Bioavailability and Sources of Nutrients and the Linkages to Nuisance Drift Algae

Final Executive Report

Prepared for

The City of Sanibel in Partnership with Lee County

February 2011

Ai Ning Loh, Larry E. Brand, David W. Ceilley, Matthew Charette, Loren Coen, Edwin M. Everham III, David C. Fugate, Raymond E. Grizzle, Eric C. Milbrandt, Bernhard M. Riegl, Greg Foster, Keleigh Provost, Leslie L. Tomasello, Paul Henderson, Crystal Breier, Qian Liu, Taylor Watson, and Michael L. Parsons

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(Deliverable 10)

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Foreword

This document is the Executive Report for the Final Report (Deliverable 10) prepared for the City of Sanibel and Lee County. An accompanying document (the Technical Report) contains all of the information presented in the Executive Report, but also contains all of the methodological details, data presentation, and analysis of this study. This Executive Report is designed as a stand-alone document for those individuals interested more in the findings of the study, rather than all of the technical aspects utilized to reach the findings. The Technical Report should therefore be referred to when the reader wishes to learn more information on how the data were gathered and interpreted to obtain the presented results and findings.

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Executive Summary

Eutrophication (nutrient enrichment) is a progressively escalating problem in water bodies worldwide, including the Caloosahatchee River and Estuary (CRE). The nutrients (nitrogen and phosphorus) come from residential, agricultural, and municipal sources, entering coastal waters through a combination of surface discharges (canals and rivers) and by infiltration into groundwater and subsequent submarine discharge. Under the right set of environmental conditions (optimal growth conditions, adequate amounts of nutrients, relaxation of grazing pressure), a large bloom of macroalgae can occur, which can later detach from the seabed and drift in prevailing currents. While drift macroalgae blooms fill a number of positive ecological functions (e.g., shelter and food for invertebrates and small fish, nutrient removal), there are also a number of negative impacts associated with such blooms (e.g., shading of seagrass beds, reduction of water quality). The most apparent negative impacts are the aesthetic and odor-related issues resulting from a large biomass of drift macroalgae washing ashore.

This study, funded through a partnership between the City of Sanibel, Lee County, the Tourist Development Council and the West Coast Inland Navigation District, was prompted by a series of unusually large strandings of red drift macroalgae on the beaches of Sanibel Island, Bonita Springs, and Fort Myers Beach that occurred at various time periods between 2003 and 2007. The study was conducted over a two-year period beginning in May 2008 and was comprised of 10 study objectives (described below). The ultimate goal of this study was to provide resource managers with a clear picture of when, where and why a large-scale stranding event might occur and what actions might be taken to prevent or mitigate such an event. The findings of this study are presented in three parts: the Executive Summary, the Technical Summary, and the Technical Report.

Four of the objectives focused on the sources and availability of nutrients, and their potential role in producing macroalgae blooms in local waters. The objectives examined the relative importance of Lake Okeechobee-derived nutrients relative to basin (downstream) sources (Objective 1), the potential for decomposing organic matter within benthic sediments to promote a macroalgae bloom (Objective 2), the role of submarine groundwater nutrient inputs to coastal waters (Objective 3), and possible nutrient reduction strategies to reduce the potential for macroalgae blooms (Objective 8). Five other objectives were conducted to provide a more complete picture of the processes needed to generate large-scale stranding events, including the identification and mapping of substrate suitable for macroalgal growth and accumulation (Objective 4), identification and quantification of macroalgal species assemblages from inshore, nearshore and offshore locations to ascertain how macroalgal abundance changes seasonally and how these assemblages compared to those collected from various stranding events (Objective 5), the hydrological (tide and currents) and meteorological (wind) conditions needed to transport detached macroalgae to shore (Objective 7), the potential role of urchin grazing for controlling algal biomass, thereby preventing blooms (Objective 9), and the potential environmental impacts of macroalgae decomposing on the beach (Objective 6). The final objective (Objective 10) used the findings of the nine other objectives to synthesize management recommendations that can reduce and mitigate the impacts of drift algae strandings on our area beaches.

The primary findings of the first nine objectives can be summarized as follows. Nutrient concentrations and microalgal biomass (single-celled algae) decreased downstream from Lake Okeechobee to the Gulf of Mexico (see Objective 1). These results demonstrate that 1) the primary source of nutrients to the CRE are Lake Okeechobee and the upper watershed of the CRE, and 2) nutrients dilute downstream as the nutrient-rich fresh waters from the lake and surrounding watershed mix with nutrient-poor waters of the Gulf of Mexico via tidal (and conservative mixing) processes (see Objectives 1 and 7). Bioassay experiments indicated that microalgal growth was stimulated when additional nitrogen-based nutrients were added to collected water samples. Phosphate additions did not elicit a similar response. These results indicate that microalgae (and possibly macroalgae) will respond most strongly to changes in nitrogen-based nutrients rather than phosphate. Nitrogen-reduction strategies therefore represent a logical measure to reduce microalgal and macroalgal biomass in the CRE and surrounding waters. A large proportion of the dissolved nitrogen-containing compounds found in the CRE are organic molecules (~80% of the total), which are generally considered to be unusable for algal growth. Results of this study demonstrate that microalgae can (indirectly) utilize organic nitrogen sources for growth. Therefore, further assessments of nitrogen-based nutrients (and any nitrogen reduction strategies) should not only focus on the inorganic nitrogen-based nutrients (i.e., nitrate and ammonium), but should also include the much more abundant organic compounds found in the CRE.

An analysis of data published in earlier studies, coupled with findings of this study, indicate that 18 – 27% of the nutrients entering the tidal portion of the CRE (i.e., below S-79) are derived from Lake Okeechobee (see Objective 8). An equal proportion (25 – 27%) comes from submarine groundwater inputs (see Objective 3), with the remainder (~40 – 50%) coming from the local watershed. Nutrients regenerating from the benthic sediments are not a significant contributor of nutrients within the CRE (see Objective 2). These results indicate that nitrogen-reduction measures applied to the local watershed could have a substantial impact on nutrient levels in the tidal portion of the CRE. Additionally, the results indicate there does not appear to be a substantial "legacy effect" of past high run-off events; i.e., high flows (and related nutrient loads) from past years have not left a lasting nutrient signature in the CRE that could continue to impact water quality and stimulate algal blooms.

During the course of this study we responded to five relatively small deposition events (see Objective 6). Two of these events (Fort Myers Beach in June 2008 and Sanibel Island in July 2009) were significantly larger than the other three, but were smaller than the events of 2003-2007. The Sanibel event involved *Sargassum* spp., a brown macroalga species containing air-filled bladders that allow it to drift in surface waters over great distances. Winds and currents transported *Sargassum* from the open waters of the Gulf of Mexico. This event was therefore more of a physical nature (i.e., the product of winds and currents) rather than a local, nutrient-induced event. The other four deposition events observed during this study also differed from previous events by being relatively small and ephemeral, with durations of two weeks or less. The lack of significant algal stranding events may be related to lower freshwater inputs (and therefore nutrient inputs) in the region in 2008 – 2010 versus 2003 – 2007, as depicted by the significantly lower amounts of precipitation and water released through S-79 in the last three years (see Objective 8). Lower hurricane activity since 2007 may have also reduced freshwater inputs needed to support algal growth and wave energy to detach algae (see Objective 9).

Despite the lack of large drift algae blooms during this two-year study, we found several new lines of information related to the spatial and temporal patterns of species composition that can be used to deduce the source and timing of drift macroalgae stranding events (see Objective 5). Algal biomass tends to be highest in inshore areas during the spring in contrast to the offshore areas where peak biomass occurs during the late summer. The species composition differed consistently between inshore and nearshore/offshore communities, where nearshore/offshore communities had higher species richness and diversity. In the limited cases where intact, growing algal populations could be compared with those washing up on area beaches, inshore communities were more similar to algae deposited on the beach versus offshore communities (including artificial reefs), with a notable exception observed in November 2010, in which the stranded algae contained species most commonly associated with offshore areas. These findings suggest that the drift algae growing on Lee County artificial reefs do not appear to be a source of the drift algae washing up on beaches. Rather, local, inshore locations appear to contain the biomass potential, species composition, and large areas of optimal substrate (see Objective 4) necessary for a large-scale drift algae event.

While results indicate that algal growth is highest in the spring and summer, the resultant algal biomass is influenced by grazing organisms (e.g., sea urchins) that can consume the algae, thereby preventing the build-up of large amounts of algae. We found that significant accumulations of drift or attached algae corresponded with low grazer populations at inshore sites in Pine Island Sound and San Carlos Bay (see Objective 9). However, the lack of significant algal biomass at other locations was not due to grazer activity, but rather appeared to reflect nutrient and/or substrate limitation, where the lack of nutrients or adequate substrate was preventing a significant build-up of algal biomass. Urchins were often absent in inshore areas, where large changes in salinity may be creating areas inhospitable to urchin survival and growth. These results indicate that grazers can prevent significant build-ups in algal biomass in areas without large fluctuations in salinity (e.g., near passes). Conversely, the lack of algae in some areas may be due to grazer activity in some cases, but nutrient/substrate limitation in other cases.

Prior to this study, little was known about potential macroalgal habitat, raising a fundamental question. Were large-scale blooms initiated and propagated within nearshore habitats, on the distant offshore hard-bottom reefs, or from even more distant sources? Knowing where the blooms might originate, relative to the gradient of nutrient enrichment and available substrate, is necessary for making informed water management decisions and useful for locating and monitoring active macroalgae events. Hydroacoustic and towed-video surveys were conducted in tandem to ascertain the location and extent of seabed suitable for macroalgae attachment and growth (see Objective 4). The hydroacoustic (2-11 km offshore) and towed-video (up to 24 km offshore) data were classified into one of five visually-apparent categories of seabed roughness. The majority (approximately 80%) of acoustic classifications were of soft bottom sediments, which are not suitable for macroalgae attachment. In the Gulf of Mexico, study areas were acoustically classified as >95% soft sediments from nearshore to 11 km offshore. The towed-video transects over a larger area of focus indicated there were relatively small areas that harbored large concentrations of shelly and/or live hard-bottom, occurring sporadically at distances greater than 10 km offshore. However, there were two significant expanses of rough seabed thought to be suitable for drift algae attachment, covering an area of 19 km^2 (7.3 mi^2). The first was a large area of seagrass beds and live hard-bottom in the mouth of San Carlos Bay, where large amounts of drift algae were variably present during the April-May 2009 surveys. The second was an area of shell hash offshore of Lighthouse Point, located near a large sand bar that extends from the beach to approximately 6 km offshore. The average depths of these two areas were only 5.0 and 4.0 m, so sufficient sunlight to initiate a drift algal bloom would be likely much of the year. These two areas on or near the mouth of San Carlos Bay are presumably potential source areas for drift algae attachment and growth. Hydrodynamic modeling (see Objective 7) showed that an inshore or nearshore bloom could be readily transported to Sanibel and Fort Myers beaches, given the right set of meteorological conditions. Modeling results also showed how wind events, compared to tidal and riverine discharge, could alternatively transport water (and thus drift macroalgae) from Pine Island Sound and San Carlos Bay onto Fort Myers Beach and into Estero Bay.

