Volume I

Executive Summary

Effects of Dredge Deposits on Seagrasses: An Integrative Model for Laguna Madre

Concluding Report

INTERAGENCY COORDINATION TEAM
U.S. ARMY CORPS OF ENGINEERS, GALVESTON DISTRICT

The University of Texas Marine Science Institute
Texas A&M University Department of Oceanography
Texas Parks and Wildlife Department

March 2003

FINAL

EFFECTS OF DREDGE DEPOSITS ON SEAGRASSES: AN INTEGRATIVE MODEL FOR LAGUNA MADRE

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Abstract

This report presents the results of an interdisciplinary collaborative effort to develop an integrative model for seagrass productivity in Laguna Madre. One of the major components of this integrative model is the Laguna Madre Seagrass Model (LMSM) which was designed to interface with other component models described in this report, including carbon and nitrogen allocation, sediment diagenesis, and spectral irradiance and radiative transfer. Linkage with hydrodynamic and sediment transport models provided a potentially valuable management tool to assess the effects of maintenance dredging and resuspension of dredged material deposits on seagrasses of Laguna Madre.

The development of the models described in this report required a substantial input of data for model calibration and when possible, verification. For the seagrass models, much of this data were available from previously published studies (*e.g., Halodule wrightii*), but intensive field work, from April 1996 to December 1997, provided the additional data needed to develop the models presented in this report. We present the results of these field investigations, which were conducted at 24 transect-survey sites (12 stations paired by seagrasses and bare bottom) and six permanent stations to fill gaps in our knowledge of seagrass biology, variations in water column and sediment geochemistry, underwater irradiance, and the inherent optical properties of Laguna waters.

Studies on seagrass biology included delineation of the photosynthesis vs. irradiance (P vs. I) relationships for *Syringodium filiforme*, which were used in developing the LMSM for this species (P vs. I relationships have been previously published for *Halodule wrightii* and *Thalassia testudinum*). In addition, density and above- and below- ground biomass of the three grass species were collected over variable temporal and spatial scales at 12 transect sites and three permanent stations in Laguna Madre. Continuous measurements of photosynthetically active radiation (PAR) were also collected at the permanent sampling stations. Indices of carbon and nitrogen content were measured in leaves and below-ground tissues to provide data for the LMSM and allocation models for *Thalassia*.

Thousands of samples were analyzed in our efforts to better understand the complex geochemical relationships occurring within Laguna seagrass beds. We collected samples at 24 transect sites; in addition, sediment chemistry was examined in detail from vertical profiles conducted at four additional stations. Results demonstrated that most sediments in Laguna Madre are sandy with a relatively narrow range in their physical and geochemical characteristics and that the diagenetic activity takes place in the upper few centimeters of sediment (in contrast to most estuarine siliciclastic muds). This work also demonstrated that the flux of

ammonium from resuspended sediments (as occurs during dredging) can be substantial, thereby providing a large pulse of inorganic nitrogen that can fuel phytoplankton blooms. This finding is important, since measurements of water inorganic nitrogen levels are generally low (<3 µM) throughout the Laguna. Such low concentrations probably play an important role in regulating phytoplankton production, as reflected in water column chlorophyll levels that are <10 µg L^{-1} in the Lower Laguna.

Knowledge of the inherent optical properties (IOPs) of Laguna Madre waters is critical in developing a radiative transfer model to link with the LMSM. Strong relationships were observed between IOPs and total suspended solids (TSS). TSS is likely to contribute most to water column light attenuation during dredging events, which can result in significant reductions in both light quality and quantity. Declines in light-driven photosynthetic oxygen evolution can have serious effects on seagrass health. Sediment geochemical model simulations suggested that root zone fluxes of O_2 (produced during photosynthesis) were essential to maintaining non-toxic levels of sulfide. In addition, model results indicate that seagrass beds overlain with even modest (cm) amounts of dredged material can experience rapid increases in sulfide concentrations that can be sustained at toxic concentrations for several months.

The LMSM was developed for *Halodule, Syringodium, and Thalassia*. Of the three models, the LMSM was able to reproduce many features of a continuous nine-year data set for *Halodule*, mainly because the *Halodule* set contained a prolonged period of light stress (brown tide event) interspersed between two periods of favorable light climates. Simulations using worst-case light attenuation profiles show that the seagrasses are able to withstand short periods (one to two weeks) of very high water column light attenuation. However, under prolonged periods of low PAR (ca. 100 days or more) of even moderate levels of water column attenuation, model predictions indicate potentially dangerous decreases in plant biomass.

Our efforts have produced an integrative and quantitative model that predicts the response of seagrasses to changes in their environment, particularly with respect to changes in light availability, based on extensive interdisciplinary field observations and experimental studies conducted over the past two years. Model simulations and *in situ* measurements of an actual dredging event strongly suggest that dredging operations are very likely to have a measurable negative impact on the health when (1) dredging activities occur over extended periods (weeks) when the plants are metabolically most active (spring through autumn), and (2) the dredging activity and/or disposal of materials occurs within 1 km of the grass bed.

The results of the LMSM depend, as does any model, upon a variety of inputs (in particular TSS) and assumptions that are used in the interpretation of simulation results. For example, the seagrass model was run at sites that were not immediately adjacent to disposal areas. This was done to simulate the impact of disposal on the Laguna as a whole. The Seagrass Model addresses a representative area and can be applied at any location along the length of the Laguna. Similarly, the hydrodynamic and sediment transport models cover the whole length of Upper and Lower Laguna Madre. Given such a wide spatial coverage in all three models, there will always be regions where differences occur between model output and observed data. The power of these models lies in providing information on long-term trends and large-scale spatial patterns. Consequently, when one evaluates the output from these models, consideration does need to be given to anecdotal observations that disagree with the model results. However, it is very difficult to gauge the importance of such observations without hard numerical data.

We stress that the output from our models needs to be interpreted in the context of long-term trends and large-scale spatial patterns. We are confident that the LMSM performs well in this respect. In addition, our conclusions on dredging impacts to seagrasses include results of additional model simulations based on data collected during actual dredging events (*e.g.*, model verification study at PA 235) and *in situ* observations of seagrass response to chronic reductions in underwater light regimes. We recognize that environmental, political, and economical factors are likely to play key roles in the management decisions regarding seagrass resources in Laguna Madre. Therefore, we recommend efforts be undertaken, however modest, to collect accurate measurements of environmental variables (*e.g.,* TSS, light attenuation) to directly verify model predictions at test sites where dredge activities and seagrass response can be directly measured and observed.

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Contents

PART ONE

Preface

The Laguna Madre of Texas is only one of three hypersaline lagoons in the world. Seagrasses inhabit huge areas of the Laguna and provide a winter food resource for more than 75% of the world's population of redhead ducks. Because of the fundamental role that seagrasses play in the ecology of coastal ecosystems, activities that potentially threaten the productivity of the system have long been a cause for concern.

The Gulf Intracoastal Waterway (GIWW) is a 117-mile long, 12-foot deep by 125-foot wide navigation channel that bisects the entire length of the Laguna. The GIWW is maintained by the U.S. Army Corps of Engineers (USACE) by dredging activities based on an environmental impact statement (EIS) that was completed in October 1975. During the 1980s, the adequacy of the EIS was questioned by several State and Federal resource agencies and in 1993, the U.S. Army Corps of Engineers undertook the task of completing a series of Section 216 studies to address the problems and concerns along the GIWW. The National Audubon Society and others filed a lawsuit in 1994 to halt unconfined, open-bay disposal of dredged material in Laguna Madre before the 216 studies were completed. As a result of the suit, the Corps agreed to develop a long-term dredged material management plan (DMMP) for this section of the GIWW and to prepare a supplemental environmental impact statement (SEIS).

An Interagency Coordination Team (ICT) composed of the Corps, the National Marine Fisheries Service, U.S. Fish and Wildlife Service, U.S. Environmental Protection Agency, Texas Parks and Wildlife Department, Texas General Land Office, Texas Water Development Board, Texas Department of Transportation, and the Texas Natural Resource Conservation Commission (now the Texas Commission on Environmental Quality) was formed in February 1995 to help the USACE to develop the DMMP and SEIS. The U.S. Coast Guard, Padre Island National Seashore, and Coastal Bend Bays and Estuaries Program were invited to send members during subsequent meetings to provide information and advice to the ICT.

