EFFECTS OF ELEVATED TURBIDITY AND NUTRIENTS ON THE NET PRODUCTION OF A TROPICAL SEAGRASS COMMUNITY

By

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TABLE OF CONTENTS

Abstract of Dissertation Presented to the Graduate School of the University of Florida in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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December 1985

Chairman: Thomas L. Crisman
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Major Department: Environmental Engineering Sciences

Dredging effects on seagrass communities in the Florida Keys were examined by 1) comparing impacts on net production resulting from dredging and natural weather events, 2) determining changes in community photosynthetic efficiency, 3) evaluating shading and nutrient effects on net production, and 4) developing a systems dynamics model.

Net community production was estimated during numerous meteorological and dredging events using the Odum-Hoskins oxygen technique in flow-through field microcosms. In other experiments, shading and nutrients (phosphorus, nitrate, and ammonia) were manipulated to simulate dredge plume conditions. The model examined the relationships between seagrass biomass, water column and sediment nutrients, detritus, and consumers.

The greatest depression in net community production resulted from severe thunderstorms and dredging events,

respectively. Net community production measured two years after dredging showed an approximate four-fold decrease.

In field microcosm experiments, significant interaction occurred between shading and nutrient concentration. Significant metabolic reduction occurred due to shading, even with higher nutrient conditions. All but the lowest concentration resulted in significantly increased production in the light. Qualitative comparison with a control showed an enhancement of production only in the light.

The model of seagrass production was most sensitive to changes in nutrient-seagrass relationships, seagrass production estimates, and seagrass-light interactions. Recovery of seagrass biomass following numerous dredging events (3.5 years) was longer than that from the estimated total annual thunderstorms encountered (1 year) but shorter than recovery from hurricane events (4.1 years).

The effects of short-term dredging on net community production as shown by field experimentation and the model were less severe than some weather events because of differences in duration and intensity. Lowered post-dredging photosynthetic efficiency, as defined by unit biomass production per unit light, was a result of degraded system function possibly from sediment scour from the dredge cut. The major deleterious effect of dredging resulted from shading, although some production enhancement could occur from nutrient release. The model suggested that dredging effects were prolonged because of current scour from the dredge cut, that recovery time was comparable to hurricane events, and that more investigation is needed in seagrass-nutrient and light-production relationships.

CHAPTER I
PROBLEM STATEMENT

Replacement of the bridges in the Florida Keys, some of which have been in place since the early 1900's, is a major road construction project being carried out by the Florida Department of Transportation (FDOT). For the most part, construction of the new bridges has been adjacent to the older structures. As a part of the construction activities, the need arose to barge bridge span sections to the site for inclusion in the structure. This activity required the dredging of a channel through shallow marine grass flats to allow the span barge access.

Considerable interest was expressed by the Florida Department of Environmental Regulation (FDER) concerning the effects of elevated turbidity from these construction activities on the nearby biological communities. The highly flocculent nature of the sediments, the strong tidal currents known in the area and the close proximity of potentially sensitive marine ecosystems all combined to create concerns regarding the environmental effects of the dredging activities. Of special interest were the extensive seagrass beds (primarily, *Thalassia testudinum*), the dominant community closest to the planned dredging activities.

Early observations of high turbidity caused by weather events such as cold front passage and violent tropical thunderstorms indicated these ecosystems are subjected normally to periodic high-intensity turbidity pulses. The extensive areas of seagrasses present in the area suggested this community, in particular, might be adapted to these pulses and therefore would not be impacted severely by similarly intermittent dredging activities in the vicinity. Obviously, outright removal of the seagrass by the dredge would be the most severe impact. This was not considered due to the small amount removed compared to the total acreage present. Only those impacts relating to effects from the dredge plume were considered.

Therefore, dredge plume effects should be 1) comparable in intensity to those encountered during natural weather events, 2) short term, depending on the longevity of the dredge plume, 3) deleterious to net community production as a consequence of shading, 4) beneficial to net production arising from nutrient release from the sediments, and 5) dissipated quickly and show no measureable effect on net community production on a long-term basis.

The objective of this study was to test these hypotheses by 1) a comparison of the response of net community production (=metabolism) to a dredge plume and natural weather events, 2) analysis of net community metabolism in seagrass communities prior to and two years after being subjected to a dredge plume, 3) field experimentation with two major impacts believed to be associated with the dredging event, namely shading and nutrient addition, and 4) modeling of the seagrass ecosystem to identify factors that are most important in controlling change in seagrass production, to compare long-term response and recovery of the seagrass model following various perturbations, and to point out areas of research requiring further investigation.

Field measurements of community metabolism utilized the upstream/downstream oxygen technique of Odum and Hoskins (1958). This method, which is used throughout the field experiments in the determination of net community production, is explained in Chapter II. This technique has received considerable criticism (Bittaker and Iverson 1976; Phillips and McRoy 1980) on the basis that diffusion is largely uncontrolled and only roughly estimated and, because of large internal lacunae, macrophytes tend to store oxygen internally which is not released, therefore providing an underestimate of production. In this study, the issue of diffusion was eliminated through the use of covered microcosms which entrained the water and prevented gaseous exchange with the atmosphere. Underestimates of seagrass production were not an issue here since it was the response of the total community that was of interest. Although internal recycling of oxygen more than likely did occur in the seagrass blades, it is believed this was held to a minimum as a result of the use of flow-through microcosms which maintained water movement through the plants (Westlake 1967; Fonseca et al. 1982).

A final caveat regarding the model is included here. A misconception of model output exists when it is believed that output should reproduce nature exactly and that the model can always be used to prescribe policy. The major reasons why most models cannot be used for these purposes involves the lack of information required to fully document even the simplest of models. This necessitates the use of estimates for internal model constants that could lead to misleading model output. Further, differences in interpretation of how the "real world" operates in its myriad relationships can also provide a source of error.

Perhaps the greatest benefit derived from the model is the learning experience which evolves during the model development process. From the very beginning of model construction, the modeler is forced to think about how components operate internally and connect to other components. This evaluation process, which then has to be translated into precisely defined mathematical relationships, is the real power of modeling.

The following sections are divided into four chapters. Chapter II includes an analysis of short- and long-term dredging effects on seagrass community production. Chapter III contains field investigation of two of the believed major impacts relating to a dredge plume, and Chapter IV contains results and analysis of the simulation model. A summary chapter (Chapter V) is provided at the end which contains an overview of the major findings of this work.

CHAPTER II
COMPARISON OF NATURAL AND MAN-MADE DISTURBANCES ON SEAGRASS NET COMMUNITY PRODUCTION

Introduction

The effects of elevated turbidity resulting from resuspension of sediments during dredging operations are major concerns in shallow coastal marine environments. Many of these effects, which can be detrimental or beneficial, have been discussed in reviews by Stern and Stickle (1978) and Johnston (1981). Specific investigations of dredging events relevant to this study have addressed the areas of light attenuation effects on primary production in the water column (Stross and Stottlemeyer 1965; Biggs 1968), light limitations of benthic primary production (Taylor and Solomon 1968; Cambridge and McComb 1984), reduction in community metabolism as a result of high turbidity (Odum and Wilson 1962; Odum 1963), resuspension of nutrients from a dredge plume (Odum 1963; Stross and Stottlemeyer 1965; Flemer et al. 1968; Flemer 1970; Sherk 1971), and the recovery of a benthic ecosystem from a dredging event (Conner and Simon 1979).

During replacement of the bridges in the Florida Keys dredging of shallow marine areas was needed to facilitate building of the new structures. Because of concerns for turbidity-related impacts on nearby seagrass communities, documentation and examination of impacts resulting from the proposed bridge construction-related dredging activities were required.

Early field observations of the dredge in operation indicated that the dredge plume was of fairly short temporal duration following dredge stoppage and that little or no burial of the surrounding community by dredged sediments occurred. Furthermore, observations of areas already dredged indicated that strong tidal currents present in the area would also contribute to turbidity levels.

It appeared that the resultant turbidity activities would impact the seagrass ecosystems in two stages: an initial, intensive pulse during the dredging event and a longer, lower level, gradually decreasing turbidity plume resulting from current scour of sediment from the dredge cut. It was expected that the magnitude and duration of the initial turbidity pulse would be largely a function of the level of dredging activity, localized current regimes and the sediment grain size. The larger the volume of dredging activity, the more sediment that would be released into the water column; the higher the water currents, the greater the potential dispersion of the dredge plume; and the smaller the grain size the greater the distance of dispersion by these water currents. During dredging, currents would tend to disperse the plume, thereby lessening its effect on the immediate vicinity through dilution, but also causing a larger area to be impacted.

The rationale for this study included the testing of the hypothesis that, on a short-term basis, the effects on seagrass net community metabolism were comparable to those caused by weather events normally encountered by the communities. It was hypothesized that over the long-term period no appreciable degradation in net community metabolism would occur, although an initial decline might be shown due to current scour from the dredge cut. The objectives of this study, then, consisted of a comparison of the reduction in net community metabolism caused by dredging and naturally occurring weather events and a comparison of pre- and post-dredging photosynthetic efficiencies to evaluate any residual effects due to dredging operations.

Because of the observed erratic nature of a dredge plume coupled with quickly changing weather, a measurement technique was required which could monitor response of the seagrass community to frequently changing light. Measurement of community metabolism using a flow-through microcosm was selected because it was believed that this technique would provide a quantifiable index of the whole system response to the perturbations of interest (Walsh et al. 1982). Also, preliminary measurements indicated this technique would provide 1) a rapid response to short-term changes in the community's light environment, and 2) a movable apparatus enabling examination of several different areas within the community as the dredge proceeded along its course. As an aid in interpretation of any effects measured due to dredging, natural meteorological events were also monitored in an identical manner for comparison. As many different dredging and weather events as possible were monitored, compared, and ranked based on their level of impact on net community production.

Materials and Methods

The study was conducted at the western end of 7-Mile Bridge in the middle Florida Keys (Figure 1). Construction of the new structure paralleled the old bridge to the south, necessitating the dredging of a channel through the shallow areas to a depth of approximately 1.5 m at mean low water (MLW) and a width of 46 m to facilitate the movement of the span and piling barges. A clamshell dredge (crane with a bucket) excavated the sediment which was then barged to upland disposal sites. Dredging was intermittent throughout its period of operation because mud barges were usually exchanged only during high tide and the clamshell dredge required frequent repair.

The benthic biotic community in these areas is characterized by extensive beds of turtle grass (*Thalassia testudinum*) along with less dense patches of manatee grass (*Halodule wrightii*) and shoal grass (*Syringodium filiforme*). Interspersed between these grass areas are sea rod (*Plexaura homomalla*), sea fan (*Gorgonia ventalina*), and sponge communities in the deeper swash channels. Other nearby areas that are extremely shallow and often exposed at low tide are dominated by dense areas of the finger coral, *Porites* sp.,

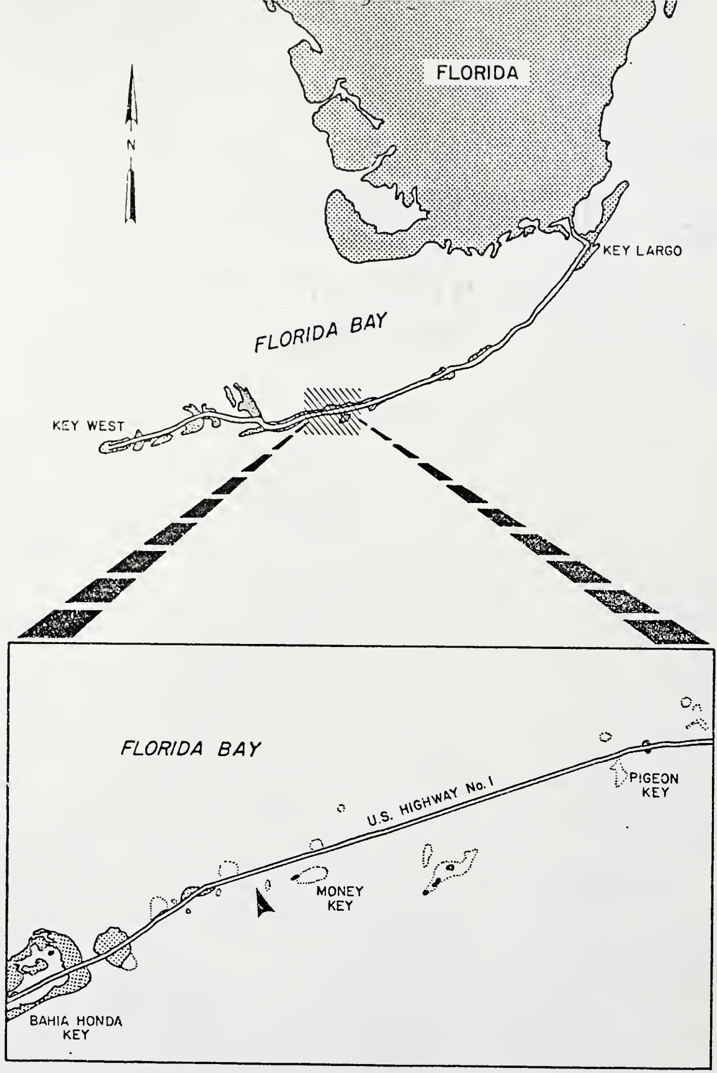


Figure 1. Map showing sampling location in the Florida Keys.

clumps of coralline algae, and patches of *Thalassia testudinum*.

Strong tidal currents are a dominant physical feature of this area. These currents likely serve as major exchange mechanisms between adjoining communities by importing and exporting materials. In addition to materials exchange, these currents can also function as a rapid metabolic waste removal mechanism.

Estimates of metabolism of the seagrass-dominated communities were made using the upstream/downstream oxygen method of Odum and Hoskins (1958). Flow-through microcosms (=tunnels) which were placed over the seagrass community were constructed of a polyvinyl chloride (PVC) framework covered with 6 mil clear polyethylene (Figure 2). The tunnel length was approximately 4 m with an average height of 0.35 m. Residence time of water passing through the chamber was regulated with baffle plates applied to each tunnel end. Each plate contained numerous holes which were plugged with corks until a desired current speed was attained. Current regulation through the system was important because residence times which were too short resulted in oxygen differences below the detection limit of the oxygen monitoring equipment. Residence times approaching 20 min were found to provide adequate upstream/downstream oxygen differences under most situations while still allowing flushing of the system.

Microcosms were sampled by pumping water from either the upstream or downstream end to the sensing sonde of a

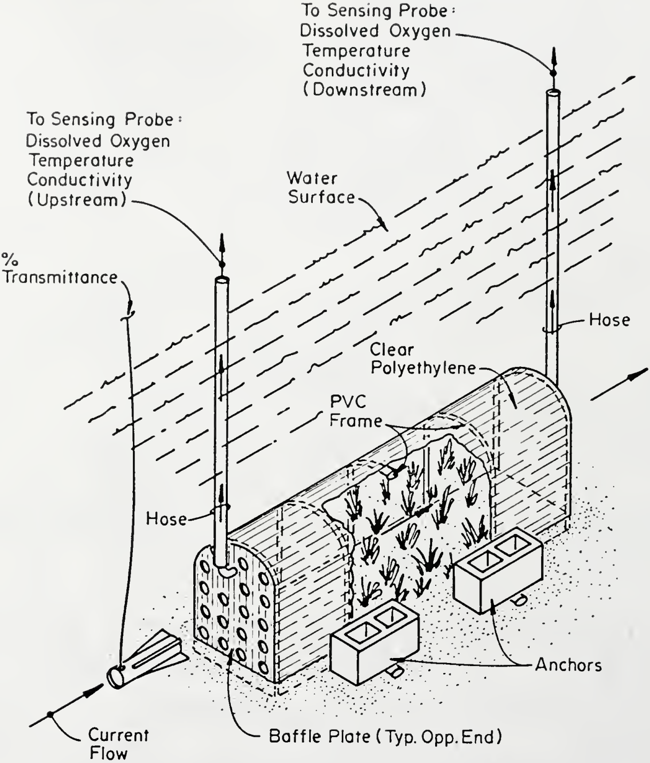


Figure 2. Diagram showing field set-up of flow-through microcosm.

Hydrolab, Inc., Model 6000 Water Quality Surveyor (Figure 2). Triplicate dissolved oxygen measurements were collected by alternating these with single temperature and conductivity recordings collected during each sampling of a tunnel end. Other routine measurements noted included hourly readings of solar input (Lamda Instruments, Li-Cor Model 175), and percent transmission of light through water (Hydroproducts, Inc., Model 612S Transmissometer).

The average residence time of water in the tunnel was determined at each station from several timed dye flow studies. It was assumed that the residence time of water in the tunnel represented an average flow time over the entire tidal cycle. Tunnels were sampled on a frequency of five minutes. In other words, given a 20 min residence time, the upstream end would be sampled every 5 min for fifteen minutes. The 5 min sampling frequency at the lower end of the tunnel then began at the 20 min interval (from the start of the sampling cycle) and was repeated every 5 minutes. In this manner, a plug of water was followed as it entered the tunnel and then was sampled again at the exiting end in order to determine the change in oxygen over the time interval. This procedure was repeated throughout several consecutive diurnal periods and varying environmental conditions.

The microcosm was set up parallel to the north-south tidal currents, approximately 50 m south of the bridge and slightly ahead of the dredge's path which paralleled the bridge as it proceeded to the west. This enabled the collection of background data to ensure proper working of the microcosm prior to sampling during the dredging event. As the dredge moved to a position directly north of the tunnel, the system was monitored to record the metabolic response of the community to the presence of the dredge plume in the water column. Response of the seagrass community to weather disturbances was monitored in an identical manner.

All dissolved oxygen levels were corrected for temperature and conductivity using the following relationship:

$$CDO=1-[(3.439+0.0361/(T+22.1^2)) \times (C/1000)]$$

where CDO=corrected dissolved oxygen

T=temperature in °C

C=conductivity in mhos/cm at 25° C

constants in the equation are specific for the monitoring instrument and were supplied by the manufacturer (Hydrolab, Inc., Austin, Texas).

Diffusion of oxygen through the polyethylene plastic covering the tunnels was evaluated according to the following:

$$Q = D \times S\ ((P_1-P_2)/T)$$

where Q=oxygen diffusion through polyethylene ($ccO_2/cm^2/sec$)

D=diffusion constant for polyethylene

S=solubility constant for polyethylene

P_1,P_2=partial pressure of oxygen inside and outside of tunnel, respectively

T=thickness of plastic

(From Crank and Park 1968)

Calculations indicated less than 1% of the ambient oxygen diffused through the plastic during an average 20 min residence time, so this diffusion type was ignored.

The oxygen production values were calculated according to the following equation:

ROC= (DOD-DOU) X (D/T)

where ROC=rate of oxygen change ($gO_2m^{-2}hr^{-1}$)

DOD=dissolved oxygen at the downstream tunnel end

DOU=dissolved oxygen at the upstream tunnel end

D=mean tunnel depth (0.35m)

T=residence time of water in the tunnel in factors of an hour

A stylized diurnal rate of change curve is shown in Figure 3. A rapid increase is shown in the morning hours with a peak occurring shortly after mid-day. Net production was usually confined to the time period from approximately 2 hours after sunrise to 2 hours before sunset. Integration of the area under the curve yields the average community metabolism for any desired time period. Net community metabolism was calculated as all areas under the curve with metabolism greater than 0 $gO_2m^{-2}hr^{-1}$ (the portion of the curve above the 0.0 rate line). Negative oxygen production values after sunrise and before sunset were subtracted from the total net production value.

Dredging and weather effects on net community metabolism were compared on the basis of the percent reduction of net community metabolism by each type of occurrence. This

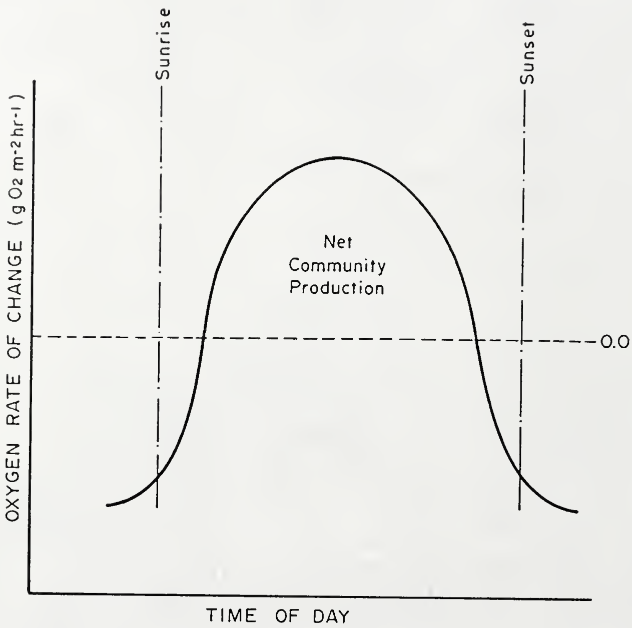


Figure 3. Ideal production curve showing area of net community production.

comparison was evaluated over two time intervals. First, an assessment was made of the effect at the time of the event based on a comparison of a projection of the net community metabolism level had the event <u>not</u> occurred and the actual measured values during the perturbation. The projection was made by connecting the data points at the beginning and end of the perturbation time period (Figure 4). The integrated solar values at hourly intervals are plotted across the top of each productivity curve for comparison. The reduction in net metabolism was calculated by the following:

$$RED=P/P + A$$

where RED=reduction in net community metabolism resulting from the event

P=projected metabolism had the event not occurred for the discrete event time interval (based on straight-line connection of points between the last measured value before the perturbation and the first measurement after the perturbation).