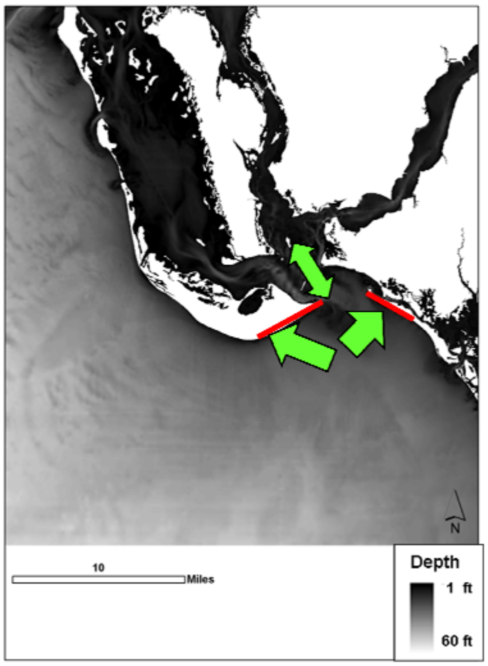
Based on the results of this study, coupled with the information gathered in previous stranding events, we have devised four possible scenarios for macroalgal production and stranding on Sanibel and Lee County beaches. These scenarios are presented in order of likelihood of occurrence and potential frequency, with the most likely and frequent presented first and the least explained, and low probability for prediction presented last. The first scenario (Scenario A) is the production of high amounts (biomass) of macroalgae inshore and around the Sanibel Causeway from local sources (e.g., mapped high irradiance seagrass and live bottom areas). The algal biomass achieved in Scenario A is greater than any observed in this study, and would be the product of greater nutrient inputs related to rainfall and/or discharges through S-79 greater than those recorded since 2008. The local production of algae is not controlled by abundant grazers (urchins), but appears to be inhibited by warm temperatures (>30° C), which may be a factor leading to algal detachment from the bottom. The community of macroalgae growing in this area reaches a maximum biomass between February and June and once large enough, fragments will be transported by tidal exchange out the tidal passes and onto the beaches. The composition of this community is distinguishable, to some degree, from the other scenarios because of the species composition and its condition (e.g., appears fresh). For example, the most common algae reported from the 2003/4 stranding events are species that we found commonly at inshore and nearshore locations (e.g., *Solieria filiformis* and *Hypnea spinella*).

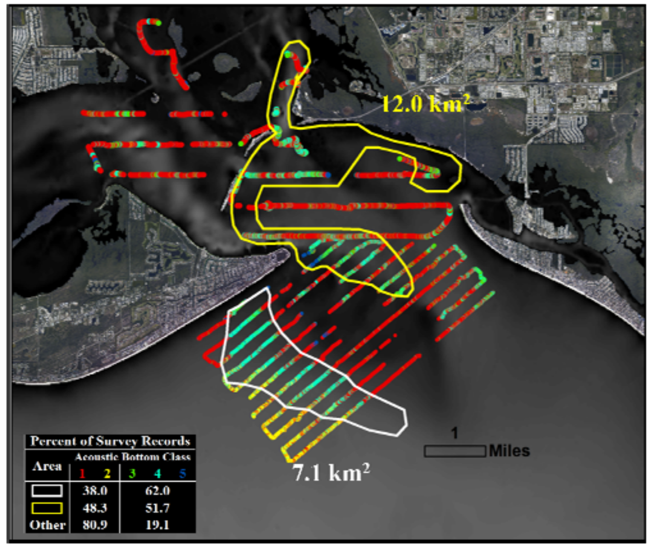
In Scenario B, the sources of macroalgae are not as clearly delineated but are relatively small areas of limestone ledges and live bottom in the nearshore waters. One example can be found near Redfish Pass, a ledge in 12 m of water with a diverse assemblage of macroalgae and a variety of corals and other invertebrates. The biomass of these events will be low and they are most likely to occur on W. Sanibel beaches (Bowman's Beach) as a result of storm activity or large waves causing fragmentation of the algae. The relatively small area of these limestone outcroppings are not likely to produce high drift algae biomass. The most likely period for Scenario B stranding is in the late summer and early fall (August – November) because of the timing of maximum annual biomass and may help distinguish this type of event from the other scenarios described because it occurs at a different time of year.

Scenario C is a non-local source of algae or other material (e.g., bleached manatee grass, necrotic algae) that is transported from a large distance, such as a basin scale ocean current or another bay or estuary (e.g., Tampa). There have been two occurrences of this scenario in recent years including when a large offshore population of *Sargassum* was transported to Sanibel and Fort Myers' beaches (July 2009). The other event was bleached manatee grass that occurred from Redfish Pass to Marco Island (June 2009). These events are unpredictable and can occur at any time of year and are likely caused by basin scale ocean currents.

The final scenario (Scenario D) was largely captured from events in 2005-2007 in aerial photographs. The photographs document a high biomass event occurring on the beaches and in shallow, shore-parallel depressions, where fragmented macroalgae continued to grow and be deposited on the beach. While our research indicates that nutrient releases from decaying macroalgae on the beach will not contribute many nutrients to support further growth (see Objective 6); macroalgae found near or within the swash zone will likely continue to grow (under ambient nutrient conditions), fragment, and be transported in longshore currents down the coastline (towards Bonita Beach). Scenario D may also require elevated nutrient levels related to increased precipitation and/or discharge through S-79 as outlined in Scenario A.

Scenario A: January-May; High Biomass/Local Inshore Production; Low Rainfall/High Irradiance/Low Discharge/High Salinity/Low Grazer Abundance



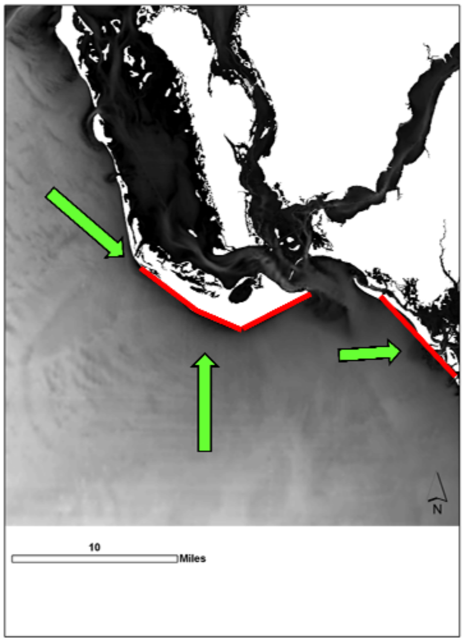


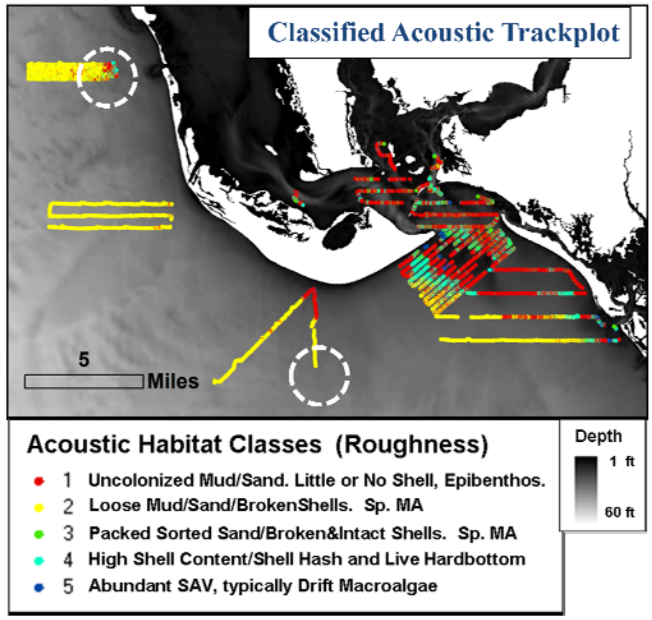
Timing: January through May is a period of low rainfall and low flow. High salinities (> 30), greater transparency, and warmer temperatures in shallow waters are favorable for macroalgal growth. There is a general absence of potential macroalgal grazers (e.g., urchins) in areas around the causeway contributing to low grazing pressure.

Sources of Macroalgae: As depicted, the spatial distributions of acoustically 'rough' areas in shallow water in blue are located around the Sanibel Causeway. Extensive areas (right panel: Acoustic Bottom Classes 3, 4 and 5) and optimal water conditions produce abundant macroalgal growth in areas with patchy seagrass and dense tube-dwelling polychaetes. Peak biomass at inshore stations is between January through May for these species; *Acanthophora spicifera, Dasya crouaniana, Dictyota cervicornis, Gracilaria tikvahiae, Spyridia filamentosa, Lomentaria baileyana, Sargassum filipendula.*

Transport conditions: Macroalgae will grow loosely attached to sand bottom or shell fragments and will detach either by shear or through fragmentation. Northerly winds and strong cold fronts can dislodge and transport algae to deeper water and the Gulf of Mexico. The detached algae will be transported out of the passes via tidal currents and deposited on the beaches around the Sanibel Causeway (left panel: green arrows).

Scenario B: July-November; Low Biomass/Offshore Reef, Shelly Bottom Production; High Irradiance/High Salinity/Moderate Grazer Abundance



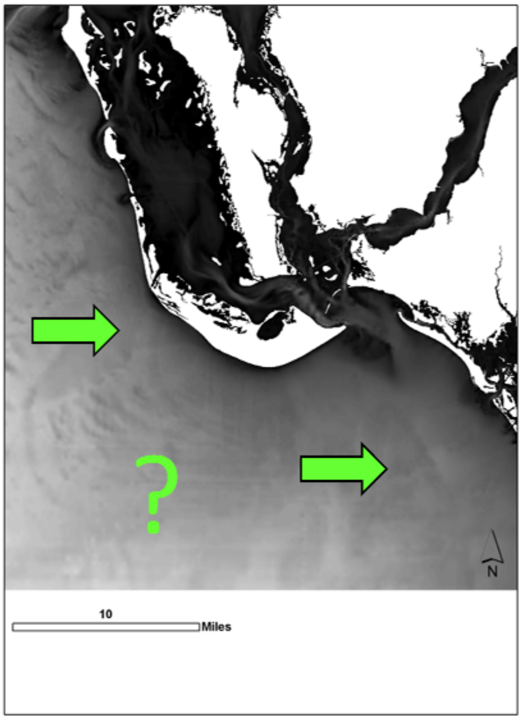


Timing: Higher rainfalls and flows cause lower salinities (<20) inshore. At 'live bottom' areas offshore, salinity and water transparency remain high from July through November.

Sources of Macroalgae: The 'live bottom' areas are relatively small in overall area relative to the total area surveyed. Shelly areas make up a much larger area and stranding events from July through November. The areas highlighted by a white dashed circle (right panel) are 'live bottom' as determined by underwater video, divers, and hydroacoustic surveys. Green areas have high shell content and are capable of producing macroalgae. These events would most likely be low biomass events, such as what occurred during the study. There is also likely considerable top-down control as grazers are abundant. Abundant macroalgal growth occurred from June through November at offshore sites for the following macroalgal species; *Botryocladia occidentalis, Soliera filifomis, Hypnea spinella, Gracilaria blodgettii, Gracilaria mammillaris, Gracilaria tikvahiae, Agardhiella subulata, Dictyota cervicornis*.

