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A GIS Analysis of Seagrass Resources and Condition Within Padre Island National Seashore, Texas

Open-File Report 2007–1261

U.S. Department of the Interior
U.S. Geological Survey

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By Christopher P. Onuf and Jaimie J. Ingold

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Acknowledgments

This is the Final Report for Element 1 of a project to assess condition and trend of seagrass communities in Laguna Madre, Padre Island National Seashore, most at risk from channel dredging, oil and gas exploration, and recreational fishing activities.

Element 1 was conducted under Interagency Agreement NPS NO: 7490-D-0050 between National Park Service and U.S. Geological Survey (USGS) and Cooperative Agreement No. 02CRAG0029 between USGS and University of Texas Marine Science Institute (UTMSI), Christopher P. Onuf (USGS) and Kenneth H. Dunton (UTMSI), Principal Investigators.

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Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
Length		
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
Area		
square meter (m^2)	0.0002471	acre
hectare (ha)	2.471	acre
square kilometer (km^2)	247.1	acre
square centimeter (cm^2)	0.001076	square foot (ft^2)
square meter (m^2)	10.76	square foot (ft^2)
square centimeter (cm^2)	0.1550	square inch (ft^2)
hectare (ha)	0.003861	square mile (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
Mass		
gram (g)	0.03527	ounce, avoirdupois (oz)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F = (1.8 × °C) + 32

A GIS Analysis of Seagrass Resources and Condition Within Padre Island National Seashore, Texas

By Christopher P. Onuf and Jaimie J. Ingold [1]

Abstract

A survey of the seagrass resources of Padre Island National Seashore was conducted in fall 2002 and 2003, with additional sampling through 2006, to resolve distribution questions. Location coordinates were recorded to thousandths of minutes of latitude and longitude and converted to decimal degrees (minus decimal degrees for longitude) for import into ArcView™ (Environmental Systems Research Institute, Inc.). The seagrass core frequency data were developed as a theme in ArcView™ and overlaid on digital orthophoto quarter quadrangles of the U.S. Geological Survey to show sample depth with respect to mean sea level and frequency of occurrence of seagrass for five samples collected from every station sampled. These data were used to draw boundaries of area submerged at mean sea level and seagrass meadow in relation to the boundary of Padre Island National Seashore. Frequency of seagrass occurrence, mean plant height, shoot density, plant height multiplied by shoot density, live biomass, and dead biomass on a 1' latitude by 0.25' longitude grid were collected, and their distribution was plotted in space and according to depth. A User Guide for displaying data in ArcView™ is included at the end of this report.

Seagrasses covered almost two-thirds of the regularly flooded part of Laguna Madre within the borders of Padre Island National Seashore. Comparisons with earlier surveys showed that substantial areas of seagrass cover had been lost in deep water between 1988 and 1998 as a result of a persistent phytoplankton bloom, and little recovery has occurred since. Maximum depth of seagrass occurrence responded to changes in water clarity. In contrast, much of the cover at shallow to intermediate depths lost at the south end of the study area between 1988 and 1998 was replaced by 2003. The seven stations with greatest plant height were located in this area of recent recolonization. Continuity of cover as measured by frequency of occurrence was high except near the edge of seagrass meadow. Decrease in this measure may be an indicator of meadow fragmentation, signaling deterioration of seagrass meadow before loss. The other measures of condition were so variable that they were insensitive indicators of impending change.

Introduction

Padre Island National Seashore is best known for its 100 km of little-disturbed beach and sand dunes facing the Gulf of Mexico. Less well known is its even longer shore on the west side of Padre Island and the 101 km^2 of Laguna Madre's waters that lie within Padre Island National Seashore (fig. 1). Laguna Madre is a natural wonder in its own right, being one of only five

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hypersaline ecosystems in the world (Javor, 1989). Seagrasses carpet most of the bottom and are the foundation of a highly productive environment. Because seagrasses introduce physical structure and absorptive surface into the water column, they effectively filter suspended particles and nutrients in the water column (Short and Short, 1984), baffle waves and stabilize bottom sediments (Fonseca, 1989), and provide sanctuary from large predators for the young of commercially important species (Rooker and others, 1998).

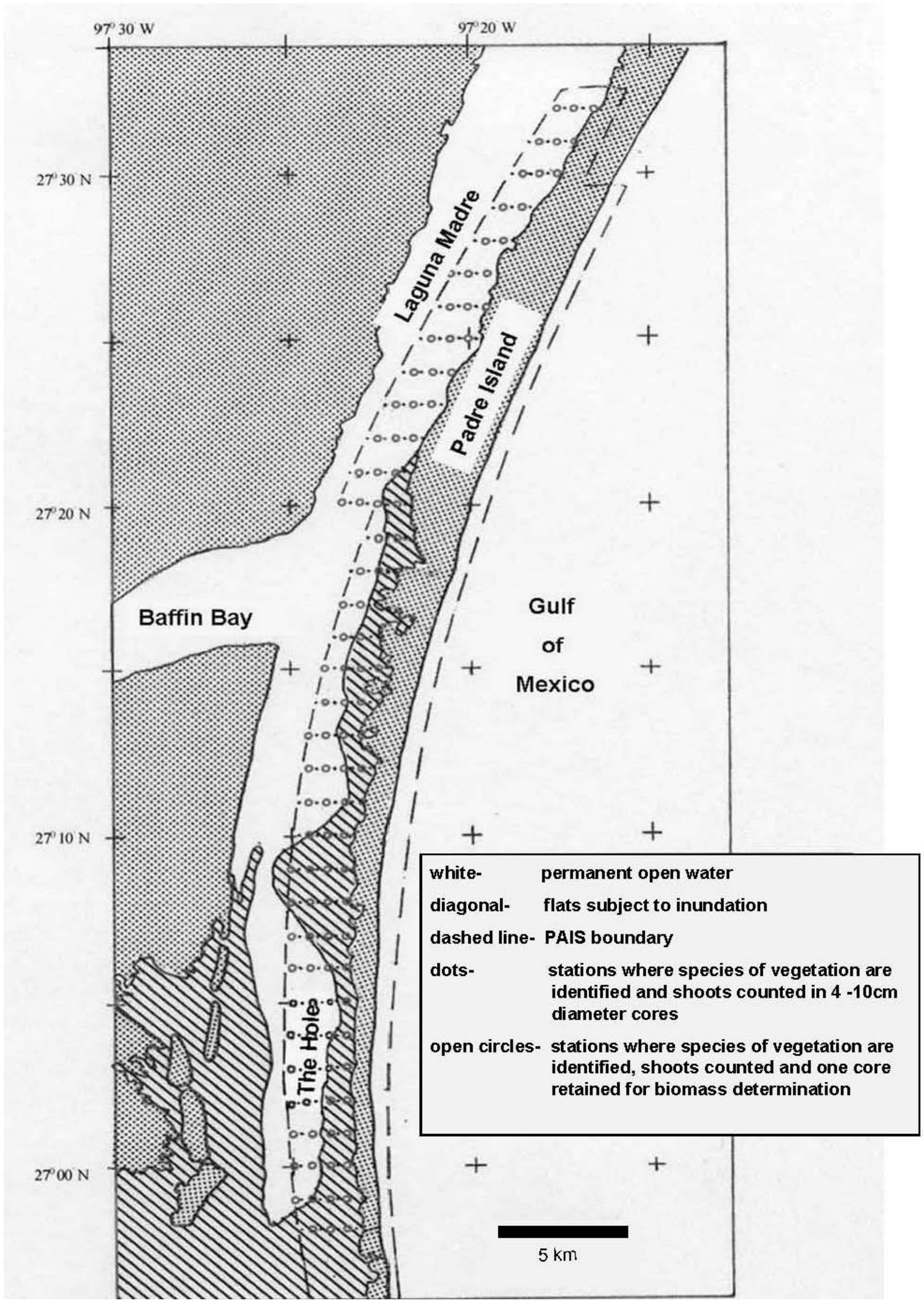

Figure 1. Map of the study area of Laguna Madre within the boundaries of Padre Island National Seashore (PAIS) showing the sampling grid for measures of seagrass condition.

In general, epiphytic algae and other organisms growing on the large, complex, self-renewing surface area provided by growing seagrass leaves support the dense and diverse assemblage of consumers associated with seagrass meadows (Moncreiff and Sullivan, 2001); however, there are a few direct consumers of seagrasses that pose significant concerns to management of Padre Island National Seashore. Three-quarters of the world population of redhead ducks (*Aythya americana*) overwinter on the Laguna Madre ecosystem of southern Texas and northern Mexico (Weller, 1964). While in residence, the redheads feed almost exclusively on the rhizomes of one seagrass species, shoal grass (*Halodule wrightii*) (McMahan, 1970; Cornelius, 1977; Woodin, 1996; Woodin and Michot, 2002). About 9 percent of the lagoon's total seagrass coverage and 15 percent of the lagoon's *Halodule wrightii* coverage lie within the Padre Island National Seashore boundary. Juvenile green turtles (*Chelonia mydas*) feed primarily on seagrasses. Historically, green turtles were the leading marine product of lower Laguna Madre. Recently, the few reports of green turtles from within the lagoon have been from gill net surveys conducted by the Texas Parks and Wildlife Department, with five reports for lower Laguna Madre and only one for upper Laguna Madre (Smith and Childs, 2002). Additionally, manatees (*Trichechus manatus*) are direct consumers of seagrasses that occur in Laguna Madre. So far, it is only evident that they show up briefly as solitary individuals (Baumgardner and Brooks, 2001).

Subtidal and regularly flooded portions of Laguna Madre make up as much as a quarter of the area of Padre Island National Seashore. Most of this area is or potentially could be covered by seagrass meadow. Because of the large but imprecisely documented extent of seagrass meadows within the national seashore and the many valuable services provided by these meadows, Padre Island National Seashore staff needs a detailed inventory of the extent and condition of this resource within the boundaries of the national seashore to guide management. In this study, we have capitalized on past efforts by supplementing the existing array of transects, by adapting the methods already in use by the U.S. Geological Survey (USGS) (Quammen and Onuf, 1993; Onuf 1996a, b, 2000), and by adding a major geographic information system (GIS) component.

Methods

Distribution

To characterize Padre Island National Seashore seagrass resources adequately, the array of 6 transects within the national seashore sampled in 1988 and 1991–98 was expanded to 35 east-west transects at 1' intervals of latitude, with stations at 0.25' intervals of longitude (fig. 1). Actual locations sampled were determined by using a Precision Lightweight GPS Receiver (Rockwell PLGR) with error less than 10 m. Four 80-cm^2 by 15-cm-deep cores with plants were collected at each station about 2.5 m apart along the port side of the boat. For each core and the anchor, all seagrass species, algal presence, and the dominant contributor to vegetative cover were assessed by visual inspection and recorded. At places where a meadow boundary was crossed or where dominant seagrass species changed between stations, the interval between stations was progressively decreased, and cores were collected until the boundary was determined to within 0.01' of longitude. Time and depth were recorded at each station, and depths were standardized by adjusting measured depth according to the deviation from mean sea level at sampling time for the Texas Coastal Ocean Observation Network tide gage at Bird Island, located toward the northern end of the study area. The planned transect sampling was carried out between October and

December in 2002 and 2003. Additional sampling to resolve questions about distribution was conducted as needed through October 2006.

Condition

Shoot density and length were chosen as the most useful measures of condition in this study because they can be quickly determined in the field. The more labor-intensive use of biomass would be cost prohibitive to achieve the same level of coverage. Shoots were counted for each species present in all cores collected at the predetermined sampling stations (fig. 1). Too many seagrass leaves are cut off by the coring device to reliably determine shoot length from plant material retrieved in cores. Therefore, a posthole digger with handles extended with a length of polyvinyl chloride (PVC) pipe was used to tear a section of seagrass turf from the bottom of the lagoon in the vicinity of each core sample, and the longest shoot for each sample was measured from rhizome to tip with a plastic ruler.

