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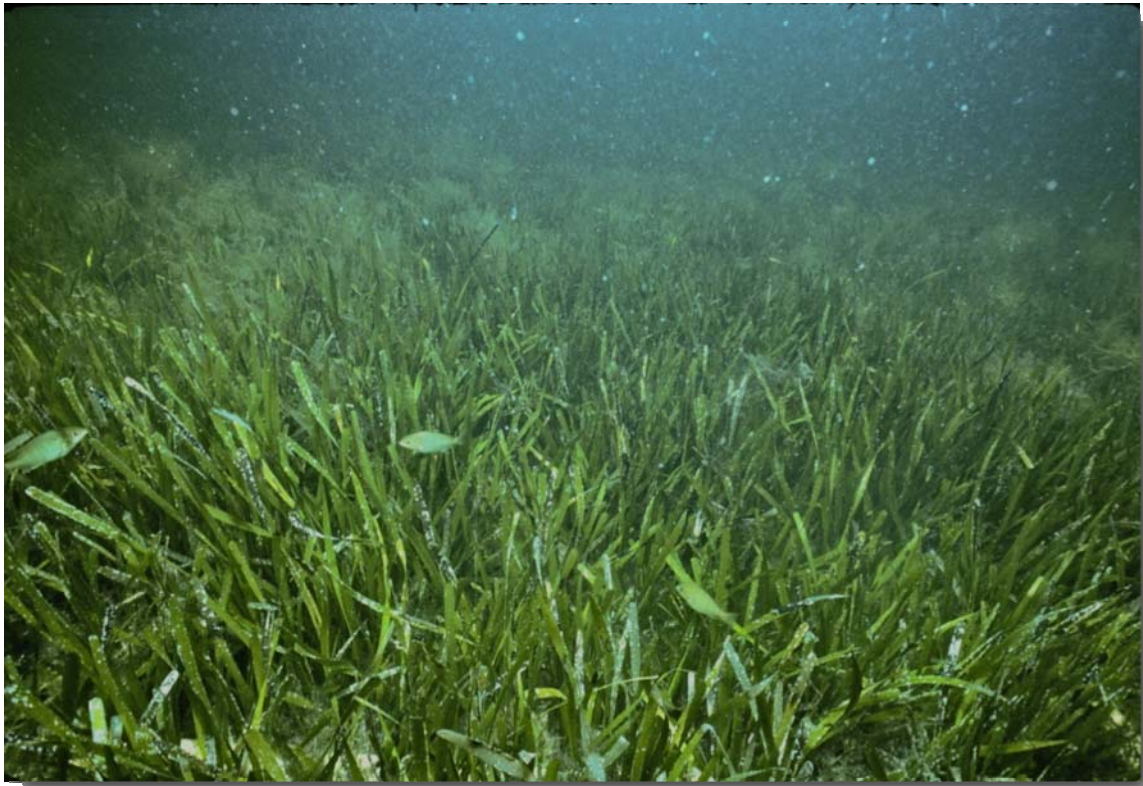
Contract No. 0627

to

Coastal Bend Bays & Estuaries Program

1305 N. Shoreline Blvd., Suite 205
Corpus Christi, Texas 78401

A SEAGRASS MONITORING PROGRAM FOR TEXAS COASTAL WATERS:

MULTISCALE INTEGRATION OF LANDSCAPE FEATURES WITH PLANT AND WATER QUALITY INDICATORS

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EXECUTIVE SUMMARY

This report outlines an implementation program for monitoring Texas seagrasses following protocols that evaluate seagrass condition based on landscape-scale dynamics. We recommend a **hierarchical strategy for seagrass monitoring** in order to establish the quantitative relationships between physical and biotic parameters that ultimately control seagrass condition, distribution, and persistence. The monitoring protocols are based on conceptual models that link: (1) light and nutrient availability to seagrass condition indicators and landscape level dynamics, including patchiness and depth limit distributions, and (2) physico-mechanical stressors, including hydrodynamic processes and human activities, to landscape feature indicators of seagrass bed degradation. The three-tiered approach follows a broad template adopted by several federal and state agencies across the country, but which is uniquely designed for Texas. This plan accommodates the immense hydrographic diversity in the State's estuarine systems and its associated seagrass habitats, recent advances in seagrass monitoring techniques, and current economic constraints associated with long-term studies. Based on this approach, we describe a multiscale monitoring protocol that, when implemented, integrate plant condition indicators with landscape feature indicators to detect and interpret seagrass bed disturbances. The program includes:

- a remote sensing component at two levels of resolution for status and trends mapping [Tier 1] and high resolution photoimagery analysis for deep edge delineation [Tier 2],

- a regional rapid assessment program using fixed stations sampled annually from a shallow-draft vessel [Tier 2] and,

- an integrated landscape approach that includes permanent stations and transects that are aligned with high resolution photoimagery to examine the presumptive factors associated with changes in seagrass maximum depth limits and patchiness [Tier 3].
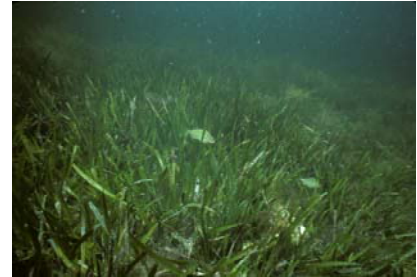
Active involvement and support from the Texas Seagrass Monitoring Work Group in all aspects is critical to the implementation of a coast-wide seagrass monitoring program. Tier 1 monitoring has already been implemented by state agencies in cooperation with federal mapping efforts. We envision a program of implementation that encourages cooperation and support among the state and federal agencies responsible for the stewardship of these valuable coastal habitats.
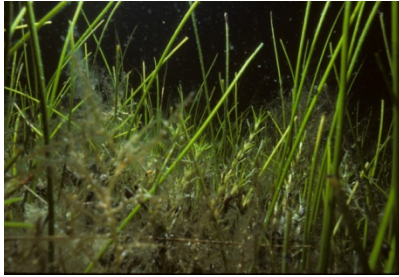
Syringodium filiforme   Aerial view of seagrass beds   *Thalassia testudinum*

INTRODUCTION

In 1999, the Texas Parks and Wildlife Department (TPWD), along with the Texas General Land Office (TGLO) and the Texas Commission on Environmental Quality (TCEQ), drafted a Seagrass Conservation Plan that proposed, among other things, a seagrass habitat monitoring program (Pulich and Calnan, 1999). One of the main recommendations of this plan was to develop a coastwide monitoring program. In response, the Texas Seagrass Monitoring Plan (TSGMP) proposed a monitoring effort to detect changes in seagrass ecosystem conditions prior to actual seagrass mortality (Pulich et al., 2003). However, implementation of the plan required additional research to specifically identify the environmental parameters that elicit a seagrass stress response and the physiological or morphological variables that best reflect the impact of these environmental stressors.

Numerous researchers have related seagrass health to environmental stressors; however, these studies have not arrived at a consensus regarding the most effective habitat quality and seagrass condition indicators. Kirkman (1996) recommended biomass, productivity, and density for monitoring seagrass whereas other researchers focused on changes in seagrass distribution as a function of environmental stressors (Dennison et al., 1993, Livingston et al., 1998, Koch 2001, and Fourqurean et al., 2003). The consensus among these studies revealed that salinity, depth, light, nutrient concentrations, sediment characteristics, and temperature were among the most important variables that produced a response in a measured seagrass indicator. The relative influence of these environmental variables is likely a function of the seagrass species in question, the geographic location of the study, hydrography, methodology and other factors specific to local climatology. Because no generalized approach can be extracted from previous research,

careful analysis of regional seagrass ecosystems is necessary to develop an effective monitoring program for Texas.

A second approach to determining seagrass condition involves a combination of remote sensing data analysis, coupled with field sampling, to examine plant response at landscape or bed scales (Bell et al., 2006). Field-based sampling of plant condition indicators and environmental variables involves processing a large volume of point samples collected over broadly distributed sampling sites. Concurrent analysis of high-resolution aerial photography or digital imagery can provide an additional layer of resolution to these spatial approaches, but historically this has been labor-intensive, and analytical techniques have needed refinement. However, early detection of impending impairments to seagrass ecosystems may be possible if point measurements of habitat quality and seagrass condition indicators are correlated with prominent landscape features and seagrass bed morphological patterns in high resolution imagery. Such an analysis would help separate hydrodynamic stressors from human impacts that are most often reflected in landscape patterns and apparent in high resolution aerial photography.

Because of the complexity of these systems, it is important to identify the factors that drive seagrass dynamics. At both micro- and bed-scales, stress - response relationships must be examined carefully. Environmental stressors can influence seagrass condition directly, eliciting a positive or negative effect, or they may act indirectly through interaction with other variables. Consequently, identifying causative factors requires deciphering complex interactions at both point- and landscape scales.