This report reflects the completion of one of about 35 studies that have been sponsored by the ICT and funded by the USACE to provide the latest scientific information on the impacts and benefits of the GIWW. In 1996, the USACE provided Texas A&M University, the University of Texas Marine Science Institute, and Texas Parks and Wildlife Department funds to conduct a study with the following objectives:

1) To collect additional field measurements to fill gaps in our knowledge related to the biology of seagrasses and their geochemical and physical environment, and

2) To develop an integrative model for seagrass productivity in Laguna Madre that could be used as a management tool to assess the effects of maintenance dredging.

In addition to this report, a number of peer-reviewed publications have resulted from this research (see below) and are available to the public.

PUBLICATIONS RESULTING FROM RESEARCH SUPPORTED UNDER THIS USACE SPONSORED PROGRAM

Burd, A.B. and K.H. Dunton. 2000. Field verification of a light-driven model of biomass changes in the seagrass *Halodule wrightii*. *Marine Ecology Progress Series* 209:85-98.

Eldridge, P.M. and J.W. Morse. 2000. A diagenetic model for sediment-seagrass interactions. *Marine Chemistry* 70:89-103.

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Lee, K-S. and K.H. Dunton. 2000b. Effects of nitrogen enrichment on biomass allocation, growth, and leaf morphology of the seagrass *Thalassia testudinum*. *Marine Ecology Progress Series* 196:39-48.

Major, K.M. and K.H. Dunton. 2000. Photosynthetic performance in *Syringodium filiforme*: seasonal variation in light-harvesting characteristics. *Aquatic Botany* 68:249-264.

Major, K.M. and K.H. Dunton. 2002. Variations in light-harvesting characteristics of the seagrass, *Thalassia testudinum*: evidence for photoacclimation. *Journal of Experimental Marine Biology and Ecology* 275:173-189.

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PART TWO

Field Measurements

Figure 1. The Laguna Madre of Texas. Samples and data were collected at a variety of sites over periods ranging from one to nine years.

LAGUNA SEAGRASS BEDS

This final report presents the results of an integrative study to develop quantitative models to evaluate the growth response of seagrasses, as reflected by changes in their biomass, to changes in underwater light availability. Our studies were almost exclusively directed toward the seagrass beds of the Texas Laguna Madre ecosystem, which extends from the southern edge of Corpus Christi Bay to the Brazos Santiago Pass on southern tip of South Padre Island (Fig. 1).

The research program we implemented to develop these models was divided into two phases. The first phase focused on the collection of *in situ* field measurements to fill gaps in our knowledge related to the biology of the plants and their geochemical and physical environment. This phase involved an intensive field effort that included sampling at 12 survey sites and at six permanent sites over an 18-month period starting in April 1996.

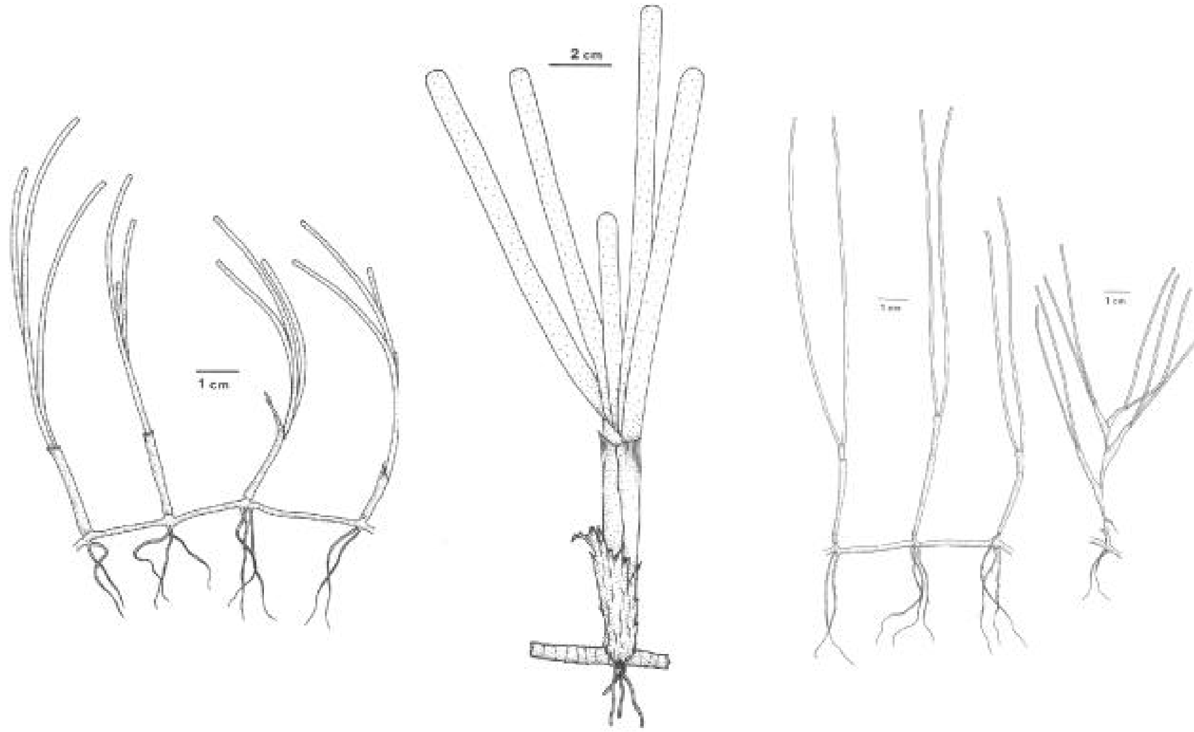

Figure 2. Diagram of four common seagrasses present in Texas estuaries (from left: *Syringodium filiforme*, *Thalassia testudinum*, *Halodule wrightii,* and *Ruppia maritima*).

We studied three species (Fig. 2) that occur in high frequency in the upper and Lower Laguna Madre, *Thalassia testudinum* (turtle grass), *Halodule wrightii* (shoal grass), and *Syringodium filiforme* (manatee grass). There were distinct seasonal variations in both density and above- and below- ground biomass that reflected changes in both day length and water temperature. Ratios of below-ground to above-ground biomass were highest in winter (3-8) and lowest in summer (2-6). *Thalassia* exhibited the highest biomass (over 900 gdw m^{-2}), but highest shoot density was characteristic of *Halodule* (over 8,000 m^{-2}), with *Syringodium* intermediate between the two species. Carbon content in *Thalassia* leaf and rhizome tissues averaged 36% and the nitrogen content of leaf tissues (1.7-2.7%) was higher than that of rhizomes (<1%).

Continuous measurements of photosynthetically active radiation (PAR), the diffuse light attenuation coefficient (*k*), and water column chemical parameters were also taken at several stations in Laguna Madre over an 18-month period starting in April 1996. We found average water transparency highest at station LLM 2 (k = 0.7 m^{-1}), which was surrounded by dense seagrass beds, and lowest at LLM 1 (*k*

= 2.4 m^{-1}), an unvegetated site. The decline in the brown tide algal bloom in the Upper Laguna led to significant increases in water clarity. At ULM 3, *k* values dropped from over 7.0 m^{-1} in January 1997 to less than 2 m^{-1} by June 1997. Water column chlorophyll levels were generally <10 µg L^{-1} in Lower Laguna, and declined in Upper Laguna from 20-70 µg L^{-1} to <10 µg L^{-1} following the decline in the brown tide. Nitrite and ammonium levels were generally less than 3 µM and salinity ranged from 30-45 ‰ at all sites.

SEDIMENT GEOCHEMISRY

Based on analytical analyses of large numbers of samples, most (80%) Laguna sediments possess the following characteristics: <50 wt. % silt and clay fraction (<63 µm); <1 wt. % organic-C; <8 µmol/g total reactive sulfides (TRS); <500 µM NH_4^+, <12 µM PO_4, <4000 µM DOC (dissolved organic carbon); and <200 µM H_2S (the value above which sulfides can negatively influence seagrasses). A much lower percentage of samples have values outside these ranges for the various parameters: About 69% of the high DOC values are in grass beds, none of which are *Thalassia* beds, whereas all but one of the high H_2S values are in bare areas. A possible interpretation is that the influence of the seagrasses is to elevate DOC, possibly as exudates, and H_2S is oxidized to sulfate by the pumping of oxygen into the sediment by the plants (Fig. 3).