Biomass

To allow comparisons with other studies, biomass was determined for a limited subset of samples collected. One core sample randomly selected from the four collected at every other station along each transect (0.5’ longitude intervals, open circles in fig. 1) was retained for biomass determination. As per Onuf (1996b), samples were washed on 1-mm mesh screens. All plant material retained on the screens was placed in plastic bags and stored on ice for transport to the laboratory where the samples were frozen until processed. Processing consisted of thawing and separating into live (turgid green, white to beige, and pink structures) and dead (flaccid brown to washed-out maroon) fractions. The live fraction was sorted further according to species and into aboveground (green portions of shoots) and belowground (root, rhizome, and unpigmented portions of shoots) fractions. The sample fractions were dried to constant weight at 60°C (72 hours), weighed, ashed at 530°C for 1 hour, and weighed again. Dry weight and ash-free dry weight were calculated for all plant parts and dead material. Station biomass determinations were reported on a per meter squared basis, and these were used to compute mean biomass for each species where present and for the whole study area. Regressions between biomass and shoot density multiplied by height were used to investigate whether shoot density multiplied by height can serve as a surrogate for biomass.

Data Processing and GIS Analysis

Data on location, depth, and number of cores with seagrass cover were compiled in a Microsoft® Excel® spreadsheet for all sites visited, along with date and approximate time of sampling. Depths were referred to mean sea level by using a record of hourly water level for the Texas Coastal Ocean Observation Network (*http://lighthouse.tamucc.edu/pquery*) for their South Bird Island platform and the mean sea level datum for that station. Location coordinates were recorded to thousandths of minutes of latitude and longitude and converted to decimal degrees (minus decimal degrees for longitude) for import into ArcView™ (Environmental Systems Research Institute, Inc.). The seagrass core frequency data were developed as a theme in ArcView™ and overlaid on USGS DOQQs. Boundaries of the seagrass meadow were drawn as interpolating between determined boundary locations by using features in the aerial imagery where useful. These polygon features were used to display the results of the survey visually and to compute the area of seagrass cover. All location data were projected in the North American Datum of 1983 at Universal Transverse Mercator Zone 14N.

The data for mean shoot density, mean shoot length, and mean shoot density multiplied by mean shoot length sampled at 1' latitude by 0.25' longitude intervals were normalized for map display by computing the value of each measure for each station as a percent of the maximum value sampled in the study and expressing it in a scale from 0 to 9, where 0 corresponds to the interval from 0 to less than 10 percent of the maximum found in the study, 1 corresponds to the interval from 10 to less than 20 percent, and so on. These measures were then developed as themes in ArcView™ as was done for the distribution data and displayed as overlays of the DOQQs in ArcView™, and they were also developed as hardcopy outline maps.

The same approach was used to display the data for biomass at 1' latitude by 0.5' longitude intervals. In addition, depths with respect to mean sea level for all stations sampled and at the edges of seagrass meadows were developed as ArcView™ themes for possible application in management.

Results

Distribution

On the basis of surveys at 1' intervals of latitude, supplemented with additional sampling where boundaries were in question, it was found that seagrasses cover 6,284 ha of Laguna Madre bottom within Padre Island National Seashore. This amounts to approximately 62 percent of the area of the lagoon below mean sea level within the national seashore (10,194 ha). At the northern end of the study area, from latitude 27°32' to latitude 27°28', seagrass cover (exclusively of *Halodule wrightii*) was continuous from shore to the western boundary of Padre Island National Seashore at the Gulf Intracoastal Waterway, except for narrow bare strips along the shore of Padre Island and other natural (North and South Bird Islands) and artificial islands (mostly formed from dredged material deposits along the Gulf Intracoastal Waterway).

Detailed instructions for viewing data in ArcView™ are provided in the User Guide at the end of this report. To view distribution in ArcView™, open (C:)\PAIS GIS\Seagrass Distribution\seagrassdistribution.apr. Turn on themes Boundary.shp, Mapticks.shp, Noseagrass.shp, Coresamples.shp, and Waterarea.shp. Zoom in on the top three rows of map ticks (white crosses) at north end as per the "Zoom In" tool directions in the Methods section. Red and green squares show where seagrass was found in sampling, and seagrass meadow is outlined in red. Bare areas within the boundaries of the seagrass meadow are shown in yellow. The western boundary of Padre Island National Seashore is depicted with a dotted blue line, and estimated mean sea level is shown in green. For further instructions on using ArcView™, please see the User Guide at the end of this report.

Use the pan tool (hand icon) to drag the view to include map ticks latitude 27°28' to latitude 27°24'. South from latitude 27°28' to latitude 27°26', the western edge of the seagrass meadow ended east of the Gulf Intracoastal Waterway in relatively deep water. In order to view depths at the edges of the seagrass meadow, turn on Edgedepth.shp. To view depths of all stations sampled, turn off Edgedepth.shp, and turn on Alldepth.shp. It will be necessary to zoom in further as described in the Methods section to read depths in many cases. From latitude 27°26' to latitude 27°24' in the area known as Big Cove, seagrass cover was again continuous from the Padre Island shore to the western boundary of Padre Island National Seashore in depths less than 150 cm at mean sea level (m.s.l.). Turn off Alldepth.shp.

Drag the view to include map ticks latitude 27°24’ to latitude 27°20’. In this segment, large areas of deep water were unvegetated, with seagrass mostly confined to a narrow band along the Padre Island shore and a finger of seagrass extending south to near latitude 27°22’ near the western boundary. At the south end of the segment, the seagrass meadow broadened over the shoal area opposite Point of Rocks.

Drag the view to include map ticks latitude 27°20’ to latitude 27°16’. At latitude 27°20’ the western boundary of Padre Island National Seashore turns due east for 1.7 km. Only a narrow strip of shoal water opposite the mouth of Baffin Bay lies within the national seashore in this segment. Seagrass cover extended from close to estimated mean sea level to the western boundary of the national seashore except over a light sand body at latitude 27°18’.

Drag the view to include map ticks latitude 27°16’ to latitude 27°12’. Seagrass cover in this segment was continuous to the western boundary of Padre Island National Seashore to near latitude 27°13’, where it was constricted to a narrow strip bordering on a broad expanse of deep water at Yarborough Pass, near latitude 27°12’.

Drag the view to include map ticks latitude 27°12’ to latitude 27°08’. The narrow belt of seagrass adjacent to deep water extended to latitude 27°11’ and then expanded over a broad shoal area interrupted by abandoned channels and spoil islands, known as Middle Ground. Two small beds of widgeon grass (*Ruppia maritima*) were found in an otherwise bare shoal area near latitude 27°09’, close to the western boundary (red polygons 2 and 3). At latitude 27°08’ the shallow bare zone increased greatly in width and extended almost to the western boundary.

Drag the view to include map ticks latitude 27°08’ to latitude 27°04’. Between latitude 27°08’ and latitude 27°06’ the shallow bare zone narrowed around an area of deeper water known as Nine-Mile Hole. Two extensive bare areas were found within the seagrass meadow at moderate depths between latitude 27°06’ and latitude 27°04’.

Drag the view to include map ticks latitude 27°04’ to latitude 27°00’. The southern limit of seagrass within Padre Island National Seashore was close to latitude 27°00’. Cover was continuous to the western boundary. The shallow bare zone was narrow at latitude 27°04’ and was much broader at the southern end.

Changes in Distribution over Time

In addition to the survey of seagrass distribution within the boundaries of Padre Island National Seashore conducted for this study in 2002–03, four other surveys of the whole lagoon provide less precise information on seagrass distribution within the national seashore at earlier dates (mid-1960s from McMahan [1965–67], mid-1970s from Merkord [1978], 1988 from Quammen and Onuf [1993], and 1998 from Onuf [in press]), as compiled in similar format in Onuf (in press). According to this treatment, in the mid-1960s, seagrasses were absent between latitude 27°20’ and latitude 27°25’ and south of latitude 27°12’ (fig. 2, left). In the mid-1970s, the extreme southern part of the study area was completely vegetated (in Nine-Mile Hole), as was much of the eastern shore in the more northerly bare area of the 1960s (fig. 2, middle left). In 1988, seagrass cover in Nine-Mile Hole was less than in the 1970s but was almost continuous north of latitude 27°20’ (fig. 2, middle). In 1998, the extent of bare bottom was greater in both areas than it had been in 1988 (fig. 2, middle right). In 2002–03, cover was greater in the southern end than it had been in 1998, but some previously vegetated areas in the northern part of Nine-Mile Hole were again bare (fig. 2, right).

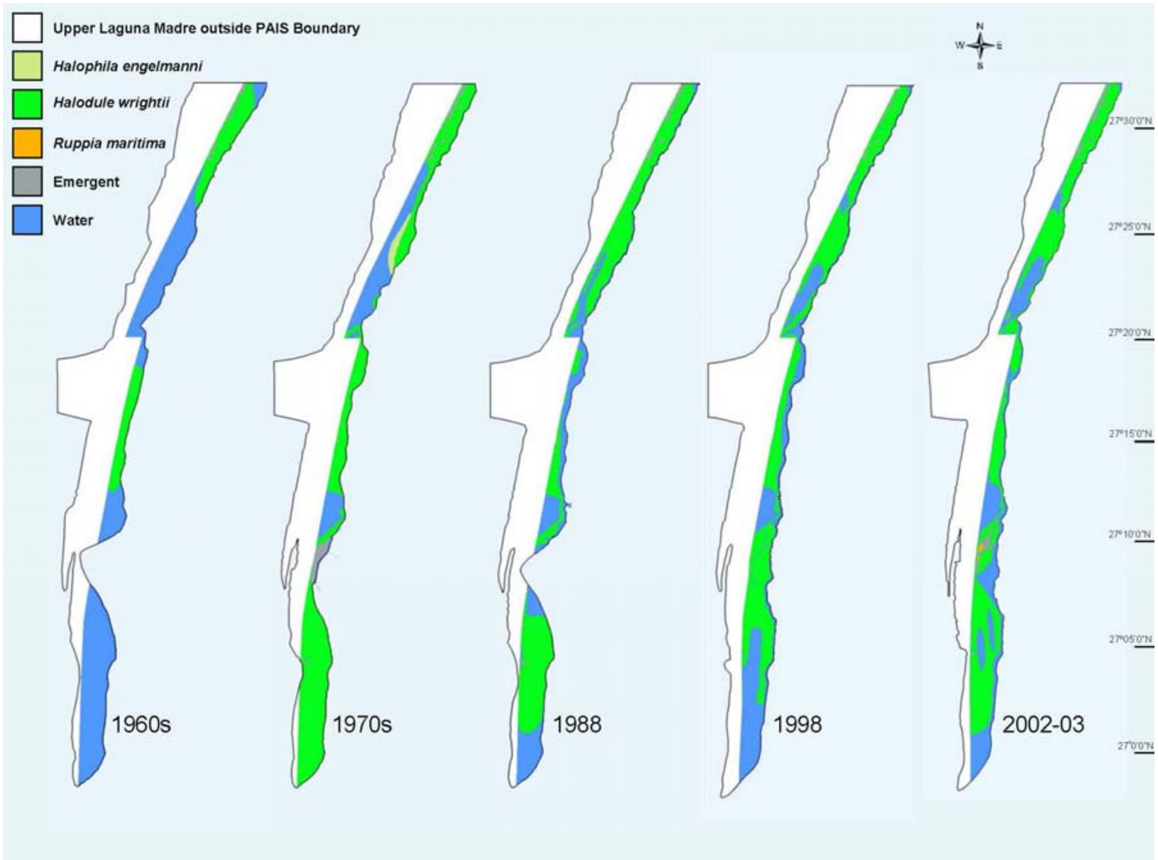

Figure 2. Maps of seagrass cover within the boundaries of Padre Island National Seashore (PAIS) in the mid-1960s (left), mid-1970s (middle left), 1988 (middle), 1998 (middle right), and 2002–03 (right).