A=actual measured net metabolism during the event time interval

For comparison between events, a percent reduction for each event was determined by

$$\%RED=(P/(P + A) \times 100$$

where %RED=per cent reduction in net community metabolism based on the timing of the event

P and A =from the previous equation

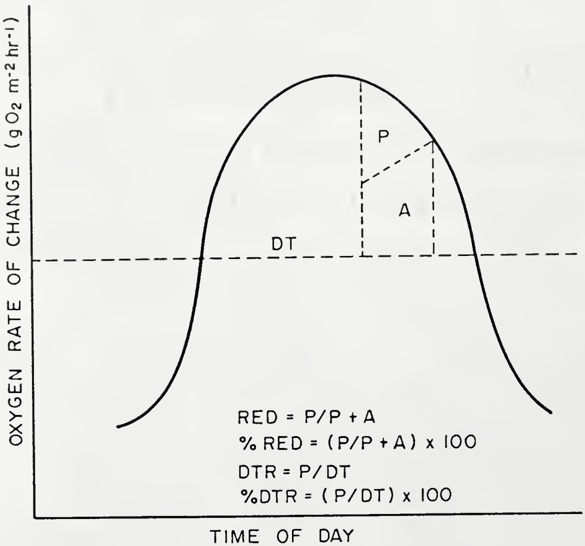


Figure 4. Ideal production curve showing the method used to calculate the reduction in net production due to perturbations.

P=projected metabolism calculated from the previous equation

The second comparison involved calculation of the event's effect in relation to the daily net community metabolism. In this case, the percent reduction in daily net metabolism was calculated by:

%DTR=(P/DT) x (100)

where %DTR=per cent reduction in daily net community metabolism

R=reduction in net metabolism, calculated as shown previously

DT=daily net community metabolism

Values for all events measured were compared and ranked in descending order according to the severity of reduction in net community metabolism.

Natural and man-made turbidity events were categorized and compared as shown in Table 1. As many of these events as possible were monitored to compare their effects on net community production.

To determine possible long-term effects on seagrass net community metabolism due to dredging, photosynthetic efficiencies were calculated from data gathered during the summer of the main dredging operation and compared with similar data collected two years later. Average net production values from each time interval were normalized for solar radiation, water depth and clarity, and biomass standing stocks.

Table 1. Categories of natural and man-made turbidity events

Natural Events	Man-made Events
Severe thunderstorms early forenoon	dredging (with silt curtain)
Severe thunderstorms late afternoon	dredging (with no silt curtain)
Hurricane-related thunderstorms	tug plume (caused by propeller scour from barge tugs in shallow seagrass beds)
Normal thunderstorms local rain, light blockage	
Distant thunderstorms no local rain, sun blocked by distant storm	
Overcast, rain	
Scattered clouds	

Solar radiation reaching the community was calculated from light transmission data measured in the field and by the following equation:

$$LD = LS \times e^{-L \times D}$$

where LD=Light at the desired water depth (watts m^{-2})

LS=Light at the surface (watts m^{-2})

D=Depth of the water column in meters

$$L = \frac{-\ln T}{PL}$$

where T =fraction of percent transmission of light

PL=optical pathlength of the transmissometer

Standing stock biomass was determined from 4-inch diameter PVC cores collected in the field from each tunnel to a depth of approximately 45 cm. Four cores containing above- and below-ground biomass from each microcosm were field-sieved through a 500 micron mesh screen, preserved with 5% formalin, stained with rose bengal, and transported to Gainesville for sorting and weighing. All samples were sorted in the laboratory and all recognizable above- and below-ground plant material removed. The plant material was dried at 105°C for approximately one week to determine dry weight. The sample was then heated to 550°C for 1 hour to determine loss on ignition (ash-free weight).

Productivity data were normalized by dividing the average net production by the calculated solar radiation reaching the community and by the dry weight and ash-free biomass estimates. This yielded the net photosynthetic efficiency (gO_2g^{-1} dry and ash-free biomass $watt^{-1}$) of the seagrass community prior to and two years after the dredging events.

Results

Effects of weather and dredging on net community production are shown in the figures described below. Hourly integrated solar radiation values are plotted in the upper part of each figure. The duration of each event as well as the amount of reduction of metabolism is indicated on each productivity curve. The productivity curves often show highly variable swings in oxygen values which are not reflected in the solar curves. Integration of the solar curves in the field on an hourly basis, however, allowed direct comparison of solar changes with changes in the production graphs in all instances of major perturbation. The duration of low-level perturbations were determined from field logs. During a dredging perturbation, the effects of background "noise" due to variable solar condition have not been removed. The response of the community during this time interval was attributed solely to the disturbance being monitored.

The effect of a severe thunderstorm (white squall) occurring early in the afternoon is indicated in Figure 5 as the solar radiation peaked at approximately 1300 hours and then dropped drastically. Most of the afternoon net production was eliminated by this event, including the midday peak. This resulted in a 68.5% reduction in the net metabolism

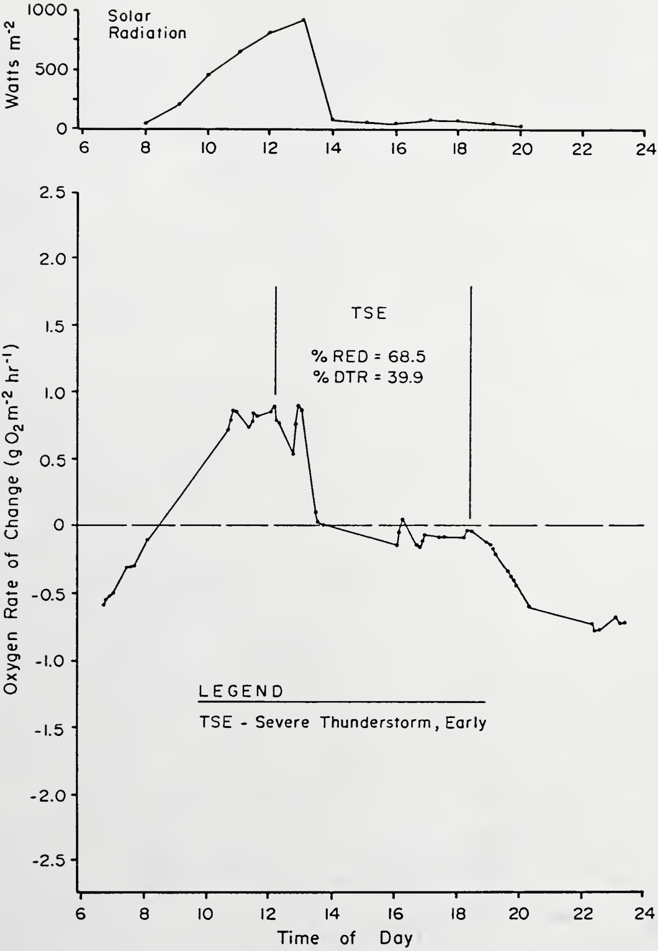


Figure 5. Reduction in net community production as a result of a severe thunderstorm occurring in the early afternoon. Solar radiation is shown at the top of the figure. Abbreviations used are explained in the text.

during the event and 39.9% across the entire day.

The effects of hurricane-associated thunderstorms on net community production are shown in Figures 6 and 7. As indicated in the figures, intense weather disturbances such as these with highly variable solar input can cause extreme fluctuations in production and can drive the oxygen rate curve negative. In Figure 6, depression of net metabolism during the time the storms occurred ranged from 58.6 to 62.9%, while the effect on the daily value went from a low of 12.0% to a high of 46.1%. Solar values peaked at noon, remained level until 1700 and showed a rapid decline thereafter. An occurrence of net production is shown at night (after 2200 hrs). This will be discussed in the following section. Generally low and variable solar input is shown in Figure 7 which is reflected in large swings in the production curve. Intense weather systems such as these cause a loss of approximately 50% of the daily net production.

The effect of a severe thunderstorm (white squall) occurring late in the afternoon is illustrated in Figure 8. Approximately 57% of the net production and 22.5% of the daily net production were lost during the thunderstorm. Solar insolation showed a sharp decline from the start of the thunderstorm (1600 hours) until its end at 2000 hours.

The effect of a distant thunderstorm which is defined as a storm which occurs in the distance usually in late afternoon, blocking the sun but causing no local rainfall, is shown in Figure 9 and 10. The reduction in metabolism

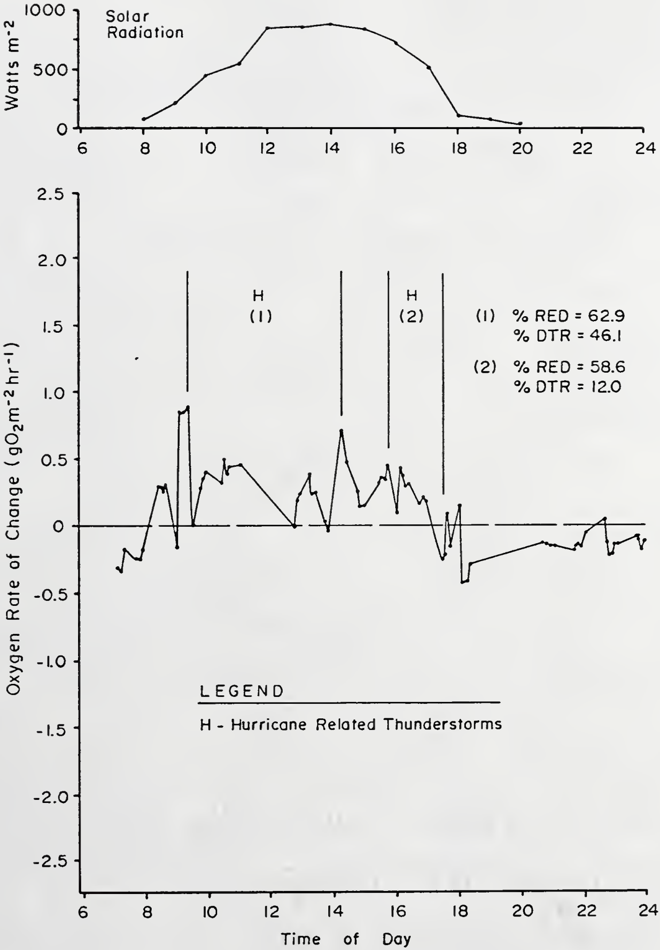


Figure 6. Reduction in net community production as a result of hurricane-related thunderstorms. Solar radiation is shown at the top of the figure. Abbreviations used are explained in the text.

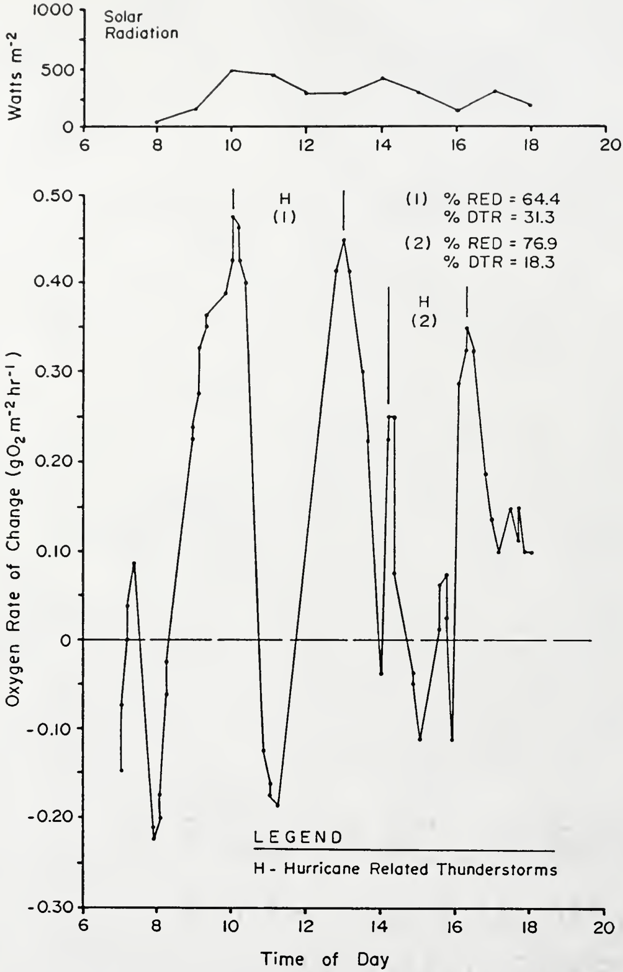


Figure 7. Reduction in net community production as a result of hurricane-related thunderstorms. Solar radiation is shown at the top of the figure. Abbreviations used are explained in the text.

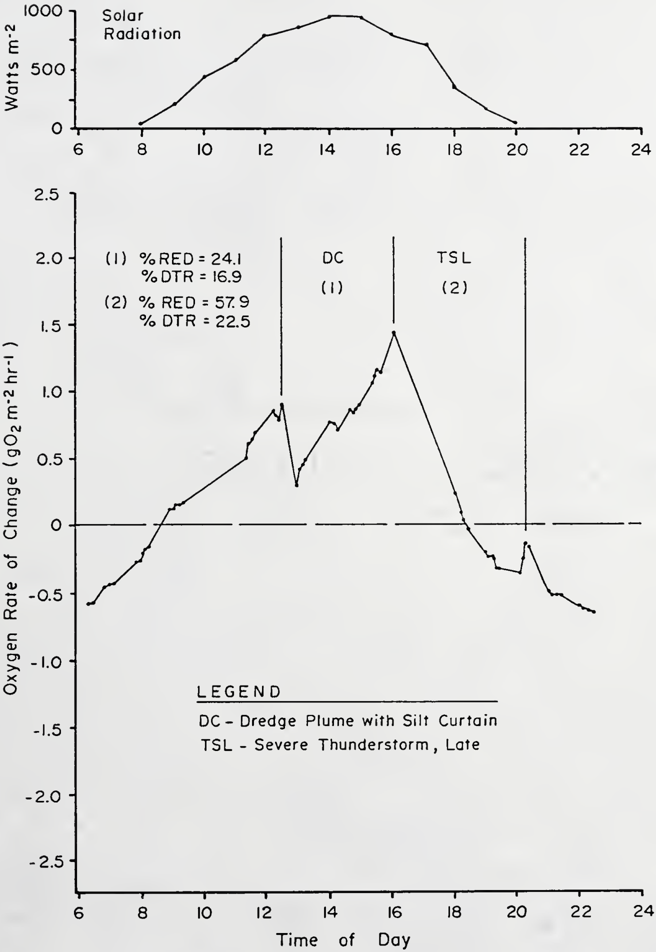


Figure 8. Reduction in net community production as a result of dredging with a silt curtain and a severe thunderstorm occurring late in the afternoon. Solar radiation is shown at the top of the figure. Abbreviations used are explained in the text.

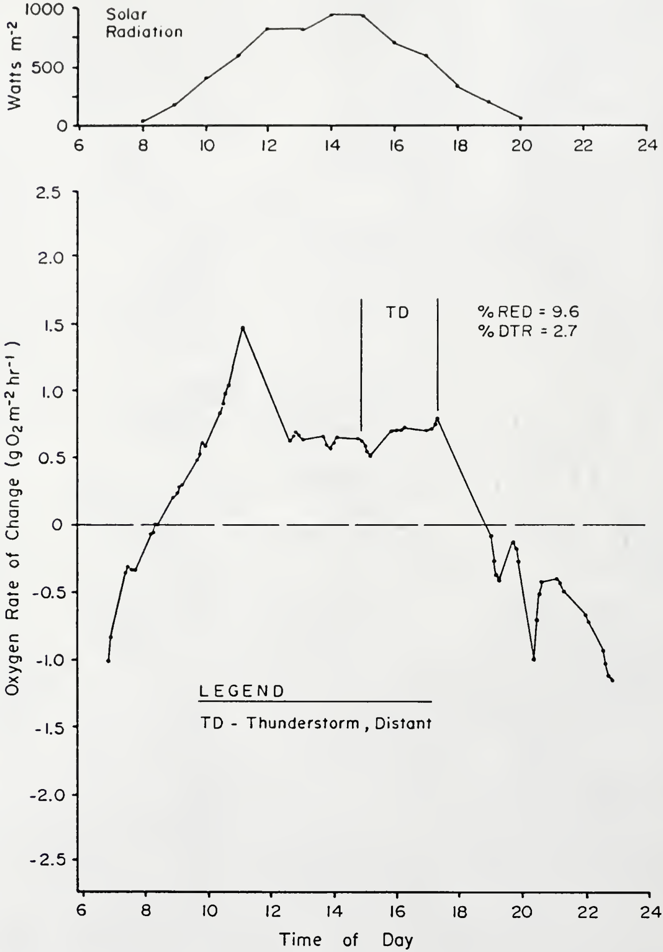


Figure 9. Reduction in net community production as a result of a distant thunderstorm. Solar radiation is shown at the top of the figure. Abbreviations used are explained in the text.

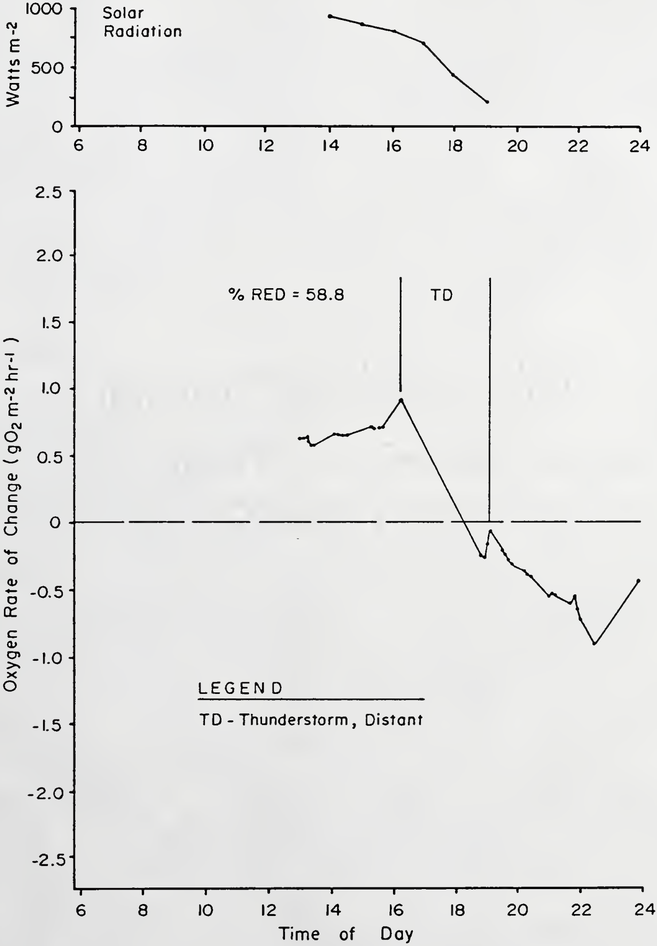


Figure 10. Reduction in net community production as a result of a distant thunderstorm. Solar radiation is shown at the top of the figure. Abbreviations are explained in the text.

in Figure 9 is 9.6% during the event and 2.7% for the day. The response of the production curve during this time period is reflected in the solar curve which shows a slightly steeper decline between 1500 and 1600 hours as compared to values shown for other time periods. Between 1600 hours and 1730 hours the decline is not as great. Reasons for fluctuation in the curve between 1100 and 1500 hours were not noted in the field log and are not included in the analysis. A more severe reduction (58.8%) resulting from a similar thunderstorm is shown in the curve in Figure 10.

Figures 11 and 12 demonstrate the effect of normal (short duration with local rainfall) thunderstorms on metabolic activity. Effects of these events at the time the storm occurred were very similar on both days (approximately 21%). Overall effects on the day's production were also very similar, ranging from 6.2-6.8%. Unfortunately, solar records were lost for both days.

Although it is a rare weather event in the Florida Keys in the summertime, an overcast, rainy day produces the response shown in Figure 13. This event caused a reduction in net community metabolism of 32.1% during the time it occurred and an overall reduction in the daily net production of 6.9%. Other variation shown in the production curve is a result of gradual cloud build-up but is not included in the analysis as the exact timing of the events as they occurred were not recorded.

Scattered clouds (Figures 14-16) were the final weather

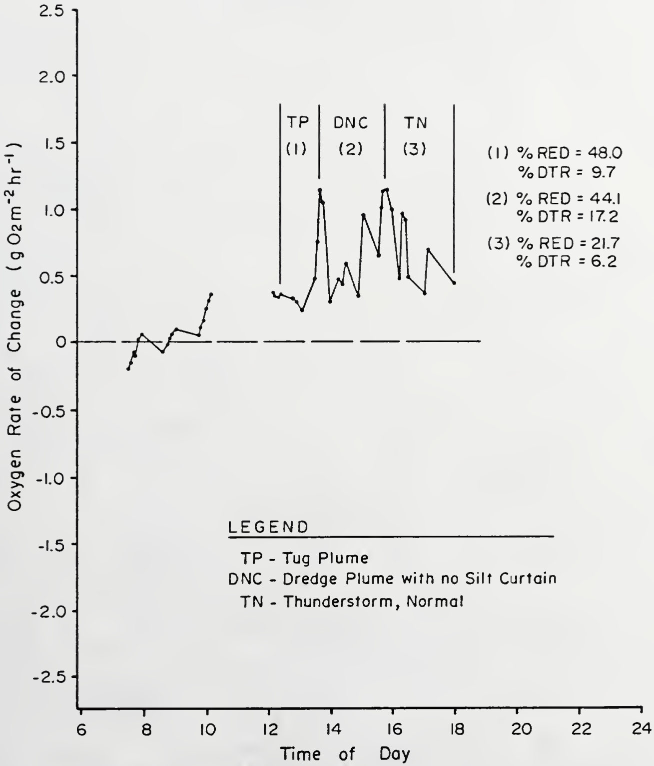


Figure 11. Reduction in net community production as a result of a tug plume, dredging with no silt curtain, and a normal thunderstorm. Abbreviations used are explained in the text.

