Seagrass Stress Response Model: The importance of Light, Temperature, Sedimentation and Geochemistry

Peter M. Eldridge and James E. Kaldy

Western Ecology Division, US EPA, Newport, Oregon

Adrian B. Burd

Department of Marine Sciences, University of Georgia, Athens

Abstract. The objective of our modeling was to better understand the relationship between seagrass and water-column and sediment stressors (i.e., light, organic and particle sedimentation, sediment nutrients and sulfides). The model was developed and optimized for sediments in *Thalassia testudinum* seagrass beds of Lower Laguna Madre, Texas, USA and is composed of a plant sub-model and a sediment diagenetic sub-model. Simulations were developed for a natural stressor (harmful algal bloom) and an anthropogenic stressor (dredging event). The harmful algal bloom (HAB) was of limited duration and the simulations showed no effect of the algal bloom on biomass trends but did suggest that sediment sulfides could inhibit growth if the bloom duration and intensity were greater. The dredging event resulted in sedimentation of a layer of organically rich material and reduction of canopy light for a period of months. The simulations suggested that the seagrass could have recovered from the effects of light but residual effects of high sulfides in the sediments would make the region uninhabitable for seagrasses for up to 2.5 years. These modeling exercises point out the importance of using a geochemical model to evaluate the impact of reduced light and enhanced organic loading from both natural and anthropogenic stressors to seagrass.

1. **Introduction**

Worldwide >90,000 ha of submerged aquatic vegetation (SAV) habitat has been lost from estuarine habitat (Short and Wyllie-Echevarria, 1996) primarily as a result of natural and anthropogenic aquatic stressors. The loss of these highly valued habitats is affecting estuarine ecosystem health and function. The importance of seagrass habitat to ecosystem function and biodiversity has convinced local and national governmental agencies to develop programs to protect seagrass habitats from degradation (U.S. EPA, submitted). As a result academic and national research laboratories have developed numerical models that can be used to evaluate the response of seagrass to natural and anthropogenic stressors. These models are viewed as a mechanism for relating present and future levels of nutrient enrichment, sediment input, and other aquatic stressors to trends in seagrass production and biomass. Models can be used to evaluate regionally and locally important physical, biological and geochemical processes that interact with seagrass and this information can be used to set priorities on how best to ameliorate detrimental effects of aquatic stressors to the seagrass. Here we present a seagrass stress-response model for the tropical seagrass *Thalassia testudinum* ("*Thalassia* model"). We use the *Thalassia* model to examine how this seagrass may respond to both natural and anthropogenic stressors in Laguna Madre, Texas, USA.

Seagrasses interact physically, biologically and geochemically with both the water column and the sediments (Fig. 1). These interactions are often complex and location dependent. Many of the interactions are described in the primary literature. It is not possible or even desirable to include all the physical, biological, and geochemical processes that effect seagrass in a single model, instead it is more important to define and incorporate the key processes that are expected to shape seagrass population dynamics. In the following we develop the conceptual biogeochemical framework used for this model.

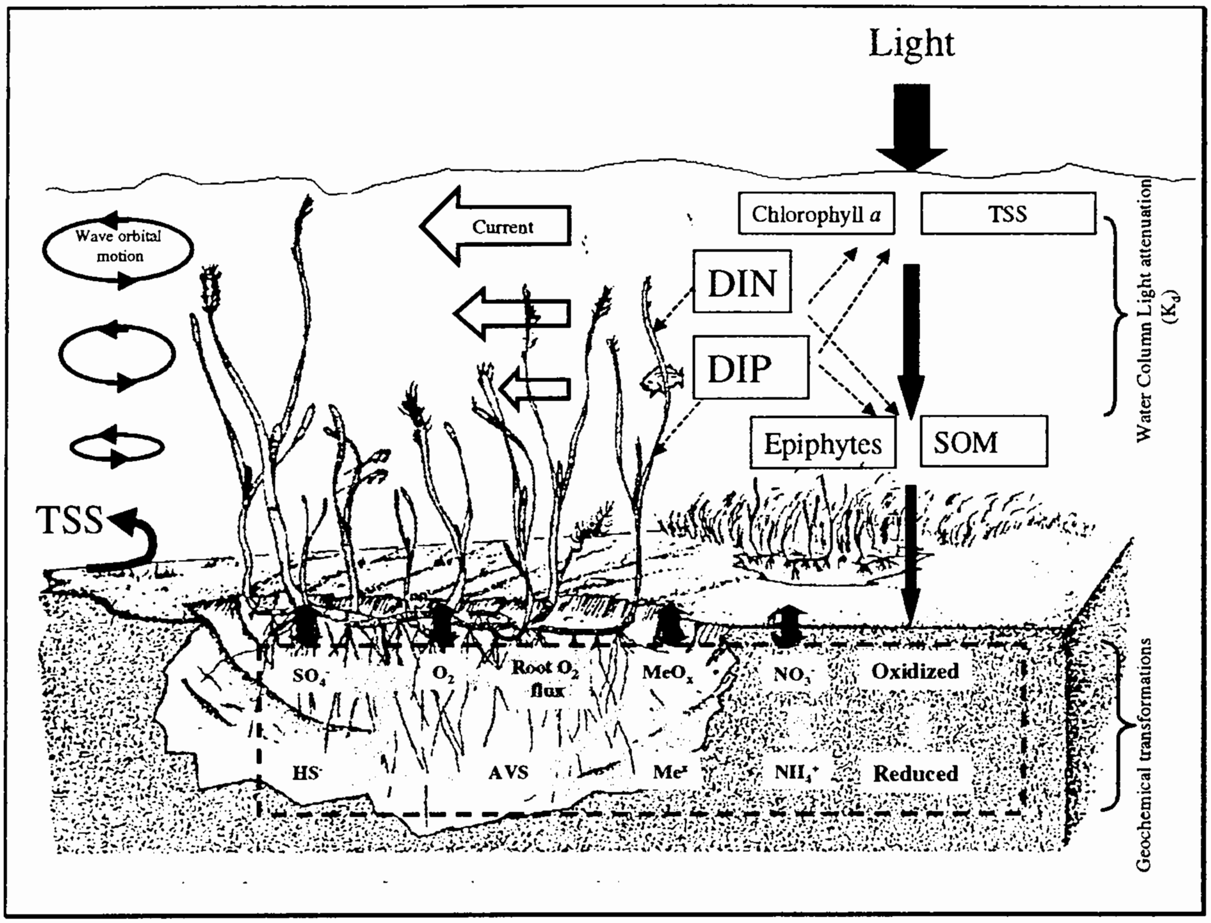


Figure 1. Interactions of seagrass with its biological, physical and geochemical environment. Seagrass illustration revised from Short 1989.

Seagrasses are "ecosystem engineers" (Koch 2001) and consequently alter the areas they colonize through feedback mechanisms. Similar to top-down and bottom-up control of phytoplankton populations in estuaries, seagrass production responds to canopy-water column and sediment-root/rhizome interactions (Hemminga and Duarte, 2000) (Fig. 2).

Seagrasses are most commonly limited by light (Zimmerman et al., 1995) and nutrients (Orth, 1977; Alcoverro et al., 1997), although CO_2 limitation can occur in isolated quiescent habitats. Most declines in seagrass are related to decreased light availability (Short and Wyllie-Echeverria, 1996). Low light stress is manifested in a cascade of effects that are intimately related to the geochemistry (Fig. 2).

Phytotoxic substances produced by anaerobic bacterial metabolism can limit seagrass distributions and may be determinates of anthropogenic effects on seagrass distribution (Carlson et al, 1994; Koch, 2001). A poorly understood yet key component controlling sediment geochemistry is the input of organic particles that are available for remineralization. Complex hydrodynamic interactions can cause seagrass beds to be either sources or sinks for particulate matter (Nepf and Koch, 1999).