Condition

Maximum and Minimum Depth of Occurrence

The depth at the outer (deeper) edge of seagrass meadow tended to increase toward the northern end of the study area (fig. 3). Depths at the shallow edge were mostly between 0 and 0.5 m at m.s.l., except from latitude 27°23’ to latitude 27°28’, where they were greater than 1 m. *Ruppia maritima* was dominant only at depths less than 0.2 m at m.s.l.

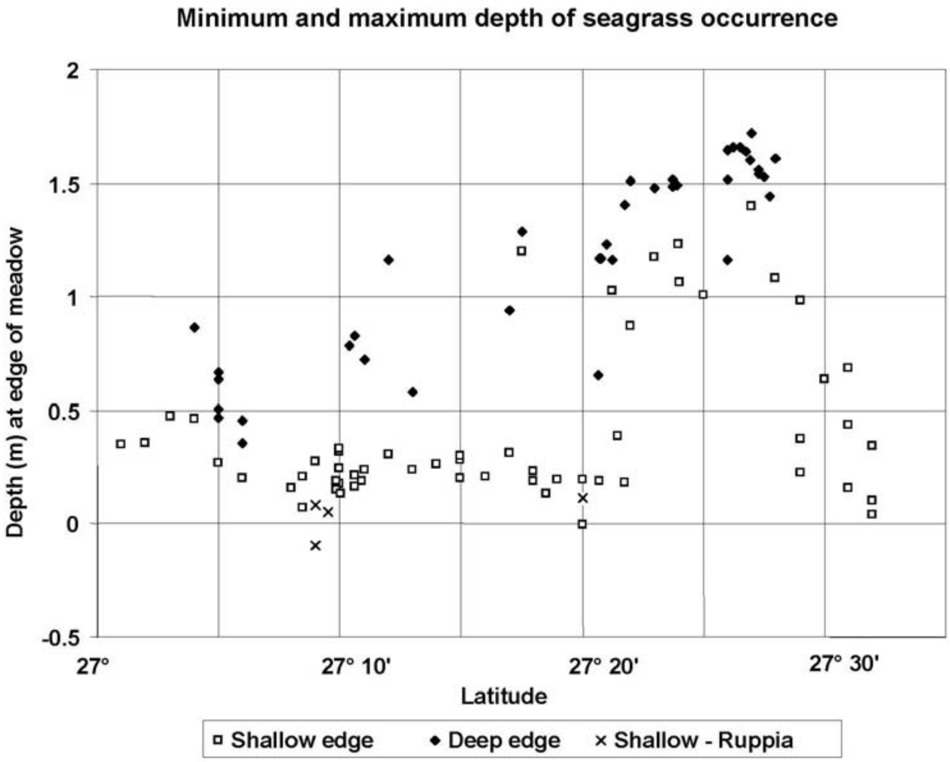

Figure 3. Minimum and maximum depth of seagrass occurrence along different transects.

Continuity of Cover

Where seagrass occurred, cover tended to be continuous. Of 80 stations in the 1' latitude by 0.25' longitude sampling grid where any seagrass was found, 57 (71 percent) had seagrass in all five samples collected (fig. 4). Most of the stations where seagrass was present (albeit not in every sample) were in the southern section (20 south, 4 north). Most were near a meadow edge (adjacent to a station without seagrass or to shore, 17 of 23 stations [fig. 4]). The majority (59 percent) of stations with seagrass in all five cores were in the depth range 0.6–1.5 m at m.s.l., whereas only 20 percent of stations with fewer or no cores with seagrass were in that intermediate depth range (fig. 5).

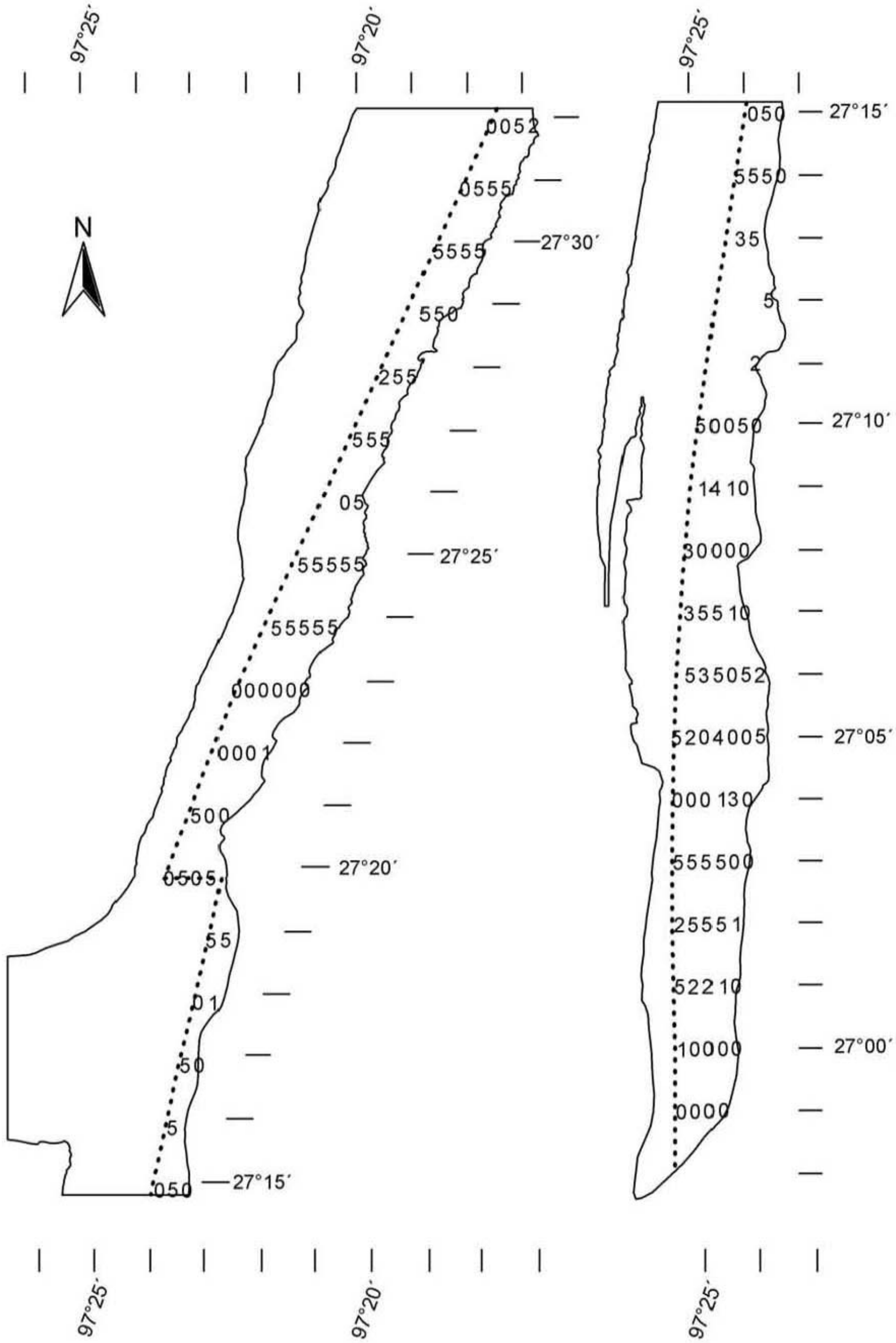

Figure 4. Continuity of seagrass cover as indicated by frequency of occurrence in five samples collected at each station in the 1′ latitude by 0.25′ longitude sampling grid (see fig. 1).

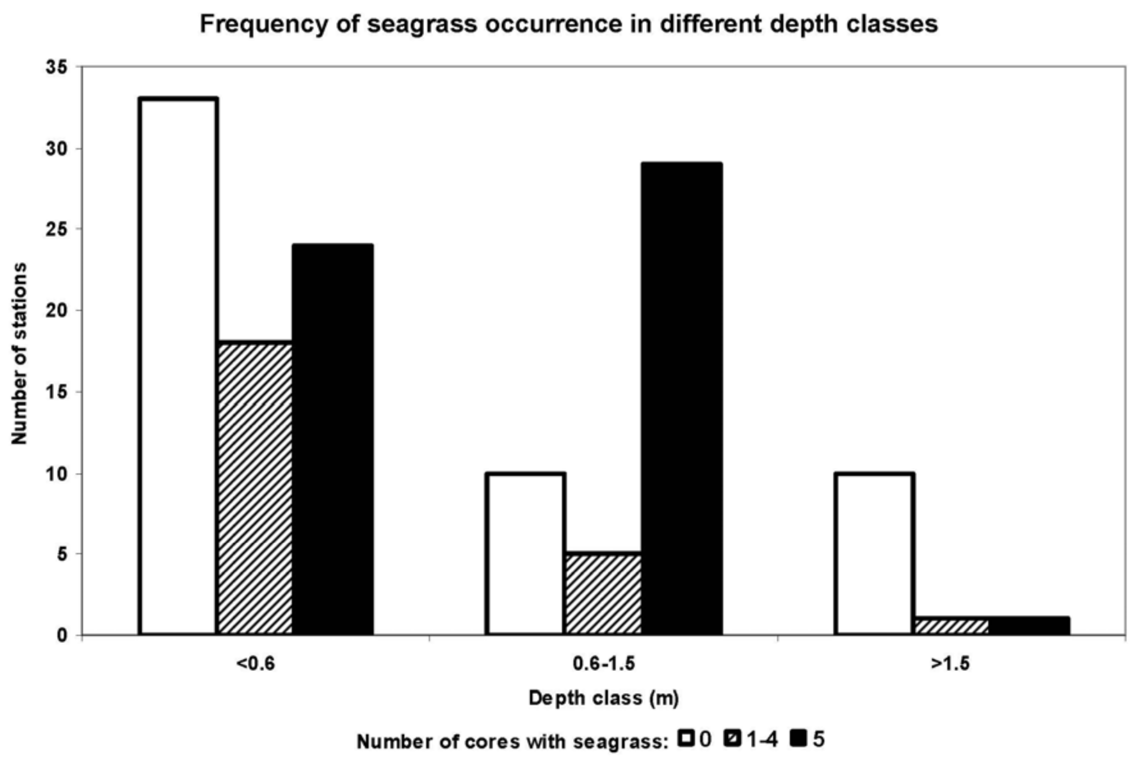

Figure 5. Frequency of seagrass occurrence in different depth classes.

Shoot Length

The height of seagrass plants was bimodal in distribution. Shoot lengths at most stations were either 50–60 percent of the maximum found in the study (18 stations) or 20–40 percent of the maximum (31 stations) (fig. 6). Plant height was uniform at intermediate shoot lengths in the northern third of the study area, uniform at short shoot lengths in the middle third, and variable in the southern third of the study area (fig. 6). Plants were short in shallow water, tallest at depths of 70–80 cm, and intermediate in height in deeper water (fig. 7).

