

**1 A reproducible and empirical approach for spatially-referenced  
2 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 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

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

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

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

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

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

## 73 **2 Methods**

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

75 colonization (DoC) relied extensively on data and partially on methods described in [Hagy, In](#)

76 [review](#). The following is a summary of locations and data sources, methods and rationale for

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

78 including relationships with water clarity.

### 79 **2.1 Locations and data sources**

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

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

82 River Lagoon (east coast) ([Table 1](#) and [Fig. 1](#)). These locations represent different geographic

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

84 that likely contributed to heterogeneity in seagrass growth patterns. For example, the Big Bend

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

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

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

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

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

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

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

92 0820 (Big Bend region), 0902 (Tampa Bay), and 1502 (Indian River Lagoon), where the first two

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

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

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

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

## 123 2.2 Segment-based estimates of seagrass depth of colonization

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

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

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

## 145 **2.3 Estimating seagrass depth of colonization using spatial information**

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

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

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

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

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

171 where the proportion of points occupied by seagrass at each depth is defined by a logistic curve  
172 with an asymptote  $\alpha$ , a midpoint inflection  $\beta$ , and a scale parameter  $\gamma$ . Starting values  $\alpha$ ,  $\beta$ , and  $\gamma$   
173 were estimated empirically from the observed data.

174 Finally, a simple linear curve is fit through the inflection point ( $\beta$ ) of the logistic curve to  
175 estimate depth of colonization (Fig. 4c). The inflection point is the depth at which seagrass are  
176 decreasing at a maximum rate and is used as the slope of the linear curve. Three measures  
177 describing seagrass growth characteristics are obtained. The maximum depth of seagrass  
178 colonization,  $DOC_{max}$ , is the x-axis intercept of the linear curve. The minimum depth of seagrass  
179 growth,  $DOC_{min}$  is the location where the linear curve intercepts the asymptote of the logistic  
180 growth curve. This depth can be considered the start of the decline in seagrass coverage with

181 increasing depth. The median depth of seagrass colonization,  $DOC_{med}$ , is the depth halfway  
182 between  $DOC_{min}$  and  $DOC_{max}$ .  $DOC_{med}$  was typically but not always the inflection point of the  
183 logistic growth curve. Functionally, each measure has specific ecological significance. The  
184 median and maximum depth estimates describe the growth limitations of seagrasses as a function  
185 of water clarity, whereas minimum depth of growth was often where the highest percentage of  
186 seagrass coverage was observed in the sample. Median and maximum depth estimates differ in  
187 that the former describes the median depth of the deep water edge, whereas the latter describes a  
188 nominal characterization of maximum depth independent of outliers.

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

202 Finally, the estimate for  $DOC_{min}$  is set to zero depth if the linear curve through the inflection  
203 point intercepts the asymptote at x-axis values less than zero. The estimate for  $DOC_{med}$  is also

204 shifted to the depth value halfway between  $DOC_{min}$  and  $DOC_{max}$ .

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

## 210 **2.4 Comparison with segment-based approach and sensitivity analysis**

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

224 The ability to characterize heterogeneity in seagrass growth patterns using the grid-based  
225 approach can be informed by evaluating the level of confidence associated with DoC estimates.

226 Confidence intervals for non-linear regression can be estimated using a Monte Carlo simulation  
227 approach that considers the variance and covariance between the model parameters and the depth  
228 measurements ([Hilborn and Mangel 1997](#)). For simplicity, we assume that the observation  
229 uncertainty associated with the depth measurements is zero such that the variability associated  
230 with parameter estimates is considered the primary source of uncertainty. A 95% confidence  
231 interval for each DoC estimates was constructed by repeated sampling of a multivariate normal  
232 distribution followed by prediction of the proportion of points occupied by seagrass as in eq. (1).  
233 The sampling distribution assumes:

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

234 where  $x$  is a predictor variable used in eq. (1) that follows a multivariate normal distribution with  
235 mean  $\mu$ , and variance-covariance matrix  $\Sigma$ . The mean values are set at the depth value  
236 corresponding to the inflection point on the logistic curve and the predicted model parameters  
237 (i.e.,  $\alpha$ ,  $\beta$ , and  $\gamma$ ), whereas  $\Sigma$  is the variance-covariance matrix of the model parameters and  
238 depth, with the latter being zero. A large number of samples ( $n = 10000$ ) were drawn from the  
239 distribution to characterize the uncertainty. The 2.5<sup>th</sup> and 97.5<sup>th</sup> quantile values of the sample  
240 were considered bounds on the 95% confidence interval.

