Seagrass Recovery in Tampa Bay, Florida (USA)

Chapter · August 2016

DOI: 10.1007/978-94-007-6173-5_269-1

Holly Greening
CoastWise Partners

Edward T. Sherwood
Tampa Bay Estuary Program

Seagrass Recovery in Tampa Bay, Florida (USA)

H. Greening, A. Janicki, and E. T. Sherwood

Contents

Abstract

In Tampa Bay, Florida, USA, reduction in wastewater nutrient loading of approximately 90 % in the late 1970s resulted in rapid reduction of more than 50 % of external total nitrogen loading. Continuing nutrient management actions from public and private sectors are associated with a steadily declining TN load rate since the mid-1980s – despite an increase of more than 1M people living within the Tampa Bay metropolitan area since then—and with concomitant reduction in chlorophyll-a concentrations and ambient nutrient concentrations. Seagrass extent has increased by more than 65 % since the 1980s, and in 2014 exceeded the recovery goal adopted in 1996. There is evidence that Tampa Bay's successful

H. Greening (✉) • E.T. Sherwood (✉)
Tampa Bay Estuary Program, St. Petersburg, FL, USA
e-mail: hgreening@tbep.org; esherwood@tbep.org

A. Janicki (✉)
Janicki Environmental, Inc, St. Petersburg, FL, USA
e-mail: tjanicki@janickienvironmental.com

C.M. Finlayson et al. (eds.), *The Wetland Book*,
DOI 10.1007/978-94-007-6173-5_269-1

seagrass recovery may provide additional benefits, including buffering of global ocean acidification trends and increased carbon sequestration, both of which can be important to compensate for negative impacts of CO_2 emissions. Maintaining Tampa Bay's positive trajectory towards recovery will require continued watershed-based nutrient management and community involvement.

Keywords
Tampa Bay, Florida, USA • Seagrass recovery • Watershed-based nutrient reduction • Climate change impacts

Introduction

Prolonged and sustained human activities within an estuarine watershed can lead to increased nutrient influxes to the coast which provides a catalyst for further ecosystem degradation – a process termed cultural eutrophication (Nixon 1995; Bricker et al. 1999, 2007; NRC 2000; Cloern 2001; Duarte et al. 2013). For many coastal environments, loss of seagrass resources is a result of cultural eutrophication whereby persistent nutrient influxes cause enhanced primary production from phytoplankton and macroalgae reducing water clarity and blocking sunlight from reaching submerged aquatic vegetation. Cases of gradual estuarine eutrophication and seagrass declines have been documented include systems such as Chesapeake Bay (Boesch et al. 2001; Kemp et al. 2005; Williams et al. 2010), the Baltic Sea (Osterblom et al. 2007; Helsinki Commission 2009), and smaller systems such as Waquoit Bay, Massachusetts (Valiela et al. 1992; Valiela and Bartholomew 2014). Reversal of eutrophic conditions and recovery of lost seagrass habitats has been observed less commonly. Duarte et al. (2013) examined definitions of estuarine and coastal ecosystem recovery in published examples and found that partial (as opposed to full) ecosystem recovery often prevailed. Most successful examples involve the restoration of specific estuarine habitats rather than whole ecosystem processes: eelgrass recovery in Virginia coastal bays (Orth and McGlathery 2012) and the Danish coast (Cartensen et al. 2011; Riemann et al. 2016) and water quality and seagrass recovery in Tampa Bay, Florida (Greening et al. 2011, 2014).

Here, we provide a synopsis of seagrass recovery in Tampa Bay as more fully described in Greening et al. 2014.

Tampa Bay Characteristics

Tampa Bay is a large (water surface area of 1,036 km^2), shallow (mean depth 4 m), Y-shaped embayment located on the west-central coast of the Florida peninsula, USA (Fig. 1). The bay receives fresh water runoff from a watershed that covers an area of about 5,700 km^2. Its bathymetry has been modified by the construction and maintenance of shipping channels, dredged to depths of about 13 m. Model-based

