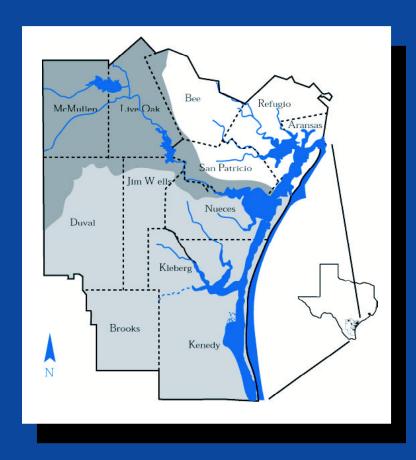
Current Status and Historical Trends of Brown Tide and Red Tide Phytoplankton Blooms in the Corpus Christi Bay National Estuary Program Study Area



Corpus Christi Bay National Estuary Program CCBNEP-07 • January 1996



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# Current Status and Historical Trends of Brown Tide and Red Tide Phytoplankton Blooms in the Corpus Christi Bay National Estuary Program Study Area

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#### CORPUS CHRISTI BAY NATIONAL ESTUARY PROGRAM

The Corpus Christi Bay National Estuary Program (CCBNEP) is a four-year, community based effort to identify the problems facing the bays and estuaries of the Coastal Bend, and to develop a long-range, Comprehensive Conservation and Management Plan. The Program's fundamental purpose is to protect, restore, or enhance the quality of water, sediments, and living resources found within the 600 square mile estuarine portion of the study area.

The Coastal Bend bay system is one of 28 estuaries that have been designated as an **Estuary of National Significance** under a program established by the United States Congress through the Water Quality Act of 1987. This bay system was so designated in 1992 because of its benefits to Texas and the nation. For example:

- Corpus Christi Bay is the gateway to the nation's sixth largest port, and home to the third largest refinery and petrochemical complex. The Port generates over \$1 billion of revenue for related businesses, more than \$60 million in state and local taxes, and more than 31,000 jobs for Coastal Bend residents.
- The bays and estuaries are famous for their recreational and commercial fisheries production. A study by Texas Agricultural Experiment Station in 1987 found that these industries, along with other recreational activities, contributed nearly \$760 million to the local economy, with a statewide impact of \$1.3 billion, that year.
- Of the approximately 100 estuaries around the nation, the Coastal Bend ranks fourth in agricultural acreage. Row crops -- cotton, sorghum, and corn -- and livestock generated \$480 million in 1994 with a statewide economic impact of \$1.6 billion.
- There are over 2600 documented species of plants and animals in the Coastal Bend, including several species that are classified as endangered or threatened. Over 400 bird species live in or pass through the region every year, making the Coastal Bend one of the premier bird watching spots in the world.

The CCBNEP is gathering new and historical data to understand environmental status and trends in the bay ecosystem, determine sources of pollution, causes of habitat declines and risks to human health, and to identify specific management actions to be implemented over the course of several years. The 'priority issues' under investigation include:

- altered freshwater inflow
- declines in living resources
- loss of wetlands and other habitats
- bay debris

- degradation of water quality
- altered estuarine circulation
- selected public health issues

The **COASTAL BEND BAYS PLAN** that will result from these efforts will be the beginning of a well-coordinated and goal-directed future for this regional resource.

#### STUDY AREA DESCRIPTION

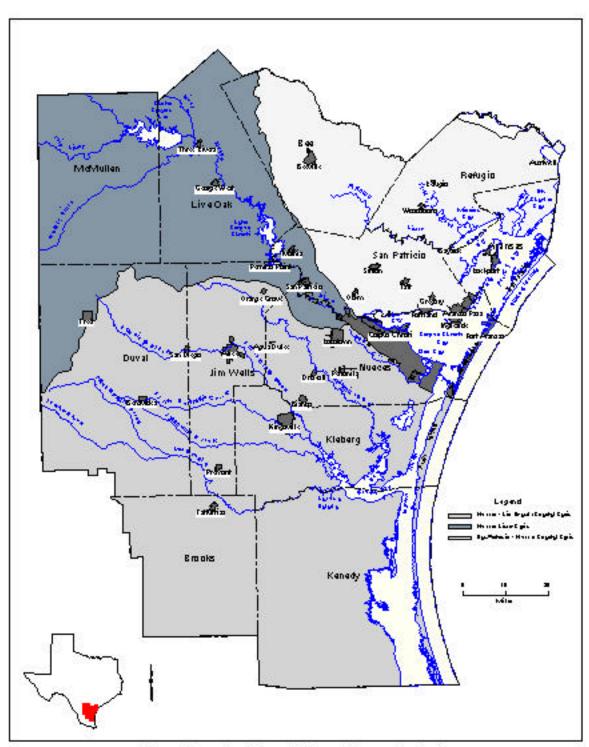
The CCBNEP study area includes three of the seven major estuary systems of the Texas Gulf Coast. These estuaries, the Aransas, Corpus Christi, and Upper Laguna Madre are shallow and biologically productive. Although connected, the estuaries are biogeographically distinct and increase in salinity from north to south. The Laguna Madre is unusual in being only one of three hypersaline lagoon systems in the world. The study area is bounded on its eastern edge by a series of barrier islands, including the world's longest -- Padre Island.

Recognizing that successful management of coastal waters requires an ecosystems approach and careful consideration of all sources of pollutants, the CCBNEP study area includes the 12 counties of the Coastal Bend: Refugio, Aransas, Nueces, San Patricio, Kleberg, Kenedy, Bee, Live Oak, McMullen, Duval, Jim Wells, and Brooks.

This region is part of the Gulf Coast and South Texas Plain, which are characterized by gently sloping plains. Soils are generally clay to sandy loams. There are three major rivers (Aransas, Mission, and Nueces), few natural lakes, and two reservoirs (Lake Corpus Christi and Choke Canyon Reservoir) in the region. The natural vegetation is a mixture of coastal prairie and mesquite chaparral savanna. Land use is largely devoted to rangeland (61%), with cropland and pastureland (27%) and other mixed uses (12%).

The region is semi-arid with a subtropical climate (average annual rainfall varies from 25 to 38 inches, and is highly variable from year to year). Summers are hot and humid, while winters are generally mild with occasional freezes. Hurricanes and tropical storms periodically affect the region.

On the following page is a regional map showing the three bay systems that comprise the CCBNEP study area.



Corpus Christi Bay National Estuary Program Study Area

#### **Preface**

The following report has been an attempt to bring together all available information on harmful algal blooms, commonly referred to as brown and red tides, in the Corpus Christi Bay National Estuary Program (CCBNEP) area. Since the number of published studies on this subject is very small, especially if only studies from within the CCBNEP area are included, unpublished data and data from non-peer reviewed technical reports are also presented. This is especially true in the case of the brown tide report, since many studies are still ongoing and much essential data has not yet been written up for publication. Unpublished data is clearly identified as such, and cited as a personal communication from the scientist providing the data. I want to thank the many scientists who shared unpublished data with us for this report. Many scientists are reluctant to share unpublished data, but few conclusions could have been drawn on the brown tide based on the paucity of published data. I have attempted to check with those providing data to ensure that I have interpreted them correctly, but any errors in interpretation in this report are only my own.

The organization of the red tide report is different from that of the brown tide report, since there were relatively few published reports or unpublished data from the CCBNEP study area because of the rarity of these events. In addition to presenting information available on blooms in this area, relevant generalities are presented based on the more frequent occurrences of these blooms in other locations, especially the west coast of Florida.

Dr. Edward J. Buskey Project Leader November 28, 1995 Port Aransas, Texas

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## **Executive Summary**

Harmful algal blooms appear to be increasingly common phenomena on a worldwide scale. These blooms can be considered "harmful" either because of their potential threat to human health through the consumption of contaminated seafood, as in the case of many toxic phytoplankton blooms, or through the changes in species abundances and distributions (often including species of commercial value), as in the case of recent "brown tide" blooms. In the Corpus Christi Bay National Estuary Program area, harmful algal blooms have been relatively rare; there appear to have been fewer than a dozen documented red tide blooms over the entire Texas coast and only one documented (although extremely persistent) brown tide bloom. This may be due in part to blooms going undocumented, especially in the years prior to World War Two when the cause and effect relationship between toxic dinoflagellate blooms and fish and other marine life kills had not been established. In any event, harmful algal blooms are quite rare events and there is little evidence to suggest that they are increasing in frequency locally.

Since January of 1990 the Laguna Madre has been experiencing a persistent bloom of small phytoplankton species generally referred to as the "brown tide". The brown tide began in January 1990 in Baffin Bay in an ecosystem that was already disrupted by persistent high salinities that reduced the populations of planktonic and benthic grazers. Two severe freezes in December of 1989 caused massive fish kills. The decomposition of these fish released a large nutrient pulse that was sufficient to fuel the initial bloom of brown tide. This nearly monospecific bloom has been caused by high densities of a small (4-5  $\mu$ m diameter) algal species that was previously undescribed. The proposed name for this new species is *Aureomonas lagunensis*. Brown tide cell concentrations have ranged from 0.5 - 6 million cells/ml throughout the course of the bloom, and chlorophyll a concentrations have reached as high as 120  $\mu$ g/l with a mean of about 60  $\mu$ g/l.

The brown tide has reduced the clarity of waters of the Laguna Madre, shading out sea grass beds and disrupting sports-fishing activities. The biomass of roots and rhizomes in the seagrass beds has decreased dramatically in the past two years of the brown tide, indicating the seagrasses are using up their energetic reserves. It is estimated that over 9 square kilometers of seagrass beds had been lost by the end of 1994. The nearly 200 square miles of seagrass beds in Laguna Madre represent the largest undisturbed seagrass habitat on the Texas coast and these seagrass beds are an important nursery habitat for fish and an essential winter food resource to migrating waterfowl.

Zooplankton are the major consumers of phytoplankton in most marine systems, and it is puzzling that zooplankton populations have not increased during this algal bloom. Mesozooplankton populations declined at the beginning of the bloom and have remained low in areas impacted by the brown tide. The size of adult copepods was lower and egg production rates were reduced in brown tide affected areas,

indicating that brown tide was a poor food for these grazers. The brown tide has also had a dramatic affect on the benthic organisms of Laguna Madre; abundance, biomass and diversity of benthic fauna have all decreased.

The extended brown tide bloom has had no apparent effect on populations of adult fish and shellfish. This is in contrast to the apparent effects of brown tide on larval fish populations. Both laboratory and field studies suggest that the brown tide may be toxic to newly hatched larval fish and that larval fish populations are reduced in areas severely impacted by the brown tide.

Perhaps the most important unanswered question is: why has the brown tide persisted for so long? Part of the answer lies in long turnover times for waters in Laguna Madre and Baffin Bay. The lack of freshwater inflow and restricted exchange with the Gulf of Mexico make it difficult to disperse an algal bloom once it becomes established. It also seems likely that this algal species may be competitively superior to other species in the harsh conditions of the Laguna Madre. It is also possible that this species suppresses other algal species through allelopathic effects. It also appears to have negative effects on populations of grazers that might help bring the bloom under control.

Apart from brown tides, red tides comprise the other common harmful algal bloom in Texas coastal waters. Two species of dinoflagellates are responsible for toxic red tides in Texas: *Gymnodinium breve* and *Alexandrium monilata*. The toxins of both these dinoflagellate species can cause extensive mortality in fish and invertebrate populations. Only *G. breve* blooms have been reported to cause human health problems through neurotoxic shellfish poisoning and respiratory irritation associated toxin containing aerosols. Red tides have been infrequent events on the Texas coast compared to other areas of the Gulf of Mexico, such as the West coast of Florida. There have been only 4 documented *G. breve* and 7 *A. monilata* red tide blooms.

Although occasionally the economic impacts of red tides are very severe, such as in the 1986 red tide, they appear to have no long term affects on the ecosystem, as may be the case with the brown tide. Fish populations, and tourism, soon return to normally following the infrequent blooms, and no basic changes in marine policy seem warrented to deal with them. Should toxic blooms in Texas increase in frequency and/or severity, however, monitoring efforts should be considered to provide warning of bloom initiation and transport along the Texas coast.

#### Introduction to the Texas brown tide.

Regions of the South Texas coast centered around the Laguna Madre (Figure 1) have experienced a dense algal bloom since January 1990 referred to as the "brown tide". This persistent algal bloom has reduced the penetration of sunlight, shading out seagrass beds (Onuf, submitted) and disrupting sports fishing activities. The nearly 200 square miles (518 km²) of seagrass beds in Laguna Madre represent the largest undisturbed seagrass habitat on the Texas coast and these seagrass beds are an important nursery habitat for fish and an essential winter food resource for migrating waterfowl. The brown tide has also caused changes in the planktonic and benthic food webs of the Laguna Madre, and appears to be toxic to larval fish (G.J. Holt, personal communication) and some planktonic organisms (Buskey and Hyatt, 1995). Having now persisted for over five years, this appears to be the longest phytoplankton bloom that has been scientifically documented. The current economic loss of tourism and recreational fishing to the local communities has been estimated to be several million dollars each year.

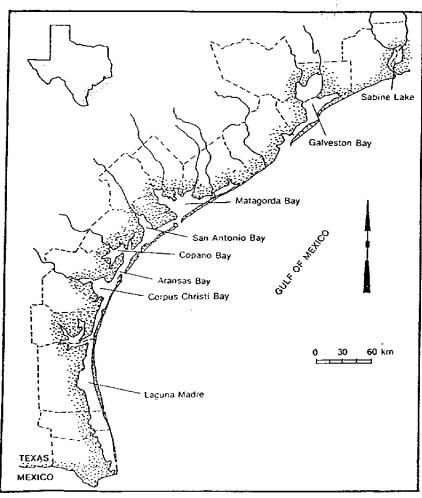


Figure 1. Map of the estuaries of the Texas Gulf Coast. Adapted from Armstrong (1987).

#### II. Historical trends of Texas brown tides

Since the algal species responsible for the Texas brown tide bloom has not been previously described taxonomically, it is difficult to know with certainty if there have been previous occurrences of the Texas brown tide. Certainly algal blooms have occurred in the past in the Laguna Madre, as in any body of water. Long time residents of south Texas recall periods of "brown water" in the Laguna Madre, but it is impossible to know if the causative organism was the same one present in the current brown tide. Gunter (1945) cites reports of "reddish colored 'bad' water", observed by pilots for the Texas Game, Fish and Oyster Commission, in Laguna Madre, and Simmions (1957) refers to red waters in the Laguna Madre as possibly being caused by: 1) dissolved iron 2) decaying vegetation 3) phytoplankton or 4) clay deposits. None of the previous reports seem to compare to the present bloom in either duration or severity.

Examination of the stable carbon isotope ratios of organic carbon from sediment cores collected in Baffin Bay suggest that the relative importance of seagrasses, macrophytic algae and phytoplankton may have shifted for decade long periods over the last several thousand years (Parker and Scalan, personal communication). This alone is not proof that the brown tide organism dominated the Laguna Madre at any point in the past, but it does suggest that the relative importance of phytoplankton and seagrasses as primary producers in Baffin Bay have been different than the pattern existing in historical periods before the brown tide. To determine if the brown tide were the organism responsible for phytoplankton dominance during these periods, biomarkers specific to the brown tide alga would be needed, and cores could be examined for these compounds. This would require study of the diagenesis of brown tide derived organic material.

