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PROFILE

Toward Reversal of Eutrophic Conditions in a Subtropical Estuary: Water Quality and Seagrass Response to Nitrogen Loading Reductions in Tampa Bay, Florida, USA

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ABSTRACT / Coastal waters have been significantly influenced by increased inputs of nutrients that have accompanied population growth in adjacent drainage basins. In Tampa Bay, Florida, USA, the population has quadrupled since 1950. By the late 1970s, eutrophic conditions including phytoplankton and macroalgal blooms and seagrass losses were evident. The focus of improving Tampa Bay is centered on obtaining sufficient water quality necessary for restoring seagrass habitat, estimated to have been 16,400 ha in 1950 but reduced to 8800 ha by 1982. To address these problems, targets for nutrient load reductions along with seagrass restoration goals were developed and actions were implemented to reach adopted targets. Empirical regression models were developed to determine relationships between chlorophyll *a* concentrations and light attenuation adequate for sustainable seagrass growth. Additional empirical relationships between nitrogen loading and chlorophyll *a* concentrations were developed to determine how Tampa Bay responds to changes in loads. Data show that when nitrogen load reduction and chlorophyll *a* targets are met, seagrass cover increases. After nitrogen load reductions and maintenance of chlorophyll *a* at target levels, seagrass acreage has increased 25% since 1982, although more than 5000 ha of seagrass still require recovery. The cooperation of scientists, managers, and decision makers participating in the Tampa Bay Estuary Program's Nitrogen Management Strategy allows the Tampa Bay estuary to continue to show progress towards reversing many of the problems that once plagued its waters. These results also highlight the importance of a multi-entity watershed management process in maintaining progress towards science-based natural resource goals.

The effects of nutrient overenrichment have been well documented as early as the 1950s from the Baltic to the North and Wadden Seas and from Chesapeake Bay to the Gulf of Mexico (Andersson and Rydberg 1988; Cornwell and others 1996; Rabalais and others 1996; Jansson and Dahlberg 1999; Deegan 2002). Today, eutrophication is common in many marine ecosystems. Eutrophication is a broad term used to describe enhanced plant growth in water bodies such as lakes, rivers, and estuaries that receive excess nutrients, mainly nitrogen (N) and phosphorus (P) (Nixon 1995). Consequences of increased nutrient loading, resulting from reduction of dissolved oxygen in the water column when excess organic matter decomposes, include increased episodes of noxious blooms, reductions in aquatic macrophyte communities, and hypoxia and/or anoxia, often leading to substantial shifts in ecosystem processes (Nixon 1995; National Research Council 2000; Cloern 2001; Paerl and others 2003). N and P are the nutrients of greatest concern because they most often control eutrophication and their inputs are often anthropogenic (Paerl and others 2003). The single largest global change in the N cycle results from synthetic inorganic fertilizers that became widely used after the 1950s. In addition to widespread use of fertilizers, increased use of fossil fuels and production of N-fixing crops have dramatically increased nitrogen loading across the globe (Seitzinger and others 2002). Prior to the 1990s in the United States, P loading was dominated by point sources, specifically wastewater. With the successful effort to reduce P loading in wastewater, non–

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point source loading has increased in significance (Howarth and others 2002). As in most estuarine systems (National Research Council 2000), N is the limiting nutrient in Tampa Bay. Strong empirical evidence, based on annual water quality sampling in the region and bioassay results, points to the importance of nitrogen in controlling algal biomass and growth in this estuary (Johansson 1991). Therefore, the focus of nutrient reduction in Tampa Bay is N loading.

Currently, there are no specific nutrient reduction laws mandated by any U.S. government agency, although certain mandates under the Clean Water Act are acting to implement water quality standards and reduce total maximum daily loads (Boesch 2002). Every watershed is unique, and setting standards must account for the individual characteristics of each. This makes enacting and implementing nutrient reduction strategies very difficult, especially given the need to determine how to achieve locally desired resource management goals. The U.S. Environmental Protection Agency's National Estuary Programs have been instrumental in establishing site-specific goals and implementing these goals through the participation of national, regional, and local agencies, governments, and private entities. The reality is that the central process of eutrophication is not a single focused issue but rather a multitude of factors that combine to cause water quality issues that change, depending on ecosystem location and sources of pollution.

One commonly used method to assess and control eutrophication is to identify indicators, such as seagrass growth and coverage and primary production, for management of estuarine systems. Light availability is the principal factor limiting seagrass distribution (Gallegos 2001). Management of primary production as a result of increased nitrogen loading has a direct effect on surface irradiation depth. For example, in Chesapeake Bay, Dennison and others (1993) established habitat requirements for submerged aquatic vegetation based on total suspended solids of <15 g m^{-3}, chlorophyll *a* concentrations of <15 mg m^{-3}, and median photosynthetically active radiation of <1.5 m^{-1}. A similar management approach was also used in the Indian River Lagoon, Florida, U.S.A. (Gallegos and Kenworthy 1996; Kenworthy and Fonseca 1996).

Overall declines in water quality in Tampa Bay in the 1970s prompted a call to action among managers, scientists, and residents of the region, and legislative action resulted in significant reductions of nitrogen loading from wastewater treatment plants (Johansson 1991). During the mid-1990s, agencies around Tampa Bay adopted a water quality management strategy that linked nitrogen loading management to seagrass restoration and protection (Greening 2001). As a result of this strategy, participants in the Tampa Bay Estuary Program (TBEP), one of 28 "estuaries of national significance" included in the U.S. EPA's National Estuary Program, agreed to adopt nitrogen loading targets for Tampa Bay. These targets were based on water quality requirements of turtle grass (*Thalassia testudinum*) with the goals of restoring seagrass acreage to 95% of that observed in 1950 and to improve overall water quality of the system (Greening 2001). The year 1950 was selected as a baseline year for seagrass coverage because this time period preceded rapid population increases in the watershed and because aerial photographs were available for the entire Tampa Bay shoreline and adjacent shallow water. In coming years, Tampa Bay hopes to typify how nutrient loading reductions can improve water quality, increase seagrasses, and promote a productive estuarine ecosystem while addressing increased loadings anticipated from projected population growth within its watershed. In this article, we describe long-term changes in eutrophic conditions observed in Tampa Bay in response to decreased nitrogen loads and measures taken to address anticipated increases in loads with an ever-increasing population within Tampa Bay's watershed.

The Study Area

The Tampa Bay estuary is located on the eastern shore of the Gulf of Mexico in Florida, USA (Figure 1). At 882 km^2, it is Florida's largest open water estuary. More than two million people live in the 5617 km^2 watershed with a 20% increase in population projected by 2010. Population in the three counties surrounding Tampa Bay has increased substantially since 1940 (Figure 2) after the advent of mosquito screening and air conditioning. This population increase has resulted in a significant change in land use/cover in the watershed. Currently, land use in the watershed is mixed, with about 40% of the watershed undeveloped, 35% agricultural, 16% residential, and the remaining as commercial and mining (TBNEP 1996).