Figure III.1 – Texas seagrass monitoring program regions. Regions include Christmas Bay and Galveston Bay in the Trinity-San Jacinto estuary (Region 1), the Matagorda Bay system in the Guadalupe estuary (Region 2), the San Antonio Bay area (Region 3), the Mission-Aransas National Estuarine Research Reserve, including Aransas and Copano Bays (Region 4), south Redfish Bay and southeast Corpus Christi Bay in the Nueces estuary (Region 5), the Upper (Region 6), and Lower Laguna Madre (Region 7).

In a recent Coastal Bend Bays and Estuary Program (CBBEP) study, we used a multi-scale approach to identify the measurements best suited to initiate a seagrass monitoring program for the state of Texas. The overarching goal of this study was to validate a landscape analysis approach to seagrass monitoring and establish protocols to evaluate stress on seagrass systems. Our monitoring protocol builds on data obtained from recent ecosystem studies that included intensive field sampling of environmental variables (Chapter 1) in combination with landscape analyses of true color aerial photoimagery (Chapter 2). Our major objectives addressed (1) the development of a conceptual "working" model that outlines the important linkages among stressors and condition indicators, (2) identification of the relevant environmental and landscape indicators that are responsive to both natural and anthropogenic stressors, and (3) the development of a hierarchical strategy for seagrass monitoring in Texas coastal waters. This plan incorporated the utilization of both new and historical data to establish the natural baselines of condition indicators to enable status and trends assessment of seagrass populations unique to Texas estuarine systems. Our approach was entirely inclusive of the known distribution of seagrasses along the entire Texas coast, from Galveston to the Brazos Santiago Pass near the U.S.-Mexican border (Fig. III.1).

OVERALL PROJECT SCOPE AND OBJECTIVES

The objectives of the recent CBBEP-funded project were to (1) design a monitoring program to detect environmental changes with a focus on the ecological integrity of seagrass habitats, (2) provide insight to the ecological consequences of these changes, and (3) help decision makers (e.g. TPWD, TCEQ, TGLO) determine if the observed change necessitated a revision of regulatory or management policy or practices. We defined ecological integrity as the capacity of the seagrass system to support and maintain a balanced, integrated, and adaptive community of flora and fauna including its historically characteristic seagrass species. Ecological integrity is assessed using a suite of condition indicators (physical, biological, hydrological, and chemical) measured on different spatial and temporal scales.

In this chapter we summarize our preliminary results that provide a framework for discussion and consideration by the Seagrass Monitoring Work Group (SMWG), a State advisory group formed in 2004. This group is composed of knowledgeable scientists and natural resource managers from local universities and a variety of local, state, and federal agencies (e.g. USGS-NWRC, USF&WS, TPWD, TCEQ, TGLO, and USACE). Other sources of information include EPA's R-EMAP (Regional Environmental Monitoring and Assessment Program), which utilized conceptual models as part of the EMAP process, and on-going seagrass monitoring programs in the Florida Keys National Marine Sanctuary (FKNMS, Fourqurean et al,. 2002), Chesapeake Bay (Moore and Reay 2009), Indian River Lagoon in Florida (Mattson 2000), the northeastern United States (Neckles et al., 2010), and Puget Sound, Washington (Dowty et al., 2005). Our products include a conceptual model that can help guide selection of appropriate environmental, water quality and landscape indicators with respect to stressors, the selection of appropriate indicators based on a variety of criteria, and the collection of baseline data associated with the development of a coast-wide monitoring effort to assess seagrass status and trends.

A Conceptual Model (Version 1)

It is important to develop a conceptual model that outlines the linkages among seagrass ecosystem components and the role of indicators as predictive tools to assess seagrass response to stressors at various temporal and spatial scales. Tasks for this objective include the identification of stressors that arise from human-induced disturbances which can result in seagrass loss or compromise seagrass condition (health). For example, stressors that lead to higher water turbidity and light attenuation (e.g. dredging, and shoreline erosion) have been shown to result in lower below-ground seagrass biomass and changes in sediment nutrient concentrations. The linkage between light attenuation and plant response is often evaluated through long-term light measurements, examination of porewater nutrient, sulfide, and dissolved oxygen levels, and the biomass of above- versus below-ground tissues (Fig. III.2).

An exhaustive listing of anticipated stressors, the ecological consequences of stressor action, and how they would be measured are first steps toward indicator identification and selection. Conceptual models can help show the linkages between stressors and their consequences and

summarize how a given component functions. These exercises will provide a current understanding of ecosystem processes and cause-and-effect relationships, which are critical to appropriate indicator selection. These models can be built at several different scales to accommodate the complexity of the system, the variety of stressors, and the possible synergisms with natural disturbance events. It is important to integrate scales of time/space with dynamic processes (e.g. nutrient cycling, trophic interactions).
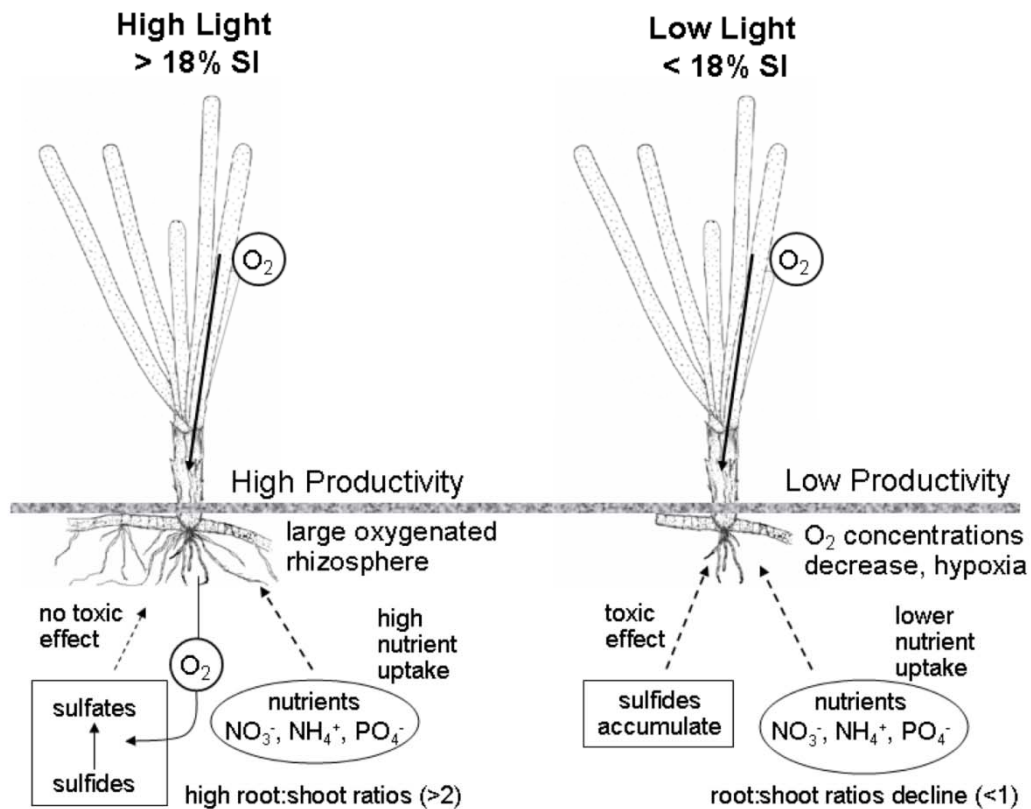

Figure III.2 - Effect of light attenuation on seagrass productivity, sediment chemistry, and root:shoot biomass ratios. Photosynthetic oxygen transported into seagrass roots and rhizomes plays a significant role in the maintenance of aerobic conditions in the rhizosphere. Light attenuation that drops the percent surface irradiance (SI) to less than 18% (for seagrasses in the northwestern Gulf of Mexico) produces less oxygen for below-ground tissue respiration, which can result in build-up of sulfides and ammonium, toxic to seagrasses at high concentrations (from Dunton, unpub. and Mateo et al., 2006).

Environmental and Landscape Indicators

Relevant and measurable environmental, water quality and landscape indicators must be sensitive to human-induced activities and accurately characterize the condition of seagrass communities within the major estuarine systems of Texas. The success of a monitoring program is related to the choice of condition indicators that are (1) reflective of a seagrass ecosystem response, (2) linked to a cause-effect process identified in the conceptual model, and (3) measured at reasonable cost and effort. In our CBBEP project, we provided a list of candidate indicators (Table III.1) based on an evaluation of measurements collected in two estuarine systems between 2003 and 2005 (Dunton et al., 2005). We focused on those indicators with the following properties:

- unambiguously related to conceptual models

- relatively simple to measure and not influenced by observer subjectivity

- consistently responsive to change

- accurately and precisely estimated

- possess measurable changes in magnitude

- natural variability is readily distinguished from background

- societal relevance

- integrative qualities

Table III.1. Some recommended condition indicators for inclusion into an integrated seagrass monitoring program for Texas coastal waters based on Neckles (1994), Dunton et al. (2005), and this study.

