DEVELOPMENT OF WATER QUALITY TARGETS FOR CHARLOTTE HARBOR, FLORIDA USING SEAGRASS LIGHT REQUIREMENTS

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ABSTRACT: *Owing to the catastrophic loss of seagrasses after the 1950s, resource managers in several southern Florida estuaries established water clarity targets to restore seagrass coverage to historical conditions or maintain existing coverage. Recently, analyses of water quality data suggest declining water clarity in some areas of Charlotte Harbor, which may lead to the dramatic impacts to seagrass ecosystems similar to those in other estuaries in Florida. Therefore, resource management strategies for Charlotte Harbor should consider minimum water clarity standards to conserve seagrass resources for the future. This effort provides an optical model to set water quality targets for color, turbidity and chlorophyll* a *that maintain percent-light-at-depth requirements to achieve the maximum seagrass depth distribution presently observed in seagrass transect monitoring. Analysis of recently-collected water quality data show that in all regions of the harbor, dry season water quality in general met the percent-light-at-depth goals proposed in this effort but less than half the data met the goals during the wet season. The methods proposed here can be refined to better incorporate seasonal and spatial changes in water clarity variables but are an important first step in establishing resource-based water quality targets for the Charlotte Harbor region.*

Key Words: Charlotte Harbor, seagrass, water clarity, estuaries, optical model, chlorophyll, TSS, turbidity, color, light attenuation

IN southwest Florida, substantial research and restoration efforts have focused on seagrass meadows as an environmental indicator for coastal environmental conditions. Charlotte Harbor, FL is contiguous to the northwest with Lemon, Sarasota and Tampa Bays where seagrass management strategies focus on nutrient load and phytoplankton concentration reductions. Charlotte Harbor confronts different issues, and phytoplankton concentrations do not have as large an influence on light attenuation in Charlotte Harbor as dissolved and suspended matter (McPherson and Miller 1987; Dixon and Kirkpatrick 1999). Also, analyses of seagrass coverage data demonstrate that seagrass coverage in Upper Charlotte Harbor is stable since 1988 (Kurz et al., 1999; Corbett et al., 2005; Tomasko et al., 2005; Corbett, 2006). Seagrass management strategies in the Charlotte Harbor region have not focused on nutrient load reductions, and currently, resource managers have not established restoration goals for seagrass coverage.

In Tampa Bay, where historical losses have been linked to both direct and indirect impacts, resource managers have set goals for restoring seagrass coverage to approximately ninety-five percent of the coverage present in 1950. Reductions in nitrogen loads since 1982 have led to reduced phytoplankton concentrations and increased water clarity, a cascade of effects which has allowed increases in seagrass extent (Johansson, 1991; Johansson and Ries, 1997; Lewis et al., 1998; Johansson and Greening, 1999). Increases in seagrass coverage is also a restoration objective for seagrass managers in Sarasota Bay, where recent increases (1988–1996) may be linked to decreased nitrogen loads to the bay by the City of Sarasota and Manatee and Sarasota counties (Kurz et al., 1999). In both Tampa and Sarasota Bays, water clarity and quantity of light reaching the tops of seagrass blades is related to nitrogen loading and its effects on phytoplankton populations (cited in Tomasko et al., 2005); thus, seagrass restoration strategies in these areas have focused on nitrogen load reductions.

Lemon Bay, a comparatively small estuary that connects Sarasota Bay to the north to the Venice inlet and Charlotte Harbor in the south, is included within the larger Charlotte Harbor estuarine complex. It is very similar to Tampa and Sarasota Bays in that its water clarity is strongly tied to phytoplankton levels and nitrogen loads (Tomasko et al., 2001). Phytoplankton biomass was calculated to contribute 12 to 39% of light attenuation within the water column with a mean percent of 29%, and depth distribution of seagrasses in Lemon Bay is largely a factor of chlorophyll *a* concentrations (Tomasko et al., 2001). Seagrass mapping efforts have not documented trends in seagrass coverage in Lemon Bay since 1988 (Tomasko et al., 2001; Tomasko et al., 2005). Nonetheless, estimated nitrogen loads to the bay have increased an estimated 59% from historical levels and are expected to increase further with future urbanization (Tomasko et al., 2001; Tomasko et al., 2005). Thus, seagrass management strategies within Lemon Bay region also focus on nutrient load reductions.

South of Lemon and Sarasota Bays along the southwest Florida coast lies the Charlotte Harbor estuarine complex, which includes a number of interconnected estuaries. The Charlotte Harbor watershed extends approximately 210 km (130 mi) from its northern headwaters of the Peace River to southern Estero Bay, and three large rivers, the Peace, Myakka and Caloosahatchee Rivers are the major sources of freshwater (Hammett, 1990). Relative to Tampa, Sarasota and Lemon Bays to its northwest, Charlotte Harbor is strongly influenced by the freshwater inflows from its large watershed. One result of this large watershed is that the water clarity of the harbor is greatly influenced by dissolved and suspended matter from the watershed, as opposed to the dominant influence of phytoplankton found in Tampa and Lemon Bays. Using data collected in Charlotte Harbor, McPherson and Miller (1987) found that non-chlorophyll suspended matter (including detritus, cellular material and minerals) accounts for an average of 72% of light attenuation in the water column, color (dissolved organic matter) accounts for 21% and phytoplankton chlorophyll for only 4%. Dixon and Kirkpatrick (1999) found that color, turbidity and chlorophyll accounted for 66%, 31% and 4% of light attenuation. Hence, there are clear differences in the components of water column light attenuation between Charlotte Harbor and Tampa Bay.

Six species of seagrass are found within the Charlotte Harbor region: *Halodule wrightii* (Ascherson), *Thalassia testudinum* (Banks ex König), *Syringodium filiforme* (Kützing), *Halophila englemanni* (Ascherson), *Halophila decipiens*

(Ostenfeld) and *Ruppia maritima* (Linnaeus). Harris and co-workers (1983) documented a 29% harbor-wide decrease in seagrass coverage from 1940s to 1982 and postulated some of this loss resulted from seagrasses receding from deeper depths because of decreasing water clarity resulting from hydrologic changes and increased pollutant loads. From 1982 to 1999, Charlotte Harbor as a whole demonstrated a 6% decrease in seagrass extent, with 77% of that loss located in the Lower Charlotte Harbor region (Corbett et al., 2005). Subsequently, from 1999 to 2003 seagrass areal extent displayed increases in the Lower Charlotte Harbor region, and no significant trend was found in the Upper Charlotte Harbor region since 1982 (Corbett, 2006). However, analyses of water quality data demonstrate significant increases in total suspended solids in the Lower Charlotte Harbor and Upper Charlotte Harbor regions and increasing turbidity and nutrients in the Lower Charlotte Harbor region (Janicki Environmental Inc., 2003). Thus, resource management strategies in this area may need to focus on the long-term maintenance of seagrass coverage. This study presents an optical model which can be used to establish water clarity goals to maintain percent-light-at-depth requirements to achieve seagrass maximum depth distribution by segment within the Charlotte Harbor estuarine complex. The water clarity goals proposed in this effort are meant to maintain the present seagrass coverage and depth distribution into the future.