Sediment sulfides are the most important of the potentially toxic metabolites from sediment diagenesis of organic matter (Koch, 2001). Experimental work has shown that anaerobic conditions inhibit internal carbohydrate transport (Zimmerman and Alberte, 1996) and that sulfides reduce seagrass photosynthesis (Goodman et al., 1995; Holmer and Bondgaard, 2001). To counteract sulfide concentrations in the rhizosphere, seagrasses transport photosynthetically produced O_2 through lacunae to the roots (Kraemer and Alberte 1993). This transport mechanism probably evolved to support aerobic root respiration, but excess O_2 diffusing from the roots has the additional benefit of oxidizing sulfide to non-toxic sulfate (Caffrey and Kemp, 1991). Model simulations indicate that O_2 diffused from the seagrass root system effectively reduce sulfide concentrations (Eldridge and Morse, 2000); additionally field experiments support these model results (Lee and Dunton, 2000)

The US EPA as part of the national effort to protect sensitive habitats from degradation is developing seagrass nutrient stress-response models. The *Thalassia* model is a prototype developed using data from a regional program (funded by the US Corps of Engineers, Galveston, TX) and undertaken by local universities and agencies to evaluate the effect of dredging on seagrasses in Laguna Madre, Texas, USA. While the plant model and the geochemical model of seagrass processes have been previously published (Burd and Dunton, 2001; Eldridge and Morse, 2000), this modeling study combines these models in a single coupled plant-sediment model that describes the effect of the interactions of water-column and sediment stressors.

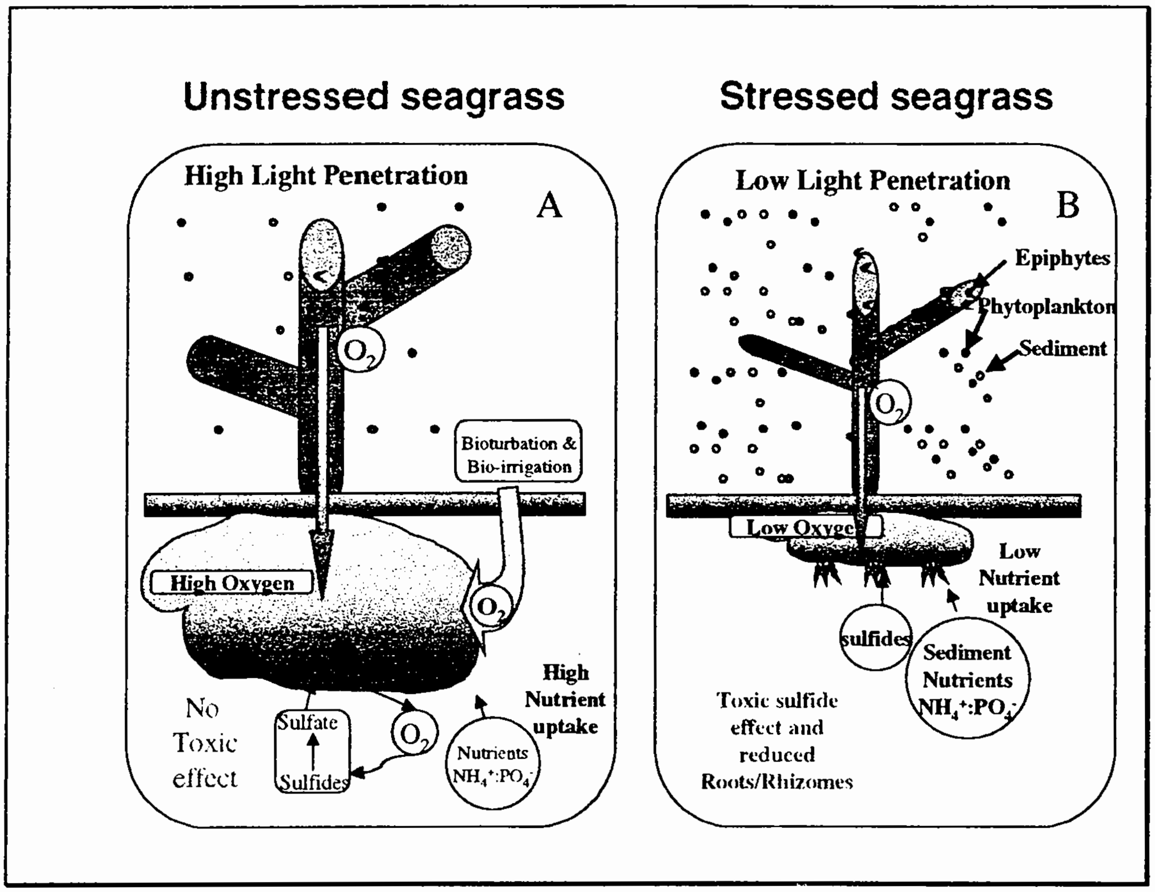


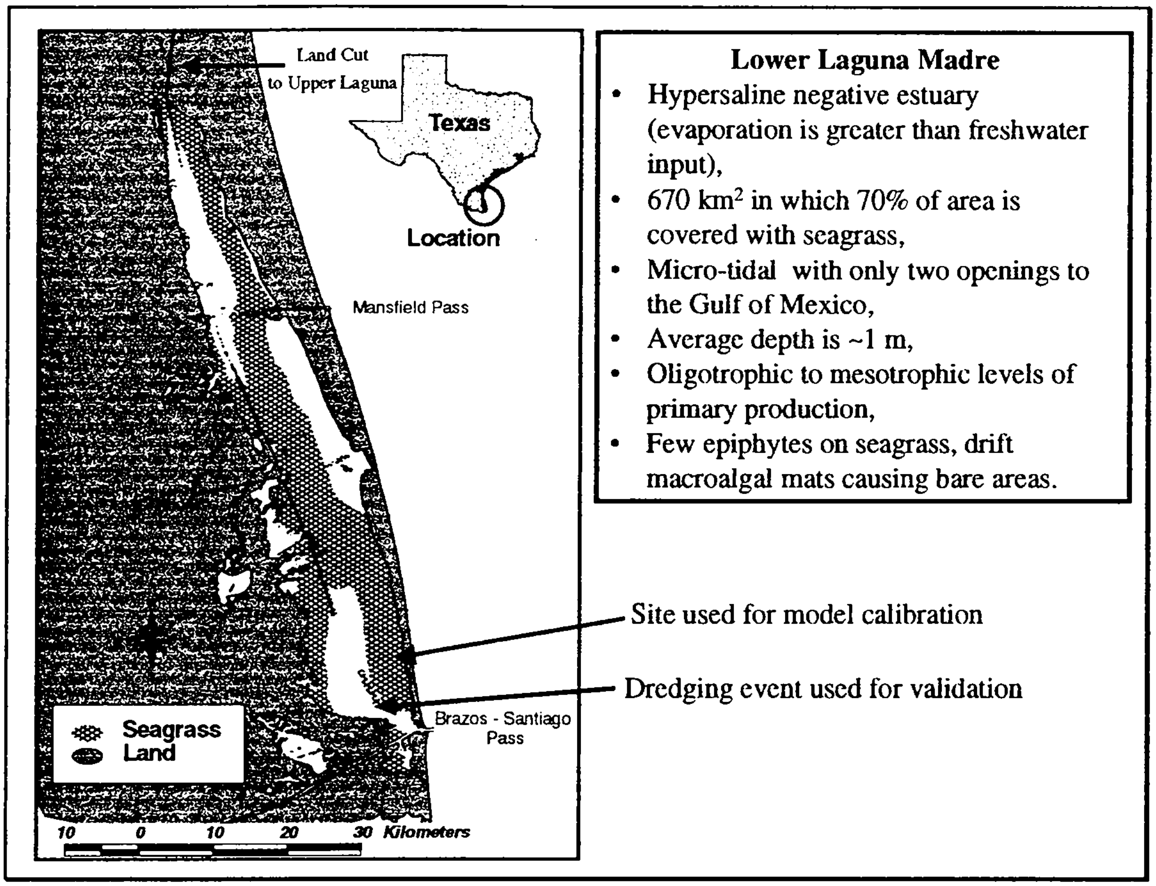
Figure 2. Seagrass sediment geochemical interactions. Part of the photosynthetic O_2 production is transported through lacunae to roots and sediments. The O_2 supports aerobic respiration in the roots and diffuses into sediments to re-oxidize toxic sulfides to non-toxic sulfate. A) During periods of high photosynthesis, seagrass can reduce sulfides to non-toxic levels. B) During periods of low photosynthetic activity, less O_2 is transported in the root zone and the plant is exposed to toxic sulfides.