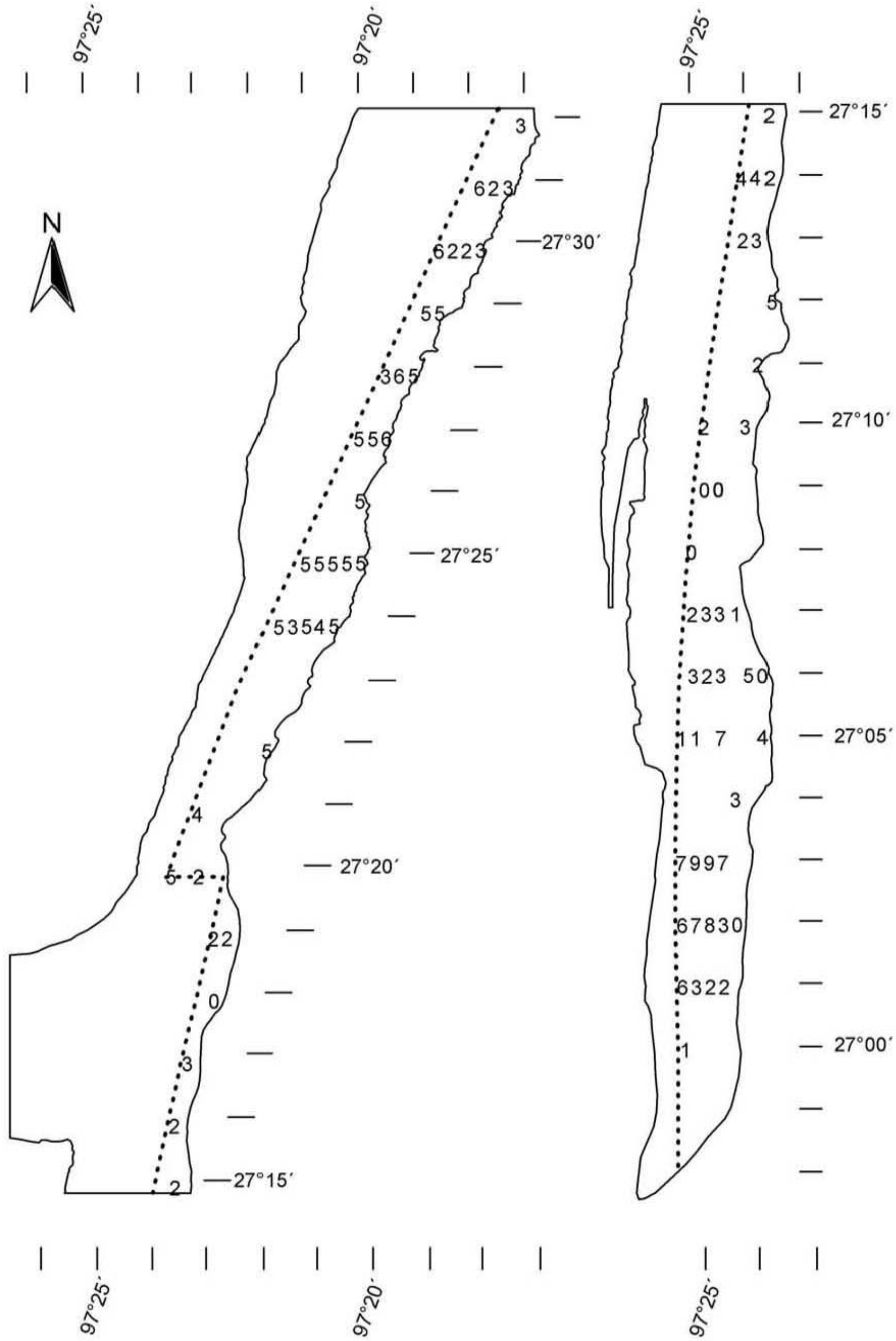

Figure 6. Mean plant height determined from four samples collected at each station in the 1′ latitude by 0.25′ longitude sampling grid (see fig. 1) expressed as 10 percentile classes of highest mean plant height found in the study.

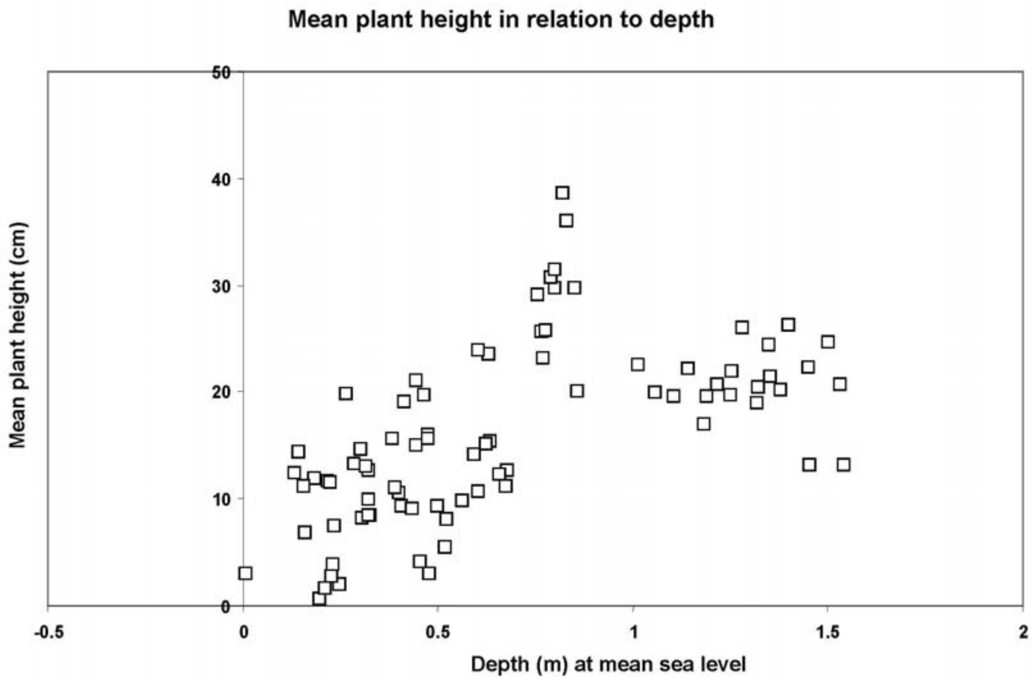

Figure 7. Mean plant height in relation to depth.

Shoot Density

Spatial differentiation was not as strong in shoot density as in shoot length. All four high-density stations were located in the middle third of the study area, and most of the low-density stations were located in the south (fig. 8). Density was extremely variable at shallow stations and more uniform at intermediate densities in deeper water (fig. 9).

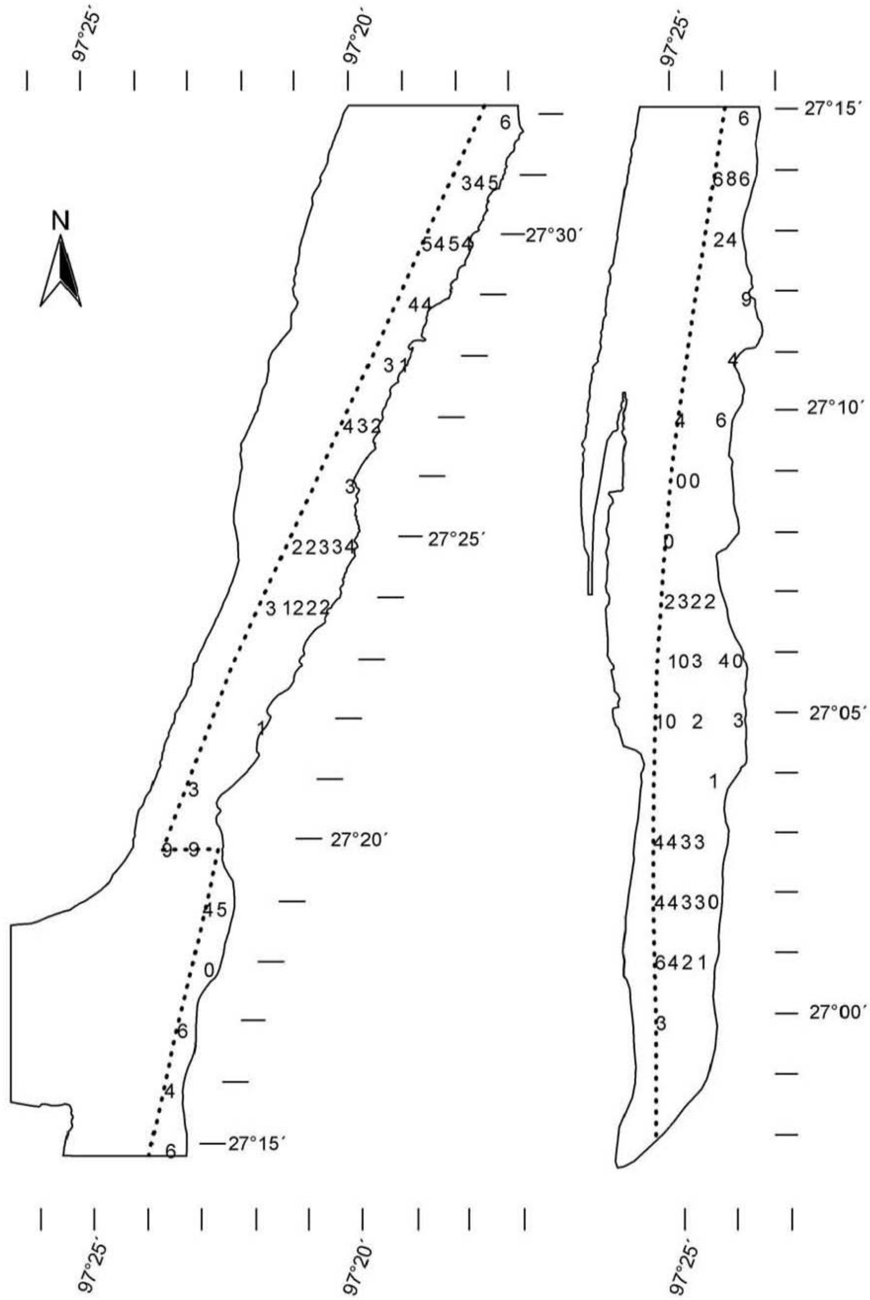

Figure 8. Mean shoot density determined from four cores collected at each station in the 1′ latitude by 0.25′ longitude sampling grid (see fig. 1) expressed as 10 percentile classes of highest mean shoot density found in the study.

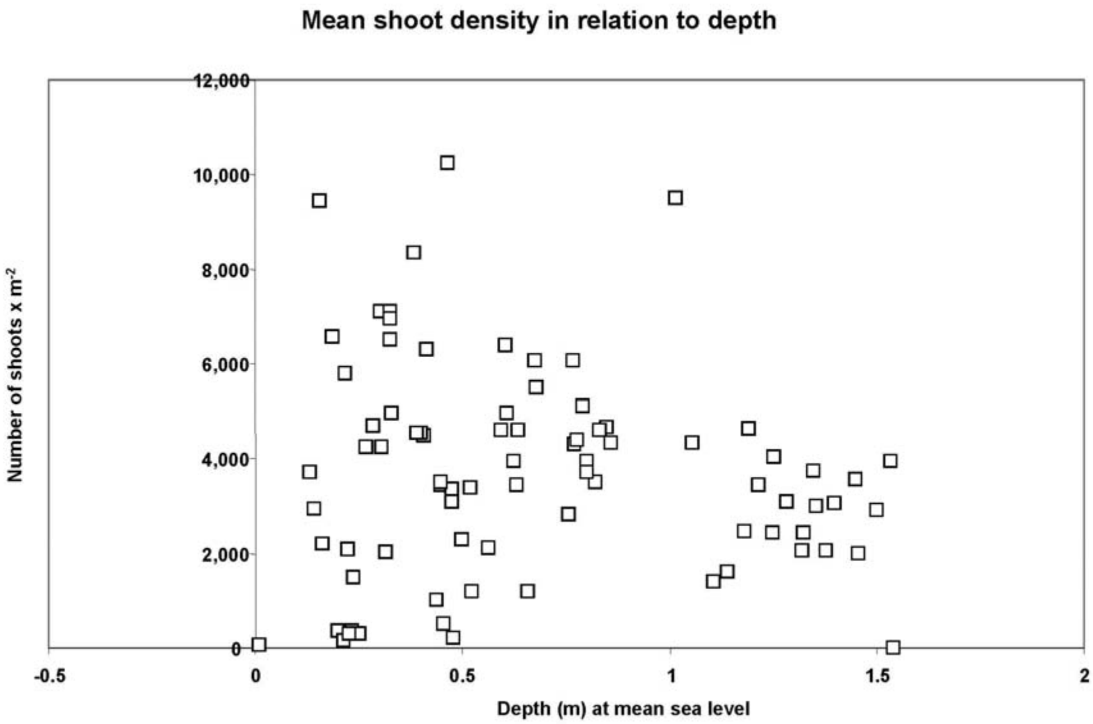

Figure 9. Mean shoot density in relation to depth.