Commercial, agricultural, and mining operations are important contributors to the Tampa Bay economy. The Tampa Bay watershed is located in one of the world's largest phosphate mining areas. Mining of raw product, as well as production and transportation of phosphate fertilizer products, are principal economic factors in the region. Tonnage of freight transported through the three major ports in Tampa Bay is consistently among the 10 highest in U.S. port areas. Intensive agricultural production of vegetables and strawberries in winter and citrus throughout the year is

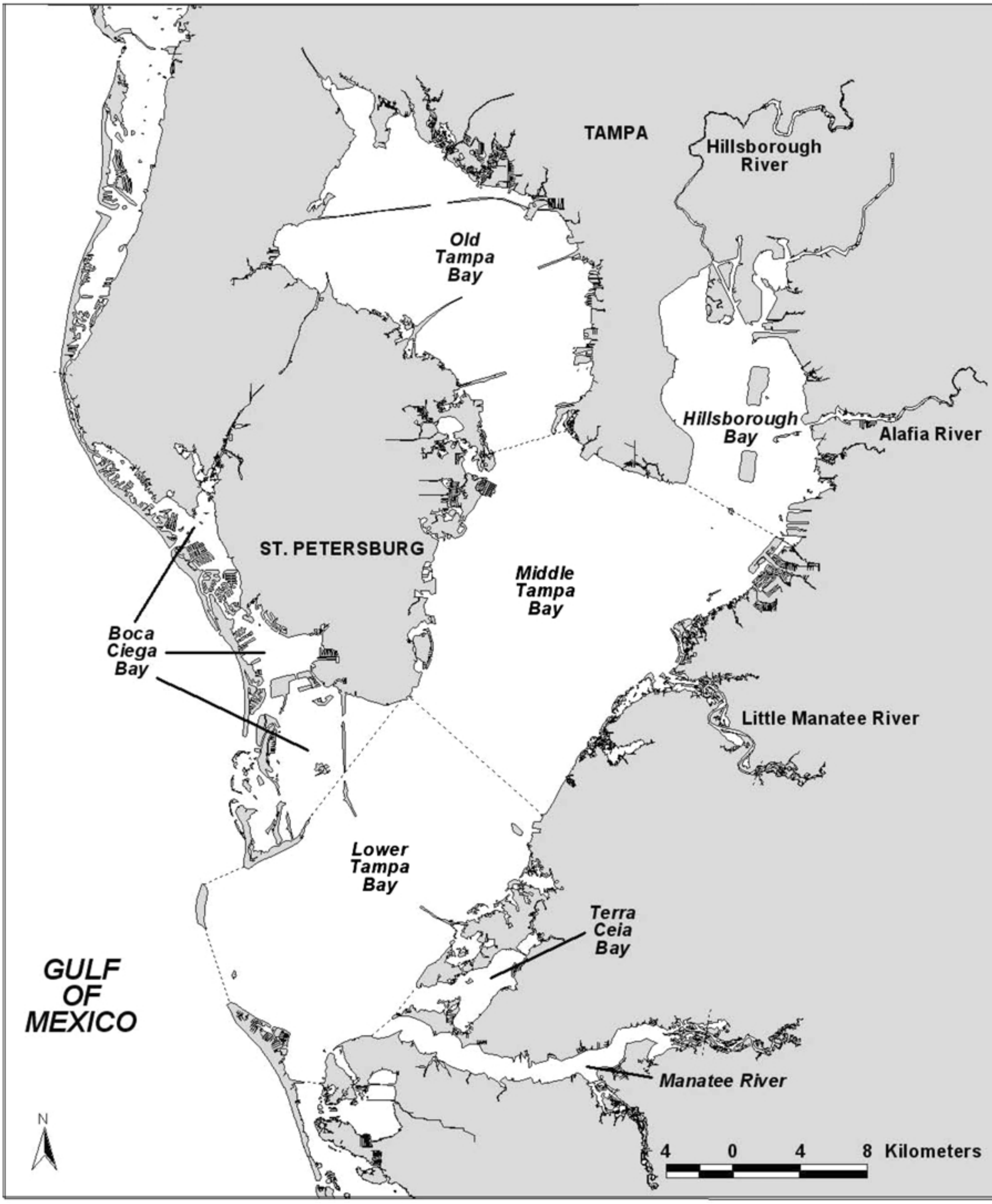

Figure 1. Tampa Bay, Florida, USA depicting the major segments and tributaries.

a principal component of the economy and land use within the watershed.

Tampa Bay is also valued for its natural resources (estuarine resources, habitat value, and fisheries and wildlife). Its shallow depth, averaging 4 m, makes it an important nursery ground for fish, shellfish, and crustaceans spending a portion of their life developing in its near shore waters. Major habitats in the Tampa Bay estuary include mangroves, salt marshes, and submerged aquatic vegetation. These habitats have expe-

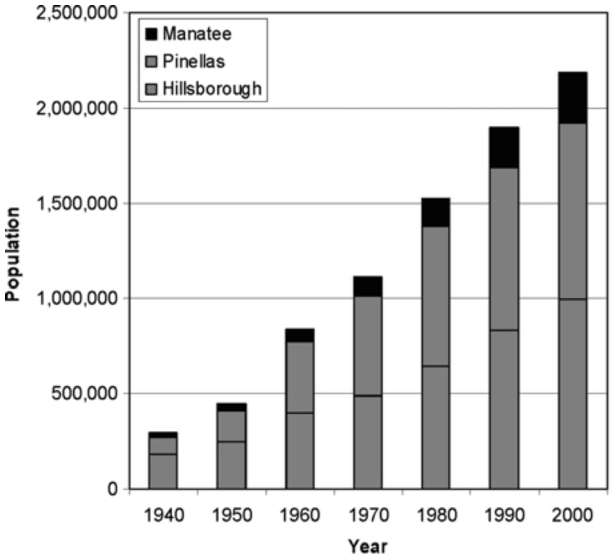

Figure 2. Population growth for the three counties in the Tampa Bay watershed since 1940. Source: US Census Bureau.

rienced significant areal reductions since the 1950s because of physical disturbance (dredge and fill operations) and water quality degradation. Seagrasses were particularly impacted because of increased light attenuation. Four species of seagrass are commonly found in Tampa Bay, with *Thalassia testudinum* (turtlegrass) and *Syringodium filiforme* (manatee grass) dominating in higher salinity areas and *Halodule wrightii* (shoalgrass) and *Ruppia maritima* (widgeon grass) most commonly found in lower salinities.

Major salinity gradients exist in the bay's four major segments: Old Tampa Bay, Hillsborough Bay, Middle Tampa Bay, and Lower Tampa Bay (Figure 1). Four major rivers and more than 100 tidal streams flow into these segments. Recent (1985–1998) average annual flow rates are similar in three of the four rivers (Hillsborough River: 9.3 $m^3\ s^{-1}$, Alafia River: 9.6 $m^3\ s^{-1}$, Manatee River: 10.6 $m^3\ s^{-1}$), with the Little Manatee River being slightly lower (6.5 $m^3\ s^{-1}$). Hillsborough Bay is the smallest segment in terms of surface area, volume, and watershed area, yielding a watershed area:volume ratio that is more than 10 times that of the other three segments (Table 1).

In the 1970s, many eutrophication symptoms were observed in Tampa Bay, particularly in Hillsborough Bay (Figure 1). Phytoplankton and macroalgal blooms were common occurrences leading to odor and aesthetic problems, especially along the urbanized shoreline of the City of Tampa and in Hillsborough Bay (Johansson and Greening 2000). Hypoxia and anoxia development in some areas in Hillsborough Bay led to adverse responses in the benthic community of Tampa Bay (Santos and Simon 1980). In the 1970s, complete depauperation of the benthos was common in late summer along the western shoreline of Hillsborough Bay. The most visible symptom of the eutrophication of Tampa Bay was the increased degree of light attenuation that accompanied elevated algal biomass. The concomitant seagrass loss during this period was also dramatic (Figure 3). In 1950, more than 16,000 ha of seagrass were present. By the early 1980s, more than half of this area was lost. Since 1988, biannual photography and mapping has shown seagrass recovery in Tampa Bay (Tomasko and others 2005).

Methods and Results

Nitrogen Loading to Tampa Bay

The sources of nitrogen loads to Tampa Bay are varied and include point sources, nonpoint sources, atmospheric deposition, groundwater/springs, and fertilizer losses from port facilities (Poe and others 2005). Nitrogen loading estimates combine both measured and estimated nitrogen loads. Brief descriptions of the methods used to estimate each source type are described here. A complete description is included in Pribble and others (2001).