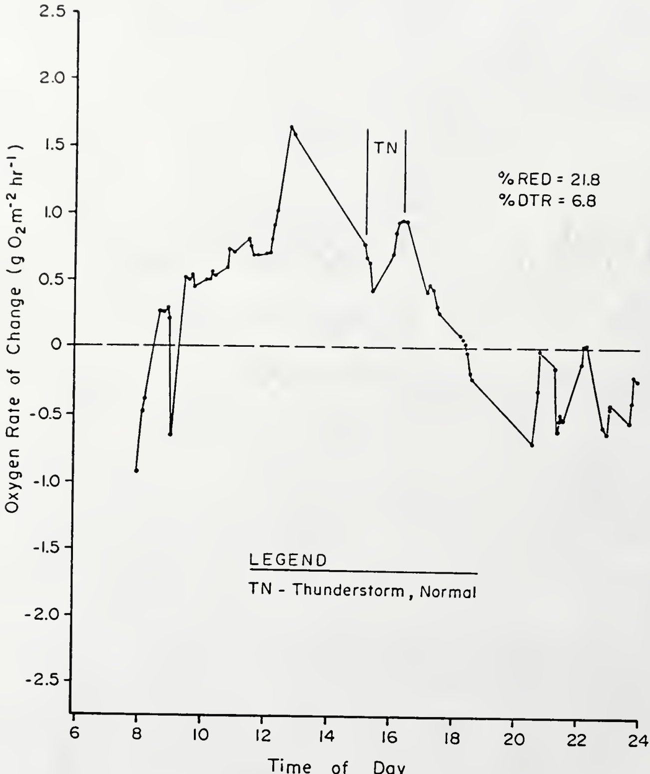


Figure 12. Reduction in net community production as a result of a normal thunderstorm. Abbreviations used are explained in the text.

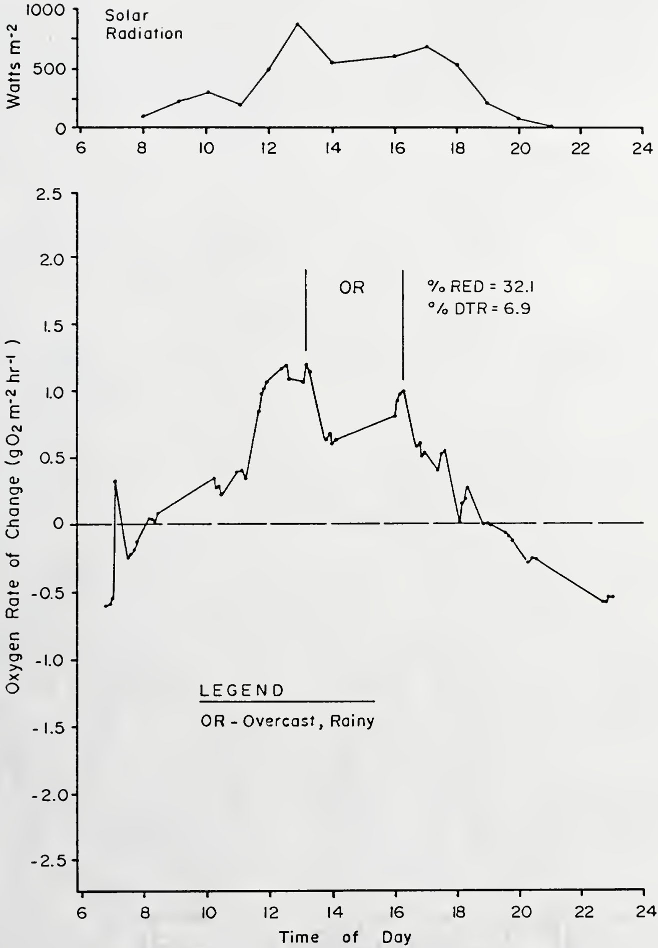


Figure 13. Reduction in net community production as a result of overcast, rainy conditions. Solar radiation is shown at the top of the figure. Abbreviations used are explained in the text.

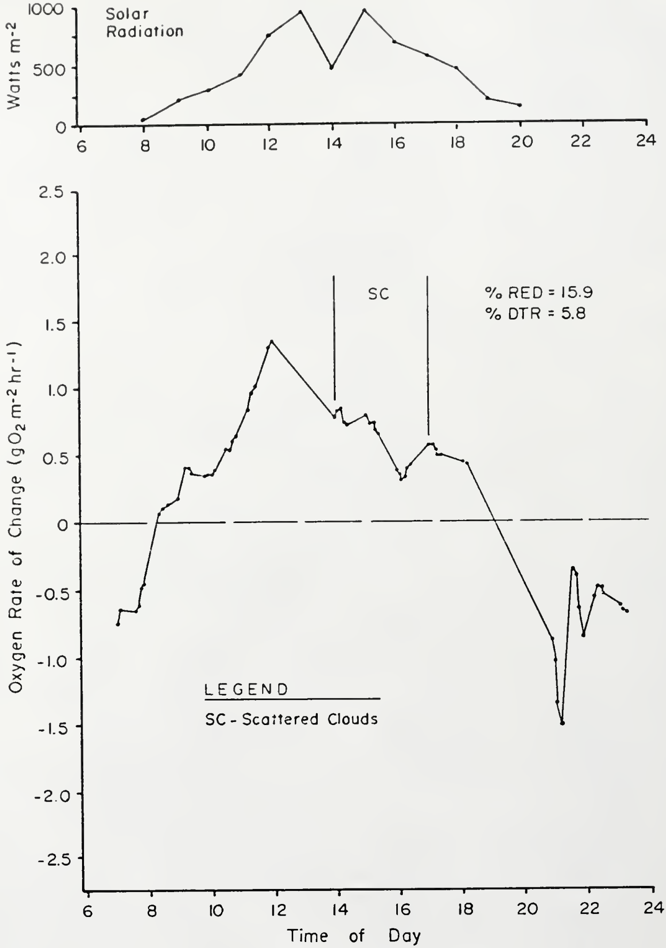


Figure 14. Reduction in net community production as a result of scattered clouds. Solar radiation is shown at the top of the figure. Abbreviations used are explained in the text.

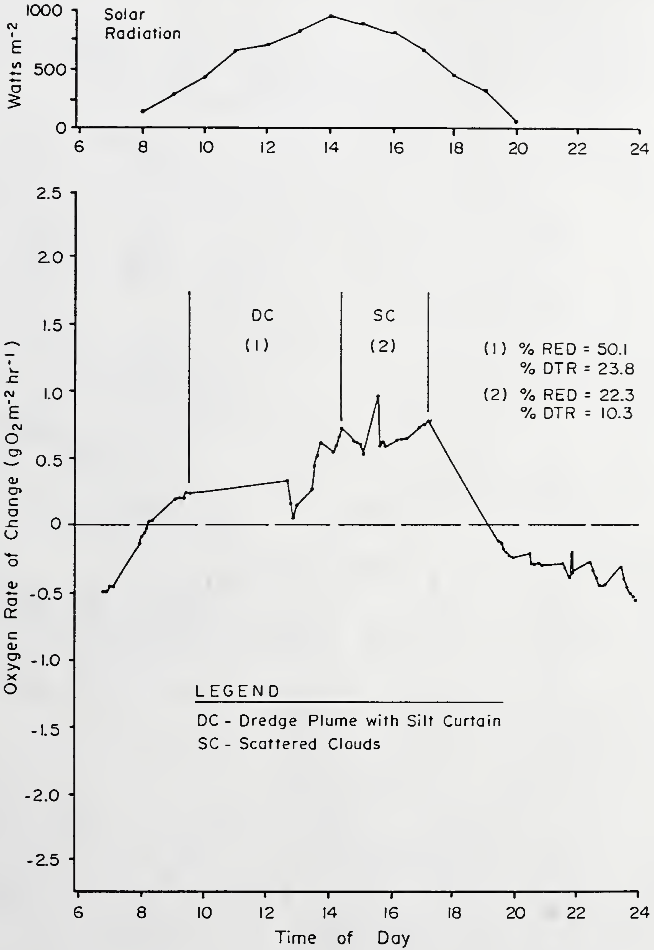


Figure 15. Reduction in net community production as a result of dredging with a silt curtain and scattered clouds. Solar radiation is shown at the top of the figure. Abbreviations used are explained in the text.

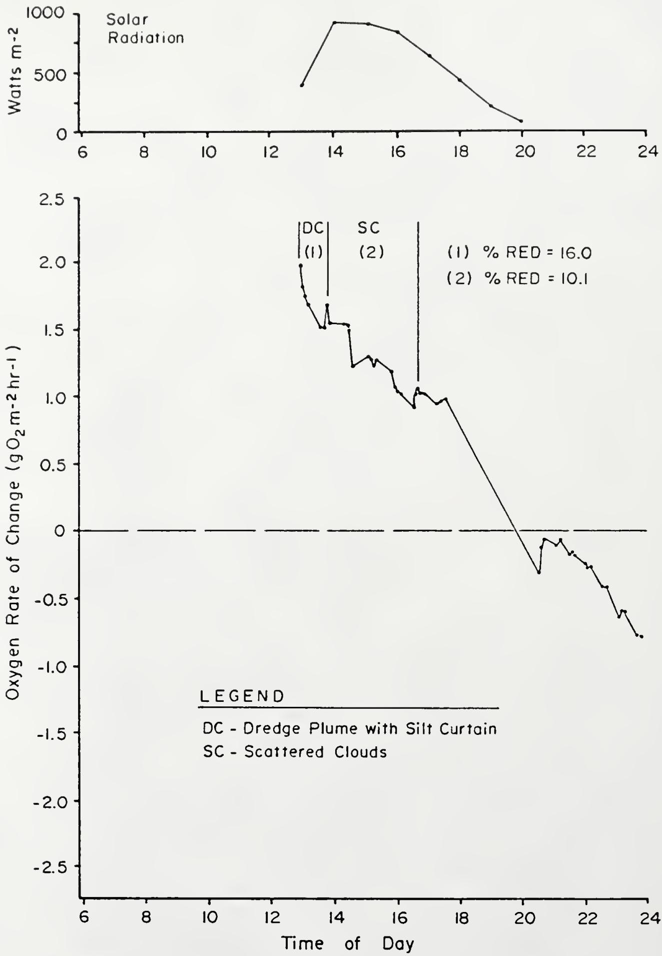


Figure 16. Reduction in net community production as a result of dredging with a silt curtain and scattered clouds. Solar radiation is shown at the top of the figure. Abbreviations used are explained in the text.

category observed and resulted in a reduction of 10.1-22.3% during the period in which this event was recorded and a 5.8-10.3% alteration of the daily amount. Effects of this weather type are not well documented in the solar record since the clouds pass over at a frequency greater than the hourly intervals over which sunlight was integrated. Again, field logs were used to document the occurrence of this weather event.

Dredging effects on net community metabolism are highly variable as shown in Figures 8, 11, and 15-23. Reduction in net production during dredging with a silt curtain (Figures 15-21) ranged from a low of 10.0% to a high of 74.9%. Reduction in daily net metabolism showed a low value of 1.3% and a high of 23.8%. Solar radiation showed no major fluctuation during these events. Of this group, Figure 20 showed evidence of a small amount of net production occurring in the dark. This will be discussed in the following section. The effect of dredging with no silt curtain is shown in Figures 11, 22 and 23. This event is also extremely variable in its effects, the reduction in net community metabolism ranging from a low of 44.1% (Figure 11) to a high of 98.0% (Figure 22). A decline in solar radiation is indicated in Figure 22 during this dredging event which reinforces the effect of dredging. The effect on daily net production was less drastic, showing a low of 17.2% and a high value of 43.1%.

The effects of another dredging-related event, shown in Figures 11, 18, and 24, is the turbidity plume resulting

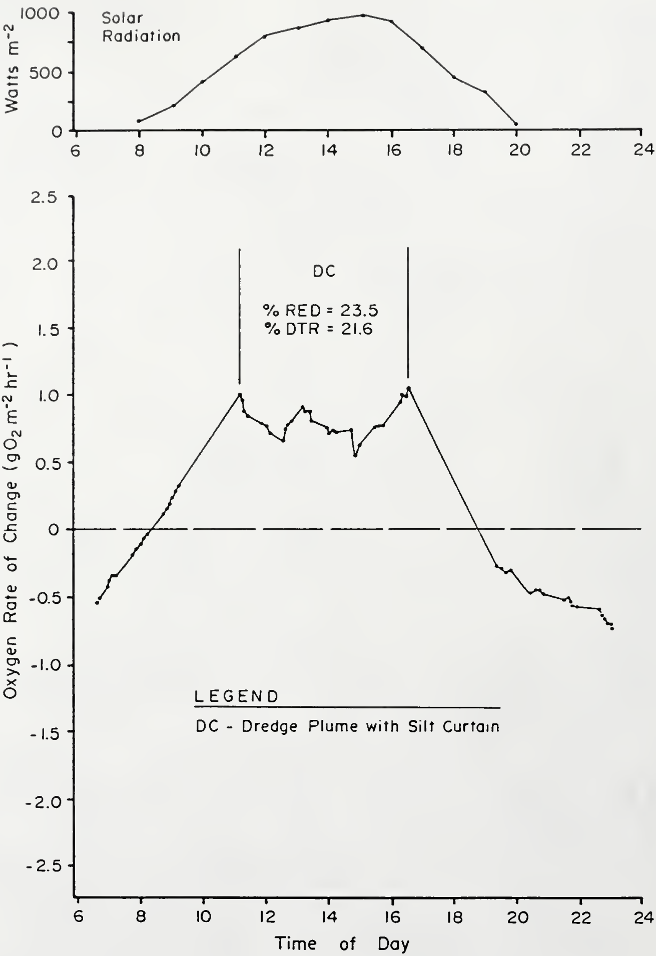


Figure 17. Reduction in net community production as a result of dredging with a silt curtain. Solar radiation is shown at the top of the figure. Abbreviations used are explained in the text.

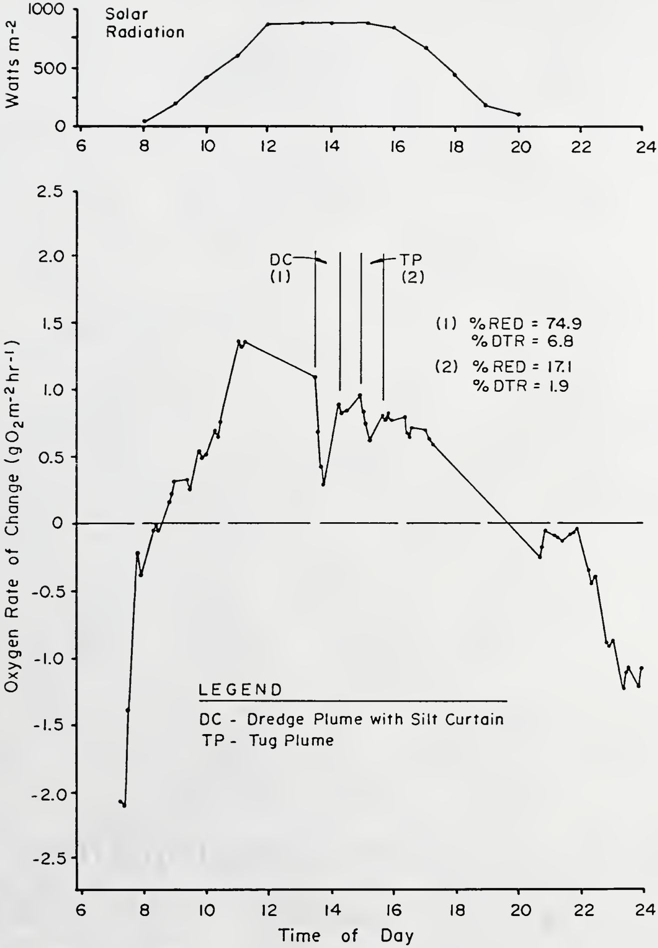


Figure 18. Reduction in net community production as a result of dredging with a silt curtain and a tug plume. Solar radiation is shown at the top of the figure. Abbreviations used are explained in the text.

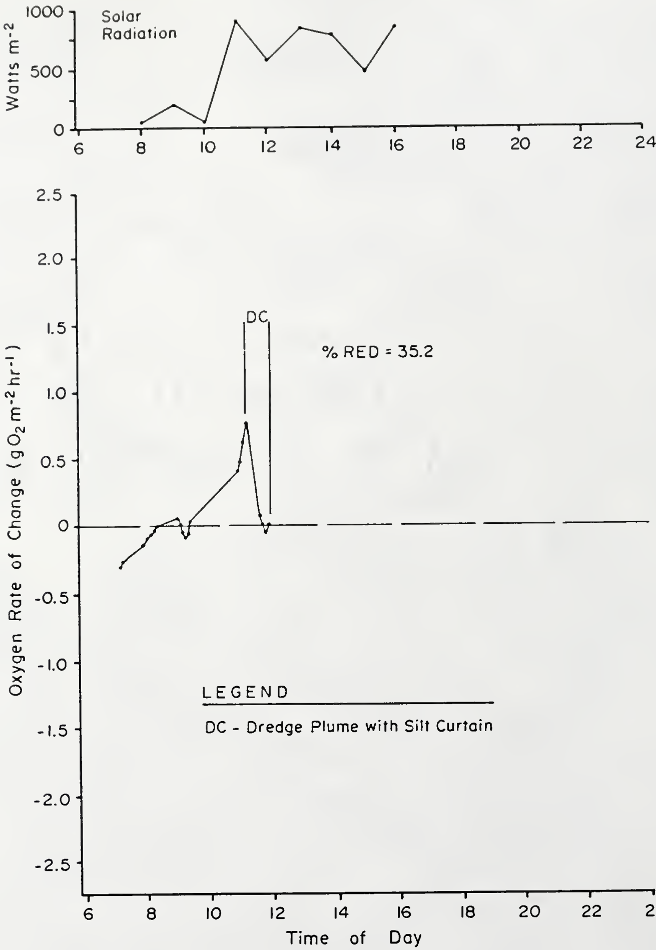


Figure 19. Reduction in net community production as a result of dredging with a silt curtain. Solar radiation is shown at the top of the figure. Abbreviations used are explained in the text.

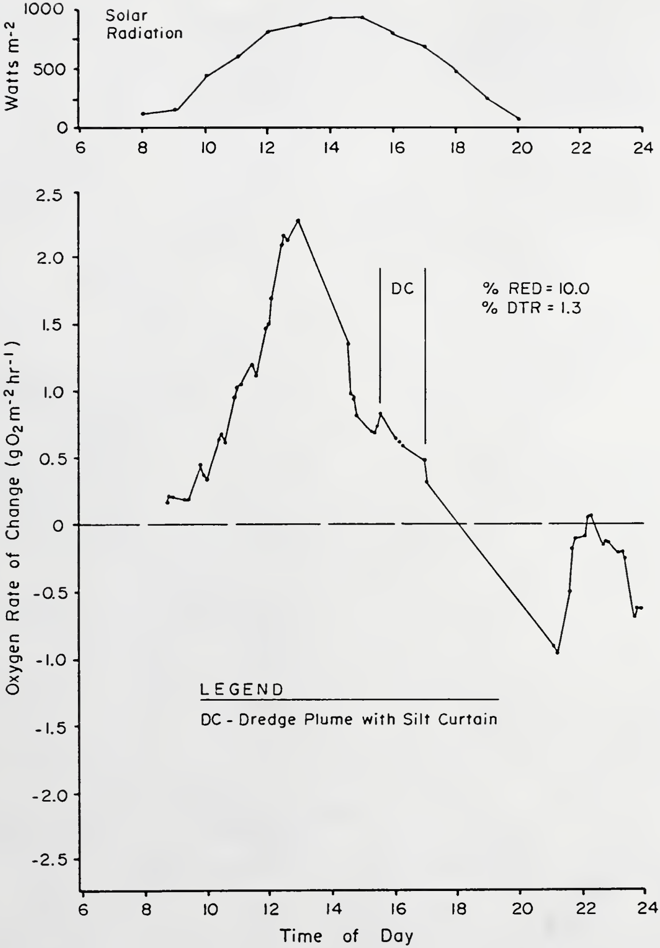


Figure 20. Reduction in net community production as a result of dredging with a silt curtain. Solar radiation is shown at the top of the figure. Abbreviations used are explained in the text.