Volume of Water Column Occupied by Seagrass

Average shoot length multiplied by shoot density provides a measure of the relative volume of water column occupied by seagrass at different locations (fig. 10). Most stations in the northern segment of the study area were low-intermediate for this measure (30–50 percent of the maximum found in this study at 19 of 34 stations), whereas values in the southern segment tended to be lower (0–30 percent of the maximum at 24 of 40 stations) or higher (more than 50 percent of the maximum at 11 of 40 stations), as compared to only 5 of 40 stations in the 30–50 percent of maximum range. Lowest values of plant height multiplied by density occurred in shallow water, but relatively high values were reached there as well. Highest values occurred at intermediate depths and intermediate values at depths greater than 1 m (fig. 11).

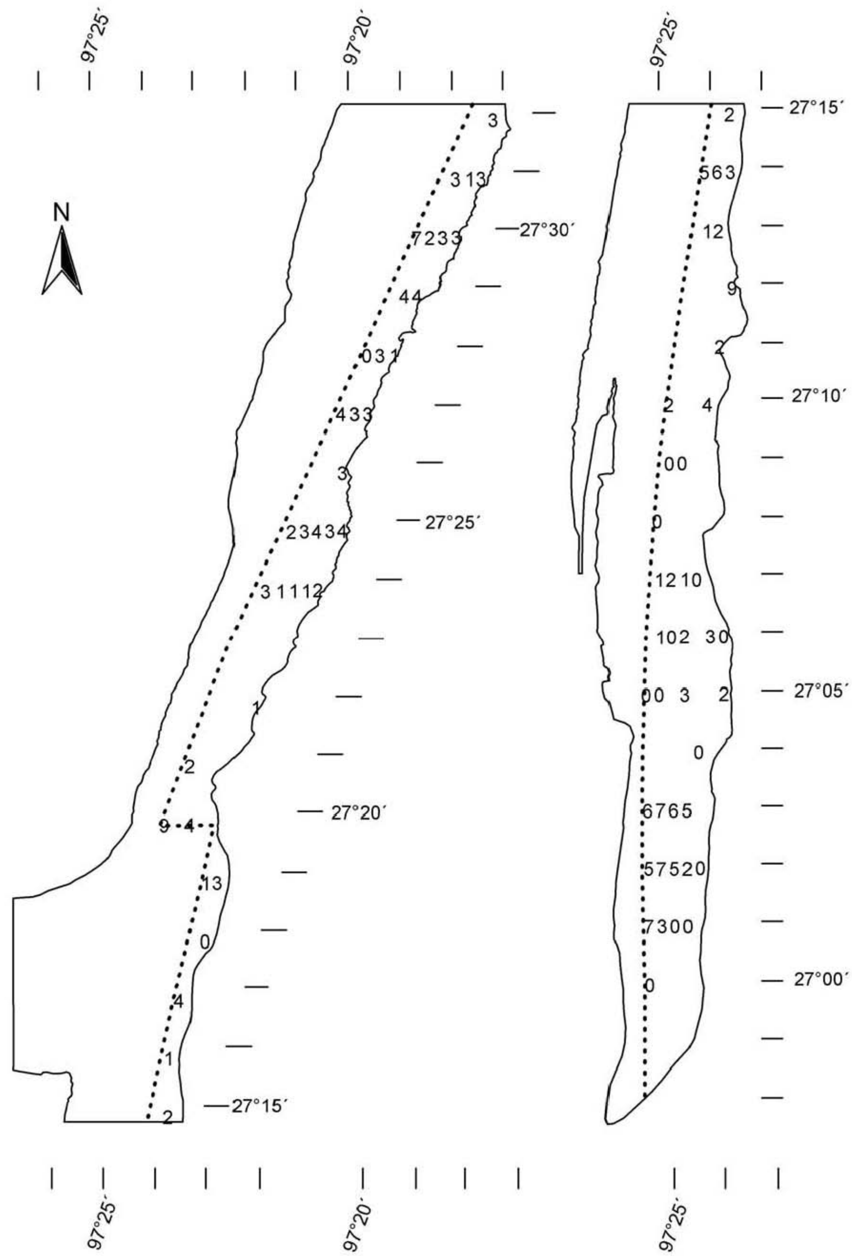

Figure 10. Mean plant height multiplied by mean shoot density determined from four samples collected at each station in the 1′ latitude by 0.25′ longitude sampling grid (see fig. 1) expressed as 10 percentile classes of highest mean plant height multiplied by mean shoot density found in the study.

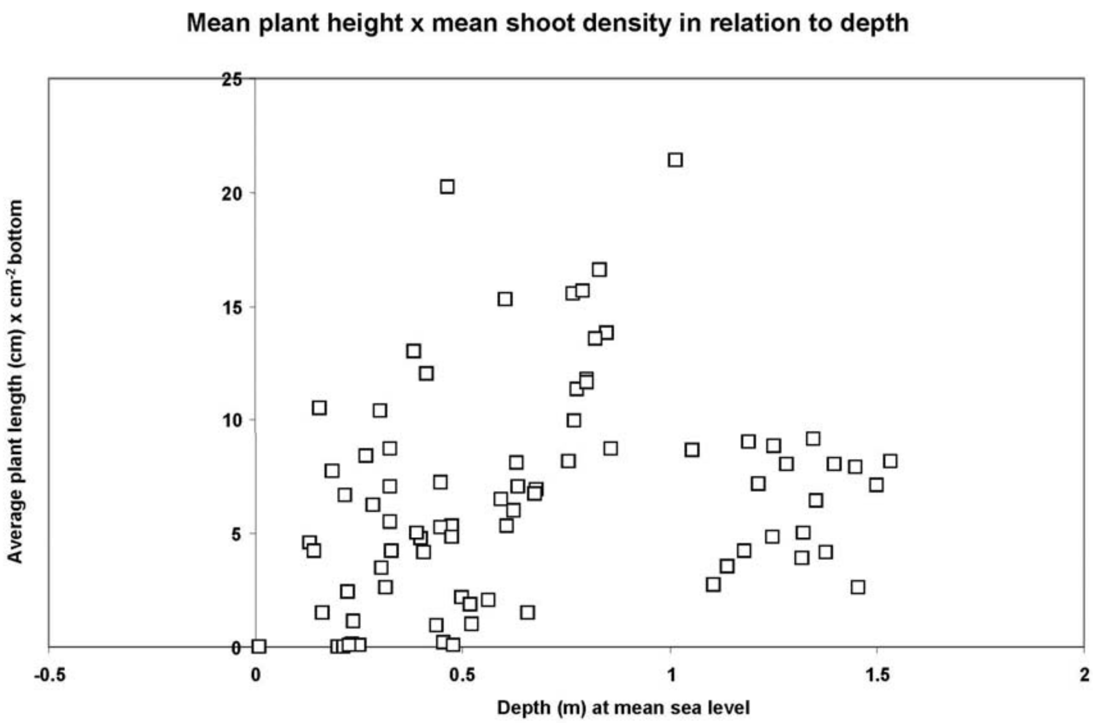

Figure 11. Mean plant height multiplied by mean shoot density in relation to depth.

Live Biomass

Highest live biomass values occurred at one station in the northern section and one location in the south (fig. 12). Otherwise, live biomass ranged from low to intermediate values with no clear pattern. Lowest biomass values occurred at shallow and deep sites; highest biomass values occurred at intermediate depths but were highly variable across the whole depth range (fig. 13).

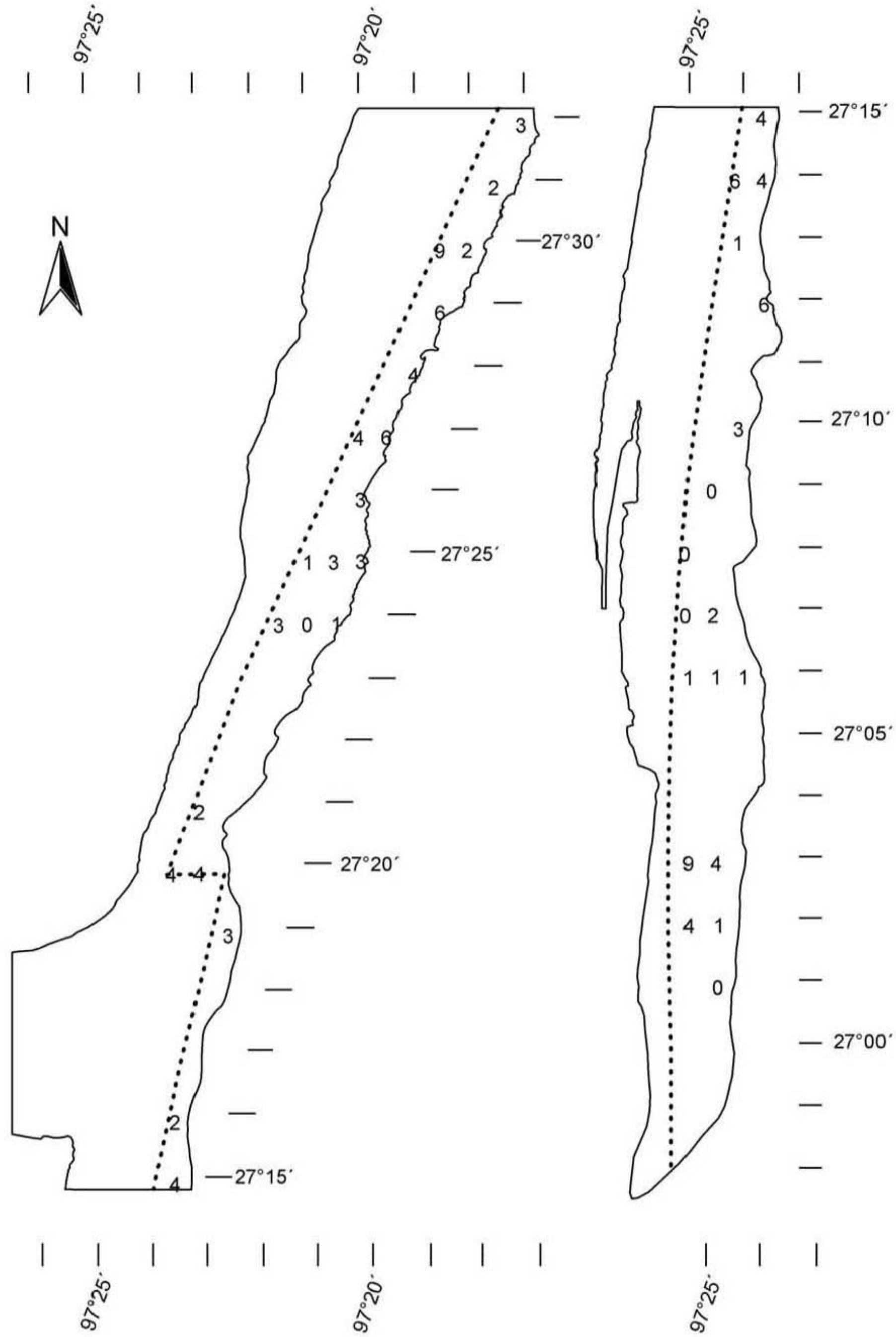

Figure 12. Mean live biomass determined from four samples collected at each station in the 1′ latitude by 0.5′ longitude sampling grid (see fig. 1) expressed as 10 percentile classes of highest mean live biomass found in the study.

