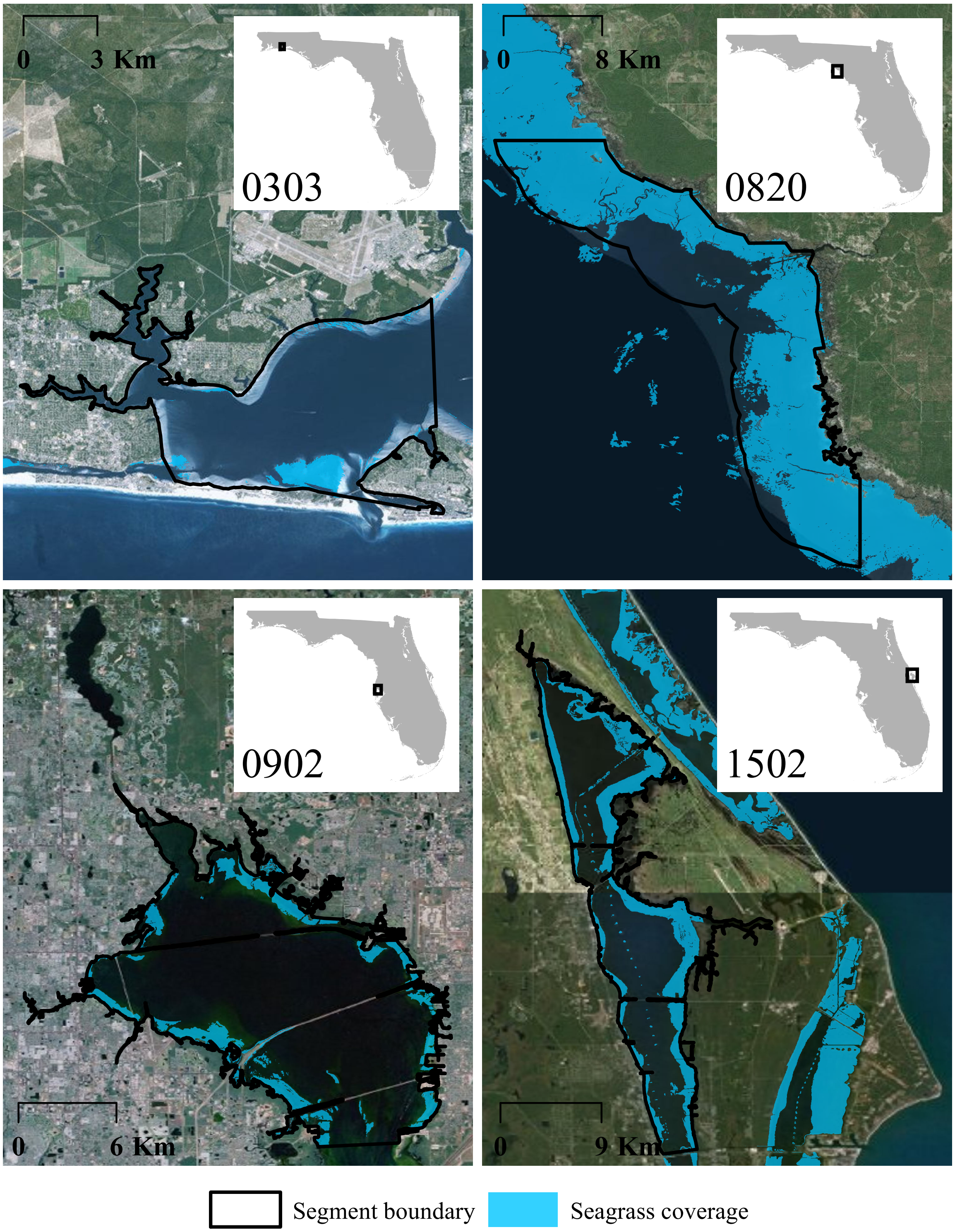

Fig. 1: Locations and seagrass coverage of estuary segments used to evaluate depth of colonization estimates. Seagrass coverage layers are from 2007 (Choctowatchee Bay, 0303), 2006 (Big Bend, 0820), 2010 (Old Tampa Bay, 0902), and 2009 (Indian River Lagoon, 1502). {fig:seg_a