METHODS—The Florida Fish and Wildlife Conservation Commission-Fisheries Independent Monitoring Program and the Coastal Charlotte Harbor Monitoring Network divide Charlotte Harbor into 12 hydrologic segments for their fisheries and water quality sampling programs (FIG. 1). Using the methodology described below, we developed water quality goals specific for each segment.

Maximum depth of seagrass distribution—We calculated the annual mean maximum depth distribution of seagrass per segment based on the results of 50 fixed-transects monitored throughout Charlotte Harbor and Lemon Bay since 1999 and 5 additional transects in Estero Bay started in 2002. Each transect consists of a fixed line, determined by a compass heading and marked with PVC stakes, extending from the shoreward seagrass edge out to the deep edge of the meadow where seagrass was sparse or no longer existent. Program researchers collect depth measurements, seagrass species abundance (Braun-Blanquet cover scale [Braun-Blanquet, 1965]), blade length, sediment type and epiphyte coverage and type at 50-meter intervals along each transect (or 10-meter intervals for transects shorter than 50 m) from shore to edge of bed (Staugler and Ott, 2001). Depth measurements are adjusted to mean water depth by adjusting the tide level observed in the field to mean water based on the 12 National Oceanographic and Atmospheric Administration (NOAA) tide stations located throughout the study area (Staugler and Ott, 2001). There are several transects for each segment; we used the greatest value of the segment's mean maximum depths by year for 1999–2004 or 2002–2005 as the target depth. There were no comparable transect data for the Tidal Caloosahatchee River segment, so we used a goal of 1 meter based upon vertical scan hydro-acoustic research by Chamberlain (2005).

Percent light at depth—Using published analyses, we estimated percent-light-at-depth targets required to achieve the estimated seagrass maximum depth distribution in each segment. Numerous estimates for percent-light-at-depth requirements of seagrass exist, and depending on the species composition of a bed, these estimates indicate a wide range of surface irradiance requirements reaching the deep edge of grass beds. For instance, Gallegos and Kenworthy (1996) cite a general range of 10–30% for efforts documenting requirements of seagrass in other estuaries and 23–37% in Indian River Lagoon, Florida for *H. wrightii* and *S. filiforme*, specifically. Grasses in Charlotte Harbor require between 15–30% photosynthetically active radiation (PAR) penetrating to depth (Dixon, 2000).

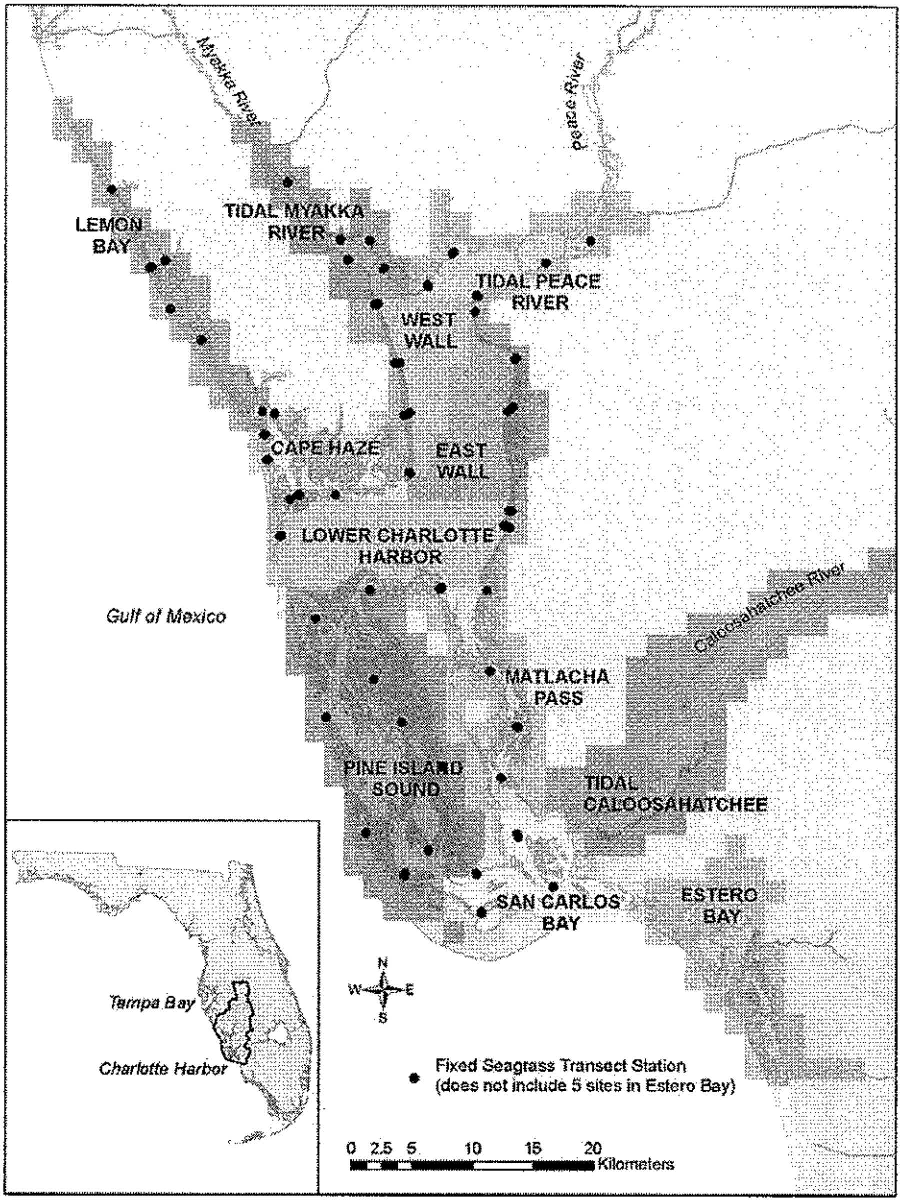

FIG. 1. Charlotte Harbor Segments and Seagrass Transect Monitoring Stations, excluding Estero Bay stations.

