Spatially-referenced estimates of seagrass depth of colonization

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1   Introduction

Issues related to excessive nutrient pollution have motivated a substantial body 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 harmfal 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

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71 from Florida although the technique is transferable to other regions with comparable data.

2 Methods

73   Development of a spatially-referenced approach to estimate seagrass depth of {acro:doc}

74 colonization (DoC) relied extensively on data and partially on methods described in Hagy, In

75 review. The following is a summary of locations and data sources, methods and rationale for

76 incorporating spatial information in seagrass DoC estimates, and evaluation of the approach

77 including relationships with water clarity.

2.1 Locations and data sources

79   Four unique locations were chosen for the analysis: Choctowatchee Bay (Panhandle), Big

80 Bend region (northeast Gulf of Mexico), Tampa Bay (central Gulf Coast of Florida), and Indian

81 River Lagoon (east coast) (Table 1 and Fig. 1). These locations represent different geographic

82 regions in the state, in addition to readily available data and observed gradients in water clarity

83 that likely contributed to hetereogeneity in seagrass growth patterns. For example, the Big Bend

84 region was chosen based on location near an outflow of the Steinhatchee River where higher

85 concentrations of dissolved organic matter are observed. Seagrasses near the outflow were

86 observed to grow at shallower depths as compared to locations far from the river source. Coastal

87 regions and estuaries in Florida are divided into individual spatial units based on a segmentation

88 scheme developed by US Environmental Protection Agency (EPA) for the development of {acro:EPA}

89 numeric nutrient criteria. One segment from each geographic location was used for the analysis to

90 evaluate estimates of seagrass DoC. The segments included numbers 0303 (Choctowatchee Bay),

91 0820 (Big Bend region), 0902 (Tampa Bay), and 1502 (Indian River Lagoon), where the first two

92 digits indicate the estuary and the last two digits indicate the segment within the estuary.

Data used to estimate seagrass DoC included a suite of publically available 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

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

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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

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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:

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

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

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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}.

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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. Initial spacing between sample points was chosen arbitrarily as 0.02 decimal degrees, which is approximately 2 km at 30 degrees N latitude. Similarly, the sampling radii around each sampling location in the grid was chosen as 0.06 decimal degrees, or approximately 6 km.

Three factors influence the estimates at each sampling point, as well as the ability compare values between points. First, the starting location of the first point of the sampling grid is chosen arbitrarily such that a unique grid is obtained comparisons of within-segment estimates may vary slightly given the starting location. Second, the spacing between sampling points affects the degree of collinearity between estimates that are near each other. For a set sampling radius around each point, estimates will be less correlated at larger spacing between sampling points, whereas the converse is true for smaller spacing. Third and most important, the radius around

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each sampling point determines the number of seagrass depth points that are included in the estimate. The chosen radius is considered an explicit area within which the estimate applies. As before, increasing the radius around each sample point will increase the collinearity between estimates at adjacent points for a set grid spacing. Collinearity between sample points based on the sampling scheme is not inherently problematic provided the results are interpreted in the context of the question of interest. For example, small spacing and large sampling radii will create very similar estimates between points. This approach does not necessarily invalidate the estimate at each point, although comparisons between points become less valid as the estimates are not related to a unique sampling area for each location. Similarly, a grid with large spacing and small radii facilitates comparison between points as each location represents a unique collection of samples, although each estimate is relevant for a small location with undescribed and potentially important variation in seagrass growth patterns between points.