Transport conditions: Macroalgae will grow attached to limestone or shell fragments that can be detached either by shear or fragmentation. Southerly winds during the summer months and longshore drift currents can transport algae from offshore and nearshore sites and deposit it on area beaches.

Scenario C: Any time of year; Low Biomass/Large Scale Currents; Originating from the Gulf of Mexico

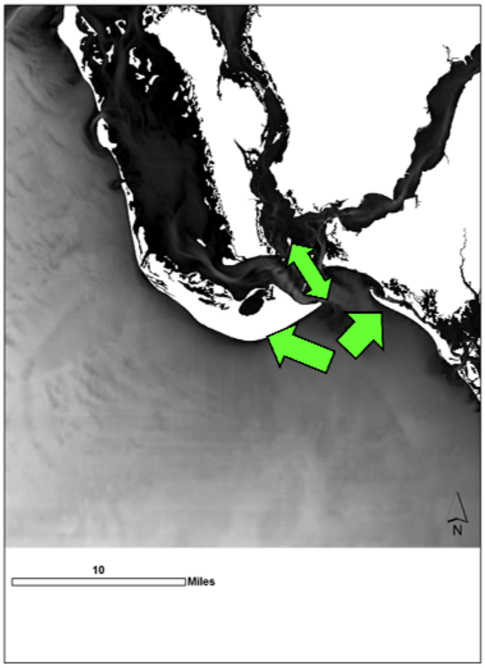


Timing: Consecutive days or weeks with westerly/southwesterly winds may result in the deposition of pelagic, offshore macroalgae. These events are comparatively rare and do not correspond with any specific time of year. During the study period, large amounts of *Sargassum* on beaches occurred in July 2009.

Sources of Macroalgae: Offshore macroalgae commonly grow in mid-ocean gyres and have small floats to maintain buoyancy.

Transport conditions: Westerly winds or storms will help transport macroalgae or bleached macrophytes (e.g., manatee grass, right panel) to beaches from outside of the region. The meteorological and oceanic conditions that lead to this type of stranding are poorly understood.

Scenario D: High Biomass/Fragmentation; Growth in Swash Zone/Shallow-Shore Parallel Depressions



Timing: January through May, corresponding to peak inshore biomass and fragmentation of macroalgae growing inshore.

Sources of Macroalgae: Inshore seagrass areas, high density shelly bottoms, similar species to Scenario A.

Transport conditions: Tidally delivered to the beaches, and then continues to grow in the swash zone and in shallow shore-parallel depressions. Concentrated by Southeasterly winds and distributed further by longshore transport.

Technical Summary

The sources of available nutrients and their role in producing large-scale macroalgae blooms on Sanibel Island and the waters of Lee County, Florida are the focus of this study, which integrates hydroacoustic surveys with bioassays, macroalgae surveys, stable isotope analyses, and a hydrodynamic model. Sampling was conducted from the Caloosahatchee River downstream of Lake Okeechobee, down to the lower tidal Caloosahatchee Estuary, San Carlos Bay and the nearshore coastal waters from Redfish Pass to Wiggins Pass. This broad geographic scope represents a hypothesized gradient of nutrients and algal biomass downstream and away from the mouth of the Caloosahatchee Estuary, and includes hypothetical areas of algal growth and accumulation at inshore and nearshore locations. This study was funded by a partnership between the City of Sanibel, Lee County, the Tourist Development Council and the West Coast Inland Navigation District. This two-year study began in May 2008 and has completed two full years of field sampling. This is the final report for the study.

Over-fertilization of estuaries with nutrients from urban and agricultural sources is both a local problem for the Caloosahatchee Estuary and a problem for most estuaries worldwide (Bach and Josselyn, 1978; Maze et al., 1993; Valiela et al., 1997). Beginning in the winter of 2003-2004, unusually large masses of drift red macroalgae accumulated on Sanibel Island, Bonita Springs and Fort Myers Beach. Several subsequent drift macroalgae events have been a nuisance to area beaches since then, prompting the City of Sanibel, Lee County, the Tourist Development Council and WCIND to collect additional information specifically targeting the sources and possible causes of drift algae blooms in SW Florida. Earlier work suggested that enriched nutrient concentrations (approximately 10 fold) were found in 2005 associated with large freshwater discharge events (Lapointe and Bedford, 2007). Concentrations at offshore reefs, however, were only 2-3 times enriched, suggesting that there was substantial absorption and cycling of nutrients en route to offshore locations (Lapointe and Bedford, 2007). Additional information and research was needed to determine the sources and fate of nutrients in the coastal zone along with several additional objectives listed below which were identified by the study team with City of Sanibel and Lee County officials.

The first three objectives of this study set out to study the importance of surface water (Lake Okeechobee versus basin sources; Objective 1), sediment-regenerated (Objective 2), and submarine groundwater discharge (Objective 3) inputs of nutrients in the overall nutrient budget of the Caloosahatchee River and Estuary (Objective 8), and subsequent macroalgal bloom events. Other factors (besides nutrients) must also be considered when discussing the build-up of macroalgal biomass and subsequent deposition on area beaches. There must be suitable substrate upon which macroalgae can grow and/or attach (Objective 4). Light, temperature, and salinity also play a role in algal physiology and growth (Objective 5). Hydrologic processes have to detach and transport the algae to the shoreline (Objective 7). Grazing activities may keep algal growth in check, preventing a significant build-up of biomass (Objective 9). The overall goal of this study was to determine the conditions leading to massive algal stranding events on local beaches that occurred between 2003 and 2007. Any knowledge gained on this front can therefore be incorporated into current and future management practices to control, or respond to, future events.

Water discharges from S-79 and salinity along the Caloosahatchee Estuary during this study showed typical seasonal patterns of high flows and low salinity during the wet season (August – October) and low to no flow and high salinity during the dry season (May – July and November – June). Surface and bottom salinities along the Caloosahatchee Estuary were higher during S-79 low flow periods and were lower during S-79 high-flow periods. Synoptic nutrient and phytoplankton surveys (Objective 1) were conducted to determine whether Lake Okeechobee or basin nutrient sources were more important to nuisance algal growth and to provide information on cumulative inputs of nutrients from Lake Okeechobee and the East Caloosahatchee Basin into the Caloosahatchee Estuary and Gulf of Mexico. Monthly sampling along the Caloosahatchee River and Estuary began in May 2008 while bi-monthly sampling of coastal Gulf of Mexico stations began in June 2008. All field work continued for a full 24 months and ended in June 2010. Samples from the Caloosahatchee River were collected upstream of the control structures (S-77, S-78 and S-79), while samples in the Caloosahatchee Estuary were collected at four stations along the salinity gradient from S-79 to San Carlos Bay (Figure 1). Gulf of Mexico samples were collected from 12 stations (Figure 1) and overlapped with nutrient microcosm experiments and sampling of macroalgae (see below).

Dissolved inorganic nitrogen and phosphorus (DIN and DIP, respectively) concentrations along the Caloosahatchee River (upstream of S-79) increased during the wet season and decreased during the dry season, corresponding with water flows and were similar at all three stations (S-77, S-78 and S-79). Dissolved organic carbon (DOC) concentrations also showed the same seasonality and station-to-station differences, although the November 2008 – May 2009 dry season saw higher DOC concentrations than the wet season preceding it. Dissolved organic nitrogen (DON) concentrations were fairly constant during the study period and made up of ~80% of the total dissolved nitrogen pool for the Caloosahatchee River. Dissolved organic phosphorus (DOP) concentrations showed similar trends as DIP concentrations and was comprised of ~30% of the total dissolved phosphorus pool. Concentrations of DON and DOP were also fairly similar between all three stations. The highest abundance of microalgae was upstream near Lake Okeechobee, suggesting that this is the major source of nutrients generating algal blooms in the system. Cyanobacteria were also most abundant upstream near Lake Okeechobee.

Within the Caloosahatchee Estuary (downstream of S-79), dissolved organic matter (as DOC, DON and DOP) and dissolved inorganic nutrients (as DIN and DIP) concentrations were generally higher at the upstream site (near Beautiful Island) compared to the San Carlos Bay site. Concentrations of DOC, DON, DOP, DIN and DIP did not differ between surface and bottom water samples and showed similar seasonal trends as for salinity at these sites (higher concentrations during wet season, lower concentrations during dry season). Dissolved organic N again made up the majority of the total dissolved nitrogen pool. There was an increase in chromophyte algae (probably diatoms) as river water flowed into the estuary (near Beautiful Island) and the increasing salinity changed the species composition of the algal community. In general, microalgal abundance showed dilution with increasing salinity in the estuary, indicating that freshwater is a much greater source of nutrients than seawater in this area. Abundance of benthic microalgae on the sediment surface is highest in the Caloosahatchee Estuary and declines going offshore, indicating the major source of nutrients to benthic microalgae is derived upstream from the Caloosahatchee River.

In the coastal Gulf of Mexico, dissolved organic matter and dissolved inorganic nutrient concentrations were lower than those found within the Caloosahatchee Estuary. Concentrations of DOC, DON, DOP, DIN and DIP were fairly similar between sites and season. Dissolved organic N again made up the majority of the total dissolved nitrogen pool while DOP and DIP comprised similar fractions of the total dissolved phosphorus pool. Phytoplankton concentrations were significantly more abundant offshore during the wet season than during the dry season.

Bioassays indicate that nitrogen is the limiting nutrient throughout the system. Nitrogen bioassays show the highest amount of bioavailable nitrogen upstream near Lake Okeechobee, suggesting that this is the major source of nitrogen generating algal blooms in the system. A comparison of these data with nutrient data indicates that not only inorganic nitrogen but much of the organic nitrogen is available to algae. Bioavailable nitrogen shows dilution with increasing salinity in the estuary indicating that freshwater is a much greater source of nitrogen than seawater in this area.

Daily dissolved inorganic nutrient (NO_2^-, NO_3^- and NH_4^+ and DIP) fluxes from sediment microcosm experiments (Objective 2) were calculated for June 2008 – 2010 for three long-term stations (Figure 1); Blind Pass (GOM04), Estero Island (GOM06) and San Carlos Bay (GOM16). For NO_2^-, NO_3^- and DIP, fluxes being regenerated from the sediment were generally balanced by fluxes of nutrients into the sediments during the course of the year regardless site. The magnitude of NO_2^-, however, was very small compared to NO_3^- and DIP fluxes. The magnitude of the exchange of DIP fluxes measured was greater at the Estero Island and San Carlos Bay stations compared with the Blind Pass station while the opposite was true of NO_3^- fluxes. There were no differences in the magnitude of NO_2^- between sites. Ammonium (NH_4^+) fluxes however, were mainly positive and were highest at the Estero Island station. However, there were two significant negative flux events at the Blind Pass station, which occurred during the two driest sampling period of the study (May 2009 and May 2010). Ammonium fluxes were also the highest of the four nutrient measured, and the predominant nitrogen species.

Groundwater discharge (Objective 3) was quantified using the naturally occurring radioisotopes radon and radium. These tracers are useful in this regard due to their natural enrichment in groundwater (100-1000 times greater than surface water) relative to other sources of freshwater to coastal systems (e.g., runoff and rainfall). Groundwater radium concentrations are among the highest we have observed in over 10 years studying submarine groundwater discharge(SGD), influenced by deposits of phosphorite, a naturally occurring phosphate-bearing mineral that also contains appreciable quantities of uranium and its decay products. It is also notable that radium was enriched in groundwater irrespective of salinity and wet vs. dry season. Concentrations of four isotopes of radium (223, 224, 226, and 228) from the Gulf of Mexico, through the estuary salinity gradient and along the river to its origin at Lake Okeechobee were only a factor of 2-5 times lower than groundwater, which suggests significant groundwater-surface water exchange.