241 The uncertainty associated with the DoC estimates were based on the upper and lower  
242 limits of the estimated inflection point on the logistic growth curve. This approach was used  
243 because uncertainty in the inflection point is directly related to uncertainty in each of the DoC  
244 estimates that are based on the linear curve fit through the inflection point. Specifically, linear  
245 curves were fit through the upper and lower estimates of the inflection point to identify upper and  
246 lower limits for the estimates of  $DOC_{min}$ ,  $DOC_{med}$ , and  $DOC_{max}$ . These values were compared

247 with the initial estimates from the linear curve that was fit through the predicted logistic curve  
248 (i.e., Fig. 4c). This approach provided an indication of uncertainty for individual estimates for a  
249 set radius. Uncertainty estimates were obtained for each DoC estimate for the grids in each  
250 segment.

## 251 **2.5 Developing a spatially coherent relationship of water clarity with depth 252 of colonization**

253 Potentially useful information describing seagrass light requirements can be obtained  
254 from the maximum depth estimates by evaluating spatial relationships with water clarity. In  
255 particular, increased resolution of seagrass depth estimates compared with multiple measures of  
256 water clarity can potentially improve the ability to empirically describe light requirements leading  
257 to the development of numeric criteria. Secchi measurements provide a precise estimate of water  
258 clarity and have been obtained at numerous locations documented in the Florida Department of  
259 Environmental Protection's Impaired Waters Rule (IWR) database. All available secchi {acro:IWR}  
260 data for each of the four segments were obtained from the IWR database, update number 40. Prior  
261 to analysis, all secchi data were screened to exclude observations that were flagged indicating that  
262 the value was lower than the maximum depth of the observation point. Secchi data were also  
263 compared with bathymetric data to verify unflagged values were not missed by initial screening.

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

$$I_z = I_O \cdot \exp(-K_d \cdot Z) \quad (3) \quad \{eqn:lambert\}$$

267 such that the irradiance of incident light at depth  $Z$  ( $I_Z$ ) can be estimated from the irradiance at  
 268 the surface ( $I_O$ ) and a light extinction coefficient ( $K_d$ ). Minimum seagrass light requirements  
 269 have also been estimated numerous times. For example, [Duarte \(1991\)](#) indicate that minimum  
 270 light requirements for seagrass are on average 11% of surface irradiance. Others have shown that  
 271 light requirements are species dependent and variable by latitude with estimates ranging from  
 272 less than 5% to greater than 30% ([Dennison et al. 1993](#)). Estimated light requirements (e.g., 20%)  
 273 can be used with eq. (3) to describe  $DOC_{max}$ :

$$0.20 = \exp(-K_d \cdot DOC_{max}) \quad (4)$$

274 A conversion factor is often used to estimate the light extinction coefficient from secchi depth  $Z_d$ ,  
 275 such that such that  $c = K_d \cdot Z_d$ , where  $c$  has been estimated as 1.7 ([Poole and Atkins 1929](#), [Idso and Gilbert 1974](#)). Thus,  $K_d$  can be replaced with the conversion factor and the equation is  
 276 rearranged to describe  $DOC_{max}$  as a function of secchi depth  $Z_d$ :

$$DOC_{max} = \frac{-\log(0.20)}{1.7} \cdot Z_d \quad (5) \quad \{\text{eqn:sgres}\}$$

278 A regression of seagrass depth estimates against secchi measurements is expected to have a slope  
 279 corresponding to the constant in eq. (5). The geographic coordinates for each secchi measurement  
 280 were used as locations for estimating  $DOC_{max}$  in each segment. These estimates were compared  
 281 with the secchi estimates using linear regression forced through the origin. However, the  
 282 relationship is expected to vary depending on the specific radius around each sample point for  
 283 estimating  $DOC_{max}$ . An appropriate radius was chosen that minimized the difference between

284 the empirically estimated slope and that in eq. (5). Scatter in the regression through these points  
285 can be considered biologically meaningful, such that points below the curve are locations where  
286 seagrasses are observed at maximum depth with less irradiance than expected given eq. (5),  
287 whereas points above the curve are those where seagrasses are growing deeper than expected. The  
288 estimated light requirements of each point can be plotted using the cartesian coordinates to  
289 evaluate spatial variation in seagrass growth as a function of light-limitation.

### 290 **3 Results**

291 Describe spatial heterogeneity within segments reasons why  
292 Describe why estimates were unavailable in particular areas of each segment  
293 Acknowledge that comparisons with segment wide estimate are specific to grid spacing  
294 and radii that were used, thus the comparison is only useful for illustrating the presence of  
295 heterogeneity within segments, as well as variation between segments. Absolute values will vary  
296 with different spacing and radii.