The hydrologic load to the bay via precipitation was estimated using an inverse distance-squared method applied to data from 22 National Weather Service rainfall-monitoring sites in the Tampa Bay watershed. Monthly rainfall estimates were used to develop direct wet deposition loads to the bay's surface and to estimate non–point source pollutant loads from ungauged parts of the watershed.

Approximately 57% of the watershed is gauged for both flow and water quality, allowing for direct estimates of loads. For ungauged areas, loads from stormwater runoff were estimated using predictions based on rainfall, land use, soils, and seasonal land-use-specific water quality concentrations. For domestic and industrial point source load estimates, values for all individual facilities with direct surface discharges and all land application discharges with an annual average daily flow of 0.1 MDG or greater were calculated from measurements of discharge rates and constituent levels required for maintaining permit compliance. These loads were then summed for all point sources (Poe and others 2005).

Wet atmospheric deposition of nitrogen directly to open waters of Tampa Bay was calculated by multiplying the volume of precipitation onto the bay by nitrogen concentration in rainfall. Dry deposition was estimated using a seasonal dry:wet deposition ratio

Table 1. Surface areas, volumes, and watershed drainage areas for the four major bay segments in Tampa Bay

Segment	Surface area (km^2)	Volume (km^3)	Watershed area (km^2)	Watershed area: surface area	Watershed area:volume
Old Tampa Bay	234	531	640	2.74	1.21
Hillsborough Bay	108	263	3209	29.71	12.20
Middle Tampa Bay	292	1108	771	2.64	0.70
Lower Tampa Bay	248	1028	997	4.02	0.97
Total	882	2930	5617	6.37	1.92

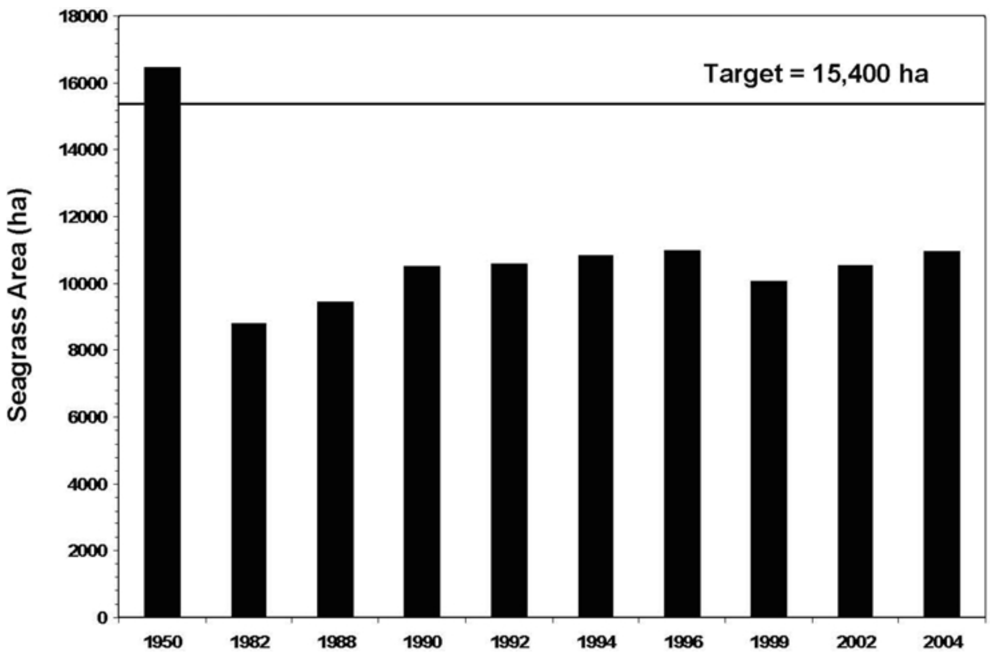

Figure 3. Changes in the areal coverage (ha) of seagrasses in Tampa Bay since 1950. The long-term seagrass recovery target of 15,400 ha is shown. Source: Tomasko 2002, Tomasko and others 2005.

derived from 5 years of concurrent wet and dry deposition measurements (Poor and others 2001).

Groundwater flows were estimated for each bay segment. Only groundwater inflow that entered the bay directly from the shoreline or bay bottom was considered. Groundwater and septic tank leachate inflow to streams were already accounted through measured or modeled surface water flow as non–point source loading and therefore were not included in groundwater loading estimates. Wet and dry season groundwater flow estimates were calculated using a flow net analysis and Darcy's equation, following the methods of Brooks and others (1993). Total nitrogen (TN) concentration data for surficial, intermediate, and Floridan aquifers were obtained from the Southwest Florida Water Management Ambient Ground Water Monitoring Program (Poe and others 2005).

Worst-case nitrogen loads were estimated for the mid-1970s. Approximately 8200 metric tons entered Tampa Bay annually during this period. Point sources dominated nitrogen loads, accounting for 55% of the total load. Contributions of atmospheric deposition directly to the bay's surface, nonpoint sources, groundwater, and fertilizer losses were 22%, 16%, 3%, and 5%, respectively (Figure 4).

Since the mid-1970s, a number of actions were taken to address the problem of excessive nitrogen loading to Tampa Bay. First, in 1980, all municipal wastewater treatment plants were required to provide advanced wastewater treatment (AWT) for discharges directly to the bay and its tributaries. AWT required TN concentrations in wastewater discharged to the bay to not exceed 3 mg/L, reducing TN loads from this source by 90%. In addition to significant reductions in nitrogen loadings from municipal wastewater treatment plants, stormwater regulations enacted in the 1980s also contributed to reduce nitrogen loads to the bay (Johansson and Greening 2000). Lastly, the phosphate industry initiated a number of best management practices to reduce nitrogen loads from port facilities

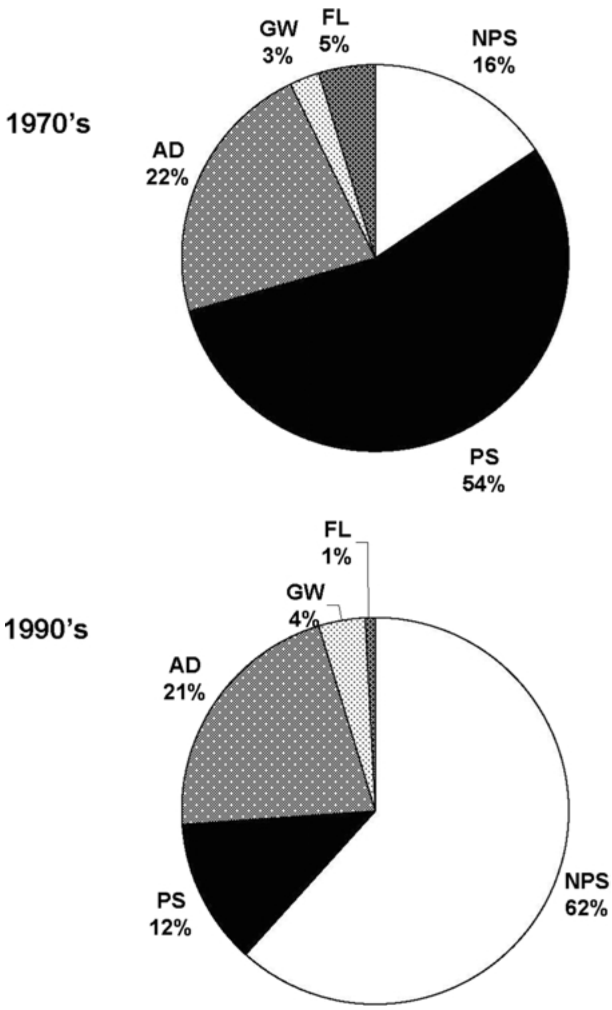

Figure 4. Relative contributions of the various sources of nitrogen loads to Tampa Bay in the 1970s and 1990s. PS = point sources, NPS = nonpoint sources, AD = atmospheric deposition, FL = fertilizer losses, GW = groundwater and springs. Source: Pribble and others 2001.

from which its fertilizer products are shipped. These management actions resulted in a significant reduction (60%) in estimated nitrogen loading from the 1985–2003 period compared to the estimated loadings from the mid-1970s (Figure 5). Also, the relative contributions from various nitrogen sources changed appreciably since the 1970s (Figure 4).

