Evaluating the Spatial and Temporal Variability of Eelgrass in Great Bay Estuary, New Hampshire

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ABSTRACT:

INTRODUCTION

Great Bay Estuary, on the border between New Hampshire and Maine, is one of 28 waterbodies designated as "estuaries of national significance" by the United States Environmental Protection Agency (EPA) under Section 320 of the Clean Water Act (CWA). This Estuary has been the focus of study for over 30 years by the Piscataqua Region Estuaries Partnership (PREP) and the University of New Hampshire (UNH) in Durham, NH. Over this time period, eelgrass (*Zostera marina*) within the Estuary has been extensively studied. Eelgrass is at the foundation of the food web in Great Bay Estuary, provides essential habitat for aquatic organisms, and performs other ecosystem services including trapping sediment (Salo & Pedersen, 2014; Short *et al.*, 1993).

Eelgrass is a monoecious seagrass species of SAV that can grow from seed or propagate through vegetative rhizome growth. Depending on various conditions, eelgrass populations typically follow a two-year (perennial) life history but can also exhibit an annual life cycle (Fonseca & Uhrin, 2009). In the first year, seeds from perennial plants germinate at the end of winter and spread through vegetative growth, creating daughter shoots every 2 – 4 weeks during the growing season. The plants enter a slow growth phase during the winter. In the second year, these shoots transform into flowering structures that produce dozens of seeds. The shoot dies after seeding. The seeds tend to stay near the parent plant, although flowering stalks can break off and transport seeds for many miles. In low-stress environments and subtidal habitat, eelgrass tend to behave as perennials while in high-stress environments and intertidal settings, eelgrass tend to behave as annuals (Kuo & den Hartog, 2006; Costa, 1988).

Historical accounts suggest that eelgrass cover was very widespread with eelgrass found throughout the Estuary in the early part of the twentieth century. The eelgrass ecosystem was nearly wiped out in the 1930s due to wasting disease (*Labyrinthula zostera*), but slowly recovered (Short, 1992). Most recently, the primary habitat for eelgrass in the Estuary has been Great Bay, accounting for approximately 80% of the eelgrass cover in the Estuary, with most of the eelgrass beds lost from the tidal rivers. Over the past 30 years, eelgrass levels have fluctuated, reaching a peak in the 1990s but more recently exhibiting reduced distribution in comparison with prior years.

In 2009, the New Hampshire Department of Environmental Services (DES) expressed concern that eelgrass populations in the Estuary appeared to be in decline. This contemporaneous eelgrass decline, in combination with concerns over increasing levels of dissolved inorganic nitrogen (DIN) and the presence of macroalgae (in some areas previously inhabited by eelgrass) led regulatory agencies to conclude that the eelgrass declines were due to excessive amounts of nitrogen entering the Estuary. Consequently, DES prepared draft water quality criteria for DIN, deemed necessary to prevent further deterioration and restore eelgrass in the Estuary (NHDES**,** 2009). These draft criteria became the subject of an external peer review and were subsequently withdrawn for insufficient scientific justification (Bierman *et al.*, 2014).

This paper presents a review of the available data, with a specific focus on eelgrass cover in Great Bay, to provide perspective on the nature of eelgrass fluctuations in the bay and to assess potential causes for the apparent decline using the historical water quality database. While prior regulatory efforts focused on nutrient pollution as the cause, numerous other factors (*e.g.*, wasting disease, physical conditions) have been demonstrated to negatively affect eelgrass health, survival, and propagation. This paper synthesizes the available data for the Bay to characterize the spatial and temporal patterns of eelgrass changes and to identify possible causes for the observed patterns in annual eelgrass cover in Great Bay.

Study Site

Great Bay Estuary is composed of several hydrologically distinct regions – the tidal rivers (*e.g.*, Lamprey River), shallow bays (*e.g.*, Great Bay), deep bays (*e.g.*, Little Bay), tidal straits (*e.g.*, Piscataqua River), and the mouth of the estuary (*e.g.*,

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Portsmouth Harbor) (See, Figure 1), which influence the occurrence of eelgrass and other aquatic vegetation. The Estuary has a drainage area of approximately 2,650 km^2 (1,023 mi^2) and a surface area of 54 km^2 (21 mi^2) (Truslow *et al.*, 2010). It is relatively shallow with a tidal amplitude to mean depth ratio of 0.18 (Bilgili *et al.*, 2003). The tidal range at the mouth of the Estuary is on the order of 2.6 m. The Piscataqua River, a tidal strait, connects the mouth to Great Bay/Little Bay, with a tidal range of 2.0 m (Trowbridge, 2007). Due to the shallow bathymetry of Great Bay and the large tidal variation, much of Great Bay becomes tidal flats during low tide, exposing the majority of the eelgrass populations growing in the system.

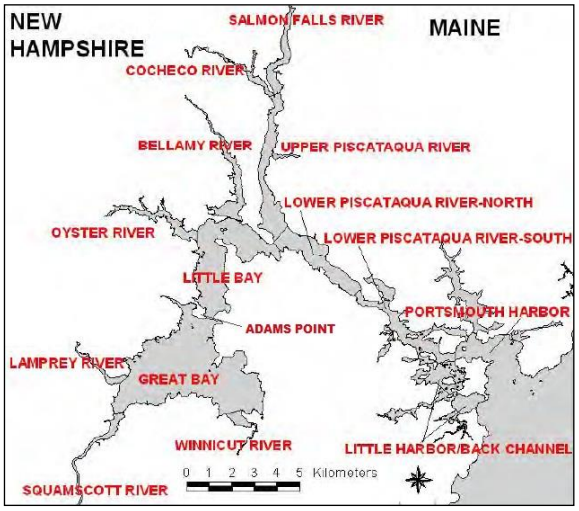

Figure 1: Great Bay Estuary

The Estuary is a well-mixed, tidally dominated waterbody with relatively short detention times estimated at 3-7 days for Great Bay and Little Bay and less than one day for the Lower Piscataqua River through Portsmouth Harbor (HDR|HydroQual, 2013). The Lower Piscataqua River branches off to the Upper Piscataqua River, which receives freshwater flow from the Cocheco and Salmon Falls Rivers, and to Little Bay. Little Bay constricts at Adams Point, marking the boundary with Great Bay. The bulk of the freshwater flow enters the Estuary through Great Bay from the Winnicut, Squamscott, and Lamprey Rivers in southern and western Great Bay. The overall freshwater flow entering the Estuary represents approximately 2% or less of the tidal prism under typical conditions (Jones *et al.*, 2000). Tidal currents through much of Great Bay are relatively low (<0.5 m/s) while elsewhere in the Estuary, tidal currents reach 2.2 m/s (Erturk *et al*., 2002; NOAA, 2013).

The bathymetry map of Great Bay Estuary (Figure 2; NOAA & Jakobsson, 2000) reveals the drowned ancient river valley that formed Great Bay Estuary and Great Bay's deep (5-20 m) forked central channels (Green & Short, 2003). Over 50% of Great Bay's area is characterized as mudflats that become exposed at low tide (Short, 1992). As a consequence, the tidal prism is a significant portion of the overall volume. Using GIS, Trowbridge (2007) estimated the water volume in Great Bay totaled 3.8×10^6 m^3 at mean low tide and 36.9×10^6 m^3 at mean high tide. Based on these estimates, approximately 90% of the water volume in Great Bay flushes through Little Bay twice during each tidal cycle.