297 Fig. 5

298 Table 2

299 Fig. 6

300 Fig. 7

### 301 **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 Rule, update number 40.<sup>tab:seg\_summ</sup>

	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.<sup>tab:est\_summ</sup>

Segment	Whole segment	Mean	St. Dev.	Min	Max
<b>0303</b>					
$DOC_{min}$	1.92	1.65	0.54	0.52	2.30
$DOC_{med}$	2.26	2.01	0.34	1.52	2.46
$DOC_{max}$	2.60	2.36	0.35	1.90	2.85
<b>0820</b>					
$DOC_{min}$	1.50	1.71	0.96	0.06	3.23
$DOC_{med}$	2.92	2.07	0.94	0.52	3.46
$DOC_{max}$	4.34	2.42	0.97	0.69	3.97
<b>0902</b>					
$DOC_{min}$	0.52	0.45	0.34	0.00	1.03
$DOC_{med}$	0.79	0.82	0.31	0.29	1.59
$DOC_{max}$	1.07	1.18	0.38	0.59	2.15
<b>1502</b>					
$DOC_{min}$	1.25	1.33	0.24	0.90	2.02
$DOC_{med}$	1.51	1.50	0.23	0.98	2.08
$DOC_{max}$	1.77	1.66	0.23	1.06	2.16

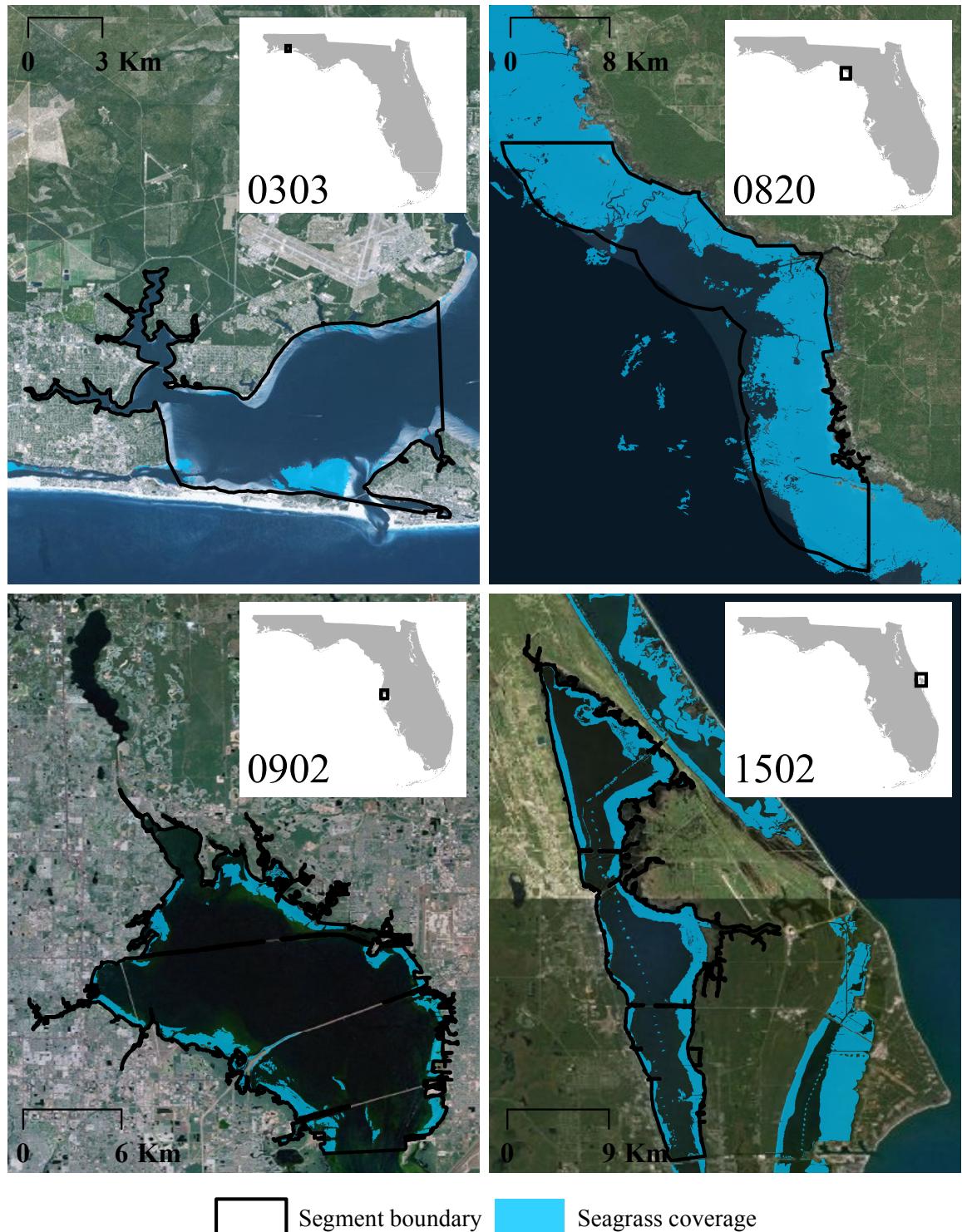


Fig. 1: Locations and seagrass coverage of estuary segments used to evaluate depth of colonization estimates. Seagrass coverage layers are from 2007 (Choctowatchee Bay, 0303), 2006 (Big Bend, 0820), 2010 (Old Tampa Bay, 0902), and 2009 (Indian River Lagoon, 1502).

