

¹ 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 anthropogenic 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 (Justic 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 ecosystem 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

25 functional role in altering aquatic habitat often through different feedback mechanisms with other
26 ecosystem components. For example, seagrass beds create habitat for juvenile fish and crabs by
27 reducing wave action and stabilizing sediment (Williams and Heck 2001, Hughes et al. 2009).
28 Seagrasses also respond to changes in water clarity through direct physiological linkages with
29 light availability. In short, increased nutrient loading contributes to reductions in water clarity
30 through increased algal concentrations, inhibiting the growth of seagrass through light limitation
31 (Duarte 1995). Empirical relationships between nutrient loading, water clarity, light requirements,
32 and the maximum depth of seagrass colonization have been identified (Duarte 1991, Kenworthy
33 and Fonseca 1996, Choice et al. 2014), such that quantitative standards have been developed to
34 maintain light regimes sufficient for seagrass growth targets (Steward et al. 2005). Conversely,
35 seagrass depth limits have formed the basis of quantitative criteria for nutrient load targets
36 (Janicki and Wade 1996). Contrasted with numeric standards for nutrients and phytoplankton,
37 seagrass-based criteria may be more practical for developing water quality standards given that
38 seagrasses are integrative of system-wide conditions over time and less variable with changes in
39 nutrient regimes (Duarte 1995).

40 The development of numeric criteria and standards for coastal waters has been a
41 management priority within the United States (USEPA (US Environmental Protection Agency)
42 1998) and internationally (WFD 2000). Numerous agencies and management programs have
43 developed a variety of techniques for estimating seagrass depth limits as a basis for establishing
44 numeric criteria, either as restoration targets or for identifying critical load limits. Such efforts
45 have been useful for site-specific approaches where the analysis needs are driven by a particular
46 management or research context (e.g., Iverson and Bittaker 1986, Hale et al. 2004). However, a
47 lack of standardization among methods has prevented broad-scale comparisons between regions

48 and has even contributed to discrepancies between measures of depth limits based on the chosen
49 technique. For example, seagrass depth limits based on in situ techniques can vary with the
50 sampling device ([Spears et al. 2009](#)). Despite the availability of data, techniques for estimating
51 seagrass depth of colonization using remotely sensed data have not been extensively developed.
52 Such techniques have the potential to facilitate broad-scale comparisons between regions given
53 the spatial coverage and annual availability of many products. For example, recent analyses by
54 [Hagy, In review](#) have shown that standardized techniques from seagrass coverage maps and
55 bathymetric data can be used to compare growth patterns over time among different coastal
56 regions of Florida. Such methods show promise, although further development to improve the
57 spatial resolution of the analysis are needed. Specifically, methods for estimating seagrass depth
58 limits should be reproducible for broad-scale comparisons, while also maintaining flexibility for
59 site-specific estimates depending on management needs.

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

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

72 **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.

78 **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 heterogeneity 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.

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

107 Seagrass coverage maps were combined with bathymetric depth layers to characterize
108 location and depth of growth in each location. Bathymetric depth layers for each location were
109 obtained from the National Oceanic and Atmospheric Administration's (NOAA) National
110 Geophysical Data Center as either Digital Elevation Models (DEMs) or raw sounding data from {acro:DEM}
111 hydroacoustic surveys. Tampa Bay data provided by the Tampa Bay National Estuary Program
112 are described in [Tyler et al. \(2007\)](#). Bathymetic data for the Indian River Lagoon were obtained
113 from the St. John's Water Management District ([Coastal Planning and Engineering 1997](#)). NOAA
114 products were referenced to mean lower low water, whereas Tampa Bay data were referenced to
115 the North American Vertical Datum of 1988 and the Indian River Lagoon data were referenced to

116 mean sea level. Depth layers were combined with seagrass coverage layers using standard union
117 techniques of raster and vector layers in ArcMap 10.1 (Environmental Systems Research Institute
118 2012). To reduce computation time, depth layers were first masked using a 1 km buffer of the
119 seagrass coverage layer. The final layer used for analysis was a point layer with attributes
120 describing location (latitude, longitude, segment), depth (m), and seagrass (present, absent).
121 Additional details describing the data are available in Hagy, In review.