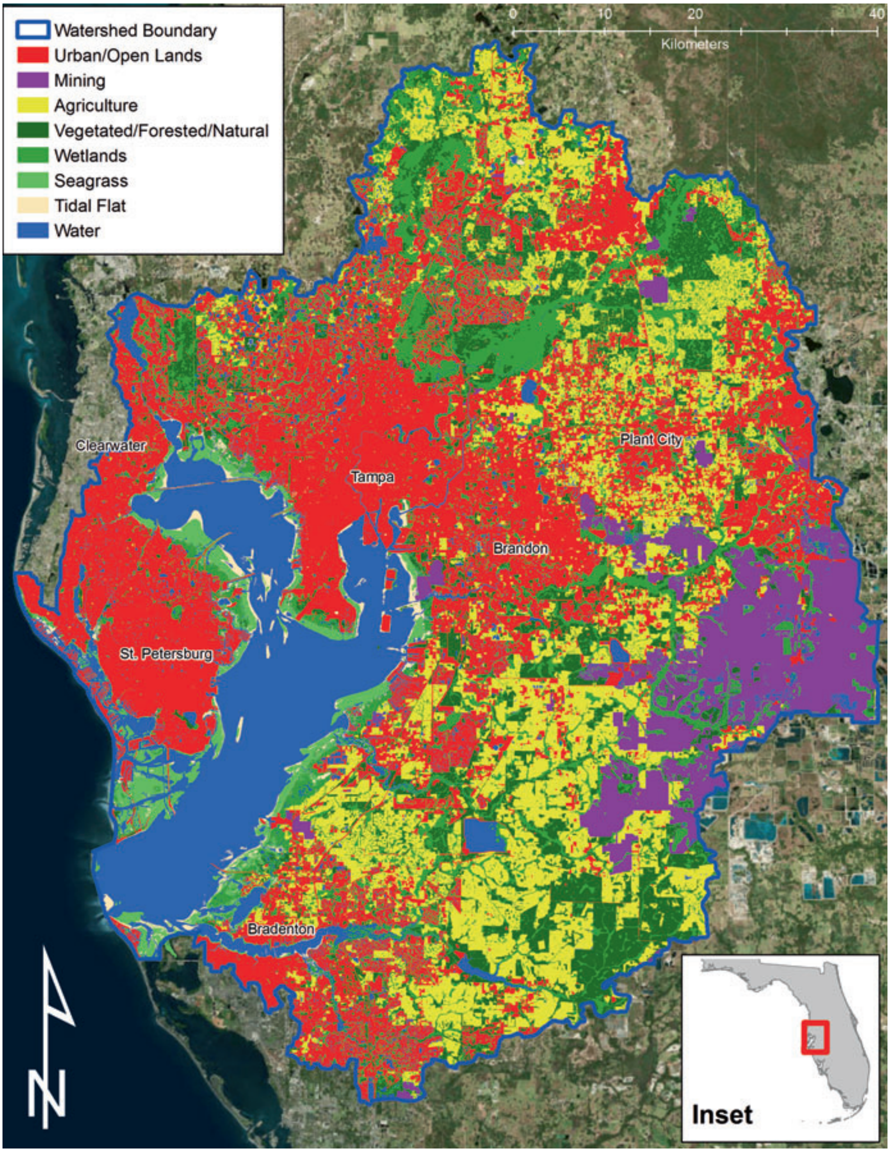

Fig. 1 Tampa Bay location and 2011 land use map of the watershed (Data source: Southwest Florida Water Management District (SWFWMD))

estimates of baywide residence times range from weeks to months and are primarily influenced by tides, winds, and the historic dredging alterations to bathymetry (Weisberg and Zheng 2006; Meyers et al. 2013).

Much of the land area that adjoins the bay is highly urbanized, including the cities of Tampa, St. Petersburg, Clearwater, and Bradenton, as well as numerous smaller municipalities. More than 2.3 million people currently live within the jurisdictions that directly border the bay, a number that has more than quadrupled since the early 1950s (US Census Bureau). The bay shoreline is dominated by urban land uses on its northern and western sides and by a combination of agricultural, industrial, and suburban land uses on the east, while much of the southern extent is natural shoreline. Several active port facilities with bulk commercial shipping interests and cruise terminals occur in the upper and lower bay and are an important component of the local economy.