Water Quality	Sediment Quality	Seagrass Light Response Indicators	Plant Nutrient Response Indicators
dissolved oxygen	grain size	biomass (above- & below-ground)	C:N:P blade ratios
conductivity, salinity, and temperature	total organic carbon	root:shoot ratio	epiphytic algal species composition and biomass
nutrients (NH_4^+, NO_3^-, NO_2^-, PO_4^{-3})	porewater NH_4^+	percent cover and related morphometric data (blade width, blade height)	drift macroalgal abundance and composition
chlorophyll *a*		shoot density	$\delta^{13}C$ and $\delta^{15}N$ of leaf tissues and attached algal epiphytes
total suspended solids (TSS)		chlorophyll fluorescence	
light attenuation (*k*)		species composition	
surface irradiance (%SI)		maximum depth limit	

We plan on utilizing certain candidate indicators in the existing literature for the proposed study. Starting in 2002, core EMAP seagrass indicators were measured (Neckles, 1994) along with additional parameters in Laguna Madre and Redfish Bay from 2002-2004 (Dunton et al., 2005) and in Redfish Bay and East Flats in 2005 (this study). The 2005 project (Chapters 1-2, this report) also addressed landscape indicators for seagrass monitoring to establish protocols for evaluating stress on seagrass systems from landscape-scale dynamics determined from aerial remote sensing data. In addition to the indicators listed in Table III.1, other possible candidates

include leaf scars on individual shoots (to assess growth), assessment of seed reserves, and benthic infaunal diversity.

Table III.2. Indicators and proposed measurement frequency under a Tier 2 (annual) seagrass monitoring program. Note: k = light attenuation, %SI = percent surface irradiance, PDR = Precision Depth Recorder. Asterisks denote minimum criteria for a Tier 2 sampling effort.

Indicator	Field Method
Stressor	
*k, %SI	underwater light sensor
*water transparency	Secchi
*depth	PDR
*temperature, salinity, pH, dissolved oxygen	SONDE
*TSS	water collection
NH_4^+, NO_3-, PO_4^{-2}	water collection
*chl a	in situ fluorescence
drift algal biomass	0.25 m^2 quadrats
sediments (grain size/organics)	benthic cores
algal epiphyte biomass	benthic cores
Seagrass Condition Indicator	
canopy height	benthic cores
shoot density	benthic cores
seagrass biomass	benthic cores
root:shoot ratios	benthic cores
*seagrass species composition	0.25 m^2 quadrats
C:N:P and ^{15}N:^{14}N ratios	benthic cores
*percent cover	0.25 m^2 quadrats

Our recommended list of Tier 2 indicators for annual sampling (Table III.2) is based on data collected in Texas estuarine seagrass systems that is available in over 20 peer-reviewed publications, numerous M.S. and Ph.D. theses, and various unpublished reports. These data represent an extremely valuable source of historical measurements collected over the past two decades in seagrass systems located from Lower Laguna Madre to San Antonio Bay in the Guadalupe Estuary. In addition, information from other seagrass monitoring programs across the U.S. (referenced above) has also proved an invaluable set of resources.

We examined many of these condition indicators at 40 sites in seagrass beds of Redfish Bay and East Flats to determine the strength of their relationship with seagrass biomass, density, cover and community composition (Chapter 1). Strong relationships would have suggested possible stressors as well as identify potential indicators of current and future seagrass condition. We used both univariate and multivariate statistical analyses to assess these relationships and identify candidate variables for inclusion in a monitoring program. All variables except N:P of *Thalassia testudinum* leaves exhibited significant site x sampling date interaction terms, indicating both spatial and temporal variability in Redfish Bay and East Flats. Parametric and nonparametric analyses, however, revealed only modest associations between both abiotic and biotic variables and seagrass measurements.

In many cases, dried seagrass tissues from quantitative samples have been archived and are available for constituent analysis. We are particularly interested in the differences in elemental ratios (carbon, nitrogen, and phosphorus) among estuaries that reflect nutrient availability (see below). At one site in Upper Laguna Madre, seagrass and water quality measurements have been collected continuously since 1989 (Dunton, 1994); the data and seagrass samples from this work are particularly appropriate for inclusion in our evaluation of condition indicators.

An increase in nutrient loading is one water quality change that is most likely to affect seagrass populations as a consequence of human population growth in coastal areas, and has already caused eutrophication of many estuaries. Nutrient concentrations are relatively low in seagrass-dominated environments and therefore, seagrasses are normally nutrient limited by either nitrogen (N) or phosphorus (P) (Fig III.3). Consequently, nutrient addition can shift the competitive balance from seagrasses to faster-growing primary producers, such as

phytoplankton, epiphytes, or benthic macroalgae. Under high nutrient concentrations, estuaries previously dominated by mixtures of turtle grass (*Thalassia*) and manatee grass (*Syringodium*), will revert to more weedy vegetative assemblages characterized by widgeon grass (*Ruppia*) and benthic seaweeds (Fourqurean and Rutten, 2003). Lapointe et al. (2004) found that the $\delta^{15}N$ values of macroalgae accurately identified different sources of nitrogen enrichment, from sewage to fertilizer. Consequently, changes in seagrass tissue stable isotopic composition may reveal the onset of environmental shifts in nutrient availability (Fourqurean et al., 2005) that can ultimately influence seagrass composition.
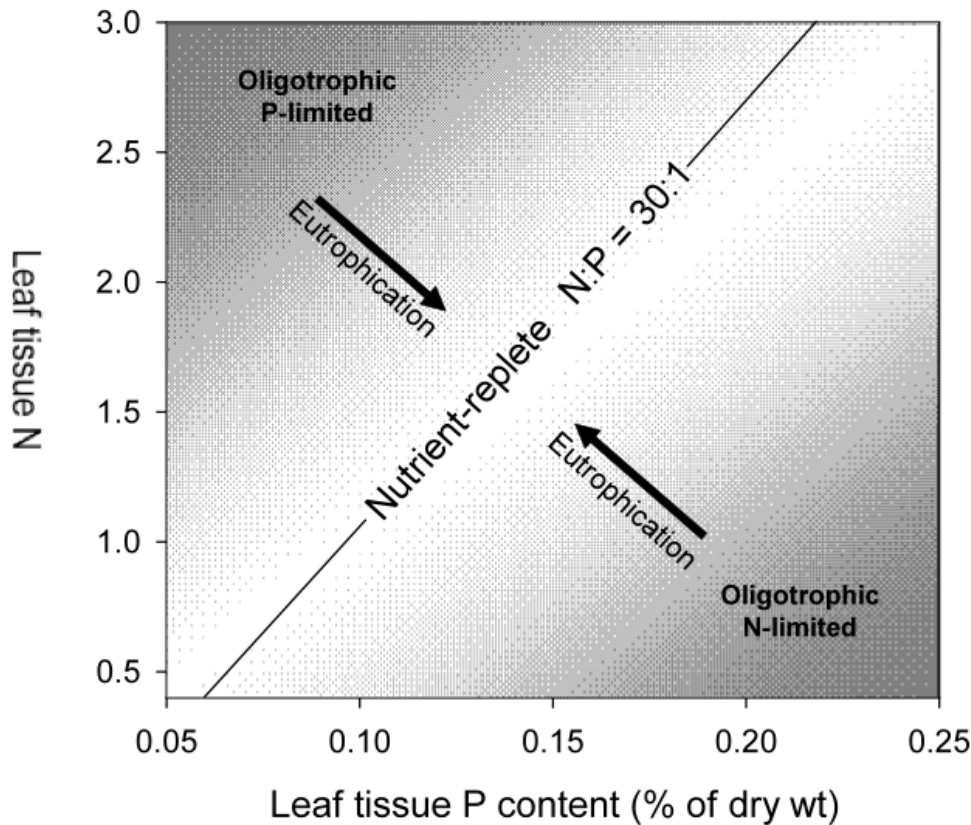

Figure III.3 - A conceptual model of the relationship between seagrass leaf nutrient content and nutrient availability in south Florida (from Fourqurean and Rutten, 2003).