From 1985 to 2003, variation in TN loads was driven largely by interannual variation in rainfall. Increased annual rainfall amounts were associated with increased annual TN load (Figure 6), further substantiating the shift in relative importance of contributions of point sources to nonpoint sources and atmospheric deposition.

Water Quality Responses to Load Reductions

Changes in eutrophic conditions resulting from decreased N loads were first observed as significant chlorophyll *a* concentration decreases beginning in 1985. Since 1974, the Environmental Protection Commission of Hillsborough County has conducted monthly water quality sampling at more than 50 fixed sites in Tampa Bay. Figure 7 presents the mean annual chlorophyll *a* concentrations for each of the four bay segments.

Given its morphometry and size and nature of its watershed, Hillsborough Bay has consistently exhibited the highest chlorophyll *a* concentrations in Tampa Bay. This was particularly true during the mid- to late 1970s. Management actions (particularly reductions from wastewater treatment plants) taken to reduce TN loads primarily affected Hillsborough Bay, and declines in chlorophyll *a* concentrations in this segment were most pronounced. Chlorophyll *a* concentrations in the mid-1970s typically varied between 25 and 35 μg/L; current mean annual values are typically less than 15 μg/L. During the same period, chlorophyll *a* concentrations in other bay segments also declined in response to TN load reductions.

Changes in chlorophyll *a* concentrations observed after 1985 were accompanied by decreases in light attenuation as measured by Secchi disc depth (Figure 8). As observed for chlorophyll *a* concentrations, the most dramatic response in Secchi disc depth was found in Hillsborough Bay, where mean annual low values of less than 0.6 m observed in the 1970s increased to values between 1.0 and 1.4 m in most years after 1985. Similar increases in Secchi disk depth values were observed in other major bay segments over this time. Declines in chlorophyll *a* concentrations and light attenuation were followed by increased seagrass coverage (Figure 3) and a reduction of extent and duration of hypoxic events (Janicki and others 2001b).

Seagrass Cover Extent Changes

Since 1988, seagrass maps have been produced approximately every 2 years by the Southwest Florida Water Management District through a multistep process, as described by Tomasko and others (2005) and summarized here. First, aerial photography is obtained in late fall, corresponding with a time of good water clarity and relatively high seagrass biomass (Tomasko and others). Seagrass polygons are delimited based on photo interpretation of the aerial photographs, with a minimum mapping unit of 0.2 ha. Polygons are integrated into an ARC/Info program. From 1988 through

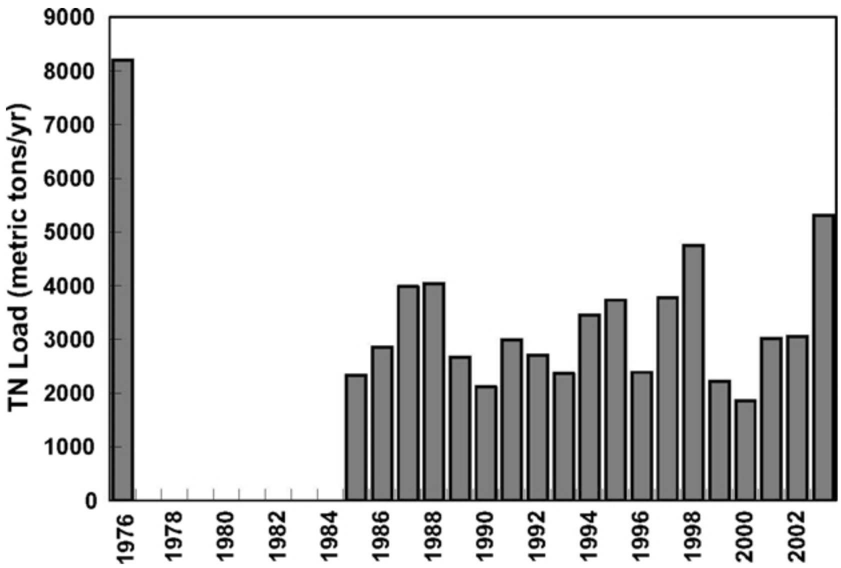

Figure 5. Annual nitrogen loads (metric tons) to Tampa Bay for 1976 and 1985–2003. Source: Pribble and others 2001, Poe and others 2005.

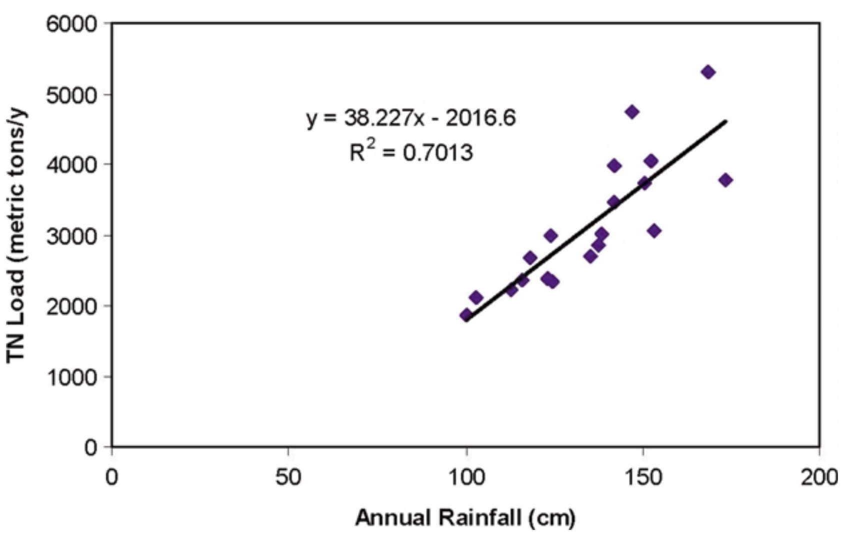

Figure 6. Relationship between annual nitrogen loads (metric tons/yr) to Tampa Bay and total annual rainfall (cm) in the watershed.

1996, individual polygons were delineated on Mylar overlays and digitally transferred to an ARC/Info database for further analyses. For 1999, 2002, and 2004 seagrass maps, georeferenced digital files were produced using analytical stereo plotters, eliminating the need for additional photo-to-map transfer as for earlier efforts. A 90% post-map production classification accuracy assessment standard (obtained from randomly selected field location visits) is required for acceptable mapping products (Tomasko and others 2005). Historical (1950 and 1982) estimates of seagrass coverage have been developed using 1:24,000 scale true color aerial photographs (Tampa Bay Regional Planning Council 1986).

Tomasko and others (2005) found a pattern of seagrass loss (1950 to 1970s), followed by recovery (1970s to 1990), followed by periods of slight increases and reductions since 1990. Seagrass coverage in Tampa Bay decreased by 7685 ha between 1950 and 1982 followed by a 2127 ha increase in coverage between 1982 and 1996. Between 1996 and 1999 (years that included a strong El Niño rainfall event), coverage decreased by 839 ha, followed by recovery and expansion of 883 ha between 1999 and 2004. Baywide, seagrass coverage in Tampa Bay in 2004 was the highest observed since 1950, but still 5512 ha lower than 1950 coverage.

Development of a Nitrogen Management Strategy to Restore Seagrasses in Tampa Bay

A focus of the Tampa Bay resource management community has been to establish nitrogen-loading targets for Tampa Bay to encourage seagrass recovery.