Box model results yielded radium-derived SGD rates of 3.3 x 10^6 m^3/d (dry) and 1.3 x 10^6 m^3/d (wet) for the Caloosahatchee Estuary and compared well with water and salt balance checks for the system. Using nutrient concentrations from groundwater sampling wells located as close to the location of discharge as possible, i.e., at the estuarine land-water interface and not at inland wells, groundwater nutrient fluxes were estimated. For TDN, the groundwater flux to the estuary during the dry (3410 kg/d) and wet (1400 kg/d) seasons were of the same order of magnitude as the flux through the Franklin Lock. However, the flux of DIN, a significantly more bioavailable form of nitrogen, was almost 7-times higher for groundwater than from the river. Like TDN, groundwater phosphate fluxes were of the same order of magnitude as the river. These results show that the groundwater is highly enriched in nitrogen and phosphate, making groundwater a likely important component of the local nutrient demand of bloom-forming algae.

Areas within San Carlos Bay and offshore of Sanibel Island were surveyed using hydroacoustics and towed-video methodologies (Objective 4). The overall objective was addressed in three phases from 2008 through 2010. These included an initial effort in October 2008 (Phase I) and a second effort in April-May, 2009 (Phase II). Finally, an additional towed-video survey (Phase III) was conducted in May 2010 to assess (i.e. "ground-truthing") Phases I and II hydroacoustic classifications and to add an additional biogenic layer (e.g., worm tubes, pen shells, etc.) that was relevant to potential macroalgal attachment and growth given that during the effort no major macroalgal events were observed. The hydroacoustic data were acquired with a BioSonics DT-X echosounder and a multiplexed single-beam digital transducers operating at 38 and 418 kHz. Eleven acoustic parameters derived from the 38 and 418 kHz signals were submitted to a novel multi-pass Discriminant Function classification scheme to refine the training dataset into end-member structural and biological elements.

The hydroacoustic surveys ranged from nearshore depths of 2 m to as far as 11 km offshore. The towed-video surveys included sub-meter depths within San Carlos Bay and extended as far as 24 km offshore (approximately 15 m depth). The hydroacoustic and towed-video data were classified into one of five (total of 5) visually-apparent categories of seabed roughness, reflecting the variable potential of the seabed to act as a macroalgae attachment site. Classes 1 and 2 consisted primarily of unconsolidated mud and sand sediments, and are least suitable for macroalgal attachment and growth. Class 3 is a marginal substrate for a macroalgal "bloom", consisting of packed sand and large, intact shell debris. Classes 4 and 5 offered the best conditions for macroalgal attachment and growth. Class 4 consisted of either unconsolidated shell hash or exposed rocky bottoms. Class 5 consisted primarily of submerged aquatic vegetation (SAV), mainly seagrasses.

The majority (approximately 80%) of acoustic classifications were of soft bottom sediments (Classes 1-2), but there were two significant expanses of rough seabed thought to be suitable for macroalgae attachment. These two areas covered a total of 19 km^2, within which approximately 56% of the hydroacoustic 'records' were classified as "rough" (Classes 3, 4 and 5). The first was a large area of seagrass beds and "live hard-bottom" in the mouth of San Carlos Bay, where large amounts of macroalgae were variably present during the April-May 2009 surveys. The second was offshore of Lighthouse Point, near the mouth of San Carlos Bay. This area is located near a large sand bar that extended from the beach to approximately 6 km offshore. Along the west side of this sandy area was substantial acreage of moderate to high bottom "roughness", mostly in the form of unconsolidated, shelly hash. The average depths of these two acoustically-rough areas were only 5.0 and 4.0 m, so sufficient irradiance to initiate a macroalgal 'bloom' would be likely much of the year. These textured and shallow areas on or near the mouth of San Carlos Bay are presumably potential source areas for the initiation of macroalgal biomass (attachment and growth). Under the appropriate conditions algae could be readily transported onto the areas' beaches, especially given the close proximity to the islands beaches.

In contrast, the areas further offshore in the Gulf of Mexico were classified predominantly as soft sediments with low bottom "roughness" based on both the hydroacoustic and video surveys. The area offshore of Redfish Pass had a moderate (approximately 22%) proportion of "rough" acoustic classifications out to 5 km offshore, but from 5-10 km offshore the bottom was classified as >95% soft sediments. The other two Gulf of Mexico areas of focus were acoustically classified as >95% soft sediments from nearshore to 11 km offshore. The towed-video transects over a larger area of focus indicated there were relatively small areas that harbored large concentrations of shelly and/or "live hard-bottom" occurring sporadically at distances greater than 10 km offshore. Further assessments of these survey data in the context of available nutrients and ambient light levels will be needed to fully assess the bloom potential for these offshore sites, but it would appear that the open Gulf of Mexico waters around Sanibel-Captiva are probably not a major source of drift macroalgae.

Thirteen macroalgal sampling stations were established in June 2008 to conduct quantitative sampling of macroalgal communities (Objective 5), and overlap with sampling water samples for nutrient analyses (Objective 1) and for sediment microcosm experiments (Objective 2). Stations were visited bimonthly for a total of 12 sampling events concluding in June 2010. The study area included the area North from Captiva Pass to the southern boundary of Wiggins Pass. Stations were established inshore and offshore, from Sanibel down to Fort Myers Beach in an effort to address gradients related to nutrients and freshwater (decreasing away from the

Caloosahatchee River) and to ensure locations near Sanibel and Fort Myers Beach were included (Figure 1).

During the two-year study, there were no large-scale beach stranding events equal in magnitude to the events that were photographed and described from 2003-2007. Despite the lack of catastrophic macroalgal strandings, we found several new lines of information about the spatial and temporal patterns of macroalgal populations and characterized the types of habitats where they commonly occur. When the detailed information from the 13 stations is combined with large-scale habitat mapping efforts (Objective 4), the area's most likely to be sources of macroalgae and times of year when it is expected to wash up on area beaches are better understood.

There were a total of 96 macroalgal species collected and identified during the two-year study. Most of these species are branching red algae (Rhodophyta), with 12 species of brown algae (Phaeophyta), 14 total species of green algae (Chlorophyta) and 1 common cyanobacteria (Cyanophyta). A total of 20 macroalgal species were collected and identified on area beaches since 2008. Only four of the 13 stations sampled routinely had macroalgae in moderate abundances. Inshore algal communities differed from offshore communities, in which offshore communities had higher species richness and diversity. Offshore algal species typically had well-developed discoid and rhizoid holdfasts, likely making them less susceptible to dislodgement or breakage versus inshore species.

Seasonal patterns indicated a late spring to summer growth period, maturing in late summer, and disappearing in early winter. Algal biomass tends to be highest in inshore areas during the spring, and offshore areas during the late summer. Algal physiologic parameters (quantum yields, a proxy for growth, and nutrient content) are highest in the spring, indicating that the algae are likely growing faster (inshore) at this time. The conditions most suitable for algal growth appear to be moderate temperatures (<25°C), high salinities (>35), and low/moderate light intensities (15 – 35 $\mu E/m^2/s$), conditions which are more typical of the dry season and spring (or deeper, cooler offshore waters). In order to obtain massive algal biomass, however, one requires a large nutrient pool. The results of Objective 5 suggest that the nutrient pool may be from a groundwater, sediment, or local source. The algae growing on the artificial reefs do not appear to be a source of the drift algae washing up on beaches, although the lack of a major stranding event prevents this statement from being presented strongly. Some sites are more conducive to algal growth than others, which when coupled to the results of Objective 4 indicate that there may be "hot spots" for growth that might be monitored on a regular basis.

The Volunteer Scientific Research Team (VSRT) is a not-for-profit group of divers that has assisted Lee County staff in the mapping of the structural aspects of artificial reefs following deposition and more recently in conducting fish surveys on the various reefs. For this study, the VSRT assisted in the location of natural reefs and in the collection of attached algae from three natural and three artificial reefs with training and supervision by FGCU faculty. No less than 45 individual species of attached macroalgae were identified from the reef surveys including 28 species of Rhodophyta, six species of Phaeophyta, and 11 species of Chlorophyta. The most frequently encountered taxa included *Botryocladia occidentalis*, *Euchema isiforme denudatum*, *Udotea sp.*, *Gracilaria mammillaris* and *Dictyota cervicornis*. However, the greatest biomass was observed to be *Sargassum* spp. (mostly *S. filipendula*) with little differences between the natural and artificial reefs in terms of species composition. Geographic location of reefs and season of the year was more important than reef type (artificial vs. natural) in determining the overall algal community structure. The GH artificial reef is closest to the mouth of the Caloosahatchee and consistently had lower species richness than most other sites further offshore. Anecdotally, urchins tended to occur in groups of many individuals together and were associated with a lack of macroalgae where they occurred even when the same type of substrate nearby was colonized by numerous macroalgal species. A cluster analysis using the SIMPROF test found that the beach algae communities were significantly different than all the reef samples and separated from reef clusters at approximately 7% similarity or were at least 93% dissimilar.

Toward the achievement of Objective 6, the ecological consequences of algal deposition beaches, we: 1) established 16 monitoring sites for bimonthly quantification of background levels of algal deposition; 2) responded to five deposition events, two of which, the event on Fort Myers Beach in June, 2008 and the *Sargassum* event on Sanibel in July 2009, were larger (approximately 1050 and 750 tons of wet algal biomass respectively); and 3) initiated laboratory experiments on the rate of decomposition of algae and subsequent release of nutrients.

Generally background levels of algae deposition on the beaches were low. The most commonly occurring red algae taxa, where mechanical damage and decomposition did not preclude identification, included: *Botryocladia, Gracilaria, Solieria, and Lomentaria.* Algal biomass was typically too fragmented from mechanical damage resulting from wave action and was usually significantly decomposed, precluding an ability to quantify relative abundance of taxa.

Beach decomposition experiments showed that approximately 30% of the biomass is lost in the first week, and approximately 40% of the biomass persists through two months. In microcosm decomposition experiments, the nutrient export approached zero after approximately two weeks. In that time the biomass was reduced on average 12% in the aquaria. A total nutrient release was calculated, and related to per unit dry biomass lost (599 mg N/Kg dry biomass decomposed) and used to scale up and estimate the total nitrogen that could be released from a deposition event (e.g., 125-130 kg for the larger events like the June 2008 deposition on Fort Myers Beach). This estimate may be too low, as the field decomposition experiments indicated approximately three times the biomass loss in the field, relative to biomass loss in the microcosms. The larger volume of beach sand and greater distance to pass through sand, may counter balance the nutrient release along a beach.

The deposition events during the study period were much less intensive and extensive than the events in 2003-2007. The events examined during this study were also relatively ephemeral, with durations of two weeks or less. In deciding the response to a deposition event, municipalities must consider the: cost for removal, potential for high tides to remove the deposition, negative impact on the recreational use of the beach, and possible positive ecological implications of the deposition; i.e., stabilization of beach sands and enrichment of beach biotic communities.