{fig:seg\_a}

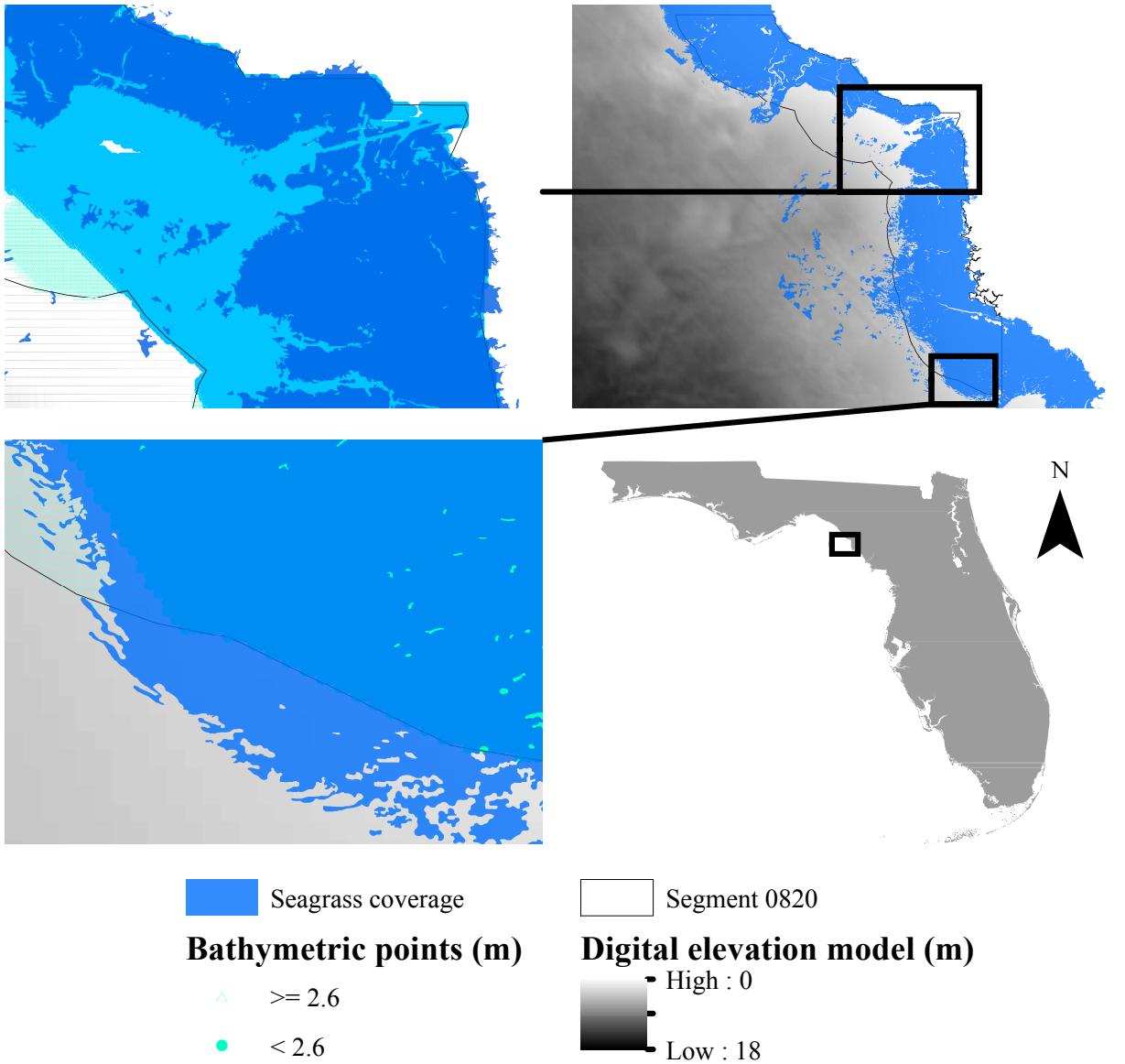


Fig. 2: Example of over- and under-estimates for seagrass depth of colonization for segment 820 in the Big Bend region, Florida. Layers include a seagrass coverage layer, bathymetric depth points, bathymetric digital elevation model, and spatial extents for the segment and Florida. The top-left figure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