A systematic approach was used to evaluate validity of comparisons between sampling points given parameters that influence collinearity or spatial autocorrelation. For the analysis, 'validity' is considered relative uniqueness of estimates at each point in the context of grid spacing and sampling radius. The effect of the random starting location of each grid was considered negligible for this analysis and set constant between analyses for comparison. For each segment, unique combinations of grid spacing and sampling radii were used to estimate maximum seagrass DoC. Spatial autocorrelation between all estimates was measured by semivariance

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

3 Results

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

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) from all grid locations in Fig. 5. Whole segment estimates were obtained from all seagrass depth data for each segment. tab:est_summ

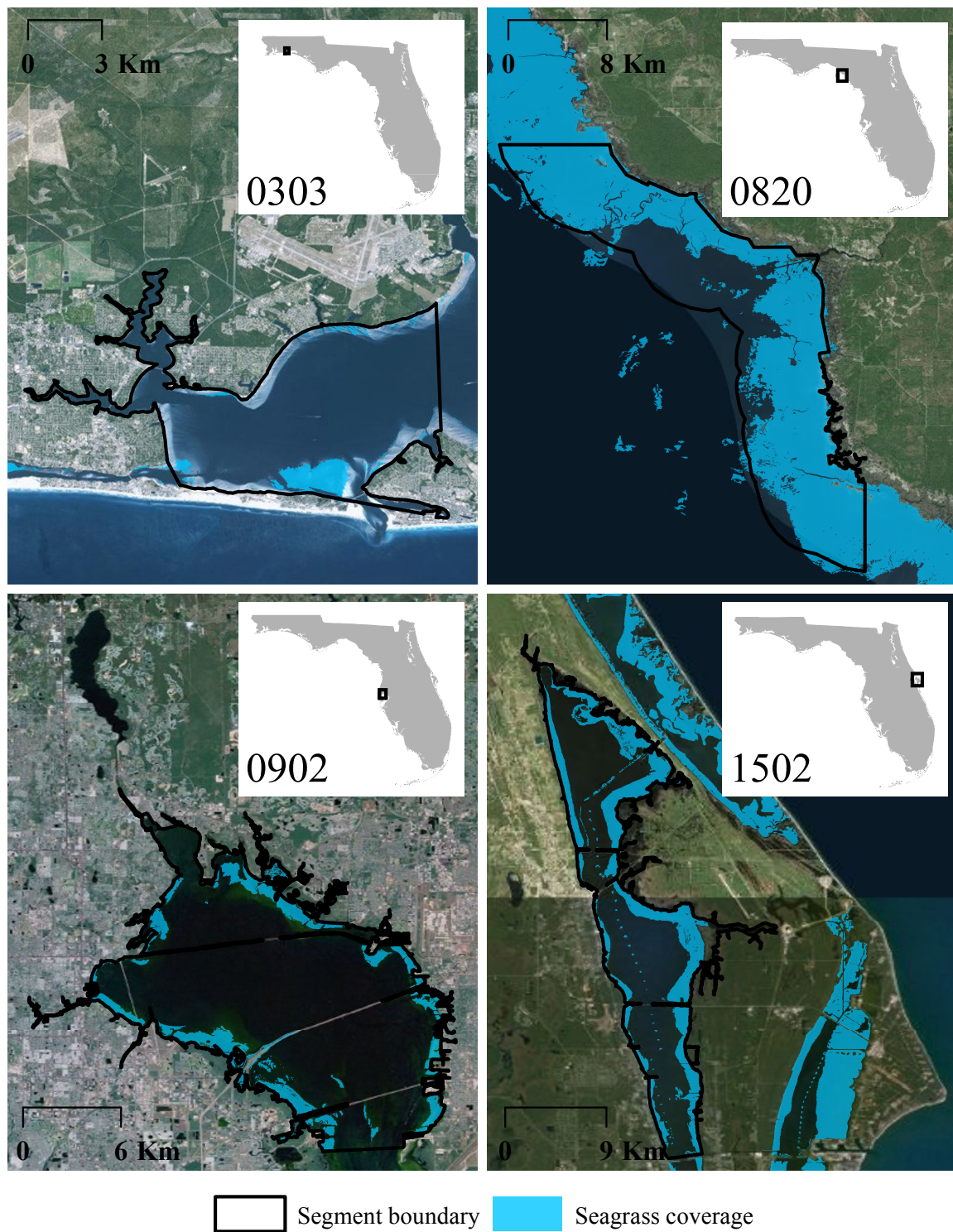| Segment	Whole segment	Mean	St. Err.	Min	Max
0303					
SG_{max}	1.92	1.93	0.08	1.62	2.22
DOC_{med}	2.26	2.22	0.09	1.86	2.49
DOC_{max}	2.60	2.52	0.10	2.09	2.75
0820					
SG_{max}	1.50	1.47	0.48	0.00	2.96
DOC_{med}	2.92	2.39	0.37	0.96	3.49
DOC_{max}	4.34	3.30	0.33	1.86	4.18
0902					
SG_{max}	0.52	0.28	0.13	0.00	0.81
DOC_{med}	0.79	0.66	0.10	0.35	1.04
DOC_{max}	1.07	1.03	0.10	0.70	1.62
1502					
SG_{max}	1.25	1.29	0.07	0.93	1.81
DOC_{med}	1.51	1.51	0.08	1.08	1.98
DOC_{max}	1.77	1.73	0.10	1.23	2.21