Tampa Bay – Historical Loss and Stage for Recovery

In the late 1970s and 1980s, the degrading ecological condition of Tampa Bay became more visible to the people living along its shoreline and in the watershed. Macroalgae mats (including *Ulva* sp) were washing up on shorelines, large phytoplankton blooms were occurring, seagrass beds were disappearing, and populations of valued and visible fauna such as birds, fish, and manatees were decreasing (Yates et al. 2011; Morrison et al. 2014). These observations coincided with a rapid increase in human population, from less than 0.5 million in 1950 to 1.5 million in 1980 (Greening et al. 2014).

Several key events have occurred within the Tampa Bay region which led to the bay's recovery. Beginning in the late 1970s and continuing throughout the present recovery period, citizen engagement and pressure shaped the management efforts of both public and private entities. A major turning point for Tampa Bay occurred in the 1980s when implementation of state legislation requiring more stringent treatment standards for wastewater plants discharging to Tampa Bay was enacted. This legislation was prompted by citizen demands to local and state elected officials to improve the water quality of Tampa Bay. Upgrades to wastewater treatment plants and initiation of large-scale reclaimed wastewater programs during the late 1970s reduced the amount of total nitrogen (TN) being discharged from these sources into the bay by 90 % (Johansson 2003). Implementation of advanced wastewater treatment and reuse provided the beginnings of the bay's recovery. In 1996, local and regional partners working together through the Tampa Bay Estuary Program (TBEP) adopted numerical seagrass protection and restoration goals (ca. 15,400 ha or ca. 95 % of 1950s levels), and adopted numerical water transparency targets (expressed as annual mean Secchi disk depths), annual mean chlorophyll-a concentrations, and annual TN loading rates which supported attainment of the seagrass goals. The development of the goals and targets followed a multistep process (Greening and Janicki 2006; Greening et al. 2011, 2014) involving joint collaboration between public and private sectors.

To help meet the TN loading rate target, TBEP created an ad hoc public/private partnership known as the Tampa Bay Nitrogen Management Consortium (TBNMC) in 1996. The TBNMC's objective is to implement actions to meet the nutrient load

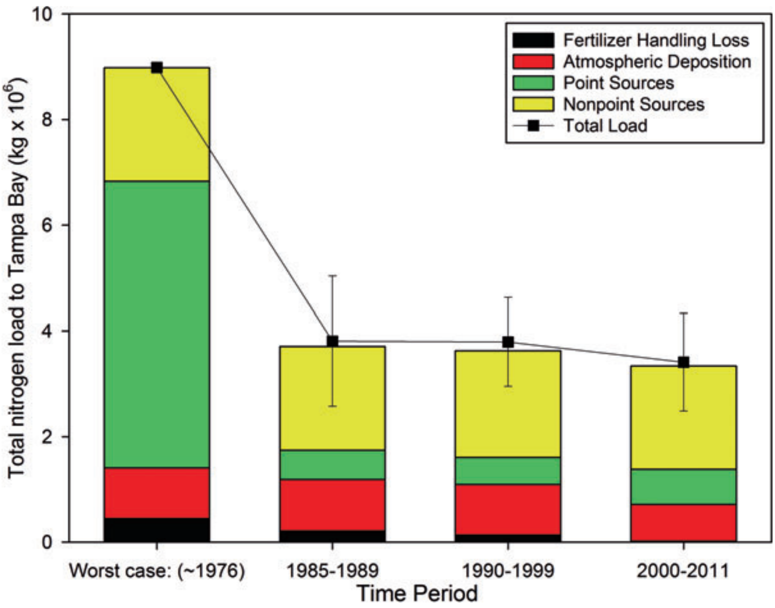

Fig. 2 Estimated annual loads of total nitrogen from various sources to Tampa Bay summarized from 1976 to 2011 (From Greening et al. 2014)

targets developed for Tampa Bay. Since 1999, projects have been implemented to reduce nitrogen loads to the bay by about 270,000 kg each year (or about 7.9 % of the average total Tampa Bay load from 2000 to 2011). In total, from 1992 to 2015, TBNMC participants have invested over US$450 million in projects and actions to reduce nutrient loads to Tampa Bay to meet the protective load targets for the bay. These voluntary actions and associated improvements in water quality have now been accepted by federal and state regulatory agencies as adequate to meet regulatory requirements (Greening et al. 2014).