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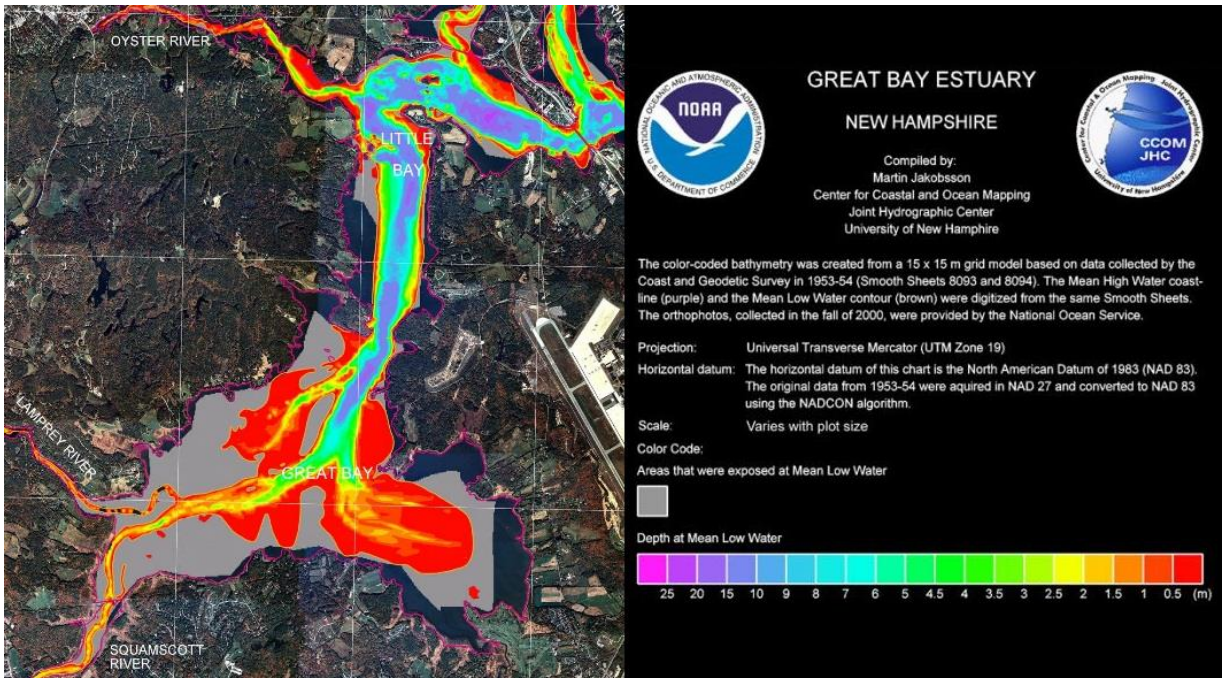

Figure 2: Great Bay Bathymetry (NOAA & Jakobsson, 2000)

SOURCES OF DATA

Eelgrass

Eelgrass coverage data are available for the period from 1981 and 1986 – 2013 based on aerial photographic surveys (UNH & NH GRANIT, 2014). Annual aerial photographs are used to delineate eelgrass acreage and estimate density of eelgrass beds. Since 1986, aerial photographs have been taken from an elevation of 1,000 m during low spring tide when the sun was at a low angle to minimize reflection (Short & Trowbridge, 2003). Overflights are conducted in late summer (late August-early September) to characterize the maximum extent of eelgrass cover in the Estuary. Prior to 2003, Great Bay eelgrass surveys were conducted without a quality assuran ce/quality control plan, although the procedures used in the earlier surveys are believed to be similar to the procedures used in subsequent surveys, and without associated annual reports that further explain the results. From 2003-2012, surveys were conducted in accordance with an approved Quality Assurance Project Plan (QAPP) following the methods of Short and Burdick (1996). Since 2010, the QAPP has included a precision/accuracy goal of ±5 meters for eelgrass bed boundaries. Ground-truthing observations were made from small boats at low tide to spot check 10-20% of the aerial estimate boundaries. Spot checks were usually limited to validating eelgrass growth at the edge of the deeper channels. In 2013, a new, substantially more robust and detailed QAPP was developed and implemented by PREP (Trowbridge, 2013). Ground-truthing is now conducted using small boats and kayaks with GPS-enabled drop cameras as well a separate EPA scuba dive team, with assessments made throughout the mudflat areas.

The annual synoptic surveys were used to generate GIS shapefiles of eelgrass areal distribution and density, with area characterized as percent cover in four ranges (10-30%, 30-60%, 60-90%, 90-100%). Eelgrass cover less than 10% cannot be delineated from the aerial photographs (Short, 2004). Eelgrass biomass cannot be readily assessed from the aerial photographs (NOAA, 1995). However, estimates of eelgrass biomass (g/m^2) accompany the cover data in the GIS shapefiles. The basis for the biomass assigned to the percent cover classes is not documented and the variability around the density estimates for each class is not available (Short, personal

communication). Consequently, the biomass estimates were not considered sufficiently reliable for analysis and areal cover has been used as the metric for assessing the health of the eelgrass community in Great Bay.

Macroalgae

A consistent monitoring program for macroalgae has not historically existed for Great Bay Estuary. Most of the available data are anecdotal, with only a few actual measurements. Baseline measurements were made by UNH researchers (*e.g.*, A. Mathieson) between 1972 and 1980 for a few locations in Great Bay (NHDES, 2009) adjacent to the shoreline. These limited measurements identified very low levels of macroalgae in 1980 (PREP, 2013) at those sites.

More detailed measurements were made in 2007 via aerial imagery (Pe'eri *et al*., 2008) and in 2008-2010 by on-site survey (Nettleton, 2011). The Pe'eri study was primarily conducted to evaluate the use of hyperspectral imagery as a tool for mapping macroalgae throughout Great Bay. A PREP study in 2013 sampled macroalgae (*Ulva* spp., *Gracilaria* spp., fucoids (*Ascophyllum nodosum* and *Fucus vesiculosus*)) in transects and made recommendations for a macroalgae monitoring program (Cianciola & Burdick, 2014).

Epiphytes

The available data on epiphytes are more limited than the available data on macroalgae. Reports of excessive epiphyte growth have not appeared in the various annual eelgrass surveys completed by Dr. Short. Dr. Short has further noted that epiphytes historically were not a major problem affecting eelgrass in the Estuary (Jones *et al.*, 2000).

Water Quality Sampling

Water Quality sampling was conducted by the University of New Hampshire and PREP throughout the period of eelgrass monitoring. Data from the UNH Buoy in Great Bay were obtained from the DES Environmental Monitoring Database via the UNH website (UNH, 2014). Water quality samples for nutrients (*e.g.*, DIN), total suspended solids (TSS), and phytoplankton chlorophyll-a (corrected for pheophytin) are collected at Adams Point, at the boundary between Little Bay and Great Bay. Samples are collected at a depth of one half meter below the surface, at high and low tide, once a month, throughout the year. Samples are analyzed using EPA-approved methods. Continuous monitoring (measurements at 30 minute intervals) for salinity and temperature is conducted using data sondes from the UNH buoy in Great Bay. This buoy is located in central Great Bay, about two kilometers due south of Adams Point. Temperature and salinity data for each analysis were averaged into a single daily value.