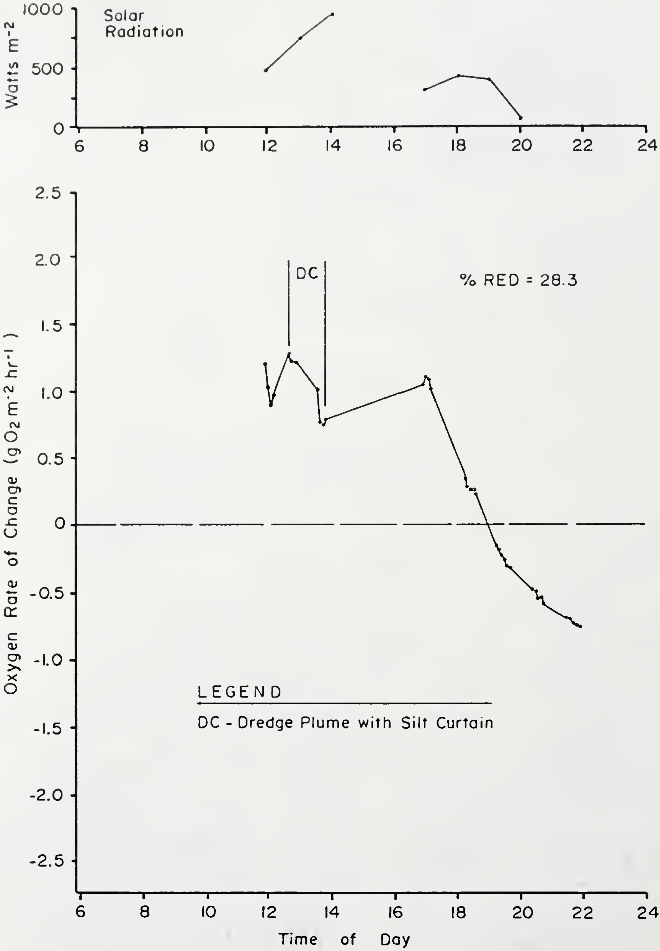


Figure 21. Reduction in net community production as a result of dredging with a silt curtain. Solar radiation is shown at the top of the figure. Abbreviations used are explained in the text.

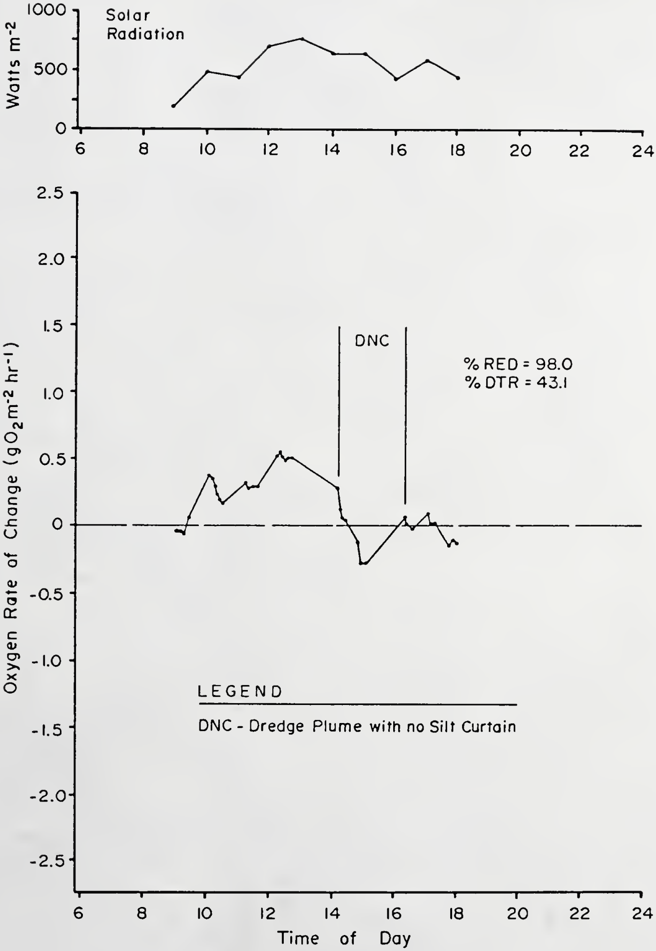


Figure 22. Reduction in net community production as a result of dredging without a silt curtain. Solar radiation is shown at the top of the figure. Abbreviations used are explained in the text.

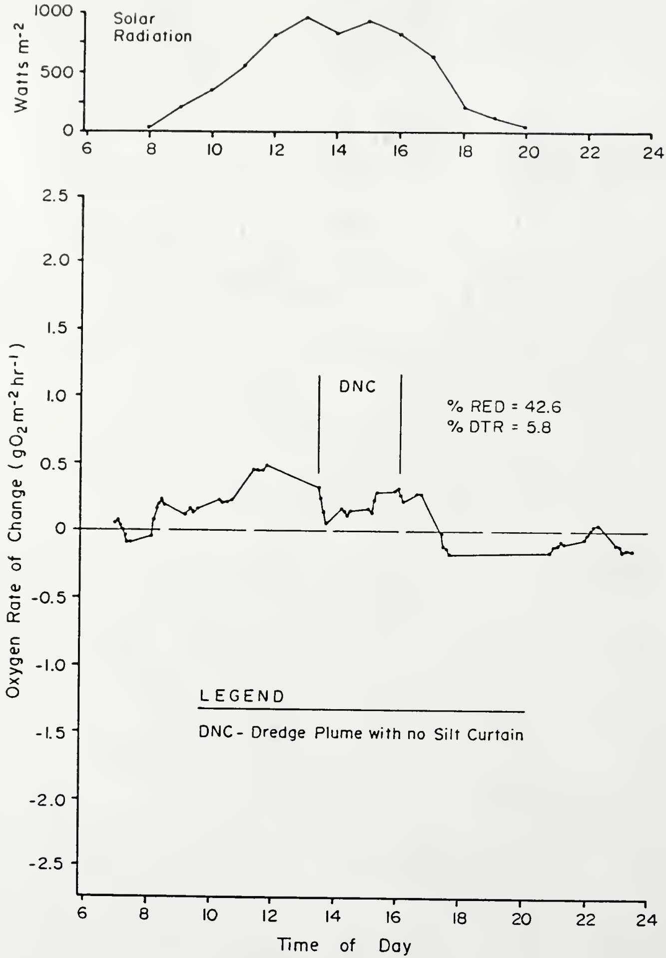


Figure 23. Reduction in net community production as a result of dredging without a silt curtain. Solar radiation is shown at the top of the figure. Abbreviations used are explained in the text.

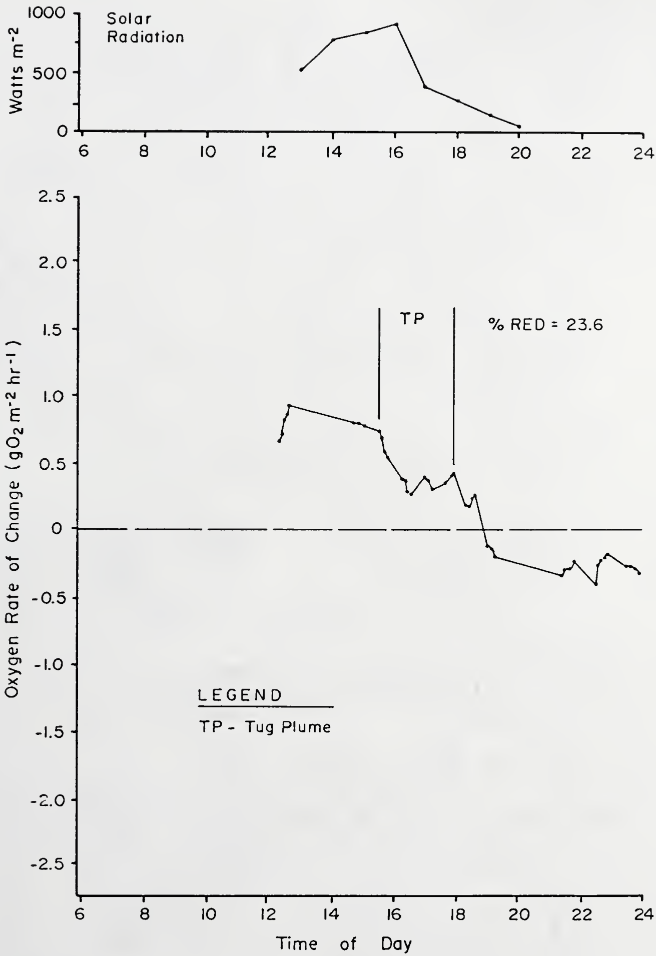


Figure 24. Reduction in net community production as a result of a tug plume. Solar radiation is shown at the top of the figure. Abbreviations used are explained in the text.

from the passage of tug boats moving work barges through the shallow areas. This activity resulted in a range of reduction 9.7-48.0% during the time interval in which they occurred and an overall daily reduction of 1.9-17.2%. A drop in sunlight also occurred during this time interval.

A summary ranking all turbidity events monitored is presented in Table 2. The three events in both categories (time interval and daily metabolism reduction) resulting in the greatest reduction in net community metabolism are naturally occurring weather events: a severe pre-noon thunderstorm, hurricane-related thunderstorms, and a severe late thunderstorm, respectively. Although some events changed in order between the two time comparisons (time of occurrence and reduction in the total metabolism), dredging events generally reduce metabolism less than thunderstorms. Less intense weather events and dredging events (tug plumes) rank lowest of the categories examined.

In the comparison involving the time period in which the event occurred, the high variability of the measurements associated with both dredging types (with and without a curtain) indicates the erratic nature of this activity. Distant thunderstorms also show high variability in their reduction of metabolism. Reduction of daily net production remained highly variable for only one dredging event (no curtain) but variability of the metabolism reduction was decreased substantially when a silt curtain was in place.

Table 2. Percent reduction in net community metabolism.

Reduction At Time of Occurrence					Reduction of Total for Day				
Rank	Event	$\bar{x}$	S.D.	N	Rank	Event	$\bar{x}$	S.D.	N
1	Severe Thunderstorm, Early in Day	68.5	--	1	1	Severe Thunderstorm, Early in Day	39.9	--	1
2	Hurricane-related Thunderstorms	65.7	7.9	4	2	Hurricane-related Thunderstorms	26.9	15.1	4
3	Severe Thunderstorm, Late in Day	57.9	--	1	3	Severe Thunderstorm, Late in Day	22.5	--	1
4	Dredge Plume, No Curtain	47.6	33.8	4	4	Dredge Plume, With Curtain	20.8	3.5	3
5	Thunderstorms, Distant	34.2	34.8	2	5	Overcast, Rain	15.5	--	1
6	Dredge Plume, With Curtain	32.2	11.2	5	6	Dredge Plume, No Curtain	14.8	16.8	5
7	Overcast, Rain	32.1	--	1	7	Scattered Clouds	8.1	3.2	2
8	Tug Plume	29.6	16.3	3	8	Thunderstorm, Normal	6.5	0.4	2
9	Thunderstorm, Normal	21.8	0.1	2	9	Tug Plume	5.8	5.5	2
10	Scattered Clouds	16.1	6.1	3	10	Thunderstorm, Distant	2.7	--	1

S.D. = Standard deviation
N = Number of events in sample

Hurricane-related thunderstorm effects were also highly variable throughout the day as were tug plume-associated responses.

A comparison of net photosynthetic efficiencies prior to the dredging events and two years later is shown in Table 3.

The average depths of all the stations are similar, ranging from 0.9 to 1.4 m. Mean percent light transmission of the water column was approximately 40% higher in the post-dredging period, 50.6 as compared to 36.0 during the summer of dredging. Higher variability of the post-dredging water clarity was due to the presence of strong sustained winds during the early stages of the sampling effort. Surface solar insolation also averaged slightly higher in the post-dredging sampling period and was also less variable. The amount of solar insolation reaching the plants was also approximately 2 times higher in the post-dredging period, due mainly to the increased water clarity shown during this time. Mean dry weight and ash-free biomass estimates for the two periods were remarkably similar although some variability was noted from two separate samplings within the pre-dredging interval. Net community production estimates were approximately 2 times lower in the post-dredging period.

Comparison of net production rates per gram of both dry weight and ash-free weight of standing stock were both

Table 3. Comparison of seagrass community pre- and post-dredging photosynthetic efficiencies.

Date	Depth MLW (a)	%T	Solar Surface (Watts m^{-2})	Solar At Depth (Watts m^{-2})	Biomass DW (g)	AF (g)	Net Prod (gO_2 m^{-2})	Net Prod g^{-1} Bio DW	Net Prod g^{-1} Bio AF	EFFICIENCY g O_2 g^{-1} biomass $watt^{-1}$ DW	EFFICIENCY g O_2 g^{-1} biomass $watt^{-1}$ AF
PRE-DREDGING											
15 JUL 80	1.4	37.9	3388	871.4	581.66	438.11	4.64				
16 JUL 80	1.4	41.3	4885	1414.0			6.74				
26 JUL 80	1.4	35.1	6857	1580.1			4.98				
17 AUG 80	1.4	26.22	3995	613.2			3.20				
18 AUG 80	1.4	38.6	6599	1737.4			6.13				
19 AUG 80	1.4	35.3	6024	1403.7			6.38				
25 AUG 80	0.9	27.8	3690	1165.2	1467.17	1003.92	7.48				
26 AUG 80	0.9	45.5	5674	2794.3			7.87				
Mean		36.0	5139	1447	1024.42	721.02	5.93	5.79E-03	8.22E.03	4.00E-06	5.86E.06
S.D.		6.1	1260	615	442.76	282.91	1.46				
N		8	8	8	2	2	8				
POST-DREDGING											
5 AUG 82	1.3	29.8	4857	1032	1150.58	786.95	1.70				
6 AUG 82	1.3	26.4	5410	986			1.91				
7 AUG 82	1.3	36.0	5351	1449			2.54				
9 AUG 82	1.3	59.9	7035	3654			4.12				
11 AUG 82	1.3	59.3	5822	2982			2.37				
12 AUG 82	1.3	65.2	6939	4014			4.75				
13 AUG 82	1.3	67.9	6167	3755			2.90				
14 AUG 82	1.3	59.5	6871	3533			2.63				
15 AUG 82	1.3	51.2	4457	1893			2.25				
Mean		50.6	5878	2589	1150.58	786.58	2.80	2.43E-03	3.55E-03	9.39E-07	1.37E-06
S.D.		14.8	888	1171	--	--	0.95				
N		9	9	9	1	1	9				
RATIOS (Pre-dredging/ post-dredging)		0.71	0.87	0.56	0.89	2.12	2.12	2.38	2.31	4.26	4.14

%T = Percent trasmittance of light in the water column
DW = Dry weight biomass in grams
AF = Ash free weight biomasss in grams
S.D. = Standard deviation
N = Number of observations
E = Signifies scientific notation is used
Prod = Production
Bio = Biomass

approximately 2 times higher during the sampling period unaffected by dredging. Final efficiency values (solar insolation included) were approximately 4 times greater in the communities unaffected by turbidity due to dredging.

Discussion

The rapid response of autotrophic communities in clear-water environments to changes in sunlight has been shown in previous work (Knight, 1983). The similar response shown by the marine seagrass communities in this study indicates that they are also very highly responsive to changes in their environment. Permanent changes in water quality (including light) would be expected to result in alteration of the primary producer communities. Turbidity impacts associated with human activities, such as dredging, would be expected to be most severe on those primary producers less tolerant of lower light conditions or higher siltation rates. Several authors have shown loss of seagrass habitat and degradation of benthic communities resulting from increased turbidity, nutrients, toxic pollutants or storms (Grady 1981; Birch and Birch 1984; Bulthius et al. 1984).

A commonly used approach in environmental studies is to monitor changes in a parameter of interest over time as a result of some perturbation. Seldom are attempts made to place observed changes in perspective by comparing these with naturally occurring events. However, when making comparisons of this type, caution must be exercised to ensure that the natural and man-made perturbations contain similar components. In the present study, the weather events used for comparison are believed to be similar to dredging events in that light blockage occurs in each case.

In the present study of short-term effects, both the event intensity and timing appear to be the major factors influencing the ranking of all the perturbation events. The highest ranking activities, all weather events, achieved this level because they had a high intensity level of light blockage and were of sufficient duration to eliminate most of the net primary productivity for that day. Occurrence of the severe thunderstorm early in the daylight period caused elimination of much of the net photosynthesis during this time of rapid photosynthetic increase.

The dredging activities, both with and without silt curtains, were intermediate in effects compared to natural events. Reduction of net productivity resulting from these two dredging events was approximately similar during the time in which they occurred and in their effect on the daily production level. However, the variability of the data resulting from dredging with no curtain was much higher compared to the value determined during dredging with silt curtains in place. This could indicate that in this high current area the presence of a silt curtain does cause a more even dispersion of the dredge plume. The plume emanating from the dredge within the curtain may tend to lose some of the larger particles and at the same time be more evenly dispersed in the water column from turbulent mixing as it flows under the curtain.

In general, the major short-term effects of dredging (both with and without a silt curtain) on seagrass net community production fall somewhere in the middle of the spectrum of meteorological events that the system encounters normally. This agrees with the findings of Tramontano and Bohlen (1984) in which effects of a dredging operation in an estuary were short-lived and less severe than those due to storms. One of the reasons the dredging events in this study achieved their ranking is that in practice the dredging operations were intermittent because of tidally dictated work schedules, equipment malfunctions and transportation of sediment to shore.

Recommendations for future dredging in this area should consider maintenance of this intermittent nature of the operation. Development of a dredging scheme which would provide continuous dredging would very likely elevate dredging activities to the top of the present list because continuous dredging throughout all periods of the day would increase the intensity of dredging operations and eliminate most, if not all, of the net primary production.

Net productivity measured during nighttime hours is a phenomenon not uncommon in oxygen-based productivity calculations (Caldwell and Odum 1980). The net production of oxygen measured at this time can be explained by several sources of error inherent in a microcosm system of this nature. Nighttime net production may be a result of release of oxygen from the sediments as a result of translocation of oxygen from the leaves to the plant rhizomes during peak production periods of the day. Zieman (1975) has shown that this can happen on a somewhat unpredictable basis and is not well correlated with any particular peak production level.

Another explanation could be that either highly oxygenated patches of water or water of oxygen content similar to that which entered the upstream end may be entering the downstream end of the tunnel. This could occur from turbulent flow as a result of the overlying water column passing along the top and sides of the tunnel and then swirling in the tunnel. Although the sampling hose was assumed to be inserted into the end of the tunnel far enough to avoid this problem, it is possible a small amount of this water from outside the tunnel could enter and be picked up by the downstream hose. If this happened, the water from the downstream could be higher in oxygen content than the upstream end, therefore falsely indicating photosynthetic activity. The magnitude of such an error is small if one assumes it is similar to the magnitude of the 2,200 hours occurrence in Figure 6.

Seagrasses such as Thalassia testudinum have lacunae in the leaves where gases are stored during peak photosynthesis periods (Phillips and McRoy 1980). It is possible that stored oxygen is released in a burst from the leaves later in the day, elevating the oxygen readings to give the appearance that photosynthesis had taken place.

Finally, the residence time of water in the tunnel was determined crudely with dye and represents an average flow time during a tidal cycle. Since tidal flow is a dynamic process which would continuously alter the residence time of water in the tunnel, sampling of the upstream and downstream portions of each slug of water as it passes through is more than likely not completely synchronized. This probably is not critical when large differences occur during the day, but may become a factor when respiration is fairly balanced during the nighttime hours.

Thus, it appears the microcosm method of upstream/downstream oxygen measurement utilized for calculation of net community metabolism is not designed for detection of minute changes in oxygen production or consumption. The system is designed to be a simple field monitoring device able to detect major changes in seagrass community function.

Criticisms of the oxygen method of seagrass community metabolism measurement (Bittaker and Iverson 1976; Phillips and McRoy 1980) regarding oxygen storage within the plant itself and problems with advective diffusion were not considered appropriate for the present study. The absolute production of the seagrass itself was not critical; the parameter of interest was the response of the entire community to natural and man-made perturbations, regardless of potential internal gas storage or recycling. Advective diffusion was eliminated through the use of covered microcosms. The measurement of oxygen flux provided a rapid response to fluctuations in the light regime and served as an index of ecosystem function. Kemp and Boynton (1980) have shown that community metabolism measurements utilizing oxygen techniques where horizontal oxygen diffusion is controlled are a useful index of ecosystem function and therefore can be used to compare natural and perturbed conditions. Additionally, all of the methods of currently used seagrass productivity measurement suffer from some disadvantages peculiar to the method which prevented their use in this study. Standing stock measurements, leaf area index, and leaf growth measurement all require long periods of time for obtaining results and are not readily adaptable to the measurement of short-term phenomena. Tagged carbon methods suffer from the same criticism as oxygen methods in that it is likely that recycling of carbon products does occur (Bittaker and Iverson 1976).

The pre- and post-dredging measurements of photosynthetic efficiency provide a different perspective on possible effects relating to dredging in the area. Net community production, when adjusted for pre- and post-dredging biomass, water clarity and solar differences, has been substantially reduced. Sampling during the post-dredging interval was accomplished during a period of higher solar radiation (low number of storms). Further, water clarity was also higher in the post-dredging period. These two parameters, when coupled together, show that more light was reaching the plants in the period of measurement following dredging operations. Both dry weight and ash free biomass estimates also are very similar, so decreased biomass can not account for lowered net productivity.

There are several plausible explanations for lowered post-dredging photosynthetic efficiency. Epiphytic organisms are perhaps more susceptible to dredging effects such as elevated turbidity or high siltation which may result in excessive abrasion, clogging or covering. Since this component can contribute a substantial amount to the net community metabolism while being a small component of the standing stock biomass (Pomeroy 1974), this portion of the community could have been depressed severely and not be indicated by a drastic change in biomass estimates. This segment of the community was not separately measured, however.