Ecosystem Responses to Management

Nutrient Loadings

On a baywide basis, there were marked responses in the environment to the management and regulatory actions taken since the early 1980s. Most notable was the reduction in TN load from point sources (PS). Point source TN loads declined from a ca. 1976 worst case load of 5.4 million kg/year to 0.5 million kg/year by the mid-1980s. Nonpoint sources have now become the predominant TN load to Tampa Bay, contributing >57 % of the total external nutrient load to the bay (Fig. 2).

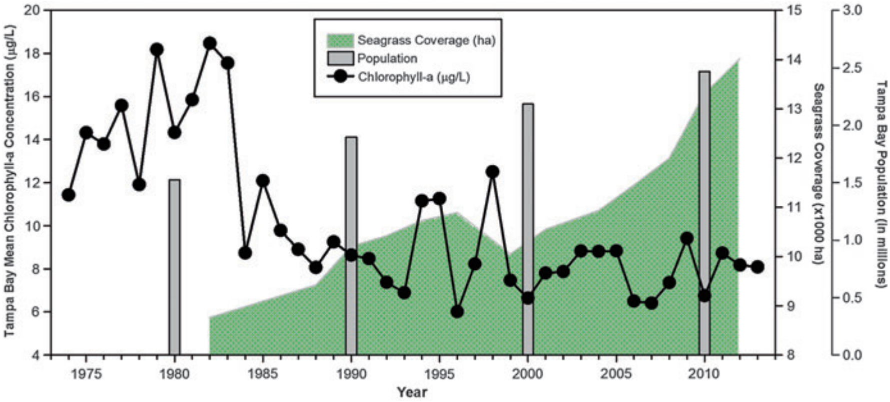

Fig. 3 Trends in mean annual chlorophyll-a concentrations and Secchi disk depth seagrass extent and watershed population estimates for Tampa Bay (Data sources: Environmental Protection Commission of Hillsborough County (chlorophyll-a concentrations and Secchi disk depths); Southwest Florida Water Management District (seagrass extent) and US Census Bureau (population))

While the human population residing in the Tampa Bay watershed from 1980 to 2011 increased by more than 1.1 million, TN load per capita continues to decrease. In the early 1980s, per capita TN load was approximately 6.6 kg/person/year. From 1985 to 1989 it was approximately 2.1 kg/person/year; from 1990 to 1999, 1.8 kg/person/year; and from 2000 to 2011, 1.3 kg/person/year. These continued per capita declines reflect an ever expanding human population, but declining TN loads entering the bay from the watershed due to implementation of multiple nutrient reduction projects and programs as outlined above. Further translated, current per capita TN load has declined by about 80 % since the early 1980s (Greening et al. 2014).

Bay Water Quality and Clarity

Both TN and total phosphorus (TP) concentrations in each of the four major bay segments declined significantly following nutrient loading reductions (Greening et al. 2014). Reductions in chlorophyll-a concentration were also observed over the period of record (Fig. 3). Current chlorophyll-a concentrations have been consistently lower than historic periods with a few exceptions related to above-average rainfall conditions (e.g., 1994 and 1998 El Niño years), and to occasional summer nuisance algae blooms (*Pyrodinium bahamense*) in one segment. Concurrent with decreased nutrient loads, concentrations and chlorophyll-a concentrations, significant increasing trends in Secchi disk depth were observed in all four major bay segments (Fig. 3; Greening et al. 2014). The increasing trends in monthly mean Secchi disk depths and decreasing trends in chlorophyll-a and nutrient concentrations for each of the bay segments are all highly significant ($P < 0.001$).

Seagrass Cover

On a long-term basis, changes in seagrass cover in the bay have reflected changes in water quality. Analysis of aerial photographs, habitat maps, and the extent of urbanization show that seagrass cover in Tampa Bay has fluctuated markedly during the roughly six-decade period (1950–2014) for which baywide photography is available. Cover declined by an estimated 7,600 ha (or about 50 %) between the early 1950s and early 1980s, during a period characterized by widespread physical impacts (e.g., dredging and filling) and increasingly poor water quality. Cover then increased by about 7,550 ha from the early 1980s through 2014, as the magnitude and frequency of physical impacts were reduced and water quality improved. Aerial photographs taken in 2014 show that the seagrass extent met and exceeded the recovery goal, and is now 16,307 ha, surpassing the original recovery goal of 15,400 ha set in 1996 (Fig. 3).