It is important to note that sediments in seagrass beds and bare areas contrast sharply with those found in dredged channels. Average values from samples collected from six sites in the GIWW, three in Lower and three in Upper Laguna Madre, were 82% <63 µm grain size fraction, 1.9 wt. % organic-C and 2957 µM NH_4^+. They are much finer grained and contain roughly double the organic-C and six times the NH_4^+ compared to the upper limits for sediments outside the GIWW. These major compositional differences suggest that dredged channel sediments may be poor substrates for rapid establishment of healthy grass beds. However, an observation that an old dredged material deposit had, with the exception of grain size, largely evolved into a geochemical composition similar to most other Laguna Madre sediments demonstrates that significant geochemical transformation of these areas does occur with time.

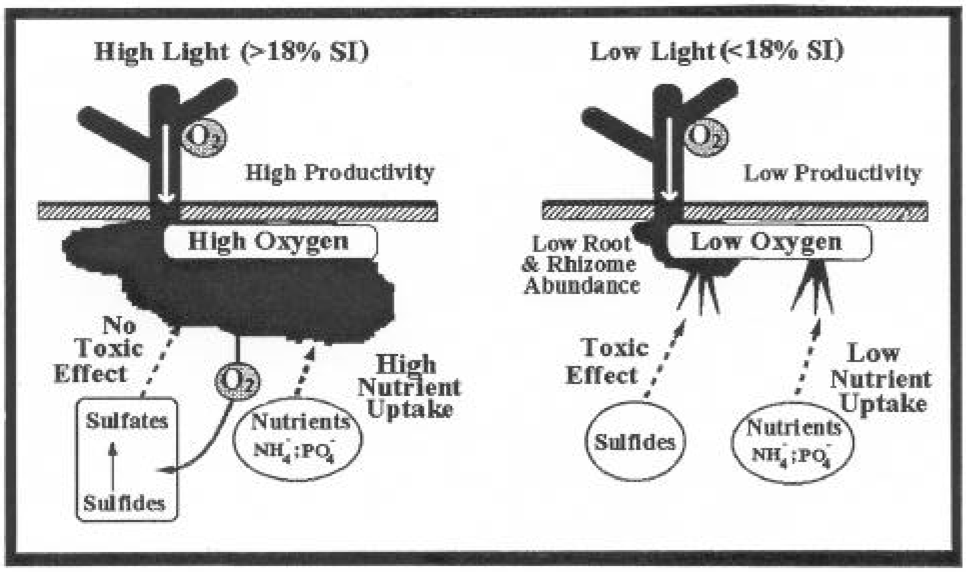

Figure 3. Oxygen produced in photosynthesis and transported into seagrass root and rhizome tissues plays an important role in the maintenance of aerobic conditions in the rhizosphere. Under low light conditions, less oxygen is available for below-ground tissue respiration, resulting in the buildup of sulfides and ammonium, which are toxic at high concentrations.

NUTRIENT RELEASE BY SUSPENDED SEDIMENTS

Resuspension of sediments by dredging, large ship traffic, and storms represents a potentially important local source of nutrients for Laguna Madre waters. Closed system NH_4^+ release experiments, conducted on sediments collected from potential dredge sites in the Laguna GIWW, revealed significant releases of pore water NH_4^+. In addition, a “fast release” fraction increased resuspension concentrations significantly. Fast release refers to NH_4^+ loosely bound to particles and quickly (within 5 min. of resuspension) desorbed during relocation of sediments. Using these data (specifically results from Marker 41 LLM), we performed calculations on the potential release of NH_4^+ during previous dredging events in the Laguna (*e.g.*, Port Mansfield, 1989). Essentially the volume of material was converted using pore water NH_4^+ concentrations and the fast release attached fraction (per gram) to arrive at a quantity that could potentially enter the region due to sediment relocation.
Our results revealed a release of inorganic-N in excess of 46 metric tons over a time period of two months in this small area. For comparison, monthly flux calculations from surficial sediments in the entire Lower Laguna Madre basin are about 80 metric tons.

SEAGRASS RESPONSE TO A DREDGING EVENT

Changes in the distribution and population characteristics of the seagrass *Thalassia testudinum* were assessed in Lower Laguna Madre following a dredging event in September 1998 (Fig. 4). Underwater photosynthetically active radiation (PAR), shoot density, biomass and blade chlorophyll content were monitored before and after the dredging event at a station (PA235) located near the disposal site and at an adjacent but unaffected control site (LLM 2).

Dredging of the GIWW and placement of dredged materials in Placement Area 235 (PA235) began in early September 1998. Two of the sampling sites at the placement area (PA235a & b) were buried by dredge materials and all plant shoots disappeared within two months after dredging; two remaining sites (PA235c & d), located within 200 m of the buried sites (about 0.5 km distant from PA235) were exposed to heavy siltation but not buried. Underwater irradiance at the PA235 sites was reduced significantly compared to the control site during and following dredging activity. This increased light attenuation was sustained for over nine months (Fig. 5). Water column chlorophyll and NH_4^+ concentrations increased significantly after dredging.

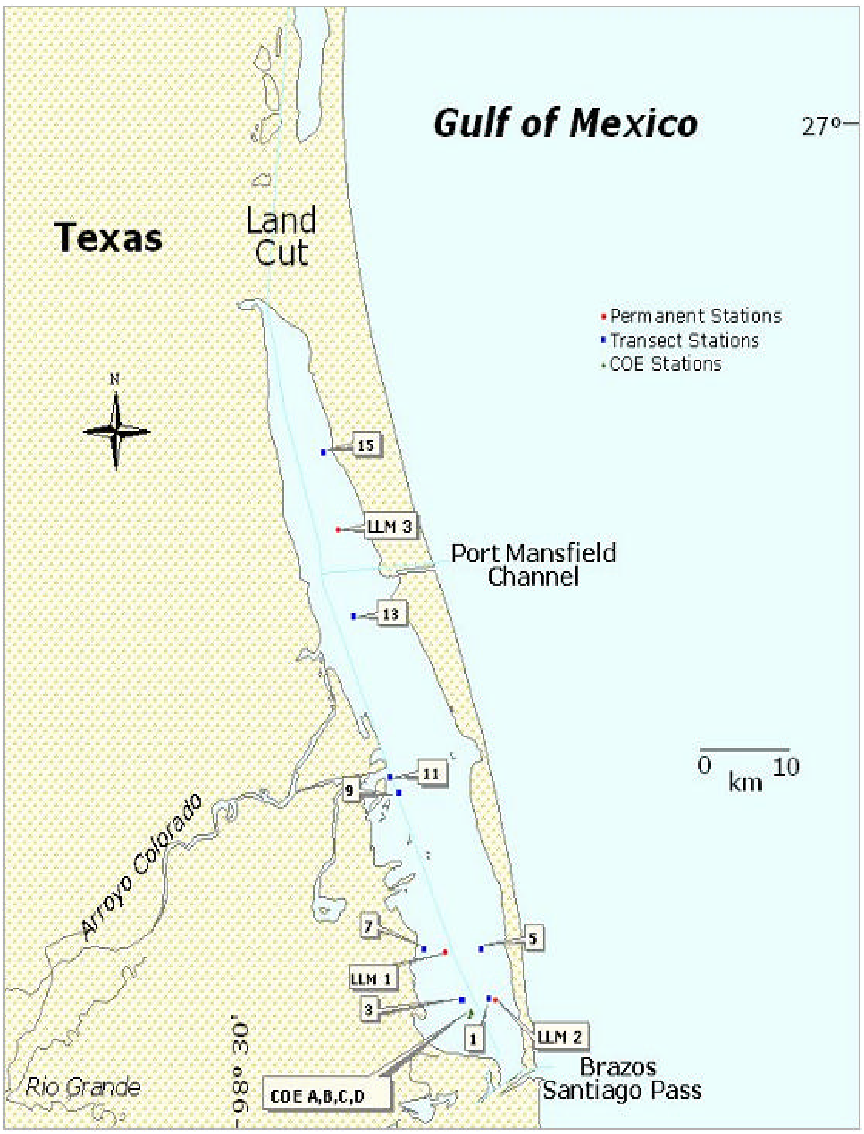

Figure 4. The Lower Laguna Madre. The location of dredge disposal placement area PA235 is indicated by sites COE (A-D). Dredging started in early September 1998 and ended three weeks later.