2. **Model development**

As part of a large multi-investigator project, we developed a series of seagrass models for Laguna Madre, Texas (Fig. 3). Lower Laguna Madre (LLM) is a shallow, micro-tidal, wind-mixed estuary that is generally not subjected to anoxia or hypoxic events. Because of restricted access to the Gulf of Mexico and low fresh water inflows, the residence time of water and nutrients is long. The system's nutrient status is oligo- to mesotrophic and as a result there is little epiphyte interaction with seagrass. *Thalassia testudinum* (turtle grass) is the dominate species in the southern part of LLM and is the subject of this study. *T. testudinum* is a broad leaf seagrass with a canopy extending about 0.5 m from the bottom, and 80-90% of biomass in the below ground root and rhizome structure. These sub-tidal beds are not subjected to desiccation and wind-generated waves are rarely large enough to cause physical damage except during hurricanes. We explicitly deal with sediment resuspension and deposition; however, sediment transport issues were addressed with hydrodynamic and sediment transport models described elsewhere (Teeter et al., 2001).

The *Thalassia* model explicitly focuses on how light and sediment diagenesis influence seagrass biomass. To examine the interaction of stressors and seagrass we simulated two time periods; 1) during an interval when there were two harmful algal blooms in LLM (natural stressor), and 2) during a dredging event (anthropogenic stressor).

During both of these time periods, we collected time-series data on the physical properties of the system most likely to affect seagrass physiology. These measurements included continuous measurements of underwater irradiance at the seagrass canopy and temperature at a nearby site (Kaldy and Dunton, 2000) and sediment geochemical data (Eldridge and Morse, 2000).



Lower Laguna Madre

- Hypersaline negative estuary (evaporation is greater than freshwater input),
- 670 km^2 in which 70% of area is covered with seagrass,
- Micro-tidal with only two openings to the Gulf of Mexico,
- Average depth is ~1 m,
- Oligotrophic to mesotrophic levels of primary production,
- Few epiphytes on seagrass, drift macroalgal mats causing bare areas.

Figure 3. LLM was the site for the development work on the stress response model for *Thalassia testudinum.* The location map shows the position of the data collection site used for model calibration, and for the model validation during a dredging event. See Kaldy and Dunton (2000) for additional site description. Source of map is www.glo.state.tx.us/gisdata/gisdata.html

The factors that can inhibit seagrass production explicitly incorporated in the model are reduced light, nutrient limitation and increased phytotoxin concentrations. The effect of light was determined with a plant model (Burd and Dunton, 2001), while the production of nutrients and the sulfide phytotoxin were estimated using a sediment diagenetic model (Eldridge and Morse, 2000). We incorporated nutrient uptake kinetics for both above- and below-ground tissues (Lee and Dunton, 1999) and inhibition kinetics for toxic sulfide and ammonium concentrations (Carlson et al., 1994; Pulich, 1989)

2.1 Plant model

The governing equations used in the plant model are shown below. The Smith-Talling function (Talling 1957) was used to estimate gross primary production (P(I)) (EQ. 1) while the derivative function (EQ. 2) (Burd and Dunton, 2001) was used to estimate changes in above ground biomass (C_a). The parameter definitions for these equations are shown in Table 1. *T. testudinum* photosynthetic parameters were from Herzka and Dunton (1997).

$$P(I) = P_{\max}\left(\frac{\alpha I}{\sqrt{P_{\max}^2 + (\alpha I)^2}}\right) \tag{1}$$

$$\frac{dC_a}{dt} = (1-\tau)P(I)e^{\kappa\Delta T}C_a\left(1-\frac{C_a}{\kappa}\right) - R_a e^{\kappa\Delta T}C_a - M_a C_a \tag{2}$$

The *Thalassia* model contained the below ground compartment implicitly. The two years of below ground biomass data available for this analysis showed no seasonal trends (Kaldy and Dunton, 2000). Below ground losses were interpolated from an inverse analysis of the root zone for a summer and winter analysis (Kaldy and Eldridge, unpubl. data). The inverse analysis is a constrained optimization in which gross primary production, shoot, rhizome net production, above and below ground respiration and other data are used to estimate unknown flows such as DIC, DOC, and detritus in the below ground compartment.

2.2 Diagenetic model

There are many pathways by which organic matter may be oxidized and the oxidation may form various organic intermediates (Lovley and Phillips, 1989; Kristensen and Blackburn, 1987; Postma and Jakobsen, 1996). To keep the analysis manageable, only one generalized biogenic reaction for each oxidant is included and we assume the reaction goes to completion (CO_2 and water). The relationships between growth and substrate concentration are incorporated in the model using hyperbolic Monod relationships, while inhibition is modeled with a hyperbolic feedback (see equations 58 through 62 in Boudreau, 1996).

The diagenetic model has 13 geochemical compartments encompassing solid and porewater organic and inorganic species that are important in Laguna Madre sediment diagenesis (Table 2). The model was calibrated with vertical sediment geochemical profiles (2 cm increments) from *T. testudinum* beds and adjacent bare sediment sites (Eldridge and Morse, 2000). The model includes organic matter loading, diffusion processes (molecular, bioturbation, and irrigation), and advective processes (burial and porewater flow) as well as important geochemical interactions (see Eldridge and Morse (2000) for details).

Table 1. Symbols and parameters used in *Thalassia* model.

Parameter	Symbol	value	Reference
time	t	d	
Irradiance at canopy depth	I(z)	Continuous measurements by LiCor spherical (4π) light sensor	Kaldy and Dunton (2000)
Carrying capacity	κ	gdw m^{-2}	
DOC release	δ	As a fraction of production	Kaldy and Eldridge (in prep)
Temperature difference	ΔT	Current temperature and reference temperature (31) at which measurements were made (°C)	Burd and Dunton (2001)
Max. Photosynthesis	P_{max}	190 (μmol O_2 gdw^{-1} hr^{-1})	Herzka and Dunton (1997)
Initial slope of P vs I curve	α	0.4 (μmol O_2 mg chl^{-1} hr^{-1})/(μmol photon m^{-2} s^{-1})	Herzka and Dunton (1997)
Above ground plant respiration	R_a	35 (μmol O_2 gdw^{-1} h^{-1})	Herzka and Dunton (1997)
Above ground plant mortality	M_a	0.0052 (d^{-1})	Kaldy and Eldridge (in prep)

Our goal in the study was to determine how seagrass modified geochemical sediment profiles. The model simulates root-zone fluxes and leaf-detrital inputs. Comparing the model results with the actual sediment chemical profiles provides an assessment of seagrass-geochemical interactions.

Removal of the seagrass fluxes in some model simulations then provides a means to quantify modifications of sediment chemistry caused by the seagrass. The model simulations suggest that between 25 to 50% of the photosynthetic O_2 had to be transported below ground to account for the observed chemical profiles (Fig 4., not all simulations are shown).

Table 2. Solid and dissolved species used in the sediment diagenesis model. The model assumes an oxidation state of zero for organic material. C:N:P of surface flux is that of seagrass above ground tissues. Root zone C:N:P flux is that of the below ground tissues.