DISCUSSION

Eelgrass Cover

The eelgrass cover results are illustrated in Figure 3 for each annual eelgrass survey. Eelgrass habitat with essentially continuous cover is located immediately adjacent to the deep forked central channels. This area is characterized with elevations from zero to one meter below mean low water. Less suitable habitat, where eelgrass cover fluctuates from year to year, is typically located in the intertidal mudflats exposed at mean low water, especially along the southern and eastern shorelines of Great Bay. Approximately 75% of the eelgrass in Great Bay is found in intertidal regions, where plant leaves lie on the water surface at mean low water (Beem & Short, 2008). Eelgrass generally does not grow in the central channels with water depths greater than one meter below mean low water.

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Figure 3: Annual Great Bay Eelgrass Cover

Periods of Eelgrass Decline

Total measurable eelgrass cover (acres) in Great Bay is plotted by year in Figure 4. Throughout most of the 1990s, eelgrass cover ranged from 2,000-2,500 acres.

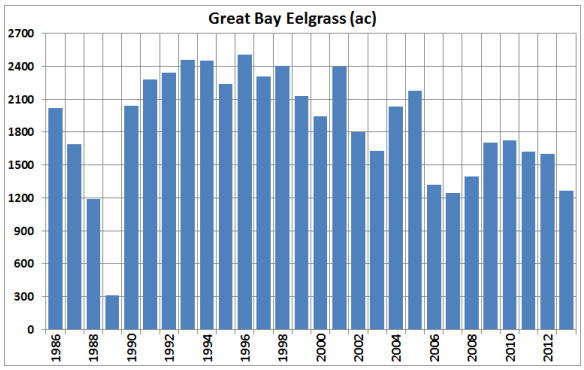

Figure 4: Great Bay Eelgrass Cover Declines

Notable decreases below these levels occurred during four periods: 1987-1989, 1999-2000, 2002-2003, and 2006-2007. Following the areal cover losses in 2007, recovery has not returned to 1990s levels, but had stabilized at about 1,600 acres through 2013. Each of these periods of decline and the available information regarding the causes of the decline are considered below.

1986-1989 Decline

Figure 5 illustrates eelgrass cover prior to the decline in 1986 (black) and afterwards in 1989 (green). By 1989, the coverage of eelgrass in Great Bay fell to 313 acres, with eelgrass lost throughout the entire area of the Bay (PREP, 2012).

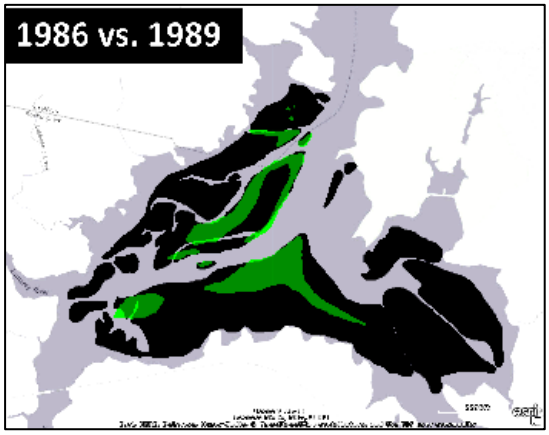

Figure 5: 1986 vs. 1989 Great Bay Eelgrass

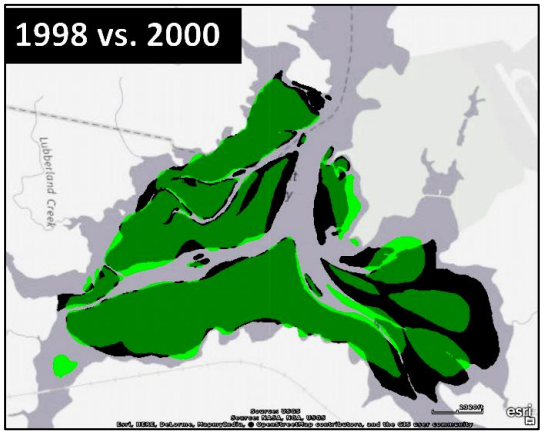

Figure 6: 1998 vs. 2000 Great Bay Eelgrass

From 1987-1989, eelgrass populations in Great Bay Estuary were almost completely eliminated due to a widespread outbreak of wasting disease (Burdick, Short & Wolf, 1993; Short, 2005). Great Bay lost all of the eelgrass cover in the eastern region as well as the shallow areas in the remainder of Great Bay. This constitutes the greatest recorded decline in Great Bay eelgrass cover since the 1930s. Subsequently, eelgrass cover rebounded to 2,000 acres in 1990. This rebound is most likely attributed to reseeding given the dramatic increase since the prior year.

1998-2000 Decline

After a considerable period of stable eelgrass populations from 1990- 1998, a noticeable declined occurred in 1999/2000. Figure 6 illustrates eelgrass cover in 1998 (black) prior to the decline in 1999 and 2000 (green). Great Bay lost approximately 440 acres of measureable eelgrass cover, representing a relatively minor decline to 1,960 acres. Sizeable portions of the large, continuous eelgrass meadow present in the shallow southeastern sector of the Bay in 1998 were thinned out and lost by 2000. In 2001, these beds recovered and eelgrass cover totaled 2,390 acres.

The cause of this decline is undetermined. However, the 2002 eelgrass distribution report (Short, 2004) referenced the persistent aftereffects of a wasting disease episode in 2000 as the cause of a decrease in eelgrass density in the Piscataqua River. The relationship between this episode and the downturn in eelgrass cover observed in Great Bay is not known. However, it is clear that wasting disease was present in the Estuary adjacent to Great Bay concurrent with the observed eelgrass decline. Given the location of the losses in the shallow waters, water column transparency cannot be a cause of this reductions as this area has the greatest light regime.

2001-2003 Decline

Figure 7 illustrates eelgrass cover in 2001 (black) prior to the decline in 2002 and 2003 (green). Following the eelgrass recovery in 2001 to 2,390 acres, Great Bay eelgrass cover experienced a moderate decline (≈770 acres) from 2001 to 2003 to about 1,620 acres, but rebounded to over 2,000 acres in 2004. Once again, the lost eelgrass beds were located predominantly in the northern and eastern areas of the Bay.