The Regional Ocean Modeling System (ROMS) was used to simulate and predict the hydrodynamics and sediment transport in the region of interest (Objective 7). ROMS is widely used and respected by the scientific community, is open code, and has a robust support group. Unlike other proprietary models, the ROMS model that was developed for this project will be available for use and modification by the funding agencies and supported by the ROMS users group long after the completion of this specific project.

A ROMS compatible grid has been carefully constructed from high-resolution bathymetry data acquired from the South Florida Water Management District and integrated with coastline data obtained from NOAA. The major forcings of the model are wind, tide, and freshwater discharge. Winds are obtained from the Page Field General Aviation Airport located close to the Caloosahatchee River. Wind speed and direction are hourly mean values and are applied uniformly over the grid. Other forcings of secondary importance include air pressure, relative humidity, and temperature, all also obtained from Page Field. The model simulations cover a range of conditions. All of the simulations were done during the dry season or the wet season of 2008. This year and the time interval of the wet season run were chosen because it encompasses one of the more significant macroalgal stranding events which occurred in July 2008. Each simulation is run for 45 days, time to allow the model to spin up and simulate both neap and spring tides within each run. The dry season runs are from February 1 to March 16, and the wet season runs are from June 22 to August 5. Because the macroalgal stranding event did not occur during the maximum discharges, a further simulation was performed to estimate residence times during these high discharge events. This simulation ran from July 22 to September 7.

The sediment transport model, as the hydrodynamic model with which it is coupled, is from an Eulerian viewpoint, i.e., it predicts accretion, erosion and other processes within each cell and does not "know" where sediment that enters the cell originally came from, nor where sediment that leaves the cell will ultimately end up. In order to investigate where water that originates in one place, e.g., the Caloosahatchee River is transported, it is necessary to use a particle tracking model, which is from a Lagrangian viewpoint. Essentially, neutrally buoyant particles, or "drifters" are released at specified locations and followed through the simulation. Rather than being associated with specific grid cells, the drifters may move continuously within and across grid cells. The drifters provide an estimation of where neutrally buoyant material such as dissolved organics, or near-neutrally buoyant particles might be transported. It is difficult to predict the size and density of estuarine aggregates, however, very small aggregates composed of mostly organic material may behave as if they were neutrally buoyant and drifter paths give some insight into the potential transport of these very small porous organic particles as well as the transport of dissolved material. Eight locations outside of the river where macroalgal stands were discovered became of interest. At each location, five drifters were released near the bottom to simulate possible stranding sites on beaches.

Wind is the primary long term (i.e., over weekly time scale) forcing factor of the water compared to tidal action or river discharge outside of the Caloosahatchee River and Estuary. An inadvertent experiment with Redfish Pass shows that the pass is important not only for flushing of Pine Island Sound, but without the pass, the retention of particles in the sound made them available for transport south under the causeway onto Fort Myers Beach and even into Estero Bay during short term wind events. The difference in wet season results with Redfish Pass closed and opened in the model support the idea that synoptic wind events are more important physical factors to moving the water, compared to tidal and riverine forcing. When Redfish Pass was closed in the model, water remained longer in Pine Island Sound, then during a short term wind event, was blown south towards Fort Myers Beach.

At a smaller scale, tidal propagation tends to move sediment northwards once outside of Caloosahatchee River and Estuary. This is supported by the general morphology of Sanibel and Captive islands. Sediment tends to build up on ebb deltas making them available for storm transport. When winds from the north coincide with flood currents there is significant longshore sediment transport along the south coast of Sanibel.

Residence time in the Caloosahatchee River and Estuary during the wet season ranges from less than 5 days at the lower extent and 10-20 days in the mid river section, to over 45 days in the upper river between Beautiful Island and S-79. Residence times during the dry season are longer, with less along channel mixing. This is evident by the much sharper gradient between the long and shorter residence times in the mid river region. Residence times in the Caloosahatchee are relatively unaffected by winds, rather tidal dispersion and freshwater discharge are the primary determinants.

For Objective 8, we redirected our efforts to avoid unnecessary replication of current modeling efforts in the region. Modifications to this objective includes the evaluation of simulation results from existing hydrodynamic and water quality models such as the HSPF & EFDC as well as all available watershed assessments that were used for the purpose of the Total Maximum Daily Loads (TMDL) process. The existing models and watershed assessments allowed us to draw conclusions relative to the effects of high flow river run-off on the development of red tides and macroalgal growth. We also developed a list of specific resource management recommendations geared towards nutrient reduction strategies for managing drift algal blooms in the waters of Lee County.

Previous studies (CRWPP, 2009) found that while nutrient inputs from Lake Okeechobee constitute approximately 50% of the total nitrogen and phosphorus entering the lower Caloosahatchee River and Estuary, local inputs from the West Caloosahatchee and Tidal

Caloosahatchee sub-basins were also significant (approximately 40% of inputs). Non-point sources of nutrients in the West Caloosahatchee sub-basin are primarily agricultural, whereas the primary non-point sources in the Tidal Caloosahatchee include both agricultural and residential activities, with significant differences in nutrient inputs between wet and dry seasons.

These nutrient loadings did not include submarine groundwater and sediment fluxes of nutrients into the Caloosahatchee River and Estuary. When TN and TP loadings from all known sources into the Tidal Caloosahatchee are enumerated to include those quantified in this study (Objectives 2 and 3), the biggest nutrient source to the Tidal Caloosahatchee is still upstream of S-79, with 18%-27% of the nutrients coming from Lake Okeechobee. However, downstream of S-79, submarine groundwater sources of nutrients cannot be discounted, with loadings equal to those from Lake Okeechobee (25%-27%). Sediment fluxes of nutrients are low, and depending on the season may be a small sink for nutrients within the Caloosahatchee River and Estuary instead of a source (see Objective 2). Total loadings and the average nutrient concentrations for the Tidal Caloosahatchee from this study were used to calculate nutrient residence times for the dry and wet seasons. Residence times for TN and TP were higher during the dry season (19 and 15 days, respectively) compared with during the wet season (10 and 11 days, respectively) and is in agreement with modeling efforts to determine the residence time of water in the Caloosahatchee River and Estuary (see Objective 7).

The overall scope of Objective 9 was to address grazing as a top-down mechanism to control macroalgal blooms. This objective synthesized local information related to the observed blooms from 2003 to the present. It also looked at potential meso- and macrograzers in the area of study based on its and other efforts (Objectives 4 and 5 for example). Limited field and lab experiments with urchins as grazers, their survival and also an assessment of what we know from the literature on palatability, defenses, herbivore feeding capabilities were also conducted.

Interestingly and surprisingly, few meso- or macrograzers were collected in any large numbers at inshore sites in Pine Island Sound or San Carlos Bay, with the exception of a few fish such as pinfish and parrotfish. The few invertebrate grazers (e.g., 2 species of sea urchins) were collected only near passes presumably as these are areas with stable higher salinities. Few individuals were found anywhere else inshore in seagrass beds in either Pine Island Sound or San Carlos Bay. Low to variable salinities and potential for harmful algal bloom impacts may be part of the reason that urchins are rare inshore except for near passes to the Gulf of Mexico. We also found significant accumulations of drift or attached macroalgae in our trawls and in water sampling during April 2010, with the majority being Rhodophyta observed previously at two inshore sampling stations (see Objective 5).

Single species feeding trials indicates that urchins ate significantly more *Caulerpa racemosa* (offshore species), *Agardhiella subulata* (offshore/nearshore species) and *Acanthophora spicifera* (inshore/nearshore species) than they did *Gracilaria blodgettii* (offshore/nearshore), *Hypnea spinella* (inshore species) or *Spyridia filamentosa* (inshore). In addition, from observations made every 15 minutes during the first 2 hours of trials, it seems that the urchins consumed more of what they happened to come upon first, with no significant difference between species detected.

Survivability caging experiments indicated that urchins survive in many of the salinities around the island. The only cage that experienced urchin mortality was the SCCF Shell Point RECON unit, which experienced several large fluctuations in salinity often to near 5. Salinities lower than 18 perhaps for extended periods appear to be stressful for *Lytechinus*, with values < 5 perhaps causing 100% mortality. Nearshore stations that exhibit a significantly larger numbers of urchins per 100 m^2 than inshore or offshore sites, and also did not typically have large algal accumulations, were selected for exclusion cages experiments.

For the three months that cages were deployed, algae was found at only two of the eight sites. Redfish RECON site only had 1% algae growth inside the cages, with similar density of algae outside the cages. Results from GOM04 similarly illustrates that grazer control resulted in more growth inside of the cages than in unprotected area outside of cages. However, the presence of algae as well as similar species found would indicate that while reducing grazer pressure (i.e., juvenile urchins found inside cages with some algae) allowed for larger percent cover found inside the cages, other factors most likely contributed to the presence of algae at this site. While these experiments were limited, trends indicated that these areas may be more controlled by nutrient availability than by excluding grazers.

All the information from this study was synthesized in a conceptual model for algal growth. Factors such as nutrient availability or grazer pressures that influence algal growth was simultaneously assessed with when and where algae can grow, and how physical factors such as wind and currents will result in large stranding events on local beaches. Four scenarios were then developed to explain the four most likely conditions that our research findings suggest would lead to a stranding event on area beaches.