122 2.2 Segment-based estimates of seagrass depth of colonization

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

135 Considerable spatial heterogeneity in the observed seagrass growth patterns suggests that
136 a segment-wide estimate of seagrass DoC may be inadequate for fully characterizing growth
137 patterns, particularly for the examples in the current analysis. Fig. 2 illustrates spatial variation in

138 seagrass distribution for a location in the Big Bend region of Florida. Using methods in Hagy, In
139 [review](#), the estimate for median seagrass DoC for the segment is over- and under-estimated for
140 different areas of the segment. In particular, DoC is greatly over-estimated at the outflow of the
141 Steinhatchee where high concentrations of dissolved organic matter naturally limit seagrass
142 growth. This example suggests that estimates of DoC may be needed at finer spatial scales to
143 provide a more robust determination of restoration targets and nutrient criteria.

144 **2.3 Estimating seagrass depth of colonization using spatial information**

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

154 The spatially-referenced approach for estimating DoC begins by creating a grid of
155 evenly-spaced points within the segment. The same process for estimating DoC is used for each
156 point. Alternatively, a single location of interest can be chosen rather than a grid-based design.
157 Seagrass depth data (i.e., merged bathymetric and seagrass coverage data) that occur within a set
158 radius from the chosen locations are selected for estimating seagrass DoC values. The estimate
159 for each location is quantified from a plot of the proportion of bathymetric soundings that contain

160 seagrass at each depth bin (Fig. 4a). Although the chosen radius for selecting depth points is
161 problem-specific, the minimum radius must sample a sufficient number of points for estimating
162 DoC. In general, an appropriate radius will produce a plot that indicates a decrease in the
163 proportion of points that are occupied by seagrass with increasing depth.

164 A curve is fit to the sampled depth points using non-linear regression to characterize the
165 reduction in seagrass as a function of depth. Specifically, a decreasing logistic growth curve is fit
166 to the plot to create a monotonic and asymptotic function of the sample data. The curve is fit by
167 minimizing the residual sums-of-squares with the Gauss-Newton algorithm (Bates and Chambers
168 1992) and user-supplied starting parameters that are an approximate estimate of the curve
169 characteristics. The model has the following form:

$$Proportion = \frac{\alpha}{1 + e^{(\beta - Depth)/\gamma}} \quad (1) \quad \{eqn:prop\}$$

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

173 Finally, a simple linear curve is fit through the inflection point (β) of the logistic curve to
174 estimate depth of colonization (Fig. 4c). The inflection point is the depth at which seagrass are
175 decreasing at a maximum rate and is used as the slope of the linear curve. Three measures
176 describing seagrass growth characteristics are obtained. The maximum depth of seagrass
177 colonization, DOC_{max} , is the x-axis intercept of the linear curve. The depth of maximum
178 seagrass occupancy, SG_{max} is the location where the linear curve intercepts the asymptote of the
179 logistic growth curve. The median depth of seagrass colonization, DOC_{med} , is the depth halfway

180 between SG_{max} and DOC_{max} . DOC_{med} was typically but not always the inflection point of the
181 logistic growth curve. Functionally, each measure has specific ecological significance. The
182 median and maximum depth estimates describe the growth limitations of seagrasses as a function
183 of water clarity, whereas the maximum occupancy depth is considered the depth were most
184 seagrasses were encountered in the sample. Median and maximum depth estimates differ in that
185 the former describes the median depth of the deep water edge, whereas the latter describes a
186 nominal characterization of maximum depth independent of outliers.

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

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

208 **2.4 Comparison with segment-based approach and sensitivity analysis**

209 Spatially-referenced estimates for seagrass DoC were obtained for each of the four
210 segments described above. Segment-wide estimates obtained using methods in Hagy, In review
211 were used as a basis of comparison such that departures from these values were evidence of
212 spatial heterogeneity in seagrass growth patterns within each segment. A sampling grid of
213 locations for estimating each of the three depth values in Fig. 4 was created for each segment. The
214 grid is masked by the segment boundaries to remove locations that did not occur on the water,
215 whereas seagrass depth points used to estimate DoC extended beyond the segment boundaries.
216 Initial spacing between sample points was chosen arbitrarily as 0.02 decimal degrees, which is
217 approximately 2 km at 30 degrees N latitude. Similarly, the sampling radii around each sampling
218 location in the grid was chosen as 0.06 decimal degrees, or approximately 6 km.