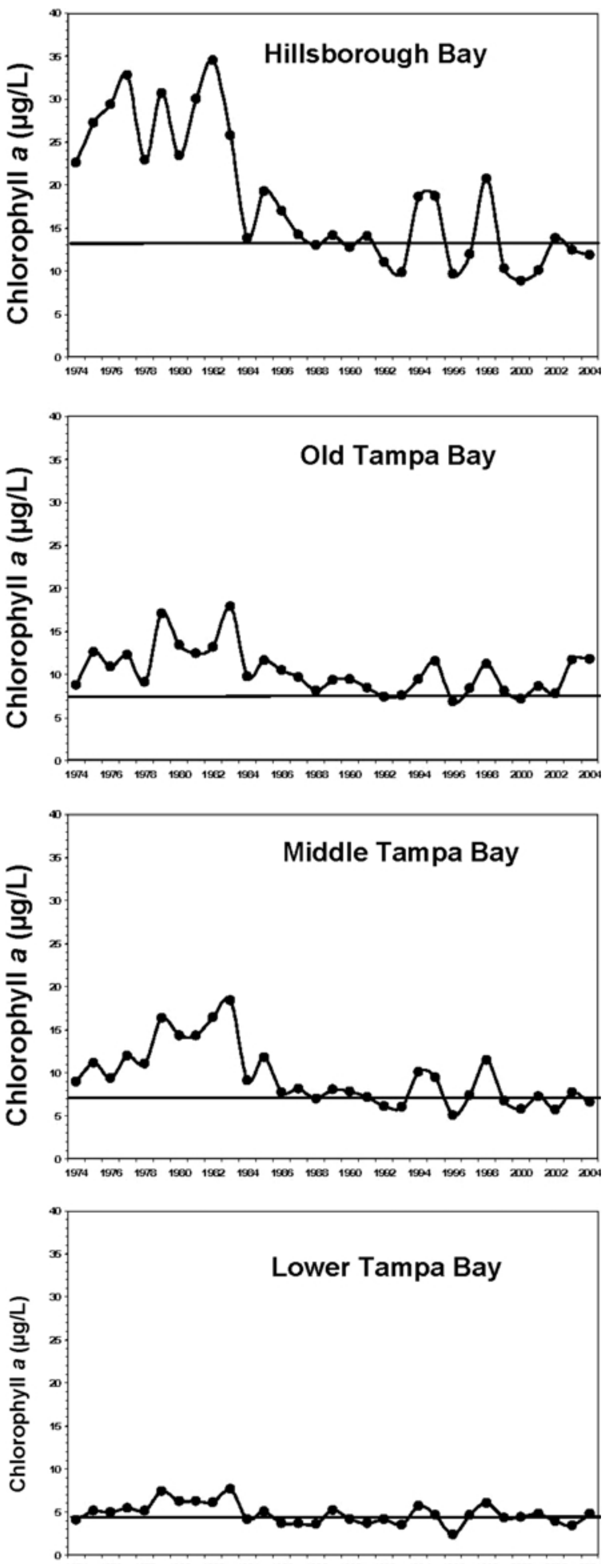

Figure 7. Interannual variation in chlorophyll *a* concentrations (µg/L) in the four segments of Tampa Bay. Horizontal line represents the target chlorophyll *a* concentrations in each bay segment. Note difference in scale. Source: Environmental Protection Commission of Hillsborough County.

Recent recommendations for addressing marine and estuarine eutrophication from the National Academy of Science National Research Council (National Research Council 2000; Greening and Elfring 2002) included a process for developing nutrient management strategies. The National Research Council recommendations are similar to the process designed to develop and implement a seagrass protection and restoration management program for Tampa Bay, first implemented in 1996. Critical elements of the Tampa Bay process are described in the following paragraphs.

Step 1. Set Quantitative Resource Management Goals

Based on digitized aerial photographic images, approximately 16,500 ha of seagrass existed in Tampa Bay in 1950. At that time, seagrasses grew to depths from 1.5 m to 2 m in most areas of the bay (Lewis and others 1985). By 1992, approximately 10,400 ha of seagrass remained in Tampa Bay. Some (about 160 ha) of the observed loss occurred as the result of direct habitat destruction associated with construction of navigation channels and other dredging and filling projects within existing seagrass meadows, and is assumed to be nonrestorable through water quality management actions (Wade and Janicki 1993).

In 1996, the Tampa Bay Estuary Program partners (including six local governments in the Tampa Bay watershed, and three state, federal, and local regulatory agencies) adopted a baywide minimum seagrass goal of 15,400 ha. This goal represented 95% of estimated 1950 seagrass cover (minus the nonrestorable areas), and included protection of the existing 10,400 ha plus restoration of an additional 5000 ha (TBNEP 1996).

Step 2. Determine Seagrass Water Quality Requirements and Appropriate Nitrogen Loading Rates

Once seagrass restoration and protection goals were established, the next steps established environmental requirements necessary to meet agreed-upon goals and subsequent management actions necessary to meet those requirements. In Lower Tampa Bay, deep edges of *T. testudinum* meadows, the primary seagrass species for which nitrogen loading targets are set, correspond

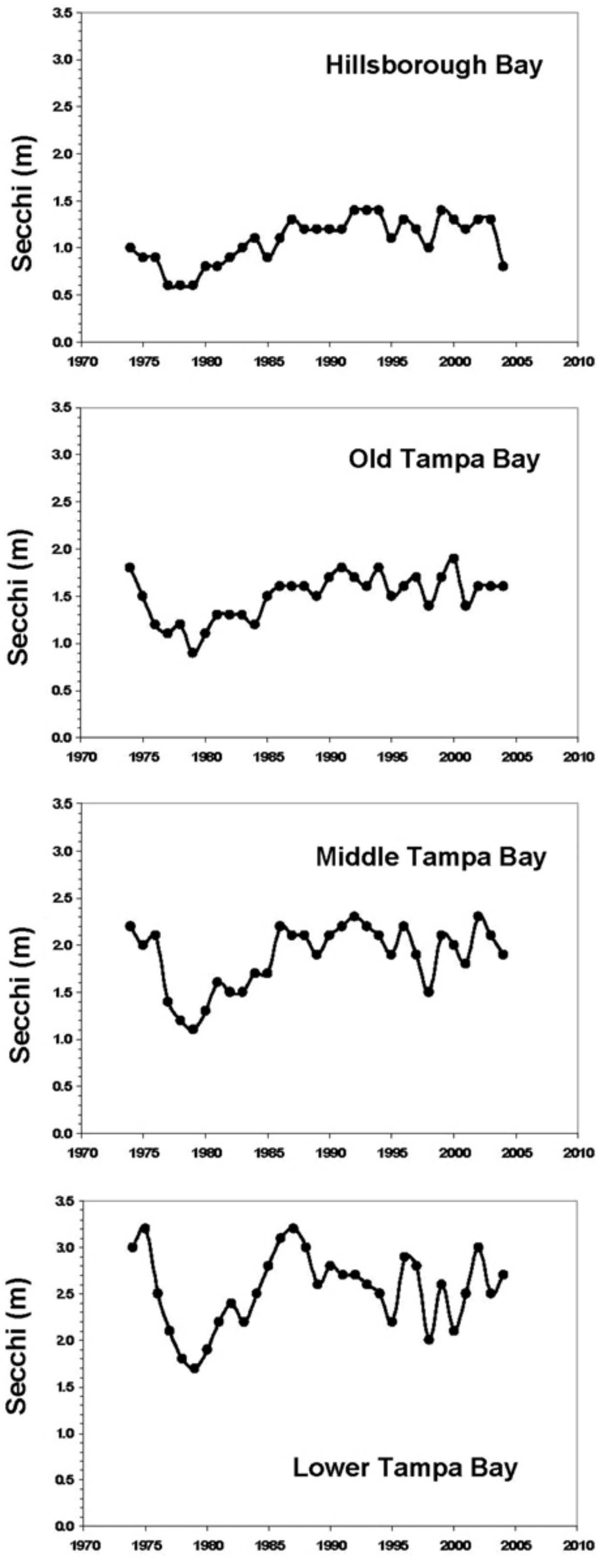

Figure 8. Interannual variation in Secchi disc depth (m) in the four segments of Tampa Bay. Note differences in scale. Source: Environmental Protection Commission of Hillsborough County.

to the depth at which 20.5% of incident light reaches the bay bottom on an annual average basis (Dixon 1999). The long-term seagrass coverage goal can be restated as a water clarity and light penetration target. Therefore, in order to restore seagrass to near 1950 levels in a given bay segment, water clarity in that segment should be restored to the point that allows 20.5% of subsurface irradiance to reach the same depths that were reached in 1950. These depths range from 1.0 m for Hillsborough Bay to 2.0 m for Lower Tampa Bay (Janicki and Wade 1996).