#### A. Causative species

The organism responsible for this bloom is a small (4-5 µm diameter) phytoplankton species which has not yet been formally classified. Attempts to formally describe this species have recently been completed and a species description has been submitted for publication. The proposed name for this new species is *Aureomonas lagunensis* (H. DeYoe, personal communication). The Texas "brown tide" alga is devoid of obvious external diagnostic features when observed by optical microscopy, but examination of ultrastructure by transmission electron microscopy and of photosynthetic pigments by high performance liquid chromatography reveal that it is similar in morphology and pigments to *Aureococcus anophagefferens* (Sieburth et al., 1988; Stockwell et al., 1993) which has been responsible for recurrent blooms in Narragansett Bay and Long Island bays since 1985 (Cosper et al., 1987). Recent molecular data indicate that both species belong to a newly recognized class Pelagophyceae (Anderson et al., 1993), but the two species appear to differ enough from one another to warrant placing them in separate genera (DeYoe and Suttle, 1995).

	Aureococcus	Texas "brown
	anophagefferns	tide"
Organism:		
Cell size (µm)	2 -3	4 - 5
Pigments	Type III Chrysophyte	Type III Chrysophyte
External Polysaccaride layer	+	+
Cell wall	None	None
Viral inclusions	+	+
DMS/cell	0.13pg	0.76pg
Polyclonal antibody		
for Aureococcus	+	-
Bloom Characteristics		
Cell density (cells x 10 <sup>6</sup> /ml)	0.5 - 2.6	0.5 - 5.0
Chlorophyll a (µg/L)	18	20 - 140
C <sup>14</sup> uptake (mgC/m <sup>2</sup> /h)	200 - 400	230 - 840
Growth rates		
(doublings/day)	3	0.3 - 0.9
Carbon:Chlorophyll	?	380:1
Maximum duration	6 months	72 months
Reoccurence frequency	3 - 5 years	?
Deleterious effects	Yes*	Yes**

<sup>\*</sup> Mussels, clams, scallops, eelgrass, zooplankton

Table 1. Comparison of the Texas "brown tide" organism with *Aureococcus anophagefferens* (adapted from Table in Stockwell et al., 1993).

#### B. Comparison to the East Coast brown tide

Algal blooms of *Aureococcus anophagefferens*, a small (2 µm diameter) pelagiophyte, are also referred to as the East Coast brown tide. These blooms have occurred in several bays in the Northeastern United States including Narragansett Bay, RI, the Peconic-Gardiners Bay system, the south shore of Long Island, NY and Barnegat Bay, NJ (Lonsdale et al., in prep). These brown tides are restricted to shallow, vertically well-mixed waters, and have not occurred in Long Island Sound (Olsen, 1989; Nuzzi and Waters, 1989). The first bloom occurred in the summer of 1985, lasting for up to six months in some locations. Widespread blooms recurred in 1986 and 1987, and on a much more localized scale and of shorter duration in recent years. During blooms of the East Coast brown tide, total phytoplankton biomass and primary production rates are similar to those in non-bloom years (Cosper et al., 1989; Dennison et al., 1989). The demise of brown tide blooms is often associated with replacement of the brown tide with other pico- and nanoplankton species present in low concentrations during the bloom (Sieburth and Johnson, 1989; Keller and Rice, 1989). There is no evidence that *A. anophagefferens* blooms are initiated from cysts, since low

<sup>\*\*</sup> Zooplankton, larval fish, seagrass

numbers of cells are found in affected waters throughout the year (Lonsdale et al., in prep).

The exact causes of blooms of the East Coast brown tide remain unknown. *Aureococcus* has the ability to adapt to decreasing light levels as a bloom progresses and to maintain high growth efficiency under nutrient limiting conditions (Milligan, 1992). *A. anophagefferens* is also tolerant of a wide range of temperature and salinity conditions. It grows best at higher temperatures found in East Coast waters in summer (20-25 °C) but can also grow at a slower rate at temperatures as low as 5 °C, allowing seed populations to be maintained through the winter (Cosper et al., 1989b).

Physical factors that might contribute to the East Coast brown tide include long residence times of bay waters and reduced rainfall (Cosper et al., 1989b). There appears to be a correlation between brown tide distribution and areas of elevated salinity. Growth rates of *Aureococcus anophagefferens* are faster at 30 ppt than 28 ppt salinity, and growth can be maintained at salinities between 22 and 35 ppt (Cosper et al., 1989b).

The biomass of the East Coast brown tide cells was inversely related to concentrations of dissolved inorganic nitrogen in both field measurements and mesocosm-based nutrient enrichment studies (Keller and Rice, 1989). Brown tide blooms were of shorter duration and lower biomass in nutrient enriched mesocosms than in controls. This suggests that the East Coast brown tide blooms are not caused by macronutrient loading, and in fact the persistence of East Coast brown tide blooms may be due in part to its ability to grow at nutrient concentrations previously demonstrated to limit the growth of diatoms (Keller and Rice, 1989). Aureococcus has greater ability for heterotrophic take up of dissolved organic compounds compared to other species of microalgae (Dzurica et al., 1989). Trace metals and their chelators have been shown to have an important effect on the growth rate of Aureococcus in culture. Both iron and selenium additions caused faster growth rates, and the use of citric acid as a chelator resulted in faster growth rates than with the chelators EDTA (ethylene-diminetetraacetic acid) or NTA (nitrilotriacetic acid) (Cosper et al., 1993). Increased use of citric acid instead of phosphates in some detergents and increased municipal use of deep groundwater with higher iron concentrations may have contributed to the brown tide blooms (Cosper et al., 1993). No evidence of allelopathic effects of chemicals released by the brown tide on the growth of other phytoplankton species has been found (Cosper et al., 1989b).

There is less information available on the factors leading to the termination of blooms of *Aureococcus anophagefferens*. Little is known about the role of microzooplankton grazing in bloom dynamics of the East Coast brown tide (Lonsdale et al., in prep). Sieburth et al. (1988) noted the occurrence of viral particles within *A. anophagefferens* cells during the 1985 bloom in Narragansett Bay, but the role of viruses in the bloom dynamics of this organism remains unknown.

Perhaps the most important impact of the East Coast brown tide has been its detrimental effects on commercially important species of benthic macrofauna, such as scallops and mussels, and on eelgrass beds. Populations of the mussel *Mytilus edulis* in Narragansett Bay experienced mass mortalities of 30 to 100% (Tracey, 1988). In Peconic Bay, New York, adult bay scallops *Argopecten irradians* suffered heavy mortality (Wenczel, 1987) and losses in mussel weight reducing harvest (Bricelj et al., 1987) resulting in economic losses to the scallop fishery estimated at two million dollars per year (Kahn and Rockel, 1988). No data has been collected on the effects of the brown tide on other benthic invertebrates (Lonsdale et al., in prep).

Early outbreaks of the East Coast brown tide also caused severe reduction in light penetration during the main growing season in shallow seagrass beds, resulting in a significant reduction in leaf biomass and confinement of eelgrass populations to shallow water (Dennison et al., 1989). Eelgrass provides an important nursery habitat for many marine species, including bay scallops, and the losses of seagrass habitat may have contributed to the lower populations of scallops during brown tide outbreaks.

#### III. Available data

A. Environmental conditions during and immediately preceding the brown tide

#### 1. Initiation of the bloom

Scientists at the Marine Science Institute of the University of Texas (UTMSI) were carrying out a multi-investigator study of the Laguna Madre during the time when the brown tide began. Most experimental work was performed at two stations over seagrass beds in the upper Laguna Madre designated stations A and B, and at two stations in Baffin Bay over muddy bottoms, designated stations C and D (Figure 2). This study also included a monthly hydrographic survey at up to 44 stations in the upper Laguna Madre where basic hydrographic data were collected including seawater temperature, salinity, pH and oxygen concentration. Seawater samples were also collected for chemical analysis of nutrient concentrations, including nitrate, nitrite, ammonium, phosphate and silicate. Water was also collected for determination of phytoplankton biomass estimated as chlorophyll a concentration. At a subset of stations in the upper reaches of Baffin Bay, whole water samples were preserved in Lugol's iodine preservative for possible future analysis of the effects of high salinities on phytoplankton and microzooplankton species composition. Secchi depth and chlorophyll a readings were taken from various transects in the Nueces and Corpus Christi Bays prior to the onset of the brown tide by Texas Water Development Board (Figure 3). UTMSI scientists first became aware of the presence of the brown tide in June of 1990, when brown waters were encountered throughout upper Laguna Madre with extremely high chlorophyll concentrations (Figure 4). The unusual nature of the brown tide bloom was not realized for several months. Previously unexamined preserved whole water samples from Baffin Bay were then examined for the presence

of the brown tide, and it was determined that the bloom began in January of 1990 (Buskey and Stockwell, 1993).

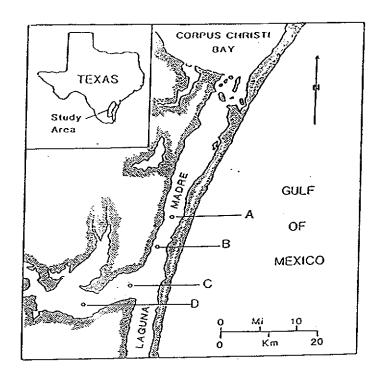


Figure 2. Map of upper Laguna Madre and Baffin Bay showing locations of the major experimental study sites during the University of Texas Marine Science Institute's study of the region. Adapted from Buskey and Stockwell (1993).

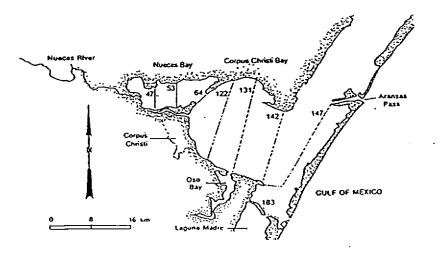


Figure 3. Map of the transects taken in the Nueces estuarine system. Adapted from Armstrong (1987).

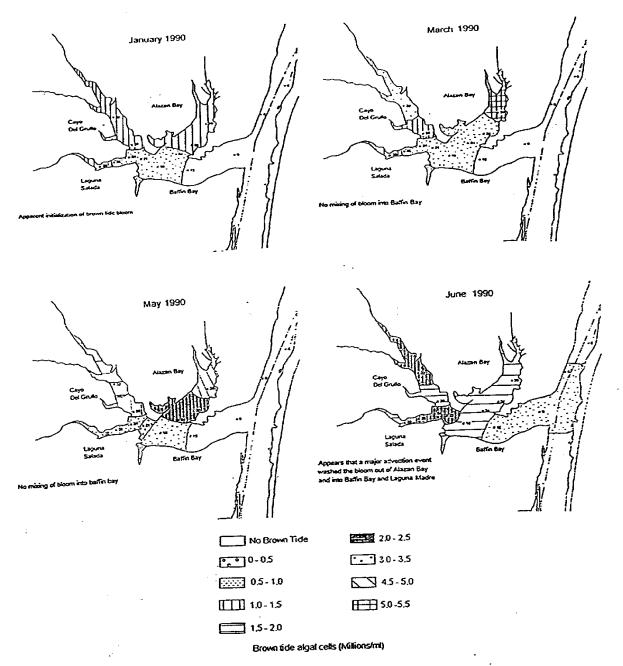


Figure 4. Distribution of brown tide in Baffin Bay during the first few months of the bloom. The bloom developed in the three secondary bays of Baffin Bay from January through May 1990, without spreading to any of the major stations in Baffin Bay. In June 1990 a major advection event spread the bloom throughout the upper Laguna Madre.

## 2. Temperature/Salinity

The onset of the brown tide followed a period of extended drought in south Texas. As a result, the upper reaches of Baffin Bay were extremely hypersaline (>60 ppt) when the brown tide began. Originally it was assumed that high salinity favored the growth of the brown tide, and that lower salinities would help bring about its demise.

This hypothesis was rejected when a brown tide bloom developed in Copano Bay in the summer of 1991 in waters of <5 ppt salinity. Subsequent laboratory experiments indicate that the Texas brown tide alga grows more rapidly at higher salinities (40ppt) than lower salinities (30 or 20 ppt) (Buskey, unpublished data).

Temperatures in the shallow waters of the Corpus Christi Bay National Estuary Program area can vary from highs of 32-34 °C in summer to lows below the freezing point during extreme, but short-lived cold fronts in winter months. Figure 5 below shows variations in temperature at two locations in the CCBNEP area, the upper Laguna Madre and at the East Flats of Corpus Christi Bay. Late spring, summer and early fall water temperatures are usually in excess of 25 °C; winter temperatures are between 10 and 20 °C. There has not been a prolonged hard freeze in the CCBNEP area since December of 1989; this event is not reflected in the temperature data shown here; sampling did not occur during the extremely windy conditions associated with the cold front and freeze of 1989.

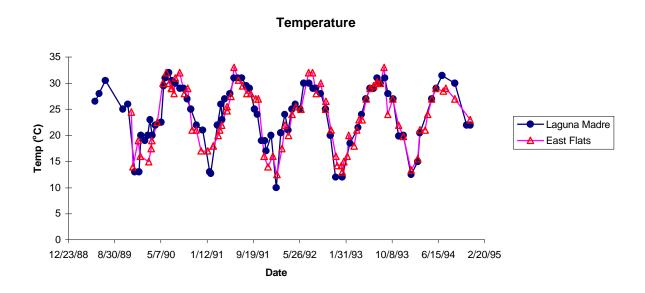


Figure 5. Water temperature at two locations in the CCBNEP area based on data collected by Dr. Ken Dunton, University of Texas Marine Science Institute.

A more detailed view of temperature and salinity records from March 1989 until August 1991 in shown in Figure 6. There is little variation in temperature between the four sampling sites, but there is often considerable variation in salinity measurements between sites. Salinities in Laguna Madre were hypersaline (greater than 35 ppt) during most of the period shown in Figure 5; salinities were occasionally in excess of 50 ppt at all four stations.

#### **Temperature and Salinity for Laguna Madre**

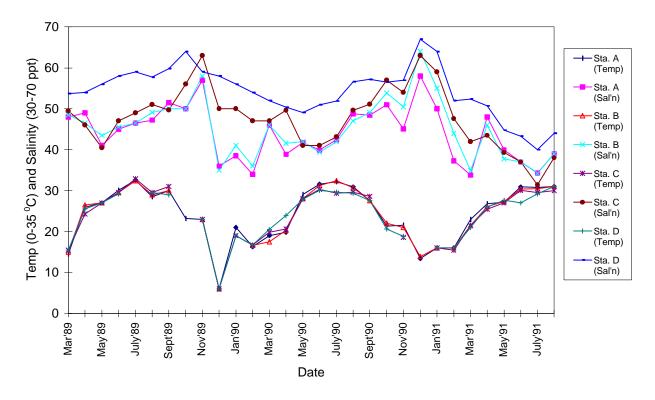


Figure 6. Water temperature and salinity at four locations in the upper Laguna Madre and Baffin Bay from March 1989 until August 1991. Data from Dr. E.J. Buskey, University of Texas Marine Science Institute.

Water temperatures in the Laguna Madre can vary by 5 °C or more over short periods of time due to changes in cloud cover and wind conditions and the shallow body of water involved. In the late fall, winter and early spring, the passage of cold fronts can cause even wider fluctuations in the temperature of the Laguna Madre over a short period of time. Daily temperatures at the intake to the Central Power and Light electrical generating station on the shore of Laguna Madre during part of 1993 and 1994 are shown in Figure 7.