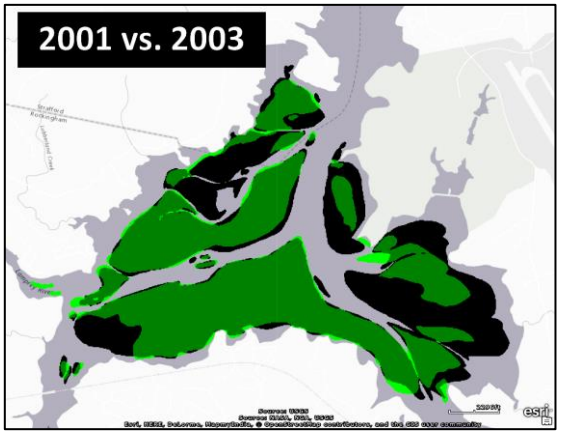

Figure 7: 2001 vs. 2003 Great Bay Eelgrass

Aside from the late 1980's wasting disease die-off, 2002 was the only year on record when eelgrass was lost along the western shoreline between the Oyster and Lamprey Rivers. The cause for this sudden reduction in Great Bay was attributed to an outbreak of wasting disease (Short, 2004; Short 2005). Following this decline, eelgrass cover in Great Bay rebounded to over 2,000 acres in 2004.

2005-2007 Decline

Figure 8 illustrates measurable eelgrass cover in 2005 (black) prior to the decline in 2006 and 2007 (green). From 2005 to 2007, Great Bay eelgrass suffered a major decline from over 2,165 acres to about 1,245 acres, a loss of 920 acres. Eelgrass began recovering in 2008 but overall acreage of eelgrass has remained at or below 1,700 acres through 2013. In 2006 and 2007, the majority of lost eelgrass beds were in the southern and eastern areas, predominantly adjacent to the shoreline in the intertidal zone. The cause of this decline has not been associated with wasting disease and is currently undetermined. However, it should be noted that this decline followed an extreme (500 year) storm event and persistent elevated rainfall which may have introduced additional stressors or exacerbated existing stressors (*e.g.*, low salinity, temperature).

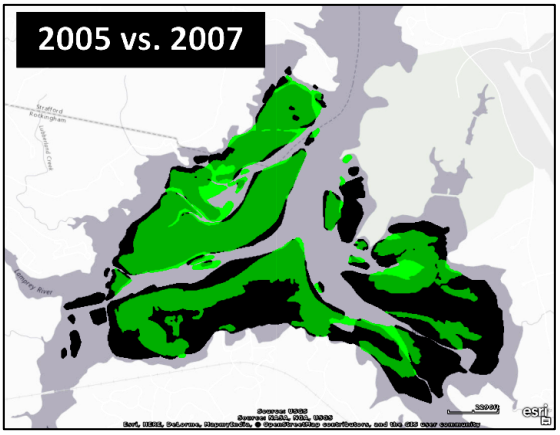

Figure 8: 2005 vs. 2007 Great Bay Eelgrass

Annual Spatial Variability of Eelgrass Cover

Typical patterns of eelgrass cover in Great Bay are separated by the Estuary's deep channels where eelgrass habitation has never been reported. As such, these channels form distinct natural boundaries to analyze eelgrass cover by geographic areas within the bay. These regions, of roughly equal area, were designated the East, South, and West sectors. The boundaries between sectors are illustrated in Figure 9, shown with the historical maximum reported eelgrass cover in 1996.

Figure 9: Great Bay Eelgrass Sectors

Individual ArcGIS polygons from the eelgrass mapping files were categorized by geographical sector. The total annual eelgrass area for each sector was summed and plotted to visualize localized variations in eelgrass coverage (Fig. 10). Values for 1987-1989 do not represent more typical conditions as a major episode of wasting disease decimated eelgrass in Great Bay.

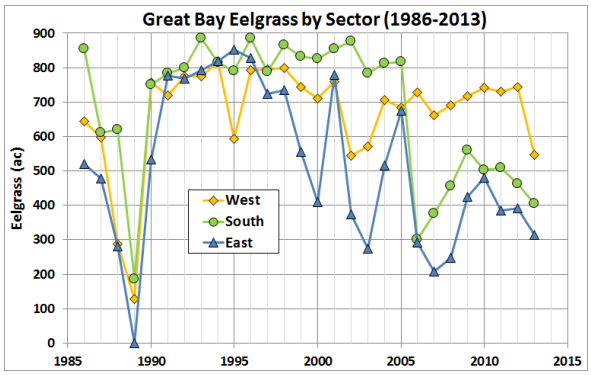

Figure 10: Annual Great Bay Eelgrass by Sector

Eelgrass cover in the West sector has ranged from 540-815 acres over the period from 1990-2013. Eelgrass in this sector has remained relatively stable, with several downturns followed by recovery. The declines in 1995 and 2002 totaled approximately 25% and 30% of the pre-decline cover. Since 2006 this sector has had the most eelgrass cover of the three sectors. In 2006, when the other two sectors experienced a dramatic decline, the West sector increased slightly and has maintained a relatively stable level of eelgrass cover through 2012.

Eelgrass cover in the South sector has ranged from 300-885 acres over the period of analysis (1990-2013). Eelgrass cover was very stable from 1990-2005, ranging from 750-885 acres. In 2006, the South sector experienced a steep decline to 300 acres (≈60% loss), coinciding with a period of very high rainfall and regional flooding. Over the next three years, eelgrass cover increased to 560 acres. Since 2009, eelgrass cover has declined to 500 acres or less. An inspection of the annual eelgrass maps shows that an area along the coast which previously supported eelgrass has also remained barren since 2006 (Fig. 11). The area of this void was estimated in ArcGIS to be 150 acres. Previous eelgrass maps (Fig. 3) indicate that this area was historically continuously covered by measurable eelgrass. In 2007, this region contained large areas of macroalgae. The prolonged period of no measureable eelgrass cover since 2006 suggests that the area may no longer be suitable as eelgrass habitat.

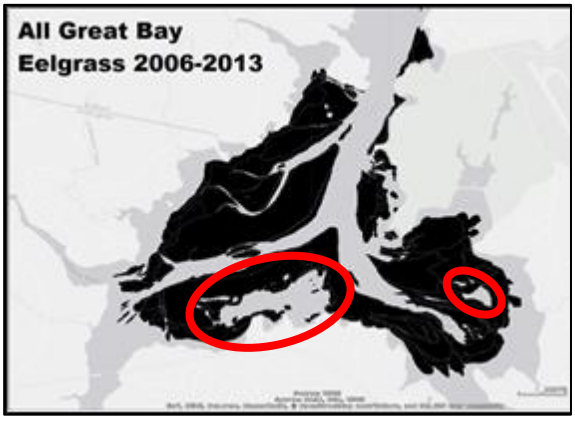

Figure 11: Great Bay Eelgrass 2006-2013

The East sector has fluctuated widely throughout the period of record, ranging from 205-850 acres. Eelgrass cover in this sector was relatively stable in the early 1990s, averaging about 800 acres (759 – 851 acres). Since 1999 eelgrass cover in this sector has exhibited high variability with steep declines followed by rapid recovery, ranging by as much as 500 acres in a two-year span. The periods of decline have been most severe in this sector, with eelgrass losses exceeding 40% in 2000, 2003 and 2007. As with the South sector, this sector experienced a sharp decline in 2006. An area devoid of measurable eelgrass appeared in 2006 (Fig. 11). This void, which routinely supported eelgrass cover prior to 2006, covers approximately 15 acres and may represent an area no longer suitable as eelgrass habitat.