Water clarity and light penetration in Tampa Bay are affected by a number of factors, including phytoplankton biomass, nonphytoplankton turbidity, and water color. An empirical regression model (Janicki and Wade 1996) was used to estimate chlorophyll *a* concentrations necessary to maintain water clarity needed for seagrass growth for each major bay segment. The relationship between chlorophyll *a* concentrations and depth to which 20.5% of incident light reaches is shown in Figure 9. The relationship between chlorophyll *a* concentrations and light attenuation, expressed as the depth to which 20.5% of the surface irradiance penetrates, was described by the following equation:

$$\ln C_{t,s} = \alpha_{t,s} + \beta_{t,s} * \ln\left(Z_{t,s}\right)$$

where $Z_{t,s}$ = depth to which 20.5% of surface irradiance penetrates in month t and bay segment s and $C_{t,s}$ = average chlorophyll *a* concentration in month t and bay segment s, and $\alpha_{t,s}$ and $\beta_{t,s}$ = regression parameters.

Least-squares regression methods were used to estimate the regression parameters (Janicki and Wade 1996). Results of the regressions indicated that variation in observed depths to which 20.5% of surface irradiance penetrates could be explained by variation in observed chlorophyll *a* concentrations. Monthly specific regression intercept terms were used to avoid any potentially confounding effects of seasonality in independent and dependent variables. The model fit was relatively good with an $r^2 = 0.67$. Turbidity and water-color data were also investigated as a possible explanation for a portion of the remaining unexplained variation in the light penetration data; however, no improvement in the model fit was found.

The adopted segment-specific annual average chlorophyll *a* targets (ranging from 4.6 μg/L to 13.2 μg/L)

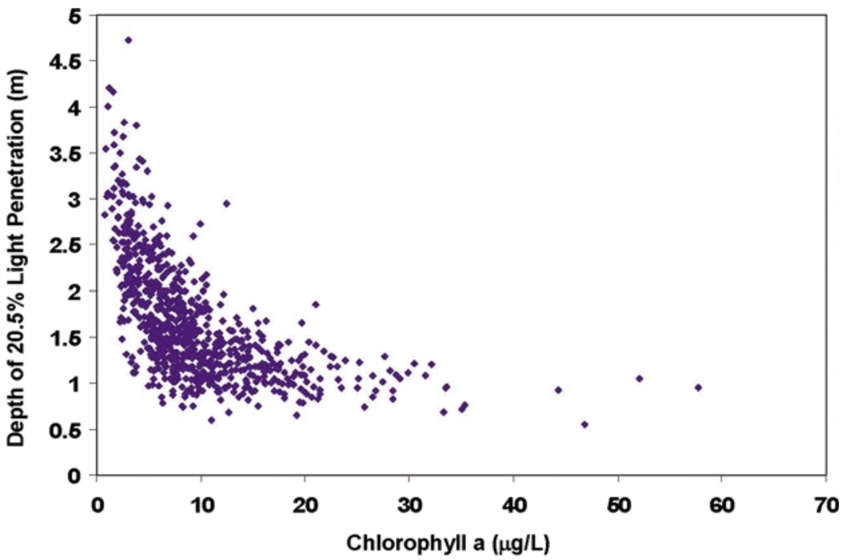

Figure 9. Relationship between chlorophyll *a* concentrations (µg/L) and depth (m) to which 20.5% of incident light penetrates in Tampa Bay. Source: Janicki and Wade 1996.

are easily measured and tracked through time, and are used as intermediate measures for assessing success in maintaining water quality requirements necessary to meet the long-term seagrass coverage goal (Greening 2001).

A separate empirical relationship between nitrogen loading and chlorophyll *a* concentrations was developed to understand how Tampa Bay responds to changes in loads (Janicki and Wade 1996). Initially, the relationship between external loads and chlorophyll *a* concentrations was investigated and found to be significant. However, the quantitative relationship was improved appreciably by accounting for the "internal" load that occurs as bay waters move between segments (Figure 10). For example, the ability to predict chlorophyll *a* concentrations in Middle Tampa Bay was improved significantly by accounting for the nitrogen flux to Middle Tampa Bay from both upstream segments (Hillsborough Bay and Old Tampa Bay). Wang and others (1999) found similar results using a mechanistic modeling approach.

Water quality conditions, specifically chlorophyll *a* concentrations, in 1992–1994 appeared to allow an annual average of more than 20.5% of incident light to reach target depths (i.e., depths to which seagrasses grew in 1950) in three of the four bay segments. Thus, a management strategy based on "holding the line" at 1992–1994 nitrogen loading rates should be adequate to achieve the seagrass restoration goals in these segments. This "hold the line" approach, combined with careful monitoring of water quality and seagrass extent, was adopted by the TBEP partnership in 1996 as its initial nitrogen load management strategy.

Step 3. Define and Implement Nitrogen Management Strategies Needed to Achieve Load Management Goals

In addition to reducing current nitrogen loadings, successful adherence to the "hold the line" nitrogen-loading strategy may be hindered by projected population growth in the watershed. A 20% increase in population and a 7% increase in annual nitrogen loading are anticipated by the year 2010 (Janicki and Wade 1996; Janicki and others 2001a). Thus, in order to "hold the line" at 1992–1994 levels, an average annual reduction of 15.4 metric tons (TN) per year is necessary to compensate for expected load generated by projected population growth.

To meet the nitrogen loading management target, a Nitrogen Management Consortium of local electric utilities, industries, and agricultural interests as well as local governments and regulatory agencies was established by the Tampa Bay Estuary Program in 1998 (Greening 2001). Together, these representatives developed the Nitrogen Management Action Plan and voluntarily committed to implementing projects that will contribute to meeting nitrogen management goals in each bay segment. Load reductions have generally been calculated on a 5-year basis (at 77 metric tons/5 years) rather than on an annual basis, because of the long-term nature of many of the nitrogen reduction projects. To ensure that each partner was using similar nitrogen load reduction assumptions for similar projects, guidelines for calculating nitrogen load reduction credits were developed with the partners (Zarbock and Janicki 1997), and were used by each of the partners in development of their action plans.