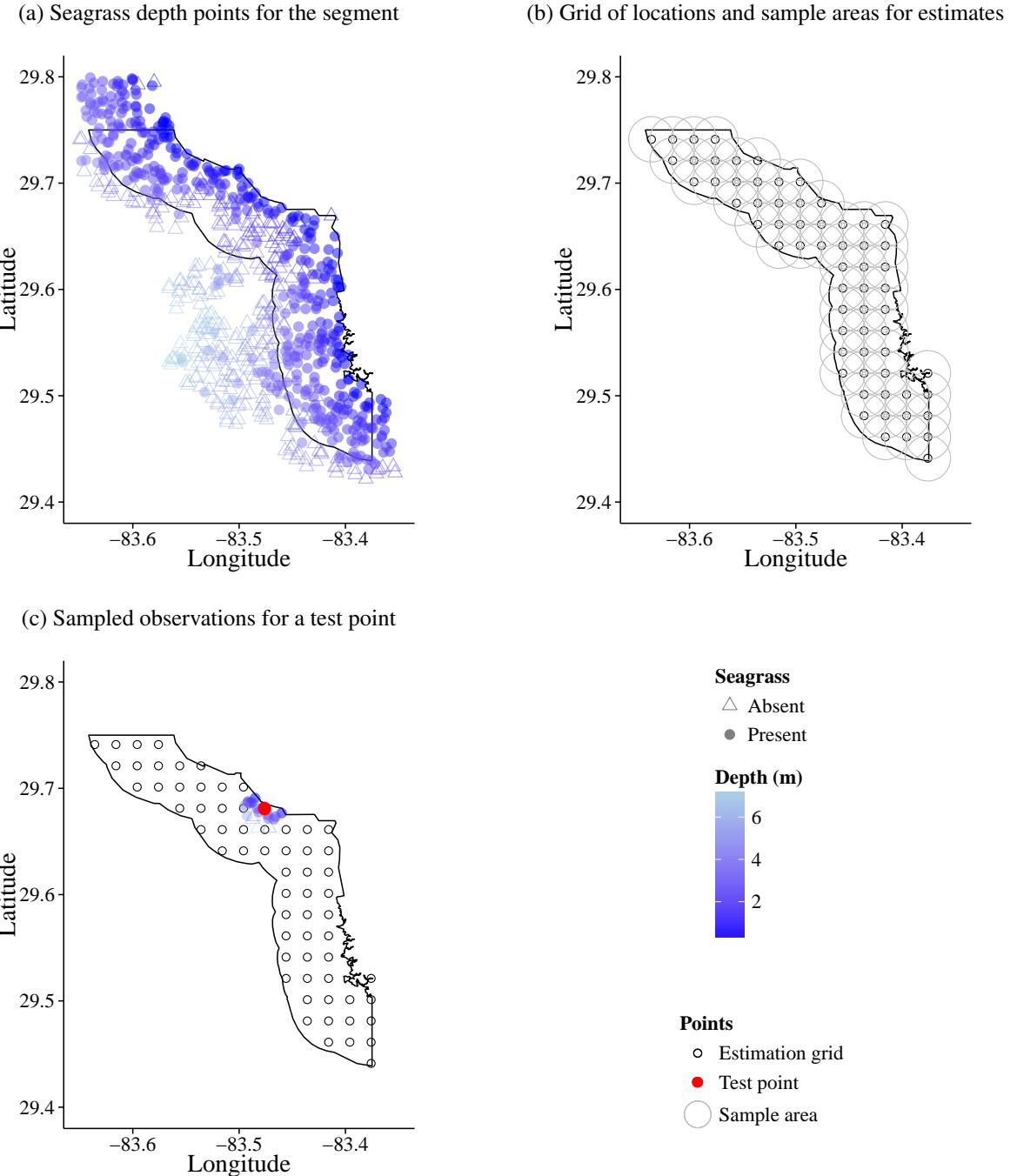


Fig. 3: Examples of data and grid locations for estimating seagrass depth of colonization for a region of the Big Bend, Florida. Fig. 3a shows the seagrass depth points that are used for sampling, Fig. 3b shows a grid of locations and sampling radii for estimating seagrass DoC, and Fig. 3c shows an example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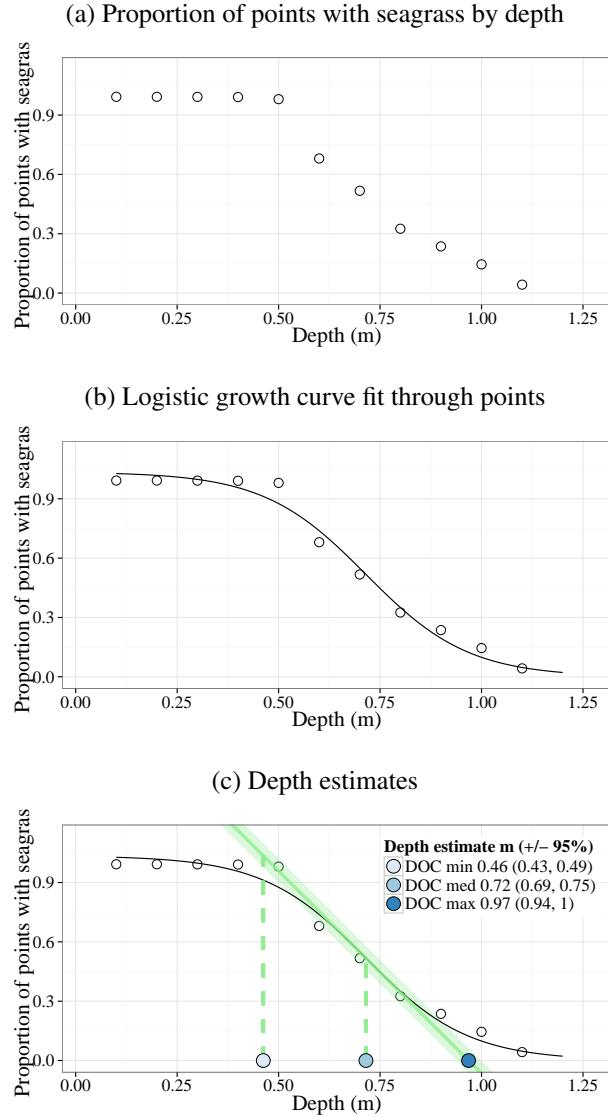


Fig. 4: Methods for estimating seagrass depth of colonization using sampled seagrass depth points around a single location. Fig. 4a is the proportion of points with seagrass by depth using depth points within the buffer of the test point in Fig. 3. Fig. 4b adds a decreasing logistic growth curve fit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