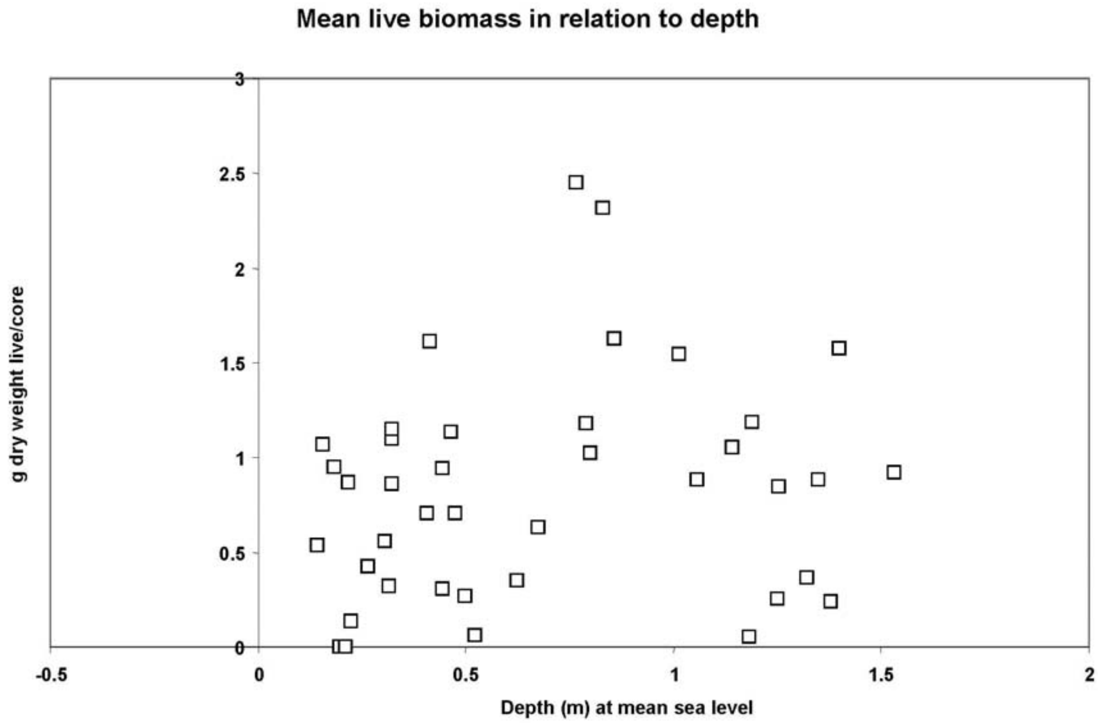

Figure 13. Mean live biomass in relation to depth.

Dead Biomass

Dead biomass was somewhat higher in the north than the south (fig. 14). The one high value was near the middle of the study area—just north of Yarborough Pass. Dead biomass tended to be twice as great as live biomass (figs. 15 and 12) but was distributed similarly with respect to depth.

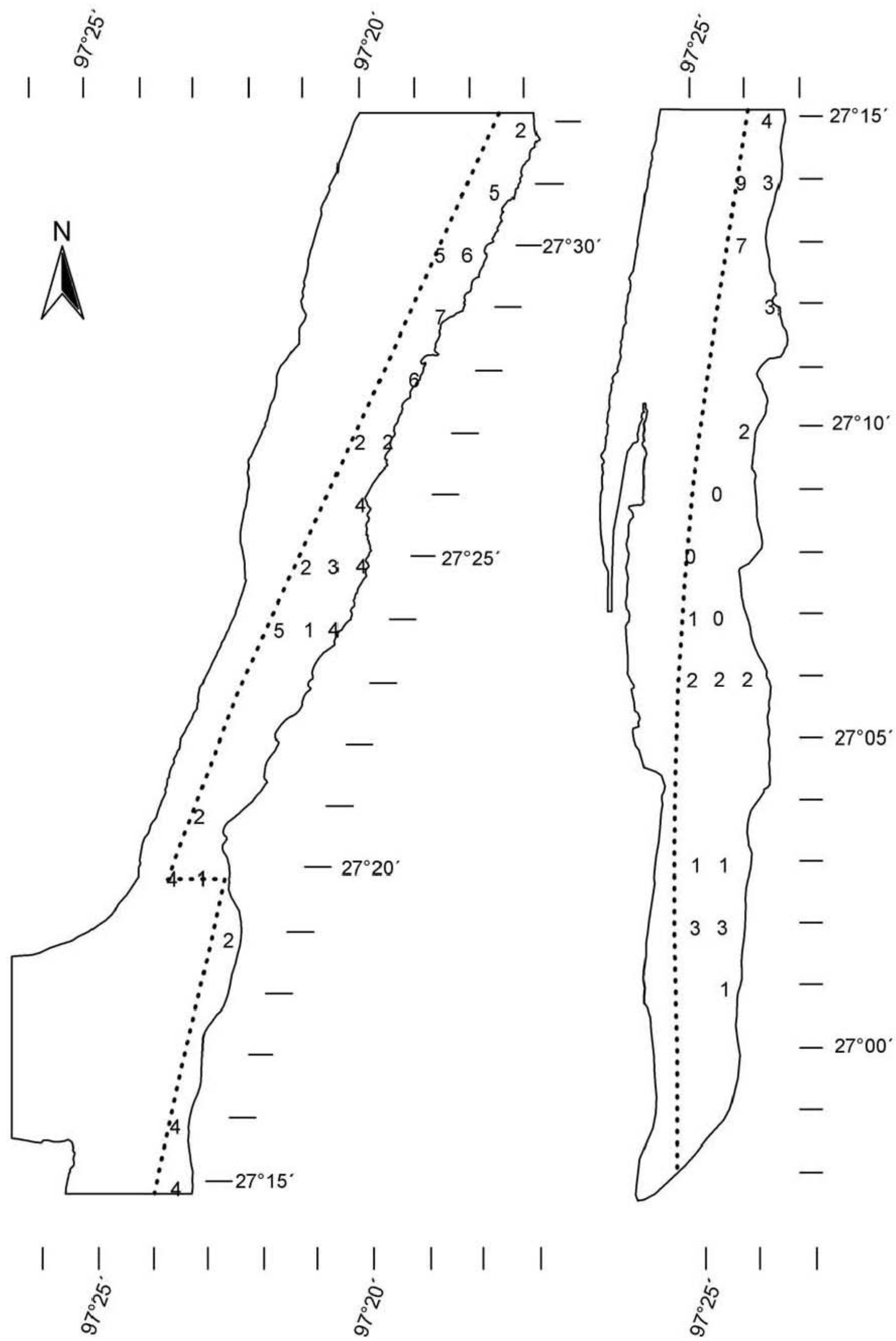

Figure 14. Mean dead biomass determined from four samples collected at each station in the 1′ latitude by 0.5′ longitude sampling grid (see fig. 1) expressed as 10 percentile classes of highest mean dead biomass found in the study.

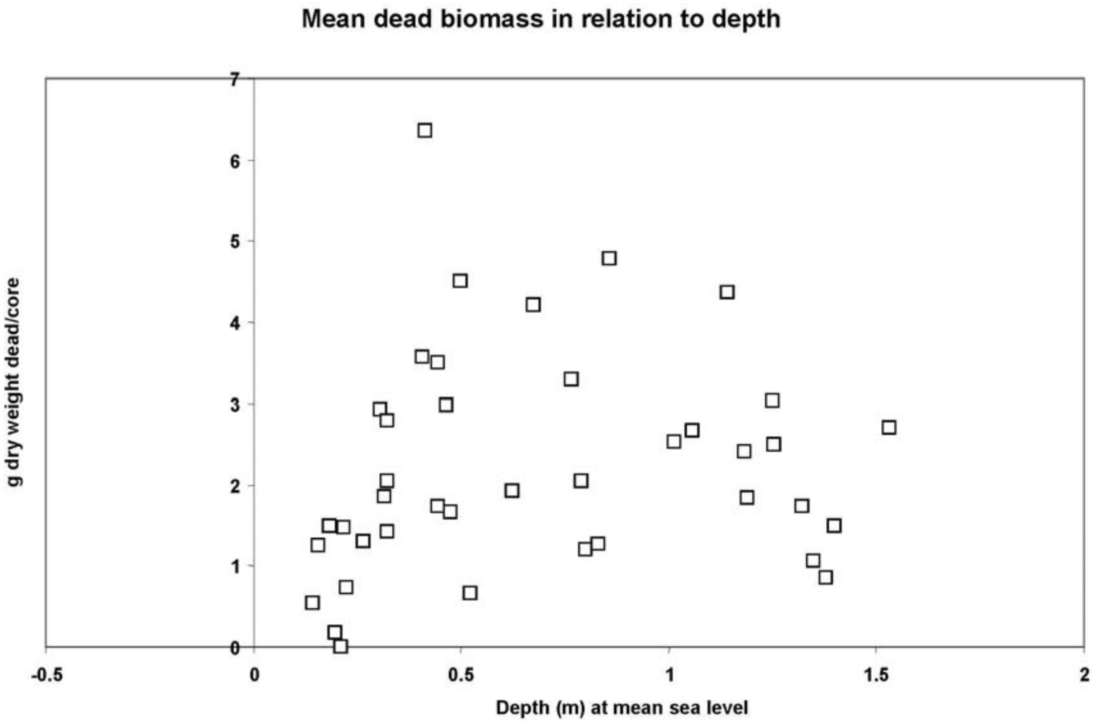

Figure 15. Mean dead biomass in relation to depth.

Biomass in Relation to Other Measures of Condition

Average shoot density and average plant height at different sample sites accounted for some of the variation in biomass encountered in the study (r^2 = 33 percent and 38 percent, respectively, table 1). The product of average shoot density and average plant height had greater predictive value of biomass (r^2 = 59 percent, table 1).

Table 1. Regression analyses of biomass on mean shoot length (in centimeters), mean shoot density (mean number × m^{-2}), and mean shoot length multiplied by mean shoot density.