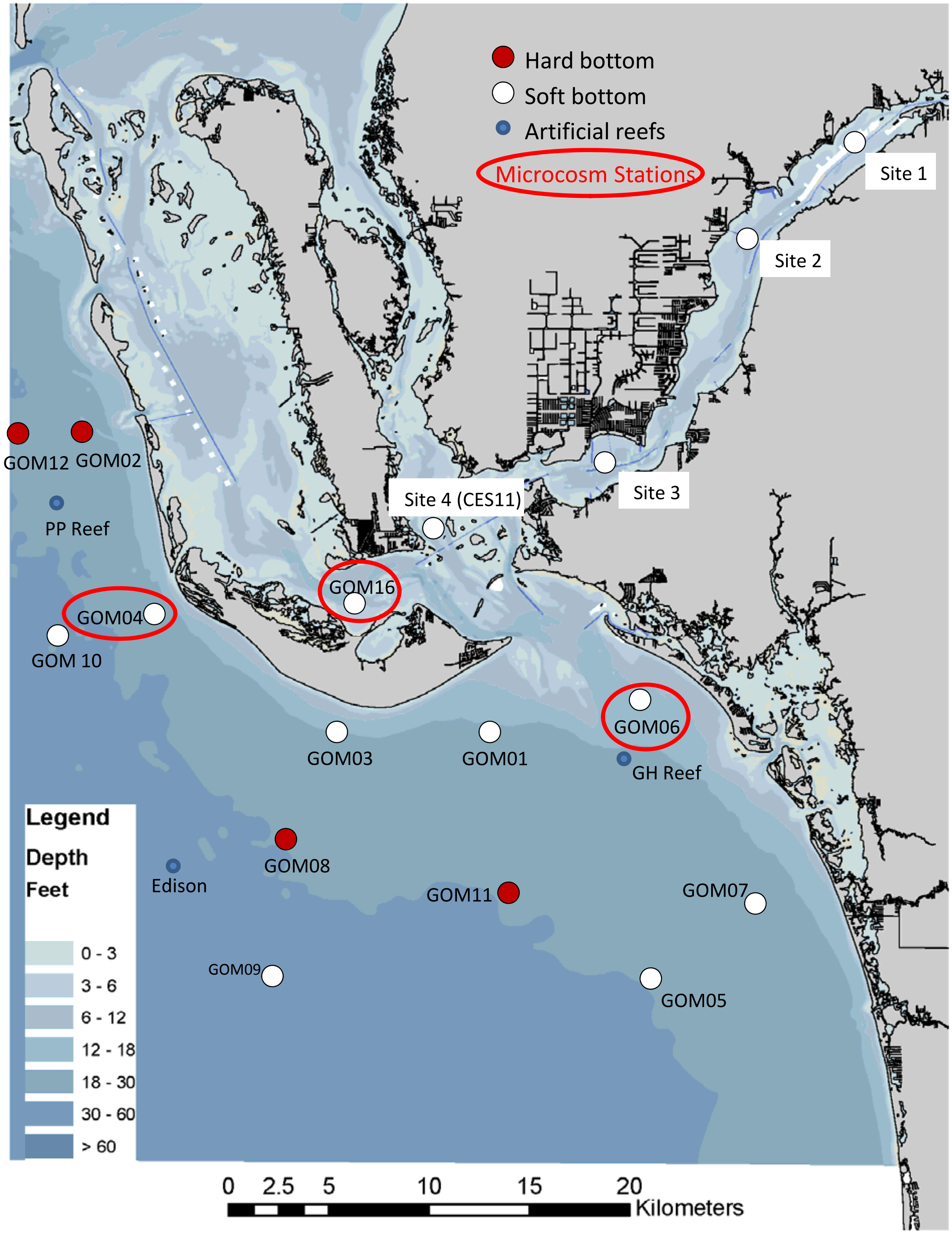
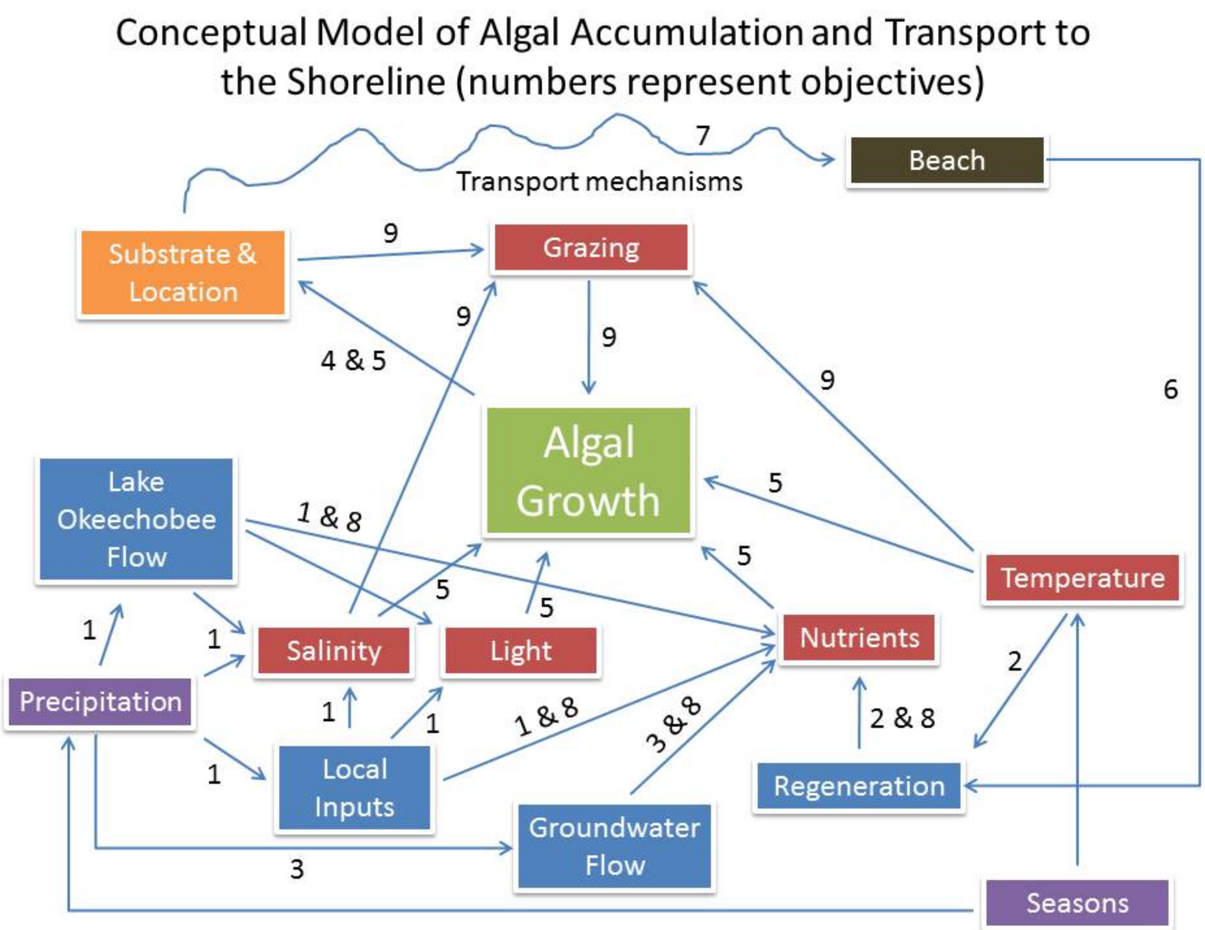


Figure 1. Map of sampling stations in the Caloosahatchee River Estuary and Gulf of Mexico.

Synthesis: Conceptual Model of Algal Growth

Background

The accompanying flowchart depicts a conceptual model of the factors that 1) influence algal growth, 2) determine when and where algae will grow, and 3) result in algal biomass being deposited on our area beaches. Each of the primary factors (i.e., those directly influencing the metabolic processes involved in algal growth) is shown as a red box. The secondary factors (i.e., those that influence the primary factors) are shown as blue boxes. Two tertiary factors (precipitation and seasons) are shown in purple, and represent regional/global processes (e.g., ENSO) that influence the secondary factors (as well as season affecting precipitation). Substrate is treated separately as an orange box as it represents a geospatial aspect where macroalgae are likely to grow and/or accumulate in our coastal/estuarine waters. Lastly, the beach box (brown) represents the condition where drift algae is deposited on area beaches. The arrows indicate how each box relates to one another, where the numbers associated with each arrow represent one or more of the nine objectives of this study to determine the conditions that lead to drift algae accumulations on area beaches. The data and literature supporting the model components presented below are presented in the respective objectives associated with each arrow.



Below is a summary of our results as they relate to each factor, thereby providing an overall synthesis of our findings on what we learned about the conditions conducive for algal growth and accumulation.

Primary Factors (red boxes)

Algal growth is dependent primarily on adequate amounts of light and nutrients. Temperature and salinity affect algal physiology (metabolism), including how well the algae utilize the available light and nutrients. Our results regarding these four factors are summarized as follows:

Nutrients

1. Nitrogen is the limiting nutrient. This means that algae will be stimulated most by additional nitrogen inputs, but not as much by adding more phosphorus. This finding also suggests that nitrogen reduction strategies can be effective in reducing algal biomass.

2. Organic nitrogen may be a nutrient source. Plants and algae typically utilize inorganic forms of nitrogen such as nitrate (NO_3^-), nitrite (NO_2^-), and ammonium (NH_4^+). Organic nitrogen is generally thought of as inert, i.e., unutilized by plants and algae. These organic compounds may be broken down into utilizable inorganic compounds by microbial (or photolytic) processes. Our results suggest that inorganic nutrients by themselves were not abundant enough to support the concentrations of microalgae encountered in this study. Therefore, it is logical to assume that the organic compounds could be a source of inorganic nutrients. The importance of this finding is that there are far greater amounts of organic nitrogen versus inorganic nitrogen in the Caloosahatchee River and Estuary. Therefore, a greater pool of nitrogen is present than if inorganic nitrogen sources were considered alone. Organic nitrogen sources should also be addressed in reduction measures. The first step in this process would be to determine what the significant sources of organic nitrogen are, and then the implementation of Best Management Practices to reduce the inputs as appropriate and feasible.

3. Nutrient concentrations generally decrease from Lake Okeechobee to the Gulf of Mexico. These results suggest that Lake Okeechobee is a significant source of nutrients to the CRE, which in turn provides a significant amount of nutrients to the coastal waters in the Gulf of Mexico. The nutrients decrease through a combination of conservative (i.e., tidal mixing with nutrient-poor Gulf waters) and non-conservative (uptake of nutrients by algae) processes.

4. Submarine groundwater discharges (SGD) are a significant source of nitrogen. These inputs vary seasonally, with nitrogen loads being over two times higher during the dry season than the wet season. The factors influencing the hydraulic head (i.e., delay between precipitation and subsequent discharge) remain unknown.

5. On an annual basis (averaged between 1995 – 2005), Lake Okeechobee provides 27% of the total nitrogen and 18% of the total phosphorus reaching the lower estuary. SGD

account for 25% of the total nitrogen and 27% of the total phosphorus reaching the lower estuary. The West Caloosahatchee sub-basin (between S-78 and S-79) provides 16% of the total nitrogen and 20% of the total phosphorus reaching the lower estuary. Therefore, there are multiple, significant sources of nutrients influencing estuarine/coastal processes (i.e., Lake Okeechobee should not be the only source of concern.

6. More total nitrogen (76%) and more total phosphorus (63%) enter the lower estuary during an average wet season versus an average dry season. On average, 60% of the total nitrogen and phosphorus enter the lower estuary during the wet season.

7. Sediments do not appear to be a significant source of phosphate over the course of an annual cycle. Nitrogen (primarily as ammonium), however, is regenerated out of the sediments during the wet season (thereby becoming a nitrogen source) and absorbed into the sediments during the dry season (thereby becoming a nitrogen sink).

8. Decomposing algae do not appear to release a significant amount of nitrogen back into coastal ecosystem (e.g., the swash zone and shoreline longshore troughs).

Algae-nutrient relationships

1. Microalgal biomass (phytoplankton and benthic microalgae) decreases from Lake Okeechobee to the Gulf of Mexico, reflecting the decrease in available nutrient concentrations from Lake Okeechobee down to the Gulf of Mexico, or dilution with nutrient-poor Gulf of Mexico water.

2. Macroalgal (seaweed) tissue nitrogen content is higher inshore and during the wet season. These results may indicate that the algae are sequestering the nitrogen during the wet season when inputs are higher, or that algae are growing more slowly in the wet season and are therefore storing rather than utilizing the available nitrogen.

3. $\delta^{15}N$ ratios from algal tissues were significantly higher during the dry season. These results suggest that inshore (and/or during the dry season), algae either rely more heavily on regenerated nitrogen, or that SGD-derived nitrogen has a heavier $\delta^{15}N$ signature than surface water nitrogen sources. SGD $\delta^{15}N$ signatures should be determined in a future study.

4. Macroalgal tissue phosphate content was significantly higher in the dry season, suggesting that phosphate may be more available (or more sequestered) during the dry season.

Temperature

1. Quantum yields were significantly, negatively correlated with temperature, suggesting that algae will grow best at temperatures below 25°C.