Causes of Eelgrass Declines

Recent efforts to identify the causes of observed eelgrass declines in Great Bay have included data collection, surveys, wasting disease assessments, and laboratory experiments. General eelgrass studies for other systems have identified major eelgrass stressors, which include wasting disease, nutrient-induced light limitation, and heat stress. Using the available data and studies performed in Great Bay Estuary, potential eelgrass stressors were assessed to determine their roles, if any, in historical Great Bay eelgrass declines.

Wasting Disease

Wasting disease is caused by a slime mold-like protist, *Labryinthula zostera.* Wasting disease initially forms

on eelgrass leaves as brown or black lesions. These grow and spread through leaf-to-leaf contact, reducing the vascular transport and photosynthetic capacity in the plants until the plant dies (Sullivan *et al.*, 2013).

Nitrogen-Induced Light Limitation (Eutrophication)

In some estuaries, excess nutrients (*e.g.*, bioavailable nitrogen and phosphorus) yield conditions which result in widespread eelgrass die offs by reducing light transmission through the water column. The primary symptoms of nutrient enrichment include phytoplankton blooms measured as chlorophyll-a concentrations and the proliferation of epiphytes and/or macroalgae. As phytoplankton concentrations increase, light penetration through the water column decreases and exerts a negative influence on SAV (*e.g.*, eelgrass) by inhibiting photosynthesis. These effects are typically first seen in eelgrass beds occupying deeper habitats where light transmission is most affected. Secondary symptoms include the loss of SAV and low dissolved oxygen (DO) concentrations. In addition, an increase in DIN loads may support the growth of epiphytes which reside on blades of eelgrass, preventing light from reaching the leaf and ultimately killing off the eelgrass, or promote the growth of macroalgae that compete with eelgrass for suitable habitat.

a) Dissolved Inorganic Nitrogen

DIN (*i.e.*, ammonia, nitrite-nitrate) load data to the Estuary are available for municipal point sources, but the majority of the annual load entering the Estuary is from non-point sources (Swanson, Bilgili & Lynch, 2014). Non-point source loading data are not available. Consequently, water quality monitoring of nitrogen concentrations in the Bay, obtained from PREP, was used as a surrogate for load. DIN concentration data for the growing season are illustrated in Figure 12. The growing season annual average was determined as the average of the daily concentrations. The whiskers indicate the range of the daily average data and periods of eelgrass decline are noted by vertical bars, with different shading to indicate the cause of the decline. The declines in 1988-1989 and 2002-2003 were attributed to outbreaks of wasting disease. The decline in 1999-2000 may be associated with an outbreak of wasting disease, although this is uncertain. The decline in 2006-2008 has no defined cause.

The growing season daily average concentrations were evaluated for significant differences between the years of high growth (> 2,000 acres of measurable eelgrass; 1990-1998, 2001, and 2004-2005), the years of decline, and the years of low measurable eelgrass cover (2009 – 2012). The DIN concentrations for these groups were significantly different ($F_{2,140}$ = 3.66, P = 0.028). The significant difference was attributed to the DIN concentrations prevalent during the years of low eelgrass cover, when DIN averaged

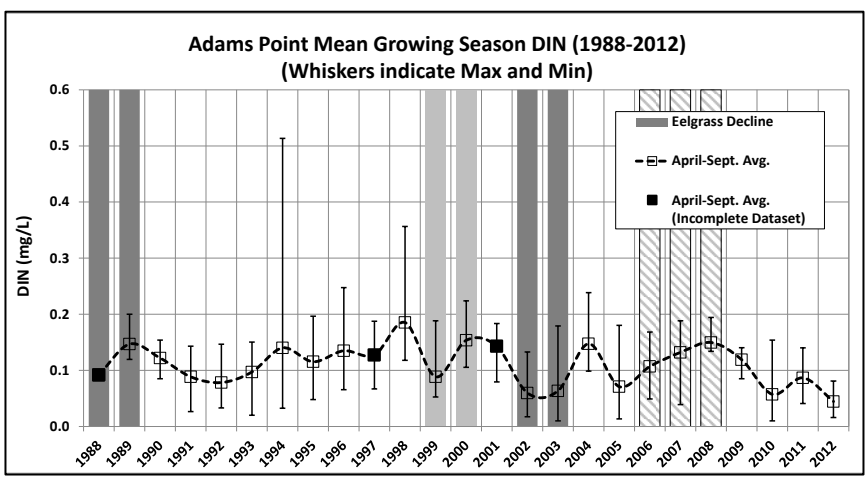

Figure 12: Adams Point Average Growing Season DIN

0.078 mg/L, which was significantly *less* than the concentration during the high cover years (0.120 mg/L; P = 0.014) and the concentration during the declining years (0.11. 0 mg/L; P = 0.012). There was no significant difference in DIN concentration between the high cover and declining years (P = 0.49).

b) Phytoplankton

Phytoplankton chlorophyll-a concentration data, from the PREP monitoring program at Adams Point (a well-mixed location between Great Bay and Little Bay), are summarized in Figure 13 for the growing season. The chlorophyll-a data were evaluated and presented in the same manner as for the DIN data.

Over this period, median chlorophyll-a concentrations generally remained quite low given the available inorganic nitrogen levels within a narrow range (2-6 µg/L), with no clear trend. The DIN level in Great Bay is capable of supporting 10-20 times the observed level of plant growth (Chapra, S., personal communication). Consequently, some other factor (*e.g.*, system hydrodynamics and short detention time) must be limiting this form of plant growth (PREP, 2013).

These data show that, in 2000, 2002 and 2006, when the eelgrass cover in Great Bay experienced major reductions, phytoplankton levels exhibited a mean

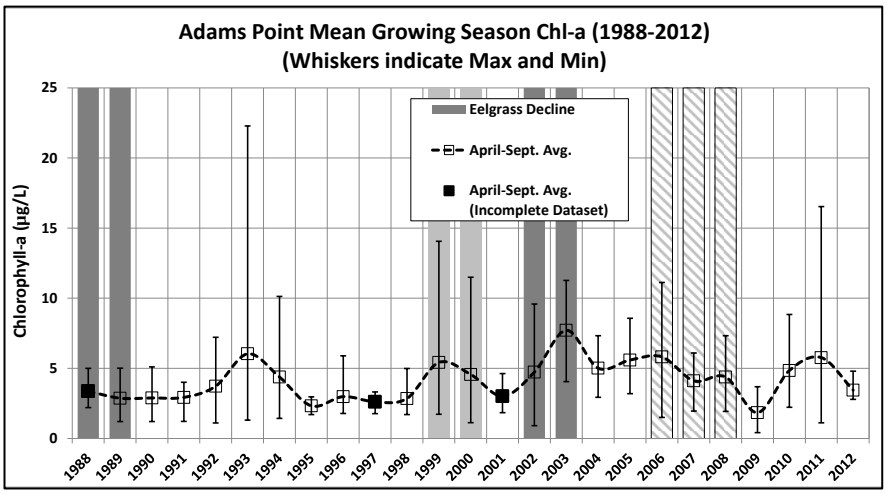

Figure 13: Adams Point Growing Season Chlorophyll-a

The growing season daily average concentrations were evaluated for significant differences between the years of high growth, the years of decline, and the years of low measurable eelgrass cover. The chlorophyll-a concentrations for these groups were not significantly different ($F_{2,143}$ = 2.07, P = 0.13). Since the probability is close to the significance threshold, comparisons between the individual groups were made. The average chlorophyll-a concentrations for the years of low measurable eelgrass cover (3.97 µg/L) was not significantly different than the average concentration for the period of eelgrass decline (4.86 ug/L; P = 0.26) or for the period of high growth (3.72 ug/L; P = 0.73). However, the period of high growth was significantly different than the period of decline (P = 0.04).