Increases in water column NH_4^+ concentrations at the PA235 sites were coincident with increases in water column chlorophyll concentrations, suggesting high re-mineralized nitrogen flux from the sediment, which had NH_4^+ values exceeding 500 µM after dredging. Shoot density and biomass declined significantly (Fig. 6), and leaf production rates decreased to a third of that recorded at the control site after dredging. Dredging activity was deleterious to seagrass growth and survival as a result of direct burial and increased light attenuation caused by sediment suspension. Burial was severe but more localized in comparison to increased light attenuation, which affected adjacent seagrass beds for a period of at least nine months following the cessation of material disposal. This increased attenuation can be attributed to continuous resuspension of dredged materials by wind-generated waves. Both below- and above-ground biomass declined appreciably within the first

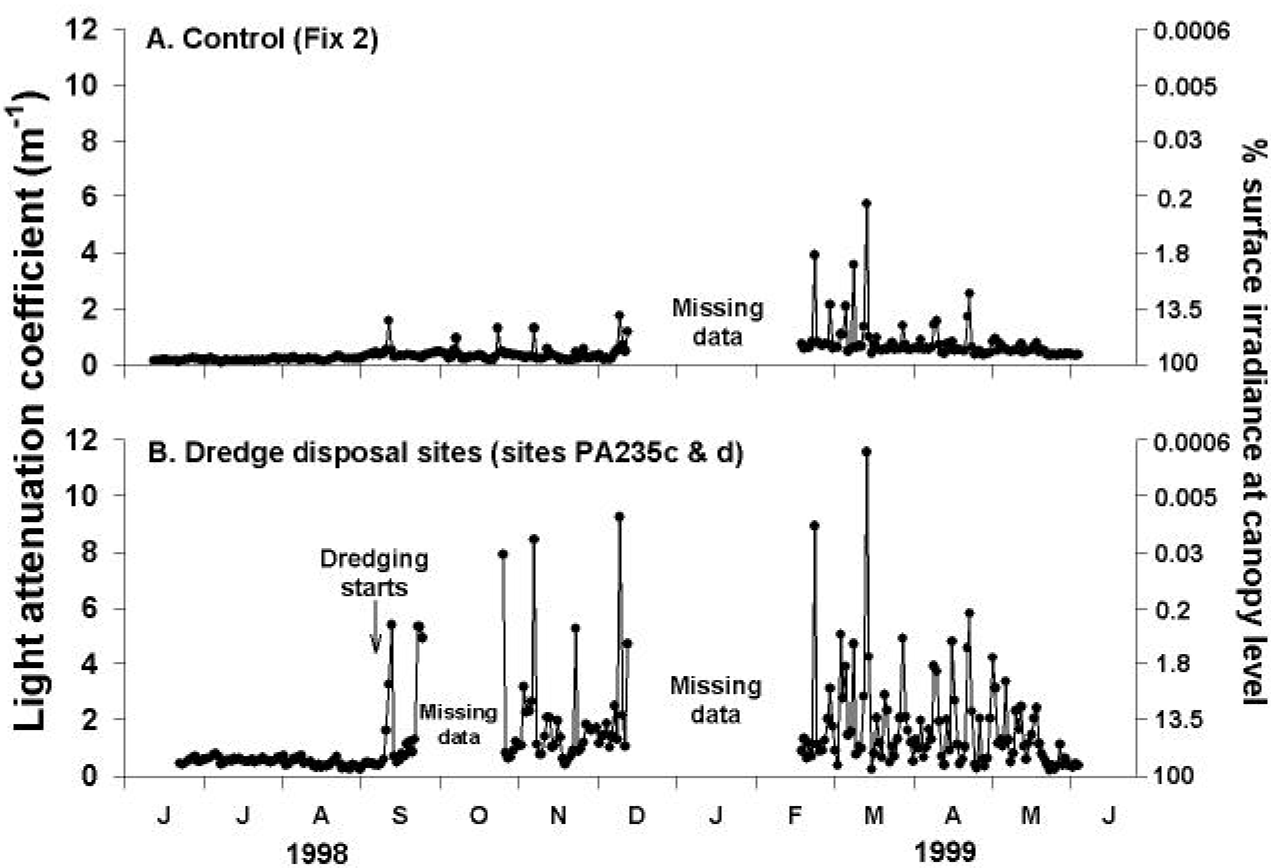

Figure 5. Variation in light attenuation at LLM 2 (Fix 2) and at two sites located about 0.5 km from dredge disposal placement area PA235. Higher variability in light attenuation at PA235c&d continued to occur nine months following the cessation of disposal in late September 1998.

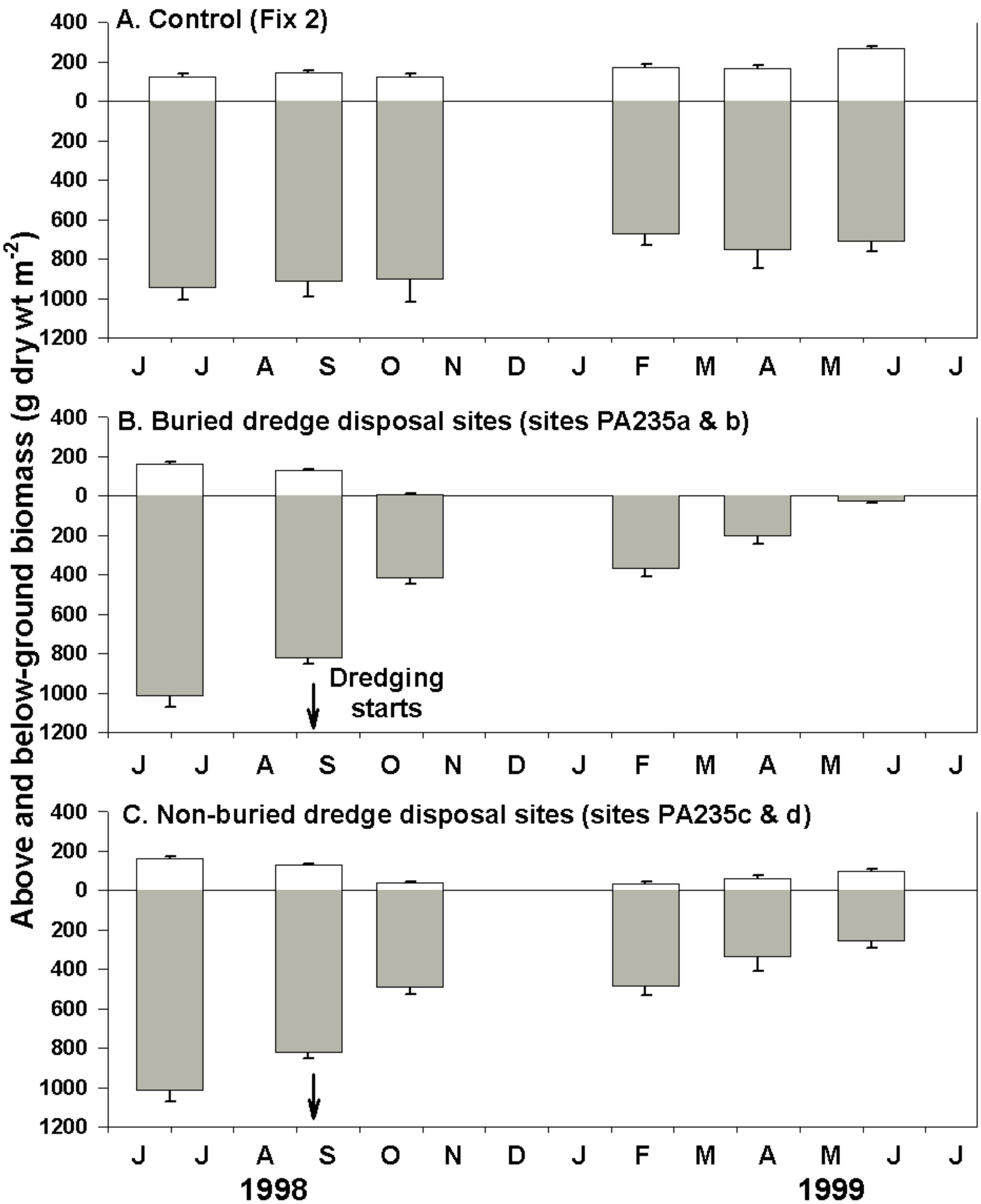

Figure 6. Above- and below-ground biomass at the control site (LLM 2/Fix 2) in comparison to PA235 sites adjacent to the deposition of dredged materials, before and after disposal began. Seagrasses at sites 235a&b were completely buried, whereas seagrasses at sites 235c&d were subject to high water turbidity from wind-driven resuspension events.

six months following disposal at PA235. Nine months later, in June 1999, leaf and shoot tissue biomass had begun to recover, but root and rhizome tissues were still in decline, presumably in response to the transfer of carbon to support the recovery of above-ground tissues. These observations support the importance of whole plant models to predict changes in seagrass biomass and the significance of resuspension events on water column transparency for extended periods following disposal of dredged materials.