Evidence suggests that these replacements occur over time scales ranging from years to decades. However, indications of a regime shift can be detected early through the monitoring of seagrass (blade) tissue nutrient concentrations, which reflect the relative availability of nutrients in an

estuary as integrated over time scales of weeks to months. For example, under nutrient replete conditions, the availability of nitrogen (N) to phosphorus (P) is reflected in a balanced ratio of 30:1 for the seagrass *Thalassia testudinum* in the FKNMS. Since the 8-yr average N:P ratio in *T. testudinum* from Florida Bay is about 38:1, reflective of a P limited environment, a change in this ratio to a value closer to 30:1 is indicative of eutrophication (Fig. III.3). For comparison, N: P ratios of *T. testudinum* collected in the Aransas-Copano Estuary in 2005 are about 32:1 (see Chapter 1, this study). However, Texas estuarine systems appear to possess unique hydrographic characteristics as reflected in the elemental composition of resident seagrasses which have distinctive estuarine specific C:N:P ratios (Dunton, unpub. data).

Similarly, ratios of carbon (C) to nitrogen (C:N) in seagrass tissues are also indicative of nutrient availability in coastal systems, especially in Texas estuaries, since they are seldom P limited. The spatial variability in C:N ratios of *T. testudinum* along the Texas coast reflect the ecological differences of our coastal ecosystems. Texas estuaries possess distinct biogeochemical signatures that are reflected in the chemical composition of the resident biota. For example, the variation in N availability between Lower Laguna Madre and the Aransas-Copano estuaries is reflected in porewater ammonium-N concentrations and plant C:N ratios. The naturally higher N levels in the Aransas system are reflected in both porewater ammonium-N concentrations, which are twice as high in Aransas Bay as Lower Laguna, and lower *Thalassia* C:N ratios in Aransas Bay. Such biogeochemical differences are reflected in morphometric and biomass characteristics (e.g. blade width and length, leaf scars, etc.)*,* which are useful condition indicators. Taken together, the attributes that characterize seagrass populations reflect the natural characteristics of the ecosystem in which they live (Table III.2), and can help identify ecologically distinct regions (Hackney and Durako, 2004).

In addition to the condition indicators noted above, we evaluated a variety of landscape indicators (Table III.3) in an effort to identify those most relevant to long-term seagrass monitoring. We examined various features (e.g. patterns in bed morphology, non-vegetated seabed, drift macroalgae, and hydrodynamic disturbances) from high-resolution true color photography in relation to seagrass plant/habitat parameters (e.g. biomass, species composition, water column and sediment porewater nutrient concentrations). We believe the results of this

work are important to our understanding of seagrass distribution and species composition, seagrass bed fragmentation, and gap (or patch) dynamics. Gaps are often produced through physical and biological disturbances, producing a mosaic of different vegetational assemblages that can be quantified from high resolution aerial imagery. The size (or "grain") of gaps and their extent (coverage) over a study area can be used to characterize spatial dynamics of seagrass beds. This approach will help us distinguish between the effects contributed by physical stressors (e.g. hydrodynamics) versus changes in water quality (e.g. water transparency) with respect to seagrass response indicators (Fonseca et al. 2002, Yamakita and Nakaoka, 2009).

Table III.3. Spatial metrics for landscape feature indicators in a specific seagrass region of interest quantified from 1:9,600 photoimagery at ~ 1m^2 resolution.

Indicator class	Landscape metrics (within region of interest)
Bare Patches	Size frequency, number, shape
Seagrass Assemblage	Size and shape of plant assemblages
Depth Distribution	Seagrass areal coverage (ha) in depth zones, deepest depth (m)
Macroalgae Deposition	Areal coverage (ha)
Seagrass Species' Distribution	Areal coverage (ha) per species

Edge dynamics, which reflect changes in the depth distribution of seagrasses, as revealed from digital aerial imagery, can also be used as an integrative measure of seagrass change, since the maximum depth penetration of seagrasses reflects overall water quality and light conditions. Consideration of landscape indicators must include an analysis of the cost and/or availability of remotely sensed imagery at the resolution required to detect change in critical landscape features (e.g. 1:24,000 vs. 1:9,600 scale) based on the results of this study (see Chapter 2).

Other practical issues pertain to indicator selection and reliability. These include the temporal frame and frequency for sampling (e.g. monthly, seasonal, biannual, annual), replication for statistical validity and hypothesis testing, optimal sample size and shape, measurement units, and cost.

A HIERARCHICAL
STRATEGY FOR SEAGRASS MONITORING

Our third objective focuses on the spatial and temporal variability of baseline indicators from both historical data and new synoptic measurements collected at sites located within seagrass dominated estuaries to establish the critical distributions that define seagrass condition (health) in Texas. Currently, the general distribution of all Texas seagrass habitat is known and encompasses six major Texas estuarine systems located in 10 coastal counties between Galveston and Brownsville (Fig. III.1; SCPT 1999). Our major task for a coast wide monitoring program is the collection of baseline measurements of condition indicators (Table III.2 and III.3), including the acquisition of remotely sensed data made available by other agencies or acquired solely for this monitoring program.

We recommend a sampling protocol for condition indicators identified above following the procedures and standards established by Fourqurean et al. (2001) for the EPA sponsored seagrass status and trends monitoring project in the Florida Keys National Marine Sanctuary (http://www.fiu.edu/~seagrass/), the USGS (for the National Park Service, see Neckles et al., 2010), the National Estuarine Research Reserve System (Moore et al., 2009), and the Puget Sound Submerged Vegetation Monitoring Project (Washington Department of Natural Resources http://www.dnr.wa.gov/ResearchScience/Topics/AquaticHabitats/Pages/aqr_nrsh_eelgrass_stress or_response.aspx). Station selection follows the stratified random method of hexagonal tessellation used by TPWD (Fig. III.4); we used this technique to locate permanent monitoring stations within the Lower Laguna and Mission-Aransas study areas under the 2002-2004 R-EMAP program (Dunton et al., 2005) and in this study. The approach ensures that all points within the landscape have an equal probability of being sampled, and that the sampling effort be quasi-evenly distributed across the landscape. Some stratification will be required in order to

sample in seagrass areas and to insure that no particular portion of the sampling area is favored more than another (Volstad et al., 1995). This can be accomplished by using the baseline seagrass maps at 1:24,000 scale that exist for most of these Texas bays (at least back to the early 1990s) and that are available and archived at TPWD. In addition, recent aerial imagery acquired in mid 2000s by NOAA for a coastal benthic mapping program can also be used to confirm the presence and substantial changes in seagrass meadows in several of the CBBEP estuarine bay areas. The analytical protocol for all condition indicators will follow guidelines established by a Quality Assurance Project Plan as approved by the EPA and TCEQ (see Radloff, 2009).