[A, mean shoot length; B, mean shoot density; C, mean shoot length multiplied by mean shoot density]

A.	biomass = 9.6024 × mean shoot length + 3.3792, df = 38, r^2 = 0.3846
B.	biomass = 0.0288 × mean shoot density + 41.946, df = 38, r^2 = 0.3316
C.	biomass = 0.8596 × mean shoot length × mean shoot density + 30.285, df = 38, r^2 = 0.5891

Discussion

Seagrasses cover 6,284 ha or greater than 60 percent of the bottom of Laguna Madre below mean sea level within the boundaries of Padre Island National Seashore. Although four previous surveys of seagrasses in Laguna Madre encompassed the study area within the national seashore, differences between surveys in methodologies used, accuracy of boundary determinations, interpretation of the extent of the regularly submerged part of the lagoon, and intensity of groundtruthing preclude quantitative assessments of change over time. The definition of the landward limit of regular submergence and seagrass cover is especially problematic in the areas of vast wind-tidal flats on the east side of Padre Island opposite Point of Rocks from latitude 27°21’ to latitude 27°18’ and north from Nine-Mile Hole at latitude 27°00’ to latitude 27°10’. The landward limit is most apparent in the lobe of upland south of latitude 27°10’ extending beyond the western boundary of Padre Island National Seashore in the surveys from the 1960s and 1988, which was determined to be shallow bare or seagrass covered in the surveys of 1998 and 2002–03 (fig. 2). The reason for this difference in classification is that the area is extremely difficult to access and is exposed for much of the year. Sampling for the 1998 and 2002–03 surveys was intentionally scheduled for the fall period of predictable high water in the lagoon. Although undetectable in aerial photographs, very sparse seagrass was found over much of the area. This area was not sampled in the earlier surveys. In addition, approximate mean sea level could be determined for the last two surveys by adjusting depths measured at sample locations by deviation from simultaneous mean sea level measured at the Texas Coastal Ocean Observation Network water level monitoring station near South Bird Island. Despite the greater accuracy and precision of these surveys, considerable uncertainty remains in interpolating mean sea level between sampling transects in the absence of signatures in DOQQs.

Although quantitative estimates of changes between surveys are not warranted, some major qualitative changes in distribution are evident that far exceed what can be accounted for by methodological differences. At the southern end of the study area, seagrass cover was absent in the 1960s, was continuous in the 1970s, and has been a shifting mosaic since then (fig. 2). The maximum depth of this part of the lagoon is less than 1 m at m.s.l. The other section of the lagoon in which major changes in seagrass cover have occurred is north from latitude 27°20’ to latitude 27°25’. Here, a large expanse of open water almost completely filled in with seagrass between the surveys from the 1960s and 1988. The bare area then expanded almost to the eastern shore between 1988 and 1998 and was little different in the 2002–03 survey. Unlike the dynamic area in the south, much of this area is greater than 1 m at m.s.l. in depth.

Measures of seagrass condition are not available in sufficient detail for earlier surveys to make any inferences about possible causes of major shifts in distribution; however, comparisons of measures of condition made in this study between stable areas and areas that have experienced widespread loss or recovery of seagrass may be informative about underlying causes. Perhaps the most widely reported measure of seagrass condition is maximum depth of occurrence at a location (Duarte, 1991). The absence of seagrass in deep water is a consequence of light limitation—available light at those depths being insufficient to meet the maintenance requirements of the plants. Where conditions are otherwise satisfactory, maximum depth of occurrence is a sensitive indicator of water clarity. The changes in seagrass distribution between latitude 27°20’ and latitude 27°25’ in relatively deep water therefore suggest the involvement of changes in water clarity. Although the determination of the outer edge of the seagrass meadow in this area in 1988 was by dead reckoning along two transects and possibly in error by as much as 100 m, it still is possible to estimate the maximum depth of occurrence at that time by determining depth with respect to mean sea level now over the range of possible locations of the 1988 outer edge along the same two transects. According to this reconstruction, the outer edge had moved shoreward 121–333 m along one of the transects and 559–769 m along the other between 1988 and 2006, corresponding to estimated maximum depths of 1.42–1.61 m and 1.69–1.79 m in 1988 and 1.42 m and 1.15–1.41 m in 2006. Although the uncertainty of these reconstructions is large, the outer edge of the meadow has moved shoreward more than 100 m, and maximum depth of occurrence probably has decreased by more than 10 cm. The large uncertainty in maximum depth of occurrence on one of the transects in 2006 has resulted from seagrass being eliminated all the way up to the steep dropoff from a sand overwash fan such that depth changed 26 cm in the minimum 0.01' longitude (16 m) interval sampled for boundary determination.

The change in water clarity that was responsible for the large reduction in maximum depth of occurrence and area of seagrass coverage between 1988 and the later surveys was the Texas brown tide, a phytoplankton bloom of unprecedented duration, initiated in June 1990 and continually present through 1997 (Onuf, 2000, in press; Buskey and others, 2001). An independent, partial confirmation of this analysis is provided by observations made at two light monitors installed in this area in 1991—one at the outer edge of the meadow and one 200 m into the seagrass meadow. Within 1.5 years under the continuing influence of the brown tide, the outer edge of the seagrass meadow receded to the inner monitor (Onuf, 1996a) and has remained there ever since.

The lack of recovery between the surveys of 1998 and 2002–03, despite abatement of the brown tide in 1997, is cause for concern. One possible reason for the failure is low available light early in the growing season, which is a critical time for establishment of newly recruited plants, despite increased light for the year as a whole (Onuf, 2000). A second reason for the failure could be higher turbidity as a consequence of easier resuspension of sediments over a lagoon bottom that is no longer protected from wave action by a dense carpet of seagrass blades and roots and rhizomes. Also, although no bloom so long-lasting as the initial Texas brown tide event has occurred since, there has been a succession of shorter blooms, including another brown tide event as recent as December 2005. Data are inadequate to determine whether blooms occur more frequently in the lagoon now than in the past; however, for purposes of future management, it is important to be alert to the possibility that changes to the lagoon or its surroundings render it more susceptible to phytoplankton blooms and make the revegetation of deeper areas more difficult. The most obvious candidate is increased nutrient input, although there is no independent evidence to evaluate this possibility.

A latitudinal gradient in maximum depth of occurrence of seagrass is apparent in figure 3. The increase between latitude 27°15' and latitude 27°28' is probably indicative of increasing water clarity toward the north, away from the mouth of Baffin Bay, where high turbidity is frequent as a result of strong breezes blowing over long fetches and large expanses of bare bottom. In contrast, much more of the bottom is protected from sediment resuspension by a continuous carpet of seagrass, and wind fetch is much reduced over narrower parts of the lagoon toward the north end of Padre Island National Seashore. The shallow edge of seagrass meadow between 0 and 0.5 m at m.s.l. across most of the study area is probably set by exposure to air or wave action. The unusually deep shallow edge between latitude 27°23' and latitude 27°28' is in an area of abrupt dropoff from sand overwash fans. The absence of a deep edge in some areas indicates continuous seagrass cover extended to the western boundary of Padre Island National Seashore.

Changes in water clarity cannot account for all the changes in seagrass cover between surveys in the segment of Padre Island National Seashore between latitude 27°20' and latitude 27°25' (fig. 2) because a considerable part of the area is shallow enough that available light could not be limiting. The absence of seagrass from the shore zone (close to the Gulf Intracoastal Waterway, and north of latitude 27°24', as well as the whole area south of latitude 27°10') in the surveys from the 1960s is more likely a consequence of the relative isolation of these areas from source populations. According to this interpretation, seagrasses were absent from most of upper Laguna Madre, except close to Corpus Christi Bay before construction of the Gulf Intracoastal Waterway in 1949, because of extreme hypersalinity beyond the tolerance of all seagrass species. Completion of the waterway through the Land Cut, a 20-km reach of the Laguna Madre only submerged during extreme high water conditions, provided a continuous water connection between upper and lower Laguna Madre. This connection afforded greater water exchange within the lagoon and with the Gulf of Mexico, resulting in moderation of the salinity regime of the lagoon to within the limits of seagrasses (Quammen and Onuf, 1993). The gradual expansion of seagrass cover through 1988 was the result of colonization of areas where seagrasses previously could not survive (Onuf and others, 2003).

No obvious environmental changes have been observed to account for the large fluctuations of seagrass cover in Nine-Mile Hole between latitude 27°00’ and latitude 27°05’ (fig. 2); however, one measure of plant condition, plant height, is maximal in this dynamic area. The 7 highest values of this measure out of a total 77 obtained in this study all were from the hole (fig. 6, values greater than 6, greater than or equal to 70 percent of the greatest mean plant height measured in the study). All seven were from locations that had been thickly vegetated in 1988, were bare in 1998, and were again vegetated in 2003 (fig. 16). Apparently, plant height is a sensitive indicator of recovery but not an indicator of impending loss, as would be more valuable in management. Morris and Virnstein (2004) have documented a similar case of dramatic loss and recovery of *Halodule wrightii* in a shallow embayment of the northern Indian River Lagoon, Fla., with no clear cause. Perhaps these systems with restricted water exchange are prone to produce too much biomass to be sustained under conditions where much dead material that they themselves produce may accumulate, augmented by drift algae and dead material deposited from elsewhere. The very high pore water ammonium levels found in this same area by Fellows (2004) in another element of this project are consistent with the luxuriance of the vegetation in the recently colonized sites described here. Decomposition of the vegetation lost between 1988 and 1998 fertilized the substrate that was recolonized between 1998 and 2003.

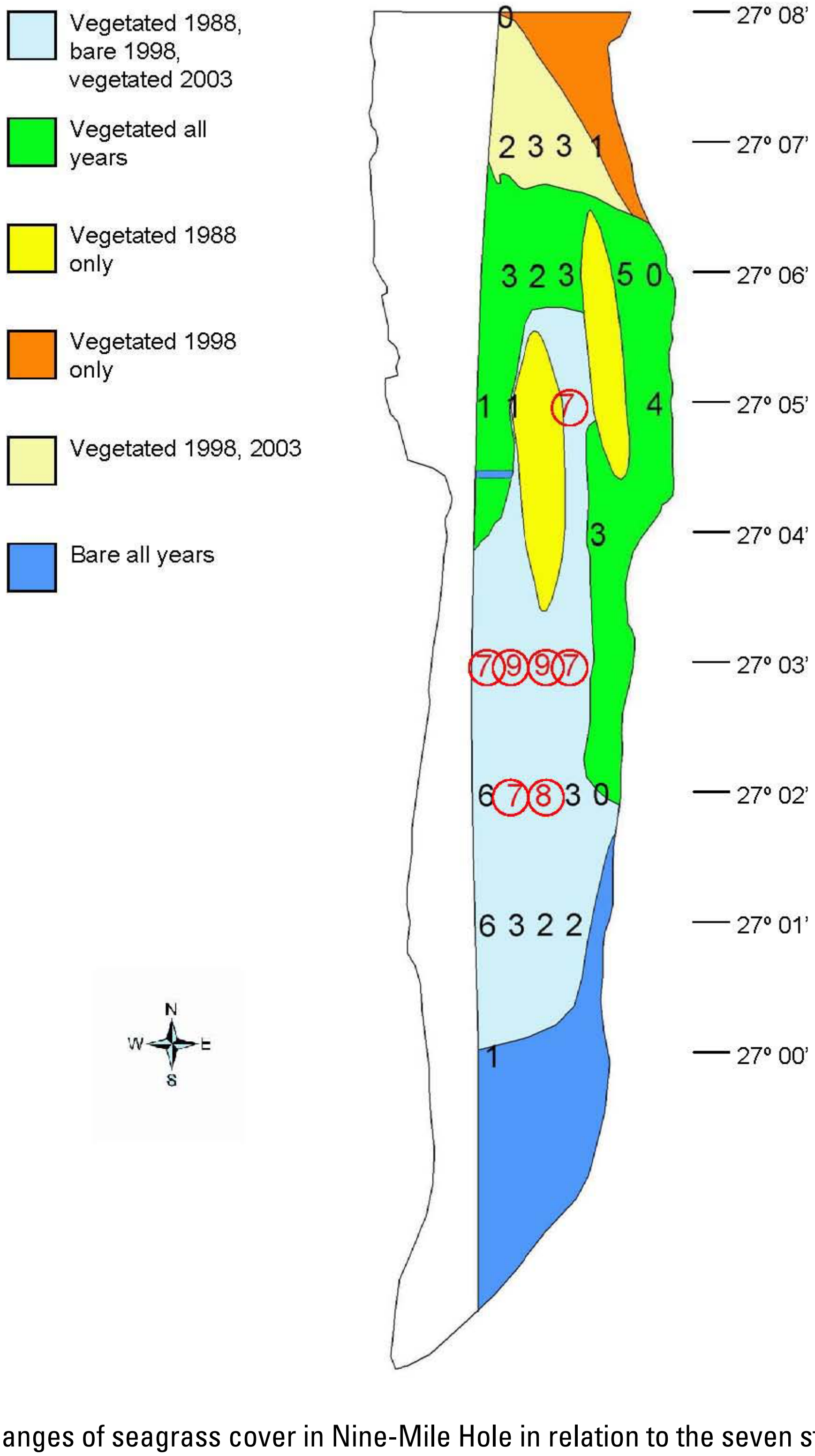

Figure 16. Changes of seagrass cover in Nine-Mile Hole in relation to the seven stations with tallest seagrass found in the study.