PART THREE

Model Conclusions

MODEL DEVELOPMENT

The second phase of our research was largely focused on data synthesis and model development. Data collected in the first phase were used in conjunction with previously published information to refine the models and ultimately, test them. The second phase included a field verification of the *Thalassia testudinum* model based on plant response to an actual dredging event.

INVERSE MODELING

The inverse modeling method is a powerful tool for understanding complex physiological relationships between seagrasses and their environment. The power of the method results from using ranges of data within a system of constraints to describe the biological system, in this case the flow of carbon and nitrogen through *Thalassia testudinum* (turtle grass). Carbon flow represents energy flow while nitrogen flow is a surrogate for the nutritional state of the plant. We used field measurements and literature values of production, growth and turnover rates, etc. to develop the data and constraint systems. The model uses an optimization routine to calculate a complete set of physiological flows within the plant based on measured rate processes. This optimization routine is a "least-squares analysis" which solves for the shortest flow network that is consistent with all constraints. The result is a partitioning of material fluxes (i.e., carbon and nitrogen) that satisfies the rates of production, growth and turnover of the different compartments as delineated by empirical measurements. Model results indicate that assimilated carbon was equally partitioned between leaves and below-ground tissues and that the flow was unidirectional during the summer months (Fig. 1). Losses to dissolved organic carbon (DOC) from the root/rhizome module were substantial and may contribute to the high DOC concentrations measured in the sediments. Nitrogen assimilation occurred in the below-ground module and model results indicate that internal recycling, particularly from the leaves, is important.

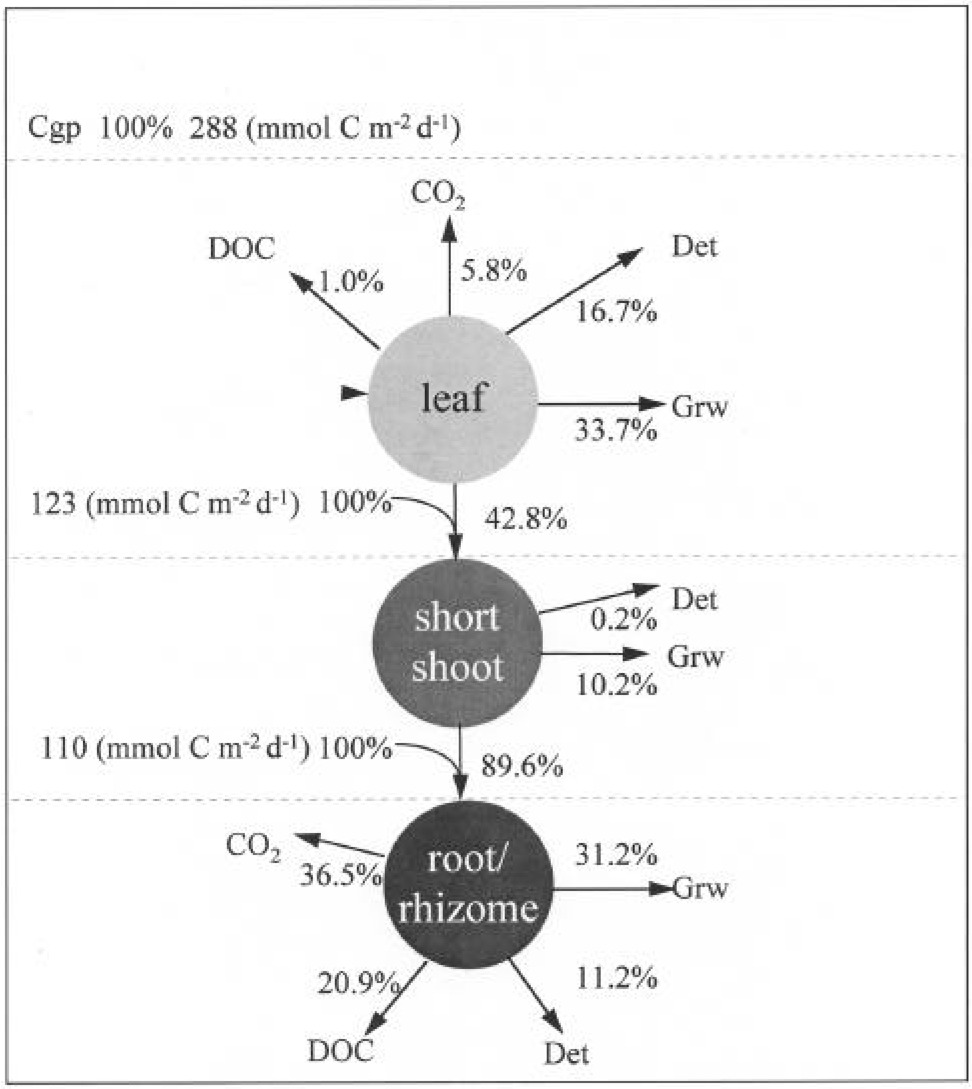

Figure 1. *Thalassia* carbon flow diagram. Arrows indicate direction and numbers (in bold) show the amount of the flow (mmol C m^{-2} d^{-1}) to other seagrass components, such as respiration (CO_2), excretion (DOC), detritus (Det), and growth (Grw) based on a net carbon input from gross primary production (Cgp) of 298 mmol C m^{-2} d^{-1}.

Losses of dissolved organic nitrogen (DON) were minimal, indicating that *Thalassia* uses nitrogen efficiently.

We ran a tracer analysis to determine the exchangeable pool size within each seagrass module (leaves, short shoot, root/rhizome) and accumulation within biogeochemical pools. Thus, using measured growth rates we were able to model the flow of carbon and nitrogen through the plant and the environment. Tracer analysis suggests that seagrasses are an important contributor to the sediment pore water DOC pool. Modeled flux rates were subsequently used to parameterize the *Thalassia* production model and the sediment-root/rhizome interactions in all of the production models.

SEDIMENT GEOCHEMICAL MODELS

Until recently, sediment geochemical models (diagenetic models) have been only able to explain sedimentary flux and concentration profiles for a few simplified geochemical cycles (*e.g.*, nitrogen, carbon and sulfur). However, with advances in numerical methods, increased accuracy and precision of chemical analyses, and a greater understanding of sedimentary processes, a new generation of models have been developed that incorporate most of the important sedimentary geochemical cycles simultaneously. We borrowed heavily from these models to develop a geochemical model that describes sedimentary processes in seagrass beds. The seagrass geochemical model is unique in that it includes a simulation of the seagrass rhizosphere (sediments geochemical zone influenced by seagrass roots and rhizomes). The rhizosphere simulation is important since seagrasses pump O_2 from their root system into the sediments to reduce the concentration of toxic sulfides. The O_2 is routed through a transport structure (lacunae) from the shoots, where it is produced by photosynthesis, to the roots and rhizomes where it diffuses into the sediments. The model is optimized to operate in the rapidly fluctuating environments found in lagoons and bays of Texas. The calibration data set was developed for sediments of *Syringodium filiforme*, *Thalassia testudinum*, and *Halodule wrightii* seagrass beds. The associated model was validated with a separate data set collected during a dredge event in Lower Laguna Madre. The results of that simulation verified the accuracy of the model under conditions found over an annual cycle.