For landscape feature indicators, we recommend the acquisition and analysis of high resolution digital true color aerial photoimagery, at least 1:9,600 scale or larger. In Chapter 2 we addressed several questions related to aerial imagery for seagrass landscapes, including development of semi-automated methods for efficiently analyzing and classifying landscape features, and the critical comparison of scales (1:24,000 vs. 1:9,600) for detection of indicators in the classified scanned imagery. Our results indicated that 1:9,600 scale resolution or better was needed to ensure accurate delineation and quantification of drift macroalgae accumulations, bare patches and gaps of 1-2 m^2, and precise location of the deepwater edge of seagrass beds. These three landscape features are considered most critical for correlating with the plant-scale indicator measurements made by point sampling. With this high resolution imagery, we are able to extend (i.e. extrapolate) our observations from point samples over a larger area. Because each frame of 1:9,600 photography covers a seagrass bed area of approx. 2.2 km by 2.2 km (4.84 km^2), the high resolution imagery has a direct impact on our ability to detect and quantify the extent of landscape indicators chosen for long-term monitoring.
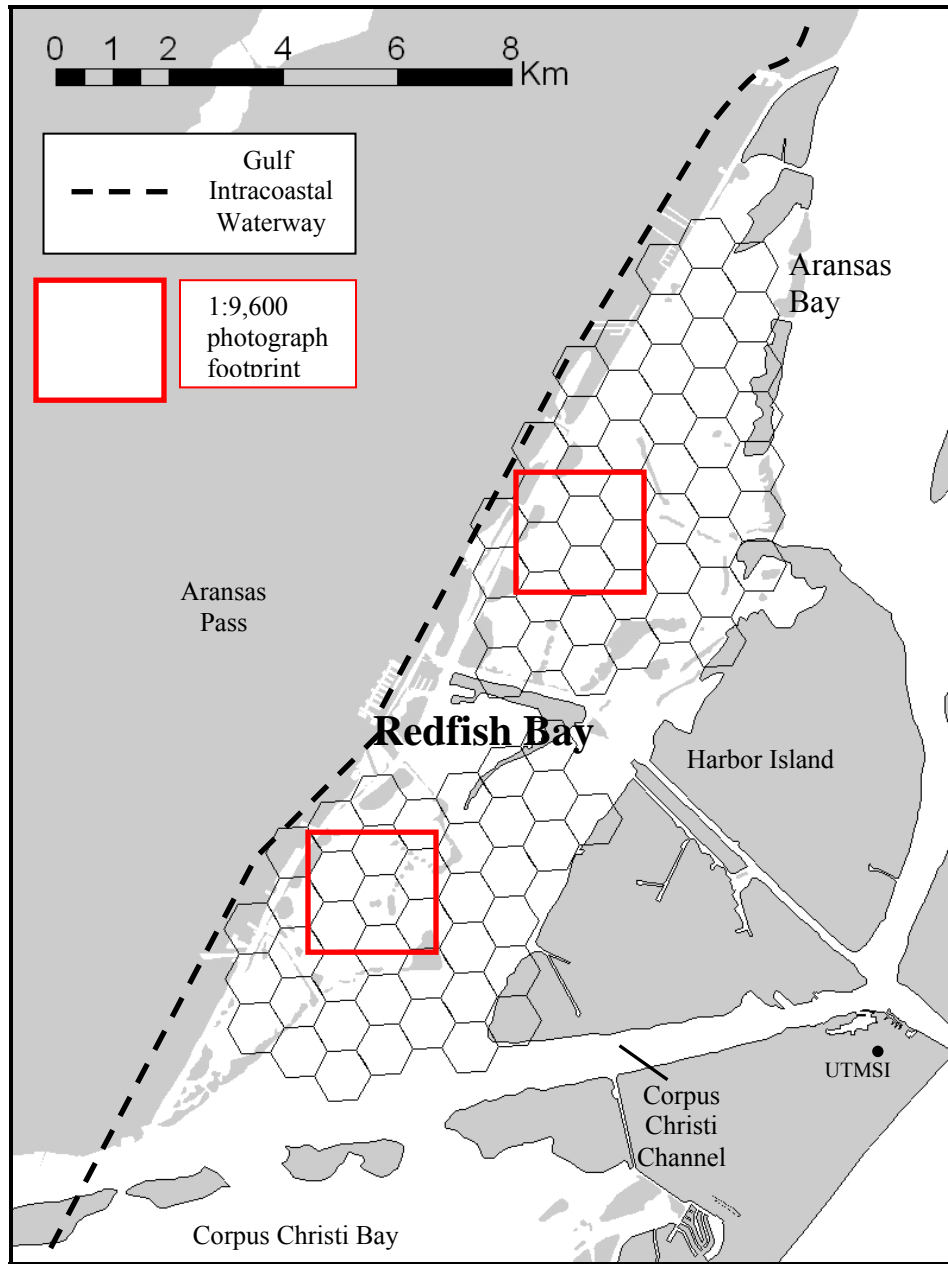
Figure III.4 - A hexagon layer superimposed on Redfish Bay. Hexagons are 500 m wide and contain one random sampling location (see text for details). Footprints of two 1:9,600 scale photographs are overlaid for comparison (adapted from Dunton et al., 2005).

Table III.4. Summary of total seagrass changes for Texas bay systems over four decades. Seagrass values are in hectares with acres in parentheses. Modified from Pulich and Onuf (2007).

Bay System	[1]Late 1950s or mid-1960s	[2]Mid-1970s	[3]1987 or early 1990s	[4]1998
Galveston Bay System				
Galveston/Christmas Bays	590[a] (1,457)	134[a] (331)	113[b] (279)	210[c] (519)
Midcoast Region				
Matagorda Bay			1,099[b] (2,716)	
San Antonio Bay		5,000[d] (12,350)	4,305[d] (10,638)	
Coastal Bend Region				
Aransas/Copano			2,871[e] (7,094)	
Redfish Bay and Harbor Island	5,380[e] (13,293)	6,200[e] (15,320)	5,710[e] (14,109)	
Corpus Christi Bay			2,568[e] (6,346)	
Laguna Madre System				
Upper Laguna Madre	12,321[f] (30,445)	20,255[g] (50,050)	22,903[h] (56,593)	22,443[i] (55,456)
Lower Laguna Madre	59,153[f] (146,166)	46,558[g] (115,044)	46,624[h] (115,207)	46,174[i] (114,095)
Baffin Bay			2,200[j] (5,436)	

[1] Data for Galveston/Christmas Bays, Redfish Bay, and Harbor Island based on 1956/58 Tobin photography. Data for upper and lower Laguna Madre based on field surveys during mid-1960s.

[2] Data for Galveston/Christmas and Redfish Bay/Harbor Island based on 1975 (National Aeronautics and Space Administration Johnson Space Center (NASA- JSC) photography; San Antonio Bay based on 1974 NASA-JSC photography. Data for upper and lower Laguna Madre based on 1974–75 field surveys.

[3] Data for Christmas, Matagorda, and San Antonio Bay systems from 1987 NASA-Ames Research Center photography. Data for Aransas/Copano, Redfish, and Corpus Christi Bay systems based on 1994 TPWD photography. Data for upper and lower Laguna Madre based on 1988 field surveys. Data for Baffin Bay based on 1992 U.S. Fish and Wildlife Service National Wetlands Inventory photography.

[4] Data for Christmas Bay from 1998 Galveston Bay National Estuary Program photography. Data for upper and lower Laguna Madre from 1998 field surveys.

[a] From Pulich and White (1991).   [b] From Adair and others (1994).   [c] From Pulich (2001).   [d] From Pulich (1991).

[e] From Pulich and others (1997).   [f] Areas computed for this review from McMahan (1965–67). See Laguna Madre vignette.

[g] Areas computed for this review from Merkord (1978).   [h] Areas computed for this review from Quammen and Onuf (1993). See Laguna Madre vignette.   [i] Areas computed for this review. See Laguna Madre vignette.

[j] Areas computed for this review by Texas Parks and Wildlife Department, Coastal Studies Program, Austin, Tex. (unpub. data)

In recognition of the unique differences inherent to Texas estuaries and the availability of reliable historical data (and samples), we propose to establish a database for the distribution of indicator values for each Texas estuarine system (Laguna Madre is additionally divided into Upper and Lower regions). This will ensure that we capture the natural temporal and spatial variability in condition and landscape indicators, especially since not all changes over time are a consequence of human-induced impacts. Changes are intrinsic to natural systems and it is important to document these sources of variation in order to detect and recognize deviations that are extrinsic and related to an anthropogenic disturbance. As described above, recognition of these deviations will be based on the historical distribution of indicators acquired for each particular estuary. The data and archived samples from the 2002-2004 R-EMAP and 2005 CBBEP projects are of particular value, as are data from a variety of published and unpublished sources that potentially relate to the distribution of selected seagrass indicators (see Table III.4).

RECOMMENDED STATEWIDE MONITORING PROGRAM FOR TEXAS

The implementation of a hierarchical strategy for seagrass monitoring reflects the need for comprehensive information on seagrass status, change, and condition. The basis of this approach is to provide an early warning of emerging ecological problems and provide a basis for establishing water quality criteria for seagrass conservation (Bricker and Ruggiero, 1998). In recognition of the financial constraints and resources associated with a seagrass monitoring program, we recommend a landscape level approach for estimating seagrass status and trends, physiological condition, and linkages to environmental processes. This approach is adapted from a very similar program developed by USGS to monitor estuarine seagrass populations in New England for the National Park Service (Neckles et al. 2002; 2010). The Tier 3 approach proposed here has been adopted by the National Estuarine Research Reserve (NERR) as the official monitoring protocol for mapping and monitoring submerged aquatic vegetation in the Reserve System (Moore et al. 2009; NERRS Research and Monitoring Plan 2006-2011). Similar protocols have been established for quantification of seagrass dynamics on a global scale (http://www.SeagrassNet.org; Short et al., 2006). This design incorporates changes in spatial

distributions from 1:24,000 scale remotely sensed data (Tier 1), rapid in situ spatial assessment in conjunction with optional high resolution (at least 1:9600 scale) aerial photo imagery (Tier 2), and fixed transects with permanent sampling stations (Tier 3).

Tier 1: System-Wide Mapping from Remotely Sensed 1:24,000 Scale Imagery

We propose to utilize remote sensing at two levels of resolution in order to compile status and trend maps for the study area. The primary purpose of Tier 1 is to characterize seagrass distribution over large spatial scales by remote sensing using 1:24,000 scale imagery. However, high resolution imagery (1:9,600) should be acquired when intensive monitoring is employed under Tier 2 or 3.