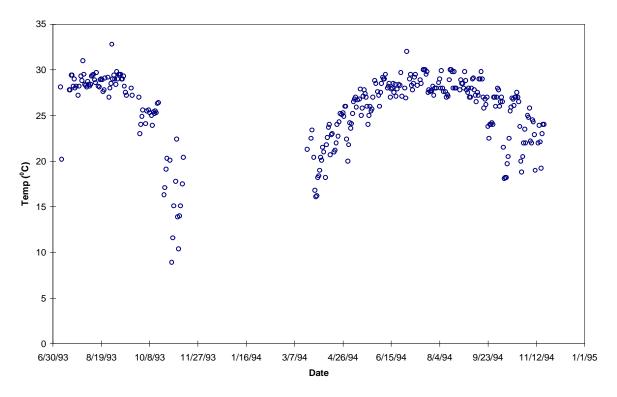


Figure 7. Water temperatures at the intake for the Central Power and Light electrical generating plant in Corpus Christi. Water for cooling the power plant is withdrawn from the Laguna Madre and returned to Oso Bay. Data provided by the GCCA/CPL redfish hatchery.

#### 3. Residence Time of Water in Bays

Water in coastal bays is in a constant state of flux. Fresh water is added through rainfall, groundwater and rivers. Freshwater can leave coastal bays directly through evaporation or indirectly as less saline waters flow out of the bays into the Gulf of Mexico. Waters from the Gulf of Mexico are also mixed into coastal bays by way of tidal exchange. The residence times of waters in Texas coastal bays depends mainly on the amount of freshwater inflow and the tidal exchange from surrounding areas. Shormann (1992) estimated the residence times of three Texas bays in the CCBNEP area, Baffin Bay, Nueces Bay and Copano Bay, in order to look into its possible effects on the persistence of brown tide blooms in these three areas. He used the equations described in Armstrong (1982) to estimate residence time based on freshwater inflow and salinity data, and the equations described in Smith (1985) to estimate the effects of tidal flushing.

Shormann (1992) assumed that tidal flushing of Baffin Bay was negligible because of the bay's isolation from any passes to the Gulf of Mexico. Based on freshwater inflow data, a residence time of approximately 12.5 years was calculated. A

second residence time was calculated taking into account the losses of water through evaporation. Based on these data, a residence time of approximately one year was calculated. However, it should be noted that this turnover time is based on water leaving by evaporation, and planktonic organisms such as the brown tide would actually be concentrated in Baffin Bay rather than be diluted out. In reality, as evaporation occurs, water becomes more dense, so some of this dense water probably flows out along the bottom of Baffin Bay and is replaced by less saline water from the upper Laguna Madre. However, the upper Laguna Madre is also heavily impacted by the brown tide, and this exchange does little to dilute the brown tide.

Shormann (1992) also calculated residence times for Nueces Bay of 25 days, and for Copano Bay of 214 days. These calculated residence times correspond approximately to the relative persistence of episodes of brown tide in each of these bays. The brown tide spread into Nueces Bay on at least one occasion in August 1992, but it only persisted for a few weeks. Examination of brown tide cells using transmission electron microscopy showed the presence of what appeared to be viral particles within cells, suggesting that termination of this short lived bloom may have been enhanced by pathogens (Stockwell, pers. comm.). The brown tide has also spread into Copano Bay, and has persisted there for periods of several months. In Baffin Bay, with a calculated residence time of a year or longer, the brown tide has persisted for over five years, and has not abated since the bloom began.

## 4. Light transmission

Light transmission through seawater is an important factor, along with temperature and nutrient availability, determining the amount of primary production that can occur in a body of water. A brown tide event, typically with a cell concentration of one million cells per ml of seawater, can severely reduce the penetration of light through seawater. Light transmission through seawater is largely affected by the presence of dissolved and suspended materials that both absorb and scatter light. As photosynthetic organisms, brown tide algal cells absorb light in order to photosynthesize; as small particles suspended in the water column they also scatter large amounts of light. One of the simplest ways to quantify the transparency of natural waters is to measure the greatest depth below the surface at which a small white disk, called a Secchi disk, can still be seen by an observer above the water's surface. The yearly average Secchi depth, the depth at which the disk can no longer be seen, for several transects along Nueces Bay, Corpus Christi Bay and the upper Laguna Madre, prior to the brown tide, is shown in Figure 8. There is a general increase in water transparency from average Secchi depths of ca. 50 cm in Nueces Bay to 80 - 100 cm as you approach the Laguna Madre. A somewhat incomplete record of Secchi depths at four stations in the Laguna Madre and Baffin Bay is shown in Figure 9. Before the brown tide began, Secchi depths were as great as 1.5m (the depth of the water column) in the Laguna Madre. During the most severe parts of the brown tide, Secchi depths were often less than 0.5 m. Water clarity often improves for short periods of time in the

winter, when cold fronts displace the brown tide laden water with relatively clear water from Corpus Christi Bay.

## Sechi depths for Nueces estuary and upper Laguna Madre

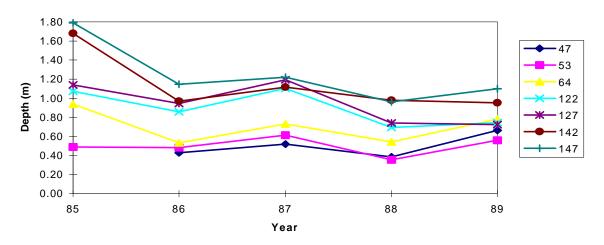


Figure 8. Yearly average Secchi depth data at various transects throughout Nueces estuary (47 & 53) and the upper Laguna Madre (64-147). Data provided by the Texas Water Development Board.



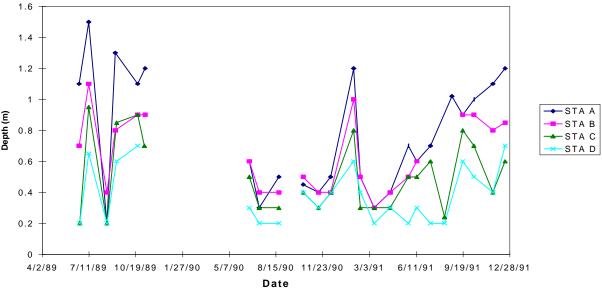


Figure 9. Monthly Secchi depth measurements taken at four stations in Laguna Madre and Baffin Bay. Data provided by Dr. Terry Whitledge, University of Texas Marine Science Institute. Station locations are shown in Fig. 2.

Continuous year-round measurements of photosynthetically available radiation (PAR) were made by Dr. Ken Dunton , University of Texas Marine Science Institute, in the Laguna Madre near Station A, in the northern portion of Corpus Christi Bay (East Flats), and the southern portion of San Antonio Bay. The brown tide bloom in Laguna Madre led to a significant decrease in PAR available to the seagrasses in that area. The annual quantum flux received by the seagrasses in 1989 prior to the initiation of the bloom was 5672 mol m<sup>-2</sup> yr<sup>-1</sup>. In the 3 years following the bloom initiation, the PAR levels have ranged between 2000 to 3000 mol m<sup>-2</sup> yr<sup>-1</sup>, a decrease of about 50% (Figure 10) The impacts of this reduction of available light is clearly reflected in the nearly 50% reduction in below ground *Halodule wrightii* biomass. Similar reductions in PAR and seagrass biomass are not present in the two other study areas in which a brown tide bloom did not occur.

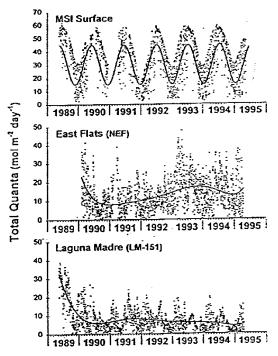


Figure 10. Photosynthetically available radiation (PAR) collected at the surface at the Marine Science Institute (MSI) and on the bottom from near Station A in the Laguna Madre and the East Flats in Corpus Christi Bay from March 1989 through April 1995 Data provided by Dr. Ken Dunton, University of Texas Marine Science Institute.

### 5. Dissolved Oxygen

In highly productive coastal waters, especially those receiving a high input of organic matter produced elsewhere, high rates of respiration can cause dissolved oxygen concentrations to fall to a level low enough to endanger marine life. Often the largest oxygen demand comes from bacteria decomposing organic matter in the water column and bottom sediments. Since decomposition rates increase, and the oxygen saturation point decreases at higher temperatures, the greatest potential for anoxic events occurs during the warm months.

In spite of the warm temperatures and high organic loads in the water column during the brown tide event, there have been no major fish kills reported in the CCBNEP that can be traced to anoxic events. This is due primarily to the shallow, well mixed water column, which does not allow water near the bottom to be isolated from the surface for long periods of time. Dissolved oxygen levels typically remain above 2 mg/l, even during warm summer months with high brown tide concentrations (Figure 11).

#### D.O. levels at the CPL intake '93-'94

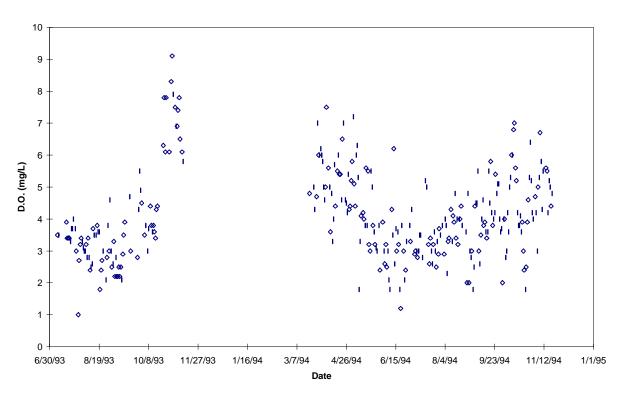


Figure 11. Morning dissolved oxygen levels measured in seawater at the intake to the Central Power and Light electrical generating station. Samples taken betwee 4:00 and 5:00 AM. Data provided by GCCA/CPL redfish hatchery.

#### 6. Nutrients

Prior to the bloom of the Texas brown tide alga, concentrations of dissolved inorganic nitrogen (DIN) in Baffin Bay and Upper Laguna Madre increased from <10 µM to ca. 20µM. Figures 12, 13, and 15 show this large peak of inorganic nitrogen.

#### NH<sub>4</sub> concentrations for Laguna Madre

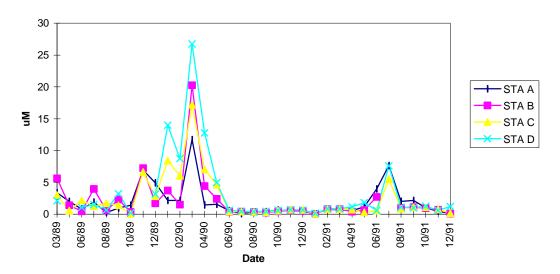


Figure 12. Ammonium concentrations in the upper Laguna Madre and Baffin Bay, from March 1989 through December 1991. The 1990 winter / spring maxima was ascribed to the freeze induced fish and invertebrate die off. Unpublished data from Dr. T.E. Whitledge, University of Texas Marine Science Institute.

#### NO<sub>3</sub> concentrations in Laguna Madre

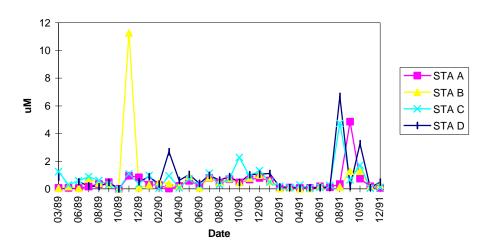


Figure 13. Nitrate concentrations in the upper Laguna Madre and Baffin Bay, from March 1989 through December 1991. Unpublished data from Dr. T.E. Whitledge, University of Texas Marine Science Institute.

#### NO<sub>2</sub> concentrations for Laguna Madre

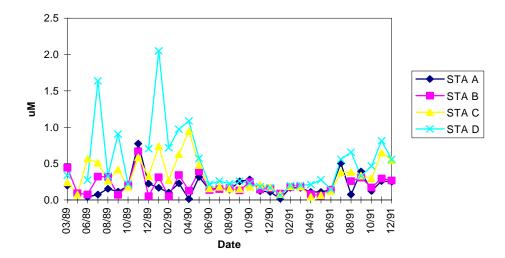


Figure 14. Nitrite concentrations in the upper Laguna Madre and Baffin Bay, from March 1989 through December 1991. Unpublished data from Dr. T.E. Whitledge., University of Texas Marine Science Institute.

Of this DIN increase, 60-95 % was in the form of NH<sub>4</sub><sup>+</sup> (Stockwell et al., 1993, Whitledge 1993, unpublished data). This large influx of ammonium was beneficial to the Texas brown tide alga since, unlike most other algae, it is unable to use NO<sub>3</sub><sup>-</sup> as a nitrogen source. *Aureococcus anophagefferens*, the algal species associated with the northeastern brown tides, is able to take up and reduce NO<sub>3</sub><sup>-</sup>, NO<sub>2</sub><sup>-</sup>, and NH<sub>4</sub><sup>+</sup>. Evidence suggests that the Texas brown tide species is able to take up all three inorganic forms of nitrogen, but is unable to reduce NO<sub>3</sub><sup>-</sup> due to a lack of a functional nitrate reductase (DeYoe and Suttle, 1994).

The large input of nitrogen is most often ascribed to two severe winter freezes which induced large fish kills and a salinity / temperature induced invertebrate die off (Stockwell et al., 1993, Whitledge, 1993, DeYoe and Suttle, 1994). An estimated 965,000 fish died in Baffin Bay and Upper Laguna Madre. This fish kill could have released approximately 2.01 x 10<sup>7</sup> g of N into the system (DeYoe and Suttle, 1994). In the year prior to the bloom, the invertebrate population decreased by over 90% releasing an estimated 0.48 g of N m<sup>-2</sup> into Baffin Bay and 6.29 g of N m<sup>-2</sup> into upper Laguna Madre (Montagna, personal communication). DeYoe and Suttle (1994) estimate that this increase in N would be sufficient to produce 6x10<sup>12</sup> cells m<sup>3</sup>, an amount larger than was actually observed during the bloom.

This pulse of ammonium has been ascribed as a factor leading to the initiation of the Texas brown tide algal bloom. However, high concentrations of DIN might not be necessary to maintain the bloom. A study of the brown tide organism, *Aureococcus anophagefferens*, in Narragansett Bay has shown that the northeastern brown tide bloom was maintained during periods of extremely low DIN levels (< 1.0 µM) (Keller

and Rice, 1989). Since *Aureococcus* is a picoplankton (cell size 2-3  $\mu$ m), its high surface area to volume ratio could allow it to take up a greater portion of the available nutrients than the other, larger, phytoplankton (Joint, 1986). Keller and Rice (1989) found that the brown tide population diminished and other phytoplankton populations recovered when nutrient levels increased in bloom waters. In Texas, after the initial pre-bloom pulse, inorganic nutrient levels remained low for ca. 12 months (DIN< 3 $\mu$ M and PO<sub>4</sub> ca. 1 $\mu$ M). However, the Texas brown tide bloom has successfully persisted through several periods of nutrient enrichment in Laguna Madre (Whitledge, 1993 and unpubl. data, Dunton, unpubl. data).

Phosphorus and silica are rarely thought to be limiting in a coastal environment (Boynton et al., 1982); as a result almost no studies have been done on the effects of these nutrients on the Texas brown tide alga. A small increase of  $PO_4^-$  was observed prior to the start of the brown tide bloom (Figure 15). Phosphate levels increased from ca. 1µM to 3 µM (Whitledge, unpubl. data). It is unlikely that this pulse of phosphate would have much effect since, phosphorous is limiting to the Texas brown tide alga only when an unnaturally large (ca.  $100\mu$ M) pulse of nitrogen is added to the system (Whitledge, pers. comm.). No studies have been done on the effect of silica levels on the Texas brown tide alga. While the brown tide organism does not have a physiological requirement for silica, it is conceivable that sufficient levels could allow diatoms to compete with the alga. A drop in silica levels prior to the bloom (Figure 16) helps support this idea.