	Explicit species	
OM1	labile organic matter	Solid
OM2	refractory organic matter	Solid
DOM	dissolved organic matter	Porewater
O_2	oxygen	Porewater
NO_3^{1-}	nitrate	Porewater
NH_3	ammonia	Porewater
SO_4^{2-}	sulfate	Porewater
TS	total sulfides	Porewater
$Fe(OH)_3$	amorphous	Solid
Fe^{2+}	ferrous	Porewater
FeS_2	pyrite	Solid
DIC	dissolved inorganic carbon	Porewater
ALK	total alkalinity (treated as a species)	Porewater
	Implicate (calculated) species	
HS^-	sulfide species	Porewater
H_2S	sulfide species	Porewater
CO_2*	sum of hydrated and unhydrate carbonic acid	Porewater
HCO_3^-	bicarbonate	Porewater
CO_3^{2-}	carbonate	Porewater
ALK_c	carbonate alkalinity	Porewater
pH	—	Porewater

3. Model results and discussion

We combined the plant and sediment diagenetic model in a coupled model that solved the seagrass and sediment geochemical equations simultaneously. This allowed us to use the outputs of the seagrass model – detritus, dissolved organic matter, etc – as inputs to the sediment model. The simultaneous solutions to both models allowed us to formulate feedbacks between sulfides, ammonium, and seagrass production. We then used the combined model to simulate the response of seagrass to a natural and anthropogenic aquatic stressor.

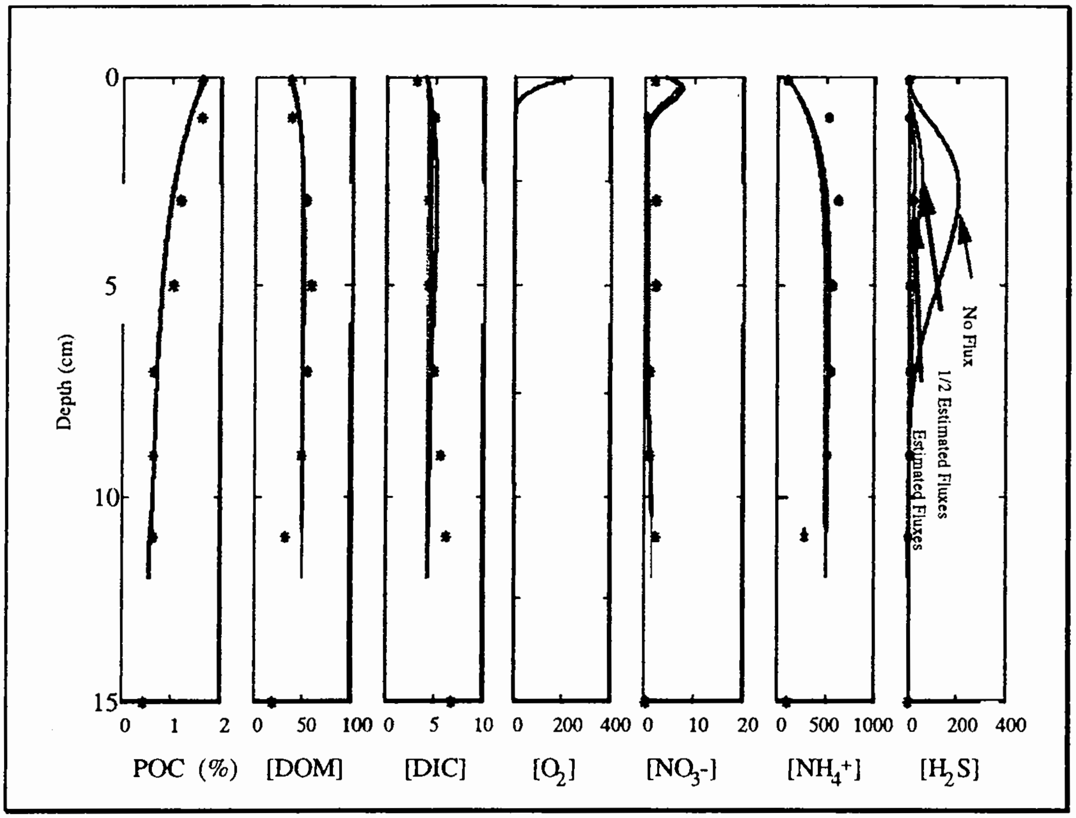


Figure 4. *Thalassia testudinum* site sediment geochemistry. Estimated flux of DOM, POC, and NH_4^+, flux to the rootzone (shaded area) is estimated using fractions of primary production from the *T. Testudium* optimization. Red line simulation has no root zone fluxes (case 1), green line is 50% of the estimated root zone flux (case 2), and the black line is the model results with the estimated root zone fluxes (case 3). Asterisks are data from the calibration site in September 1996. [DOC] and [DIC] as mM, POC in percent solid, $[O_2]$,$[NO_3^-]$, $[NH_4^+]$, and $[H_2S]$ μM.

3.1. "Brown tide" bloom – a natural aquatic stressor.

LLM is subjected to harmful algal blooms (HAB) of *Aureoumbra lagunensis* (Brown tide) which is periodically advected through the land cut from Upper Laguna Madre (ULM) (Kaldy and Dunton, 2000). The duration and intensity of these HABs are considerably greater in ULM where similar modeling studies demonstrated a reduction in the seagrass *Halodule wrightii* production and biomass (Burd and Dunton, 2001). Field studies (Onuf, 1996) also document the long-term impact of brown tide on seagrasses in ULM.

The impact of short term, episodic blooms on seagrass production is not known. Two short-term events occurred in the spring and winter of 1995 and 1996 (HAB 1 and HAB 2) during which Kaldy and Dunton (2000) sampled water-column chlorophyll *a* (Fig. 5). We used this time-series to compute organic loading to the sediment caused by the HAB. There is only one data point for the high chlorophyll levels during March 1995 that can be corroborated by increased light attenuation for about a week. During the HAB 2 bloom, similar chlorophyll *a* concentrations were measured at a site 2 km away from the calibration site (Kaldy and Dunton 2000, Kaldy, pers. obs). Chlorophyll *a* concentrations remained high for about a month longer at this reference site than was measured at the *Thalassia* collection site, suggesting that our estimate of the bloom's duration was conservative.

Both surface irradiance and the seagrass canopy light field were measured throughout 1995 and 1996 using LI-COR quantum sensors of PAR (photosynthetically active radiation 400-700 nm). An advantage of collecting canopy level light data is that it includes natural temporal stochasticity encountered by the plant. The disadvantage is that the sensors can be fouled by drift macroalgae and attached microalgae. This was the case on two occasions during the collection of the canopy light record (Herzka and Dunton, 1998).

The HAB affects both the underwater light environment and the flux of organic matter to the sediments. Consequently, the bloom influences seagrass directly through reduced photosynthesis and indirectly through geochemical cycling of settling organic material (settled brown tide cells).

Enhanced organic matter flux is explicitly modeled; hence, the coupled plant/sediment geochemical model may be uniquely capable of examining the effect of the HABs on *Thalassia*.