Standard system-wide mapping methods are used to identify seagrass meadow locations in all major Texas bays and coastal lagoons. The approach includes acquisition of remotely sensed images at 1:24,000 scale (digital true color), georectification of imagery, collection of ground truth data, interpretation of the images and delineation of vegetative areas, and importing the data into a GIS format for accuracy assessment, change detection, and reporting. The 1:24,000 scale photography acquisition and mapping should occur at about five year intervals.

Tier 2: Regional Rapid Assessment, Fixed Station Locations

Under Tier 2, broad-scale surveys in a large bay or lagoon are used to characterize the system based on specific biotic and abiotic properties of the water column, seagrasses, and sediments. Such measurements are absolutely critical to the development of a knowledge base that is *estuarine specific*, providing a foundation of data for the development of water quality and transparency criteria based on a large number of replicate samples for a selected site or area. Tier 2 monitoring is often integrated with existing high-resolution (Tier 3) studies at designated stations within a site and high resolution (1:9,600) aerial imagery (Fig. III.4). The approach incorporates random station selection in a stratified design that produces a somewhat even

dispersion of stations across the site or area of interest. Dunton et al. (2005) successfully used a grid of tessellated hexagons for random station selection in Laguna Madre and Redfish Bay with excellent results (Kopecky and Dunton 2006, Fig. III.5).
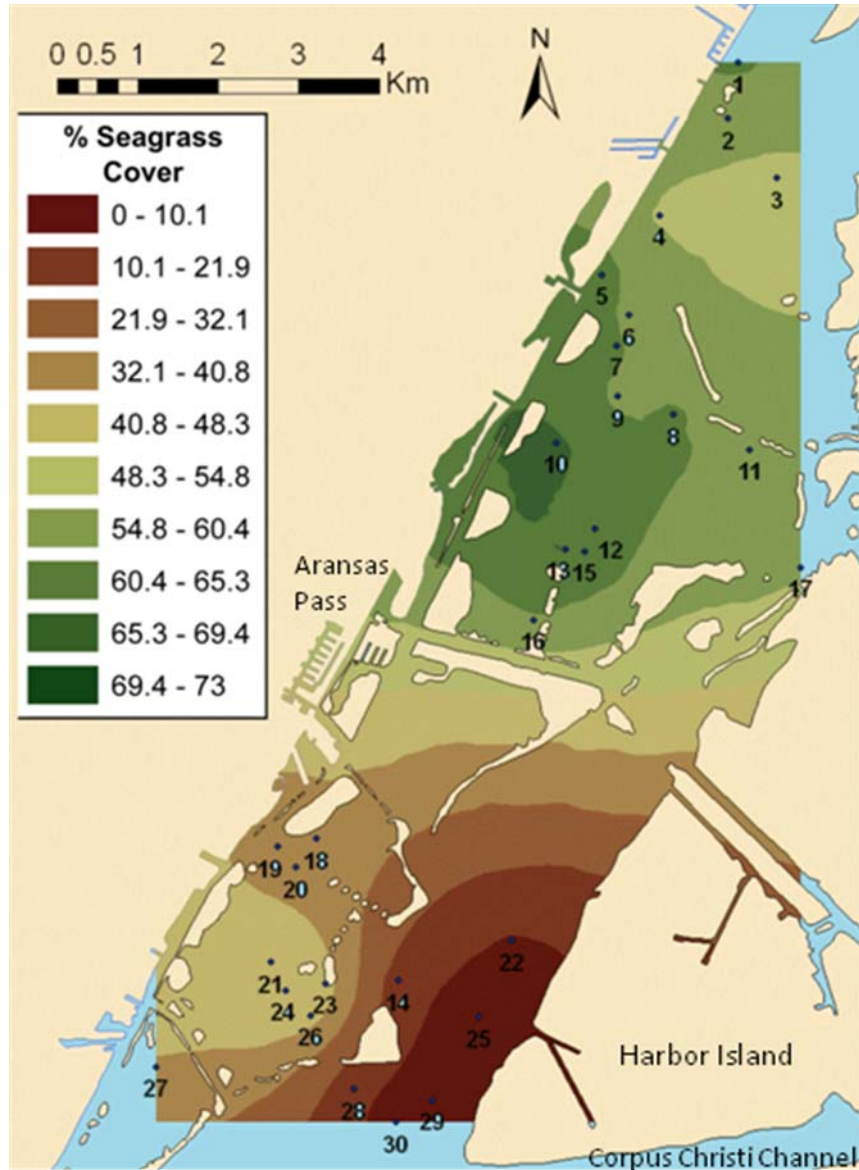

Figure III.5 - Interpolated average percent seagrass cover in Redfish Bay based on data collected at 30 randomly selected stations within each of 30 hexagons (see Fig. III.4; from Dunton et al., 2005).

Spatial design

The Tier 2 design utilizes a grid of tessellated hexagons within each regional bay system following Neckles et al. (2010). This approach forms the basis for high replication of parameters and the selection of probability-based sampling locations. In Redfish Bay, hexagons were 500 m on a side and covered 0.65 km^2, with one random sampling station located within each hexagon (Fig. III.4). The size of the hexagons within each bay system is largely dictated by sampling logistics and feasibility (e.g. 750 m hexagons may be required for Laguna Madre). The selection of stations is limited to a maximum depth of 2 m (MSL) in all regions of the Texas coast unless there is clear evidence of seagrass penetration to deeper depths in a given region (e.g. Lower Laguna Madre). This same approach has been utilized by Neckles et al. (2010) to detect changes in seagrass condition over time in Little Pleasant Bay, MA and Great South Bay, Long Island.

In addition to ground-based measurements, 1:9,600 scale, or larger, high resolution true color aerial photography can be used to assess spatial landscape indicator patterns and produce metrics for patchiness, macroalgae accumulations, and deepwater edges of existing seagrass meadows, especially in fringing habitats (Table III.4). Overlaying footprints (2.2 km x 2.2 km; 4.84 km^2) of high resolution 1:9,600 photographs over the hexagon grid (Tier 2) is employed for assessment of spatial patterns in patchiness, dense macroalgae deposits, and depth distribution of existing seagrass meadows. Because hexagons are 500 m on a side (0.65 km^2 in area), approximately 7.4 contiguous hexagons can be contained within one 1:9,600 scale photograph (Fig. III.4). The positions of randomly selected hexagon sampling points in Tier 2 are used to determine the location for acquisition of 1:9,600 photographs.

Sampling Strategy and Methods (adapted from Neckles et al., 2010)

- Annual sampling is performed during or shortly following peak seagrass standing crop (mid to late summer).

- For statistical rigor, use a repeated measures design with fixed sampling stations to maximize ability to detect change.

- Navigate to pre-selected stations with a GPS accuracy of 4 m or better.

- Stations are defined as the area within a 10-m radius of the GPS location.

- Hydrographic measurements are collected with a data sonde prior to deployment of any benthic sampling equipment.

- Water quality is determined from replicate water samples collected at each station. Water transparency is calculated from simultaneous measurements of photosynthetically active radiation (PAR) at the surface and at a measured depth using spherical quantum sensors and the Beer Lambert equation for calculation of the diffuse attenuation coefficient (k_d).

- Retrieve four replicate samples per station (for indicators listed in Table III.2) from each cardinal direction directly from the vessel. Previous work has shown that the probability of achieving a bias is less than 5% of the overall mean with only four subsamples (Neckles et al., 2011).

- Estimate percent cover within $0.25m^2$ quadrats using an underwater digital camera mounted to quadrat frame, or in shallow water, through direct observation through the water. If water transparency is extremely poor (Secchi < 1 m), make direct in situ measurements of the bottom with a mask and snorkel.

- Obtain morphometric data, biomass, shoot density, sediment characteristics, etc. using a ca. 9 cm coring device (or larger for *Thalassia*) deployed from the vessel.

- For each core sample, record the maximum leaf length of each shoot and the overall canopy height based on 80% of the leaf material and ignoring the tallest 20% of the leaves).

- All measurements and samples are collected by a crew of two from a shallow-draft vessel. Each region likely requires a commitment of one to three 12-hr days, with the exception of the Upper and Lower Laguna (up to 10 days each).

- Other monitoring programs have demonstrated that such an approach, when all sampling stations are considered together within a regional system, results in > 99% probability that the bias in overall estimates will not interfere with detection of change.

Data Analysis

- Use ArcGIS software to manage, analyze, and display spatially referenced point samples, and interpolate surfaces of all measured parameters biomass on integrated temporal and spatial scales using techniques of kriging interpolation (estimates the value of unsampled points as the weighted average of values from a given number of the closest points, giving more weight to closer points).

- Set the shoreline as an impermeable boundary (i.e. value of unsampled points is based only on sampled points within the same section of the region).

- Display the results of percent cover estimates based on Braun-Blanquet classes (Fourqurean et al., 2002).