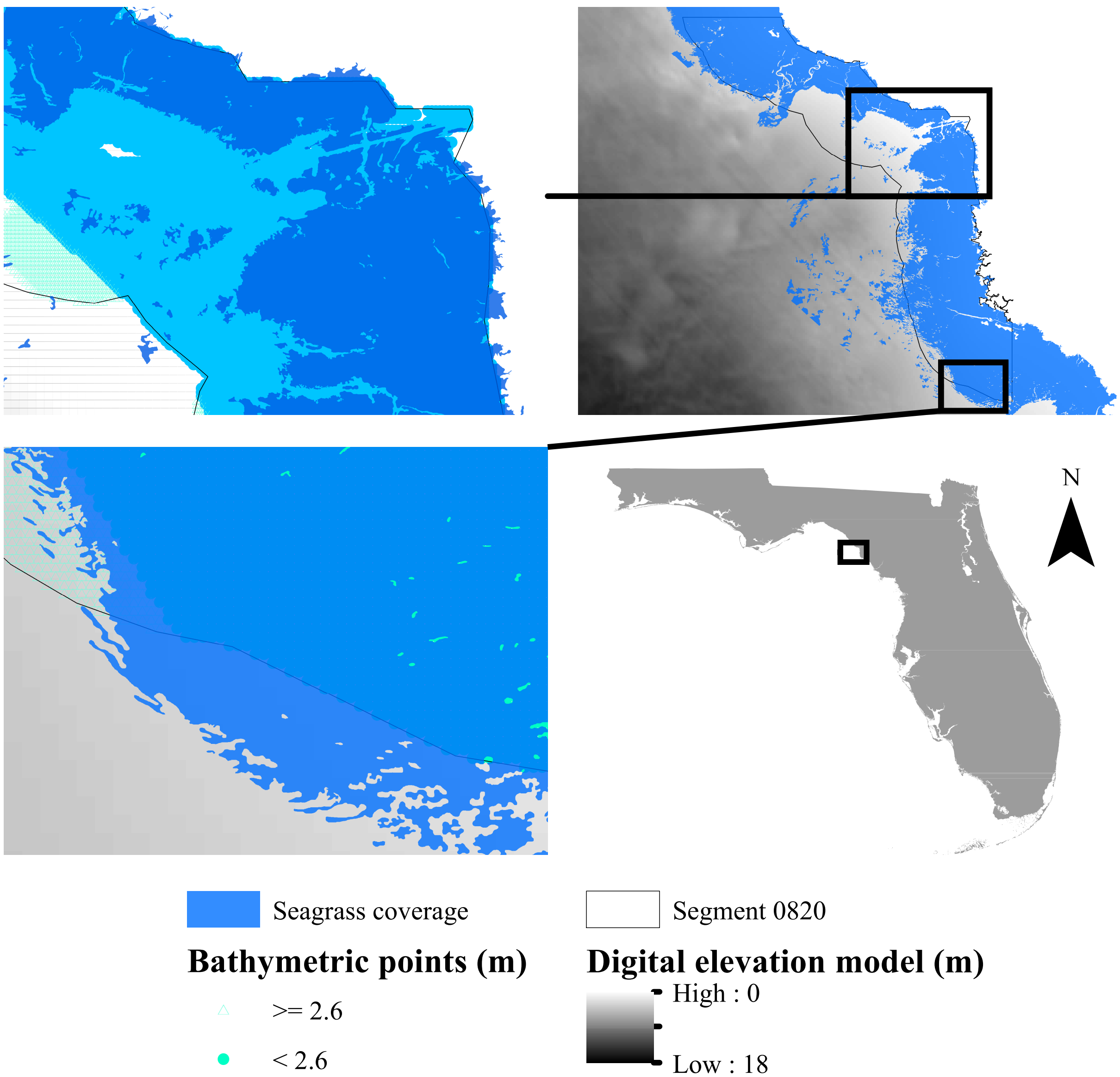

Fig. 2: Example of over- and under-estimates for seagrass depth of colonization for segment 820 in the Big Bend region, Florida. Layers include a seagrass coverage layer, bathymetric depth points, bathymetric digital elevation model, and spatial extents for the segment and Florida. The top-left figure indicates over-estimation and the bottom-left indicates under-estimation. Bathymetric points are color-coded by the median depth of colonization estimate for seagrass using data from the whole segment (2.6 m). {fig:wbid_