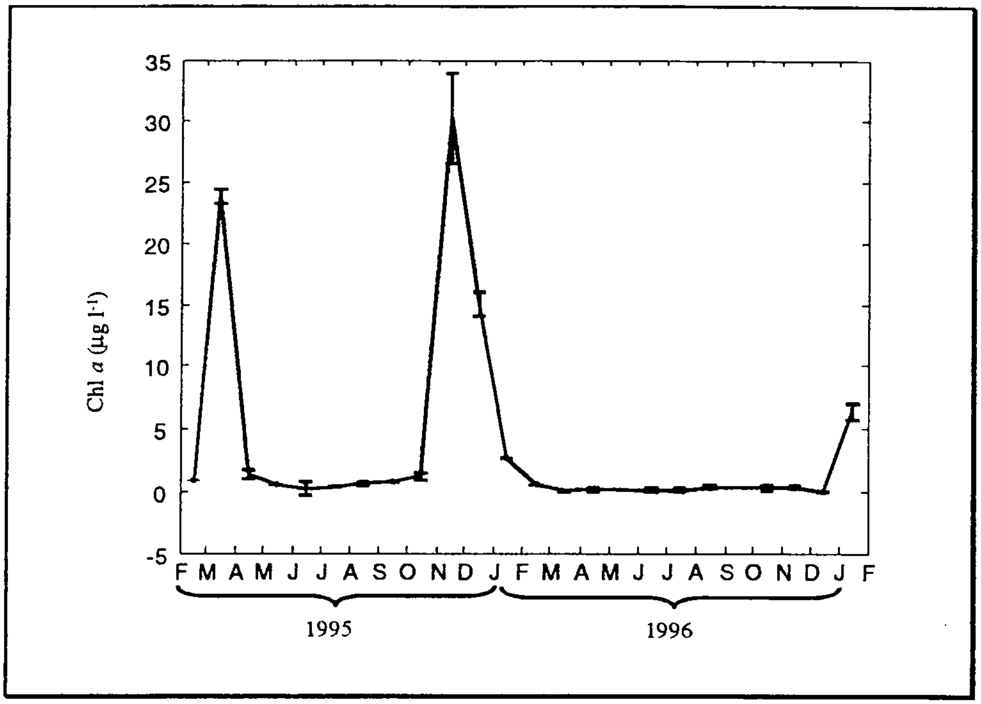


Figure 5. Water column chlorophyll a values from the calibration site measured monthly between February 1995 and January 1997.

The actual rate of bloom sedimentation to the bottom is not known. The small cell size and wind-mixing in the shallow lagoon limit the sedimentation of this alga (DeYoe and Suttle, 1994). However, the limited exchange with the ocean and minimal grazing (Buskey and Hyatt, 1995; Buskey et al., 1997) suggest that much of the *A. lagunensis* production eventually does sink to the bottom. We ran a series of simulations using available data in concert with *A. lagunensis* morphological and physiological data from DeYoe and Suttle (1994). During a dense bloom of *A. lagunensis* C:N and C:Chl were 28 and 176, respectively, and the growth rate was 0.45 d^{-1}. We used these data in the coupled seagrass diagenetic model to estimate the effect of the two HABs on seagrass in Laguna Madre.

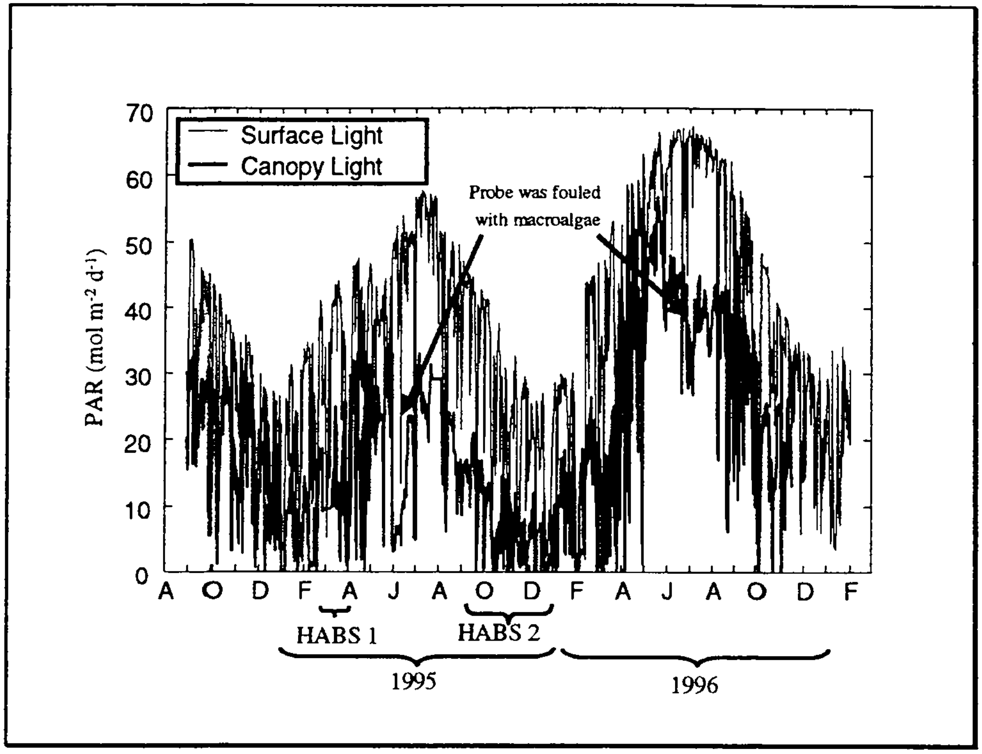


Figure 6. Surface photon flux density (PFD) from a fixed monitoring station 6 km from the calibration site and PFD at canopy level at the calibration site.

During the development of the HAB simulation we noted that different formulations for temperature variations made a large difference in the simulation results. This was unexpected and suggests it would be instructive to provide a comparison of results using modeled temperature (a sine wave function) and actual temperature measurements (Kaldy and Dunton, 2000). Both simulations were consistent with the biomass data (given the standard deviation of samples) and showed the expected seasonal variations, but were still substantially different from each other. The mean biomass data in the time-series varied by about 100 gdw m^{-2}, the simulated biomass with measured and a sine wave function for temperature varied by 70 and 55 gdw m^{-2} respectively. While none of the models exactly simulate the biomass variations in the data, the actual temperature model included significantly more of this variation (Fig. 7). Overall, the natural seasonal variation was greater than any HABs effect. HAB-1 occurred during the winter when growth rates were reduced (Kaldy and Dunton, 2000) and had a shorter duration and predictably had no obvious effect on seagrass biomass. HAB-2 may have caused an early onset of the seasonal decline in biomass but this is not distinguishable from normal variation between years.

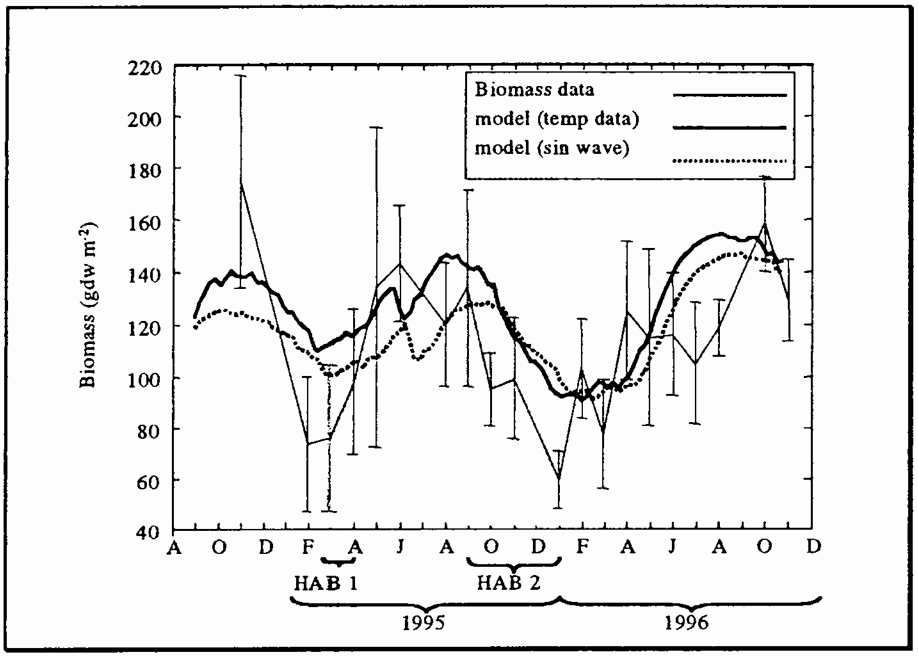


Figure 7. Comparison of biomass data and modeling results using time-series temperature data and using a sine wave approximation of temperature.