The goal of the diagenetic model development was to provide an accurate geochemical model that could be coupled to the seagrass productivity model. The results of the calibration phase of this study showed an interesting interaction between the seagrass and its sedimentary environment. The relative depth of the rhizosphere and the depth of maximum sediment metabolism largely determined the sulfide concentration in the rhizosphere. In our *Syringodium* simulation, maximum metabolism and the rhizosphere depth were the same. To protect the root and rhizome structures from sulfides, the seagrass had to allocate most of its O_2 production to the root zone. Sediment metabolism was maximal in the surficial sediments in the *Thalassia and Halodule* simulations, and as a result they required less than half of their O_2 production to maintain low sulfide concentrations in the rhizosphere. However, in each case, the seagrasses were able to keep sulfide concentrations low in the absence of measurable O_2 concentrations.

LIGHT MODELS

The preponderance of evidence suggests that light availability is one of the main factors influencing the health of seagrasses in Laguna Madre. Thus, predicting the light field over the seagrass canopy under different environmental conditions was a key issue in this study. Because phytoplankton and other suspended materials influence light attenuation, we also examined spatial and temporal dynamics of phytopigments (a biomarker for plankton) and nutrients. Pigment data indicated that Texas brown tide organism, *Aureoumbra lagunensis*, was the dominant phytoplankter, particularly in Upper Laguna Madre. In Lower Laguna Madre, brown tide was a seasonal component of the phytoplankton community, present only during the winter. Nutrient data suggested that Baffin Bay and Arroyo Colorado were sources of nitrogen to Laguna Madre and that water column production was probably nitrogen limited.

Previous work (Brown and Kraus 1997) identified a strong relationship between light attenuation and total suspended solids (TSS) in the water column. Because Brown and Kraus' observations were determined in a region of Laguna Madre where TSS is substantially higher than other regions of the estuary, we undertook a study of inherent optical properties (IOPs) throughout Laguna Madre waters including regions influenced by dredging activities. Strong relationships were observed between IOPs and TSS, suggesting that TSS was the main factor controlling light attenuation in the area studied under the environmental conditions occurring at these sites (Fig. 2). Based on these strong relationships, we used the radiative transfer numerical model, Hydrolight, to compute spectral irradiance in the water. The spectral irradiance model was then used to illustrate how different suspended materials, specifically phytoplankton and inorganic solids, influence the spectral quality of the underwater light field. The light field computed over the seagrass canopy and employed by the seagrass model incorporates recent developments in light dynamics in shallow waters.

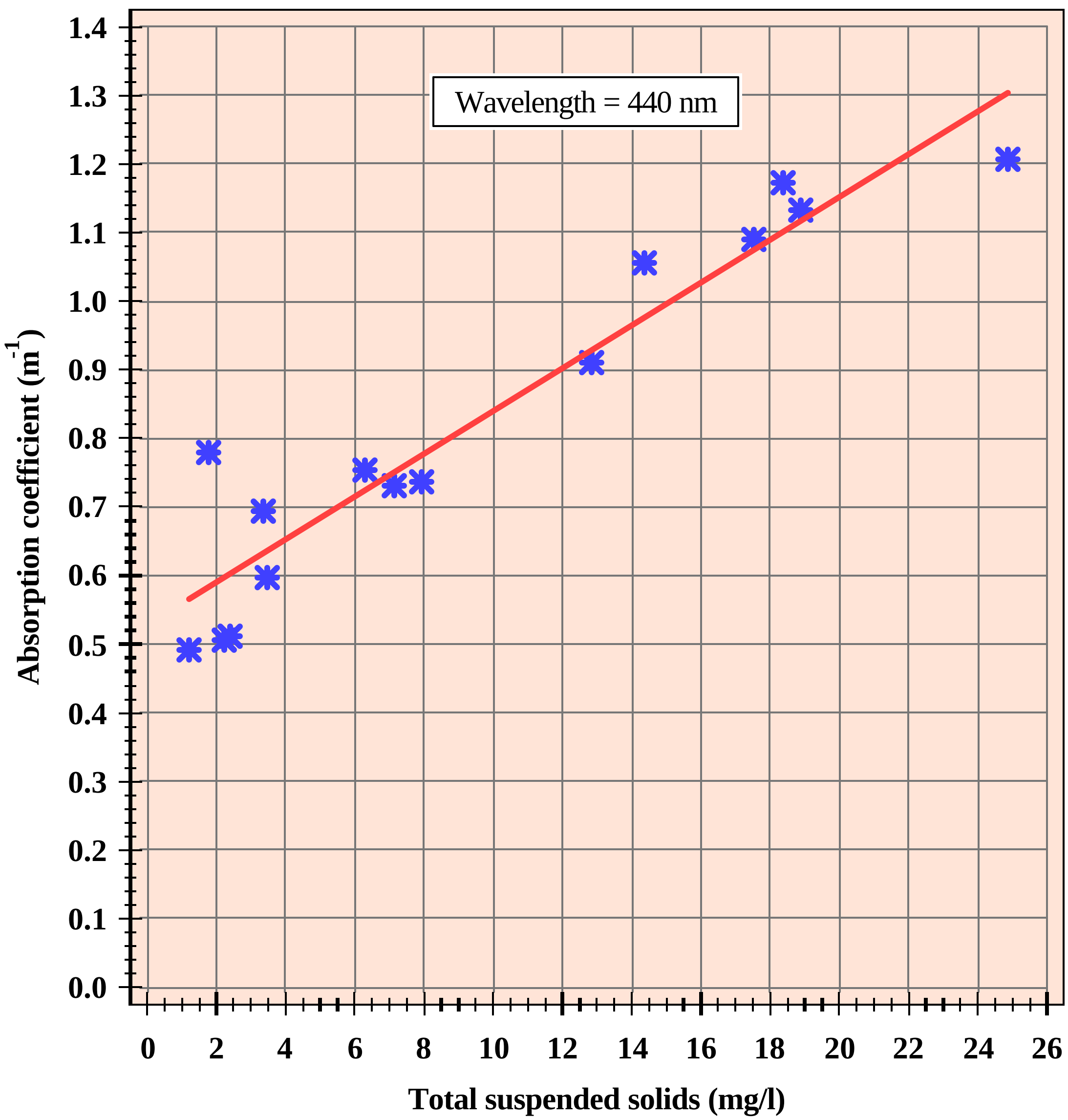

Figure 2. The absorption coefficient, *a*, vs. TSS at 440 nm in relatively clear waters. Note that the absorption coefficient does not tend towards zero as TSS approaches zero due to the presence of colored dissolved organic matter (CDOM) in the water.

THE INTEGRATED SEAGRASS MODEL

We made a concerted effort to produce detailed component models for carbon flow, below-ground geochemistry, and underwater light regimes for the integrated seagrass model. However, the lack of sufficient long-term data sets of plant biomass in relation to continuous measurements of underwater irradiance, combined with our limited understanding of source-sink relations in seagrasses, remained difficult problems. A predictive model was developed and verified for *Halodule wrightii*, largely using data collected previous to this study. However, we could not generate a predictive model that explicitly incorporated below-ground biomass for *Thalassia testudinum*, although we were able to verify the accuracy of model estimates of above-ground biomass using measurements collected during the field verification. It was also not possible to generate a constituent model for *Syringodium filiforme* from the biomass and irradiance data available for this plant.

The model was formulated to have both above- and below-ground components and to be applicable to the three dominant seagrass species in the Laguna, *Thalassia testudinum, Halodule wrightii* and *Syringodium filiforme*. The model is driven by incident light and incorporates transport from above- to below-ground tissue. A comprehensive sediment diagenesis model is coupled to the seagrass biomass model that allows the incorporation of important sediment toxicity effects (Fig. 3).

Model parameters were estimated by comparing model output with observations. For *Thalassia testudinum* the heterogeneity of the below-ground material prevented estimation of the below-ground parameters. For this plant, the below-ground compartment was modeled implicitly. Parameter estimation for the *Syringodium filiforme* model was unsuccessful. The reasons for this remain unclear.

A nearly 10-year long-term database for *Halodule wrightii*, derived from an ongoing study in Upper Laguna Madre, proved to be extremely valuable in developing a highly predictive model. As with all biological models, prediction of exact values of biomass under different conditions is impractical. The Laguna Madre Seagrass Model accurately predicts trends in biomass when the plants are exposed to different environmental conditions.