- Utilize repeated measures ANOVA to determine if significant inter-annual spatial or temporal changes are occurring within a region.

Tier 3: Integrated Landscape, Permanent Stations

Tier 3 studies are conducted at a relatively small number of stations and consist of experimental studies and intensive monitoring for assessment of baseline conditions within a specific region. Tier 3 work is designed to address specific hypotheses in response to measured environmental change. Such studies provide an opportunity to link the presumptive factors responsible for changes in seagrass landscape indicators as detected by high resolution 1:9,600 imagery (patch formation, advances and/or retreats from deep edges, color changes that may reflect abundance of drift macroalgae or algal epiphytes) to changes in water quality and/or seagrass condition

indices that are measured either continuously or frequently at permanent stations. Dunton et al. (2005) conducted high resolution monitoring at several sites, from Laguna Madre to Redfish Bay. Monitoring occurs at least annually in mid-summer, but has been often conducted quarterly.

Design

Sampling methods are generally consistent with either SeagrassNet, a global monitoring program developed to investigate and document the status of seagrass resources worldwide (Short et al., 2006), or NERR protocols (Moore et al., 2009). In either case, quadrats (0.25 m^2) are positioned along three transects placed either parallel (SeagrassNet) or perpendicular (NERR) to the shoreline (Figs. III.6). Under the NERR protocol, the permanently established transect must bisect transitional or marginal seagrass beds that are characterized by any of one of the following features: an obvious deep edge, patchiness, or a distinct depth gradient.

At each Tier 3 station, plots are sampled non-destructively for percent cover by each species or cover category (e.g., bare ground, detritus) within a 0.25 m^2 area (Fig. III.7). In some beds, SAV clonal patchiness may require a much larger sampling area than 0.25 m^2. In addition to cover estimates, shoot or stem density and maximum canopy height should be determined for each species within each plot. If the vegetation is very dense then the plot may be sub-sampled for density, height and leaf or shoot width as needed.

An area reserved for the sampling of other factors such as sediment nutrients, porewater sulfide, sediment deposition, etc. should be located at a 1 m fixed distance from the transect line point oriented 180° from the vegetation sampling plot. Voucher specimens including flowers, fruits, and below-ground material of each species and their various morphological variants should be sampled and appropriately preserved.
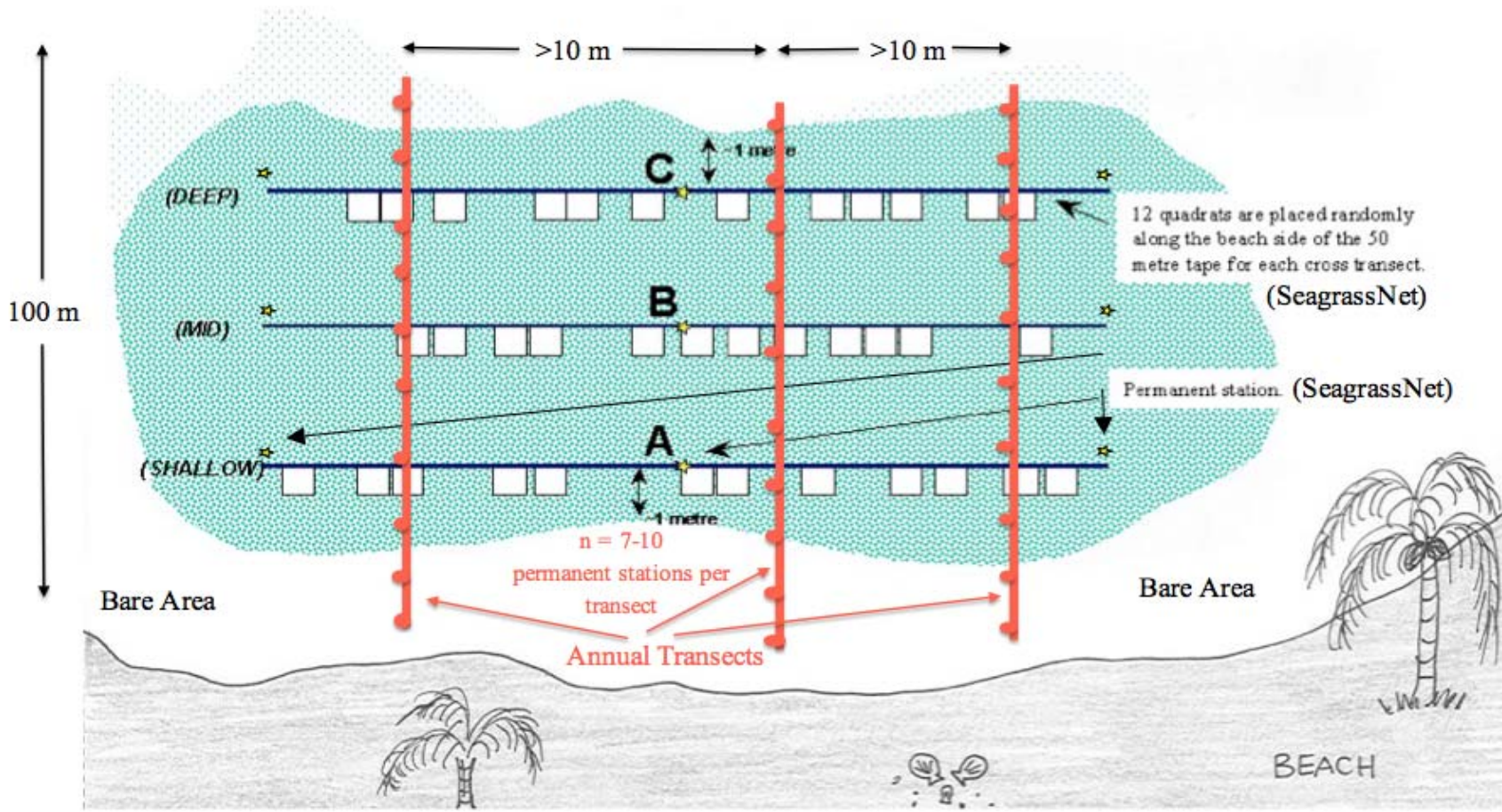
Figure III.6 – Example of permanent transects for NERR (in red; Moore et al., 2009) and SeagrassNet (blue; modified from Short et al. 2002). NERR annual transects are a minimum of 10 m apart, are 100 m long and extend past the edge of the seagrass bed. Seven to ten sampling locations along each annual transect are shown as red circles. White quadrats on blue transect lines parallel to the shoreline reflect the SeagrassNet protocol.
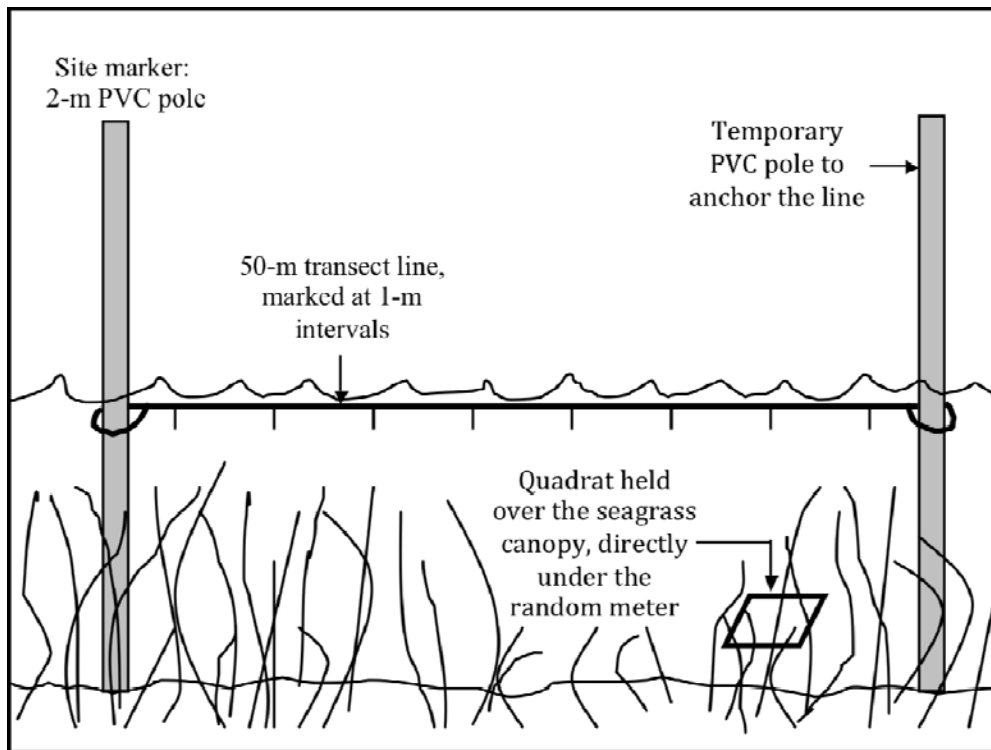
Figure III.7 - Each permanent site includes three 50 to 100-m transects over which samples are collected within permanent quadrats.