Tomasko and Hall (1999) found an average 23% subsurface irradiance reaching all study sites but documented declines in productivity of *T. testudinum* during the study period. Of the species of seagrass in Charlotte Harbor, *T. testudinum* may have the highest light requirements. Greenawalt (2005) determined that *S. filiforme* is found in areas with generally lower percent light at depth than *H. wrightii* and *T. testudinum*, while Chamberlain theorizes that *H. wrightii* extends deeper and is found in areas with lower light conditions than *T. testudinum* (Chamberlain, 2005). We propose a percent-light-at-depth goal of 25% subsurface irradiance, which is on the high end of the estimate in Dixon (2000), an estimate specific to Charlotte Harbor, and higher than the annual average found in Tomasko and Hall (1999).

Light attenuation coefficient—To calculate a water clarity target, we used the Lambert-Beer Law:

$$\%\ \text{light at depth}/100 = e^{-k*z} \tag{1}$$

where the percent light at depth is the estimated minimum amount of subsurface incident light required by seagrasses, *e* is the base of the natural logarithm, k is the light attenuation coefficient (in m-1), and z equals the measured or estimated deep edge depth of seagrass distribution in meters. To use an example of the San Carlos Bay segment in the Lower Charlotte Harbor region (Table 2), inserting a percent-light-at-depth target of 25% PAR and depth of 2.21 meters, we get the following equation:

$$0.25 = e^{-k*2.21} \tag{1a}$$

$$\ln(0.25) = \ln(e^{-k*2.21}) \tag{1b}$$

$$-1.4 = -k*2.21 \tag{1c}$$

$$k = 0.63$$

Partial contributions to light attenuation—Light attenuation in the water column is caused by scattering and absorption of light by water quality constituents (Kirk, 1983). For management purposes, light requirements of grass beds can be translated into concentrations of these constituents that meet the specified light availability target (Gallegos and Kenworthy, 1996). To do this, we adapted an optical model derived by McPherson and Miller (1994: eq. 8) which describes total light attenuation as the sum of three partial light attenuation components: color, chlorophyll *a* and turbidity:

$$K_d = 0.014*C_2 + 0.062*C_3 + 0.049*C_4 + 0.30 \tag{2}$$

Where K_d equals the light extinction coefficient at depth, C_2 is water color in Pt-Co units, C_3 is turbidity in NTU and C_4 is chlorophyll *a* in micrograms per liter. The chlorophyll *a* coefficient was derived from measurements using a fluorometric detector (see McPherson and Miller (1994) for complete discussion).

To determine the maximum concentration of each partial light attenuation component that meets a given rate of light attenuation (calculated from the percent-light-at-depth target), set two components to zero and solve for the third, color in this case:

$$0.63 = 0.014*C_2 + 0.062*(0) + 0.049*(0) + 0.30 \tag{2a}$$

$$0.33 = 0.014*C_2 \tag{2b}$$

$$C_2 = 24\ \text{Pt-Co}$$

Line of constant attenuation—To demonstrate the use of this method in describing water clarity with respect to seagrass depth limits, we compared the constants calculated above to seasonal water quality data collected for the coastal Charlotte Harbor and Lemon Bay regions, with these "targets" overlaid. This produced a line of constant attenuation for variable concentrations of the water quality parameters, given our percent-light-at-depth goal. Water quality data points located above this line identify instances when water clarity did not meet the projected targets.

Monthly water quality data from surface water samples collected between 2002 to 2005 were provided by the Coastal Charlotte Harbor Monitoring Network for 12 segments (Table 1). Additional monthly water quality data were provided by Lee County for the Pine Island Sound, Matlacha Pass, San Carlos Bay, Caloosahatchee River and Estero Bay segments as there was a shorter period of record for these areas using only the Coastal Charlotte Harbor Monitoring Network data. All data were divided into "wet" and "dry" seasons, defined as data collected during the months of July–October and November–June, respectively. Salinity data analyses support this delineation (see Greenawalt et al., 2006).

TABLE 1. Water quality data period of record by region.

Segment	Period of Record
Lemon Bay	11/02–6/05
Cape Haze	11/02–6/05
West Wall	11/02–6/05
East Wall	11/02–6/05
Tidal Peace River	11/02–6/05
Tidal Myakka River	11/02–6/05
Lower Charlotte Harbor	4/02–12/04
Matlacha Pass	3/02–10/04
San Carlos Bay	3/02–10/04
Pine Island Sound	5/03–10/04
Estero Bay	4/03–10/04
Tidal Caloosahatchee River	1/04–12/05

Nomographs—Lastly, for comparison purposes we plotted chlorophyll *a* and turbidity concentration goals for specified depths and color values in terms of optical depth, k-z. In this step, we defined our 25% subsurface irradiance objective as our target optical depth of 1.4 (see *Light Attenuation Coefficient* section above). This allowed us to use any combination of depth (z) and attenuation coefficient (k) that equaled 1.4 (e.g., $k = 0.7$ and $z = 2$ m) to derive multiple lines of constant attenuation.

For the selected optical depths, 0.5, 0.75, 1.0, 1.5, 2.0 and 2.5, we plotted our target chlorophyll *a* and turbidity concentrations, given a range of color values in 10-step increments. This process allows one to determine a combination of the maximum color and chlorophyll *a* or color and turbidity concentrations for a depth of interest that meets our minimum light objective. Similar plots of turbidity and color given a specified range of chlorophyll *a* concentrations or chlorophyll *a* and color given a specified turbidity range could also be developed.

RESULTS—Target seagrass bed depths by segment are shown in Table 2 and range from 0.81 meters in the Tidal Peace segment to 2.21 meters in the San Carlos Bay segment. These goals reflect current maximum depth distributions by segment.

"Target" concentrations for partial light attenuation coefficients for each segment are also shown in Table 2. Maximum turbidity "targets" range from 5 NTU to 23 NTU, while chlorophyll *a* maximums range from 7 μg/L to 29 μg/L.