219 Evaluations of seagrass depth estimates within segments will differ depending on the grid
220 spacing and sampling radius for each location. In practice, grid spacing and radii will be
221 problem-based and not chosen arbitrarily as for the current example. The ability to characterize
222 heterogeneity in seagrass growth patterns using the grid-based approach can be informed by
223 evaluating the level of confidence associated with DoC estimates. Confidence intervals for
224 non-linear regression can be estimated using a Monte Carlo simulation approach that

225 simultaneously considers the variance and covariance between the model parameters and the
226 input variables (Hilborn and Mangel 1997). For simplicity, we assume that the observation
227 uncertainty associated with the depth measurements is zero. A 95% confidence interval for a
228 vector of depth values was constructed by repeated sampling of a multivariate normal distribution
229 followed by prediction of the proportion of points occupied by seagrass as in eq. (1). The
230 sampling distribution assumes:

$$x \sim N(\mu, \Sigma) \quad (2)$$

231 where x is a predictor variable used in eq. (1) that follows a multivariate normal distribution with
232 mean μ , and variance-covariance matrix Σ . The mean values are set at the depth value for a given
233 observation and the predicted model parameters (i.e., α , β , and γ) for the logistic curve, and Σ is
234 the variance-covariance matrix of the model parameters and depth. A large number of samples
235 ($n = 10000$) were drawn from the distribution for each depth value to characterize the
236 uncertainty. The 2.5th and 97.5th quantile values of the sample were considered bounds on the
237 95% confidence interval for each fitted value.

238 The uncertainty associated with the DoC estimates were based on the upper and lower
239 bounds for the fitted logistic curve. Specifically, a linear curve was fit through the upper and
240 lower logistic curves to estimate SG_{max} , DOC_{med} , and DOC_{maxd} . These values were compared
241 with the initial estimates from the linear curve that was fit through the predicted logistic curve
242 (i.e., Fig. 4c). Although this approach provides an example

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

²⁴⁵ **3 Results**

²⁴⁶ Describe spatial heterogeneity within segments reasons why

²⁴⁷ Acknowledge that comparisons with segment wide estimate are specific to grid spacing

²⁴⁸ and radii that were used, thus the comparison is only useful for illustrating the presence of

²⁴⁹ heterogeneity within segments, as well as variation between segments. Absolute values will vary

²⁵⁰ with different spacing and radii.

²⁵¹ Fig. 5

²⁵² Table 2

²⁵³ **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, update 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 | 1.93 | 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 |