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).
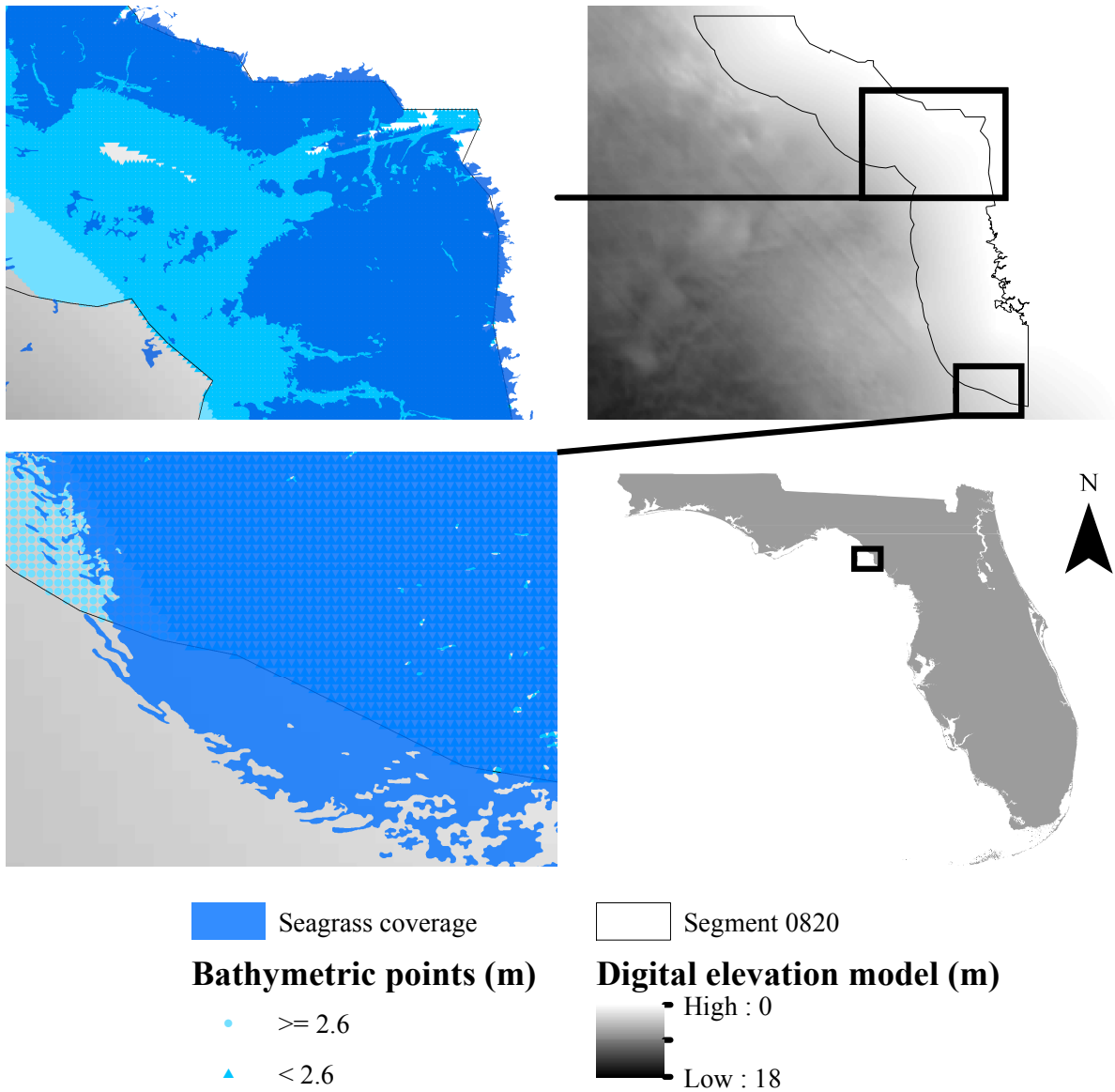
{fig:seg_a