Salinity

1. Quantum yields were significantly, positively correlated with salinity, suggesting that algae will grow better as salinity increases (especially >30 ppt).

Light

1. Quantum yields were negatively correlated with I_z (light intensity at depth). The results suggest that algae might be light limited at low intensities (<20 $\mu E/m^2/s$), and photoinhibited at higher values (>40 $\mu E/m^2/s$).

Grazing

1. Our results suggest that inshore (away from passes), algal growth may be controlled more by nutrient availability than by grazer activity (at least during the course of this study).
2. Urchin grazing appears to be a controlling factor in coastal and offshore locations (based on their abundances at these sites).

<u>Secondary Factors (blue boxes)</u>

The secondary factors (Lake Okeechobee flow, local run-off, SGD, and sediment regeneration) were discussed above in various bullets, but will be further summarized below incorporating their influences not only on nutrients, but light and salinity as well.

Lake Okeechobee Flow

1. Lake Okeechobee provides 27% of the total nitrogen and 18% of the total phosphorus reaching the lower estuary.

2. As flows out of the lake are highly managed, they do not necessarily follow wet and dry seasonal cycles.

3. Flows through S-77 affect salinity and light attenuation; salinity is reduced as flows increase, and light attenuation increases with increasing flow. These processes have been studied elsewhere (e.g., Bissett et al. 2005; Milbrandt et al. in prep.).

Local Inputs

1. On an annual basis, local inputs account for 48% of the total nitrogen and 62% of the total phosphorus reaching the lower estuary.

2. The West Caloosahatchee sub-basin (just upstream of S-79) is the largest local contributor, providing 16% of the total nitrogen and 20% of the total phosphorus reaching the lower estuary.

3. Local inputs likely affect total suspended solids and salinity, but will vary with precipitation and according to land use (i.e., erosion). Previous modeling efforts have examined the influence of local tributary discharges (see FDEP 2008).

Submarine Groundwater Discharge (SGD)

1. SGD accounts for 25% of the total nitrogen and 27% of the total phosphorus reaching the lower estuary.

2. SGD inputs are greater during the dry versus wet season, suggesting a considerable lag (>60 days) between precipitation and subsequent discharges. This relationship should be examined further.

Sediment Regeneration

1. Sediment fluxes in the tidal Caloosahatchee (between S-79 and Shell Point) account for 5% and 2% of total nitrogen and phosphorus inputs to the lower estuary respectively.

2. Sediment fluxes in San Carlos Bay account for 2% and -2% of total nitrogen and phosphorus inputs to the lower estuary respectively. The negative flux for total phosphorus indicates the sediment in this area is a sink rather than a source.

3. Sediment fluxes in the tidal Caloosahatchee are consistent between the wet and dry seasons, whereas they are positive during dry season (i.e., a source) and negative during the wet season (i.e., a sink) in San Carlos Bay.

<u>Tertiary Factors (purple boxes)</u>

The two tertiary factors of the conceptual model are precipitation and seasons. As season influences precipitation, it can also be considered a quaternary factor, but will be treated here for simplicity's sake.

Seasons

1. Inshore, algae reach maximum biomass in early spring. Offshore, maximum algal biomasses occur in mid to late summer.

2. Algal growth is more favorable inshore, especially during the dry season.

3. Therefore, the conditions most suitable for algal growth would be moderate temperatures (<25C), high salinities (>35), and low/moderate light intensities (15 – 35 $\mu E/m^2/s$). If the peaks in algal biomass in the spring (inshore) and late summer (offshore) reflect higher growth, then it suggests that these optimal conditions may be more common in inshore waters during the spring and offshore during the late summer.

Precipitation

1. Local/regional precipitation will influence local nutrient inputs and likely will affect SGD.

Substrate and Location (orange box)

We have learned several important facts regarding where algae grow and/or accumulate, and the substrates most conducive for growth and accumulation.

1. Geographic location and depth were more important than substrate type for determining the overall macroalgal community structure (i.e., sites that are closer to each other and/or occur at the same depths will have more similar assemblages).

2. Inshore algal assemblages differ from offshore assemblages.

3. Inshore (and nearshore) habitats favorable to algal growth/accumulation include patchy seagrass beds and dense tube-building polychaetes (e.g., Onuphidae, *Diopatra cuprea*).

4. Offshore habitats favorable to algal growth/accumulation include live/hard bottom substrates and worm tubes of other polychaetes (e.g., parchment worms, *Chaetopterus*) and bivalves (e.g., pen shells, Pinnidae).

5. Although the hydroacoustic and video surveys indicated that unconsolidated, soft substrates were most common (and unsuitable for algal attachment and accumulation), pen shells and parchment worm tubes are often associated with these substrates and could allow algae to grow and accumulate in regions where pen shells and worm tubes are abundant. Therefore, soft sediment environments should be included along with the live/hard bottom areas in future monitoring/survey studies.

6. Inshore quantum yield values are highly correlated to offshore values suggesting regional influences (e.g., temperature and water clarity).

7. Hydroacoustic and video survey results indicated that there are two significant expanses of rough seabed thought to be suitable for macroalgae attachment. These two areas covered a total of 19 km^2 (7.3 mi^2), including a large area of seagrass beds and "live hard-bottom" in the mouth of San Carlos Bay, and a site offshore of Lighthouse Point, where a large sand bar extends from the beach to approximately 6 km offshore. Along the west side of this sandy area is a substantial area of predominately composed of unconsolidated, shelly hash.

8. Areas further offshore in the Gulf of Mexico appear to be predominantly soft sediments, indicating that the open Gulf of Mexico waters around Sanibel-Captiva are probably not a major source of drift macroalgae (but see #5 above).

Transport mechanisms

The above factors provide information on the conditions optimal for algal growth as well as the locations where algae can be expected to grow and/or accumulate. The next step is to determine the mechanisms involved in detaching and transporting the algae onto the beaches of Sanibel and Fort Myers. A summary of these mechanisms is provided below.

1. Wind is the primary long term (i.e., over weekly time scales) forcing factor of the water compared to tidal action or river discharge outside of the Caloosahatchee River.

2. Northwest winds can transport water (and therefore drifting algae) onto Estero Island (and southward) from within the tidal Caloosahatchee, near the Causeway, and from offshore sites west of Sanibel (e.g., GOM12 off Redfish Pass). The southeastern shore of Sanibel Island can be impacted by these transport vectors as well, primarily from within the tidal Caloosahatchee.

3. Southwest winds can transport water onto south Sanibel beaches from nearshore locations southeast of Sanibel, as well as from San Carlos Bay and the tidal Caloosahatchee during wet season. Fort Myers Beach may also be affected.

4. During the dry season simulation using actual wind, tide, and river flow data from February 1 – March 16, 2008, the southern shore of Sanibel was significantly exposed to water that originated near the Causeway. Small amounts of accumulated drift algae were noted on Sanibel in February and March 2008 (please refer to references 36 and 37 in Appendix 9.1).

5. The largest stranding event that occurred during this study happened in June 2008. The wet season simulation results (based on actual wind, tide, and river flow data from June 22 – August 5, 2008) suggest the algae came from nearshore locales (i.e., near the Causeway) rather than inshore sites (i.e., within San Carlos Bay or Caloosahatchee Estuary).

6. During the dry season, the largest sediment transport events are clearly associated with strong wind speeds, especially when the wind direction is parallel with the orientation of the southern coast of Sanibel.

7. During the wet season, sediment is deposited onto the ebb deltas at the barrier island passes via the ebb dominant currents. These deposits likely represent significant reserves of sand just offshore of the passes which are available for cross shore transport into the passes during storms.

8. When winds from the north coincide with flood currents there is significant longshore sediment transport along the south coast of Sanibel.

9. At a smaller scale, tidal propagation tends to move sediment northwards once outside of Caloosahatchee River. This is supported by the general morphology of Sanibel and Captive islands.

Beach

While no major algal strandings occurred during the course of this study, there were several small events that provided useful information.

1. Beach algae assemblages collected during the winter of 2009-2010 were significantly different from all the artificial and natural reef (hard bottom) samples. These hard bottom sites were likely not the sources of algae for this event.

2. Algae collected from a later stranding (November 2010) were composed of primarily hard-bottom associated species, suggesting that these sites (e.g., GOM12) were the source in this instance. Fig. 7.18 of the hydrodynamic model indicates that it is possible for algae to be transported from these sites to the beach.

3. The species composition of the stranded algae in events occurring from January through March 2010 appeared to match more closely with the composition at the inshore stations, near the causeway. Hydrodynamic modeling results support this scenario, as do the results of the hydroacoustic/video survey.

4. Algae collected during minor stranding events between January and March 2010 were most similar to inshore algal assemblages, again supporting the above scenario.

Conditions Leading to Excessive Algal Growth and Subsequent Stranding Events

While no large-scale stranding events occurred during this study, the results presented above can be used to construct a plausible scenario leading to such an event.

1. Build-up of a significant algal biomass

The results of this study suggest that algae grow best (and accumulate the most biomass) on either side of the wet season (just beforehand offshore; just after inshore). Algal biomass is lowest during the peak of the wet season, typically when nutrients and temperatures are highest, but when salinity and light availability are lowest. It appears that the higher temperatures, coupled with the lower salinity and light levels, hinder algal growth. Algae do not grow, therefore, until the discharges related to local run-off and lake releases drop significantly. While our initial hypothesis was that regenerated nutrients from the sediments would support algal growth at this juncture, our results indicate that such inputs appear to be insignificant. Rather, submarine groundwater discharges (SGD) are extremely significant, especially during the dry season. We are now hypothesizing that SGD are the source of nutrients building up the algal biomass (inshore and offshore) during the dry season and before/after the peak of the wet season. This hypothesis is substantiated by the fact that SGD accounts for 25% of the total nitrogen and 27% of the total phosphorus reaching the lower estuary annually, but 76% and 62% of each respectively during the dry season. Hu et al. (2006) hypothesized a similar scenario for the extensive red tide that initiated in 2005, where SGD related to an active hurricane season in 2004 provided the "nutrient boost" needed to initiate the bloom. A similar scenario may be active for macroalgae, in which SGD-derived nutrients can build up biomass of macroalgae (nearshore and inshore) prior to a large stranding event. Hydroacoustic/video survey results indicate that this algal biomass is most likely to grow and/or accumulate near the causeway and/or Lighthouse Point. Therefore, these areas should be closely monitored for such a build-up in algal biomass that would (hypothetically) precede a stranding event.

2. Detachment of algae

After a significant algal biomass has built up, the next step would be for the algae to detach. Algae can detach for a variety of reasons including nutrient deficiency, extremes in temperature and salinity, wave action, grazing animals, and natural life history processes (Norton and Mathieson, 1983). While we do not know the specific triggers for algal detachment in local waters, algae have been observed to detach when they reach 15 – 20 cm in height in the Indian River Lagoon (Foster, pers. obs.). Such detachment could be part of the natural life cycle, or may be triggered by warming temperatures and falling salinities as wet season conditions intensify into August. As beach strandings have been documented in all seasons throughout the year, detachment may be caused by different factors (e.g., wave energy during hurricane season, falling temperatures in winter, low salinities in fall, nutrient limitation in dry season). Further study of potential triggers will be needed to narrow these possible detachment scenarios.