Future Challenges and Opportunities

The observed relationship between increased urbanization in coastal areas and decreased estuarine condition throughout the world has been well documented (NRC 2000; Cloern 2001; Garnier et al. 2002; Bricker et al. 2007; Duarte et al. 2013). In contrast to many coastal systems throughout the world, the water quality and seagrass improvements that started to be observed in 1985 in Tampa Bay have occurred simultaneously with an increase in the extent of urbanized land and an additional 1.1 million people (a population increase of 40 %) living in the watershed during this same time period. The many projects and actions completed by public and private sectors appear to have offset nutrient loading contributions (both wastewater and nonpoint sources) typically contributed by increased population and urbanization.

Although Tampa Bay's recovery to date is on a positive trajectory, maintaining that trajectory will require continued action, assessment, and adjustment. Following evaluation of 28 long-term datasets, Carstensen et al. (2011) found that individual ecosystems exhibit unique chlorophyll-a concentration to TN relationships, such as those exhibited in Tampa Bay's different major bay segments. Carstensen et al. (2011) state that changes are likely derived from large-scale forcing associated with global change, and they imply that current chlorophyll-a and nutrient relationships cannot be used to predict future relationships. Sea level rise scenarios developed for Tampa Bay show the potential need to revise habitat restoration strategies over time, as well as nutrient management plans (Sherwood and Greening 2014).

However, the Bay's successful seagrass recovery may offer additional benefits for future resilience to impending climate change and coastal development impacts, as long as current seagrass areas are maintained and potentially expanded in the future with maintaining adequate water quality conditions. For example, Tampa Bay pH conditions have been shown to be increasing coincident with the recent expansion of seagrass areas (Fig. 4) (Sherwood et al. 2016). Increasing Tampa Bay pH trends are

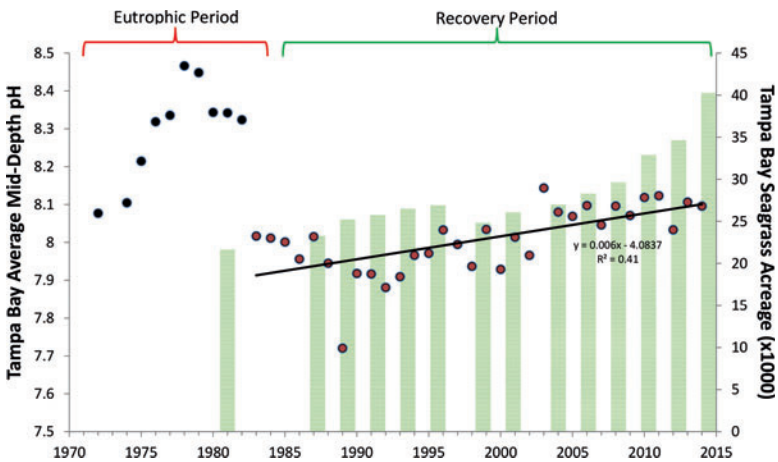

Fig. 4 Average daytime mid-depth pH (*dots*) from water quality monitoring stations in Tampa Bay relative to baywide seagrass coverage (*bars*) (From Sherwood et al. 2016). Water quality data from Environmental Protection Commission of Hillsborough County, seagrass data from Southwest Florida Water Management District

contrary to global ocean acidification observations. So, an added, unforeseen ecological benefit of Tampa Bay's seagrass recovery may be the future buffering of potential ocean acidification impacts on sensitive estuarine biota, thereby making Tampa Bay a regionally significant ocean acidification refugia within the Gulf of Mexico.