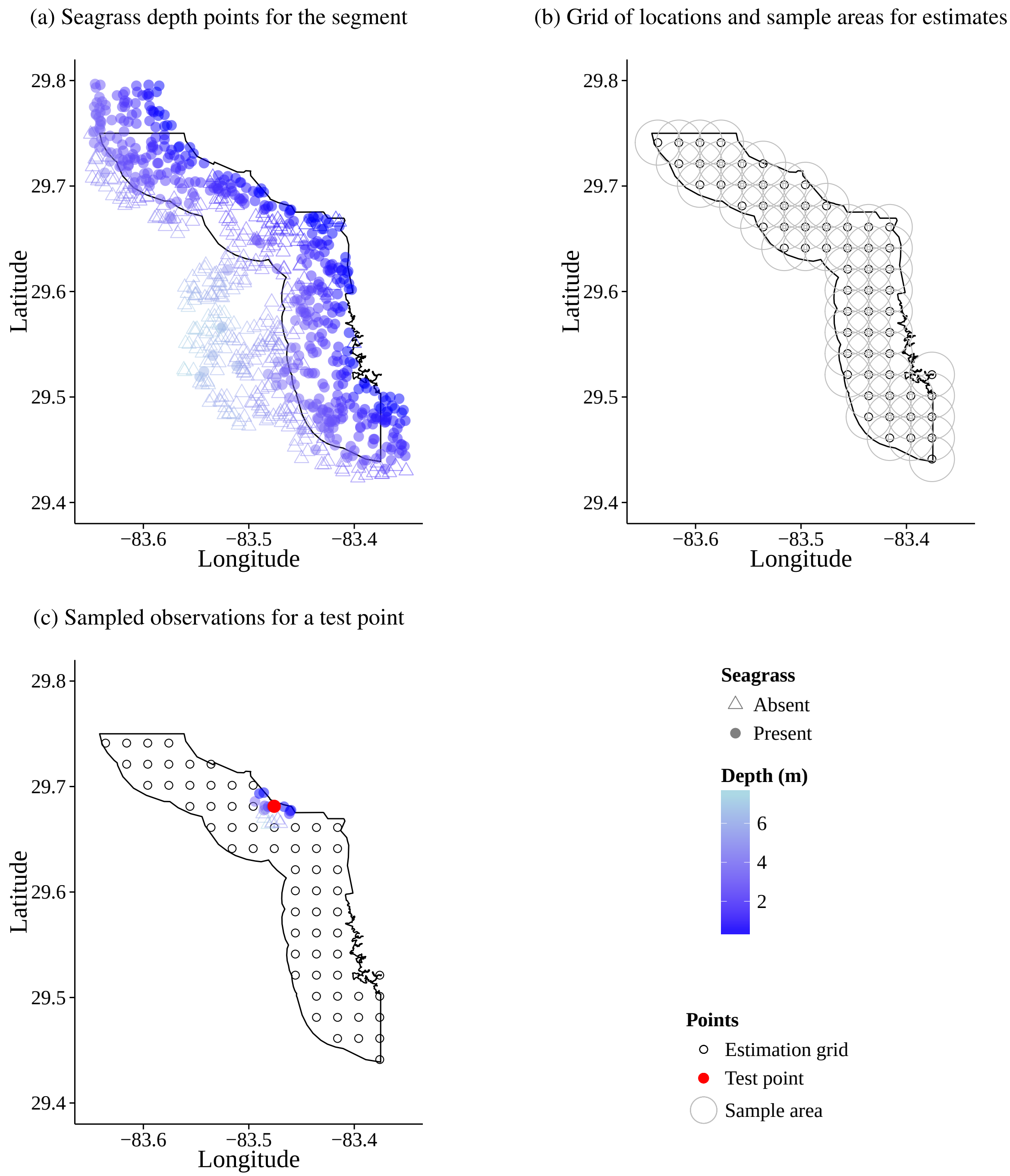

Fig. 3: Examples of data and grid locations for estimating seagrass depth of colonization for a region of the Big Bend, Florida. Fig. 3a shows the seagrass depth points that are used for sampling, Fig. 3b shows a grid of locations and sampling radii for estimating seagrass DoC, and Fig. 3c shows an example of sampled seagrass depth points for a location. Estimates in Fig. 4 were obtained from the sampled location in Fig. 3c.