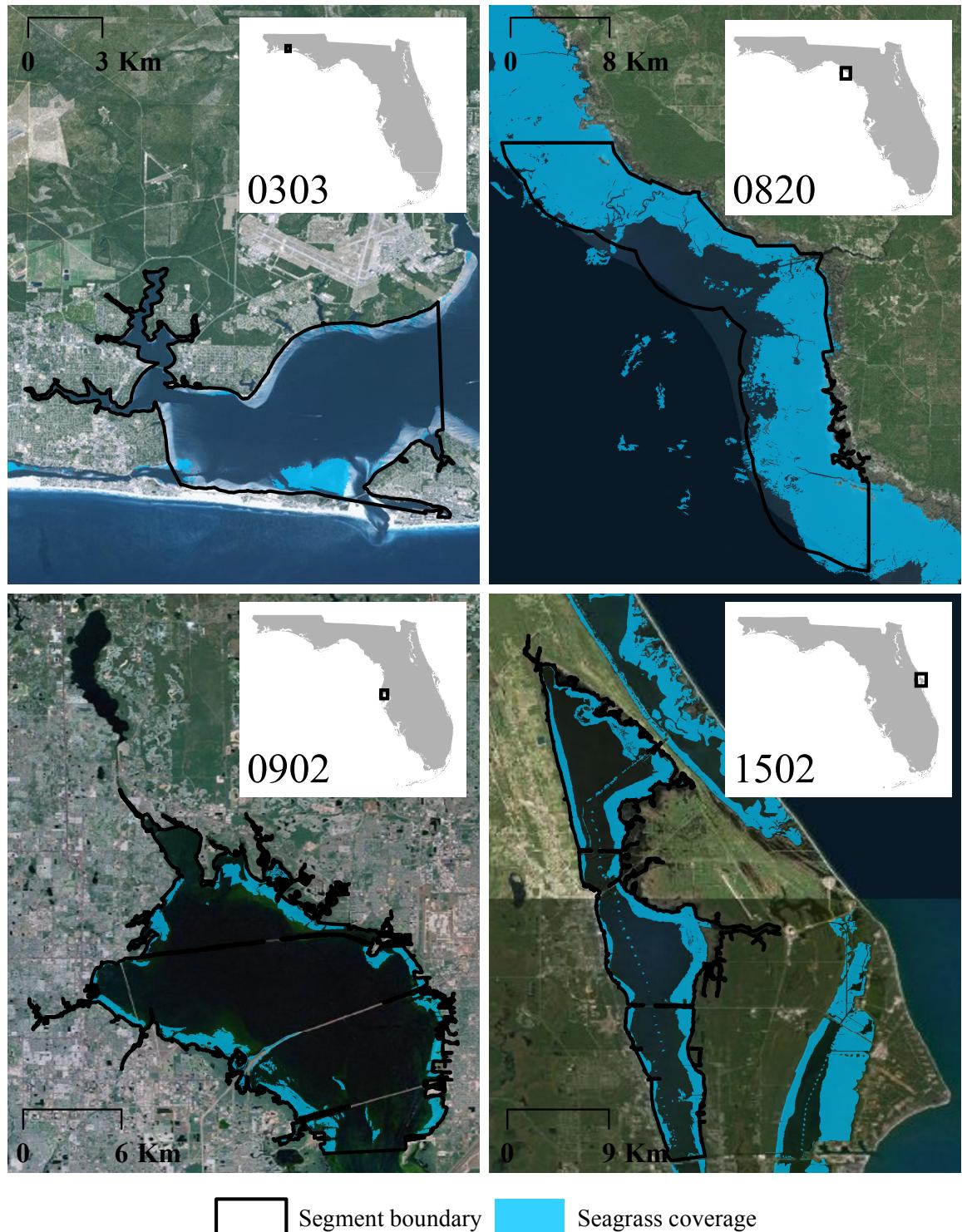


Fig. 1: Locations and seagrass coverage of estuary segments used to evaluate depth of colonization estimates. Seagrass coverage layers are from 2007 (Choctowatchee Bay, 0303), 2006 (Big Bend, 0820), 2010 (Old Tampa Bay, 0902), and 2009 (Indian River Lagoon, 1502).