A comparison of wet and dry season water quality data from the Lower Charlotte Harbor segment suggests how water quality parameters differ by season. Generally, most data points fall within the line of constant attenuation and, in turn, meet or exceed required goals to produce minimum water clarity for each pair of parameters in the dry season, November through June (FIG. 2). In contrast, approximately half of the data collected during the wet season fall outside the line of constant attenuation and would not meet minimum water clarity goals to provide 25% subsurface irradiance at the target maximum seagrass depth distribution for this segment (FIG. 3). Similar results were found for the other 11 segments as well.

Nomographs of chlorophyll *a* and color as well as turbidity and color demonstrate that as color values rise, the concentrations of the other partial constituents must simultaneously decrease to meet our optical depth goal (FIGS. 5 and 6). The graphs also demonstrate that as depths increase from 0.5 to 2.5, the concentrations of all 3 partial constituents must then decrease. It follows then that

TABLE 2. Mean maximum seagrass depth distribution and water clarity constants by region. Stars represent target seagrass depths. Extinction coefficients (K_d) were determined using the 25% subsurface irradiance goal and the target maximum grass bed depth by region. Each partial attenuation component was then determined by setting the other 2 components to zero and using the optical model equation derived by McPherson and Miller (1994).

	Mean Maximum Depth by Year								Maximum Color	Maximum Turbidity	Maximum Chlorophyll
Region	1999	2000	2001	2002	2003	2004	2005	K_d	(Pt-Co)	(NTU)	a (μg/L)
Lemon Bay	1.44	1.57	1.51	1.38	1.85*	1.56		0.75	32	7	9
Cape Haze	1.48	1.67	1.63	1.78	1.6	1.83*		0.76	33	7	9
Lower Charlotte Harbor	1.51*	1.41	1.07	1.13	1.3	1.3		0.92	44	10	13
West Wall	1.13	1.41*	1.2	1.36	0.92	1.41*		0.98	49	11	14
East Wall	1.08	1.21	0.97	1.26	1.3*	1.12		1.07	55	12	16
Tidal Myakka	0.88*	0.85	0.55	0.83	0.62	0.79		1.58	91	21	26
Tidal Peace	0.81*	0.79	0.77	0.74	0.79	0.73		1.71	101	23	29
Pine Island Sound	1.71	1.63	1.58	1.56	1.69	1.82*		0.76	33	7	9
Matlacha Pass	1.03	1.46*	1.22	1.34	1.12	1.35		0.95	46	10	13
San Carlos Bay	1.7	1.64	1.74	1.87	2.07	2.21*		0.63	24	5	7
Estero Bay				1.01	1.03*	1.03*	0.84	1.35	75	17	21
Tidal Caloosahatchee				1.00*				1.39	78	18	22

the deeper our depth target, the lower the target concentrations of the partial attenuation constituents must be to meet our light goal.

DISCUSSION—Immediately visible from the "targets" listed in Table 2 are that some of these constants are relatively high. For instance, the chlorophyll a values for 6 segments are higher than the Florida water quality standards for chlorophyll a of 11 μg/L for marine and estuarine waters. These constants are the maximum potential concentration of the analytes and are acceptable for meeting the percent-light-at-depth goal only when the concentrations for both the other 2 analytes are zero, an unlikely situation except when color is sufficiently high to limit phytoplankton production. Excepting those periods when chlorophyll a concentrations are very low due to high color concentrations, the concentrations for all 3 light attenuation components will be greater than zero, thereby requiring concentrations of all 3 components to be less than these maximums to maintain the percent-light-at-depth goal. The "targets" are a necessary step in developing the resulting line of constant attenuation, which denotes the acceptable concentration of a component of light attenuation in relation to the concentrations of the other components. This line allows the concentration for each component to assume any concentration between zero and its target maximum; its value dependent on the concentrations of the other 2 components. This objective is in contrast to many water quality targets that set a discrete maximum for each specific analyte without regard to concentrations of other relevant constituents affecting the targeted outcome.

The results from plotting the derived lines of constant attenuation over water quality data collected in the recent past (i.e., between 2002 and 2005) show that