We also examined the influence of the brown tide on modeled seagrass habitat sediment biogeochemistry. Assuming that sufficient HABs biomass settled and was metabolized, seagrass production could be effected by the additional sulfide production. Seagrass is not sensitive to sulfide concentrations below 200 μmol l^{-1} in the root zone (Pulich, 1989) and production is not strongly inhibited until mmol concentrations (Carlson et al, 1994). The model predicted that the amount of material settled from the HABs in concert with material entering the sediments as leaf, root, rhizome and other detritus based on our earlier model calibration were unlikely to cause sulfide concentrations to reach even 200 μmol l^{-1}. Thus, model results suggest that neither of the HABs blooms in LLM during 1995 had an impact on *Thalassia* habitats. However, the higher sulfide concentration due to the bloom continued for several months suggesting that concentrated blooms of greater duration could reduce *Thalassia* biomass.

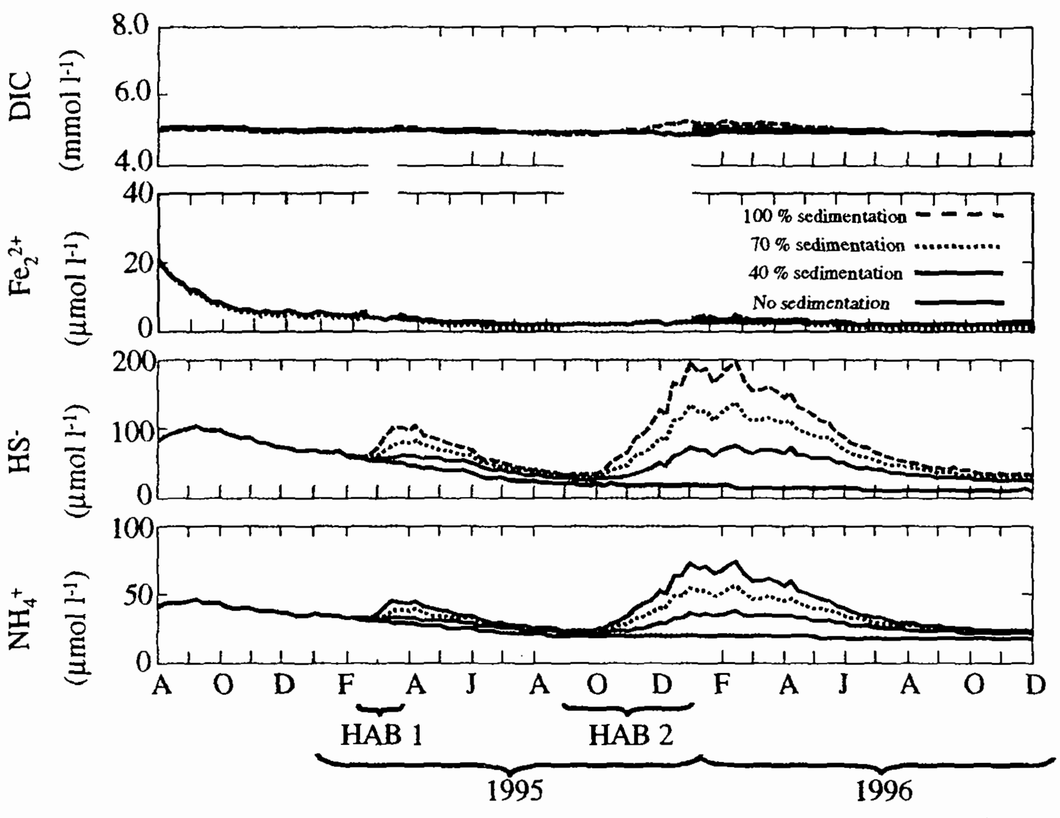


Figure 8. Simulated root zone pore-water dissolved inorganic carbon (DIC), Fe^{2+}, reduced sulfides (HS^-,H_2S, etc) and NH_4^+ for 4 levels of sedimentation of HABs.

3.2 Dredging event—an anthropogenic stressor

The intracoastal waterway bisecting the Laguna Madre requires periodic dredging to maintain the 4 m depth required for commercial vessels. The dredged materials are deposited along the channel. Environmental concerns that reduced water clarity from dredged material placement could change seagrass distribution, biomass and production patterns prompted local, state, and federal agencies including the US Army Corps of Engineers to assess alternative dredging practices. As part of this, we developed a series of simulations using the *Thalassia* model to examine loss and recovery of seagrass associated with a dredging event.

3.2.1. Validation of the combined plant-sediment diagenetic model.

To provide a verification of the combined plant/sediment model, several *Thalassia* habitats were monitored during a dredging event in late 1998. The validation process required that the model predict the outcome of the dredging event on seagrass biomass and rhizosphere geochemistry from light data and the thickness and composition of the depositional layer from dredged material disposal. Because of logistical problems (exact placement areas, sensor burial, etc), there was no single data set of continuous light or biomass, and sediment geochemistry. Consequently, for this simulation we combined light and initial biomass data from other sites with the sediment geochemistry of a site buried with 7 to 10 cm of dredge materials. Much of the leaf material at this site remained above the sediment layer while the roots and rhizomes were buried to 9-12 cm.

Data for the model validation was collected for about 1 year. Trends in measured biomass and model results were similar (Fig. 9) although the model was not able to simulate the rapid reduction in biomass in the first 2 months, possibly as a result of sediments settling on leaves – a process not considered in the model. The model was able to simulate the 1800 to 2600 μM concentration of sulfides and the 600 to 1000 μM ammonium (shown as the first year of the futures analysis, Fig 10).

3.2.2. Simulation of loss and recovery of seagrass after a dredging event—a future analysis.

The objectives of these analyses were to predict trends in biomass after a dredging event and to identify water-column or sediment stressors that inhibit seagrass. The assumption of any multiple year futures analysis is that annual cycles of physical, biotic and geochemical processes are similar. Unusual storm events, and other unexpected events, such as prolonged cloud cover, can make the simulations meaningless. Likewise, because models are simplifications of real systems, model results must be interpreted based on local knowledge. Our simulations encompassed 3 rates of organic matter reactivity and 3 root-zone depths in order to provide an envelope of possible responses.

Based on our assumption of similar seasonal trends our light time-series started with the record from the dredging event and was followed with annual light time-series from a nearby site unaffected by the dredging event. For additional years of the simulation we simply added the same annual time-series multiple times. As is typical in any underwater time-series of measurements, there were time periods for which we had no data. Gaps were filled by connecting measurements from the last date collected to the first measurement for the next set (Fig. 10A).

Model simulations show a continued reduction in biomass (Fig. 10B) even though light levels had returned to a normal annual cycle of irradiance (Fig 10A). Microbial metabolism of organic material in the dredged sediments, combined with the reduction in plant productivity (i.e., small root zone O_2 flux), produced lethal concentrations of sulfide in the root zone (Fig. 10C).