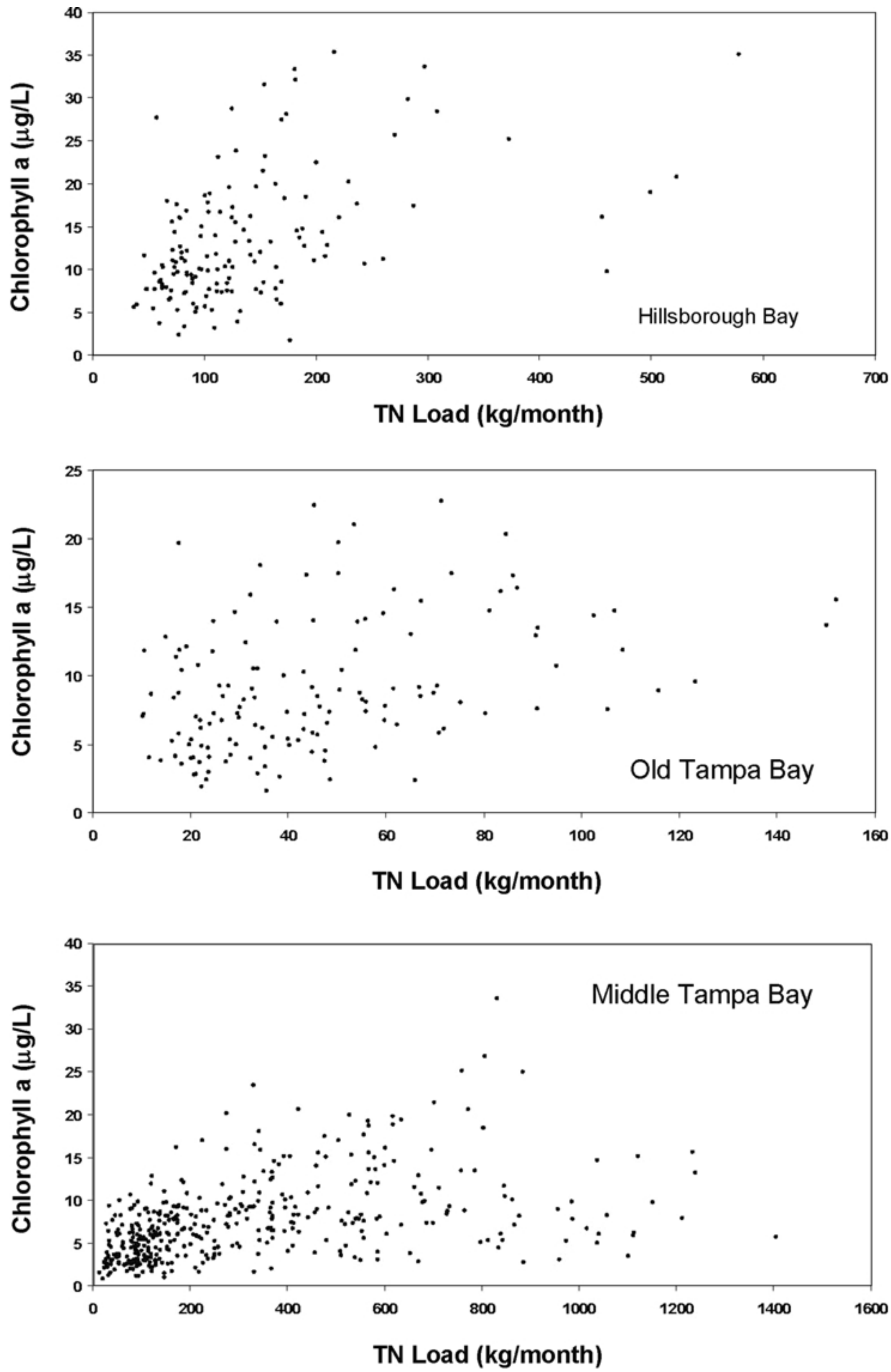

Figure 10. Relationship between monthly TN loads (kg/month) and mean monthly chlorophyll *a* concentrations (µg/L) in Tampa Bay, 1985–2003.

The types of nutrient reduction projects included in the Consortium's Nitrogen Management Action Plan range from traditional nutrient reduction projects, such as stormwater upgrades, industrial retrofits, and agricultural best management practices to actions not primarily associated with nutrient reduction, such as land acquisition and habitat restoration projects. More than 200 projects submitted by local governments, agencies, and industries are included in the Plan for 1995–2004. In the first 5-year period, 50% of the total load reduction was achieved through public sector projects, and 50% by industry (Greening and DeGrove 2001). A total reduction of 97 metric tons of nitrogen to Tampa Bay was estimated from the completed projects during the 1995–1999 period, which exceeded the 5-year reduction target of 77 metric tons by 20 metric tons. N reduction projects for the 2000–2004 period are currently in final review, but preliminary estimates indicate that the loading reduction target will be met (Tampa Bay Estuary Program, unpublished data).

Estimating total nitrogen reductions to Tampa Bay from changes in atmospheric emission sources poses a particular challenge. A multiyear assessment of changes in atmospheric emissions and local deposition rates includes estimates from a long-term atmospheric deposition monitoring program and changes in emissions (Poor and others 2001; N. Poor, personal communication). Estimated reductions of dry deposition (HNO_3-N) from conversion of the Tampa Electric Company Gannon plant to natural gas were 17.2 metric tons/year. However, dry deposition was approximately half of the total nitrogen deposition, according to wet and dry estimates from Poor and others (2001). Therefore, the estimate of total reduction (wet plus dry) was 34.5 metric TN tons/year. Pollman (2005) estimated that 82% of atmospheric TN deposited in the watershed is retained. Thus, the amount of TN delivered to the bay via indirect deposition to the watershed is 18% of that deposited on the land surface. Assuming that deposition is evenly distributed over Tampa Bay and its watershed, reduction estimates were calculated based on area of each major basin and bay segment. Direct and indirect deposition reductions are added for each basin to provide total reductions for each basin, for a total TN reduction estimate of 10.2 metric tons/year starting in 2003 (Tampa Bay Estuary Program, unpublished).

Tracking Progress in Tampa Bay

Data and observations from Tampa Bay indicate that initial efforts to reduce nitrogen loading and continuing efforts of the TBEP and NMC partners are resulting in adequate water quality for expansion of seagrasses. Time series plots (Figure 7) show that, with the exception of the 1998 El Niño year, chlorophyll *a* targets have been met in three of the four major bay segments since 1994. The Old Tampa Bay segment did not meet chlorophyll *a* targets in 2003 and 2004. Seagrass acreage increased an average of 142–202 ha per year between 1988 and 1996. Heavy rains associated with El Niño resulted in seagrass loss of approximately 809 ha between 1996 and 1999 (Tomasko 2002); however, seagrass estimates taken in January 2002 and 2004 show seagrass recovery in many areas of the bay where seagrass was lost between 1996–1999 (Tomasko and others 2005; Figure 3).

Water quality responses in Tampa Bay to heavy rains in 1995 and 1997–1998 were as expected: increased chlorophyll *a* concentrations (Figure 7) and light attenuation (Figure 8). However, the bay rebounded in the year after each of these recent events, suggesting that the bay has the ability to withstand these relatively large, albeit short-term, load increases. This may also suggest that the levels of primary production in Tampa Bay are being driven more directly by external loads rather than by the internal recycling of nitrogen from the sediments.

The expected rate of seagrass recovery for dominant species in subtropical waters in response to maintained water quality conditions is unclear, and appears to be variable depending upon local conditions. A recent synthesis of seagrass communities of the Gulf Coast of Florida (Dawes and others 2004) found that four estuarine systems within this region for which historic aerial photographs are available (Charlotte Harbor, Tampa Bay, St. Joseph Sound, and Sarasota Bay) all showed a loss of seagrass coverage between 1950 and 1982. Dawes and others (2004) note that recent seagrass-coverage trends in this region appear somewhat irregular, apparently responding to site-specific situations within the different estuaries. Relative increases between 1988 and 2004 show that Tampa Bay seagrass experienced an estimated 13.8% increase (1513 ha), whereas Charlotte Harbor seagrass coverage decreased slightly (0.3% or 30 ha) and Sarasota Bay seagrass coverage increased by 6.4% (240 ha) (Tomasko and others 2005).

The continued monitoring of water quality and seagrasses in Tampa Bay will allow managers to assess progress towards meeting established goals. An important component of this effort is the routine comparison of mean annual chlorophyll *a* concentrations and light attenuation to desired targets. TBEP has developed a tracking process to determine whether water quality targets are being achieved. The process to track status of chlorophyll *a* concentration and light attenuation involves two steps. The first step utilizes a decision framework to evaluate differences in mean annual ambient conditions from established targets. The second step incorporates results of the decision framework into a decision matrix, leading to possible outcomes dependent upon magnitude and duration of events in excess of the established target (Janicki and others 2000).