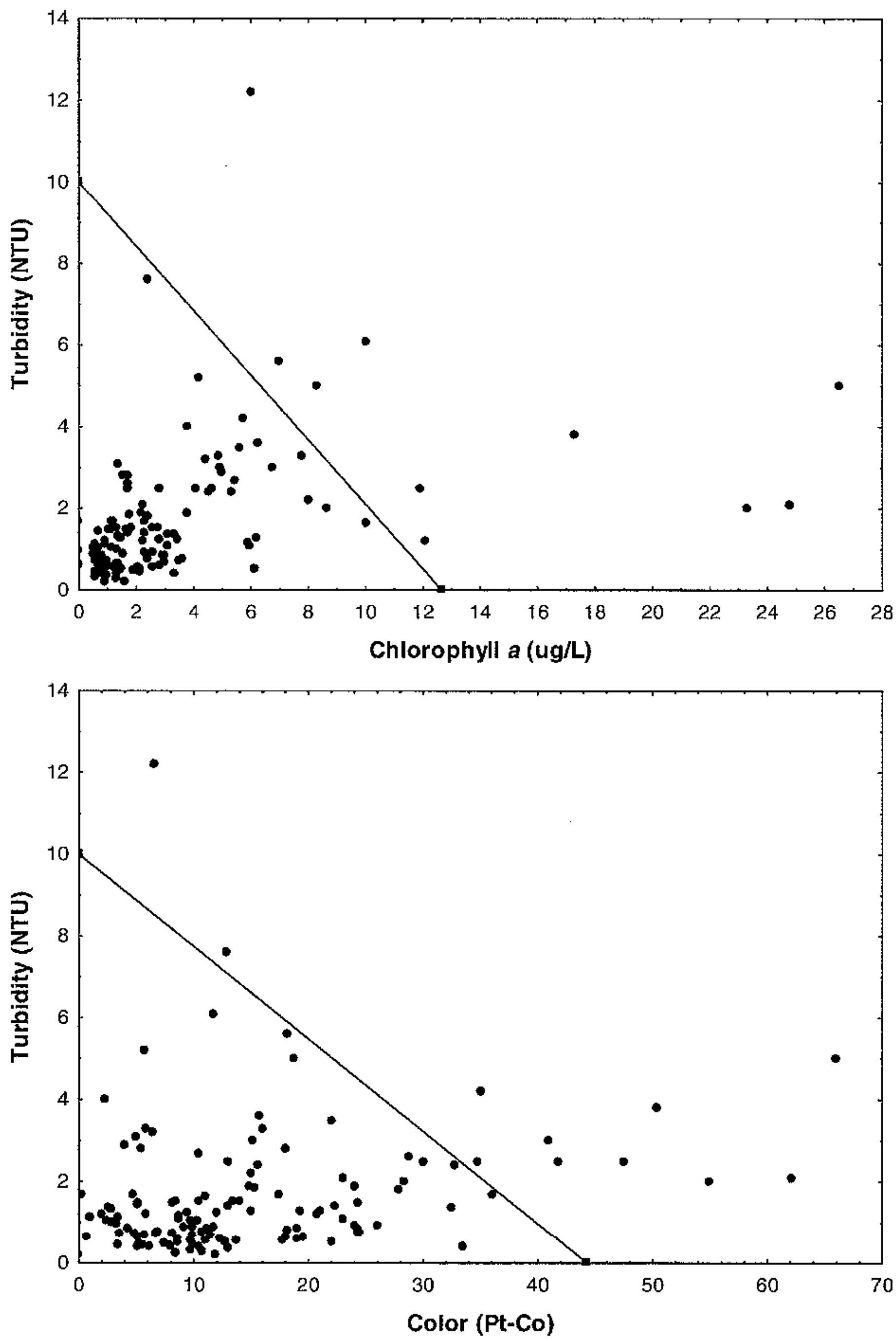

FIG. 2. Instances of dry season water quality which met (below line) or exceeded (above line) water quality goals for chlorophyll *a* and turbidity and color and turbidity in the Lower Charlotte Harbor segment. Data from 4/02–12/04.

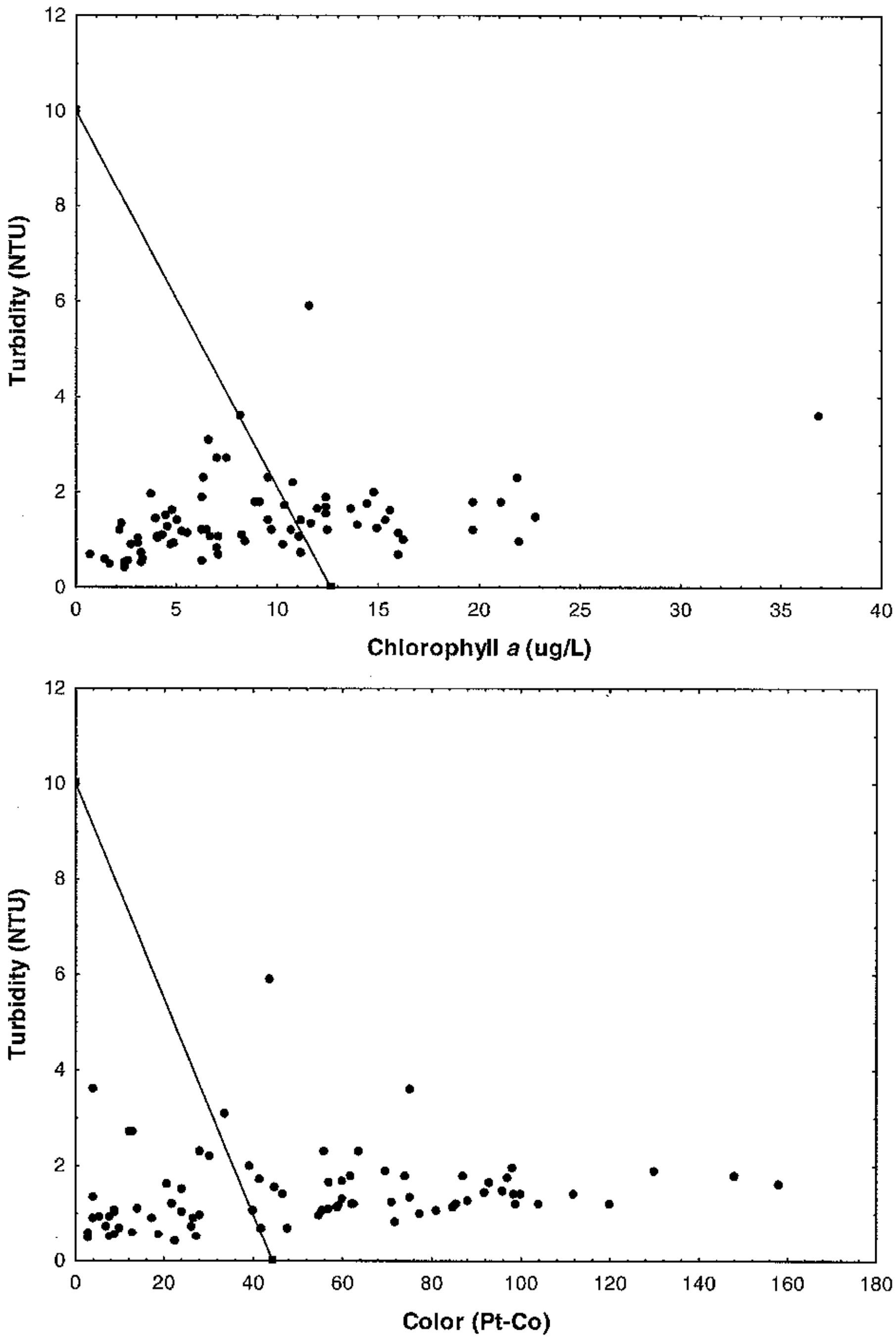

FIG. 3. Instances of wet season water quality which met (below line) or exceeded (above line) water quality goals for chlorophyll *a* and turbidity and color and turbidity in the Lower Charlotte Harbor segment.