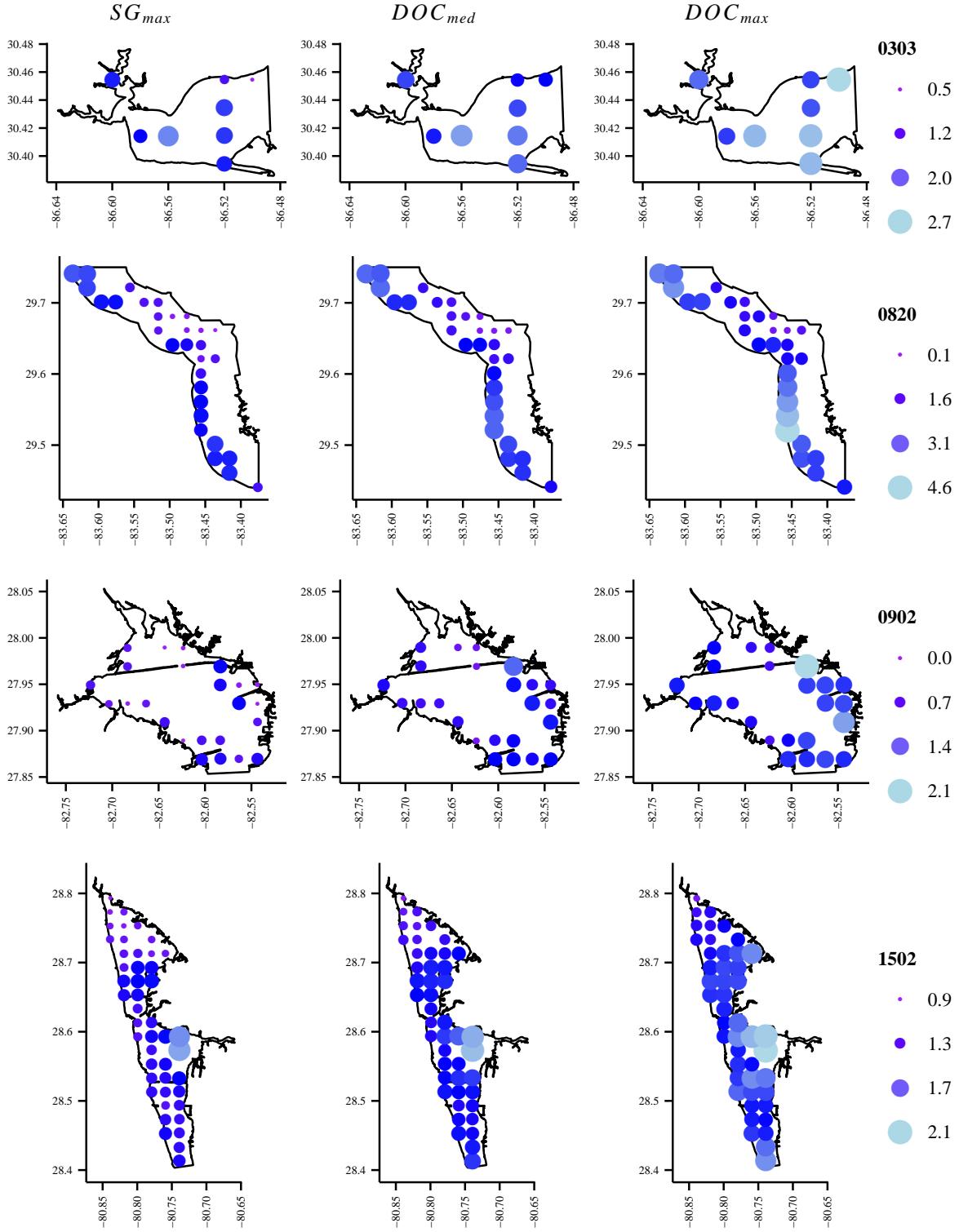


Fig. 5: Spatially-referenced estimates of seagrass depth limits (m) for four coastal segments of Florida. Estimates include minimum ( $DOC_{min}$ ), median ( $DOC_{med}$ ), and maximum depth of colonization ( $DOC_{max}$ ). Estimates are assigned to grid locations for each segment, where grid spacing 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}