#### PO4 concentration for Laguna Madre

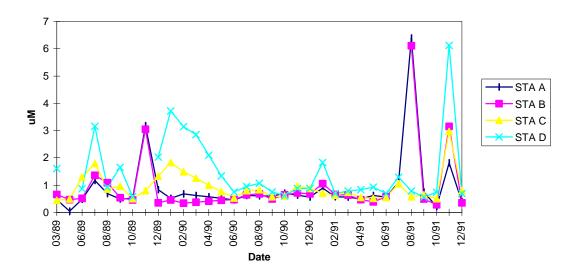


Figure 15. Phosphate concentrations in the upper Laguna Madre and Baffin Bay, from March 1989 through December 1991. Unpublished data from Dr. T.E. Whitledge, University of Texas Marine Science Institute.

#### SiO<sub>4</sub> concentrations for Laguna Madre

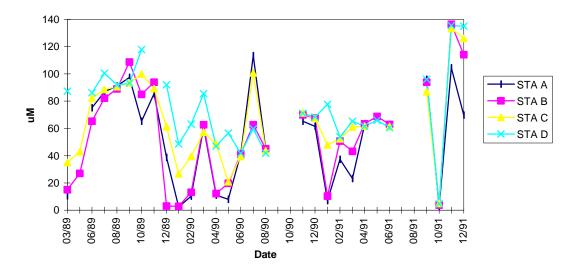


Figure 16. Silica concentrations in the upper Laguna Madre and Baffin Bay from March 1989 through December 1991. Unpublished data from Dr. T.E. Whitledge, University of Texas Marine Science Institute.

#### B. Brown tide biomass

One way to estimate the severity of the brown tide bloom at any specific place or time is to collect a water sample and count the number of brown tide cells present in a volume of water. Since most marine phytoplankton populations are quite diverse, it can be a very difficult and time consuming task to try to identify all the species of phytoplankton present in a water sample and determine their abundance through quantitative microscopic analysis of samples. A more common practice is to concentrate plankton samples on filters and measure the concentration of photosynthetic pigments characteristic of all phytoplankton, such as chlorophyll a. The amount of chlorophyll a present in a volume of water is then assumed to be proportional to the total biomass of phytoplankton present. The pigment composition of phytoplankton varies both with species and environmental conditions, so the ratio of chlorophyll a to total biomass can vary considerably from sample to sample. In the case of a nearly monospecific phytoplankton bloom such as the brown tide, most of the pigment is produced by a single species, so some of the variability is reduced and chlorophyll concentrations can be guite useful for comparing the concentrations of brown tide within different areas of the bloom and at different times of the year. However, since all phytoplankton species contain chlorophyll a, this parameter provides no information about the proportion of the phytoplankton biomass contributed by the brown tide compared to other species. It can provide no indication of when brown tide is present or absent in the water.

It is also possible to enumerate the concentration of brown tide cells microscopically. The cells of the brown tide alga are small (4-5  $\mu$ m in diameter) and very abundant in areas obviously affected by the brown tide. However, cells of the brown tide alga are morphologically indistinct, and there are no external characteristics that can be used for positive microscopic identification.

#### 1. Cell counts

In the spring of 1990 the first "bloom" level abundances of the brown tide alga were observed in Laguna Madre. Prior to this time, the brown tide alga had not been observed in this area. Due to its indistinct appearance, this does not mean it was not present in low numbers and simply not recognized in phytoplankton samples. As figure 17 shows, brown tide levels quickly increased from their initial observed levels of ca. 500,000 cells/ml in June 1990 to over 2 x 10<sup>6</sup> cells/ml in July 1990. Population abundances decreased from this summer high during the winter months but remained at bloom levels (ca. 1 x10<sup>6</sup> cells/ml). Cell counts once again increased during the summer months. Unlike *A. anophagefferens*, the Texas brown tide is able to maintain high abundance levels through the winter months. Thus, instead of a bloom which lasts for several months, Texas has experienced a bloom of brown tide alga which has lasted over 5 years and still has an abundance over 500,000 cells/ml (Figure 18).

#### **Brown Tide Counts for Laguna Madre**

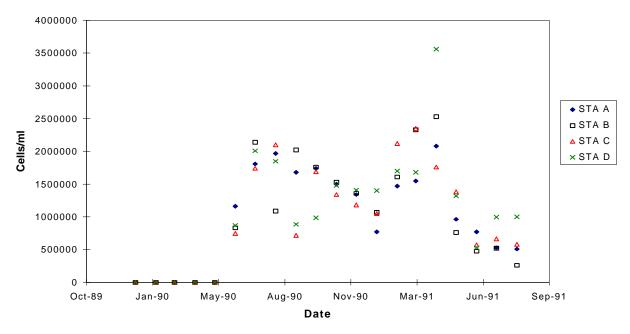


Figure 17. Brown tide cell counts for 4 locations in upper Laguna Madre and Baffin Bay from December 1990 through August 1991. Buskey and Stockwell (1993) and unpublished data of Dr. E.J. Buskey, The University of Texas Marine Science Institute.

#### **Brown Tide Counts Upper Laguna Madre**

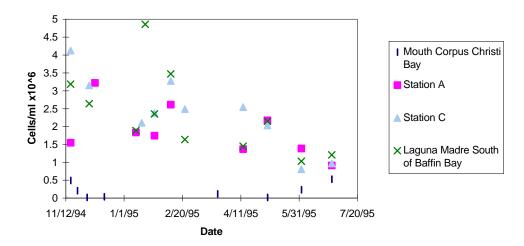


Figure 18. Brown tide counts for 4 locations in upper Laguna Madre and Baffin Bay from November 1994 through June 1995. Unpublished data of Dr. Roy Lehman, Texas A&M University - Corpus Christi, Center for Coastal Studies.

## 2. Chlorophyll a

From 1983 through 1989, prior to the initiation of the brown tide bloom, the chlorophyll  $\underline{a}$  maxima never exceeded 17  $\mu$ g/L (Figure 19). After the bloom, chlorophyll  $\underline{a}$  concentrations, during peaks, have exceeded 40 $\mu$ g/L (Figure 20).

CHlorophyll a Concentrations for Nueces Bay and Laguna Madre

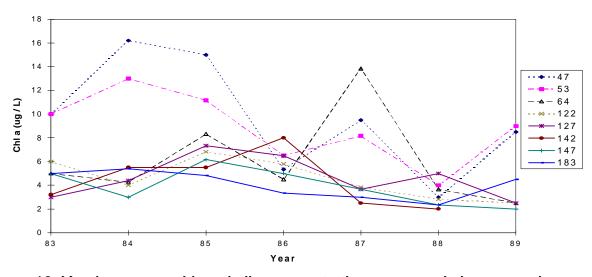
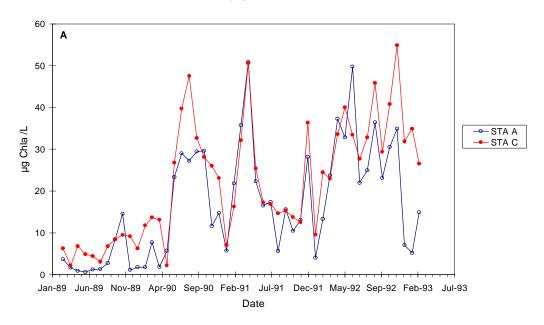


Figure 19. Yearly average chlorophyll <u>a</u> concentrations averaged along cross bay transects running from Nueces Bay through the upper Laguna Madre. (See Figure 3 for the location of these transects.) Data provided by the Texas Water Development Board.

#### **Chlorophyll Data From STEPS**



### **Chl concentrations for Laguna Madre**

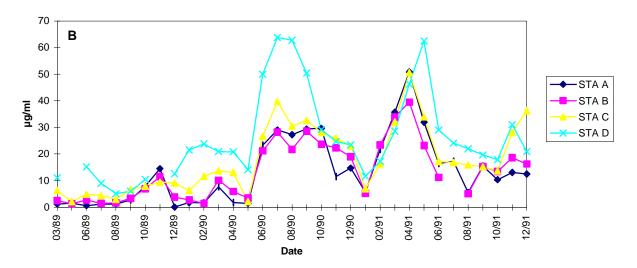


Figure 20. (A) Chlorophyll <u>a</u> data from stations A and C in the upper Laguna Madre and Baffin Bay, respectively, from March 1989 through February 1993. Unpublished data from Dr. Dean Stockwell, University of Texas Marine Science Institute.

(B) Surface chlorophyll <u>a</u> concentrations (μg/l) from four stations in the upper Laguna Madre from March 1989 until December 1991. Unpublished data of Dr. Terry Whitledge, University of Texas Marine Science Institute.

Primary production (gC m<sup>-2</sup> d<sup>-1</sup>) before the brown tide averaged 1.2 gC m<sup>-2</sup> d<sup>-1</sup>, while after the brown tide the average increased to 2.0 gC m<sup>-2</sup> d<sup>-1</sup> (Figure 21). Both

these values of primary production are lower than values previously reported for the upper Laguna Madre (2.68 gC m<sup>-2</sup> d<sup>-1</sup>, Odum and Wilson, 1962) but higher than values previously reported for Corpus Christi Bay (0.48 gC m<sup>-2</sup> d<sup>-1</sup> Flint, 1984). Even values for primary production during the brown tide are well within the range commonly observed in estuarine ecosystems throughout North America (see table 2 in Flint 1984), indicating that primary production rates are not excessive during the brown tide. The large biomass present during the brown tide would appear to be due to a reduction in the normal loss processes for phytoplankton populations, including grazing, sinking and advection.

# Laguna Madre Mean Primary Production

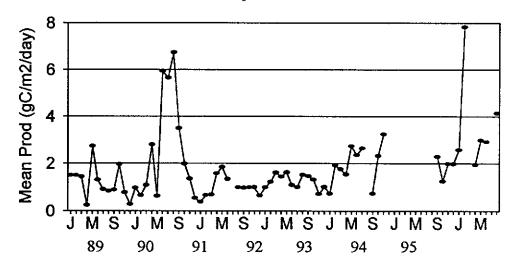


Figure 21. Primary production data for Laguna Madre from January 1989 through March 1995. Unpublished data of Dr. Terry Whitledge, University of Texas Marine Science Institute.

## C. Spatial distributions

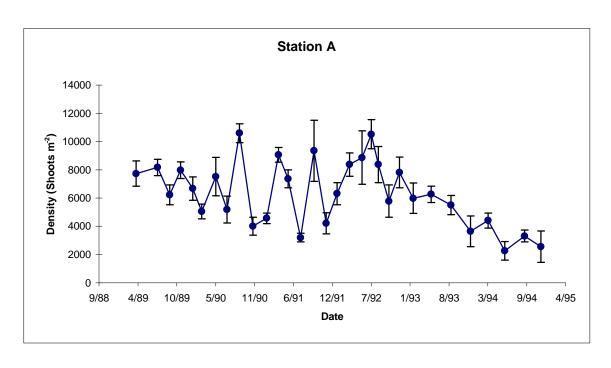
Data on brown tide biomass (chlorophyll <u>a</u>) distribution have been collected at monthly intervals at up to 44 sites in the upper Laguna Madre by Dr. Dean Stockwell and Dr. Terry Whitledge since March 1989, ten months before the brown tide began, in projects funded by the Texas Higher Education Coordinating Board and other Texas State Agencies. This data contains a wealth of information about distributional patterns of the brown tide over the course of this bloom, which could reveal important information concerning the factors affecting the growth and dominance of this bloom organism. Data from two locations are shown in Figure 20

# D. Environmental impact

# 1. Seagrasses

One of the greatest potential impacts of the brown tide on the Laguna Madre ecosystem is the loss of seagrass due to reduced light penetration. Reductions in water clarity are thought to have been responsible for large scale losses in seagrass habitat in the past (Kenworthy and Haunert, 1991), and the depth limit of seagrass meadows is often assumed to be constrained by the depth of light penetration required for photosynthesis (Dennison, 1987; Duarte, 1991). The brown tide has caused a reduction in light penetration which increases with depth of the water column, so the greatest impact of the brown tide should be on seagrasses at the greatest depths.

A study by Dr. Ken Dunton at the University of Texas Marine Science Institute compared seagrass growth characteristics at sites in the Laguna Madre near station A which has been heavily impacted by the brown tide and a site in the East Flats of Corpus Christi Bay that has been generally free of the brown tide. Seagrass shoot density can be quite variable at both sites, particularly during the period from 1989 until the summer of 1992 (Figure 22). Following the summer of 1992, shoot density at the site in the East Flats of Corpus Christi Bay remained largely unchanged, whereas shoot density showed a steady decline during the same period at the site in Laguna Madre, decreasing from 8-10 thousand shoots per square meter in the summer of 1992 to less than 4,000 shoots per square meter by the end of 1994 (Figure 22). Seagrass areal shoot biomass, measured in grams dry weight per square meter also shows considerable variability, but a seasonal pattern of high shoot biomass in late summer is observed in each year except 1991 at the East Flats site, whereas summer biomass peaks appear to be dampened out after 1991 at the Laguna Madre site (Figure 23). However, above ground shoot density and biomass measures may not necessarily be the best indicators of stress induced by reduced light intensities because seagrasses store reserve energy in their rhizomes, and can use these reserves to produce above ground biomass during periods of reduced light. The biomass of roots and rhizomes has been declining steadily since 1992 at the Laguna Madre site, compared to a more variable pattern at the East Flats site (Figure 25). The ratio of root and rhizome biomass to shoot biomass dropped from a high of 16 in Laguna Madre before the brown tide began, and then fell to a value of 2 to 4 during the brown tide bloom, where it has stabilized. The range of ratios observed at the East Flats site, unlike Laguna Madre, varied with a relatively consistent seasonal pattern from 1 to 3 (Figure 25).



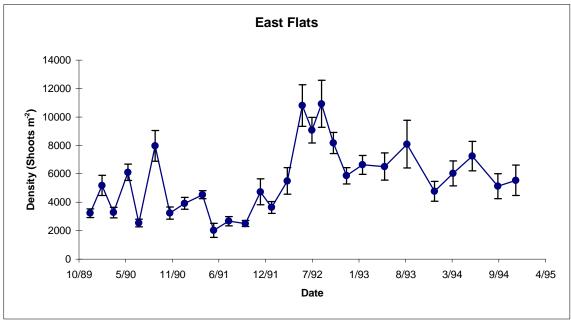
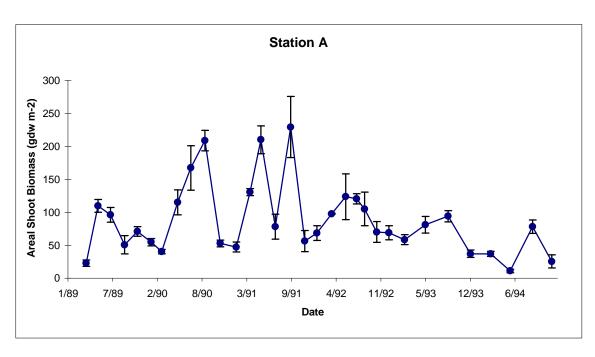


Figure 22. Seagrass shoot density (shoots/m²) at a location in upper Laguna Madre (top) and a location in East Flats of Corpus Christi Bay (bottom). Data from Dr. Ken Dunton, University of Texas Marine Science Institute.