Likewise, recent habitat modeling suggests that carbon sequestration benefits of Tampa Bay seagrass will be important to compensate for potential future emergent tidal wetland habitat carbon sequestration losses (Sheehan and Crooks 2016; Sherwood and Greening 2014). Sea level rise and coastal development may synergistically reduce future emergent tidal wetland habitat areas, thereby reducing their potential to sequester atmospheric CO_2. If seagrass are able to rapidly expand to newly inundated areas where emergent tidal wetlands may be lost, then Tampa Bay seagrass habitats may continue to offer "blue carbon" benefits to global efforts to mitigate the negative impacts of CO_2 emissions. Based on this scenario, it has been estimated that the suite of Tampa Bay coastal habitats, including expanding seagrass areas, may sequester up to 74 million metric tonnes of greenhouse gas emissions, an equivalent of removing 160,000 cars from Tampa Bay roads every year until 2100 (Sheehan and Crooks 2016).

Conclusions

Two broad conclusions can be drawn from the Tampa Bay example. First, under certain conditions some of the impacts of estuarine eutrophication, including loss of seagrass, can be reversed. The second conclusion is that continued watershed-based nutrient management and community involvement is critical for addressing the impacts brought about by an increasing human population, and potentially by future climate change.

Key management elements that have contributed to the observed improvements in Tampa Bay during the past several decades, as summarized in Greening et al. 2014, include:

- **Development of numeric water quality targets.** The water quality targets were developed to meet a quantitative long-term goal of restoring seagrass coverage to baseline 1950s levels. Establishing quantitative goals early in the process resulted in meaningful participation by public and private sectors in the comprehensive nutrient management strategy for Tampa Bay. The availability of long-term monitoring data, and a systematic process for using the data to evaluate the effectiveness of management actions, has allowed the Tampa Bay management community to track progress and make adaptive changes when needed. Annual reporting to the community and regulatory agencies on the attainment of water quality targets (Fig. 5) has been an essential part in continuing public and private entity engagement in the Tampa Bay nutrient management strategy.
- **Citizen involvement**. The initial reductions in TN loads, which occurred in the early 1980s, were a result of state regulations that were developed in response to citizens' demand for action. Improved water clarity and better fishing and swimming conditions were identified as primary goals by citizens again in the early 1990s, and led to development of numeric water quality targets and seagrass restoration goals. More recently, individual citizen and community actions, from pet waste management campaigns to support for reductions in residential fertilizer use, are important elements of the nitrogen management strategy in the increasingly urbanized Tampa Bay watershed.
- **Collaborative actions.** In addition to numerous other collaborative ventures that have benefitted Tampa Bay, the public/private, stakeholder-driven TBNMC, which includes more than 45 participating organizations, has implemented 500+ nutrient reduction projects since 1995. These projects have addressed stormwater treatment, fertilizer manufacturing and shipping, agricultural practices, reclaimed water use, and atmospheric emissions from local power stations, providing more than 450,000 kg of TN load reductions since 1995.
- **State and federal regulatory programs.** Regulatory requirements, such as state statutes and rules requiring compliance with advanced wastewater treatment (AWT) standards by municipal wastewater treatment facilities and stormwater treatment in residential developments, have played a key role in Tampa Bay management efforts. The technical basis and implementation plan of the Tampa Bay nitrogen management strategy was developed in cooperation with state and federal regulatory agencies, and the strategy has been recognized by them as an appropriate tool for meeting water quality standards.

Local governments, municipalities, and private businesses around the world realize the importance of a healthy watershed and bay environment to the economy

Fig. 5 Average annual chlorophyll-a concentration threshold attainment for the four major bay segments(From: Sherwood 2016). *Red* (no) indicates years when a bay segment-specific threshold was not attained, while *green* (yes) indicates years when a threshold was attained (Data source: Environmental Protection Commission of Hillsborough County – EPCHC)