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).

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(a) Seagrass depth points for the segment

(b) Grid of locations and sample areas for estimates
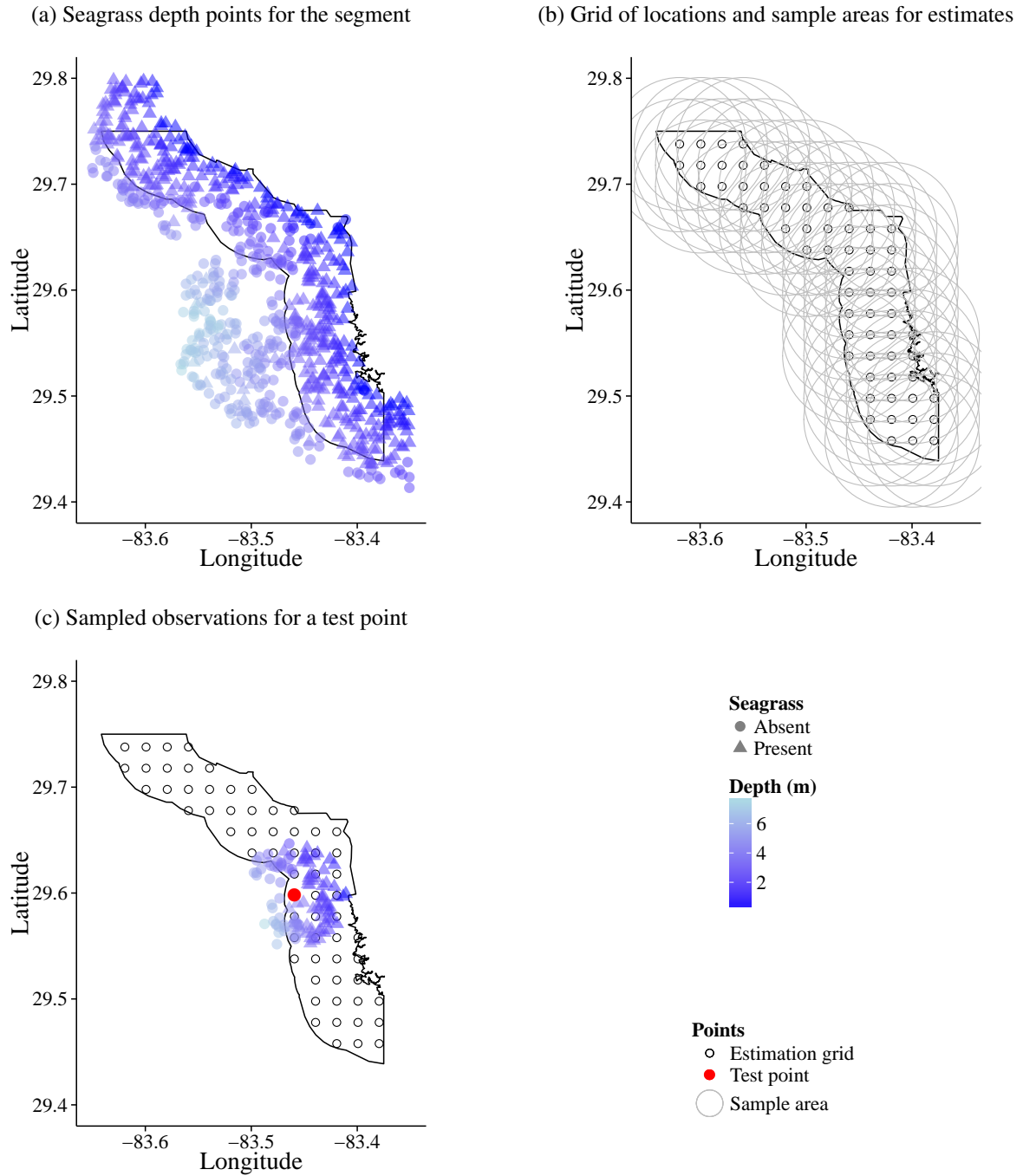
(c) Sampled observations for a test point