concentration around 4 µg/L with no major increases or decreases in concentration before or after the eelgrass declines. This level of phytoplankton chlorophyll-a is relatively low and falls within the bracket of phytoplankton concentrations prevalent in the 1990s, when the eelgrass cover in the Bay was at its maximum (PREP, 2012). Without any increase in phytoplankton chlorophyll-a, water clarity was not adversely affected by increased phytoplankton populations in the period from 1990 to 2011. Consequently, eutrophication, evidenced by a link between eelgrass loss and a TN-induced increase in phytoplankton, is not supported by the relevant data for this system.

The negative impacts of eutrophication due to increased algal growth manifests as measurably reduced water clarity sufficient to limit eelgrass

growth. In 2005, the Great Bay coastal buoy at Adams Point was fitted with instrumentation for colored dissolved organic matter (CDOM) automated monitoring. Using these data and hyperspectral remote sensing data, Morrison *et al.* (2008) developed a multivariate model of water clarity to evaluate the factors contributing to light attenuation in Great Bay. The resulting model related phytoplankton chlorophyll-a, CDOM, and non-algal particles (NAP; *i.e.*, turbidity not associated with phytoplankton) to the measured light attenuation coefficient (K_d, m^{-1}), accounting for 95% of the variability in the data.

Based on data collected in 2007, these researchers determined that phytoplankton were responsible for approximately 12% of the overall light attenuation, with CDOM and NAP responsible for the majority of the observed light attenuation (27% and 29%, respectively; Morrison *et al.*, 2008). Morrison *et al.* (2008) also concluded that the CDOM present in the Estuary originated from terrestrial sources based on a regression of CDOM with salinity. These results suggest that the water clarity in Great Bay was sufficient for the growth of eelgrass in 2007. Based on this analysis, chlorophyll-a levels appear to have a relatively minor contribution to water column light attenuation and therefore, do not pose a major threat to eelgrass, especially given Great Bay's generally shallow eelgrass habitat.

c) Macroalgae

Macroalgae are present in all estuarine waters to varying degrees. In the Great Bay Estuary, the primary areas with considerable macroalgae growth are the more quiescent southern and eastern waters of Great Bay. Excessive macroalgae growth can shade eelgrass beds, thereby reducing light availability and potentially resulting in eelgrass die offs. Macroalgae generally meet their nutrient requirements from water column inorganic nitrogen (Wang *et al.*, 2014). Macroalgae are opportunistic species capable of rapidly colonizing open habitat. It may be that the loss of eelgrass beds in 2006 provided an opportunity for macroalgae to take residence in the Bay in 2007 but this has yet to be demonstrated.

A consistent monitoring program for macroalgae has not historically existed for Great Bay Estuary. Most of the available data are anecdotal, with only a few actual measurements. Baseline measurements were made by UNH researchers between 1972 and 1980 for a few locations in Great Bay (NHDES, 2009). These limited measurements identified very low levels of macroalgae in 1980 (PREP, 2013). More detailed measurements were made in 2007 via aerial imagery (Pe'eri *et al.*, 2008) and in 2008-2010 by on-site survey (Nettleton, 2011). The Pe'eri study was primarily conducted to evaluate the use of hyperspectral imagery as a tool for mapping macroalgae in Great Bay. Results from a survey conducted on August 29, 2007, were used to produce a comprehensive map of eelgrass and macroalgae in the Estuary for that year (Fig. 14; NHDES, 2009).

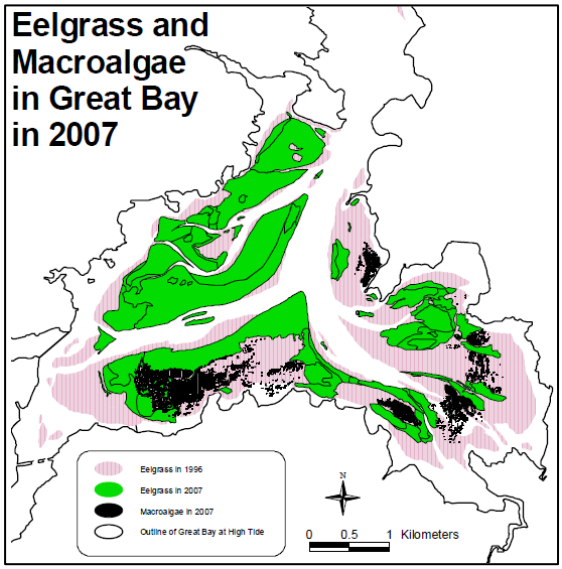

Figure 14: 2007 Macroalgae Survey

Based on this 2007 survey, it was estimated that macroalgae covered 137 acres in Great Bay and encroached into areas previously inhabited by eelgrass as illustrated above. The surveys by Nettleton evaluated percent cover and biomass of various macroalgae species at five locations in Great Bay that were convenient for access. These locations are not historical eelgrass habitat.

Based on the Pe'eri survey alone, it could not be determined if the macroalgae caused the eelgrass to decline in the Bay or if the 2006 decline provided new areas for macroalgae to proliferate. Inspection of the

figures shows that eelgrass losses were not restricted to areas with observed macroalgae beds. Great Bay eelgrass losses between 2005 and 2007 totaled 920 acres, while only 137 acres of macroalgae beds were reported. Subsequent eelgrass regrowth of approximately 230 acres, from 2008- 2011, occurred in areas that had elevated macroalgae growth in 2007. Thus, it appears that macroalgae growth, of itself, has not significantly restricted system eelgrass recovery.

However, a PREP study in 2013 sampled macroalgae (*Ulva* spp., *Gracilaria* spp., fucoids (*Ascophyllum nodosum* and *Fucus vesiculosus*)) in transects. These results indicated that peak macroalgal biomass occurs between 0.5-1.0 meters above MLLW with the highest macroalgal growth of the four transect-sampled sites at Depot Road (PREP, 2013). Random sampling identified the presence of macroalgal growth in most areas of the Estuary, ranging from southern Great Bay to Portsmouth Harbor to more than a mile up the Bellamy, Oyster, and Upper Piscataqua Rivers. The 2013 PREP study also made recommendations for a long-term macroalgae monitoring program that is currently under development.

d) Epiphytes

The potential adverse effects of eutrophication on eelgrass in estuarine environments include reduction in light availability due to epiphytes. However, the available data on epiphytes are more limited than the available data on macroalgae. Reports of excessive epiphyte growth have not appeared in various annual eelgrass surveys completed by Dr. Short. Dr. Short has noted that epiphytes historically were not a major problem to eelgrass in the Estuary (Jones *et al*., 2000). Based on these observations, it is unlikely that epiphytes played a significant role in the eelgrass losses observed in the Estuary. As with macroalgae, more data are needed to quantify whether epiphytes are adversely influencing eelgrass habitats in the Estuary and to assess the cause and resolution to such problems if they exist.