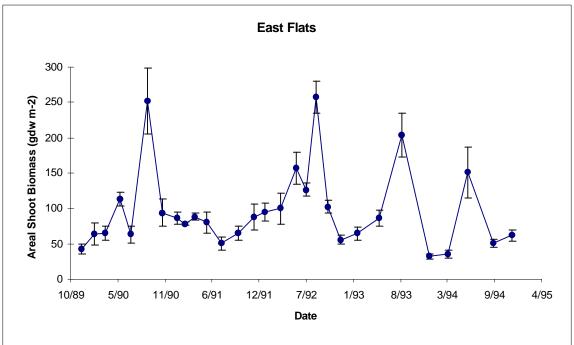
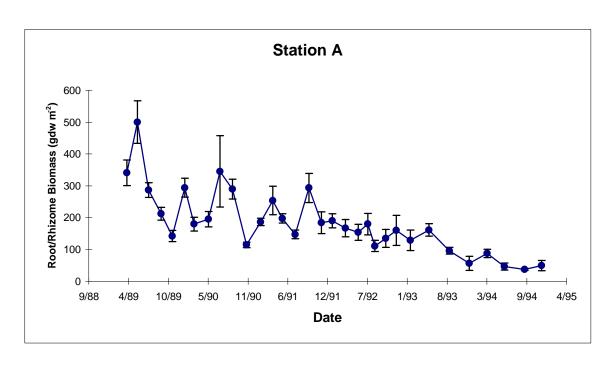


Figure 23. Seagrass areal shoot biomass (gdw/m²) at a location in upper Laguna Madre (top) and a location in East Flats of Corpus Christi Bay (bottom). Data from Dr. Ken Dunton, University of Texas Marine Science Institute.



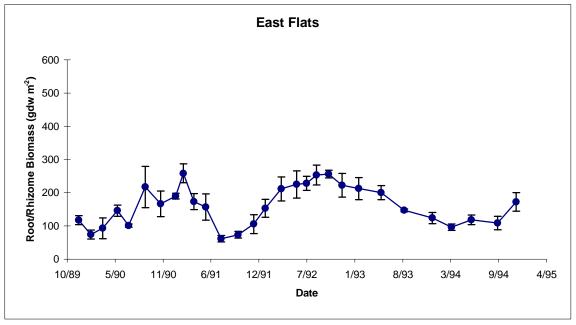
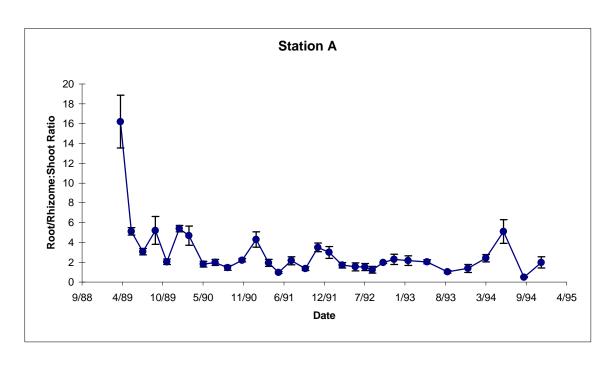


Figure 24. Seagrass root/rhizome biomass (gdw/m²) at a location in upper Laguna Madre (top) and a location in East Flats of Corpus Christi Bay (bottom). Data from Dr. Ken Dunton, University of Texas Marine Science Institute.



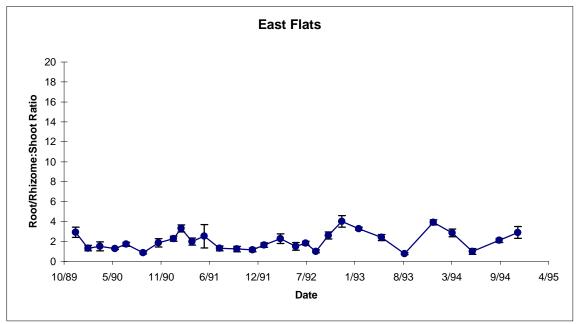


Figure 25. Ratio of root/rhizome biomass to shoot biomass at a location in upper Laguna Madre (top) and a location in East Flats of Corpus Christi Bay (bottom). Data from Dr. Ken Dunton, University of Texas Marine Science Institute.

Dr. Christopher P. Onuf (submitted), reports on changes in seagrass distribution and biomass due to light attenuation of the Texas brown tide. Comparisons of pre- and post-brown tide studies were made to give an estimate on the amount of sea grasses

lost in upper Laguna Madre. A study in 1988, before the brown tide bloom, assessed seagrass distribution and biomass (Quammen and Onuf, 1993). The 1988 transects were reassessed at approximately the same season in 1991, 1992, 1993, and 1994.

To assess distribution changes, edges of the seagrass meadows were plotted and compared year to year. Although the brown tide initiated in June 1990, no change in distribution between the surveys of 1988, 1991 and 1992 was observed. The first loss of coverage area was observed in May 1993 in the southern area of the study area. Other bare areas were observed in November 1993. A total of 2.6 km² of sea grass meadow was lost in 1993. By the end of 1994 the area of the seagrass meadow loss had increased to 9.4 km² (Figure 26). The amount of this loss was 6% of the total area covered by the seagrass meadow.

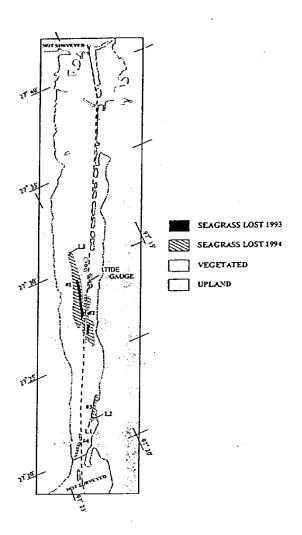


Figure 26. Area of seagrass loss during 1993 and 1994, due to reduced light penetration during the brown tide. L1, L2, and L3 indicate the location of under water light monitors. From Dr. Christopher Onuf, National Biological Service (submitted for publication).

To assess biomass changes, two random cores were taken from each station for biomass analysis. The core samples were divided into live and dead plant material, the live portion was further divided into above and below ground plant material. Dry weights and ash-free dry weights were calculated for each of the sample portions. Based on where the cores were taken, the resulting biomasses were placed into depth classes of 44-84, 85-114, 115-129, 130-139, 140-183 cm depth (Figure 27). In the two shallowest water depth classes biomass did not change over time. There was a significant loss in biomass at the 130-139 cm depth class between the pre-brown tide year and 1993. The deepest sites sampled suffered the greatest losses. Over the study period biomass diminished by more than 60% in the 140-183 cm depth class. This loss was not uniform over the study area. Biomass reached low levels more rapidly in the southern portion of the study site than the northern portion. (Figure 28).

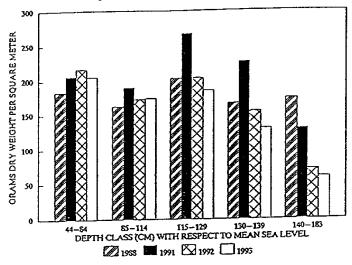


Figure 27. Seagrass biomass for beds at various water depths, for surveys taken in 1988, 1991, 1992 and 1993. From Dr. Christopher Onuf (submitted)

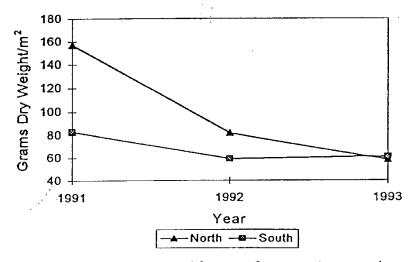


Figure 28. Mean seagrass biomass from northern and southern Laguna Madre from surveys taken in 1991, 1992 and 1993. Adapted from Dr. Christopher Onuf (submitted).

It is thought that light attenuation due to the brown tide is responsible for the seagrass losses. Underwater photosynthetically available radiation (PAR) was measured at 1 min intervals at three locations (Figure 26). Secchi depths were taken at approximately monthly intervals from March 1992 to November 1994 at stations 100m from the eastern and western shores of the Laguna and at the midpoint on east-west transects at 27° 20', 22', 26' 30', 38' and 40'. These Secchi depths were related to PAR by determining light vs. depth profiles and computing attenuation coefficients to determine the proportion of surface light reaching the bottom. Light attenuation increases from north to south which is consistent with the higher biomass seen at the greatest depths in the northern portion of the study prior to 1993 (Figure 28). The compensation point for *Halodule* has been estimated at 12 - 20% of surface irradiation (Kenworthty, et al. 1991, Onuf, 1991). Using an average compensation point of 15% surface irradiance, Onuf predicts that 23% of the study area is too deep to support *Halodule* while the brown tide persists. Prior to the brown tide only 6% of Laguna Madre was too deep.

Although 17% of the 1988 meadow has continually received light below the compensation level, only 6% of the meadow has been lost. Onuf (1995) proposes that *Halodule* is "able to survive periods of inadequate light by reducing the number of shoots it maintains and supporting the reduced demands by metabolizing the carbohydrate reserves stored in below ground tissues." The reduction in biomass prior to loss in distribution supports this hypothesis. As the brown tide persists the coverage should continue to decrease (as it did from 1993 to 1994). Since seagrasses prevent resuspension of sediment, the loss of the seagrass could increase the light attenuation of suspended particles, leading to even greater seagrass losses. These losses could have a major effect on species, such as the Redhead ducks (*Anthya americana*) which depend on *Halodule wrightii* for food and shelter.

## 2. Planktonic Grazers

Mesozooplankton populations, dominated by the copepod *Acartia tonsa*, were generally abundant before the onset of the brown tide, although there was considerable spatial and temporal variability in population density (Figure 29). In Baffin Bay, mesozooplankton densities ranged from 1,500 to 23,500 organisms per cubic meter before the onset of the brown tide. After the beginning of the brown tide, mesozooplankton densities remained below 8,000 per cubic meter through July 1991. The ctenophore *Mnemiopsis mccradyi* was abundant in Baffin Bay in March and April 1990, just prior to the spread of the brown tide.

The size of adult female *Acartia tonsa*, measured as prosome length, is usually a function of the temperature and salinity of the waters the organisms grow in. Higher temperatures and higher salinities result in smaller copepods. In Baffin Bay, where conditions were extremely hypersaline, both temperature and salinity affected the size of *A. tonsa*. In Laguna Madre, where conditions were less hypersaline, temperature had the most important influence on the size of *A. tonsa* before the brown tide, with

copepods reaching their maximum size in the cool winter months (ca. 0.75 mm prosome length) and their minimum size in hot summer months (ca. 0.55 mm prosome length) (Figure 30). During the brown tide, *A. tonsa* remained small throughout the cooler winter months (0.6 mm prosome length).

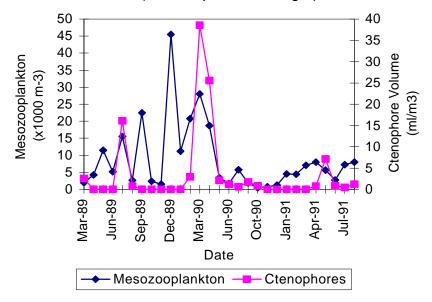


Figure 29. Mesozooplankton abundance and ctenophore displacement volume in Baffin Bay before and during the brown tide. Adapted from Buskey and Stockwell (1993).

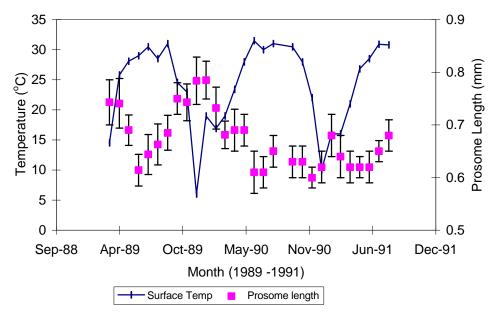


Figure 30. Prosome lengths of adult female *Acartia tonsa* at station A in Laguna Madre before and during the brown tide bloom, and temperature data from the same station. Before the brown tide, the size of copepods was a function mainly of water temperature; after the bloom copepods remained small throughout the year, indicating poor nutrition. Adapted from Buskey and Stockwell (1993).

Egg release rates by adult female\_Acartia tonsa ranged from 20-60 eggs per female per day in Baffin Bay before the brown tide began (Figure 31). After the brown tide began, the egg release rate was consistently below 5 eggs per female per day.

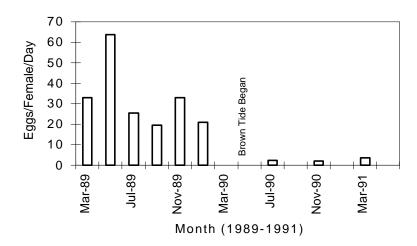


Figure 31. Egg release rates of adult female *Acartia tonsa* before and during the brown tide, based on 48 hour field incubations. Adapted from Buskey and Stockwell (1993).

Gut pigment contents can be used to estimate grazing rates of mesozooplankton. Before the brown tide began, gut pigment contents for adult female *Acartia tonsa* ranged from 2 -18 ng pigment per copepod. Gut pigment contents were at the detection limit of our analytical technique (< 1 ng chl a /copepod) following the brown tide, even though surface water chlorophyll concentrations were 2-10x higher (Figure 32).

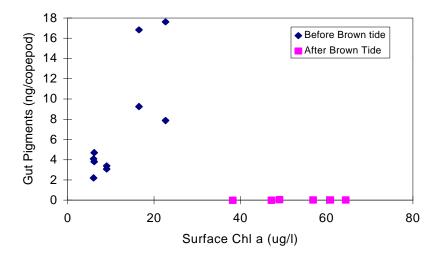


Figure 32. Daytime gut pigment (chlorophyll <u>a</u> plus phaeopigments) concentrations for adult female *Acartia tonsa* compared to phytoplankton biomass (chlorophyll <u>a</u>) before and during the brown tide. High gut pigment concentrations indicate active feeding on phytoplankton. Adapted from Buskey and Stockwell (1993).

The observed changes in zooplankton populations could have been due to the nutritional inadequacy of the brown tide alga to support zooplankton growth and reproduction, or there may be a substance produced by the algae that interferes with zooplankton feeding. Lower egg laying rates were reported for *Acartia tonsa* from Narragansett Bay, RI, when fed phytoplankton collected in the field during an *Aureococcus* bloom (Durbin and Durbin, 1989). Increases in body size, condition factor (a ratio of weight to a unit of length), egg laying rate and gut pigments were reported when field collected *Acartia tonsa* were fed cultured algae in their preferred size range during laboratory experiments.

Microzooplankton populations consisting mainly of ciliates, copepod nauplii and rotifers, were generally abundant before the brown tide began, with populations generally ranging between 20-200 per ml. After the brown tide began, the microzooplankton populations remained below 30 per ml (Figure 33). Microzooplankton grazed ca. 85-98% of the phytoplankton standing stock per day before the brown tide, but < 3% per day during the brown tide (Figure 34). The inability of microzooplankton grazers to control populations of the brown tide alga may result from the production of substances that inhibit the grazing and/or growth of microzooplankton. Another possible explanation might be that the mesozooplankton exerted additional predation pressure on microzooplankton populations during the brown tide, due to the lack of phytoplankton food in their preferred size range.

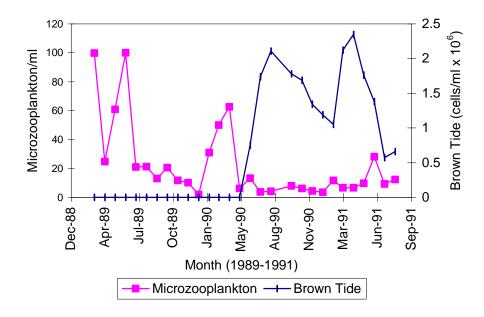


Figure 33. Microzooplankton abundance and brown tide cell concentrations at Station C in Baffin Bay before and during the brown tide. Adapted from Buskey and Stockwell (1993).