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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(a) Proportion of points with seagrass by depth

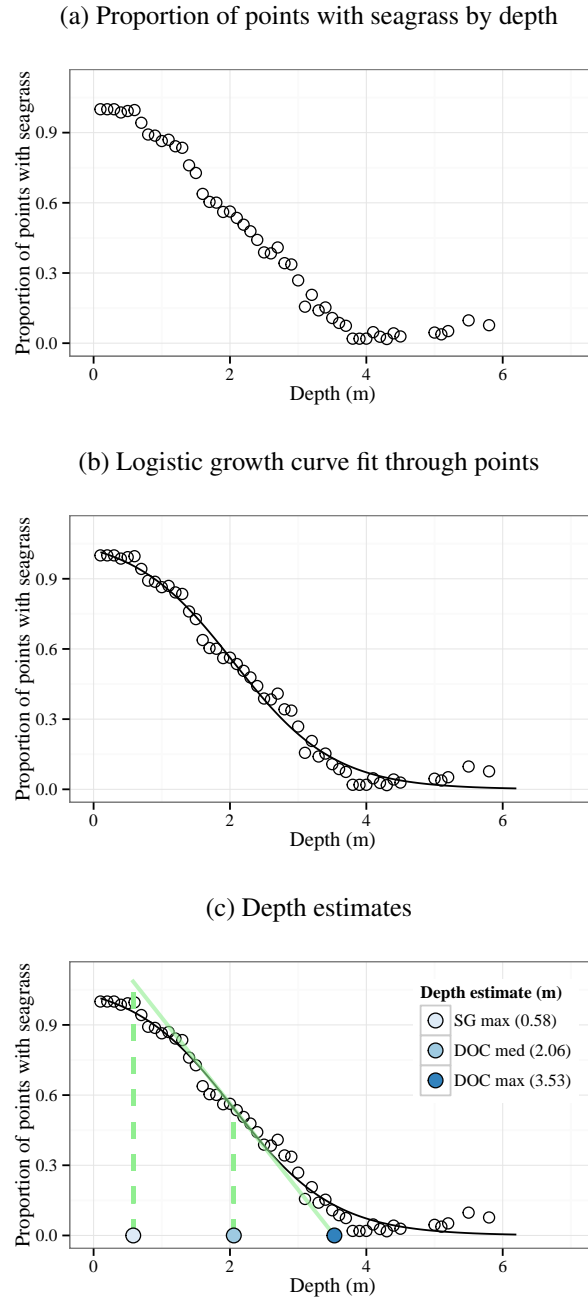(b) Logistic growth curve fit through points