Year	Old Tampa Bay	Hillsbor-ough Bay	Middle Tampa Bay	Lower Tampa Bay
1974	No	No	No	Yes
1975	No	No	No	Yes
1976	No	No	No	Yes
1977	No	No	No	No
1978	No	No	No	Yes
1979	No	No	No	No
1980	No	No	No	No
1981	No	No	No	No
1982	No	No	No	No
1983	No	No	No	No
1984	Yes	Yes	No	Yes
1985	No	No	No	Yes
1986	No	No	Yes	Yes
1987	No	Yes	No	Yes
1988	Yes	Yes	Yes	Yes
1989	No	Yes	Yes	Yes
1990	No	Yes	Yes	Yes
1991	Yes	Yes	Yes	Yes
1992	Yes	Yes	Yes	Yes
1993	Yes	Yes	Yes	Yes
1994	No	No	No	No
1995	No	No	No	Yes
1996	Yes	Yes	Yes	Yes
1997	Yes	Yes	Yes	Yes
1998	No	No	No	No
1999	Yes	Yes	Yes	Yes
2000	Yes	Yes	Yes	Yes
2001	Yes	Yes	Yes	Yes
2002	Yes	Yes	Yes	Yes
2003	No	Yes	Yes	Yes
2004	No	Yes	Yes	Yes
2005	Yes	Yes	Yes	No
2006	Yes	Yes	Yes	Yes
2007	Yes	Yes	Yes	Yes
2008	Yes	Yes	Yes	Yes
2009	No	Yes	Yes	Yes
2010	Yes	Yes	Yes	Yes
2011	No	Yes	Yes	Yes
2012	Yes	Yes	Yes	Yes
2013	Yes	Yes	Yes	Yes
2014	Yes	Yes	Yes	Yes

and quality of life of their regions. Many are also facing requirements to meet federal, state, and local water quality regulations. In Tampa Bay, local communities, governments, and industries developed voluntary water quality goals and nutrient loading targets to support recovery of clear water and underwater seagrasses in the mid-1990s, and have implemented more than 500 projects since that time to help meet the nutrient loading targets developed for Tampa Bay. Their collective efforts, starting with significant wastewater point source reductions and continuing with nutrient loading reductions from atmospheric, industrial, agricultural, and community sources, have resulted in a present-day Tampa Bay which looks and functions much like it did in the relatively predisturbance 1950s period. In total > $0.6 billion has been invested by the collective management community towards Tampa Bay's overall recovery. Maintaining this progress, and potentially expanding efforts to ensure seagrass persist into the future, is paramount to make certain that the large monetary and community capital investments to date are not squandered in the future.

Cross-References

► San Francisco Bay Estuary
► Seagrasses

References

Boesch D, Brinsfield RB, Magnien RE. Chesapeake Bay eutrophication: scientific understanding, ecosystem restoration, and challenges for agriculture. J Environ Qual. 2001;30:303–20.

Bricker SB, Clement CG, Pirhalla DE, Orlando SP, Farrow DGG. National estuarine eutrophication assessment: effects of nutrient enrichment in the nation's estuaries. Special projects office and the national centers for coastal ocean science, national ocean service, national oceanic and atmospheric administration. Silver Spring; 1999.

Bricker S, Longstaff B, Dennison W, Jones A, Boicourt K, Wicks C, Woerner J. Effects of nutrient enrichment in the nation's estuaries: a decade of change. NOAA coastal ocean program decision analysis series no. 26. Silver Spring: National Centers for Coastal Ocean Science; 2007.

Carstensen J, Sánchez-Camacho M, Duarte CM, Krause-Jensen D, Marbâ N. Connecting the dots: responses of coastal ecosystems to changing nutrient concentrations. Environ Sci Tech. 2011;45:9122–32.

Cloern JE. Our evolving conceptual model of the coastal eutrophication problem. Mar Ecol Prog Ser. 2001;210:223–53.

Duarte CM, Borja A, Carstensen J, Elliott M, Karawuse-Jensen D, Marbâ N. Paradigms in the recovery of estuarine and coastal ecosystems. Estuar Coasts. 2013. doi:10.1007/s12237-013-9750-9.

Garnier J, Billen G, Hannen E, Fonbonne S, Videnina Y, Soulie M. Modeling transfer and retention of nutrients in the drainage network of the Danube River. Estuar Coast Shelf Sci. 2002;54:285–308.

Greening H, Janicki A. Toward reversal of eutrophic conditions in a subtropical estuary: water quality and seagrass response to nitrogen loading reductions in Tampa Bay, Florida, USA. Environ Manag. 2006;38:163–78.

Greening HS, Cross LM, Sherwood ET. A multiscale approach to seagrass recovery in Tampa Bay, Florida. Ecol Restor. 2011;29:82–93.

Greening H, Janicki A, Sherwood ET, Pribble R, Johansson JOR. Ecosystem responses to long-term nutrient management in an urban estuary: Tampa Bay, Florida, USA. Estuar Coast Shelf Sci. 2014;151:A1–16.