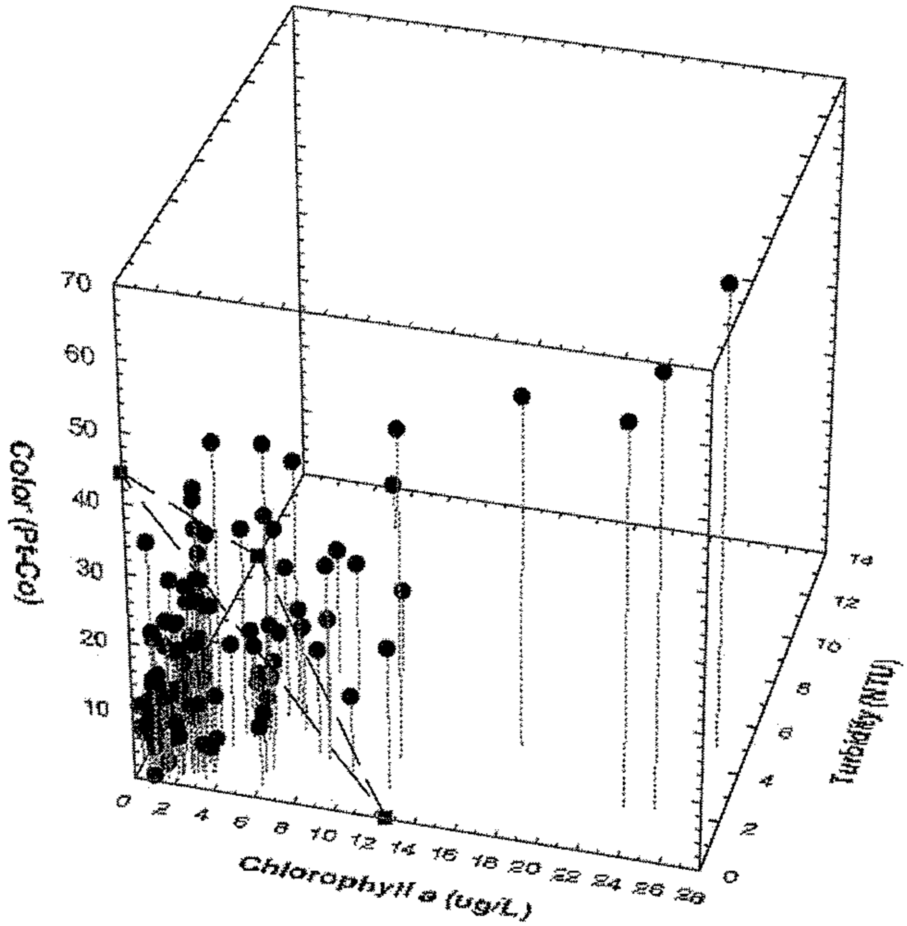

FIG. 4. 3-D Scatterplot with Lower Charlotte Harbor Stratum Dry Season Water Quality. Clarity targets (Table 2) and the line of constant attenuation are overlaid. Water quality data points located above of the line of constant attenuation identify instances when water clarity did not meet these targets.

there are times and locations within each segment that current water quality would not meet the percent-light-at-depth goals proposed in this effort. The locations in which these data were collected may support seagrass if, for instance, they are shallower than the depth target. Also, some data points on the scatterplots may represent locations in which data were collected that are deeper than our depth goal. However, both the light and maximum depth distribution targets are reasonable goals based upon current observations.

Nonetheless, other region-specific maximum depth distribution goals could be developed. The line of constant attenuation and the maximum concentration "targets" are based upon seagrass bed depth goals derived from fixed transect data collected between 1999 and 2005. The depth targets were created using the greatest annual average maximum seagrass deep edge per segment. A different strategy

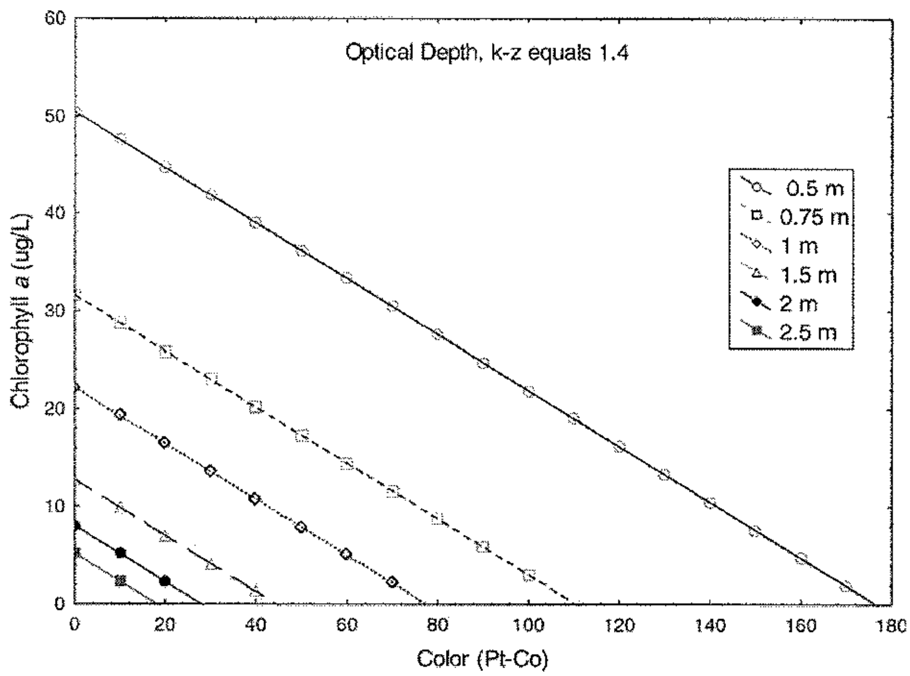

FIG. 5. Nomograph of Chlorophyll *a* Concentrations and Color for Specified Depths. For a given depth, combinations of color and chlorophyll *a* concentrations can reach the values under the line and maintain our light attenuation target.

could use the maximum deep edge value per segment as calculated by the fixed transect data to create water quality goals that would protect the transect with the deepest seagrass bed for each segment or alternatively, the mean annual average maximum seagrass deep edge. A quick review of the nomographs herein will demonstrate how the concentrations of the 3 water clarity components will change depending on depth.

Light requirements of seagrasses within Charlotte Harbor could be refined as well. We used the estimate of 25% subsurface irradiance, but future research may document that more light is needed to be protective of seagrasses. Salinity can affect seagrass photosynthesis (e.g., Torquemada et al., 2005), productivity (Tomasko and Hall, 1999) and abundance (Montague and Ley, 1993). As both Tomasko and Hall (1999) and Dixon and Kirkpatrick (1999) cite salinity stress as possible reasons for reduced *T. testudinum* productivity in this area, seagrasses in Charlotte Harbor would benefit from research to determine actual light requirements based on environmental gradients such as salinity as well as water clarity.