On the other hand, the impairment of the photosynthetic ability of the community may have occurred uniformly within each community component but at a lower level and not to the extent of reducing standing stocks. In either case, the net community production is lower. Since no measurements were collected in either the interim period or over a longer term, it is difficult to determine if the community is gradually rebounding from an impacted state or whether it is on a gradual decline. It is apparent, however, that water clarity has returned to pre-dredging levels. Only additional measurements over a longer time period will document the long-term adjustment of the seagrass community.

<u>Summary</u>

1. Reduction in net community production due to elevated

turbidity from natural and anthropogenic events was compared by estimating the reduction during the time period in which the event occurred and also by comparing this reduction to the daily production. The greatest reduction was shown by severe summer and hurricane-related thunderstorms. Dredging activities in which no silt curtain was used were next in the ranking followed by distant thunderstorms and dredging with a silt curtain, respectively. Overcast conditions, tug plumes, normal thunderstorms and scattered clouds, respectively, completed the ranking. Severe and hurricane-related thunderstorms also ranked highest in the percentage reduction of the daily production, followed in order by dredge plumes with a curtain, overcast conditions, dredging with no curtain, scattered clouds, normal thunderstorms, tug plumes, and distant thunderstorms, respectively.

2. Comparison of pre- and post-dredging net community production normalized for solar radiation and standing stock biomass showed an approximate 4-fold decrease two years after dredging. Severe impairment of photosynthesis of the epiphytic community or low-level impairment of all community components were offered as explanations for this finding.

3. Occasional measurement of nighttime production of oxygen in the microcosm was attributed to inaccuracies inherent in the microcosm technique. It was suggested

that the method may be most useful for detection of gross changes in highly productive systems rather than small differences when production is minimal.

CHAPTER III
EFFECTS OF SHADING AND NUTRIENT ADDITION ON NET COMMUNITY PRODUCTION

Introduction

Two of the major components of a dredge plume, shading and elevated nutrients from resuspended sediments, have been the subject of numerous investigations which have dealt with these phenomena on an individual basis and not as interacting entities. A review of the pertinent literature pertaining to effects of dredging-associated turbidity and shading on marine primary production is contained in Chapter II. Relevant previous research includes investigation in four areas: nitrogen sources, requirements and limitations for macrophytes (Patriquin 1972; McRoy et al. 1973; Capone and Taylor 1977; Stirling and Wormald 1977; Khalid et al. 1978; Capone et al. 1979; Barko and Smart 1981; Capone 1982; Strom and Biggs 1982; Short 1983), forms of nitrogen preferred by seagrasses (Fisher et al. 1982; Iizumi et al. 1982; Dortch and Conway 1984), phosphorus requirements of macrophytes (McRoy and Barsdate 1970; Carnigan and Kalf 1982), and enrichment studies using various forms of nitrogen and phosphorus (Orth 1977; Parker 1982; Thursby 1984; Dawes et al. 1984; Roberts et al. 1984; Ulrich and Barton 1985).

The present study investigates the short-term effects on net seagrass community production resulting from two facets of a dredging event: 1) shading by the dredge plume and 2) addition of nutrients into the water column as a result of nutrient release from resuspended sediments. Early field observations of a very rapid community response to shading suggested the hypothesis that these communities could be responsive to other changes such as addition of nutrients and also might be able to absorb and quickly utilize these nutrients from the water column when they are available. Hence, higher nutrient levels might cause an immediate increase in community metabolism. Further, this metabolic enhancement could perhaps offset reductions in metabolism due to shading.

The objectives of this study were 1) to establish the effects of shading and nutrient addition on net seagrass community metabolism separately and in combination, 2) to determine the relative importance of each factor by measurement of the levels of response of net community metabolism, 3) to help determine whether the two factors cause an overall reduction or increase in net community production, and 4) if both increases and decreases do occur, determine the over-all direction of influence of a dredge plume. The objectives were investigated in the field using flow-through microcosms to determine net community metabolism from upstream/downstream oxygen measurements.

Materials and Methods

Seagrass community metabolism was determined using the upstream/downstream oxygen method of Odum and Hoskins (1958). General methods, including equipment, oxygen data corrections, and calculation were identical to those described in the previous chapter. Variations of the general scheme will be included as appropriate.

Field experimentation involved the application of two treatments, namely shading and nutrients, to the microcosm at various levels and in as many different combinations as possible over several diurnal periods.

Four microcosms, positioned in parallel, each approximately 1-meter wide and 4-meters long, were used for the experimental field apparatus. Three of these tunnels were used exclusively for nutrient addition (ammonia, nitrate, and phosphorus) and one tunnel remained as a measure of baseline conditions. The same tunnel was used for each nutrient throughout the experiments. The microcosms were covered and anchored as described in Chapter II.

Baffle plates at each tunnel end were used to control water movement through the tunnel so that sufficient residence time existed to measure oxygen change within the detection limits of the oxygen sensor. Rubber hoses were inserted into each end of each tunnel and connected to a valve system on the boat. By opening and closing the valves, water was selectively pumped from the desired tunnel end to a Hydrolab Model 8000 (Hydrolab Corporation, Austin, Texas) for determination of dissolved oxygen, temperature, and conductivity in the same manner as described in Chapter II.

The shading portion of the experiment was carried out by shading the tunnels with nursery shade cloth having a mesh size approximating 60% sun blockage (40% light passage). Three different nutrients were added: nitrate, ammonia, and phosphorus. The levels of nutrients added consisted of four concentrations designed to bracket the concentration of nutrients actually measured in a dredge plume in the field (Table 4). Ammonia and phosphorus were determined colorimetrically using the procedures described in Stickland and Parsons (1972). The four concentrations consisted of 1×10^{-5} µmol l^{-1}, 1×10^{-7} µmol l^{-1}, 1×10^{-9} µmol l^{-1}, and 1×10^{-10} µmol l^{-1}. A concentrated solution was added to the tunnel to achieve the final concentration based on the assumptions of a water residence time of 20 minutes and a uniform mixing of water throughout the tunnel.

Shading of each microcosm was accomplished by attaching the nursery shade cloth to one end of the tunnel and unrolling it to the other end and tying down the sides. When not in use, the shade cloth was rolled up and secured to one end of the microcosm.

Nutrients were added with a gravity feed system that consisted of 5-gallon carboys lashed to the top of a truck innertube that floated at the surface. The jugs were connected to the tunnels with tygon tubing that was attached to the upstream end of the tunnel through a horizontal diffuser in the baffle plate. This diffuser, which consisted of four polyvinylchloride (PVC) nipples, allowed dispersal

Table 4. Nutrient analysis in a dredge plume.

		50m	Plume		150m
		Surface	Bottom	Surface	Bottom
Phosphorus (μmol P l^{-1})	$\bar{x}$	1.18×10^{-7}	1.30×10^{-7}	1.32×10^{-7}	1.10×10^{-7}
Ammonia Nitrogen (μmol N l^{-1})	$\bar{x}$	7.76×10^{-7}	5.85×10^{-7}	7.94×10^{-7}	8.18×10^{-7}

of the nutrients in the tunnel as evenly as possible. Nutrient flow from the jugs was controlled by in-line PVC ball valves. The flow required to release the contents of the jug into the tunnel to achieve the desired final concentration was determined through field experiments with dye release.

Residence time of the water in each microcosm was determined through several timed dye studies to be an average of approximately 20 minutes. This residence time was used during the entire tidal cycle. Initially, the water in each tunnel was sampled for oxygen, conductivity, and temperature at 5-minute intervals beginning with the upstream end. At the end of 20 minutes, the downstream end was sampled which allowed sampling of the plug after the 20-minute residence time. With the number of tunnels being nearly simultaneously monitored, this allowed only one measurement per tunnel per hour. Sampling effort was therefore increased to a frequency of 1 per minute. Each separate upstream end was sampled at 1-minute intervals for 4 minutes. Sampling was suspended for 1 minute out of every 5 to allow readjustment of sampling so they occurred at the same minute of every hour. At the beginning of minute 20, the valves were switched so that the downstream ends of all four tunnels were sampled in a similar sequence beginning with Tunnel 1. This enabled the downstream sampling to be timed to coincide with the 20-minute residence time of water. This 1-minute interval sampling continued during the entire experiment over an approximate 14- to 18-hour day.

The experimental treatments were applied over 4-hour time blocks throughout the day. These time blocks covered the time period from 7 to 10 A.M., 10 A.M. to 1 P.M., 1 to 3 P.M., and 3 to 7 P.M. The combined treatment of nutrients and shade were applied to the experimental chambers in as many combinations as possible over each 4-hour test period throughout the experiment. At the end of 2 weeks, the tunnels were moved and the experiment was replicated.

Data were analyzed using the general linear model (GLM) procedure of the Statistical Analysis System (SAS) at the Northeast Regional Data Center (NERDC) at the University of Florida. This variation of the ANOVA procedure was utilized because of the unbalanced design of the experiment. The dependent variable calculated in this set of experiments was the rate of change of oxygen (community metabolism) calculated from the difference equation (see Chapter II) utilizing the upstream and downstream oxygen values from the microcosms. The independent variables, or treatments were 1) shading, with two levels of shading on and shading off; 2) nutrient addition with three types of nutrients corresponding to nitrate, ammonia, and phosphorus, each with four levels of concentration; and 3) station differences with two levels corresponding to each of the replicate sampling episodes.

The procedure for analysis of the ANOVA results consists of a step-wise examination of significance levels (α=.05) of F values resulting from the least square determination of the general linear models procedure. The first step involves determination of the significance level (α=.05) of the interaction term which contains all of the main effects, in this case shading, the type of nutrient added, and the concentration of the nutrient. If the interaction term is not significant, then all two-way interactions of the main effects are evaluated. If none of these interactions are significant, then each main effect is inspected separately. In this manner, significance in the model is attributed to the main effects acting either singly or in combination.

The ANOVA compared only the tunnels receiving nutrients and shading. This allowed determination of differences between nutrient type, concentration, and shading effects. A comparison was also made between these microcosms and a control. This allowed a qualitative assessment of nutrient and shading effects compared to background.

Results

Comparison of treatment effects between the experimental tunnels showed that the 3-way interaction term was not significant (Table 5). Examination of all the 2-way interaction terms showed significant differences (p=.003) only in the shade-nutrient concentration term (Table 5) indicating a significant interaction between shading and the concentration of the nutrients added. Evaluation of the nutrient main

Table 5. ANOVA results of interaction terms

Treatment	N[a]	DF[b]	F Value	Probability[c]	Significant
Shade-nutrient type-nutrient concentration interaction	263	6	0.41	0.87	No
Shade-nutrient type interaction	263	2	0.18	0.83	No
Nutrient type -nutrient concentration interaction	263	6	0.26	0.96	No
Nutrient type	263	2	0.05	0.95	No
Shade-nutrient concentration interaction	263	3	4.96	0.003	Yes

[a] number of observations

[b] degrees of freedom

[c] $\alpha=0.05$

effect term showed no significance, indicating there was no significant difference in the response variable due to the type of nutrient being added so this term was dropped from further analysis.

The results of combining all nutrient concentrations and comparing the net production with shade on and off are shown in Table 6. In the unshaded condition, the effects due to the addition of different concentrations of nutrients were highly significant (p=.0001), i.e., different concentrations of nutrients caused a different response. No significance was noted with the shaded tunnels.

The effects of each nutrient concentration under shaded and unshaded conditions are shown in Table 7. The nutrient concentration in the unshaded microcosms was significant at all levels except the lowest concentration (1×10^{-10} μmol l^{-1}). The nutrient concentration of 1×10^{-9} μmol l^{-1} showed the largest difference (0.416) between shading treatments. This was followed in order by each of the increasing concentrations.

A qualitative comparison of mean net production between an unshaded control and communities exposed to the three nutrient types under shaded and unshaded conditions is contained in Table 8. Net production of the unshaded seagrass was higher than the control for all three nutrient types. In the shaded case, the experimental microcosms were lower than the control although the seagrass subjected to nitrate addition showed considerably higher production than

Table 6. ANOVA results of combined nutrient concentrations under shaded and unshaded conditions.

Treatment	N[a]	DF[b]	F Value	Probability[c]	Significance
Unshaded	144	3	12.84	0.0001	Yes
Shaded	119	3	0.54	0.6608	No

[a]number of observations

[b]degrees of freedom

[c]$\alpha = 0.05$

Table 7. ANOVA results of shading effects at each nutrient concentration.

Treatment	LEAST SQUARES MEAN			N^a	DF^b	F Value	$Probability^c$	Significant
	Unshaded	Shaded	Difference					
1×10^{-5} µmol l^{-1}	0.144	-0.006	0.150	60	1	8.60	0.0049	Yes
1×10^{-7} µmol l^{-1}	0.250	0.029	0.221	67	1	17.11	0.0001	Yes
1×10^{-9} µmol l^{-1}	0.425	0.009	0.416	74	1	71.46	0.0001	Yes
1×10^{-10} µmol l^{-1}	0.114	0.023	0.091	62	1	1.80	0.1857	No

[a] number of observation

[b] degrees of freedom

[c] $\alpha=0.05$

Table 8. Qualitative comparison of mean net community production in shaded and unshaded microcosms to a control.

Nutrient Type	Shade Off Mean Net Production ($gO_2m^{-2}hr^{-1}$)		N[a]	Shade On Mean Net Production ($gO_2m^{-2}hr^{-1}$)	
	Experimental	Control		Experimental	Control
Ammonia	0.2526	0.1750	451	0.0015	0.4457
Nitrate	0.2439	0.1750	452	0.1232	0.4457
Phosphorus	0.2589	0.1750	453	0.0069	0.4457

[a]Number of observations

the other two shaded microcosms.

To test for differences between plots, the microcosms were moved and the experiment replicated. Table 9 shows no significant differences existed between stations.

Discussion

The metabolic response of these clear-water seagrass communities to changes in their physical environment is very rapid, sometimes on the order of minutes as determined from field observations described in Chapter II. Because of this rapid response time, the present experiments were designed to examine the response of the community to two components (shading and nutrient addition) of a dredge plume.

The response of the community to shading was not unexpected as effects of light blockage on net community production has been demonstrated earlier (see Chapter II). Clearly, of the effects investigated, shading causes the most drastic alteration in net community production.

The response of seagrass communities to nutrient inputs is much less clear. Seagrass nutrient dynamics are poorly understood and the results are often contradictory. In the analysis of the effects of nutrient addition in the present investigation, similar responses of the community to all three nutrient types are not unique. Harlin and Thorne-Miller (1981) showed that both nitrogen and phosphorus stimulated growth of <u>Zostera marina</u> in the field, suggesting an almost simultaneous deficiency in both nutrients. Thursby (1984) showed that <u>Ruppia</u> in the summer contained low tissue

Table 9. ANOVA results of comparison between stations.

Treatment	N[a]	DF[b]	F Value	Probability[c]	Significance
Station	263	1	3.38	0.1084	No

[a]number of observations

[b]degrees of freedom

[c]probability $\alpha = 0.05$

concentrations of both nitrogen and phosphorus, indicating this species was deficient in both these nutrients. Ulrich and Barton (1985) found that Phragmites australis shoot growth was influenced by both nitrate and phosphorus application. Roberts et al. (1984) showed that, under conditions of nutrient enrichment by nitrogen, additional phosphorus may be needed for maximum growth. These highly productive tropical systems may have evolved very efficient relationships with nitrogen fixing heterotrophs (Patriquin and Knowles 1972) such that nitrogen is generally in excess. Similar nitrogen abundance could explain the response of this system to added phosphorus.

McRoy and Barsdate (1970) showed that phosphorus uptake is a function of the metabolic activity of the plant. Periods of high productivity such as occur in seagrass communities may momentarily deplete phosphorus stocks. Direct application of phosphorus to the community could push productivity to higher levels.

Interaction effects similar to those found in this study between shading and nutrient concentrations have been documented by Dawes et al. (1984) who showed that for an alga in nutrient-rich water, photosynthetic rates were significantly different when it was exposed to light at two different intensities. McRoy and Barsdate (1970) showed that light was required for uptake of phosphorus, implying that phosphorus is utilized only under adequate light conditions.

The highest response in net community production was found in the unshaded microcosm at concentration 1×10^{-9} $\mu mol\ l^{-1}$, indicating this may be an optimum nutrient level for seagrass production. The negative production values recorded for the highest nutrient concentration with shading may indicate that photosynthetic inhibition is occurring at the higher concentration, although this concentration was much lower than those used by Harlin and Thorne-Miller (1981) which did not produce inhibition. The absence of a significant difference at the lowest concentration indicates that in the sunlight the concentration is too low to enhance photosynthesis.

Comparison of the experimental tunnels with the control shows some production enhancement occurs in the sunlight when nutrients are added as compared to a baseline. This is consistent with work by others (Harlin and Thorne-Miller 1981; Thursby 1984; Ulrich and Barton 1985; and Roberts et al. 1984) in that several nutrients, for various reasons, can be nearly simultaneously limiting. It is also possible, that with nutrient additions higher than those experienced during a dredging event, productivity may be increased such that a significant difference could occur. Effects of high nutrient loadings are fairly well documented for algae (Tewari 1972; Waite and Mitchell 1972; Guist and Humm 1976; and Ho 1979) showing that excessive growth occurs under these conditions. However, in the lower level nutrient additions related to dredging events, the trend is toward enhancement of production only in the sunlight. Under low light conditions, the addition of nitrate caused the highest community metabolism compared to other nutrients. This is consistent with the findings of Iizumi et al. (1982) who showed that although ammonia is the most easily utilized form of nitrogen because of ammonia toxicity, nitrate is taken up more readily.

The most significant effect caused by a dredge plume is the reduction in net production due to shading. Although some enhancement is indicated resulting from increased nutrient availability from resuspended sediments, this is overshadowed by shading effects. If a mechanism existed which enabled the plume to dissipate quickly and allow nutrients to remain available, the present study indicates production would be increased. This is highly unlikely, however, in the study area since rapid plume dispersal mechanisms, such as high currents, would also quickly dissipate any elevated nutrients.

Summary

1. Shading effects were the major impact of a dredge plume, causing a reduction in seagrass net community metabolism.
2. Response of the community to shading and addition of nutrients by a dredge plume was a result of interaction between shading and the concentration of nutrients added. Net production was higher in the sunlight in the presence of nutrients with an optimum production at

a concentration of 1×10^{-9} µmol l^{-1}. There was no significant difference in net production between the three types of nutrients (nitrate, ammonia, and phosphorus) utilized.

3. Comparison of experimental and control communities' response to nutrient addition and shading showed enhancement of production only in unshaded microcosms and reduction in net production due to shading.

CHAPTER IV
SEAGRASS COMMUNITY SYSTEMS DYNAMICS MODEL

Introduction

Although seagrass ecosystems are among the most productive in the world (Phillips and McRoy 1980), few published accounts exist which examine with a simulation model their primary and secondary production, nutrient dynamics, decomposition, and response to outside influences. Thayer et al. (1975) constructed an energy flow diagram of a *Zostera marina* community and showed that organic matter was exported although they neglected primary production of the epiphyte and benthic diatom communities. Verhagen and Nienhuis (1983) modeled the production, seasonal biomass changes, and distribution of the eelgrass *Zostera marina*. Seasonal oscillations observed in eelgrass production were believed to be a function of light, water temperature, currents, and the age of eelgrass blades. According to their model, the height of the eelgrass shoots could be explained by space limitation, lack of below ground biomass, and insufficient light. They indicated that the combination of vertical, horizontal, and year-to-year variation of the community could be best explained by a parameter they had not used in earlier versions of the model: production of seeds and growth of the eelgrass shoots from seeds as opposed to the more common sprouting from rhizomes. Short

(1980) developed a simulation model of a seagrass production system and examined the effects of temperature, light limitation, tidal current interactions, respiration, and mechanical damage on seagrass production. In general, he found good correlation between the simulation and empirical data with regard to standing crop, blade length, rhizome length, and production.

In the present study, a deterministic model was used which showed explicit feedback loops coupling the various system components. This type model was believed adequate to examine cause and effect relationships in a natural seagrass ecosystem and to compare their response to natural and man-made perturbations. This systems dynamics model (Forrester 1968) showed feedbacks explicitly, portrayed information as well as material flows, and included linear and nonlinear relationships. The microcomputer program utilized to run the model was Simu-Dyn, a DYNAMO simulation program developed by Dr. Clay L. Montague.

The objective of this model was to examine five seagrass community components: standing stock biomass of the seagrass community (including epiphytes), detritus, nutrients, (water column and sediment), and consumers. The response of these components to outside influence was evaluated according to the following: 1) system response under a standard model run environment, which is a run with all constants set to a pre-determined, documented level, 2) effects of systematic alteration of model constants, 3) response to natural perturbations such as thunderstorms and a hurricane and 4) changes in output from dredging events.

Model output from the standard run provides a baseline for comparison with each run of the sensitivity analysis. The sensitivity analysis (systematic alteration of constants) indicates those model constants responsible for the greatest change in the model output, i.e., those constants to which the model is most sensitive to change. This analysis can also point out specific model relationships requiring further work (Overton 1977). Model response to perturbations provides insite into the effects of elevated turbidity due to thunderstorms, hurricanes, and dredging perturbations. Finally, model output can be used to estimate recovery time of parameters of interest following perturbations.

Materials and Methods

The modeling procedure can be subdivided into eight component processes. These are: 1) development of an influence diagram, 2) construction of a model diagram with all appropriate equations, 3) production of a standard model run, 4) testing of model parameters through sensitivity analyses, 5) observation and interpretation of model response to perturbations, 6) field validation, 7) implementation in the real world, and 8) evaluation of the implementation while continuing to revise the model. Information contained in the present model analysis includes those processes through Step 5.