No other associations between measures of condition and changes in seagrass distribution were found in this study; however, the data collected may serve as a baseline against which to assess future change. Continuity of cover, as indicated by number of samples at a location out of five possible with seagrass present, is high except where adjacent to bare areas (fig. 4). This pattern suggests that increased frequency of bare cores within seagrass meadow may be a precursor to bed loss and a diagnostic of adverse change before complete loss occurs. Unfortunately, this measure can only be obtained from a major field-sampling program. An alternative may be to identify bed fragmentation in fine-scale aerial photography, as proposed by Pulich (2006).

Mean plant height, shoot density, shoot density multiplied by shoot length, live biomass, and dead biomass all tend to have their lowest values at the shallow end of their depth range, highest values at intermediate depths, and intermediate values in deep water (figs. 7, 9, 11, 13, 15), but shoot densities are both highest and lowest in shallow water (fig. 9). All measures are so variable that they require unfeasibly great effort to detect change over time. Live biomass in this study was somewhat lower than reported for the same general area in 1988 (Onuf, 1996b, fig. 12, upper Laguna, east); however, areas in the vicinity of deep edges of seagrass meadow and extensive areas of very shallow flats that were sampled in 2002–03 were not sampled in 1988, increasing the representation of low biomass areas in 2002–03 as compared to 1988. This bias cannot be fully analyzed because it was not possible to refer to depths of sample sites to a standard datum in 1988 as it was in 2002–03.

An additional limitation to identifying patterns in this data set is that different parts of the study area were sampled in the autumns of two different years. Live biomass, the one plant characteristic checked for this possibility, was substantially higher in 2002 than in 2003, perhaps compromising the validity of some of the spatial patterns described or obscuring a pattern that could have been detected if year and location had not been confounded. Because of the qualifications inherent in other parameters, sensitivity of plant height to recent recolonization and possible changes in continuity of cover appear to be the most promising indicators of condition considered in this study.

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User Guide

Directions for Displaying Data in ArcView™

ArcView™ GIS projects seagrass distribution and seagrass condition. Projects were created by using ArcView™ GIS version 3.3. The folder PAIS GIS, located in the provided attachment, contains both projects and the various files associated with each.

Opening Seagrassdistribution.apr

1. Copy the folder "paisgis" from the provided attachment to the root (C:) drive of the computer being used.
2. Open ArcView™ GIS version 3.3 or higher.
3. Click "file."
4. Click "open project."
5. Select the (C:) drive.
6. Open the folder "paisgis" located on the (C:) drive.
7. Open the folder "Seagrass Distribution."
8. Select Seagrassdistribution.apr, and click "OK."

Seagrassdistribution.apr contains one view (View1), which is now open. View1 is made up of 8 themes and 14 USGS digital orthophoto quarter quads. Themes can be overlaid independently or together as layers on the orthophoto quarter quads. The following eight themes are located in the column (Table of Contents) to the left of the view.

Boundary.shp – Padre Island National Seashore western boundary within Laguna Madre.

Mapticks.shp – White crosses represent associated latitude and longitude.

Seagrass.shp – Red polygons represent the area of seagrass meadow within the boundaries of Padre Island National Seashore.

Noseagrass.shp – Yellow polygons represent the area without seagrass in the subtidal portion of Laguna Madre within the boundaries of Padre Island National Seashore.

Waterarea.shp – Green polygons represent estimated mean sea level of Laguna Madre within the boundaries of Padre Island National Seashore.

Coresamples.shp – Colored squares represent stations where seagrass samples were collected.

- Alldepth.shp – Green circles with associated depths (cm) with respect to mean sea level for all locations sampled.

- Edgedepth.shp – Blue circles with associated depths (cm) with respect to mean sea level for edges (shallow or deep) of seagrass meadow.

Activating and Displaying Themes

Click the name of the theme you want to make active. When a theme is active, it appears highlighted (raised up) in the Table of Contents. Editing a theme or viewing the theme's properties can only be done when the theme is active. The box next to the theme name is used to turn the theme on or off (display within the view or not display within the view). All themes can be made active by clicking on the theme's name. All themes can be turned on or off by clicking the box to the left of the theme name. Seagrass.shp is currently active (appears raised) and is turned on (box is checked).

1. Click the box to the left of Noseagrass.shp to turn on this theme.
2. Click the box to the left of Seagrass.shp to turn it off.
3. Click on the theme name Noseagrass.shp to make it active.
4. Click on the theme name Seagrass.shp to make it active.
5. Click on the box to the left of Noseagrass.shp to turn it off; click on the box to the left of Seagrass.shp to turn it back on.

All themes can be turned on and off or activated and deactivated in this manner. A theme does not have to be active to be turned on (box checked).

The bar at the top of the screen contains two rows of various buttons and tools used to work with the features of a theme. The buttons make up the top row; the tools are in the bottom row. The name of a particular button or tool can be viewed by resting the pointer on it.

Explanation and Use of Themes

Boundary.shp
Padre Island National Seashore western boundary within Laguna Madre.

1. Click the box to the left of Boundary.shp to turn on this theme.

Mapticks.shp
White crosses represent associated latitude and longitude.

1. Click the box to the left of Mapticks.shp to turn on this theme.

Seagrass.shp

Red polygons represent the area of seagrass meadow within the boundaries of Padre Island National Seashore. All polygons in this project are identified by a number displayed within or next to the polygon.

The "Zoom In" tool is required to properly interpret some themes.

1. Click the "Zoom In" tool.
2. Using the mouse, place the "Zoom In" tool in the upper left section of the area you wish to magnify.
3. Hold down the left mouse button and drag a box over the area of interest. Release the mouse button when the desired box is drawn.
4. If a mistake is made, locate and click the "Zoom to Full Extent" button to return to a full view of the project.
5. Repeat step 3, and zoom in again.
6. Click the pointer tool.
7. Use the pointer to identify the "Zoom to Previous Extent" and "Zoom to Full Extent" buttons.
8. Click the "Zoom to Previous Extent" button to return to the previous view size.
9. Click the "Zoom to Full Extent" button to return to a full view of the project.

The "Pan" tool lets you pan the view by dragging the display in any direction with the mouse.

1. Click the "Zoom In" tool and use it as described previously to zoom in on a particular area of the view.
2. Click the "Pan" tool.
3. Place the "Pan" tool anywhere over the view, hold down the left mouse button, and drag in any direction. Release the mouse button to leave the view in your desired position.
4. Click the "Zoom to Full Extent" button to return to a full view of the project.

Viewing Tables

Themes Seagrass.shp and Noseagrass.shp have associated tables. Tables identify each polygon by number and provide the following information for each polygon: Area (km^2), Perimeter (km), Acres, and Hectares. Tables can be exported to spreadsheets for manipulation and analysis.

"Open Theme Table" Button

1. Use the pointer to identify the "Open Theme Table" button.
2. Click the "Open Theme Table" button to view the table for Seagrass.shp.

Exporting Tables

3. With the table open, click "file."
4. Click "export."
5. Click "dBASE" as the export format you wish to use, and click "OK."
6. Select the directory and folder where you would like to save the table.
7. Click "OK."
8. Click the X box in the upper right corner of table to close the table.

"Theme Properties" button

A brief description of the active theme can be viewed in the Comments Box of the Theme Properties.

1. Use the pointer to identify the "Theme Properties" button.
2. Click the "Theme Properties" button to view a description of Seagrass.shp.
3. Close the "Theme Properties" box.

Noseagrass.shp

Yellow polygons represent the area without seagrass in the subtidal portion of Laguna Madre within the boundaries of Padre Island National Seashore.

1. Click the box to the left of Noseagrass.shp to turn on this theme.
2. Click the theme name Noseagrass.shp to make it the active theme.
3. Use the "Zoom In" tool to look at areas of interest and "Zoom to Full Extent" when finished.
4. Click the "Open Theme Table" button to view the table for Noseagrass.shp and close the table when finished.

Waterarea.shp

Green polygons represent estimated mean sea level of Laguna Madre within the boundaries of Padre Island National Seashore.

1. Click the box to the left of Waterarea.shp to turn on this theme.

Coresamples.shp

Each square represents a station where seagrass samples were collected. The white squares represent no seagrass present in samples. The green squares represent seagrass present in one or two samples out of four or five possible. The red squares represent seagrass present in more than two samples out of four or five possible. The "Zoom In" tool is required to properly interpret this theme.

1. Click the box to the left of Coresamples.shp to turn on this theme, and click the theme name to make it active.
2. Use the “Zoom In” tool to drag a box over an area of interest.
3. Repeat step 2 until desired separation of sampling stations of interest is achieved.
4. Click “Zoom to Full Extent.”
5. Turn off Coresamples.shp.

● Alldepth.shp
Green circles with associated depths (cm) with respect to mean sea level for all locations sampled. The “Zoom In” tool is required to properly interpret this theme.

1. Turn on Alldepth.shp.
2. Use the “Zoom In” tool to achieve desired separation for depths of sampling locations.
3. Click “Zoom to Full Extent.”
4. Turn off Alldepth.shp.

● Edgedepth.shp
Blue circles with associated depths (cm) with respect to mean sea level for edges (shallow or deep) for seagrass meadow. The “Zoom In” tool is required to properly interpret this theme.

1. Turn on Edgedepth.shp.
2. Use the “Zoom In” tool to achieve desired separation of depths at edges.
3. Click “Zoom to Full Extent.”
4. Turn off Edgedepth.shp.

Close project Seagrassdistribution.apr.

1. Click “file,” “close,” “file,” “close project.” Do not save changes.

Seagrasscondition.apr

This project was created for the purpose of displaying seagrass condition data as overlays of the orthophoto quads. These data are also provided as hardcopy outline maps. Seagrasscondition.apr (located in the “Seagrass Condition” folder) contains two views: SeagrassConditionNorth and SeagrassConditionSouth. Each view contains the following six themes, which are designed to be turned on and viewed independently with no magnification required.

Continuity.shp – Number of samples out of a possible four or five with seagrass.

Shootlength.shp – Mean shoot length.

Shootdensity.shp – Mean shoot density.

Lengthxdensity.shp – Mean shoot length multiplied by mean shoot density.

Biomasslive.shp – Live biomass.

Biomassdead.shp – Dead biomass.

Mean shoot length, mean shoot density, mean shoot length multiplied by mean shoot density, and biomass data were normalized for map display by computing the value of each measure for each station as a percent of the maximum value sampled in the study and expressing it in a scale from 0 to 9, where 0 corresponds to the interval from 0 to less than 10 percent of the maximum found in the study, 1 corresponds to the interval from 10 to less than 20 percent, and so on.

Seagrasscondition.apr can be opened and data displayed by following the procedures listed above for opening and displaying data in Seagrassdistribution.apr.

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