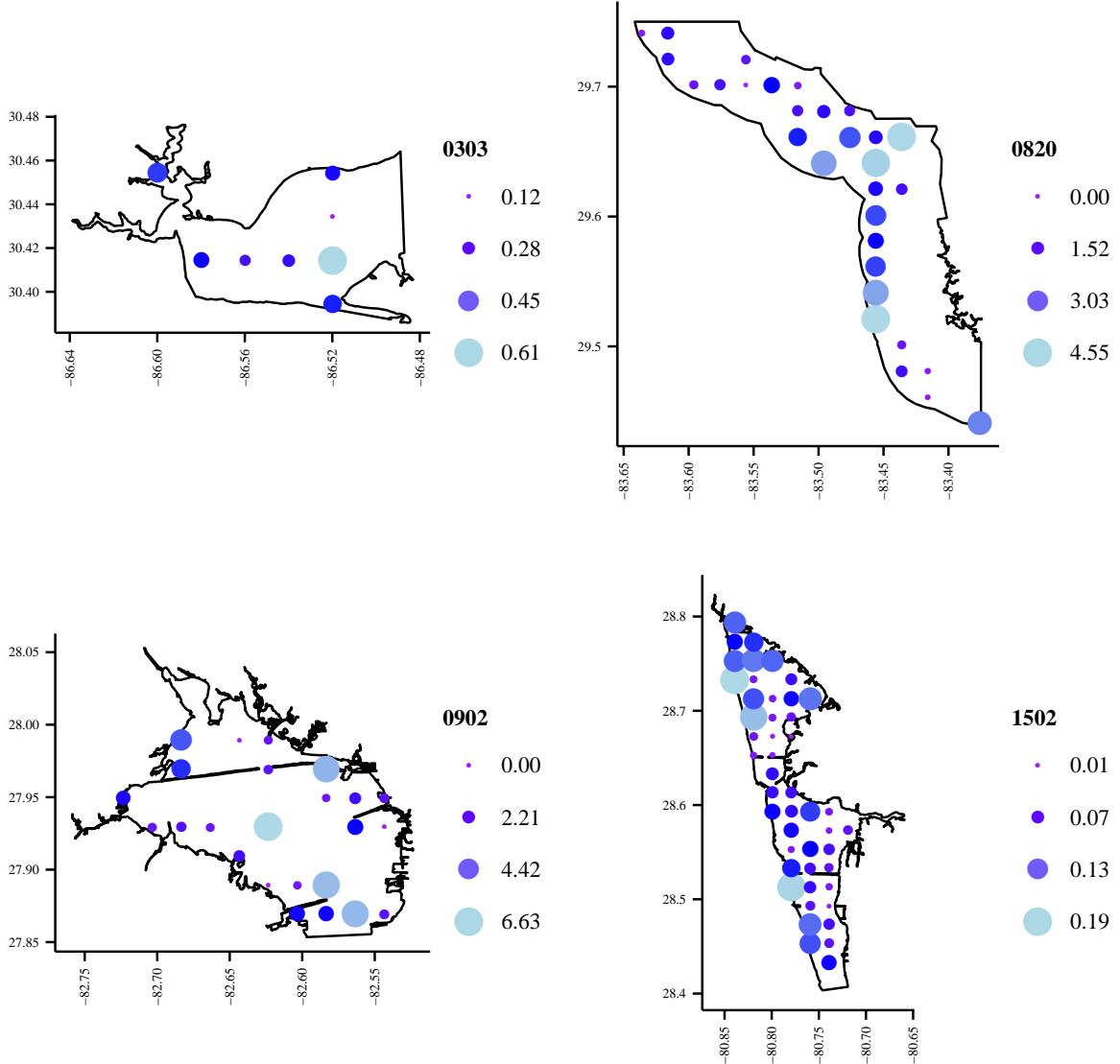


Fig. 6: Size of confidence intervals (m) for depth of colonization estimates in Fig. 5. Points are colored and sized based on the difference between the upper and lower bounds of a 95% confidence interval for all three DoC estimates ( $DOC_{min}$ ,  $DOC_{med}$ ,  $DOC_{max}$ ). Bounds were obtained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