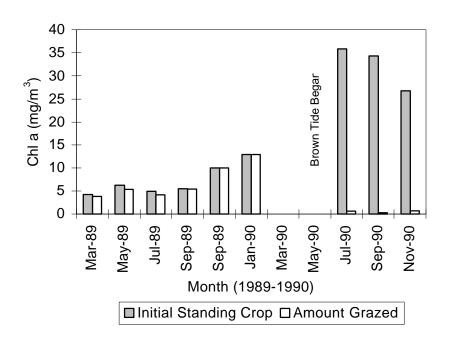


Figure 34. Microzooplankton grazing of phytoplankton standing stock before and during the brown tide, based on field incubation using the dilution technique of Landry and Hassett (1982). Adapted from Buskey and Stockwell (1993)

# **Laboratory Studies**

Laboratory studies of the effects of the Texas brown tide alga on zooplankton have been carried out by Dr. Edward J. Buskey of the University of Texas Marine Science Institute. The ciliate *Strombidinopsis sp.* showed a typical numerical response of increasing specific growth rate with increases in food concentration until maximum growth rate is reached, when the food offered was *Pyrenomonas salina*. The threshold concentration for growth appeared to be ca. 0.1 mg C I<sup>-1</sup>, and a maximum specific growth rate of 0.96 d<sup>-1</sup> was achieved at a food concentration of 1 mg C I<sup>-1</sup> (Figure 35). When this same species was fed the Texas brown tide alga, a different numerical response was found. All specific growth rates were negative, indicating mortality rather than growth on this food source. Since specific growth rates became more negative as food concentrations of brown tide increase (i.e. death rate increased), it appears that the brown tide is toxic to this species.

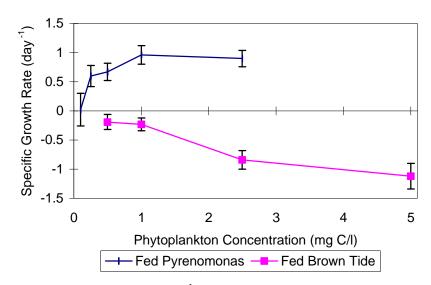


Figure 35. Specific growth rate (d<sup>-1</sup>) of the ciliate *Strombidinopsis sp.* on various concentrations of the Texas brown tide alga and on *Pyrenomonas salina*. Error bars represent the standard error of the slope of line for the natural logarithm of the number of cells regressed against time, used to determine specific growth rates. Adapted from Buskey and Hyatt (1995).

In contrast, the ciliates *Fabrea salina* and *Euplotes sp.* grew well on the brown tide. Maximum specific growth rate for *F. salina* of 0.52 d<sup>-1</sup> was achieved at 1 mg C l<sup>-1</sup> of brown tide. However, the numerical response of *F. salina* to various concentrations of the brown tide alga shows a decreasing growth rate at food concentrations above 1 mg C l<sup>-1</sup>, falling to 0.25 d<sup>-1</sup> at 5 mg C l<sup>-1</sup> (Figure 36). In contrast, *F. salina* fed *Isochrysis galbana* showed a more typical numerical response curve, with growth rate remaining high at higher food concentrations (maximum specific growth rate of 0.71 d<sup>-1</sup> at 5 mg C l<sup>-1</sup>.) The ciliate *Euplotes sp.* showed a similar numerical response when fed the brown tide alga. Maximum specific growth rates of 0.5 d<sup>-1</sup> were observed at a brown tide concentration of 1 mg C l<sup>-1</sup>, but specific growth rates fell to 0.29 at 5 mg C l<sup>-1</sup> (Figure 37). Growth of *Euplotes sp.* was higher when fed *I. galbana* at 2.5 or 5 mg carbon l<sup>-1</sup> than when fed similar concentrations of the brown tide.

The Texas brown tide alga did not support the growth of the heterotrophic dinoflagellate *Noctiluca scintillans*. However, there is no evidence that the brown tide alga is highly toxic to *N. scintillans*, since growth (death) rate was only -0.04 d<sup>-1</sup> at 5 mg C I of brown tide. Specific growth rates of *N. scintillans* on *Thalassiosira sp.* ranged from 0.38 d<sup>-1</sup> for 0.1 mg carbon I<sup>-1</sup> to 0.6 d<sup>-1</sup> for 1.0 mg carbon I<sup>-1</sup> (Figure 38). When a mixture of *Thalassiosira sp.* and the brown tide alga was offered as food, the specific growth rate ranged from 0.22 d<sup>-1</sup> to 0.38 d<sup>-1</sup>. Even though total food concentration was twice as high when equal amounts of brown tide and *Thalassiosira sp.* were offered as food, growth rates were always lower than when *N. scintillans* were offered *Thalassiosira sp.* alone.

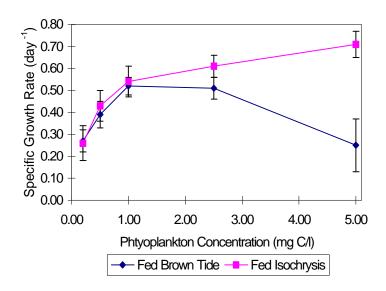


Figure 36. Specific growth rate (d<sup>-1</sup>) of the ciliate *Fabrea salina* on various concentrations of the Texas brown tide alga and on *Isochrysis galbana*. Adapted from Buskey and Hyatt (1995).

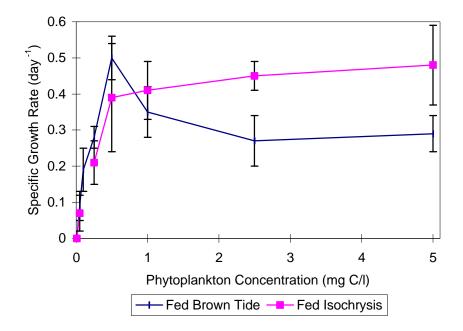


Figure 37. Specific growth rates (d<sup>-1</sup>) of the ciliate *Euplotes sp.* on various concentrations of the Texas brown tide alga and on *Isochrysis galbana*. Adapted from Buskey and Hyatt (1995).

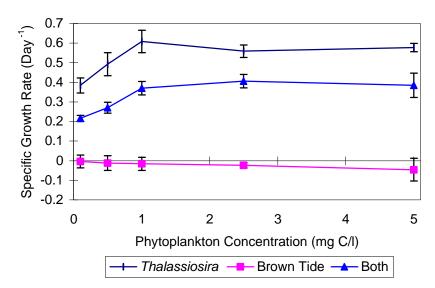


Figure 38. Specific growth rates (d<sup>-1</sup>) of the heterotrophic dinoflagellate *Noctiluca* scintillans on various concentrations of the Texas brown tide alga, *Thalassiosira sp.* or equal concentrations of both species (twice the total food concentration). Adapted from Buskey and Hyatt (1995).

The small heterotrophic dinoflagellate *Oxyhrris marina* did not grow on brown tide at food concentrations below 0.1 mg C I<sup>-1</sup>, but grew well on higher concentration of this species (Figure 39). Maximum specific growth rates of 0.55 d<sup>-1</sup> were observed at a concentration of 5 mg C I<sup>-1</sup>. However, *O. marina* grew faster on low concentrations of *Isochrysis galbana*, and reached maximum growth at 0.5 mg C I<sup>-1</sup>. Growth rates of *O. marina* were higher when fed equivalent concentrations of *I. galbana* than when fed the brown tide alga at concentrations below 5 mg C I<sup>-1</sup> (Figure 39).

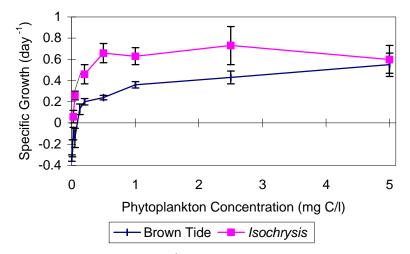


Figure 39. Specific growth rates (d<sup>-1</sup>) of the heterotrophic dinoflagellate *Oxyhrris* marina on the Texas brown tide alga and on *Isochrysis galbana*. Adapted from Buskey and Hyatt (1995).

The Texas brown tide alga did not support the growth of the rotifer *Brachionus* plicatilus at any food concentration. Specific growth (death) rates were similar to those for rotifers that were starved over the same 3 day period (ca. -0.15 d<sup>-1</sup>). At a brown tide concentration of 5 mg C I<sup>-1</sup>, specific growth (death) rate decreased to -0.39. When the rotifers were fed *Isochrysis galbana*, specific growth rates ranged from 0.19 to 0.61 d<sup>-1</sup> (Figure 40). However, when *B. plicatilus* was fed an equal amount of both *I. galbana* and the Texas brown tide alga (yielding twice the total phytoplankton concentration), *B. plicatilus* showed little or no growth.

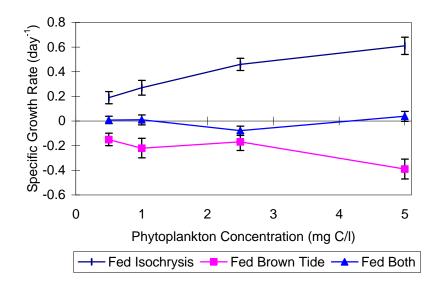


Figure 40. Specific growth rates (d<sup>-1</sup>) of the rotifer *Brachionus plicatilus* on the Texas brown tide alga, *Isochrysis galbana* and equal concentrations of each (twice the total food concentration). Adapted from Buskey and Hyatt (1995).

When groups of 36 *Acartia tonsa* nauplii were raised in 3 ml cell wells in tissue culture plates, the group held without any food exhibited daily mortality and were all dead by the end of a five day period. For a similar group of nauplii held in 3 ml of seawater containing brown tide at a concentration of 5 mg C I<sup>-1</sup>, there was extensive mortality on the second day, and all nauplii were dead by day 3. For groups of nauplii raised on 5 mg C I<sup>-1</sup> of *Isochrysis galbana, Pyrenomonas salina* or a combination of the two foods, over 85% of the nauplii were still alive at the end of the 5 day period (Figure 41). Since the brown tide appeared to settle to the bottom of the cell wells over the course of the experiment, subsequent experiments were done with groups of 50 nauplii in 50 ml tissue culture flasks rotated at 2 rpm to keep the algae in suspension. Replicate experiments were run at 2, 3.5 and 5 mg C I<sup>-1</sup>. Survival of *A. tonsa* nauplii ranged from 1% to 6% on the brown tide alone, from 70 to 83% on *I. galbana* alone and from 41 to 55% on a combination of equal amounts of each food (twice the food concentration) (Figure 42).

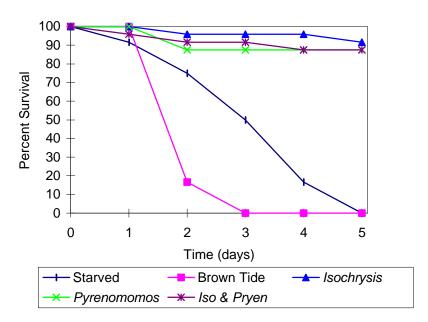


Figure 41. Survival of groups of 24 nauplii of the copepod *Acartia tonsa* fed 5 mg C I<sup>-1</sup> of the Texas brown tide alga, *Isochrysis galbana*, *Pyrenomonas salina*, a combination of *I. galbana* and *P. salina* or starved over a 96 hour period. Adapted from Buskey and Hyatt (1995).

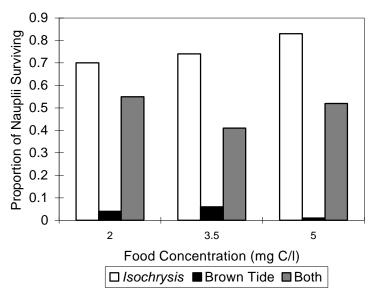


Figure 42. Survival of groups of 50 nauplii of the copepod *Acartia tonsa* fed *Isochrysis galbana*, the Texas brown tide alga or a combination of both (twice the total food concentration) at food concentrations of 2, 3.5 and 5 mg C I<sup>-1</sup> over a 96 hour period. Each bar is the mean value of two replicate experiments. Adapted from Buskey and Hyatt (1995).

Egg release rates for adult female *Acartia tonsa* fed the Texas brown tide alga at a food concentration of 1.5 mg C I<sup>-1</sup> was  $3.4 \pm 2.3$  (mean  $\pm$  1 SD, n=6) eggs per female per day, which was not significantly different from the egg release rates of  $1.7 \pm 0.7$  for *A. tonsa* that had been starved over the same 48 h period (t-test, p = 0.05). *A. tonsa* females fed similarly sized small phytoplankton species showed intermediate egg release rates of  $9.3 \pm 2.6$  eggs per female per day when fed 1.5 mg C I<sup>-1</sup> of *Isochrysis galbana* (5 µm diameter) and  $13.1 \pm 3.5$  eggs per female per day when fed 1.5 mg C I<sup>-1</sup> of *Emiliania huxleyi* (4 µm diameter). Highest egg release rates of  $25.9 \pm 7.2$  eggs per female per day were measured for *A. tonsa* fed 1.5 mg C I<sup>-1</sup> of the diatom *Thalassiosira sp.* When *A. tonsa* females were offered a combination of 1.5 mg C I<sup>-1</sup> each of *Thalassiosira sp.* and the Texas brown tide alga (3 mg C I<sup>-1</sup> total), egg release rates were  $26.9 \pm 3.6$  eggs per female per day, which is not significantly different from the release rate when the copepods were fed *Thalassiosira sp.* alone (t-test,  $\alpha = 0.05$ ) (Figure 43).

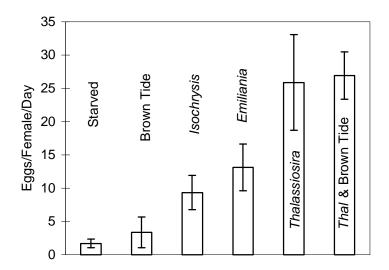


Figure 43. Mean egg release rates (eggs female<sup>-1</sup> day<sup>-1</sup>) of adult female *Acartia tonsa* fed 1.5 mg C I<sup>-1</sup> of the Texas brown tide alga, *Isochrysis galbana, Emiliania huxleyi*, *Thalassiosira sp.*, a combination of *Thalassiosira sp.* and brown tide, or starved. Each bar represents the mean (± SD) of eight replicate experiments. Adapted from Buskey and Hyatt (1995).

The Texas brown tide alga appears to be a poor food for a variety of zooplankton species. It supports no growth of the ciliate *Strombidinopsis sp.*, the heterotrophic dinoflagellate *Noctiluca scintillans* or the rotifer *Brachionus plicatilus*. It is not unusual to find zooplankton that can not be cultured on a particular species of phytoplankton; some can only capture particles in a relatively narrow size range (Fenchel, 1980). However *N. scintillans* can be grown on a wide range of phytoplankton species, including species of similar size (Buskey, 1995) and *B. plicatilus* is an easy to

culture organism widely used as a food for larval fish. Based on the results of this study, there is evidence that the brown tide may be directly toxic to some species of zooplankton, at cell concentrations similar to those found in nature. For the ciliate Strobidinopsis sp. (Figure 35) and for the rotifer B. plicatilus (Figure 40), mortality rates increase with increasing brown tide concentration. For one experiment with Acartia tonsa nauplii, mortality was faster in the presence of the brown tide than when no food was offered (Figure 41). Additional evidence for toxicity of the brown tide to some species of zooplankton comes from the decrease in survival of A. tonsa nauplii when both a suitable food (Isochrysis galbana) and the brown tide are offered together (Figure 42). In addition, when both *I. galbana* and the brown tide are offered together, growth of the heterotrophic dinoflagellate N. scintillans and the rotifer B. plicatilus are inhibited (Figures 38 & 40). In contrast, there is little evidence that the related species Aureococcus anophagefferens is toxic to microzooplankton. No evidence was found for changes in protozoan grazing rate or for suppression of growth in protozoans fed A. anophagefferens, nor was there any evidence that A. anophagefferens caused a reduction in protozoan populations in nature (Caron et al., 1989).