Influence Diagram

Closed cycles of influence between model components are shown in Figure 25. Arrows indicate cause and effect (i.e., influence): the influencing parameter is indicated at the tail of the arrow while the parameter that is influenced is shown at the arrow head. Positive and negative signs at each arrow head indicate the direction of influence, i.e., a positive sign indicates that as the influencing parameter changes, the affected parameter also changes in the same direction. Conversely, a negative sign indicates an influence in the opposite direction, for example, a decrease in one parameter will cause an increase in another. Positive and negative signs indicated within the small dashed arrow inside a loop show the overall sign of the particular loop of interest. Positive loops reinforce changes, negative loops oppose change and yield stability. Parameters shown outside the closed cycle of influence are those which affect loop components but are not a part of the closed loop system. These parameters are added as they contain perturbations and energy sources of interest as well as influencing parameters within the closed cycle.

Five loops are shown in the model closed cycle of influence. These loops vary in size and consist of influences between the following components. The loops are numbered to correspond with Figure 25: 1) water column nutrients-seagrass, 2) sediment nutrients-seagrass, 3) consumers-detritus, 4) sediment nutrients-consumers-detritus-seagrass, and

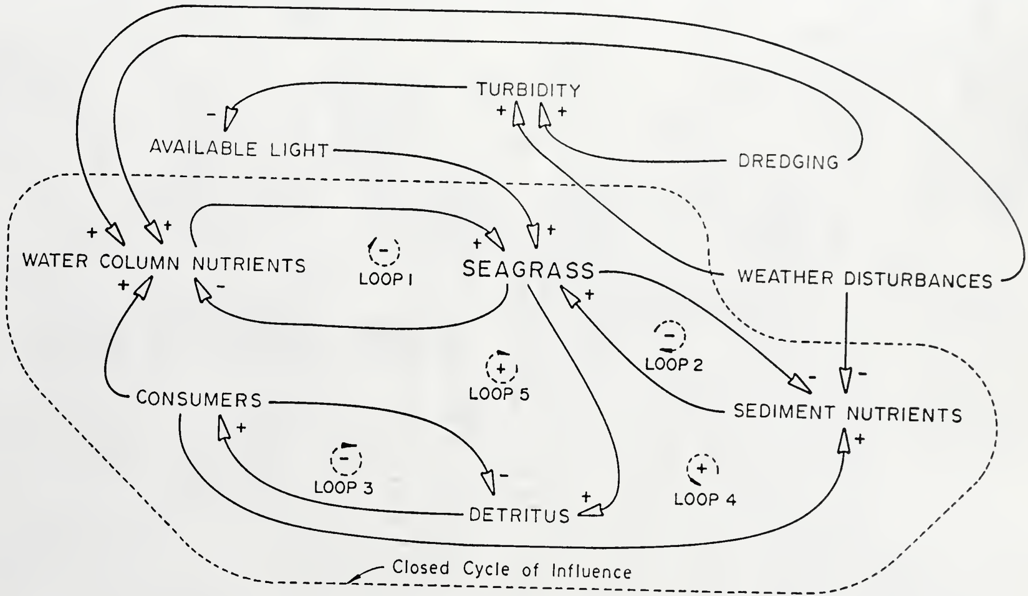


Figure 25. Seagrass community influence diagram.

5) seagrass-detritus-consumers-water column nutrients. Loop 1 shows a negative influence between seagrass and water column nutrients. As a seagrass community grows, the available water column nutrients decrease through uptake by the plants during photosynthesis (Patriquin 1972). In addition, the model also contains an equation structure that allows some leakage of nutrients back into the water column (McRoy and Barsdate 1970) either through passive plant release or active pumping. The same arrangement of nutrient uptake and release is also suggested for Loop 2. Loop 3 is a negative influence as the availability of detritus and consumers tends to keep the other in check. As the food source (detritus) increases, the consumer population also begins to grow due to the higher food availability. However, with growth of the consumer populations, demand for food increases and the food stocks are consumed. As food stocks dwindle, the growth rate of the consumers slows down. This relationship. as opposed to Loops 1 and 2, can cause oscillations in both populations which resemble the classical predator-prey oscillations shown by Lotka and Volterra (from Pianka 1978). Because this loop is short (two accumulations only) information delays between these components are minimal and response time is short.

Delays in Loop 4 are longer. Loop 4 is also positive, meaning the changes within the loop components tends to reinforce the original loop direction. Increases in sediment nutrients can increase seagrass biomass (Patriquin

1972; Penhale and Smith 1977) which causes more detritus to be formed due to the death of more seagrass. More food availability stimulates growth of the consumer population which causes more nutrients to be released into the sediments (Mann 1982).

Loop 5 is also a positive loop. This loop structure is very similar to Loop 4 with the substitution of water column nutrients for the sediment nutrient accumulation. Both Loops 4 and 5, because they contain more components, could show a longer response time to changes within the loop, especially if one of the components were limited as to its magnitude of response during a given cycle. External influences which are shown outside the closed cycles of influence consist of perturbations which affect nutrients and water clarity. Dredging influences water clarity by increasing turbidity as dredging intensity increases (McCarthy et al. 1974). With increasing turbidity, available light decreases which slows the growth of the seagrass community. Dredging also increases the water column nutrients due to resuspension of sediment nutrients from the dredge plume (Tramontano and Bohlen 1984). No increase in sediment nutrients from the dredging process was included because it was assumed nutrients released to the water column were removed rapidly, leaving only negligible amounts to settle out. Loss from the sediment nutrient pool during dredging was also not considered because only communities in close proximity to the dredge were evaluated. Weather disturbances such as thunderstorms affected a larger area and impacted both water column and sediment nutrients. During storm events, sediment nutrients were stirred up from the bottom into the water column, increasing the nutrient levels. Turbidity increases due to storm activities caused a reduction of available light.

Model Flow Diagram

The flow diagram for the model is presented in Figure 26. Material flows are represented by solid lines and information flows by dotted lines. Constants are indicated by the symbol ϕ, numbered, described, and referenced in Table 10. Auxiliaries, which represent convenient additional calculation steps, are shown as larger open circles. The rectangular boxes indicate levels or accumulations of material. Arrows going into and out of each box from left to right represent the inflow and outflow to the accumulation, respectively. "Valves" shown on each arrow represent controllers of rates of inflow and outflow; parameters which affect an accumulation impinge on a rate of inflow or outflow and are shown with dashed lines drawn to the rate controllers. In this manner, all feedback loops and influences, constants, auxiliaries, material flows, information flows, and interactions are indicated.

Model Rationale

The rationale for the model is explained on the basis of the relationship of each accumulation to its component parts. The units of all constants are shown in Table 10.

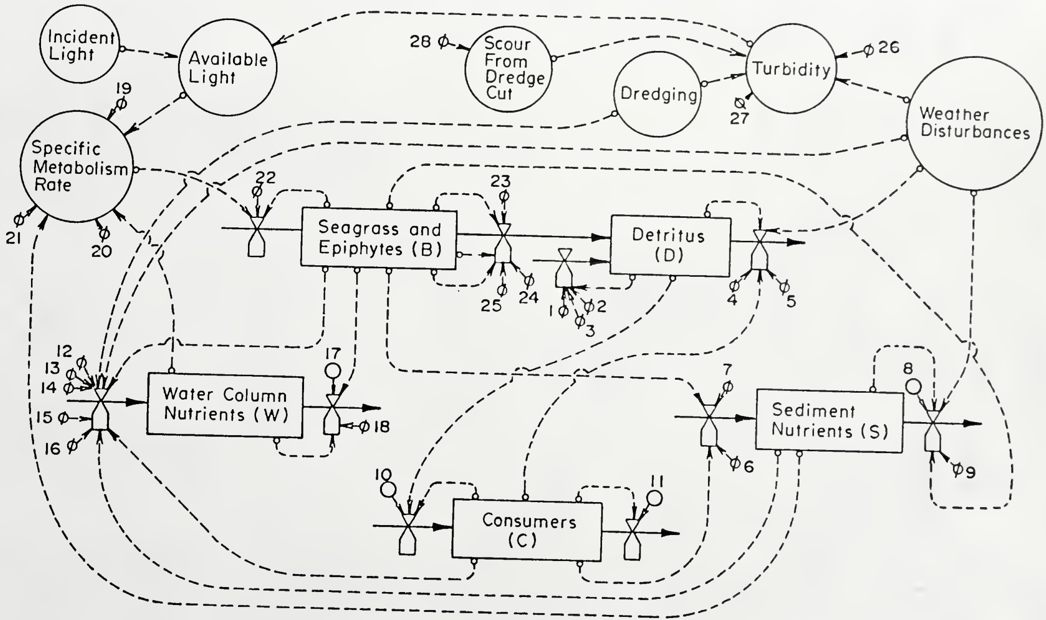


Figure 26. Model diagram of seagrass community. Symbols used are explained in the text. Descriptions of numbered constants are contained in Table 11.

Table 10. Model constant description, units, and documentation.

Constant	No.	Description	Units	Reference
NTULOSS = 00.2	19	Light lost per nephelometric turbidity unit (NTU)	%	Calculated from field data
INLIGHT = 6,000	19	Incident light	watts day^{-1}	Field measurement
NATLOSS = 40	19	Light lost due to natural scattering	%	Field Measurement
SETTLE = .5	27	Particle settling rate	settling $12hr^{-1}$	Field measurement
DRNTU = 17625600	27	Total amount of NTU'S released per dredging level (DL)	NTU DL^{-1}	Calculated from field data
TSNTU = 50	26	NTU'S released per thunderstorm level (TL)	NTU $TL^{-1}m^{-3}$	Field measurement
SRPMAX = 50	22	Maximum gross producton	$gO_2m^{-2}day^{-1}$	Field measurement
LTKS = 321	19	Half saturation for production as a function of light	$m^{-2}watt^{-1}$	Williams, S.L. and C.P. McRoy. 1982.
SEDKS = .1	21	Half saturation for production as a function of sediment nutrients	mmole $l^{-1}day^{-1}$	Estimated to allow production to be saturated at low nutrient levels
WKS = .1	20	Half saturation for production as a function of water column nutrients	mmole $l^{-1}day^{-1}$	Estimated to allow production to be saturated at low levels
LTBLK = 25	19	Light blockage due to clouds in thunderstorms	%	Field measurement
TSDETR = 50	2	Amount of detritus stirred up per thunderstorm	%	Estimated from field observation
SEAGRLOSS = .27	24	Loss (death) rate of seagrass equivalent to 100% per year	%	Calculated from Phillips, R.C. and and C.P. McRoy 1980.

Table 10--continued.

Constant	No.	Description	Units	Reference
RESP = 10	25	Seagrass respiration	$gO_2m^{-2}day^{-1}$	Field measurement
CONSKS = .001	5, 10	Half saturation value for detritus uptake by consumers	$mgl^{-1}consumer^{-1}$	Estimated to allow detritus to be to saturated at low detritus levels
CONSNUTR = .001	6	Sediment nutrients released by consumers	$mmolel^{-1}consumer^{-1}day^{-1}$	Calculated from Parsons et al. 1977.
SEAGRSEDNUTR = .01	7	Sediment nutrient lost from seagrass biomass	mmole g $biomass^{-1}day^{-1}$	Calculated from McRoy and Barsdate 1970.
TSSEAGR = .1	23	Loss of live seagrass due to thunderstorms	%	Estimated from field observation
SEAGRNUTR=.001	12	Nutrients leaked by seagrass biomass	mmole 1^{-1} g $biomass^{-1}$ day^{-1}	Calculated from McRoy and Barsdate 1970.
MCCONV=.001	14	Conversion factor for m^3 to m		
CONSNUTRREL = .0001	13	Water column mutrients released by consumers	mmole $1^{-1}consumer^{-1}day^{-1}$	Estimated from Parsons et al. 1977.
WCNUTRKS = .41	17	Half saturation constant of nutrient uptake by seagrass	mmole $1^{-1}day^{-1}$	Eppley, R.W. and W.H. Thomas. 1969.
AMBWCNUTR - .0001	16	Ambient water column nutrient level	mmole 1^{-1}	Field measurement
H2ODEPTH - 1.5	1	Average water depth over seagrass	m	Field measurement
CURRENT = 1.7	1,8	Standard current	cm/sec^{-1}	Field measurement

Table 10--continued.

Constant	No.	Description	Units	Reference
DPWIDTH = 100	1	Width of standard dredge plume	m	Field measurement
PLENGTH = 864	1	Length of dredge plume	m	Calculated from field data
DRNUTR = 22.032	14	Nutrients released by a dredging event	mmole l^{-1} $event^{-1}$	Calculated from field data
TSNUTR = 10	8, 15	Sediment nutrients lost due to thunderstorms	%	Estimate
BIOMAX = 1,000	22, 25	Maximum seagrass standing crop	g m^{-2}	Field measurement
WCMAX = 100	17	Maximum uptake of water column nutrients by seagrasses	mmole l^{-1} g $biomass^{-1}$ day^{-1}	Calculated from McRoy and Barsdate, 1970
DMAX = .01	5	Maximum uptake of detritus by consumers	g $consumer^{-1}$ day^{-1}	Estimate which allowed detritus uptake to be saturated at low levels.
SMAX = 324	9	Maximum uptake of sediment nutrients by seagrass	$mmole^{-}$l day^{-1}	Mann, K.H. 1982.
SKS = 50	9	Half saturation for seagrass sediment nutrient uptake	$mmole^{-}$l day^{-1}	Estimate which allowed uptake to be saturated at low levels of nutrients
CTORG = .465	22, 25	Conversion from carbon to organic matter	g	Phillips, R.C. and C.P. McRoy. 1980.
DETRITUS = 1.0	1	Detritus load in water	mg m^{-3} day^{-1}	Estimated from field observation

Table 10--continued.

Constant	No.	Description	Units	Reference
PQ = 1.3	22, 25	Oxygen to carbon photosynthetic quotient	——	Parsons et al. 1979.
GROWMAX = 1.0	10	Maximum consumer growth rate	consumer day^{-1}	Estimate based on doubling population each day.
CONSDIEINT = 1.0	11	Y-intercept for exponential death rate of consumers	——	Calculated
CONSLOPE = .05	11	Slope of consumer death rate curve	——	R.D. Spain, 1982
SCDEL = 450	28	Scour delay time	days	Calculated from field data
TSTORMS = 0	2,8, 15,19, 23,26	Intensity level of thunderstorm	——	Field observation
DREDGE = 0	14, 27	Intensity level of dredging	——	Calculated from field data

Accumulation units are included in the text description.

Seagrass Community Biomass Compartment

Accumulation of seagrass community biomass (g m^{-2} day^{-1}) in the modeled ecosystem was considered to be a function of several major inflows and outflows. Inflow includes the photosynthetic production of organic matter through the use of light and uptake of nutrients available from water column and sediments. These parameters were coupled by calculating an arithmetic mean of the contribution of the available nutrients to seagrass production (μmol l^{-1} day^{-1}) and then calculating the geometric mean of this value and the contribution to community production by light. In this fashion, if one factor was severely limiting, production became very low. Use of an arithmetic mean by itself would allow some production to occur even if one of the parameters was absent entirely, eliminating the concept of limiting nutrients. This combined estimate was then multiplied by a theoretical productivity maximum. This inflow represented an estimate of the maximum possible production given the existing level of available light and nutrients. The expression was then converted to standing stock biomass (g m^{-2}) by dividing by maximum standing stock (g m^{-2}), a photosynthetic quotient of oxygen: carbon (gO_2 gC^{-1}), and a carbon to organic matter conversion gC g^{-1} biomass). This resulted in a final value for the specific seagrass rate of biomass production (growth) in units of g biomass m^{-2} g standing $stock^{-1}$.

Outflow from this compartment was attributed to three components: loss of seagrass due to breakage by wind and waves during storms (g m^{-2} day^{-1}), routine die-off (g m^{-2} day^{-1}) and respiratory losses (gO_2 m^{-2} day^{-1}). Blade loss during storms was estimated to be 1% per event. Routine die-off (death rate) was equivalent to complete annual turnover. Maintenance loss was estimated from field measurements of oxygen change (gO_2 m^{-2} day^{-1}) (as described in Chapter II) and converted to standing stock biomass in the same manner as the inflow measurements.

Detritus

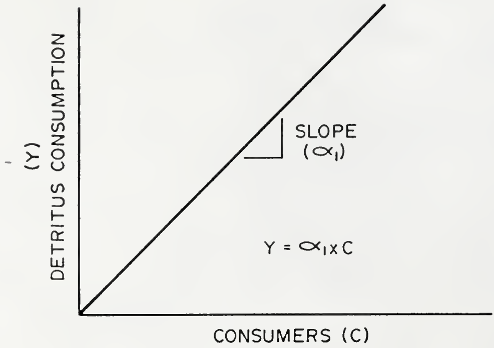
The detritus component (g m^{-2}) in the model represented the net accumulation resulting from three inflows and two outflows. The three input factors included imported detritus from nearby areas due to tidal currents (Ogden 1980), dead seagrass from routine die-off in the seagrass compartment, and detritus gained from stirring of the adjacent areas by thunderstorms with subsequent import by currents. This latter amount was estimated from field observations that the gain of detritus during a thunderstorm from an adjacent square meter of seagrass appeared to equal approximately 50 percent of the total in the adjacent area less 10% which settled out quickly. This thunderstorm mechanism also stirred up an equivalent amount of detritus from the modeled square meter. This resulted in simultaneous detritus import and export.

The major outflow from the detritus compartment was the amount of detritus consumed or decomposed by consumers (Klug 1980). This outflow was calculated as a linear function of the number of consumers present and their detritus consumption rate (g consumer^{-1}) as shown in Figure 27a. The slope of this curve (α_1) is not a constant; it is a variable which is a rectangular hyperbolic function of the amount of detritus present (Figure 27b). As the amount of detritus increases, consumption also increases but approaches a point of saturation where further addition of detritus causes little increase in consumption.

This association of a linear curve with a variable slope described by a hyperbolic function is a recurring relationship throughout this model. It will be redescribed in each pertinent section to delineate the specific relationships included in the model, but the rationale is the same. Use of this convention allows the limitation of the linear relationship by the saturation curve. In this manner, rates are not allowed to increase without limit. As the rate begins to increase, saturation is approached and the slope of the linear curve begins to get smaller, thus flattening the curve.

Consumers

The inflow and outflow to this compartment were characterized using one relationship for each case. Inflow, or growth of the population, was described as the growth of new consumers formed as a linear function of the number of



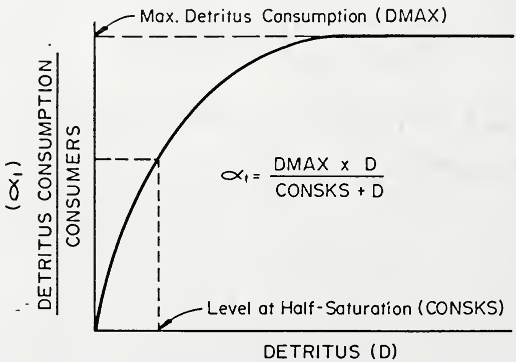


Figure 27. A description of the uptake of detritus by consumers. a) Linear relationship between the number of consumers and detritus consumption; b) Rectangular hyperbolic relationship between the amount of detritus consumed and the amount present.

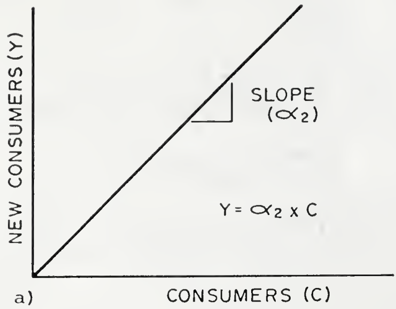
existing consumers in the population (Figure 28a). The slope of this line (α_2) which has the units of new consumers consumer^{-1} is the growth rate of the population. This growth rate was calculated as a rectangular hyperbolic function of the amount of detritus present (Figure 28b), the maximum consumer growth rate (1.0 consumer day^{-1}) and the maximum growth rate of consumers (0.5 consumer g detritus^{-1}). In this manner, consumers were allowed to grow only if they had food to consume within the defined constraints.

The outflow of consumers followed a linear relationship with the number of consumers present (Figure 29a). The slope of this curve (α_3) is the loss per consumer or the death rate. At very low food levels, the death rate is high. As food levels (detritus) increase, the death rate declines exponentially to a very low level (Figure 29b).

Sediment Nutrients

Inflow into this accumulation, which has the units of μmol l^{-1} was a function of nutrients released by infaunal consumers in the sediments (Parsons et al. 1977) and nutrients released by below-ground seagrass community (primary producer) components (McRoy and Barsdate 1970). Both functions were calculated from coefficients applied to the number of consumers and standing stocks of seagrass biomass, respectively.