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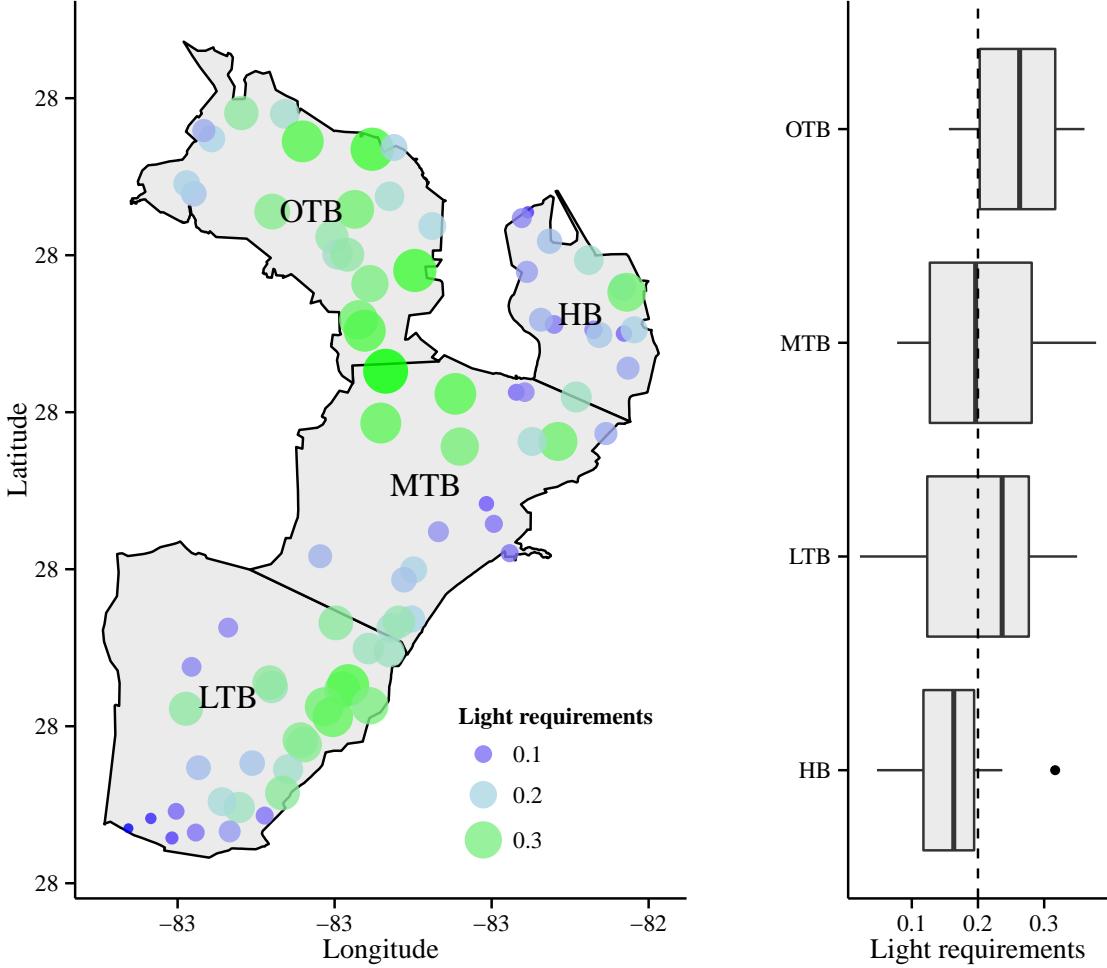


Fig. 7: Estimated light requirements of seagrass for multiple locations in Tampa Bay, Florida. Map locations are georeferenced observations of water clarity from secchi measurements in the Florida Impaired Waters Rule database, update 40. Data are also summarized by bay segment as boxplots where the dimensions are the 25<sup>th</sup> percentile, median, and 75<sup>th</sup> percentile. Whiskers extend beyond the boxes as 1.5 multiplied by the interquartile range. Light requirements are based on daily average secchi values for each location using all observations for Tampa Bay, estimated maximum depth of colonization using a radius of 0.7 decimal degrees for each secchi location to sample seagrass depth points for 2010 coverage data, and empirical relationships described by eq. (3). HB: Hillsborough Bay, LTB: Lower Tampa Bay, MTB: Middle Tampa Bay, OTB: Old Tampa Bay.

{fig:light}