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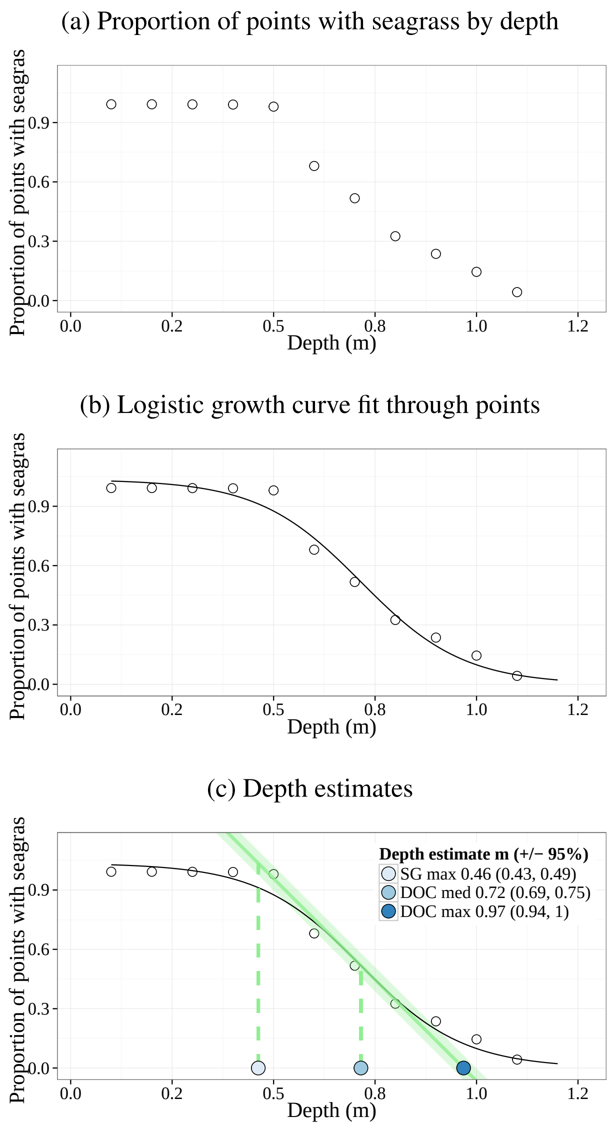

Fig. 4: Methods for estimating seagrass depth of colonization using sampled seagrass depth points around a single location. Fig. 4a is the proportion of points with seagrass by depth using depth points within the buffer of the test point in Fig. 3. Fig. 4b adds a decreasing logistic growth curve fit through the points. Fig. 4c shows three depth estimates based on a linear curve fit through the inflection point of logistic growth curve. {fig:est_e