3. Mass stranding event

Once a significant amount of algae has been detached, a consistent northwest wind would provide the best mechanism to blow the algae onto the beaches of Sanibel and Fort Myers. Longshore currents could also transport the algae further north (towards Captiva) or south (towards Bonita Beach). A southwest wind will result in a similar, yet smaller stranding, as more water (and drifting algae) will stay off the beaches. Accompanying this report are four scenarios that we believe are most likely in leading to a mass stranding event, further elaborating on the processes presented here.

<u>Why was there no significant stranding event in the past two years?</u>

We offer the following hypotheses for the lack of a stranding event during the course of this study:

1. Lack of significant rainfall. Average monthly precipitation at S-79 was 69% lower in 2008 – 2010 versus 2003 – 2005 (0.13" versus 0.42"). Correspondingly, average monthly flow through S-79 was 61% lower in 2008 – 2010 versus 2003 – 2005 (1,467 cfs versus 3,810 cfs). The differences were greater for wet season-only averages: (0.18" versus 0.74" for a 75% difference; 2,116 cfs versus 5,707 cfs for a 63% difference).

2. Lack of wave action. The lack of significant winter and/or tropical storm activity in the past several years likely caused a reduction in wave energy and/or currents needed to detach algae. Not only is there less algae biomass present because of the lack of rainfall, but the algae that are present are not detaching as frequently because of the lack of energy.

3. Lack of consistent northwesterly winds. An examination of historical wind data has indicated that winds can be quite variable on a daily to weekly basis as cold fronts move through and high pressure cells shift position. Additionally, accurate initiation dates for algal stranding events are not consistent and/or available. This ambiguity, coupled with the variable nature of the winds, prevents us from further examining historical wind data as needed to verify this hypothesis. But if there have been less consistent northwesterly winds since 2008 versus 2003 – 2007, it could result in less algae washing up on local beaches.

What could have caused a reduction in precipitation, storm activity, and northwesterly winds? One possibility is that the time period of 2003 – 2007 was dominated by El Niño conditions, whereas La Niña has been a bigger factor since 2008. This possibility is supported by the fact that La Niña conditions were more prevalent in 2008 – 2010 versus 2003 – 2007 (53% of the time versus 8% of the time; data from the NOAA Earth System Research Laboratory: http://www.esrl.noaa.gov/psd/people/klaus.wolter/MEI/rank.html). Simply stated, La Niña conditions can result in lower precipitation and river discharge in south Florida (Schmidt et al. 2001), so this hypothesis seems likely. However, the processes involved are complex, so this statement may not apply everywhere in south Florida, or during all La Niña conditions. Conversely, La Niña conditions tend to stimulate hurricane activity for storms similar in dynamic and track to Donna, Charley, and Wilma (Kossin et al. 2010), so the complexities in climate dynamics are apparent when we consider the lack of local hurricane activity since 2008 (excepting Tropical Storm Fay). ENSO influences on wind patterns in southwest Florida are complex, and may be influenced more by the Atlantic Warm Pool (Wang et al. 2006). It is unclear, therefore, if La Niña conditions could have affected local winds.

Management and Policy Implications

1. Nitrogen-reduction measures should be considered to reduce algal biomass in the CRE.

    a. Microalgae (and possibly macroalgae) are nitrogen-limited in the CRE. Reducing the levels of nitrogen-based nutrients (e.g., nitrate and ammonium) in the CRE will therefore reduce the amount of algae that can be supported in the ecosystem.

    b. 18 – 27% of the nutrients entering the tidal portion of the CRE (i.e., below S-79) are derived from Lake Okeechobee, with an equal proportion (25 – 27%) coming from submarine groundwater inputs. The remaining nutrients (40 – 50%) are then estimated to be coming from the local watershed, particularly above S-79 (the East and West Caloosahatchee sub-basins, contributing 24 – 29% of the nutrients). These results indicate that nitrogen-reduction measures should be implemented, beginning with the watershed above S-79, and later expanding to the watershed below S-79 (which contributes 12 – 20% of the nutrients).

    c. As there are significant differences in nutrient inputs between wet and dry seasons, efforts to reduce nutrient inputs should focus on those that are greatest during the wet season (i.e., non-point sources related to run-off).

    d. The best approach to reduce nutrient inputs would be through Best Management Practices (e.g., fertilizer ordinances, stormwater treatment areas, required septic system inspections, etc.), as outlined in CRWPP (2009).

2. A program should be established to monitor for greater than average ("significant") accumulations of macroalgal biomass that might precede a major drift algae stranding event.

    a. Areas conducive for macroalgal growth and accumulation have been identified.

        i. The first is the large area of seagrass beds and live hard-bottom near the mouth of San Carlos Bay, where large amounts of drift algae are often variably present (e.g., during the April-May 2009 surveys).

        ii. The second is an area of coarse "shellhash" offshore of Lighthouse Point, located near a large sand bar that extends from the beach to approximately 6 km offshore.

        iii. As no major stranding events occurred during the course of this study, we cannot confirm that algae associated with past stranding events did in fact come from these regions. However, the most common macroalgae reported from the 2003/2004 stranding events were species that we found commonly at inshore and nearshore locations from 2008-2010 (e.g., *Solieria filiformis* and *Hypnea spinella*).

iv. While nearshore artificial reefs and natural ledges do not appear to be a significant source of algae in the quantities necessary to cause a significant stranding event, algae that have washed-up on area beaches (e.g., Sanibel in November 2010) are also known inhabitants of these nearshore reef (hardbottom) environments. Therefore, regularly monitoring of these sites, especially if algae above and beyond average algal biomass would expand the spatial and environmental coverage of the future program.

b. "Sentinel" sites should be chosen for such a monitoring program (e.g., time series with quarterly monitoring of algal abundance and species composition).

  i. The recommended sites include: the mouth of San Carlos Bay, the sides of the sand bar located off the Sanibel Lighthouse, one or two natural ledges (e.g., GOM12 and 53 Ledge), and one or two of the artificial reef sites (e.g., Edison Reef and GH Reef).

  ii. These sites can be monitored by City/County personnel, the Volunteer Scientific Research Team (VSRT), or contracted scientists as funds allow (e.g., from SCCF or FGCU).

c. Standard measurements and collections should be made at these sites.

  i. Methods should be standardized to determine absolute algal abundance (e.g., video surveys, dives, snorkeling, or quadrats/transects as needed or as manpower is available).

  ii. Algal samples should be collected to determine species composition and to collect tissues (if possible) for stable isotope analysis and nutrient composition (to determine changes in nutrient conditions and sources over time).

    1. Inshore algal communities (e.g., in and around San Carlos Bay) are often composed of different species than nearshore and offshore communities based on this study.

    2. By monitoring the species composition of macroalgae at the "sentinel" sites, and comparing these assemblages to those found at a "stranding" event, we can potentially determine the source of drift macroalgae washing ashore.

    3. Standard collection and analysis methods should be agreed upon with County and City staffs.

d. A monitoring program of this nature will likely require additional resources.

    i. A permanent funding mechanism to annually contribute to the program needs be identified.

3. Efforts should continue to find ways to proactively respond to a build-up of algal biomass prior to beach deposition.

    a. Details of location, timing, and extent of future large-scale stranding events should be recorded in a complete and standardized fashion (see #4 below).

    b. After details of such events are recorded, continued modeling efforts could be focused on these events to better test the hypothesis of the interaction between seasonal nutrient advection and wind forced transport.

    c. The presence of large amounts of algae at the identified "sentinel" sites, coupled with a better knowledge of the mechanisms that transport the algae to area beaches may allow for a proactive response to any impending event.

    d. The best proactive response at this time (without an event to characterize) would be to reduce algal biomass through nutrient reduction measures as outlined in #1 above.

    e. A second option would be to further study the role of grazers, and the impacts caused by regulated releases (e.g., drastic salinity changes). A healthy grazer population can potentially help keep the local algal populations in check.

    f. A third option would be to somehow intercept the algae prior to deposition.

4. Determination of and Response to Beach Stranding Event(s)

    a. Event Determination. A mechanism needs to be put in place to monitor for, and assess whether an above average stranding event is taking place

        i. A decision tree should be constructed to determine the level of response needed for various categories of events.

            1. Categories should be defined and standardized based on clearly defined parameters including (but not limited to) size of the deposition (length, width, and height), condition of the algae (fresh or degraded), odor, and citizen reaction to the deposition.

            2. First responders should provide an initial assessment (including photographs, GPS coordinates, etc.) to the appropriate staff/personnel (second responders - to be determined).

3. The second responders should determine what additional assessments/actions are needed.

ii. These assessments/actions should follow the Event Response guidelines outlined below.

b. Event Response. Once an above average stranding event has been identified, several courses of action must be implemented. Each "event" should be documented using standard procedures and measures. A list of considerations includes the following:

i. One has to ascertain what constitutes a baseline (acceptable) level of algae on local beaches, and what amount would represent an above average stranding event.

ii. The timing of the event should be accurately recorded (i.e., when did it start, how long was algae being deposited).

iii. The spatial extent of the event should be ascertained (i.e., is it a small (and likely temporary) event or large? How is a large event categorized? What are the parameters to be quantified? Can the mass of algae be estimated?).

iv. If the event is of large scale, aerial reconnaissance is recommended to estimate biomass and the probability that the event will last days or months.

v. GIS and photos with GPS information can aid in assessing and quantifying the extent of the event.

vi. Other factors such as tourist perception and odor should also be considered.

vii. The composition of the algae must be determined. For example, do the algae appear fresh (firm and pigmented) or degraded (soft and bleached)? Are holdfasts present? What species are present? At what abundances are the species present (absolute and relative)?

viii. Algal samples must be collected and kept on ice for species identification and tissue analysis (e.g., stable isotopes, carbon and nitrogen content).

ix. Collected samples can be identified and processed with help from seaweed experts (e.g., SCCF or FGCU scientists).

x. A decision tree should be developed to determine if and when the deposited algae should be mechanically removed from the beach, allowed to be removed by natural (tidal) processes, or allowed to be left in place for natural degradation. Factors that need to be considered include:

    1. the cost for removal;
    2. the potential for tides and wave action to remove the deposition;
    3. the negative impact on the recreational use of the beach; and
    4. possible positive ecological implications of the deposition (e.g., stabilization of beach sands and enrichment of beach biotic communities).
    5. Objective 6 outlines such considerations that will be useful in constructing the decision tree.

Educational Value

While the objectives of this study did not include an educational component, FGCU faculty involved with this project have been providing FGCU students (both undergraduate and graduate) with opportunities for internships and research. These students are obtaining valuable scientific training in field- and laboratory-based research. These opportunities serve to fulfill FGCU's learning outcomes of problem solving as well as providing an ecological perspective. These students graduate to become citizens who are mindful of the vulnerability of our coastal environments and our ethical responsibility to preserve it.

To date, two Environmental Studies majors have completed their Senior Research Projects related to this study while four others (2 Marine Science and 2 Environmental Studies) completed part of their internships with this study. One of these Senior Research Projects earned a Dean's Prize at the 2009 Fifth Annual FGCU Research Day. In addition, one graduate student in the M.S. in Environmental Science also worked on this project.

Lastly, Greg Foster has included Objective 4 as a chapter in his dissertation at Nova Southeastern University. Greg was a valuable member of our research team and we are pleased that he could utilize this research opportunity in pursuit of his Ph.D.

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