Helsinki Commission. Eutrophication in the Baltic Sea – an integrated thematic assessment of the effects of nutrient enrichment and eutrophication in the Baltic Sea region: Finland. Helsinki, Finland: Baltic Sea Environment Proceedings Number 115B; 2009.

Johansson JOR. Shifts in phytoplankton, macroalgae and seagrass with changing nitrogen loading to Tampa Bay, Florida. In: Treat SF, editor. Proceedings, Tampa Bay Area Scientific Information Symposium, BASIS 4; 2003 Oct 27–30; St. Petersburg. p. 31–9.

Kemp WM, Boynton WR, Adolf JE, Boesch DF, Boicourt WC, Brush G, Cornwell JC, Fisher TR, Glibert PM, Hagy JD, Harding LW, Houde ED, Kimmel DG, Miller WD, Newell RIE, Roman MR, Smith EM, Stevenson JC. Eutrophication of Chesapeake Bay: historic trends and ecological interactions. Mar Ecol Prog Ser. 2005;303:1–29.

Meyers SD, Linville A, Luther ME. Alteration of residual circulation due to large-scale infrastructure in a coastal plain estuary. Estuar Coasts. 2013. doi:10.1007/s12237-013-9691-3.

Morrison G, Greening HS, Sherwood ET, Yates KK. Management case study: Tampa Bay, Florida. Ref Module Earth Syst Environ Sci. 2014. doi:10.1016/B978-0-12-409548-9.09125-9.

National Research Council (NRC). Clean coastal waters: understanding and reducing the effects of nutrient pollution. Washington, DC: National Academies Press; 2000.

Nixon SW. Coastal marine eutrophication: a definition, social causes, and future concerns. Ophelia. 1995;41:199–219.

Orth RJ, McGlathery KJ. Eelgrass recovery in the coastal bays of the Virginia Coast Reserve, USA. Mar Ecol Prog Ser. 2012;448:173–6.

Osterblom H, Hansson S, Larsson U, Hjerne O, Wulff F, Elmgren R, Folke C. Human-induced trophic cascades and ecological regime shifts in the Baltic Sea. Ecosystems. 2007;10:877–89.

Riemann B, Carstensen J, Dahl K et al. Recovery of Danish coastal ecosystems after reductions in nutrient loading: a holistic ecosystem approach. Estuaries and Coasts. 2016;29:82–97.

Sheehan L, Crooks S. Tampa Bay blue carbon assessment: summary of findings. Technical report #07-16 of the Tampa Bay estuary program. 2016.

Sherwood ET. 2015 Tampa Bay water quality assessment. Technical report #01-16 of the Tampa Bay estuary program. 2016.

Sherwood ET, Greening HS. Potential impacts and management implications of climate change on Tampa Bay Estuary critical coastal habitats. Environ Manag. 2014;53:401–15.

Sherwood ET, Greening HS, Janicki AJ, Karlen DJ. Tampa Bay estuary: monitoring long-term recovery through regional partnerships. Reg Stud Mar Sci. 2016;4:1–11.

Valiela I, Bartholomew M. Land-sea coupling and global-driven forcing: following some of Scott Nixon's challenges. Estuar Coasts. 2014. doi:10.1007/s12237-014-9808-3.

Valiela I, Foreman K, LaMontagne M, Hersh D, Costa J, Peckol P, DeMeo-Anderson B, D'Avenzo C, Babione M, Sham C, Brawley J, Lajtha K. Couplings of watersheds and coastal waters: sources and consequences of nutrient enrichment in Waquoit Bay, Massachusetts. Estuaries. 1992;15:443–57.

Weisberg RH, Zheng L. Circulation of Tampa Bay driven by buoyancy, tides, and winds, as simulated using a finite volume coastal ocean model. J Geophys Res. 2006;111. doi:10.1029/2005JC003067.

Williams MR, Filoso S, Longstaff BJ, Dennison WC. Long-term trends of water quality and biotic metrics in Chesapeake Bay: 1986 to 2008. Estuar Coasts. 2010;33:1279–99.

Yates K, Greening H, Morrison G, editors. Integrating science and resource management in Tampa Bay, Florida. Reston: U.S. Geological Survey Circular 1348; 2011.