(c) Depth estimates

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.
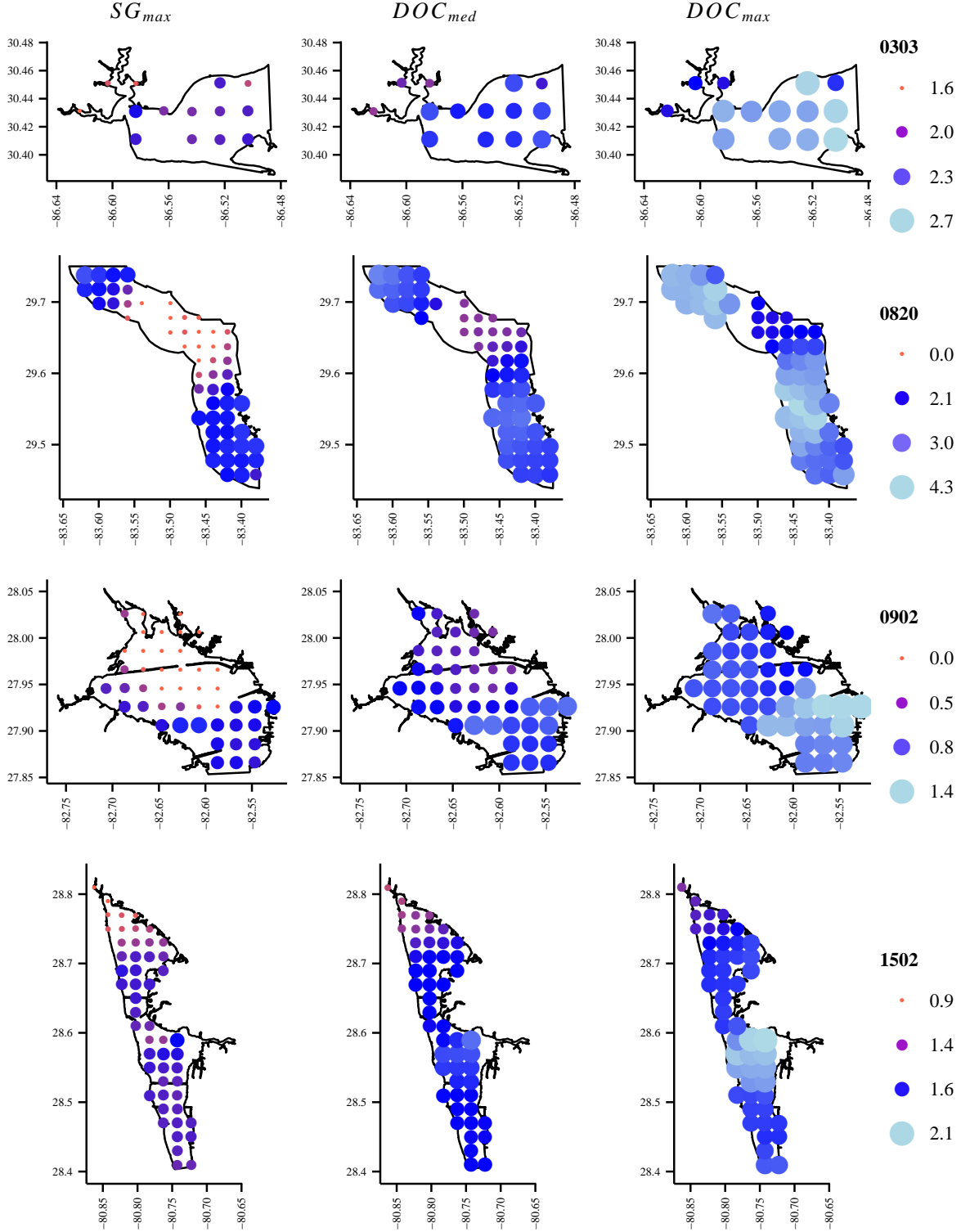
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Fig. 5: Spatially-referenced estimates of seagrass depth limits (m) for four coastal segments of Florida. Estimates include depth of maximum seagrass growth (SG_{max}), median depth of colonization (DOC_{med}), and maximum depth of colonization (DOC_{max}). 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.

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