The partial coefficients within this optical model could be refined in several ways. McPherson and Miller (1994) used water quality samples collected in Tampa Bay and Charlotte Harbor to derive the partial attenuation coefficients used in this effort, and the model could be improved by including only data collected from Charlotte Harbor. Also, although other researchers have calculated partial light

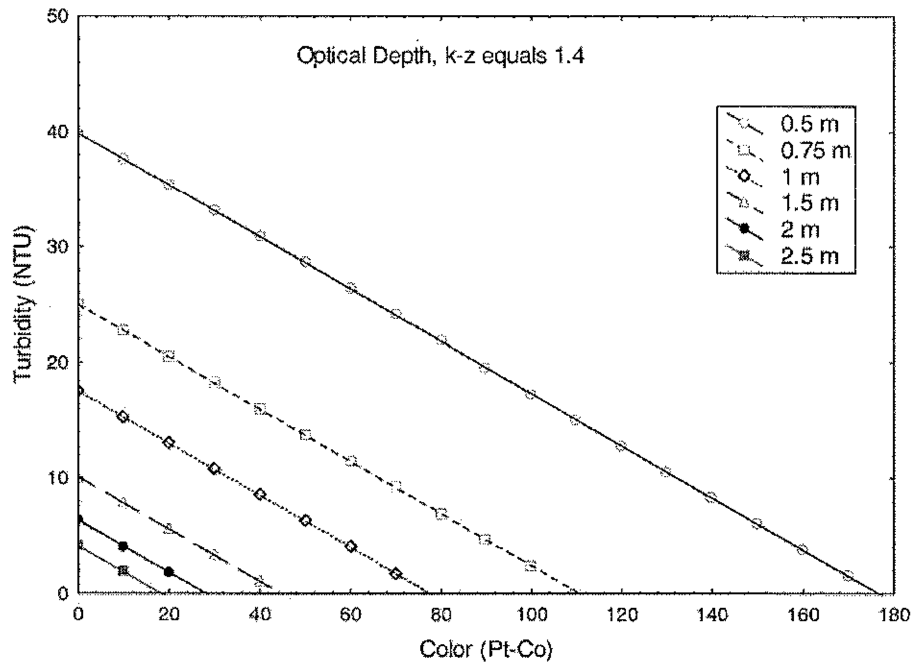

FIG. 6. Nomograph of Turbidity and Color for Specified Depths.

attenuation coefficients to support seagrass growth that differ from those in this effort (e.g., Gallegos and Kenworthy, 1996), the coefficients used here are locally derived and the best available estimates for environmental conditions in Charlotte Harbor.

The "non-algal suspended matter" partial light attenuation coefficient is an important parameter to accurately estimate, as this component is generally responsible for over 50% of light attenuation in these areas (McPherson and Miller, 1987; Dixon and Kirkpatrick, 1999). Furthermore, the actual composition of "non-algal suspended matter", represented by the turbidity term in McPherson and Miller (1994), will differ by segment and by season. Turbidity is a mixture of inorganic suspended matter, such as silt or clay, as well as plankton or other microscopic organisms (APHA, 1985). Turbidity values in Charlotte Harbor are significantly different in dry and wet seasons (Ott and Corbett, 2005), and phytoplankton communities, which also differ from season to season and from region to region, will have a variable impact on light scattering and absorption (see Kirk, 1994 and Jeffrey et al., 1997). However, McPherson and Miller (1987) suggested that re-suspended sediments may largely contribute to the non-algal suspended matter parameter in at least some of the areas in Charlotte Harbor and later estimated its value by accounting for the contribution of chlorophyll to the difference in attenuation between filtered and unfiltered water samples (McPherson and Miller, 1994). Therefore, while this effort uses the best available data appropriate for the Charlotte Harbor region, management strategies incorporating our approach to setting water clarity goals should be prepared to estimate the "non-algal suspended matter" parameter by both season and estuary segment.

The target light attenuation estimate presented here is based upon current seagrass distribution, and the water clarity goals proposed in this effort are meant to maintain the present seagrass coverage and depth distribution into the future. However, recent analysis of water quality data has demonstrated significant increases in total suspended solids in Lower Charlotte Harbor and Upper Charlotte Harbor regions and increasing turbidity in the Lower Charlotte Harbor region (Janicki Environmental Inc., 2003). These water quality constituents, along with dissolved matter, constitute the dominant influences on the light available for seagrass beds in most areas of Charlotte Harbor.

Seagrass coverage in the Upper Charlotte Harbor region is stable since 1988 (Kurz et al., 1999; Corbett et al., 2005; Tomasko et al., 2005; Corbett, 2006). Nonetheless, if seagrass depth distribution is light limited (Dixon and Kirkpatrick, 1999; Tomasko and Hall, 1999), resource management strategies in this area should focus on the long-term maintenance of present seagrass coverage through the implementation of water clarity targets. If future research efforts determine that seagrass meadows within Charlotte Harbor have indeed receded or catastrophic losses occurred since historic conditions, depth distribution goals reflecting restoration targets could be created from historic data. It should be noted then that water clarity would in turn need to improve to meet those restoration targets. Water quality that meets the goals derived in this effort should allow appropriate water clarity conditions for the maximum depth distribution of seagrass meadows that currently exist.

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LITERATURE CITED

AMERICAN PUBLIC HEALTH ASSOCIATION (APHA). 1985. Standard Methods for The Examination Of Water And Wastewater, 16th Ed. American Public Health Association, American Water Works Association, Water Environment Federation publication. APHA, Washington D.C.

BRAUN-BLANQUET, J. 1965. Plant sociology: the study of plant communities. Authorized English translation of Pflanzensoziologie 1932. Translated, revised, and edited by G. D. FULLER AND H. S. CONARD, 1st ed. McGraw-Hill, New York, NY.

CHAMBERLAIN, R. H. 2005. South Florida Water Management District, West Palm Beach, Pers. Commun.

CORBETT, C. A. 2006. Seagrass coverage changes in Charlotte Harbor, Florida. Florida Scient. 69 (00S2): 7–23.

———, P. H. DOERING, K. A. MADLEY, J. A. OTT, AND D. A. TOMASKO. 2005. Issues with using seagrass as an indicator of ecosystem condition. Pp. 229–245. *In*: BORTONE, S. A. (ed.), Estuarine Indicators. CRC Press, Boca Raton, FL.

DIXON, L. K. 2000. Establishing light requirements for the seagrass *Thalassia testudinum*. *In*: BORTONE, S. A. (ed.), Seagrasses: Monitoring, Ecology, Physiology, and Management. CRC Press, Boca Raton, FL.