Outflow from this compartment resulted from two factors: loss of nutrients from the sediment nutrient pool from thunderstorms stirring up the bottom and uptake of nutrients



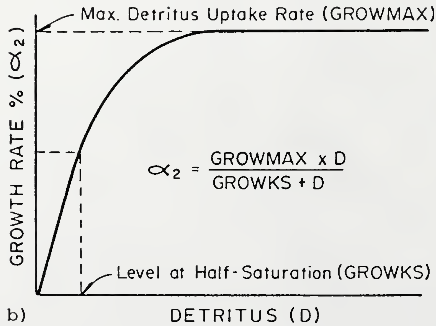
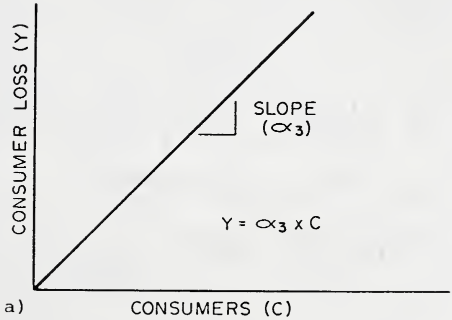


Figure 28. A description of the growth of consumers. a) Linear relationship between consumers and the number of new consumers produced; b) Rectangular hyperbolic relationship between the growth rate of consumers and the amount of detritus present.



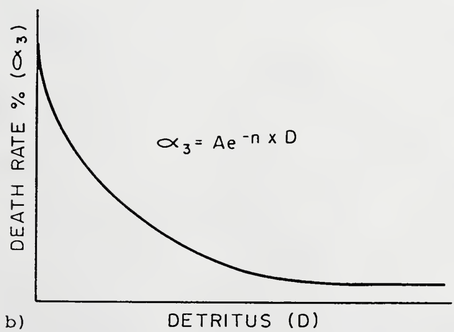


Figure 29. A descrintion of the consumer death rate. a) Linear relationship between consumers and the consumer death rate; b) exponential decay relationship between the consumer death rate and the amount of detritus present.

from the sediment by the primary producers (McRoy and Barsdate 1970). Loss of nutrients due to thunderstorms was estimated to be 10% of the amount present. Nutrient uptake by the seagrass community was calculated as a linear function of the standing stock of primary producer biomass (Figure 30a). The slope (nutrient uptake g biomass^{-1}) of this curve was determined as a rectangular hyperbolic relationship between the amount of sediment nutrients present at any time, a maximum possible rate of uptake (324 μmol l^{-1} day^{-1}), and a level of sediment nutrients of 50 μmol l^{-1} which gives half the maximum uptake rate (Figure 30b). This relationship allowed the primary producer community to grow only with adequate nutrients present while still reaching a saturation limit for growth if nutrients are available in excessive amounts.

Water Column Nutrients

Inflows comprising the water column nutrient accumulation (μmol l^{-1}) were a function of five relationships. These included release of nutrients by the seagrass community into the water column (McRoy and Barsdate 1970); release of nutrients or remineralization of nutrients by consumers; thunderstorms, which stir up the bottom, removing nutrients and suspending them in the water column; transport by water currents; and input into the water column nutrient pool from dredging operations which stir up both sediments and nutrients.

Outflow from the water column nutrient compartment

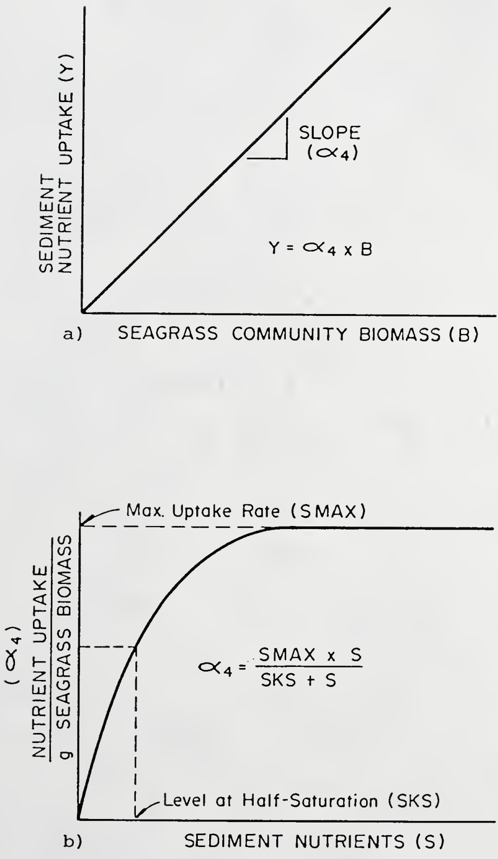


Figure 30. A description of the seagrass uptake of sediment nutrients. a) Linear relationship between the standing stocks of seagrass biomass and sediment nutrient uptake; b) Rectangular hyperbolic relationship between the sediment nutrient uptake by the seagrass and the amount of sediment nutrients present.

consisted of two parts: uptake by the seagrass community and nutrient outflow due to water currents. As in other compartments, nutrient uptake by the primary producer community was calculated as a linear function of the standing stock of the seagrass community biomass (Figure 31a). The slope of this curve (uptake g biomass^{-1}) was estimated using a rectangular hyperbolic relationship between the amount of nutrients present and the maximum uptake rate possible (Eppley and Thomas 1969) (Figure 31b). This relationship, as in the sediment nutrients, allowed nutrient uptake only if water column nutrients were present in sufficient quantity while constraining the upper limit of uptake by a maximum rate.

Nutrient outflow due to tidal currents was calculated as residence time of nutrients within the seagrass bed. As water passed over the seagrass community it bathed the community with the nutrients contained in the water. Availability of nutrients to be utilized by the seagrass was a function of the time the water spent over the bed. At the end of the tidal flushing period, these nutrients were no longer available for use in photosynthesis. However, other nutrients are imported during this period.

<u>Effect of Natural and Man-Made Perturbations</u>

Effects due to dredging were modeled in two parts. The first part consisted of a short-term, rapidly dissipating intensive pulse of turbidity resulting from the actual dredging and removal of sediments. The second phase was a

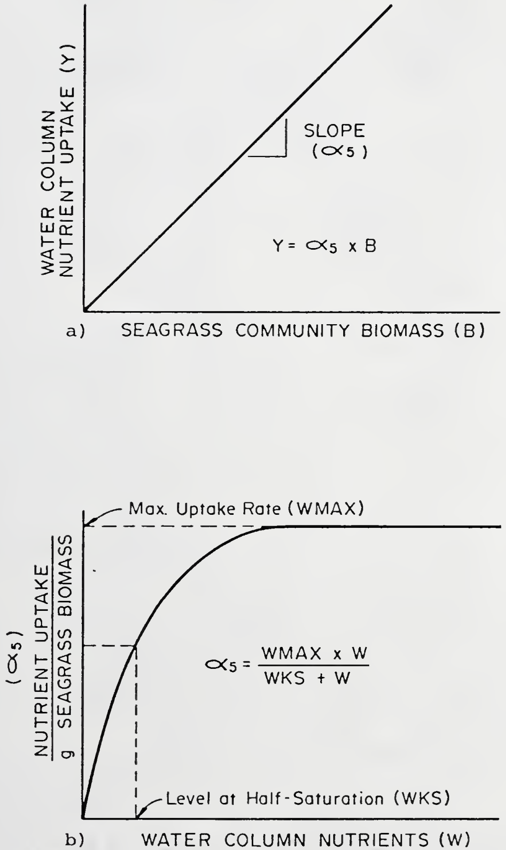


Figure 31. A description of the seagrass uptake of water column nutrients. a) Linear relationship between the standing stock of seagrass and the uptake of water column nutrients; b) Rectangular hyperbolic relationship between the water column nutrient uptake by the seagrass and the amount of water column nutrients present.

long-lasting, slowly decreasing low-level turbidity plume resulting from sediment scour in the dredge cut due to water currents. The total turbidity measured in the field was partitioned to allow for the short-term turbidity pulse to show a high initial level that was dissipated rapidly. Lower level turbidity from long-term dredge scour decayed as an exponential curve over a long period of time (450 days). The elevated turbidity caused a reduction in the available light reaching the primary producer community while also resulting in an increase in water column nutrients from sediment resuspension. Turbidity due to thunderstorms and hurricanes was calculated as a short-term high-level turbidity pulse only, with no long-term turbidity elevation. Both of these events reduced available light as a function of the intensity of the weather disturbance and increased turbidity only when the weather event was in progress. Additional effects from these perturbations included loss of nutrients from the sediments with concurrent addition to the water column nutrient pool.

Model Equations

The model equations were developed from the model diagram and are shown in Table 11. The equations describe the system as portrayed by the model diagram for an arbitrary time period of interest (daily, in this case) calculated at a frequency corresponding to the discretized time interval (DT). DT, which is a fraction of the daily time period analyzed during each calculation cycle (pass)

Table 11. Description and listing of model equations.

Equation	Description
DETREXPTS=TSTORMS*TSDETR	Detritus lost due to thunderstorms
DETRIMP=DETRITUS*NPLOTVOL	Detritus brought in by a standard current
DPLOTVOL=CURRENT*PLENGTH*DPWIDTH*H2ODEPTH	Water contained in dredge affected area
RESTIME=STDCURRENT/CURRENT	Residence time of water column nutrients
AVAILNTU=.25*((DREDGE*DRNTU*SETTLE)/DPLOTVOL)	Turbidity from scouring of dredge cut
NTUSTART=.5*((DREDGE*DRNTU*SETTLE)/DPLOTVOL)	Initial turbidity pulse which settles quickly
IF DREDGE > 0 AND SCOURFLAG=0 THEN SCOURFLAG=1: INSCOUR=AVAILNTU:QW	Checks to see if dredging has occurred, if it has, causes limited turbidity pulse to occur
IF SCOURFLAG=1 THEN QWIKSCOUR=QWIKSCOUR+DT*(QWIKSET/DT) -(QWIKSCOUR/ QWIKDEL): SCOUR=SCOUR+DT*(INSCOUR/DT) -(SCOUR/SCDEL)	Allows exponential decay of sediment scour from the dredge cut
TURBIDITY=((DREDGE*DRNTU*SETTLE)/DPLOTVOL+ TSTORMS*TSNTU+SCOUR	Determine turbidity level from dredging and thunderstorm activities
IF SCOURFLAG=1 THEN INSCOUR=0: QWIKSET=0	Allows initial scour value to be >0 for only 1 DT
AVAILLT=INLIGHT*((1-LTBLK$^{\text{TURBIDITY}}$) *(1-NATLOSS)	Calculates available light
SPRLT=((1.0*AVAILLT)/(LTKS+AVAILLT))	Light loss in the water column due to natural scatter and turbidity
SPRSENUTR=((1.0*S)/SEDKS+S))	Specific rate of production as a function of sediment nutrients
SPRWCNUTR=((1.0*W)/(WKS+W)	Specific rate of production as a function of water column nutrients
SRM=SWR(SPRLT*((SPRSEDNUTR+SPRWCNUTR)/2))* ((SRPMAX/BIOMAX/PQ)DTOORG)	Calculates specific rate of metabolism

Table 11--continued.

Equation	Description
SEAGRUP=(SCMAX*W)/(WCNUTRKS+W)	Seagrass nutrient uptake
DETRUP=(DMAX*D)/CONSK+D)	Detritus consumption by consumers
CONSGROW=(GROWMAX*D)/(CONSKS+D))	Consumer growth rate as a function of detritus
CONSDEATH=CONSDIEINT*(EXP(-CONSLOPE*D))	Consumer death rate
SEDUP=(SMAX*S)/(SKS+S)	Sediment uptake by seagrass
SGRIN=SRM*B	Seagrass inflow
SGROUT=(B*(TSTORMS*TSSEAGR))+(B*SEAGRLOSS)+ (B*(RESP/BIOMAX/PQ/CTOORG))	Seagrass outflow
DETRIN=DETRIMP+(B*SEAGRLOSS)+ (D*DETREXPTS*DETREXP)	Detritus inflow
DETROUT=(D*DETREXPTS)+(C*DETRUP)	Detritus outflow
CONSIN=C*CONSGROW	Consumer inflow
CONSOUT=C*CONSDEATH	Consumer outflow
SEDIN=(C*CONSNUTR)+(B*SEAGRSEDNUTR)	Sediment nutrient inflow
SEDOUT=(S*(TSTORMS*TSNUTR))+(B*SEDUP)	Sediment nutrient outflow
WATERIN=(B*SEAGRNUTR)+(C*CONSNUTRREL)+ (((DREDGE*DRNUTR)/DPLOTVOL*M3CONV) +(TSTORMS*TSNUTR*S)+AMBWCNUTR	Water column nutrient inflow
WATEROUT=(B*SEAGRUP)+(W/RESTIME)	Water column nutrient outflow
W=W+DT*(WATERIN-WATEROUT)	Water column nutrient accumulation
S=S+DT*(SEDIN-SEDOUT)	Sediment nutrient accumulation
C=C+DT*(CONSIN-CONSOUT)	Consumer nutrient accumulation
D=D+DT*(DETRIN-DETROUT)	Detritus nutrient accumulation
B=B+DT*(SGRIN-SGROUT)	Seagrass biomass accumulation

through the equation set, is an artifact of a digital model and represents the model's approach to a continuous simulation. An appropriate length of DT is determined through sensitivity analyses. DT must be short enough to allow the model to run accurately while being balanced against increasing computation time for a given length of simulated time as the DT length becomes shorter. In practice, DT was shortened until no significant change in the model output was noted. DT was tested by sequential halving to determine the optimal DT value. The value adopted was the highest value below which no appreciable change in the standard run occurred.

In sequential order, equations were calculated beginning with auxiliaries and supplementary equations. These are either precursors to other equations within the model (auxiliaries) or are output calculations of interest (supplementaries). Rate equations represented the inflow and outflow to each accumulation and were a composite of constants and auxiliaries calculated during each pass.

Finally, accumulations and any other information delays (e.g., the dissipation of turbidity after dredging) were calculated. Accumulations are based on the length of DT, addition of inflows and subtraction of outflows. Model constants were input at the beginning of the model and were changed manually when sensitivity analysis is performed.

As mentioned previously, Table 10 contains documentation and a brief description of the constants used in this model. As with most models, constant values are derived from a variety of sources ranging from calculations of field data to actual measurements, literature values, and estimates.

Sensitivity analysis of the model was initiated by production of a standard model run in which all constants are held at the values give in Table 10. This standard run was used as a baseline for comparison with other runs. Each model run simulated 50 days. In each separate run of the sensitivity analysis, one constant value was doubled and halved and the effect of each of the pair of changes on the accumulations of interest was compared to accumulation values in the standard model run. Each accumulation was set to its standard-run initial value prior to the start of each rerun. Variation from the standard model run was calculated as a percent positive or negative change.

The time of recovery from natural and man-made perturbations (thunderstorms, a hurricane, and dredging) on all accumulations in the model were compared with special emphasis on the seagrass community biomass. Recovery of this component was chosen as an indicator of the condition of the entire system since Ogden (1980) demonstrated that the health of the seagrass itself was the most critical factor in maintaining a viable seagrass ecosystem as it provided the substrate for the rest of the community.

The duration of the perturbations approximated the actual conditions encountered during the field study over a 3-month period (see Chapter II). Perturbations were run continuously at the beginning of the simulation. The thunderstorm duration which approximated a two hour daily storm for three months, resulted in an initial continuous seven-day run. Dredging, estimated to have occurred four hours per day for the three-month period, was run for fifteen continuous days. Hurricane-related thunderstorms were also simulated by a fifteen day continuous run at an intensity equal to and twice the level of intensity of the thunderstorms as well as twice the duration. The model was run until the level of seagrass biomass was approximately equal to the initial value. Time to recovery was determined from the model output.

Results

Output from the standard run of the model is shown in Figure 32. All variables are scaled individually as indicated across the top horizontal axis. The vertical axis represents time in days. The difference between the initial and ending value is expressed as a percent change on the bottom horizontal axis. The table at the bottom of the figure shows initial values for each accumulation.

All standard run values showed a slight positive increase over the 50-day run period, although the detritus and sediment nutrients do not show this graphically due to the scaling factor selected. Sensitivity analysis results were adjusted by subtracting these positive changes inherent in the standard run.

Examination of DT values ranging from 0.25 to 2.0 in

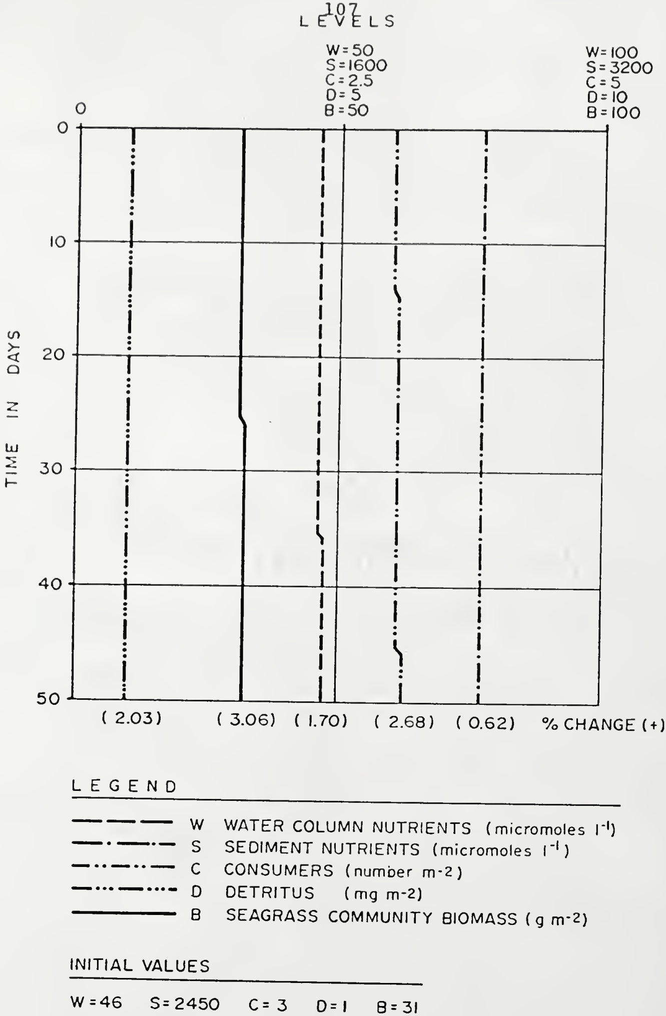


Figure 32. Output from the standard run of the model.

0.25 step intervals indicated that a DT of 0.5 was most appropriate. No change in standard run output was indicated below DT = 0.5 except in two constants in the sensitivity analysis (WCMAX and SEAGRNUTR). These were run at DT = 0.1 in the sensitivity analysis only.

Table 12 contains the results of the sensitivity analysis which is a listing of those constants causing a greater than 50-percent change in any accumulation when the constant was halved or doubled. Accumulation values arising from changes in these constants ranged from 50- to greater than a 500-percent change.

SEAGRSEDNUTR and SEAGRNUTR represent the amount of nutrients released to the sediment and water column nutrient pool, respectively, by seagrasses. Doubling of these constants resulted in a 500-percent increase in the nutrient pools and no effect on seagrasses. The next grouping of effects included those from halving SEAGRNUTR, the amount of water column nutrients released by seagrasses, halving SMAX, which represents the maximum sediment nutrient uptake rate by seagrass, and halving WCMAX, which represents the maximum uptake rate of water column nutrients by seagrasses. These constants, at half their standard run value, caused a 250- to 500-percent change in the model run. SEAGRNUTR caused a decline in water column nutrients while the other two constants (SMAX and WCMAX) caused an increase in sediment and water column nutrients, respectively. No effects on the seagrass community were noted.

SRPMAX, RESP, and CONSKS comprised the next lower

Table 12. Results of sensitivity analysis showing only those constants causing greater than a 50 percent change in any accumulation.

Constant Changed and Direction of Change	Description	Altered Accumulation	Percent Change at Indicated Intervals 50-100 +	50-100 -	100-250 +	250-500 +	>500 +
SEAGRSEDNUTR = 2X	Sediment nutrients lost by seagrass biomass	Sediment Nutrients					X
SEAGRNUTR = 2X	Nutrients lost by seagrass biomass	Water Column Nutrients					X
SRPMAX = 2X	Maximum gross production	Seagrass					X
SMAX = .5X	Maximum uptake of sediment nutrients by seagrass	Sediment Nutrients				X	
WCMAX = .5X	Maximum uptake of water column nutrients by seagrasses	Water Column Nutrients				X	
SRPMAX = .5X	Maximum gross production	Water Column Nutrients			X		
RESP = .5X	Seagrass respiration	Seagrass			X		
CONSKS = 2X	Half saturation value for detritus Uptake by consumers	Detritus			X		
DMAX = .5X	Maximum uptake of detritus by consumers	Detritus	X				
WCMAX = 2X	Maximum uptake of water column nutrients by seagrasses.	Water Column Nutrients					
SEAGRNUTR = .5X	Nutrients lost by seagrass biomass	Water Column Nutrients					
SEAGRSEDNUTR = .5X	Sediment nutrients lost by seagrass biomass	Sediment Nutrients		X			
SMAX = 2X	Maximum uptake of sediment nutrients by seagrass	Sediment Nutrients		X			
SRPMAX = 2X	Maximum gross production	Detritus	X				
RESP = 2X	Seagrass respiration	Seagrass	X				
DETRITUS = 2X	Detritus in water	Detritus	X				
RESP = 2X	Seagrass respiration	Water Column Nutrients		X			
SRPMAX = .5X	Maximum gross production	Seagrass		X			
RESP = 5X	Seagrass respiration	Water Column Nutrients	X				
CONSKS = .5X	Half saturation value for detritus uptake by consumers	Detritus		X			

.5X = constant halved
2X = constant doubled

group, all causing a positive change in the model run in the 100- to 250-percent range. At half of its model run value, SRPMAX, which is the maximum specific rate of seagrass production, caused an increase in water column nutrients. RESP, which is the maintenance loss of the seagrass community, caused an increase in seagrass biomass at half its standard run value while CONSKS, which is the half saturation value for detritus uptake by consumers, caused an increase in the level of detritus in the seagrass system.