The *Halodule wrightii* model was calibrated using one year of a nine-year data set. Model validation was done using the remaining eight years. This data set included a prolonged period of light limitation caused by the brown tide algal bloom as well as the recovery from this bloom in 1996 and 1997. The model accurately reproduced observed trends in both above- and below-ground biomass.

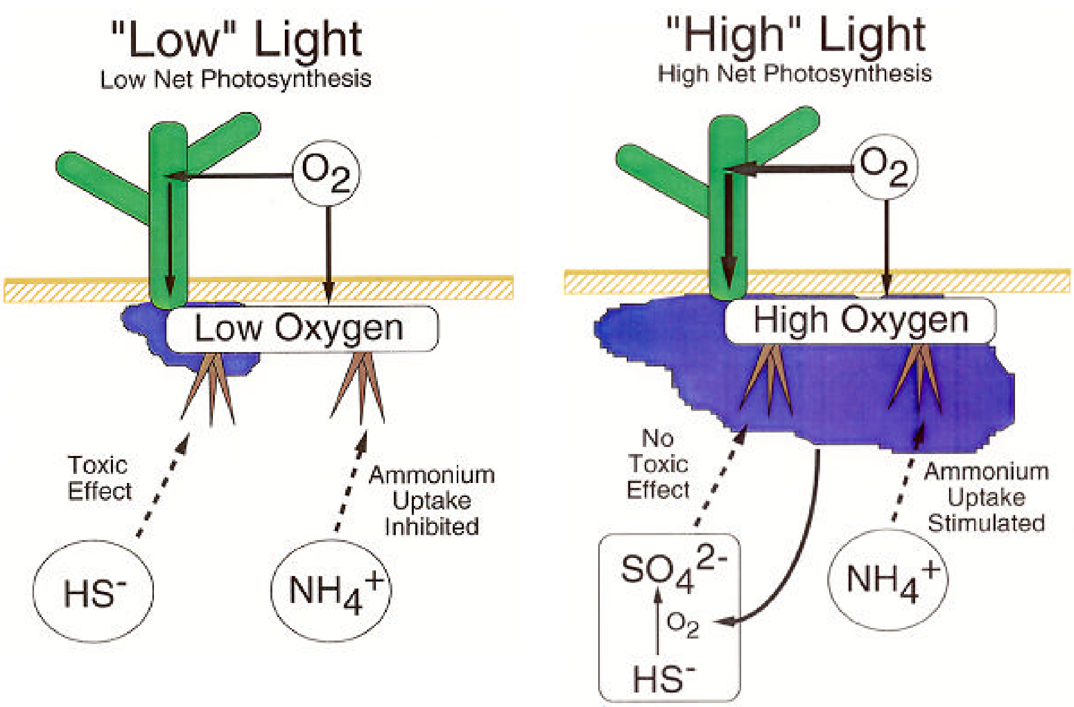

Figure 3. The components of the seagrass model incorporate both the above- and below-ground portions of plant biomass and the changes in sediment geochemistry that occur in relation to underwater light fields.

The *Thalassia testudinum* model was calibrated using one year of a two-year data set collected in Lower Laguna Madre and validated with the remaining year. The short duration of this data set was insufficient to provide a good test or calibration of the model, particularly since the plants did not show evidence of stress. However, the model successfully reproduced trends in above-ground biomass.

MODEL SIMULATION OF A DREDGING EVENT

Dredging activities in Lower Laguna Madre provided an opportunity to test the *Thalassia* model under field conditions. In September1998, at the recommendation of the ICT, 503,600 cubic yards of dredged material was placed at PA235. This should be compared with an average of 43,053 cubic yards placed at this site every 9.25 years between 1950 and 1999 (T. Roberts, pers. comm.). Both control sites and impact sites were chosen. We have considerable confidence in the model's ability to predict the long-term response of both above- and below-ground biomass for *Halodule*. For *Thalassia*, the model also works well but only predicts above-ground biomass.

Seagrasses at the site PA235a&b (approximately 500 m from PA235) were buried by dredged material. The model was originally formulated to examine the effects of chronic levels of stress (such as prolonged levels of light limitation or increased sediment sulfide concentrations) and not sudden impacts such as burial. Consequently, the model was modified to deal with this situation and was able to reproduce the rate at which plant biomass disappeared.

Detailed sediment chemistry profiles were also available for site PA235c&d (approximately 700 m from PA235) so the full seagrass-sediment chemistry model was tested at this site. A time series of underwater irradiance was constructed using data from all four PA235 sites with gaps in the final record filled using a combination of interpolated values and modeled surface irradiance. The model reproduced the decline in biomass during the winter of 1998 but was unable to capture the start of the recovery in the spring of 1999.

Field data collected at site PA235c&d during and following the September 1998 dredging event were used to develop two three-year simulations which included deposition of dredge material on the seagrass bed (as was seen at PA235c&d).

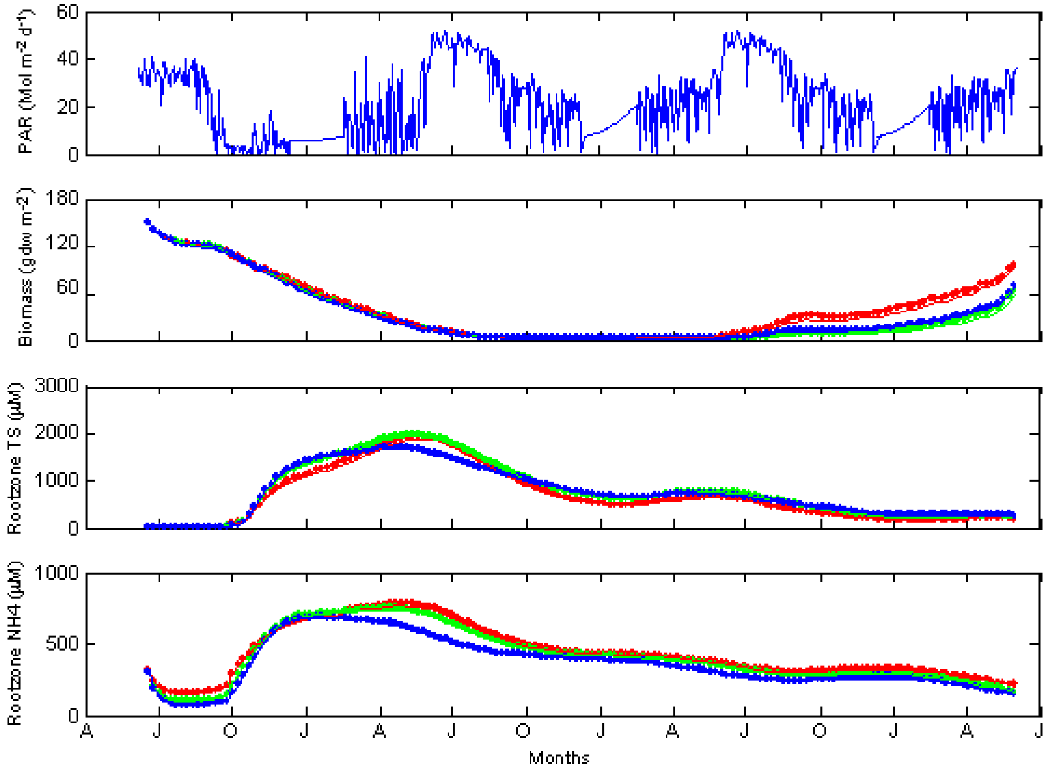

Figure 4. Underwater irradiance, above-ground biomass, root-zone total sulfides and ammonia for a three-year simulation with dredging occurring only in the first year. Model simulations include root zone depths at 5 cm (red), 7 cm (green), and 9 cm (blue).

The first simulation was defined with disposal of dredged material occurring only in the first year (Fig. 4). Model results one year into the simulation were in general agreement with measurements collected at site PA235 a year following the initial dredging event. Above-ground biomass predicted by the model was less than observed *in situ* but this might be related to our inability to incorporate below-ground biomass in the *Thalassia* model. Consequently, model results could be considered *conservative* estimates of seagrass response. In this case, the model predicted that water column and sediment conditions would be favorable for seagrasses to colonize the area after 2-3 years. This is reflected by the modeled biomass approaching 50% of its pre-dredging value at the end of a three-year simulation. The model also predicted a significant decline in sediment sulfide and ammonium concentrations to near pre-dredge values, which was consistent with *in situ* measurements collected during the first year following the dredging event.