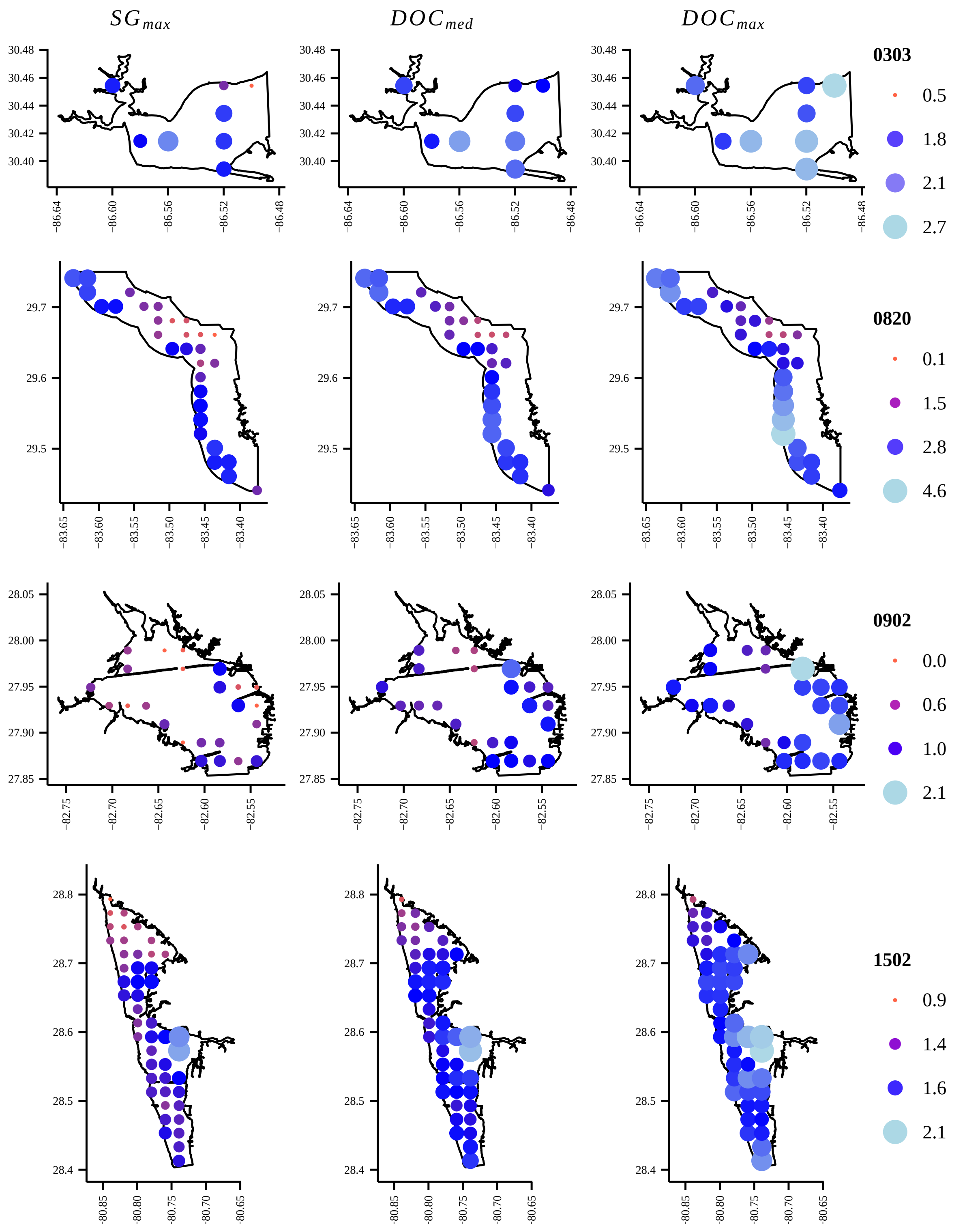

Fig. 5: Spatially-referenced estimates of seagrass depth limits (m) for four coastal segments of Florida. Estimates include depth of maximum seagrass growth (SG_{max}), median depth of colonization (DOC_{med}), and maximum depth of colonization (DOC_{max}). Estimates are assigned to grid locations for each segment, where grid spacing was fixed at 0.02 decimal degrees. Radii for sampling seagrass bathymetric data around each grid location were fixed at 0.06 decimal degrees. {fig:all_e