——— AND G. J. KIRKPATRICK. 1999. Causes of light attenuation with respect to seagrasses in upper and lower Charlotte Harbor, Report to Southwest Florida Water Management District, SWIM Program and Charlotte Harbor National Estuary Program. Available from the Southwest Florida Water Management District, SWIM Program, Tampa, FL and Charlotte Harbor National Estuary Program, Fort Myers, FL.

GALLEGOS, C. L. AND W. J. KENWORTHY. 1996. Seagrass depth limits in the Indian River Lagoon (Florida, U.S.A.): Application of an optical water quality model. Estuar. Coast Shelf Sci. 42: 267–288.

GREENAWALT, J. M. 2005. Sanibel Captiva Conservation Foundation, Sanibel, FL. Pers. Commun.

GREENAWALT-BOSWELL, J. M., J. A. HALE, K. FUHR, AND J. OTT. 2006. Seagrass species' composition and distribution as estuarine indicators in Charlotte Harbor, FL. Florida Scient. 69 (00S2): 24–35.

HAMMETT, K. M. 1990. Land use, water use, streamflow and water quality characteristics of the Charlotte Harbor inflow area, Florida. Water Supply Paper 2359-A. Prepared in cooperation with the Florida Department of Environmental Regulation. U.S. Geological Survey, Tallahassee, FL. Available from USGS, Tampa, FL.

HARRIS, B. A., K. D. HADDAD, K. A. STEIDINGER, AND J. A. HUFF. 1983. Assessment of fisheries habitat: Charlotte Harbor and Lake Worth, Florida, Final Report. Florida Department of Natural Resources. Available from Florida Fish and Wildlife Conservation Commission-Florida Marine Research Institute, St. Petersburg, FL.

JANICKI ENVIRONMENTAL INC. 2003. Water quality data analysis and report for the Charlotte Harbor National Estuary Program, August 27, 2003. Available from the Charlotte Harbor National Estuary Program, Fort Myers, FL.

JEFFREY, S. W., R. F. C., MANTOURA, AND S. W. WRIGHT (Eds.). 1997. Phytoplankton pigments in oceanography. UNESCO, Paris.

JOHANSSON, J. O. R. 1991. Long-term trends in nitrogen loading, water quality and biological indicators in Hillsborough Bay, Florida. Pp. 157–176. *In*: S. F. TREAT AND P. A. CLARK (eds.), Proceedings, Tampa Bay Areas Scientific Information Symposium 2. Available from the Tampa Bay Regional Planning Council, St. Petersburg, FL.

——— AND H. GREENING. 1999. Seagrass restoration in Tampa Bay: A resource-based approach to estuarine management. Pp. 279–293 *In*: S. BORTONE (ed.), Subtropical and Tropical Seagrass Management Ecology. CRC Press, Boca Raton, FL.

——— AND T. RIES. 1997. Seagrass in Tampa Bay: Historic trends and future expectations. Pp. 139–150. *In*: S. TREAT (ed.), Proceedings, Tampa Bay Area Scientific Information Symposium-3. Available from the Tampa Bay Regional Planning Council, St. Petersburg, FL.

KIRK, J. T. O. 1983. Light and Photosynthesis in Aquatic Ecosystems. Cambridge University Press, New York, NY.

——— 1994. 2nd Edition, Light and Photosynthesis in Aquatic Ecosystems. Cambridge University Press, New York, NY.

KURZ, R. C., D. A. TOMASKO, D. BURDICK, T. F. RIES, K. PATTERSON, AND R. FINCK. 1999. Recent trends in seagrass distributions in southwest Florida coastal waters. Pp. 157–166. *In*: S. BORTONE (ed.), Seagrasses: Monitoring, Ecology, Physiology, and Management. CRC Marine Science Series, CRC Press, Boca Raton, FL.

LEWIS III, R. R., P. A. CLARK, W. K. FEHRING, H. S. GREENING, R. O. JOHANSSON, AND R. T. PAUL. 1998. The rehabilitation of the Tampa Bay Estuary, Florida, USA, as an example of successful integrated coastal management. Mar. Poll. Bull. 37(8): 468–473.

MCPHERSON, B. F AND R. L. MILLER. 1987. The vertical attenuation of light in Charlotte Harbor, a shallow, subtropical estuary, southwestern Florida. Estuar. Coast Shelf Sci. 25: 721–737.

——— AND R. L. MILLER. 1994. Causes of light attenuation in Tampa Bay and Charlotte Harbor, southwestern Florida. Water Res. Bull. 30(1): 43–53.

MONTAGUE, C. L. AND J. A. LEY. 1993. A possible effect of salinity fluctuation on abundance of benthic vegetation and associated fauna in northeaster Florida Bay. Estuar. 16(4): 703–717.

Ott, J. A. and C. A. Corbett. 2005. Combining fixed station and probabilistic water quality data to identify status and trends for the long-term health and management of the Charlotte Harbor estuaries, Presentation to the 2005 Charlotte Harbor Watershed Summit. Available from the Charlotte Harbor National Estuary Program, Fort Myers, FL.

Staugler, E. and J. A. Ott. 2001. Establishing baseline seagrass health using fixed transects in Charlotte Harbor, Florida: 2 year seagrass monitoring summary 1999–2000, Technical Report (1), Florida Department of Environmental Protection, Charlotte Harbor Aquatic Preserves. Available from Florida Department of Environmental Protection, Punta Gorda, FL.

Tomasko, D. A., D. L. Bristol, and J. A. Ott. 2001. Assessment of present and future nitrogen loads, water quality, and seagrass (*Thalassia testudinum*) depth distribution in Lemon Bay, Florida. Estuar. 24(6A): 926–938.

———, C. A. Corbett, H. S. Greening, and G. E. Raulerson. 2005. Spatial and temporal variation in seagrass coverage in southwest Florida: Assessing the relative effects of anthropogenic nutrient load reductions and rainfall in four contiguous estuaries. Mar. Poll. Bull. 50: 797–805.

——— and M. O. Hall. 1999. Productivity and biomass of the seagrass *Thalassia testudinum* along a gradient of freshwater influence in Charlotte Harbor, Florida. Estuar. 22(3A): 592–602.

Torquemada, Y. F., M. J. Durako, and J. L. Sanchez Lizano. 2005. Effects of salinity and possible interactions with temperature and pH on growth and photosynthesis of *Halophila johnsonii* Eiseman. Mar. Bio. 148: 251–260.

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