Notes on Transect Sampling

- Transect visits are conducted annually during the period of peak biomass, usually mid-summer.

- Ten permanent 0.25m^2 quadrats are randomly located along each transect following the sampling protocol as outlined in Chapter 1.

- Biomass, epiphyte cover, above- and below-ground tissue samples, seed reserves, and sediment characteristics are determined from an adjacent core sample (0.5 m distant from the quadrat).

- Continuous measurements of light, temperature, and salinity are collected at one representative site in each region through deployment and periodic maintenance of dataloggers and appropriate sensors.

- If high resolution imagery is available, the transects are aligned with the 2.2 km x 2.2 km footprint of 1:9,600 aerial photography. As noted above, because hexagons are 500 m on a side, approximately seven contiguous hexagons can be sampled within one 1:9,600 photograph for assessment of spatial patterns in patchiness, dense macroalgae deposits, and depth distribution of existing seagrass meadows.

Patchiness and Location of the Deep Edge

- Patchiness and deep edges are critical landscape-level parameters. The deep edge estimate integrates long-term water transparency and both parameters are observed in 1:9,600 imagery.

- A quantitative measure of "patchiness" (referred to as "grain" by Pielou 1977) is computed in the simplest form by considering seagrasses as a two-phase mosaic (i.e., a surface composed of two types of polygons—with and without seagrasses). We can define patchiness to be the number of patch/gap transitions along each transect.

- Deep edges of beds are first verified by diving; transects start at the deep edge and traverse the bay in a direction perpendicular to shore toward shallower depths.

- Measurements of in situ PAR reflect minimum light requirements of plants at the deep edge (Dunton has conducted high resolution monitoring for PAR since 1989 at one site in Upper Laguna Madre). This is important, as Duarte (2007) recently found that seagrasses in turbid waters appear to have higher light requirements than plants living in clear waters. This is related to a number of stressors, both in the water column and in the sediments.

Experimental Studies

One of the major objectives of Tier 3 measurements are to address the causal relationships between water quality stressors and seagrass response as assessed by any number of condition indices. An understanding of stress/response relationships is often best achieved through intensive, hypothesis-driven experimental studies that address research needs for Texas seagrasses (Pulich and Calman, 1999). A fundamental understanding of the mechanisms and response indicators is required for Tier 3 studies, since measurements often occur across temporal and spatial scales. Ultimately, response variables are largely determined by an overarching question or hypothesis, incorporating additional parameters that could possibly include:

- seed reserves
- growth
- benthic faunal diversity
- sediment chemistry, including sulfides
- organic chemical contaminants (e.g. herbicides)
- leaf chlorophyll fluorescence
- reproduction and demography
- seagrass deep edges
- genetic diversity
- light fields

As such, the studies conducted under Tier 3 sampling are likely to employ innovative approaches to achieving a better understanding of stress/response relationships, with an expectation of publication of results in peer-reviewed journals.

APPLICATIONS TO COASTWIDE SEAGRASS MONITORING IN TEXAS

Data Analysis and Future Products

- Tier 1 observations identify large scale patterns in seagrass distribution and changes over time.

- Tier 3 observations can help interpret larger scale landscape patterns observed in Tier 1 and 2.

- Data gathered from Tier 3 monitoring can be applied to calibrate a biomass model based on percent cover and canopy height.

- Percent cover and canopy height are measured through the Tier 2 rapid assessment, and thus provides an opportunity to interpolate those measurements into a prediction of biomass on a regional scale.

- Determine the physiological indicators that identify the effects of light stress on seagrass photosynthetic tissues.

- The response and sensitivity of seagrass tissue constituents to anthropogenic nutrient loadings is very important.

- Develop a linear regression model of k_d (PAR) as a function of both TSS and chlorophyll (Gallegos, 2001).

- Determine the response of drift and seagrass epiphytic algal response to nutrient loading with respect to algal species composition and tissue constituents (Collado-Vides et al., 2007).

- Integrate the abiotic and biotic components to provide an overall assessment of seagrass condition (i.e. an Index of Biological Integrity).

Program Management

- Active involvement and support from the Seagrass Monitoring Work Group (SMWG) in all aspects of the program is critical. Workshops that include participants active in other nationally recognized seagrass monitoring programs is equally important. Overall coordination of Tier 2 and Tier 3 activities are probably best served by a SMWG subcommittee in partnership with TPWD.

- The environmental, landscape, and biological data gathered on this project should be compiled into a multifunctional data management system (DMS), as outlined in the TSGMP by Pulich et al. (2003). A DMS template will facilitate data access for analysis and mapping purposes using standard GIS procedures to visualize, integrate, and interpret spatial datasets (Pulich et al., 2000). Web-based data dissemination should be an integral part of the DMP.

- Maintain partnerships with local groups to continue to assess the status of seagrasses along the Texas coast.

- This proposed hierarchical strategy for seagrass monitoring has a broad scope that should be implemented for the entire Texas coast with partner support (e.g. MANERR, National Park Service, USGS-NWRC, other universities).

- Seven seagrass monitoring regions are proposed for Texas as follows. Regions are selected based on local physiography, geomorphological characteristics, hydrography and circulation, and the spatial or contiguous extent of the seagrass beds (Table III.5).

Table III.5. Proposed seagrass monitoring regions for the Texas coast based on current distribution (Fig. III.1) and data compiled by Pulich and Onuf (2007).

	Region	Description
1	Galveston Bay	Christmas Bay, West Galveston Bay
2	Matagorda Bay system	Includes East Matagorda Bay, west Matagorda Bay, secondary bays of Cox, Carancahua, Powderhorn and others
3	San Antonio Bay system	Espiritu Santo Bay, San Antonio Bay, Mesquite Bay
4	Mission-Aransas (MA)-NERR	Includes Aransas/Copano Bays, St. Charles Bay, Aransas National Wildlife Refuge shoreline, San Jose Island, North Redfish Bay, Terminal Flats, and north Harbor Island
5	Corpus Christi Bay system	South Redfish Bay, East Flats, Mustang Island, Shamrock Island, north side of Kennedy Causeway, Nueces Bay
6	Upper Laguna Madre	Nine Mile Hole and parts of Baffin Bay, from the Land Cut north to the Kennedy Causeway, as bordered by Padre Island National Seashore
7	Lower Laguna Madre	Land Cut south to Brazo Santiago Pass and including South Bay

SCHEDULE OF TASKS FOR PROGRAM IMPLEMENTATION
(STARTING FALL 2010)

Fall 2010

Region 4: Tier 2 and Tier 3 sampling will begin in Aransas and Copano Bays under a long-term commitment from the MANERR. Ken Dunton will provide expertise, assist with program development, populate the seagrass monitoring database, and initiate the integrated field monitoring program.

Region 6: Tier 2 and Tier 3 sampling will also commence in the Upper Laguna Madre (from Nine-Mile Hole to just north of Bird Island Basin) in the area encompassed by the Padre Island National Seashore park boundary. The effort, funded by the National Park Service (NPS), is coordinated with identical seagrass monitoring in the Gulf Islands National Seashore as directed by Ken Dunton (UTMSI in Texas) and Ken Heck (DISL in Alabama).

Proposed Tasks for 2011 and Beyond

Some specific objectives include (in prioritized order):

1. Establish a DMS (partners include MANERR, NPS, and TPWD). Enter data from EPA R-EMAP study and CBBEP (this report) into the database. Provide web access.

2. Analyze existing collections of seagrass tissue for C:N:P and ^{15}N:^{14}N ratios from Laguna Madre and the CBBEP study area for entry into seagrass database.

3. Revise the conceptual models (SMWG).

4. Initiate the integrated hierarchal sampling program (Tiers 2) in selected regions of the CBBEP study area.

5. Synthesis and expansion of monitoring to include all seven seagrass regions across the entire coast of Texas.

6. Acquire 1:24,000 photography statewide in cooperation with state and federal programs.

7. Summarize physical and chemical habitat requirements for Texas seagrasses based on existing data.

8. Develop programs that monitor submerged habitat at higher spatial and temporal resolution. Gather experimental evidence on cause-effect interactions for conceptual model development. Address functionality, habitat quality, and wildlife usage.

9. Hold an annual workshop to summarize trends and relationships between seagrass condition indicators and water column properties, identify problems, and suggest appropriate responses by State agencies.

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