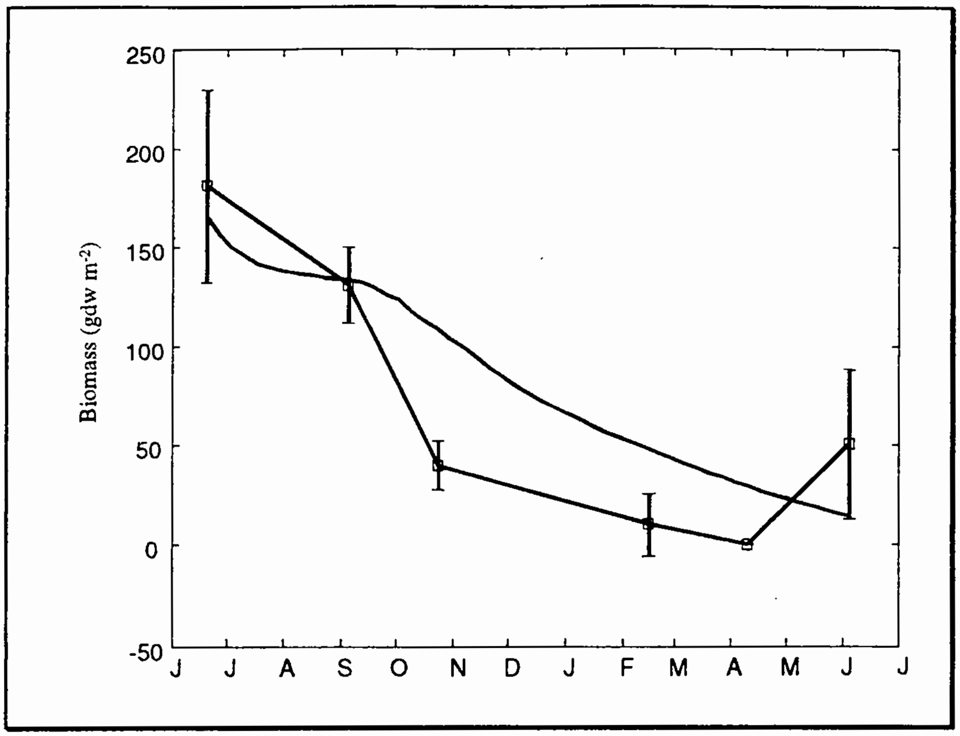


Figure 9. Comparison of observed (symbols) and simulated seagrass biomass. Biomass data were collected before, during and after a dredging event in LLM. Initial biomass was taken from a nearby site, because of the difficulty of making an *apriori* prediction of dredge deposition.

Simulations suggest that sediment conditions would not be suitable for seagrass re-colonization until 2.5 years after the dredge event. However, the model is not formulated to account for seagrass re-colonization (e.g. seed germination); consequently, we interpret the "recovery" as a return to conditions conducive to seagrass colonization. We expect to incorporate seagrass recruitment mechanisms in future models. Ammonium concentrations increase rapidly to levels found in the validation sediment cores and followed a similar duration concentration profile found in the sulfides. The literature is not clear on what the toxic levels of ammonium are (Van Katwijk et al., 1997), but these levels may also have been toxic to seagrass.

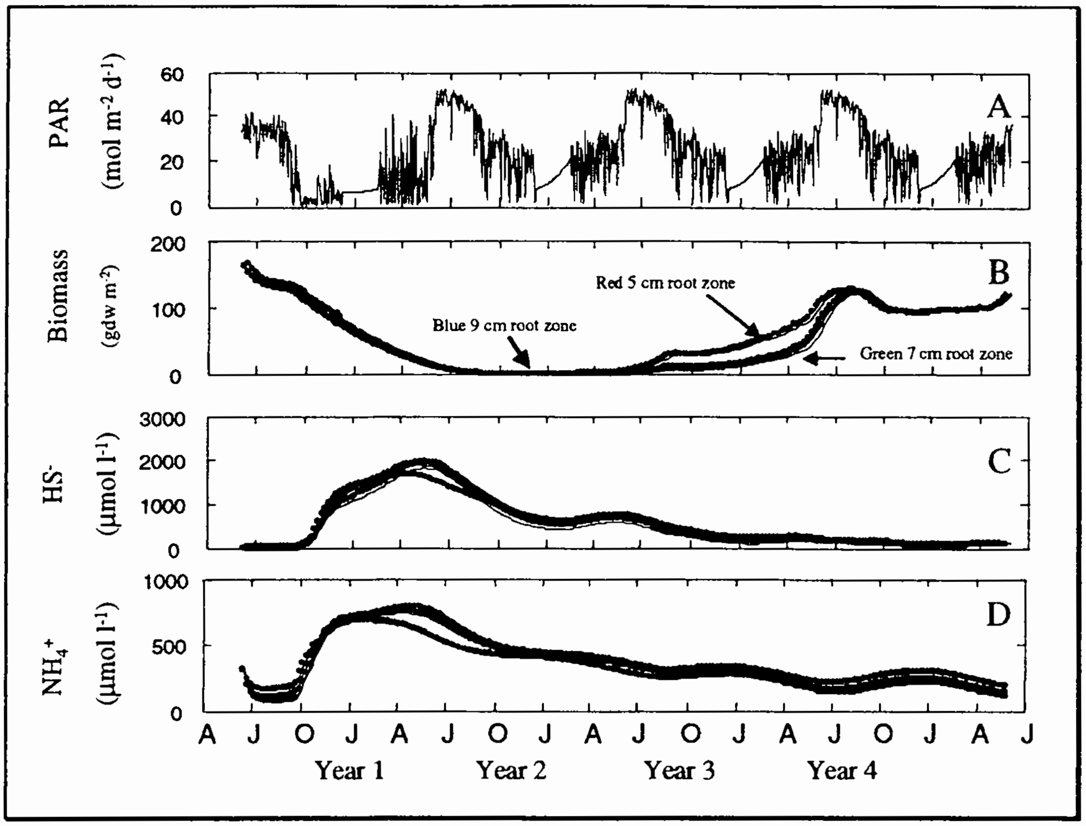


Figure 10. Four year time series of (A) canopy light, and simulated (B) *Thalassia* above ground biomass, (C) sulfide (H_2S signifies all porewater sulfides), and porewater (D) ammonium. The initial year of the simulations is the validation while years 2 through 4 are the futures analysis. Red, green, and blue lines are simulations run with root zones of 5, 7 and 9 cm depth. For each root zone depth we varied the amount of labile sediments from 40 to 50% of total sediments (K_{labile}= 25 y^{-1} and $K_{refractory}$= 0.12 y^{-1}).

4. Conclusions

Seagrass through their architecture and anatomy are successful bioengineers that alter their physical and geochemical environment to meet its physiological requirements. Our modeling simulations of *Thalassia testudinum* suggest that this seagrass can withstand exposure to an episodic natural stressor–a HAB event, but was extinguished by a chronic anthropogenic stressor –a dredging event. Short-term exposure to a HAB caused no obvious response in biomass trends, although longer exposure and higher bloom concentrations might eventually cause a decline. Exposure to dredged material eliminated the seagrass due to development of high sediment sulfide concentrations caused by metabolism of organically-rich dredged material. This example was extreme and would probably only occur close to the actual dredging event; however, it illustrates the importance of the interaction of seagrass productivity with sediment geochemical processes. An important feature the geochemical model was the time lag between stressor exposure (i.e. settling phytoplankton or sediment), and the increase in sulfide concentrations. In each simulation (HAB or dredge deposition) sulfide concentrations remain elevated for a period considerably longer than the actual exposure to the aquatic stressor. This suggests that the sediment will contain a record of aquatic stressor events that may last for months to several years.

Acknowledgement.

The information in this document has been funded in part by the U.S. Environmental Protection Agency. It has been subjected to the Agency's peer and administrative review, and it had been approved for publication as an EPA document. Mention of trade names or commercial products does not constitute endorsement or recommendation for use. We thank Cheryl Brown, an EPA Post-doctoral fellow for her comments and editing of this manuscript. We also thank John Morse for the development work he did on the original diagenetic model.

5. References

Alcoverro, T.D., J. Romero, C.M. Duarte, and N. Lopez, Spatial and temporal variations in nutrient limitation of seagrass *Posidonia oceanica* growth in the NW Mediterrranean. Mar. Ecol. Prog. Ser. 146, 155-161, 1997

Burd, A.B. and K.H. Dunton, Field verification of a light-driven model of biomass changes in the seagrass *Halodule wrightii*. Mar. Ecol. Prog. Ser., 209, 85-98, 2001

Boudreau, B. P., A method-of-lines code for carbon and nutrient diagenesis in aquatic sediments, Computers & Geosciences, 22, 479-496, 1996

Buskey, E.J. and C.J. Hyatt, Effects of the Texas "brown tide" alga on planktonic grazers, Mar. Ecol. Prog. Ser., 126, 285-292, 1995.