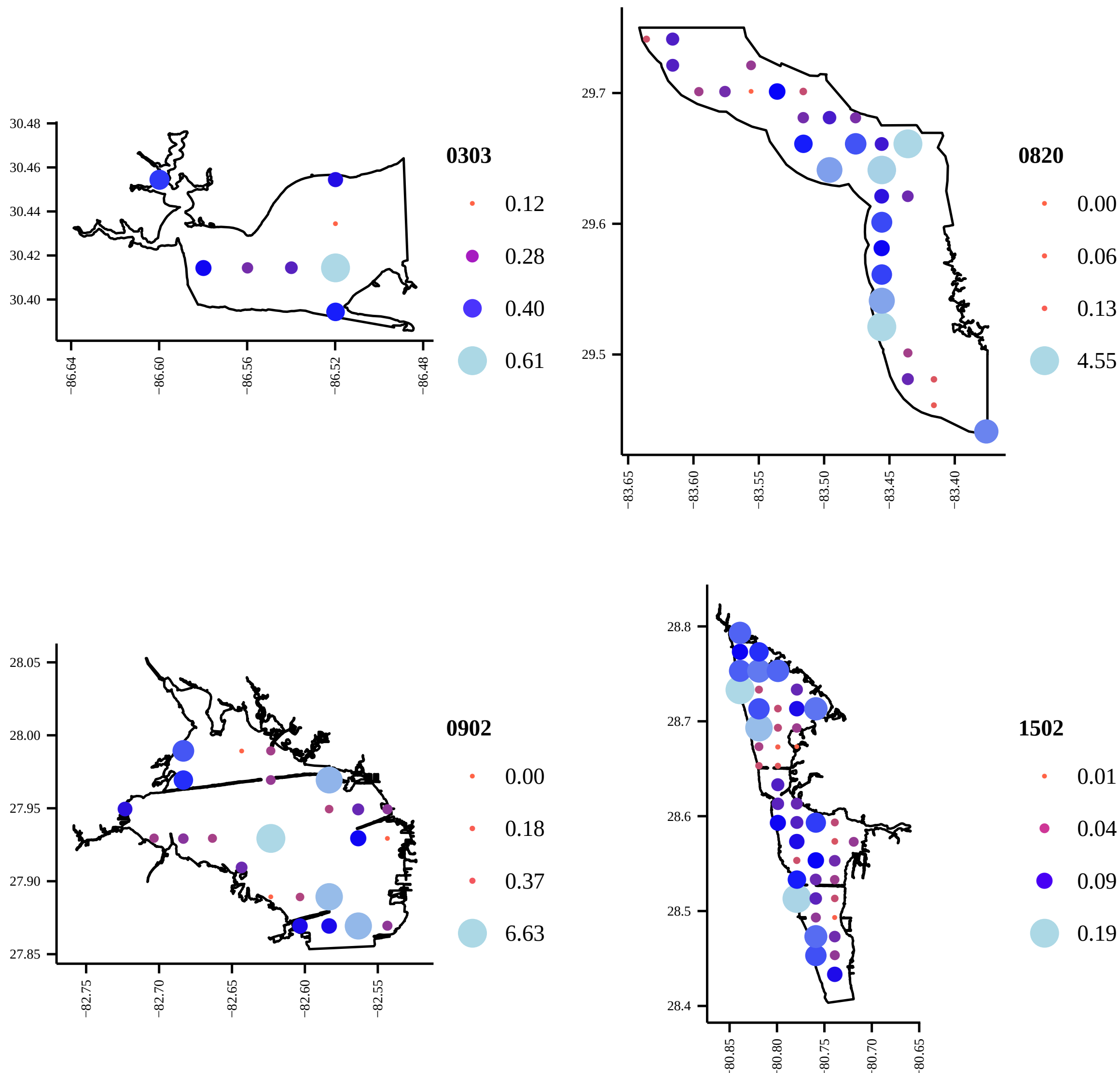

Fig. 6: Size of confidence intervals (m) for depth of colonization estimates in Fig. 5. Points are colored and sized based on the difference between the upper and lower bounds of a 95% confidence interval for all three DoC estimates (SG_{max}, DOC_{med}, DOC_{max}). Bounds were obtained using Monte Carlo simulations to estimate uncertainty associated with the inflection point of the estimated logistic curve (Fig. 4) for each sample. {fig:all_s