When outcomes for both chlorophyll *a* concentration and light attenuation are good, i.e., when both targets are being met, no management response is required. When conditions are intermediate, differences from the targets exist for either or both chlorophyll *a* concentration and light attenuation. These conditions may result in some type of management response. When conditions are problematic, such that there are relatively large, longer-term differences from either or both targets, then stronger management responses may be warranted.

The recommended management actions resulting from the decision matrix are classified by color into three categories for presentation to the Tampa Bay resource management community, as follows:

- Green: Both chlorophyll *a* concentration and light attenuation targets are met. Partners continue with planned projects to implement nitrogen reduction projects, and data summary and reporting via annual assessment and progress reports are maintained.
- Yellow: Targets for either chlorophyll *a* concentration or light attenuation are not met. The TBEP Technical Advisory Committee (TAC) reviews monitoring data and loading estimates and attempts to identify causes of target exceedences. The TBEP TAC reports to Management Board on findings and recommended responses if needed.
- Red: Relatively large or long-term deviations from targets are observed. TAC reviews and reports to TBEP Management Board on recommended types of responses. TBEP Management and Policy Boards take appropriate actions to refocus the program.

Results of the decision matrix from 1974 through 2004 are shown in Table 2 (Janicki and others 2005). The poor water conditions are clearly seen in early years of this time series, followed by marked improvements since 1984.

Since 1996, application of the decision framework has indicated two problematic (i.e., "red") time periods: in 1997 and 1998 in all bay segments (corresponding to high rainfall associated with a strong El Niño event), and in 2003 and 2004 in one bay segment, Old Tampa Bay. Recommendations from the TBEP TAC for management response to the El Niño-associated period were to support immediate actions towards repair of sewer transport and pumping systems and industrial treatment water holding systems that had failed during high rainfall amounts and rates. Actions were taken by municipalities and industrial facilities to address these failed systems. In addition to these immediate actions, the TAC recommendations were to continue monitoring to assess the need for further action after the El Niño event.

Table 2. Application of the Decision Matrix, 1974–2004

	Decision matrix results			
Year	Old Tampa Bay	Hillsborough Bay	Middle Tampa Bay	Lower Tampa Bay
1975	Red	Red	Red	Green
1976	Red	Red	Red	Yellow
1977	Red	Red	Red	Red
1978	Red	Red	Red	Yellow
1979	Red	Red	Red	Red
1980	Red	Red	Red	Red
1981	Red	Red	Red	Red
1982	Red	Red	Red	Red
1983	Red	Yellow	Red	Red
1984	Red	Green	Red	Yellow
1985	Red	Red	Red	Yellow
1986	Red	Yellow	Red	Green
1987	Red	Yellow	Red	Green
1988	Yellow	Green	Yellow	Green
1989	Red	Yellow	Red	Yellow
1990	Red	Green	Red	Yellow
1991	Green	Yellow	Yellow	Yellow
1992	Yellow	Green	Yellow	Yellow
1993	Yellow	Green	Yellow	Yellow
1994	Yellow	Yellow	Red	Red
1995	Red	Yellow	Red	Yellow
1996	Yellow	Green	Yellow	Green
1997	Yellow	Green	Red	Yellow
1998	Red	Red	Red	Red
1999	Yellow	Green	Yellow	Yellow
2000	Green	Green	Yellow	Yellow
2001	Yellow	Green	Yellow	Yellow
2002	Yellow	Green	Green	Green
2003	Red	Yellow	Green	Yellow
2004	Red	Green	Green	Yellow

[a]See text for definitions of red, yellow, and green scores. Source: Janicki and others 2005.

Recommendations for action in Old Tampa Bay in response to the decision matrix results in 2003–2004 were quite different than for the baywide El Niño-associated event. After an extensive review of existing data and information, the TBEP TAC recommended that an Old Tampa Bay Seagrass Recovery research program be implemented to examine factors potentially affecting seagrass recovery in this segment of Tampa Bay, followed by development of a recovery and management plan based on research results. Results and observations to date (summarized in Griffen and Greening 2004) show that some shallow areas in Old Tampa Bay had poorer water quality (and thus, less light available for seagrasses) than three other study areas did. Epiphytes caused significant light reduction (25–32%) in all portions of Old Tampa Bay. Transplanted seagrass survival was very low: 0.9% after two growing seasons, compared with 21% in other areas of Tampa Bay. Additional factors, such as high wave energy or inputs of submarine groundwater, were examined; however, neither of these appears to be responsible for slower seagrass recovery rates (Griffen and Greening 2004).

Further evaluations are examining additional potential causes of poor water quality and slower seagrass recovery in Old Tampa Bay, as suggested by results of the initial study. Ongoing assessments include examination of reduced circulation and slower flushing rates (possibly resulting in higher chlorophyll *a* concentrations), local sources of nitrogen loading, increased epiphyte loads, high rates of bioturbation (by stingrays and burrowing organisms), and possibly the influence of hydrogen sulfide concentrations. Management actions will be recommended based on results of these ongoing assessments.

Conclusions

There are two major conclusions that can be drawn from the experiences in Tampa Bay. First, the process of eutrophication in estuarine waters is reversible. Effective management of nitrogen loading from external sources can ameliorate many symptoms that accompany eutrophication. The ability of a system to respond to nutrient load reductions will depend upon a number of system characteristics as well as the history of excessive loading. Residence times in Tampa Bay, in general, and Hillsborough Bay, in particular, are relatively short (2 days to 2–3 months), because of the extensive network of channels that support shipping in the bay (Goodwin 1989; M. Luther, personal communication). This network of channels enhances tidal exchange within the Gulf of Mexico, thereby reducing risk of elevated algal production that would be likely if residence times in Tampa Bay were longer.

The ability of a system to respond to external load reductions also depends upon the degree to which historical loads have resulted in accumulation of nutrients, specifically nitrogen, in sediments. Internal loads due to sediment release can effectively prolong the system response to external load reductions. Hydrodynamic conditions in Tampa Bay may also contribute to what apparently has been a relatively limited accumulation of nitrogen in sediments. Organic-rich sediments are found almost exclusively in Hillsborough Bay (Johansson and Squires 1989). The spatial extent of such sediments has been reduced over the past decade, after reductions in chlorophyll *a* concentrations that have been observed since the early 1980s (JOR Johansson, personal communication). Therefore, the same characteristics of the Tampa Bay system that contributed to its sensitivity to excessive nitrogen loads may also have contributed to its ability to respond rapidly to reductions in nitrogen loads in the early 1980s.

The second conclusion that can be drawn from experiences in Tampa Bay is that watershed management is critical if expected future nitrogen loads increases due to an ever-expanding human population in the watershed are to be effectively managed. In Tampa Bay, a combination of regulatory and cooperative approaches has led to an effective, comprehensive nutrient management strategy. Initial reductions of nitrogen resulted from regulation of wastewater treatment plant discharges, but maintaining water quality gains obtained from those reductions is dependent upon controlling and precluding nitrogen loads from nonpoint sources. Although not originally developed for this purpose, the Tampa Bay voluntary nutrient reduction program has been accepted by the US EPA and the State of Florida as meeting regulatory total maximum daily load requirements for nutrients in Tampa Bay.

The Tampa Bay resource management community has agreed that protection and restoration of Tampa Bay living resources is of primary importance. Maintaining progress towards nutrient loading reductions over time will be challenging, given the expected continued population growth in the watershed. However, visible water quality and habitat improvements resulting from past and current nutrient load management actions are recognized by the Tampa Bay scientific community and general public alike, and are likely to contribute to maintaining momentum in implementation of the long-term nutrient management strategy.

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