Buskey, E.J., P.A. Montagna, A.F. Amos and T.E. Whitledge, The initiation of the Texas brown tide algal bloom: disruption of grazer populations as a contributing factor, Limnol. and Oceanogr., 42,1215-1222, 1997.

Caffrey, J. M., and W.M. Kemp, Seasonal and spatial patterns of oxygen production, respiration and root-rhizome release in *Potamogeton perfoliatus* L. and *Zostera marina* L., Aquat. Bot. 40, 109-128, 1991.

Carlson, P. R., L. A. Tarbro and T. R. Barber, Relationship of sediment sulfide to mortality of *Thalassia testudinum* in Florida Bay, Bulletin of Marine Science, 54, 733-746, 1994.

DeYoe, H.R., and C.A. Suttle, The inability of the Texas "Brown tide" alga to use nitrate and the role of nitrogen in the initiation of a persistent bloom or this organism, J. Phycol,. 30, 800-806, 1994.

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

Goodman, J.L., K.A. Moore, and W.C. Dennison, Photosynthetic responses of eelgrass (*Zostera marina* L.) to light and sediment sulfide in a shallow barrier island lagoon, Aquatic Botany, 50, 37-47, 1995.

Hemminga, M.A. and C.M. Duarte, Seagrass Ecology, Cambridge University Press, Cambridge, UK, pp.298.

Herzka, S.Z. and K.H. Dunton, Seasonal photosynthetic patterns of the seagrass *Thalassia testudinum* in the western Gulf of Mexico, Mar. Ecol. Prog. Ser. 152, 103-117, 1997.

Herzka, S.Z. and K.H. Dunton, Light and carbon balance in the seagrass *Thalassia testudinum*: evaluation of current production models. Marine Biology 132: 711-721, 1998.

Holmer, M.H. and e.J. Bondgaard, Photosynthetic and growth response of eelgrass to low oxygen and high sulfide concentrations during hypoxic events, Aquatic Botany 70, 29-38, 2001.

Kaldy, J.E. and K.H. Dunton, Above- and below-ground production, biomass and reproduction ecology of Thalassia testudinum (turtle grass) in a subtropical coastal lagoon, Mar. Ecol. Prog. Ser., 193, 271-283, 2000.

Koch, E.W., Beyond light: physical, geological, and geochemical parameters as possible submersed aquatic vegetation habitat requirements, Estuaries, 24, 1-17, 2001

Kraemer, G.P., and R.S. Alberte. Age-related patterns of metabolism and biomass in subterranean tissues of *Zostera marina* (eelgrass). Mar Ecol Prog Ser, 95, 193-203, 1993.

Kristensen, E. and T. H. Blackburn, The fate of organic carbon and nitrogen in experimental marine sediments: influences of bioturbation and anoxia, J. Mar. Res., 45, 23-257, 1987.

Lee, K. and K.H. Dunton, Diurnal changes in pore water sulfide concentrations in the seagrass *Thalassia testudinum* beds: the effects of seagrasses on sulfide dynamics, J. Exp. Mar. Biol. and Ecol., 255, 201-214, 2000

Lee, K. and K.H. Dunton, Inorganic nitrogen acquisition in the seagrass *Thalassia testudinum*: development of whole-plant nitrogen budget, Limnol Oceanogr., 44,1204-1215, 1999.

Lovley, D.R., E.J.P. and E. J. P. Phillips, Requirements for a microbial consortium to completely oxidize glucose in Re(III)-reducing sediments, Appl. Environ. Microbiol., 54, 3234-3236, 1989.

Nepf, H.M. and E.M. Koch, Vertical secondary flows in submersed plant-like arrays, Limnol. Oceanogr., 44, 1072-1080, 1999.

Onuf, C.P., Seagrass responses to long-term light reduction by brown tide in upper Laguna Madre, TX: distribution and biomass patterns, Mar. Ecol. Prog. Ser., 138, 219-231, 1996.

Orth, J.J., Effect of nutrient enrichment on growth of eelgrass Zostera marina in Chesapeake Bay, Virginia, USA., Mar Biol, 44, 187-194, 1977.

Postma, D. and R, Jakobsen, Redox zonation: Eqiulibrium constraints on the Fe(III)/SO4-reduction interface, Geochimica et Cosmochimica Acta. 60, 3169-3175, 1996.

Pulich, W. M., Effects of rhizosphere macronutrients and sulfide levels on the growth physiology of *halodule wrightii* Aschers. and *Ruppia maritima* L. s.l., J. Exp. Mar. Biol. Ecol., 127, 69-80, 1989.

Short, F.T. Eelgrass and the wasting disease. Univ. of New Hampshire Cooperative Extension, Durham NH. 1989.

Short, F.T. and S. Wyllie-Echevarria, Nature of Human-induced distributions of seagrass, Environmental Conservation, 23,17-27, 1996.

Talling, J.F., A new model for leaf photosynthesis incorporating gradients of light environment and the photosynthetic properties of chloroplasts within a leaf, Annls Bot, 56, 489-499, 1957.

Teeter, A.M. B.H. Johnson, C. Berger. G. Stelling, N.W. Scheffner, M.H. Garcia and T.M. Parchure, Hydrodynamic and sediment transport modeling with emphasis on shallow-water, vegetated areas (Lakes, reservoirs, estuaries and lagoons, Hydrobiologia, 444, 1-23, 2001.

Van Katwijk, M.M., L.H.T Vergeer, G.H.W. Schmitz, J.G.M. Roelofs. Ammonium toxicity in eelgrass Zostera marina. Mar. Ecol. Prog. Sers., 157, 159-173, 1997

Zimmerman, R.C., JL. Reguzzoni, R.S. Alberte. Eelgrass (*Zostera marina* L.) transplants in San Francisco Bay: role of light availability on metabolism, growth and survival. Aquat. Bot. 51, 67-86, 1995.

Zimmerman, R.C. and R.S. Alberte, Effect of light/dark transition on carbon translocation in eelgrass *Zostera marina* seedlings, Mar Ecol Prog Ser, 136, 305-309, 1996.

WED-02-121

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1. REPORT NO. EPA/600/A-02/066	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Seagrass Stress Response Model: the Importance of Light, Temperature, Sedimentation and Geochemistry		5. REPORT DATE
		6. PERFORMING ORGANIZATION CODE
7. AUTHORS P.M. Eldridge, J.E. Kaldy, A.B. Burd		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Western Ecology Division, NHEERL, USEPA 200 SW 35th St Corvallis, OR 97333		10. PROGRAM ELEMENT NO.
		11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS Same as above		13. TYPE OF REPORT AND PERIOD COVERED conference proceedings
		14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

The objective of our modeling was to better understand the relationship between seagrass and water-column and sediment stressors (i.e., light, organic and particle sedimentation, sediment nutrients and sulfides). The model was developed and optimized for sediments in *Thalassia testudinum* seagrass beds of Lower Laguna Madre, Texas, USA and is composed of a plant sub-model and a sediment diagenetic sub-model. Simulations were developed for a natural stressor (harmful algal bloom) and an anthropogenic stressor (dredging event). The harmful algal bloom (HAB) was of limited duration and the simulations showed no effect of the algal bloom on biomass trends but did suggest that sediment sulfides could inhibit growth if the bloom duration and intensity were greater. The dredging event resulted in sedimentation of a layer of organically rich material and reduction of canopy light for a period of months. The simulations suggested that the seagrass could have recovered from the effects of light but residual effects of high sulfides in the sediments would make the region uninhabitable for seagrasses for up to 2.5 years. These modeling exercises point out the importance of using a geochemical model to evaluate the impact of reduced light and enhanced organic loading from both natural and anthropogenic stressors to seagrass.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
seagrass/carbon sequestration/ sediment/geochemistry		

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
	20. SECURITY CLASS *(This Page)*	22. PRICE