{fig:seg_a}

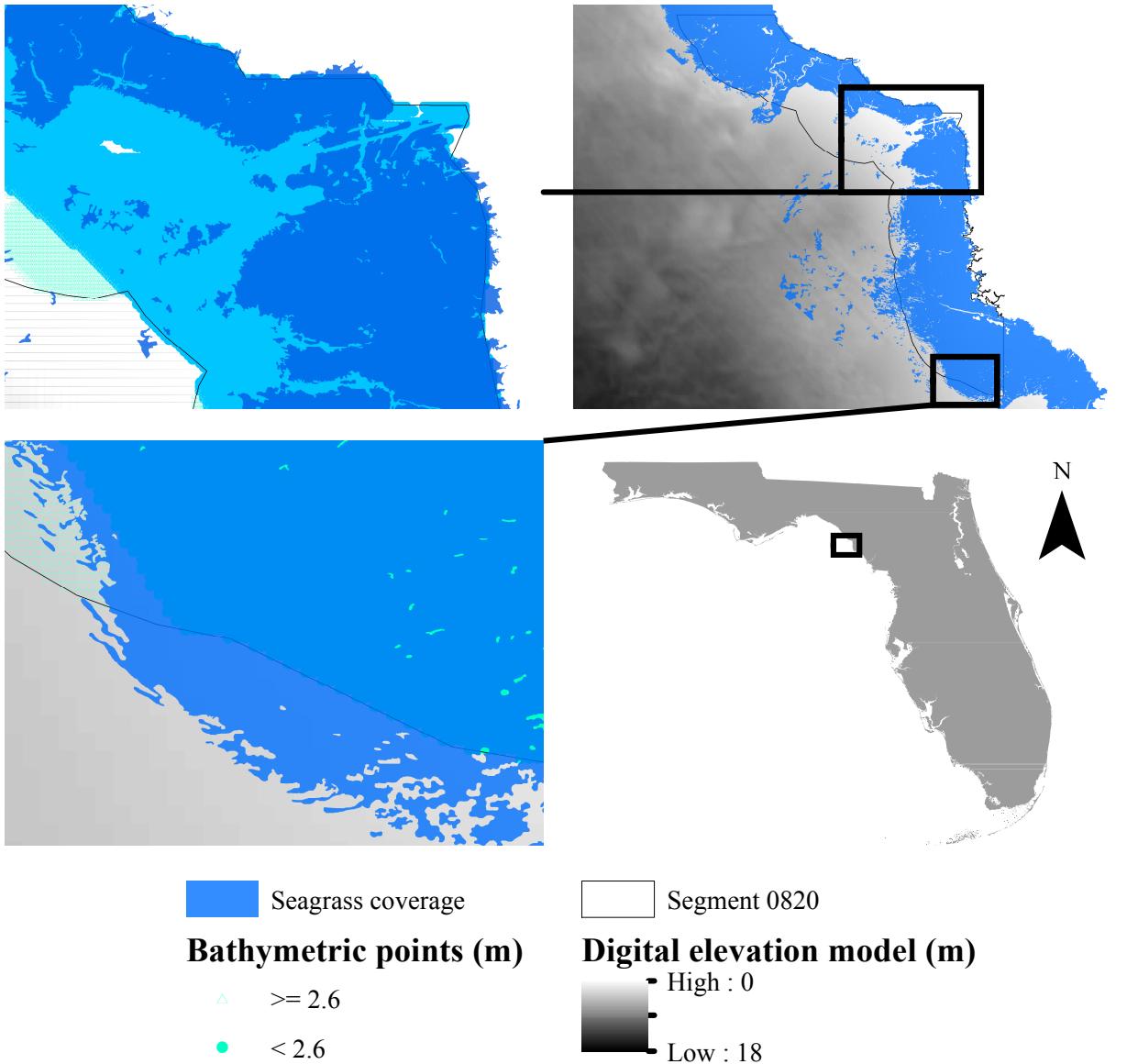
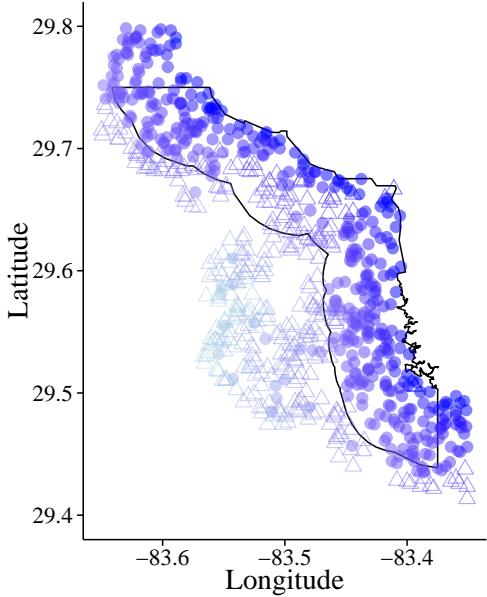


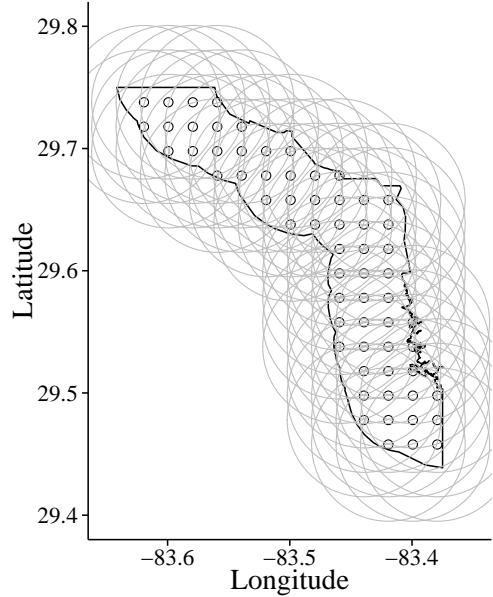
Fig. 2: Example of over- and under-estimates for seagrass depth of colonization for segment 820 in the Big Bend region, Florida. Layers include a seagrass coverage layer, bathymetric depth points, bathymetric digital elevation model, and spatial extents for the segment and Florida. The top-left figure 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