Remaining constants in this table show a 50- to 100-percent change in all parameters except consumers. All of the constants that showed a low level effect on a particular accumulation also showed large effects on other accumulations. This indicates the nonlinear sensitivity of the model to changes in these constants.

Figures 33 through 36 show the model output for the perturbations of thunderstorms, two intensity levels of hurricanes and a dredging event. The time to recovery of the seagrass biomass in days and years from each of these perturbations is summarized in Table 13. Thunderstorm effects showed the shortest time to recovery (approximately 1 year). The seagrass biomass, water column nutrient, consumers, and detritus levels dropped initially and then began to increase slowly. Sediment nutrients showed a drastic initial decrease followed by a rapid increase and a levelling off at or near its initial level. A hurricane of similar intensity to the thunderstorm but twice the duration

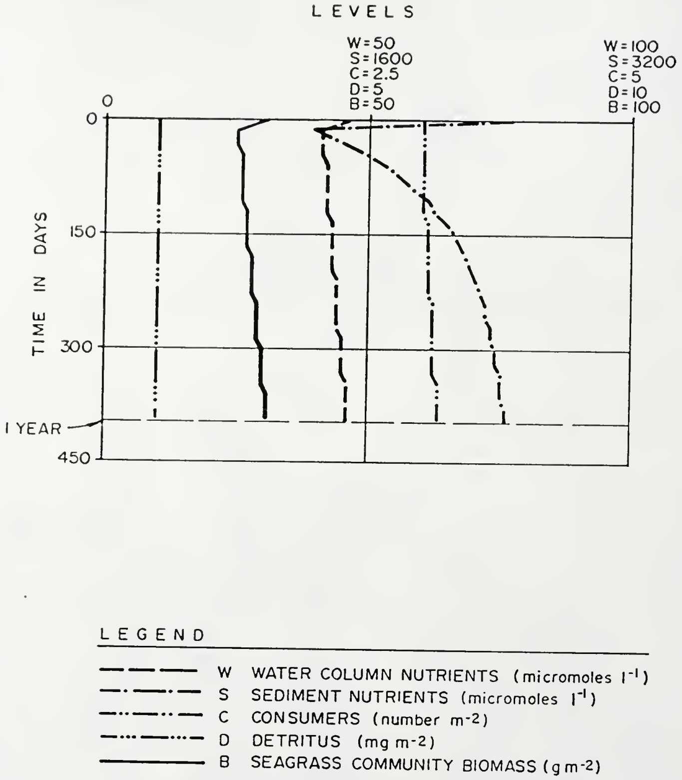


Figure 33. Model response and recovery period following a perturbation by normally-encountered thunderstorms.

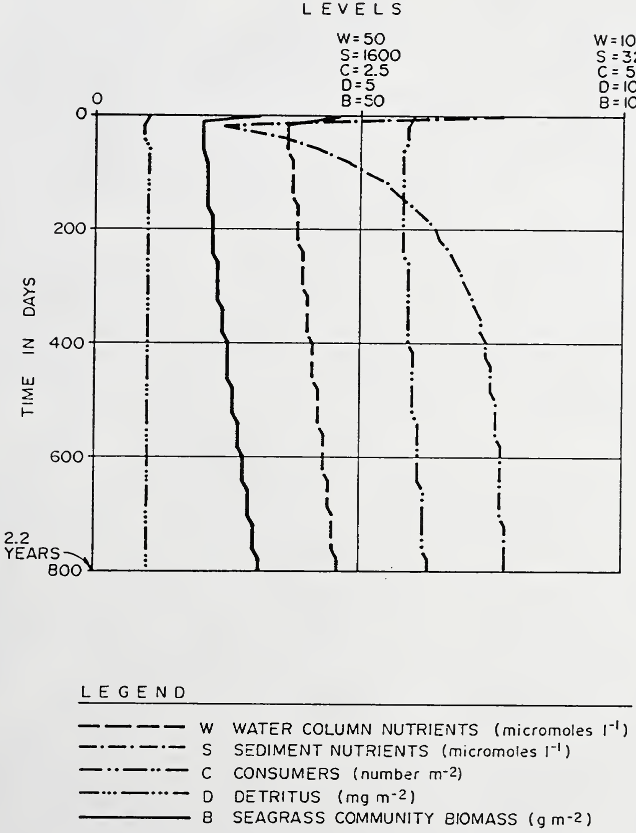


Figure 34. Model response and recovery period following a perturbation by hurricane-related thunderstorms at the same intensity but twice the duration of normally-encountered thunderstorms.

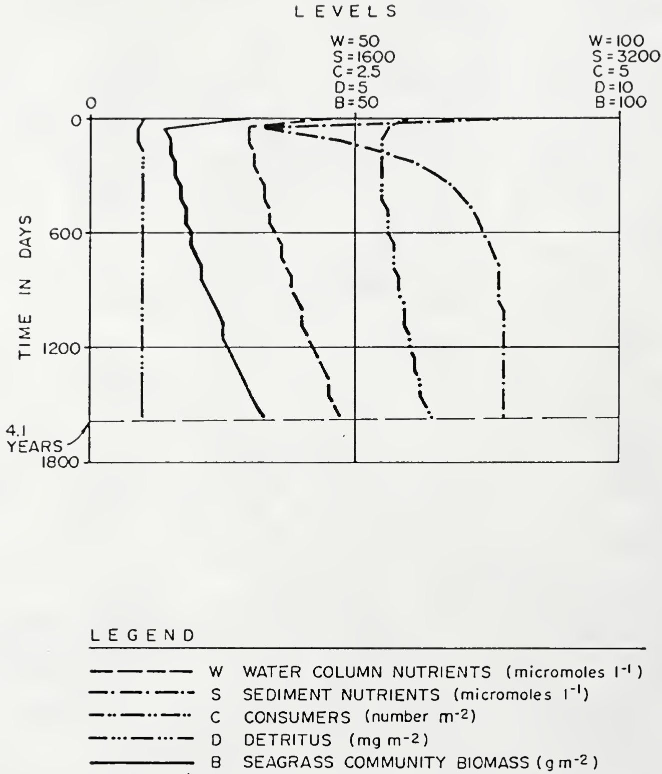


Figure 35. Model response and recovery period following a perturbation by hurricane-related thunderstorms at twice the intensity and duration of normally-encountered thunderstorms.

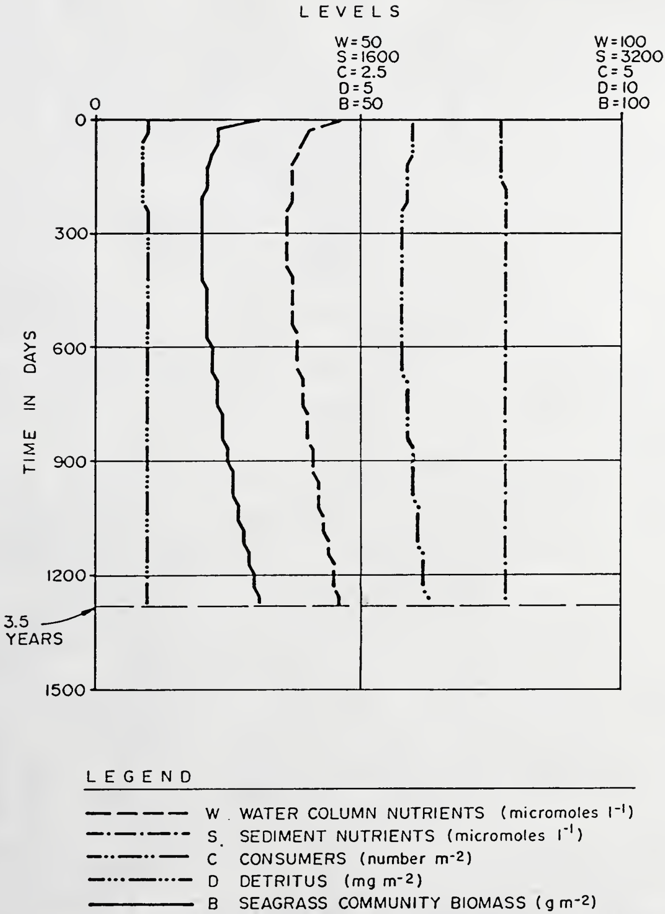


Figure 36. Model response and recovery period following a perturbation by dredging events.

Table 13. Comparison of long-term recovery times of seagrass community biomass from natural and man-made perturbations.

Perturbation	Time to Recovery	
	Days	Years (approx.)
Thunderstorms	360	1
Hurricane	800	2.2
Dredging	1260	3.5
Hurricane (2 X intensity)	1500	4.1

showed a recovery time of seagrass biomass over twice as long (2.2 years). Response of the accumulations under this scenario showed trends similar to the thunderstorm simulation.

Following the dredging event, recovery of the biomass component required approximately 3.5 years. With the exception of sediment nutrients, all accumulations in the system showed an initial sharp decrease with a gradual increase over time. Sediment nutrients showed no apparent response to the dredging operation.

The hurricane simulation, at twice its former intensity, required the longest recovery period of over four years to return to initial seagrass conditions. Accumulations during this simulation showed responses similar to the other weather disturbances.

Discussion

The most interesting results of this modeling effort lie in the analysis and interpretation of specific parameters causing the most change in model output, the time to recovery following a particular perturbation, a comparison of these recovery times between natural and man-made events, and recommendations for areas requiring further work.

The five parameters most sensitive to change as indicated by their influence on model accumulations involved those constants relating to seagrass influence on water column and sediment nutrient pools. The constants in question all pertain to either uptake or release of nutrients in the sediments and water column by the seagrasses.

Doubling of both the amount of nutrients released to the sediments and water column per gram biomass of seagrass caused large increases in the levels of these nutrients. This was a result of more nutrients being released by the same amount of biomass, thereby increasing the level of nutrients in each pool. Reducing both constants by half produced a decrease proportional to doubling this constant but in the opposite direction. Lower nutrient levels is a result of lowered release rates by the seagrass.

Alteration of the maximum sediment nutrient uptake rate by seagrass showed a similar trend, but in the opposite direction. Halving this constant caused an increase in the sediment nutrient pool. Doubling this value resulted in an approximately proportional decrease. Increasing this constant allowed the seagrass nutrient uptake to saturate at a higher level. This pulled the nutrient pool down since more nutrients were required before the rate reaches steady-state. Conversely, lowering this uptake rate caused seagrass uptake to saturate at lower nutrient levels. This allowed nutrient levels to increase since no additional increase in uptake was possible once saturation was reached.

Doubling of the maximum specific rate of seagrass biomass production affected both the seagrass itself and detritus. Seagrass biomass increased significantly for obvious reasons; doubling this constant allowed the seagrass to grow at a faster rate. The detritus accumulation increased due to increases in the seagrass population which leads to dead and dying biomass material contributing a larger quantity to the detritus component. Reduction of the maximum production rate by 50 percent resulted in a change in the seagrass and water column nutrient components. Seagrass biomass decreased because the maximum rate of production possible was lowered. Water column nutrients increased when SRPMAX was halved because the seagrass standing stock decreased which lowered the requirement for water column nutrients.

The respiratory loss term was also a sensitive measurement in relation to seagrass biomass standing stocks. Changes in this constant produced significant alteration in the model simulations of the seagrass biomass accumulation. Reduction and increase of the respiration component also caused a decrease and increase, respectively, in water column nutrients. This was due to corresponding decreases or increases in seagrass biomass, which deleted from or added to the nutrient pool depending on the biomass trends.

Doubling of the half-saturation constant for uptake of detritus by consumers resulted in a substantial increase in detritus levels. This was caused by the consumer uptake rate being saturated (reaching the maximum uptake rate) only at higher levels. This allowed a greater level of detritus to accumulate in the system. Conversely, halving of this constant caused a loss of detritus from the system as compared to the standard run. In this case, saturation of the system occurred at a lower level of detritus, causing more detritus to be consumed. Doubling the background level of detritus in the water caused an increase in detritus levels in the system. This results from the large volume of water passing through the seagrass system each day carrying with it a larger detritus load.

Response of this model to natural and man-made perturbations produced interesting results. Time of recovery of the seagrass component proved to be largely a function of the intensity and duration of the perturbation. This was caused by reduction in the light available to the community, either through a combination of elevated turbidity and light blockage by clouds as in the case of the weather disturbances or entirely through elevated turbidity from dredging. Since the seagrass was slowly but continuously growing, the level to which biomass was depressed as well as the duration of the event at this level, the longer the period required to recover. This is consistent with Zieman's (1976) findings that regrowth of seagrass following extensive damage by boat propellers was a slow process requiring more than five years in some cases. Other parameters which showed a decline included water column nutrients, detritus, and consumer levels. Sediment nutrient levels were depressed only by natural events due to physical disturbance of the bottom sediments. These returned quickly to pre-dredging levels primarily because under normal conditions they are the more abundant nutrient and are not subject to daily wash-out by currents as are the water column nutrients. Dredging events had no effect on sediment nutrients because the area being dredged was not considered; only the nearby communities under the influence of the plume were simulated.

Dredging effects related to elevated turbidity involved two effects: 1) a short-term intensive turbidity pulse, and 2) long-term, lower level turbidity resulting from current scour of the dredge cut. Although the major turbidity pulse arises from the original dredging effort, residual turbidity from the dredge cut delays the recovery process. Even though this declines exponentially, turbidity due to scour remains elevated over the former background levels for several months, adding additional time to recovery of the seagrass. In high current areas similar to the one under study, this current scour prior to revegetation is substantial (Fonseca 1983) and should be considered when evaluating turbidity effects due to dredging in areas of moderate to high currents. On the other hand, this same high current tended to disperse the initial plume much more rapidly than would be expected under low current conditions. This effectively reduced short-term effects of an intensive plume while extending the period of any long-term effects.

For the most part, the model demonstrated the over-all sensitivity of the system to those changes which directly or indirectly influence the seagrass compartment. The model system was in a delicate equilibrium, with changes in parameters causing drastic alteration of some levels. The system also appeared resilient in its response to outside influences. In no case were components lost completely as a result of perturbation. Although depressed, all accumulations recovered in time. The recovery of the system from thunderstorms appeared to be excessively long, however the intensity of the thunderstorms perhaps was overestimated.

The recovery time of the seagrass community was a direct function of numerous parameters used in the model to describe seagrass accumulation. These parameters, especially the maximum production rate and the respiration rate related directly to the growth rate of the seagrass community. Slight alterations in these values as shown by the sensitivity analysis can alter the recovery time. Until more is known about these relationships, the recovery time should be viewed as a relative comparison of the projected times among all events, rather than focusing on the absolute value of each event.

Because of the sensitivity demonstrated by the model in the areas of nutrient relationships, light and production interactions and the absence of available data, additional work is needed to clarify these relationships. Patriquin (1972), Capone et al. (1979), Capone (1982), and Carignan and Kalff (1982) have all investigated seagrass nutrient dynamics and generally support the idea that in most systems the bacterial fixation of nitrogen in the rhizome layer is a major nitrogen source. The amount of fixation appears highly variable and has not been determined to be uniform for all seagrass communities. Nutrient sources and sinks are important to establish in order to predict better the effects of dynamically changing nutrient regimes on seagrass production.

Bittaker and Iverson (1976) and Phillips and McRoy (1980) have compared several methods of production measurement including oxygen metabolism, carbon-14, and standing stock/biomass methods and have found problems associated with each. Production measurements that quantify accurately the seagrass community growth are essential to prediction of recovery times following a perturbation. The author's experience with production measurements utilizing oxygen metabolism techniques indicates that although response of the system to changes in the physical environment is extremely rapid, the direct relationship between oxygen production and actual standing stocks of biomass is not clear. Related to this is the requirement for precise analysis of light and production relationships on a frequency high enough to correlate changes in light with metabolic response. Although many of the constant values were derived from actual field measurements, the field studies as described in Chapter II were not designed to examine this relationship in minute detail.

Development of detailed relationships between perturbation types, sediment characteristics and current regimes should produce better prediction of the magnitude of turbidity expected from each event as well as predicted durations. Finally, consideration should be given to automating the data collection as much as possible. A dynamic, highly changeable system such as the seagrass community under study requires measurement of a number of simultaneous parameters on a frequency greater than or at least equal to changes in the natural parameters of interest. A combination of automated sensing devices coupled with frequent operator monitoring would provide much needed short- and long-term response data which defines the overall reaction of the system to outside influences and which can be used to provide more accurate input into the simulation model.

Summary

1. Nutrient-seagrass relationships, production of the seagrass, and seagrass-light interactions were indicated as the most sensitive model parameters.
2. Recovery time of the seagrass community biomass for dredging events compared favorably (3.5 years) to that predicted from a hurricane of the same duration and at twice the simulated thunderstorm intensity (4.1 years). Long-term thunderstorm effects on seagrass community biomass were shown to be of a much shorter duration of approximately one year. A hurricane at the same intensity as the thunderstorms but twice the duration was shown to require 2.2 years for recovery of the seagrass community to pre-perturbation levels.
3. Hurricane and thunderstorm effects resulted from intensive turbidity pulses and light blockage due to clouds during the event. Dredging related effects also

contained this short-term intensive pulse but with the added effect of long-term low level turbidity resulting from current scour from the dredge.

CHAPTER V
SUMMARY OF FINDINGS

The objective of this chapter is to provide an overview of the findings of the study which are detailed in the previous three chapters.

During actual dredging operations, reduction in seagrass community metabolism appeared to be a result primarily of shading effects of the plume due to light blockage caused by elevated turbidity in the water column. In comparison to the level of response to naturally occurring weather events, the effect of dredging ranked in the approximate middle of the list of perturbations the community experienced. This was largely a function of the duration, timing, and intensity of the individual events. Comparison of pre- and post-dredging productivity in communities separated approximately 2 years in time showed diminished photosynthetic efficiency (approximately 4 times lower) in the post-dredging communities. The reasons for this were unclear. Observations in the field at the time indicated that the seagrass community appeared less healthy than observed in the pre-dredging field observations. This observation stemmed from the qualitative estimate that more dead and dying blades appeared to be present in the post-dredging population. Further speculation implicated a reduced epiphyte population as a possible cause of the reduced photosynthesis which may or may not be caused by dredging.

Field experimentation designed to separate two major effects of a dredge plume (shading and nutrient addition) indicated that shading was the most critical factor affecting seagrass community metabolism. Some enhancement of community production was shown by the addition of nutrients although this was not statistically significant. It appeared that the type of nutrient added was not critical; responses were shown to all three nutrients utilized in this experiment. An interaction between the concentration of nutrients and shading was found. In the light the three highest nutrient concentrations showed a significant production increase. No significant difference was noted at the lowest concentration level.

The model indicated those factors which affect the seagrass component such as nutrient uptake and release and seagrass production and respiration rates were most critical in determining output behavior from the model system. Perturbation analysis of the system showed an approximate 1-year recovery period from normally encountered thunderstorms as compared to 3½-years required to recover from a dredging event and approximately a 4-year recovery time from a hurricane occurrence. The seagrass growth estimates and nutrient dynamics involved in this growth were areas in the model requiring further experimentation.

Recommendations for mitigation of environmental and cost impacts associated with dredging in communities similar to the ones under study include the following:

- o Minimize dredging effects by ensuring that the process is intermittent. Since duration and timing are two of the three critical factors involved with the degree of impact it is critical that dredging not be continuous.
- o Eliminate the use of silt curtains in high current areas such as the area investigated in this study. Little effectiveness was noted resulting from the use of silt curtains under these conditions.

The major issue, perhaps, is the determination of the need for the project requiring dredging given that a major impact will have a deleterious effect on these systems. Although the dredging effects were not excessive when compared to the naturally occurring factors to which the system is normally subjected, a reduction in photosynthetic efficiency was measured. This implies a decreased growth rate of the community. If this indeed is an effect of dredging as believed, consideration should be given to this potentially major impact as well as its effect on other ecosystems such as coral reefs which exchange organic material with the seagrass community. Results of the model indicate that longer than 3 years would be required to recover from the dredging event. This would suggest that the post-dredging measurements reported in Chapter II were gathered prior to recovery of the system. Valuable information could be gathered by measuring the system productivity at the present time, 5 years from the original dredging event. All of these factors point to the requirement for careful consideration of activities which cause alterations in water clarity in order to evaluate and prevent major impacts as a result of these activities.

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BIOGRAPHICAL SKETCH

John William Caldwell was raised on his family's farm in southeast Iowa. He attended Morning Sun Community High School, where he was active in football, wrestling, and the drama club. He graduated in 1966.

He received his undergraduate training in biology at Northeast Missouri State University in Kirksville, earning the Bachelor of Science degree (with Honors) in 1970. During his senior year he was president of Tau Kappa Epsilon fraternity, vice president of the student review board, and was elected to Blue Key. His graduate training began at the University of Florida in 1970 and resulted in the Master of Science degree in zoology in 1972. In the period following until 1984, he was an Assistant in Marine Biology at the University of Florida where he participated in numerous environmental research projects primarily as co-principal investigator and project manager.

He joined CH2M HILL Consulting Engineers in 1984 where he works presently as an environmental scientist with project management responsibilities in the areas of marine environmental studies, freshwater wetland evaluations, and hazardous waste investigations.

He is married to the former Jo Goldman. They have one son, John Edward.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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