Non-Algal Water Column Light Attenuation

Light availability is considered the most critical variable for the growth of SAV when other basic habitat requirements (*e.g.*, flow regime, wave exposure, substrate composition) are met (Dennison, 1987). Water column light transmittance can be reduced by numerous non-algal physical factors including: CDOM, suspended sediments, or turbidity due to heavy precipitation, high winds, or tidal currents. Long-term negative effects and die-offs have been observed in Chesapeake Bay eelgrass beds which were subjected to periods of high turbidity for less than three weeks (Moore *et al.*, 2012).

Using the multivariate model developed by Morrison *et al.* (2008), HDR|HydroQual (2011) developed a water quality model to assess light attenuation in Great Bay during the period surrounding the eelgrass decline in 2006. This analysis (Fig. 15) shows that water clarity in Great Bay and Little Bay was severely reduced over a three month period (May through July) in 2006, in comparison with prior and subsequent years due to record rainfall conditions.

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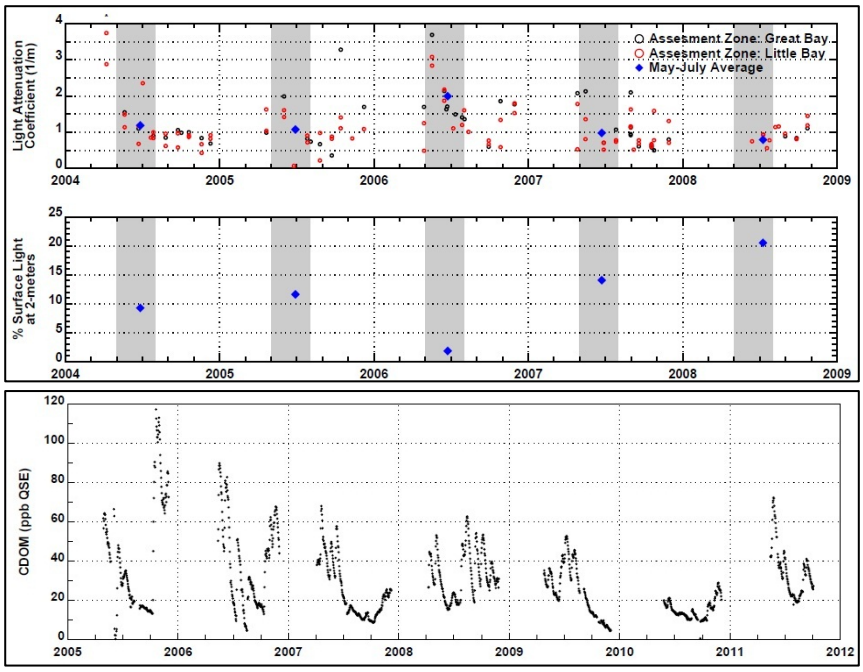

Figure 15: Great Bay and Little Bay Buoy Light Attenuation and Great Bay Buoy CDOM

Total suspended solids concentration data, from the PREP monitoring program at Adams Point, are summarized in Figure 16 for the growing season. The TSS data were evaluated and presented in the same manner as the DIN data.

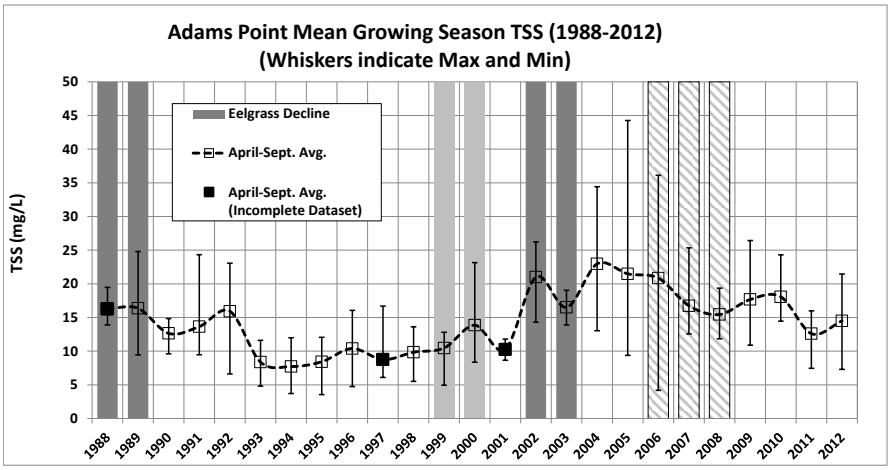

Figure 16: Adams Point Growing Season Chlorophyll-a

The growing season daily average concentrations were evaluated for significant differences between the years of high growth, the years of decline, and the years of low measurable eelgrass cover. The TSS concentrations for these groups were significantly different ($F_{2,143} = 5.41$, $P = 0.005$). The significant difference was attributed to the TSS concentrations prevalent during the years of high eelgrass cover, when TSS averaged 12.6 mg/L, which was significantly less than the concentration during the declining years (16.4 mg/L; $P = 0.003$) and the concentration during the low cover years (15.7 mg/L; $P = 0.059$). There was no significant difference in TSS concentration between the low cover and declining years ($P = 0.63$).

Extreme Precipitation

Significant increases in precipitation and flooding, particularly immediately prior to or during the

growing season, has been identified as a primary driver of seagrass loss and interannual variability in Chesapeake Bay and other estuaries (Wang & Linker, 2005). The timing of extreme precipitation events also affects the severity of impact on submerged aquatic vegetation (SAV). Wang & Linker (2005) concluded that extreme storms prior to peak biomass are detrimental to SAV in polyhaline waters while storms at the end of the growing season have a diminished effect but may reduce the potential for SAV growth in the following year. In May 2006, the Great Bay Estuary and surrounding region experienced a major flooding event. This event was credited with stressing and killing organisms of a variety of species (GBNERR, 2009). This flood also corresponds to a year of severe eelgrass loss in Great Bay with no coinciding definitive evidence of the presence wasting disease. However, the degree to which this flood was responsible for the loss of eelgrass has not been determined.

Salinity

Daily average salinity data are illustrated in Figure 17. Average daily salinity exhibits a seasonal pattern with reduced salinity in the spring, when the river inflow is typically at its maximum, and elevated salinity through the late summer and early fall when stream flows are at their minima.

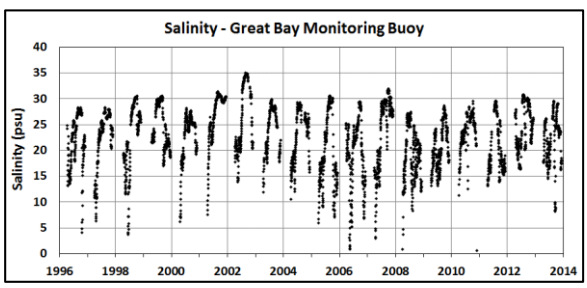

Figure 17: Great Bay Buoy Salinity

The daily salinity results reflect periods of elevated rainfall and extended drought. The 2002 growing season experienced extremely low flows and, as a consequence, the average daily salinity exceeded 30 psu from July 15 through October while most other years rarely exceed 30 psu for a single day. In 2006, April started with relatively low freshwater inflow and daily salinities above 20 psu. However, May experienced major flooding and daily salinity fell below 5 psu, levels stressful for eelgrass, for 7 days with a minimum daily average below 1 psu for two consecutive days (Nejrup & Pedersen, 2008; GBNERR, 2009).