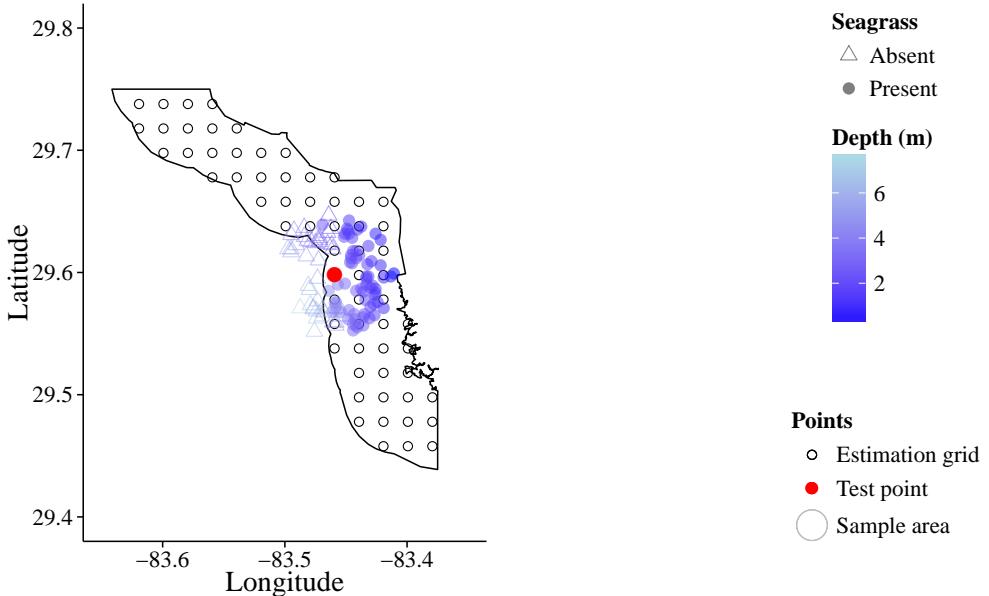
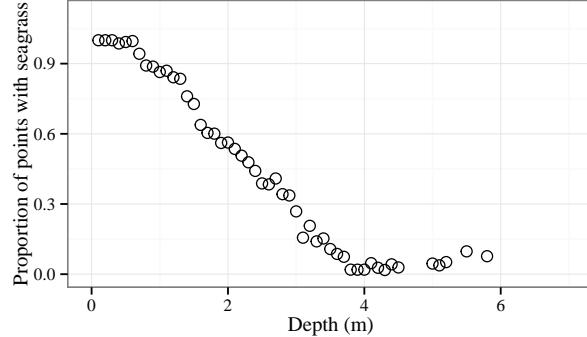


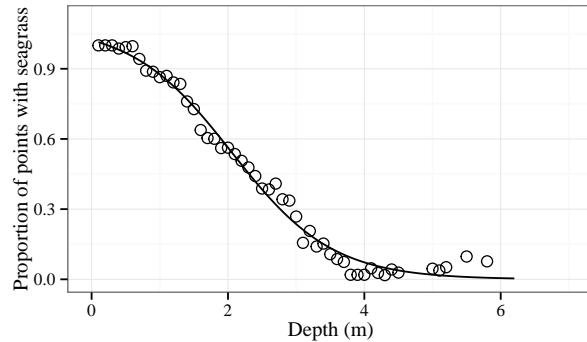
Fig. 3: Examples of data and grid locations for estimating seagrass depth of colonization for a region of the Big Bend, Florida. Fig. 3a shows the seagrass depth points that are used for sampling, Fig. 3b shows a grid of locations and sampling radii for estimating seagrass DoC, and Fig. 3c shows an example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