The brown tide alga appears to be a poor food item for Acartia tonsa, the dominant mesozooplankton in the Laguna Madre. Egg release rates of adult females fed the brown tide were not significantly different from those held without food over the same time interval. This may have been due in part to the small size of the brown tide cells (4-5 µm diameter), which is outside the optimum size range for particle capture by A. tonsa (Berggreen et al., 1988). However, A. tonsa females produced an intermediate number of eggs on two similarly small sized algal species, indicating that size alone was not the problem. There was no evidence of brown tide toxicity to adult female A. tonsa at 1.5 mg C l<sup>-1</sup>, since there was no direct mortality to adults and egg release was not lowered with the combination of Thalassiosira and brown tide. Lower egg release rates are reported for A. tonsa fed picoalgae during an A. anophagefferens bloom in Narragansett Bay, (Durbin and Durbin, 1989). In addition to lowering the egg release rates of adult females, the presence of the brown tide resulted in lower survival of A. tonsa nauplii, suggesting toxic effects. The Texas brown tide alga has also been shown to be toxic to first feeding red drum and spotted sea trout larvae (G.J. Holt, personal communication) but it does not appear to have adverse affect on adult fish populations.

Field evidence also supports the concept that the Texas brown tide alga is a poor food for zooplankton and disrupts trophic transfer in the planktonic food web. Mesozooplankton abundance (mainly *Acartia tonsa*) was lower in the Laguna Madre after the brown tide began than in the preceding year, and adult female *A. tonsa* were smaller and produced fewer eggs in field incubations than before the brown tide began (Buskey and Stockwell, 1993). Microzooplankton abundances were also lower after the brown tide began, and microzooplankton community grazing rates of phytoplankton standing stock were reduced from ca. 95% to less than 5% during the brown tide (Buskey and Stockwell, 1993). It is still difficult to understand why species of microzooplankton capable of growing on the brown tide have not flourished and helped bring the brown tide under control. It is possible that *A. tonsa* may be exerting

additional predation pressure on microzooplankton populations during the brown tide, due to the reduction of other species of phytoplankton in their preferred size range. It is well documented that *A. tonsa* also feed on microzooplankton (reviewed in Pierce and Turner, 1992), so it is possible that they are holding microzooplankton populations below a level where they can exert sufficient grazing pressure to help control the brown tide.

The related brown tide species, *Aureococcus anophagefferens*, has been demonstrated to inhibit feeding and cause mass mortality of the mussel *Mytilus edulis* (Tracey, 1988). Bricelj and Kuenstner (1989) concluded that this mortality was due to toxicity and not to small size or nutritional inadequacy of this phytoplankton species. Laboratory studies also indicate that *A. anophagefferens* reduces growth and causes high mortality of bay scallop larvae (Gallager et al., 1989). *A. anophagefferens* was shown to inhibit the cilliary activity of isolated gills of some bivalve species such as *Mercenaria mercenaria* and *Mytilus edulis* but not others that were affected by brown tide in nature such as *Argopecten irradians* (Gainey and Shumway, 1991). In contrast, the Texas brown tide alga is readily consumed by the dwarf surfclam *Mulinia lateralis* without adverse affects (Montagna et al., 1993), and there is no evidence that the Texas brown tide alga is toxic to adults of other species of invertebrates.

It seems likely that the Texas brown tide alga may produce a chemical that inhibits grazing or growth of microzooplankton, and/or may act as an allelopathic agent to reduce competition from other phytoplankton species. For example, both *Aureococcus anophagefferens* and the Texas brown tide contain high concentrations of dimethylsulfoniopropionate (DMSP) which is a precursor to dimethylsulfide (DMS) and acrylic acid (Keller et al., 1989; Stockwell et al., 1993). The role of DMSP in grazer inhibition is unclear, however. For example, *Phaeocystis pouchetii*, which also produces a large amount of DMSP (Keller et al., 1989) appears to be consumed by a wide variety of zooplankton (Admiraal and Venekamp, 1986; Huntley et al., 1987), whereas *Chrysochromulina polylepis*, which produces DMSP reduces growth and feeding rates of the tintinnid *Favella ehrenbergii* (Carlsson et al., 1990). The polysaccharide-like layer on the surface of *A. anophagefferens* contains a bioactive compound responsible for the reduction in cilliary beat frequency in bivalve gills (Gainey and Shumway, 1991), but no similar compounds have yet been identified in the Texas brown tide alga.

Many species of harmful and nuisance algae are toxic to a variety of marine organisms. Most of the toxins associated with harmful algal blooms were first noticed because of the extensive fish kills they caused or for the human health risk associated with consumption of contaminated seafood. It is difficult to understand why algal species would evolve toxins that were specifically aimed at humans or fish species that do not directly consume these algal species. It is possible that in some cases these toxins might be substances that have evolved for some other physiological function in the cell, which coincidentally happen to be toxic to human or marine life. In the cases of *Aureococcus anophagefferens* and the Texas brown tide alga, it appears as if toxic substances may be targeted at benthic and planktonic grazers that feed on these

species of phytoplankton, and although there are no direct threats to human health from these species, they may have a profound effect on the structure and function of the ecosystems in which they reside.

#### 3. Larval Fish

Red drum (Sciaenops ocellatus) and spotted seatrout(Cynoscion nebulosus) eggs and larvae were tested for survival, growth and feeding success in the presence of brown tide by Dr. Joan Holt of the University of Texas Marine Science Institute. Tests were carried out both in the laboratory and in situ in the Texas Parks and Wildlife fish production ponds at the GCCA-CPL Marine Development Center. Eggs from laboratory spawns placed in brown tide concentrations of 1 to 1.6 million cells per ml showed significantly reduced hatch rate and 2 or 3 day survival, compared to controls in seawater (Figure 44). Only 20% of spotted seatrout survived to day 3 post hatch. Red drum eggs also showed significantly reduced hatch rates and reduced survival in both laboratory studies and in in situ studies at the GCCA-CPL Marine Development Center (Figure 45) although survival rates of controls were 100% in the laboratory and only 20% on day two in the ponds. Eggs did considerably worse when placed in the ponds compared to the laboratory, probably due to high pH values, caused by the effects of high photosynthetic rates on the carbonate cycle. Values ranged from 8.9 to 9.6 in ponds with brown tide blooms, compared to normal seawater pH of 8.2. Studies are underway to determine the effect of increasing pH on red drum egg and larval survival.

# **Spotted Sea Trout**

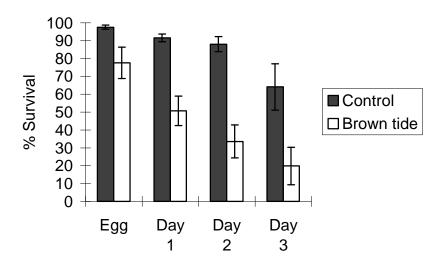


Figure 44. Survival of spotted seatrout eggs and early larvae in the presence and absence of brown tide algae at a concentration of 1.6 million cells per ml. Unpublished data from Dr. G. Joan Holt, University of Texas Marine Science Institute.

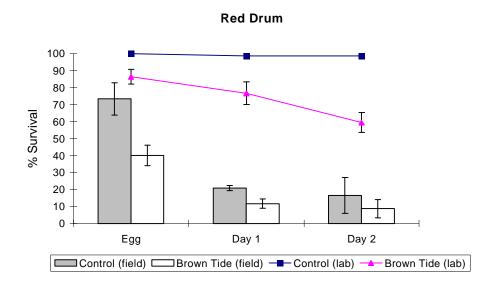


Figure 45. Survival of red drum eggs and larvae in the presence and absence of brown tide in both field and laboratory studies. Unpublished data from Dr. G. Joan Holt, University of Texas Marine Science Institute.

Feeding studies were carried out with larvae from eggs hatched in normal seawater. Spotted seatrout larvae fed at significantly reduced rates in brown tide at ages 5 to 7 days post hatch but not at day 14 (Figure 46).

# **Feeding Rates: Spotted Seatrout**

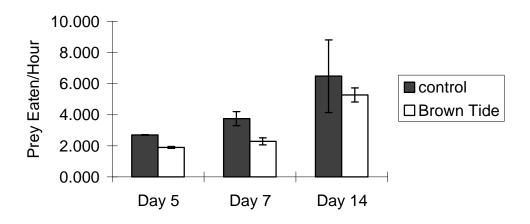


Figure 46. Feeding rates of larval spotted seatrout on rotifers at 5, 7 and 14 days posthatch, in brown tide water compared to bloom-free water. Significantly lower feeding rates were observed in the presence of the brown tide for 5 and 7 day old larvae. Unpublished data from Dr. G. Joan Holt, University of Texas Marine Science Institute.

These results are particularly important for spotted seatrout that spawn in the Laguna Madre where high concentrations of brown tide occur, and to the red drum production ponds at the GCCA-CPL Marine Development Center. The overall effects of brown tide on larvae can be interpreted to show that eggs spawned in water with high brown tide counts will not survive to first feeding and larvae that encounter high brown tide concentrations in the first two weeks of life will suffer high mortality and reduced feeding and growth rates.

Field data collected by Mr. Scott Holt of the University of Texas Marine Science Institute demonstrated that spotted seatrout larvae had reduced densities, averaged from 7 sites in the upper Laguna Madre (Figure 47), during the brown tide in 1992-1993 compared to collections from four months in 1989, before the brown tide began. Similar data from a site in the Port Mansfield channel (lower panel) where there was no measurable brown tide are quite variable, but there is no obvious reduction in larval density between the same two time intervals.

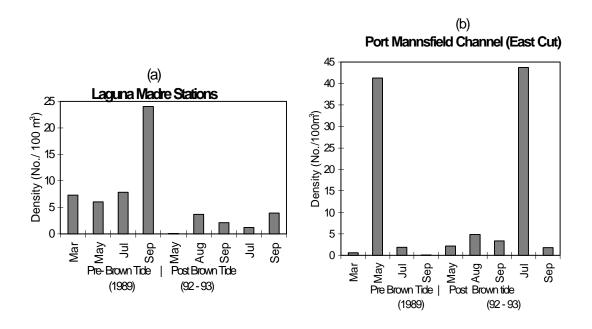


Figure 47. A comparison of spotted seatrout larval densities in two areas of the Laguna Madre for pre- and post brown tide periods. Panel a shows monthly means for seven sites in the Laguna Madre, all of which were impacted by the brown tide. Panel b shows similar data for a site in the Port Mansfield channel where there was no measurable brown tide. Unpublished data of Scott Holt, University of Texas Marine Science Institute.

When larval density of spotted seatrout is plotted against brown tide cell counts, for samples taken in the upper Laguna Madre, there appears to be a trend of decreasing larval density with increasing brown tide density (Figure 48). When the

density of black drum larvae is plotted against phytoplankton biomass measured as chlorophyll <u>a</u> concentration (Figure 49) there is a distinct pattern of lower larval density at higher chlorophyll concentrations, which are areas most highly impacted by the brown tide. In contrast, high chlorophyll concentrations seemed to have little impact on the density of larval anchovy (Figure 50).

#### **Spotted Seatrout Larvae**

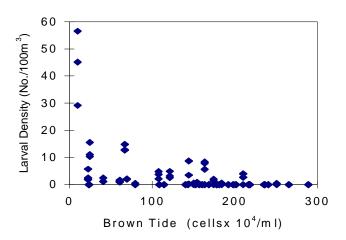


Figure 48. Variations in density of larval spotted seatrout with brown tide cell counts for collections from the Laguna Madre. Unpublished data of Scott Holt, University of Texas Marine Science Institute.

#### **Black Drum Larvae**

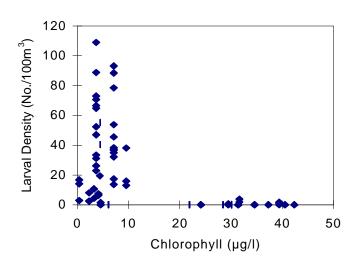


Figure 49. Variations in density of black drum larvae with changes in phytoplankton biomass measured as chlorophyll <u>a</u> concentration, for collections in Laguna Madre. Areas of high phytoplankton biomass represent brown tide affected areas. Unpublished data of Scott Holt, University of Texas Marine Science Institute.

# Larval Anchovy

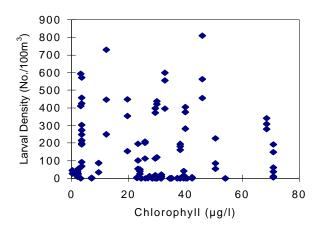


Figure 50. Variations in density of larval bay anchovy with changes in phytoplankton biomass measured as chlorophyll <u>a</u> concentration, for collections in Laguna Madre. Areas of high phytoplankton biomass represent brown tide affected areas. Unpublished data of Scott Holt, University of Texas Marine Science Institute.

#### 4. Benthos

The benthic organisms that live in the Laguna Madre include a large number of filter feeding invertebrates that could potentially have an important grazing impact on the brown tide, given the shallow depth of the water column. Also since strong seabreezes from the Gulf of Mexico generally keep the water column well mixed, stratification of the water column generally does not occur. Thus, layering which could isolate phytoplankton populations in surface water from potential grazers in the benthos does not occur.

Biomass of the macrobenthos (defined as benthic organisms > 0.5 mm) is generally higher in the seagrass beds of Laguna Madre than in the mud-bottom habitats of Baffin Bay (Figure 51). There was a decline in benthic biomass from >80 g dry weight per square meter to <30 g dry weight per square meter in Laguna Madre in 1989, preceding the brown tide, and a steep decline in the benthic biomass in Baffin Bay from 10 g dry weight per square meter to less than 0.01 g dry weight per square meter during 1990, the first year of the brown tide. The abundance of macrobenthos was quite variable in Baffin Bay before the beginning of the brown tide, but has remained low since the brown tide began (Figure 52). In Laguna Madre, macrobenthos abundance was high before the brown tide spread into the Laguna Madre, and has remained low since (Figure 52). Species diversity of macrobenthos in the Laguna Madre was > 40 species per 35 cm² before the brown tide began, and has remained at 40 species or below since the brown tide began through 1992 (Figure 53). Diversity of species in Baffin Bay has remained below 10 species per 35 cm² both before and during the brown tide (Figure 53).

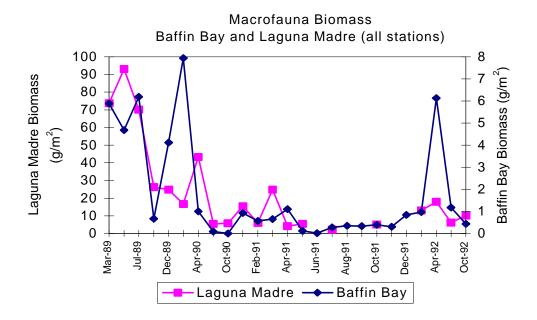


Figure 51. Macrobenthos biomass in Baffin Bay and the Laguna Madre from March 1989 through October 1992. Unpublished data provided by Dr. Paul Montagna, University of Texas Marine Science Institute.