While low salinity may protect eelgrass from wasting disease, low salinity is also a recognized stressor of eelgrass (Nejrup & Pedersen, 2008; Salo & Pedersen, 2014). Eelgrass subjected to a salinity of 5 psu for five weeks has been demonstrated to result in "higher mortality, lower leaf production, lower leaf elongation rate, less standing leaves per shoot and more necrotic tissue" than at salinities of 12.5 psu and 20 psu (Salo & Pedersen, 2014). Fonseca & Uhrin (2009) reported that photosynthesis in eelgrass essentially ceases below 10‰.

Temperature

Daily average temperature is illustrated in Figure 18 for the period from 1996 through 2013. Bay temperatures fall below 5°C at the end of the year and many areas of the bay are covered with ice over the winter. Temperatures rise steadily from April through July, typically topping out between 20 - 25°C by August. Typical water temperatures fall below 15°C by the beginning of October and 10°C by the beginning of November.

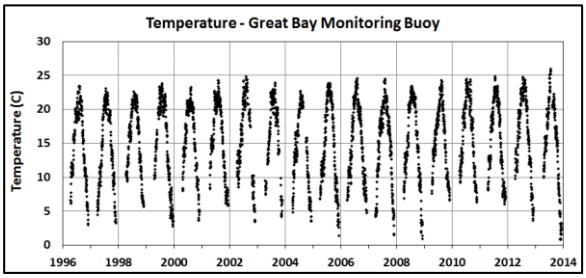

Figure 18: Great Bay Buoy Temperature Data

The observed pattern is fairly uniform over the 18-year period of record. However, over this period the maximum daily and bi-weekly average water temperature reported at the Great Bay buoy has increased (Figure 19).

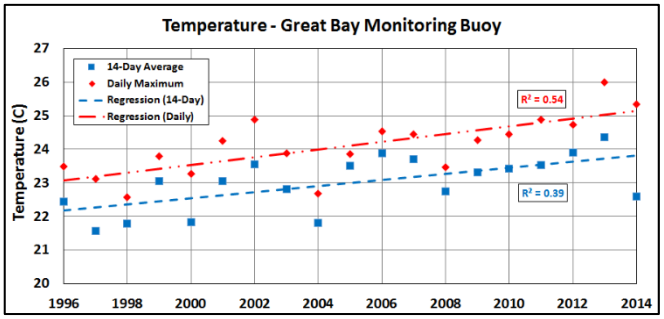

Figure 19: Great Bay Buoy Maximum Temperature Analysis

It should be noted that the temperature variation occurring in the shallow southeast section of the Bay should have responded more dramatically. The elevated temperatures may have induced thermal stress during portions of the summer, especially in the warmer intertidal regions where the majority of eelgrass was lost. Cumulatively, in 2006, a variety of stressors were observed which may have resulted in the dramatic die off by the August eelgrass survey.

CONCLUSION AND RECOMMENDATIONS FOR FUTURE RESEARCH

In the past, Great Bay eelgrass remediation efforts have generally focused on total eelgrass coverage losses in Great Bay Estuary. Parsing Great Bay into geographic thirds provides a basis for a more defined assessment of historical eelgrass declines. Historical inter-annual variation in eelgrass cover was primarily associated with shifts occurring in the shallow East and South sectors of the Bay. Significant losses of eelgrass cover occurred from 1987-1989, 1999-2000, 2002-2003, and 2006-2007. These periods of loss are distinct from the inter-annual variability observed throughout most of the 1990s. Any explanation as to the cause of these eelgrass losses in Great Bay must account for the both the temporal and spatial natures of these losses.

The primary cause of eelgrass declines in Great Bay is currently attributed to wasting disease while other declines remain undetermined. Wasting disease exhibits pronounced negative effects in eelgrass at higher salinities and temperatures (Salo & Pedersen, 2014; Sullivan *et al.*, 2013; Bull, Kenyon & Cook, 2012; Short *et al*., 1993). In addition to laboratory studies, this has been evidenced in multiple wasting disease episodes where eelgrass meadows are decimated except for areas of low salinity (Vergeer, Aarts & de Groot, 1995; Short *et al.*, 1987). Eutrophication has also been suggested as a cause of Great Bay eelgrass declines. However, if nitrogen-induced eutrophication caused or contributed to a major eelgrass loss in Great Bay, there should have been a substantial increase in growing season DIN load and chlorophyll-a concentration and a decrease in transparency in association with the eelgrass decline. The available data do not support a compelling argument that cultural eutrophication is responsible for major eelgrass losses observed in Great Bay. DIN levels have remained relatively uniform over the last two decades in Great Bay, and there has been no change in phytoplankton chlorophyll-a concentrations over the period when eelgrass losses were significant. Moreover, the observed eelgrass losses have been in the shallowest depths while eelgrass beds in deeper (*i.e.*, more light limited) areas have perennially maintained coverage. This suggests that light limitation, due to eutrophic conditions and excess algal growth or otherwise, cannot physically be responsible for major eelgrass declines. In addition, the available data for macroalgae and epiphytes do not support these as causes for eelgrass loss in the system. Consequently, increased plant growth can be responsible for neither changes in light transparency nor major eelgrass bed declines in Great Bay.

Extensive literature provides a number of additional factors with potential to negatively influence eelgrass. Combinations of these conditions have been demonstrated or implicated during eelgrass declines in Great Bay. Improved and increased monitoring efforts are critical in determining the

cause of non-wasting disease induced eelgrass declines in Great Bay. Current water quality monitoring is focused at Adams Point, central Great Bay (buoy station), and upstream in the tidal rivers. We recommend that future monitoring efforts extend the focus to areas of fluctuating eelgrass beds, especially in intertidal regions in the South, East, and West sectors to identify significant differences in physical or chemical differences in habitat or water quality associated with healthy eelgrass beds or eelgrass declines. Another focus should be on the causes of 150 acre barren patch in the South sector and the smaller void in the East sector. Monitoring should include water temperature, salinity, macroalgal levels, wasting disease prevalence, sediment chemistry, waterfowl surveys, and ice cover extent to aid in determining significant spatial and temporal differences and the independent and combined contributions of these recognized potential stressors on Great Bay eelgrass. To better understand the predominant eelgrass life cycle in areas of Great Bay, it would be useful to conduct eelgrass surveys early in the growing season as well as at the end of the growing season, as currently practiced. The addition of early season eelgrass surveys would allow for 1) estimation of baseline perennial eelgrass beds, 2) comparison of early growing season eelgrass cover with end-of-season cover, and 3) comparison of baseline perennial eelgrass beds with end-of-season eelgrass cover from the prior year.

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