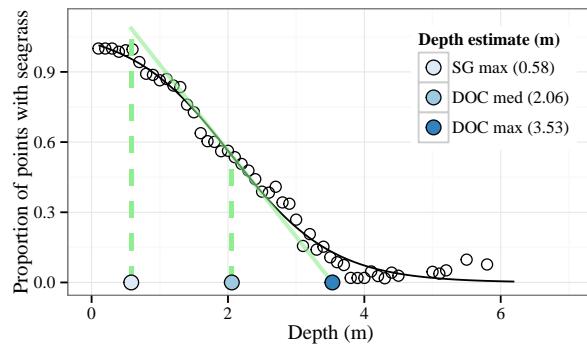


Fig. 4: Methods for estimating seagrass depth of colonization using sampled seagrass depth points around a single location. Fig. 4a is the proportion of points with seagrass by depth using depth points within the buffer of the test point in Fig. 3. Fig. 4b adds a decreasing logistic growth curve fit 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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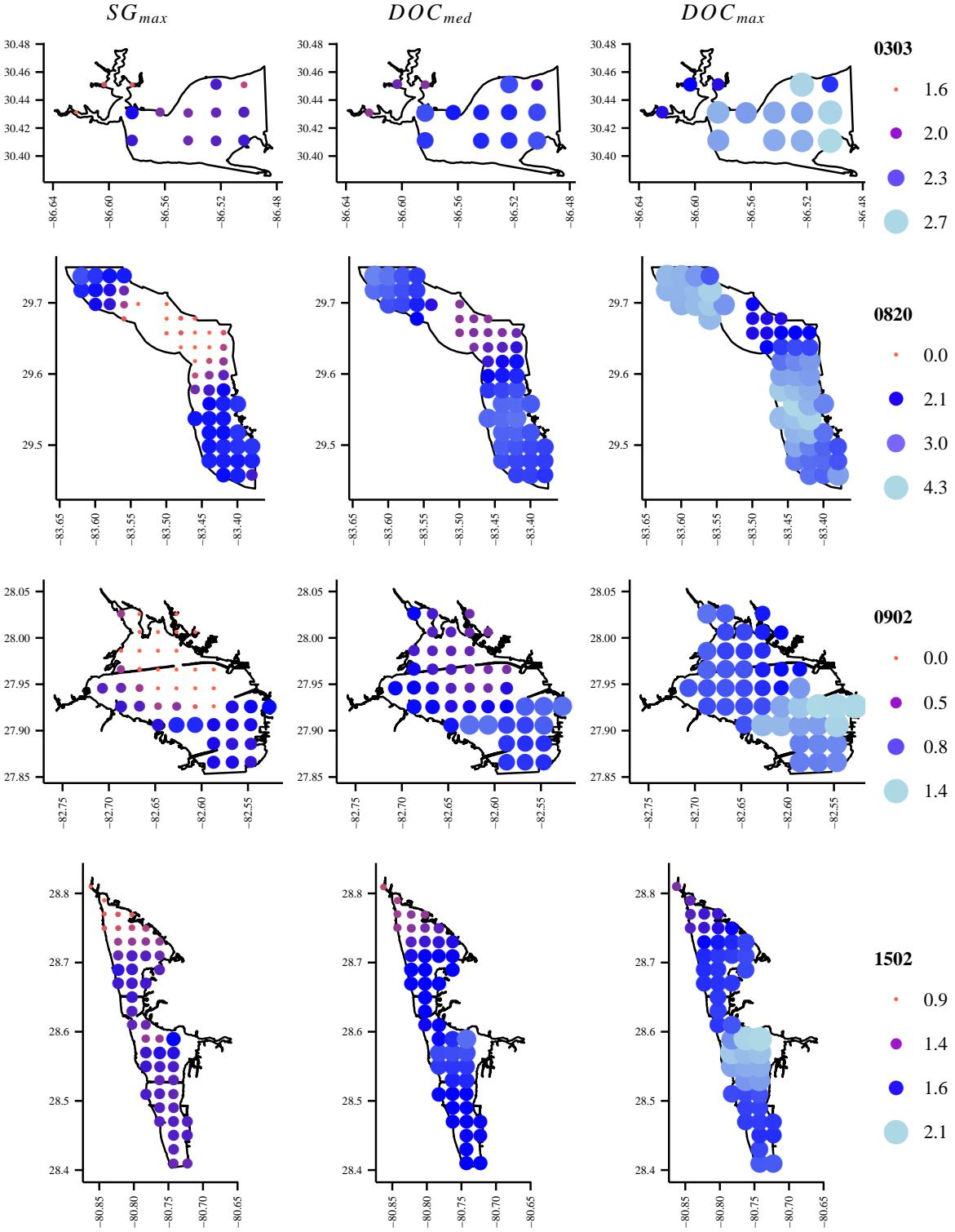


Fig. 5: Spatially-referenced estimates of seagrass depth limits (m) for four coastal segments of Florida. Estimates include depth of maximum seagrass growth (SG_{max}), median depth of colonization (DOC_{med}), and maximum depth of colonization (DOC_{max}). Estimates are assigned to grid locations for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