In the second three-year simulation, disposal occurred in both the first and third year. In this model, seagrasses do not survive (Fig. 5). This is partly because root zone sulfide and ammonium concentrations are not given sufficient time to return to pre-dredging values before the second disposal event. This leads to even greater sulfide and ammonium concentrations which, combined with the reduced irradiance from increased TSS, kills the plants.

The results of these simulations indicate that seagrasses in close proximity (*i.e.*, less than about 1 km) to a large disposal area require a period greater than three years between dredging activities in order to recover. Several caveats surround this conclusion. First, without detailed hydrodynamic and sediment transport information, erosion and resuspension of disposal material is impossible to incorporate in the model. This lack of data was partly overcome in this case by using *in situ* underwater irradiance field data, which incorporated the effects of resuspended material on the total irradiance reaching the plant

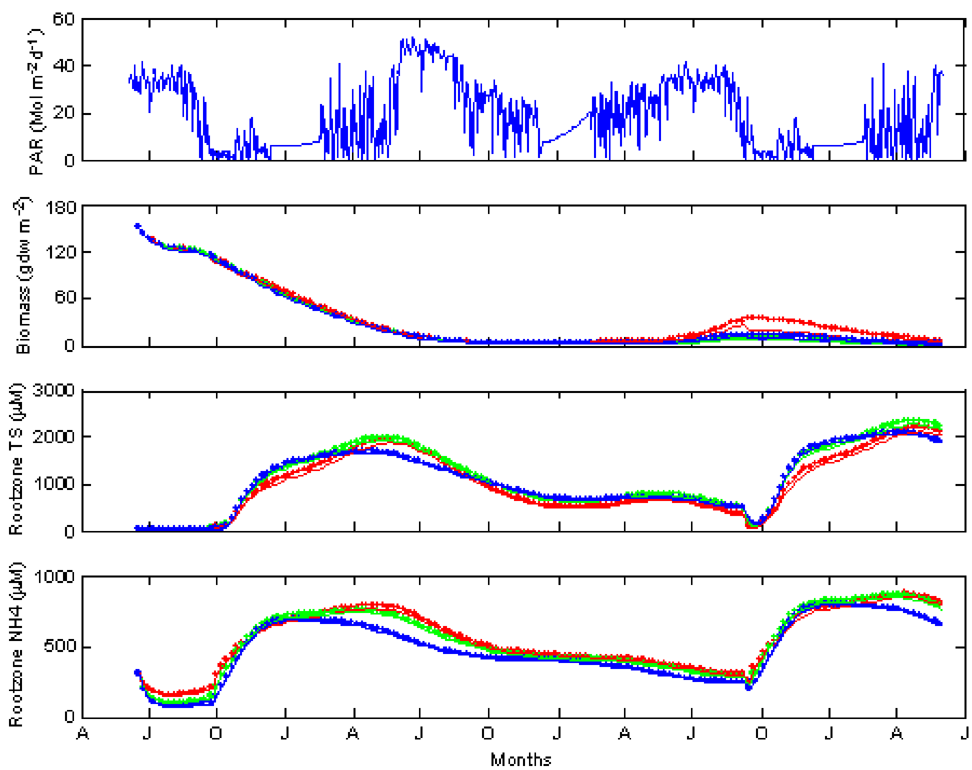

Figure 5. Underwater irradiance, above-ground biomass, root-zone sulfide and ammonium concentrations for a three-year simulation with dredging occurring in the first and third years. Model simulations include root zone depths at 5 cm (red), 7 cm (green), and 9 cm (blue). Model conditions for *Thalassia testudinum* are based on an initial biomass of 100- to 150-gdw m^{-3}, which falls within the range of measured biomass in Laguna Madre.

canopy. However, this in turn makes these conclusions site specific and caution needs to be taken in applying these results to the Laguna as a whole, where the model results given in the chapter *Final Model Results* are more appropriate. In addition, the amount of material that was placed at PA235 was significantly greater than usual.

MODEL CONCLUSIONS

The results of our production runs of the Laguna Madre Seagrass Model combine output from the W.E.S. Hydrodynamic and Sediment Transport models to provide suitable forcing conditions for the Seagrass Biomass and Diagenesis Model. The W.E.S. model was designed to address a "worst case scenario" as defined by the members of the I.C.T. Placement occurred in the model on 1 April 1995 at six sites (three in Upper Laguna Madre and three in Lower Laguna Madre) with a total of 1.5848×10^9 dry-kg of material being placed over a period of 24 hours. Sites for the seagrass model were located 1.2 to 7.1 km from the nearest placement area in the W.E.S. model. The results of the W.E.S. models and the Seagrass Model predict that at the sites simulated, seagrasses survive the impacts of disposal of dredged material with seagrass beds closer to actual disposal sites being impacted to a greater extent than those further away. In interpreting the results from this model one needs to note that material is usually deposited over a period of approximately 1 week, and not in 24 hours. In addition, the total amount of material deposited in the model was approximately 50% greater than the average annual dredging in Laguna Madre and thus the simulation modeled an extreme case.

Modeled concentrations of TSS tend to be elevated during the spring and the fall, with lower values during the summer growth period. The time series of modeled underwater irradiance reflects the changes in the TSS concentration; low light levels occur during the spring and fall months and increase during the summer. Long-term trends in modeled TSS at the sites considered in the Laguna Madre Seagrass Model show little difference between dredging and non-dredging scenarios. This is partly due to the fact that sites for the seagrass model were chosen to examine large-scale, Laguna-wide impacts of disposal. Simulations based on data collected at PA235 were performed to examine the impact on seagrasses in close proximity (less than 1 km) to a disposal site, but in this case the amount of dredged material placed at PA235 was substantially larger than usual.

Biomass at the *Halodule wrightii* model sites tends to increase and values at the end of the simulation are higher than those observed in Laguna Madre. The model predicts above-ground biomass values for *Thalassia testudinum* that generally lie between 100 and 150 gdw m^{-3}; these fall within the range of measured biomass in Laguna Madre.

Root-zone HS^- concentrations are low except at a few sites in Upper Laguna Madre. Typical values predicted by the model are between 5 and 10 µM, though in the Upper Laguna concentrations can reach as high as 400 µM. For NH_4^+, the model predicts root-zone concentrations between 100 and 350 µM, which are within the range of measured values. Both the HS^- and NH_4^+ concentrations predicted by the model are not sufficient to significantly affect the growth and production of the plants indicating that under the conditions of the production model, available irradiance is the dominant factor affecting seagrass growth and production.

The model assumes that the only factors contributing to attenuation of light in the water column are the water itself and TSS. We have not accounted for the effects of other factors such as algal mats and phytoplankton blooms. The model also does not account for the burial of seagrasses by sediment, though deposition and incorporation of dredge material into the sediment are included in the model.

The results of the model, and the caveats underpinning it, strongly suggest that efforts should be made to monitor seagrass health and water quality at periodic intervals (*e.g.*, instantaneous measurements of light attenuation, TSS, various plant parameters) at selected locations in Laguna Madre. Specific guidelines for long-term monitoring, including the criteria and indicators most appropriate for seagrass health, are currently being developed under EPA's R-EMAP program for Texas estuaries. The results of such an effort, together with the data collected in this study, would provide an invaluable opportunity to examine long-term (decadal) changes in seagrass populations that are coincident with dredging activities.

If open-bay disposal is to continue, we recommend that a buffer zone or barrier be utilized between the placement area and nearest seagrass beds to limit the impacts of elevated TSS levels on adjacent plant populations. Model simulations and *in situ* measurements of an actual dredging event demonstrated that plants located within 500 m of PA235 were completely buried and plants 700 m distant were measurably affected by chronic low levels of light up to nine months following disposal. In addition, dredging and disposal activities at open-water, unconfined sites should be limited to the period between November 1 and February 28 each year to ameliorate TSS impacts on growth. This period is characterized by low (< 20° C) water temperatures and a general dormancy in seagrass metabolism, including photosynthesis and growth. Dredging activities during this period are likely to impact seagrass populations least, although resuspension of sediments during the peak growth period in spring could result in significant drops in water column transparency and seagrass productivity. However, the relative importance of such resuspension events is likely to be site specific based on the proximity of adjacent seagrass populations. Again, such concerns should be addressed through strategic monitoring of critical parameters as described above.