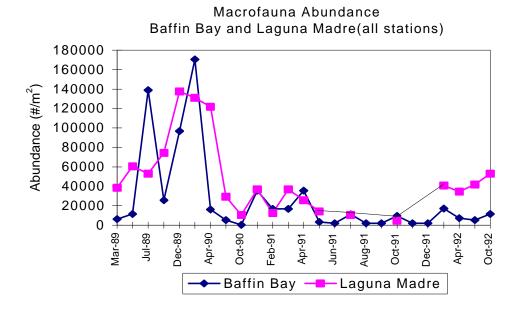


Figure 52. Macrobenthos abundance in Baffin Bay and the Laguna Madre from March 1989 through October 1992. Unpublished data provided by Dr. Paul Montagna, University of Texas Marine Science Institute.

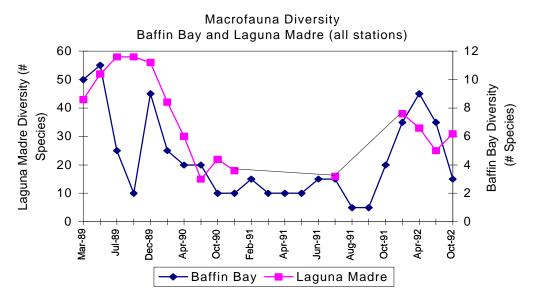


Figure 53. Macrobenthos diversity in Baffin Bay and the Laguna Madre from March 1989 through October 1992. Unpublished data provided by Dr. Paul Montagna, University of Texas Marine Science Institute.

The brown tide appears to have caused a reduction in macrobenthos biomass and abundance, and a reduction in species diversity in seagrass habitats. To the extent that this reduction is in populations of filter feeding invertebrates (as opposed to deposit and detritus feeders), this reduction in benthos may have reduced grazing pressure on the brown tide alga (Montagna et al., 1993). The filter feeding mollusk *Mulinia lateralis* nearly disappeared from Baffin Bay during 1990 and 1991 (Montagna et al., 1993). Montagna et al. (1993) found that adult *Mulinia lateralis* consumed the brown tide alga as well as three cultured species of phytoplankton. It was further estimated that at its peak density before the brown tide began (800 per square meter), its maximum clearance rate of 10 ml per hour would allow this population of clams to clear a 1.2 m water column in 150 hours or about 6-7 days. However, since the brown tide can double its population in 1-2 days under good growing conditions (Stockwell et al., 1993), even under ideal conditions these benthic filter feeders can not control brown tide populations.

#### 5. Adult fish and shellfish populations.

The extended brown tide bloom had no apparent prolonged effect on populations of adult fish and shellfish. Game fish populations (red drum, black drum, and spotted seatrout) were sampled by gill net in the spring and fall (Figure 54). There is no apparent decline in the populations of these important recreational species; in fact there appears to be a substantial increase in black drum since the initiation of the brown tide. Small forage fish (bay anchovy and striped mullet) and commercially important shellfish (brown shrimp and blue crab) populations were sampled by bag

seine during the appropriate season (Figure 55). No prolonged decline in abundance has occurred since the initiation of the brown tide. Each population did experience a temporary decline in abundance close to the time of initiation of the brown tide. This decrease in numbers may represent the large fish kill caused by the December 1989 freeze, and/or the effects of the extended drought in 1989.

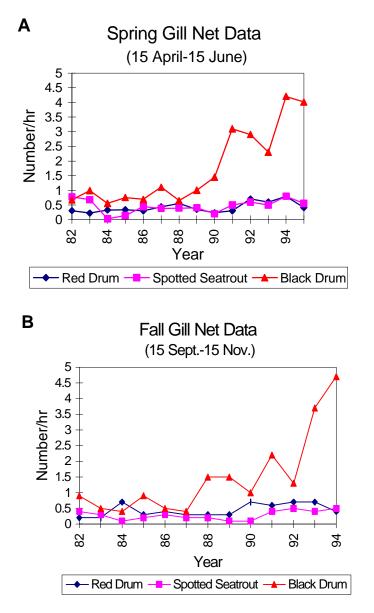


Figure 54. Seasonal average of three game fish species (red drum, spotted seatrout and black drum) based on spring (a) and fall (b) gill net sets at several randomly selected locations within the Laguna Madre. Data provided by Larry McEachron and Kyle Spiller, Texas Parks and Wildlife Department.

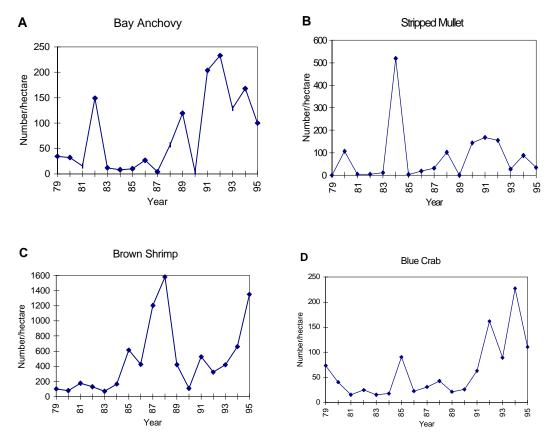


Figure 55. Seasonal average catch based on bag seine data at several randomly chosen sites within the Laguna Madre. Collection seasons for each species were: A. bay anchovy March-June, B. striped mullet May-June, C. brown shrimp April-July, D. blue crab March-June. Data provided by Larry McEachron and Kyle Spiller, Texas Parks and Wildlife Department.

The lack of adverse effects of brown tide on adult fish populations is in sharp contrast to its apparent effects on larval fish populations. In a nearly enclosed system such as the Laguna Madre, it might be expected that if larval fish abundance declined, adult fish populations would soon decline as well. Several possible explanations exist for this apparent paradox, but there is at present no way to determine which, if any, of the possible explanations is most plausible. For example, the brown tide may have enhanced the survival of post-larval, juvenile fish by reducing their susceptibility to visual predation by larger fish in the reduced visibility conditions associated with the brown tide. Another contributing factor may have been reduced sports fishing pressure in brown tide affected areas, due to reduced success experienced by many anglers in the low visibility waters. In addition, there have been no severe freezes affecting the Laguna Madre since the brown tide began, and increased fish populations may reflect recovery of populations from the severe freezes in the 1980's. A ban on commercial net fisheries since the early 1980's also could lead to the increase in adult population. It is also possible that additional fish may have migrated into the Laguna Madre from adjacent habitats not affected by the brown tide.

# IV. Identification of Probable Causes

Laguna Madre is vulnerable to ecosystem disruption due to its lack of consistent freshwater inflow, making hypersaline conditions likely during periods of extended drought. This propensity for extreme hypersaline conditions has been reduced somewhat in recent decades by the construction of the Gulf Intracoastal Waterway. This channel allows, at least, a minimum amount of water exchange with the Gulf of Mexico.

The long turnover times estimated for waters in Baffin Bay and Laguna Madre clearly contribute to the persistence of the brown tide bloom. The time required to exchange all the water contained within the Laguna Madre with adjacent areas in the Gulf of Mexico and Corpus Christi Bay is on the order of one year. This makes it difficult to disperse and dilute an algal bloom for a species that can easily double its population in a matter of days if sufficient nutrients are available. There has been much public discussion of the possibility of eliminating the brown tide through increasing the circulation of the Laguna Madre by raising the John F. Kennedy Causeway or by opening new passes between the Gulf of Mexico and the Laguna Madre. In order for these engineering projects to have an impact on the brown tide, they would have to substantially reduce the residence time of water in the Laguna Madre, from one year to a matter of weeks, as is the case in other Texas bays where the brown tide has bloomed but not persisted (Shormann, 1992). Recent studies of the impact of raising the Kennedy causeway for the Texas Department of Transportation by Shiner, Moseley and Associates indicate that the cost of raising the Kennedy causeway through most of its length would be on the order of \$50 million dollars, and that this major engineering project would have a minimal impact on the turnover time of water in the upper Laguna Madre. The total amount of water exchange may increase slightly, but the major impact would be to spread this exchange over a wider area, compared to the two channels that now handle most of the exchange. Other suggested projects, such as reopening Yarborough Pass would also be expensive, initially and in terms of maintenance costs, and there is little evidence that they would increase circulation enough to eliminated the brown tide. By comparison, the lower Laguna Madre, which has better circulation than the upper Laguna Madre due to major passes at Port Isabel to the south and Port Mansfield to the north, still has persistent blooms of the brown tide. It would be interesting to determine if the brown tide in lower Laguna Madre would persist without the major pulse of brown tide pushed south each winter by the north winds of strong cold fronts.

Laguna Madre fish populations are vulnerable to extensive die-offs during the passage of severe cold fronts. Due to a shallow (1.2 m) average depth (Armstrong, 1987), few deep water refuges and no direct passes to the Gulf of Mexico, extreme cold fronts, with below freezing temperatures, during winter can cause dramatic drops in water temperature resulting in mass mortality of fish and benthic invertebrates (DeYoe and Suttle, 1994). It has been calculated that the nutrients released from the fish and

invertebrate die-off in the freezes of December 1989 would have provided sufficient nutrients to explain the initiation of the brown tide bloom in January 1990. However, there has been much public discussion of the possible role of agricultural runoff from the King Ranch in the initiation and maintenance of the brown tide. A large amount of land adjacent to the Laguna Madre is alleged to have been changed from grazing to agricultural use prior to the initiation of the brown tide, and concerns have been raised that runoff from this agricultural land may have contributed to the initiation of the bloom, and may be a continuing source of nutrients helping to maintain the bloom. This possibility has not yet been explored, but is currently under investigation by the Texas Agricultural Experiment Station and Corpus Christi Bay National Estuary Program.

It is clear from studies of changes in the Laguna Madre ecosystem before and during the initiation of the brown tide, that changes in biotic components of the Laguna Madre ecosystem also indirectly contributed to the initiation of the brown tide. A period of extended drought in 1989 had raised the salinity in the upper reaches of Baffin Bay to >60 ppt. This is nearly twice the salinity of normal seawater, and many marine species cannot survive under these high salinity conditions. Population of zooplankton and benthic organisms, the major feeders on water column algae, were declining prior to the onset of the brown tide. With depressed populations of planktonic and benthic grazers, it became much easier for a major bloom such as the brown tide to get started, since the normal biological controls on algal growth were impaired. Once the bloom became established, the algae was capable of growing faster than the grazers could remove it.

There are indications that the brown tide alga is toxic to some species of planktonic grazers, and this resultant reduction in grazing pressure may help the brown tide bloom persist. In particular, it appears that brown tide concentrations above a threshold concentration of approximately one million cells per ml are either directly toxic to some species of zooplankton or inhibit their growth (Buskey and Hyatt, 1995). Additional research on the potentially toxic effects of brown tide on marine organisms, including their planktonic and benthic grazers and larval fish is needed.

## V. Identification of Data and Information Gaps

Compared to the body of information available on blooms of the East Coast brown tide alga *Aureococcus anophagefferens*, very little research has been performed on the Texas brown tide alga to date. Initial strong support of research efforts by the Texas Higher Education Coordinating Board (THECB) have provided a wealth of information about conditions before and during the initiation of the Texas brown tide. This is unique among studies of harmful algal bloom phenomena; usually studies do not begin until the bloom is already under way and recognized as a potential problem. The studies funded by the THECB also clearly documented the initial changes in the Laguna Madre ecosystem caused by the bloom, but much remains to be learned.

In particular, it is clear that very little is known about the autecology of the alga itself. For scientists, one clear indication of the lack of interest in this algal species itself is that after over five and one half years of algal bloom, this species has still not been taxonomically described. It is an embarrassment to everyone working with the brown tide that we still can only refer to it as the "brown tide alga". A taxonomic description of this species is critical to scientific communication, so that scientists can potentially identify this species from other parts of the world. Fortunately, a taxonomic description will soon be published (DeYoe, personal communication).

Most studies of the brown tide alga have been field studies of biomass distributions and primary production rates (Stockwell and Whitledge, unpublished), and the only studies of the alga under laboratory conditions are those of DeYoe and Suttle (1994) who provided important insights into the nutrient requirements of this species, and DeYoe et al. (1995) that examined gene sequences to examine the taxonomic relationship of this species to other algal taxa. Additional isolates of this alga need to be brought into culture, and a systematic study of the factors affecting its survival and growth needs to be undertaken. Since this species, like the East Coast brown tide *Aureococcus anophagefferens* is not readily cultured under conditions suitable for many other phytoplankton species (e.g. it does not grow well in f/2 media) a study of micronutrient requirements, including trace metals and vitamins could provide important insights into the conditions that favor the growth of this species.

VI. Recommendations for priority research and monitoring efforts

#### A. Research

- 1. To study and define the autecology of the brown tide alga in terms of the physical and chemical factors that affect its growth. Specifically to look at the effects of temperature, salinity, light intensity, macro- and micronutrients on the growth rate of the brown tide.
- 2. To identify possible toxins and/or inhibitory chemicals produced by the brown tide organism, their affects on the growth of other phytoplankton species (possible allelopathic effects) and on the survival, growth and feeding of potential grazers on the brown tide, including both planktonic (micro- and mesozooplankton) and benthic grazers. It should be emphasized that potential toxic effects should be examined on all life history stages of grazers, including the planktonic larvae of benthic macrofauna. Further study of the potential toxic effects of the brown tide on larval fish is also needed.
- 3. A method for positively identifying the Texas brown tide alga needs to be developed, such as a fluorescently labeled polyclonal antibody marker with high specificity for the brown tide, or a fluorescently labeled genetic marker, specific to a particular unique genetic sequence in the DNA or RNA of the brown tide alga. Using these methods, the brown tide alga could be positively identified at low cell concentrations to determine if it

is a common component of phytoplankton communities throughout the coastal zone of Texas and other areas of the Gulf of Mexico. Such a marker would also be useful for identifying brown tide cells in the stomach contents of grazers from protozoa to macrofauna, to help determine the extent to which natural grazer populations feed on the brown tide.

- 4. To investigate the use of various biological agents to help control brown tide populations, including planktonic and benthic grazers and possible pathogens such as viruses specific to the brown tide alga. It is doubtful if these agents could be used to eliminate the brown tide during periods of its peak abundance and extent, but they may be useful for breaking up seed populations during periods of low natural abundance of the brown tide and could also prove useful as control agents in mariculture facilities where the area that needs to be treated is small.
- 5. To investigate the role of non-point source pollutants, including fertilizer and pesticide runoff from agricultural areas on the growth and maintenance of brown tide blooms and associated plankton populations.
- 6. Historical studies of the Laguna Madre should be pursued to determine the historical importance of seagrass-based primary production versus phytoplankton based primary production in the Laguna Madre over the past several thousand years. If this can be tied in to data on paleosalinity and paleotemperature, as well as information on the occurrence of major hurricanes (via the sand deposits they leave in the sediment record) the importance of circulation with the Gulf of Mexico on the dominance of seagrass or phytoplankton can be determined. If biomarkers specific to diagenic compounds associated with the brown tide alga can be identified, it may also be possible to determine if the brown tide alga has bloomed for extended periods in the past.

# B. Monitoring

- 1. Continued monitoring of the areal distribution of seagrass beds in the Laguna Madre must be made so that the impact of the brown tide on the Laguna Madre ecosystem can be assessed.
- 2. Continued monitoring of the effects of the brown tide on the structure and function of the Laguna Madre ecosystem, especially finfish populations, will provide us with a basis for cost/benefit analysis for potential management strategies for dealing with the brown tide.
- 3. Continued monitoring of the distribution and abundance of the brown tide will increase our knowledge of the factors influencing the persistence of this bloom.

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4. A monitoring plan should be designed to quantify non-point source pollutants, including pesticides and fertilizers, and help identify their sources.

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