ASSESSMENT OF EUTROPHICATION IN THE BARNEGAT BAY-LITTLE EGG HARBOR SYSTEM: USE OF SAV BIOTIC INDICATORS OF ESTUARINE CONDITION

Michael J. Kennish, [1*] **Scott M. Haag,** [2] **and Gregg P. Sakowicz**[3]

[1]**Institute of Marine and Coastal Sciences**
Rutgers University
New Brunswick, New Jersey 08901

[2]**Center for Remote Sensing and Spatial Analysis**
Rutgers University
New Brunswick, New Jersey 08901

[3]**Rutgers University Marine Field Station**
800 Great Bay Boulevard
Tuckerton, New Jersey 08087

Corresponding author. E-mail: kennish@marine.rutgers.edu

EXECUTIVE SUMMARY

Results of a comprehensive investigation of the seagrass demographics in the Barnegat Bay-Little Egg Harbor Estuary during 2008 indicate ongoing degradation of seagrass habitat associated with increasing eutrophic conditions. Surveys of seagrass beds in Barnegat Bay and Little Egg Harbor from spring to fall in 2008 show that the seagrass beds have not yet recovered from the marked reduction of plant biomass (g dry wt m^{-2}), density (shoots m^{-2}), blade length, and percent cover recorded in 2006. Quadrat, core, and hand sampling, as well as digital camera imaging at 120 transect sites in 4 disjunct seagrass beds of the estuary during the June-November period in 2008, as in

2004, 2005, and 2006, reveal distinct changes in demographic patterns that can lead to significant shifts in ecosystem services.

In 2008, seagrass was found at less than 50% of the survey sites (46.3%) during the June-July sampling period when the median aboveground and belowground biomass values were a maximum. The mean aboveground biomass in the estuary was highest in August-September (30.93 g dry wt m^{-2}), and the mean belowground biomass was highest in June-July (81.31 g dry wt m^{-2}). Over the entire June-November sampling period, the mean aboveground biomass declined slightly from 25.01 g dry wt m^{-2} to 22.91 g dry wt m^{-2}, while the mean belowground biomass decreased markedly by 51% from 81.31 g dry wt m^{-2} to 39.86 g dry wt m^{-2}. The aboveground biomass values were low throughout the 2008 study period compared to those of the initial year of sampling in 2004 (see Kennish et al., 2007b).

The density of *Zostera marina* ranged from 239-466 shoots m^{-2} during 2008. Peak density of *Z. marina* occurred during the August-September period when the aboveground biomass also peaked. The density range of the plants was similar to that in 2005 (163-479 m^{-2}) but greater than that in 2006 (171-378 shoots m^{-2}).

The blade length of *Zostera marina* was relatively consistent during 2008, with mean values amounting to 15.35 cm in June-July, 14.57 cm in August-September, and 19.88 cm in October-November. By comparison with the previous years of sampling from 2004-2006, blade lengths during 2008 were the shortest on record, even when compared to the heavily impacted year of 2006 (see Kennish et al., 2007b). The nitrogen content of *Z. marina* blades measured at field transplantation sites ranged from 2.97% to

4.33%. Nitrogen Pollution Index values calculated for *Z. marina* in the estuary ranged from 0.58 to 2.55.

The percent cover of seagrass in 2008 was lowest in June-July (23%), highest in August-September (36%), and intermediate in October-November (27%). Seagrass biomass, density, and areal cover measurements in 2008 were higher at exterior transect sampling sites (1, 2, 9, and 10) closest to the seagrass bed margins than at interior transect sampling sites (3, 4, 5, 6, 7, and 8). These values are consistent with those measured during 2004, 2005, and 2006. This pattern indicates that seagrass located near the margins of its distribution (i.e., edge effects) is more likely to be exposed to less optimal conditions for growth and survival. The percent cover of macroalgae in 2008 was significantly lower than that of seagrass, declining markedly from June to November. The mean percent cover of macroalgae decreased from 20% during the June-July period to 10% during the August-September period and 5% during the October-November period.

Seagrass is an important indicator of estuary condition. Data collected on seagrass abundance, biomass, distribution, areal cover, and blade length are vital for assessing biotic responses in the estuary to nutrient enrichment. Therefore, annual demographic surveys of seagrass are critical for determining the status and trends in the ecological health of the system.

INTRODUCTION

Eutrophication poses the most serious threat to the long-term health of the Barnegat Bay-Little Egg Harbor Estuary (Kennish et al., 2007a). Nutrient enrichment and associated organic carbon loading in this shallow, coastal lagoon have been linked to an array of cascading environmental problems such as increased micro- and macroalgal growth, harmful algal blooms (HABs), altered benthic invertebrate communities, impacted harvestable fisheries, and loss of essential habitat (e.g., seagrass and shellfish beds). The net insidious effect of progressive eutrophication is the potential for the permanent alteration of biotic communities and greater ecosystem-level impacts. For example, hard clam (*Mercenaria mercenaria*) stocks in Little Egg Harbor declined by two-thirds between 1986 and 2001, and the hard clam harvest declined by more than 95% between 1975 and 2005. Recurring brown tide (*Aureococcus anophagefferans*) blooms occurred between 1995 and 2002, with monitoring for brown tide being discontinued after 2004 (Olsen and Mahoney, 2001; Gastrich et al., 2004). The biomass of seagrass beds in the Barnegat Bay-Little Egg Harbor Estuary decreased by 50-87.7% over the 2004-2006 period (Kennish et al., 2007b).

Accelerated growth of drifting macroalgae (e.g., *Ulva lactuca*) has produced extensive organic mats that pose a potential danger to essential habitat (e.g., seagrass beds). Rapid growth of other macroalgal species in the estuary, such as the rhodophytes *Agardhiella subulata*, *Ceramium* spp., and *Gracilaria tikvahiae*, can also be detrimental. In addition, the decomposition of thick macroalgal mats can promote sulfide accumulation and the development of hypoxic/anoxic conditions in bottom sediments that are devastating to benthic infaunal communities. Blooms of the sea nettle (*Chrysaora quinquecirrha*) have likewise developed in the estuary since 2000. These problems can then lead to the deterioration of sediment and water quality, loss of biodiversity, and disruption of ecosystem health and function. Human uses of estuarine resources can also be seriously impaired.

Because the Barnegat Bay-Little Egg Harbor Estuary is shallow, poorly flushed, and bordered by highly developed watershed areas, it is particularly susceptible to nutrient loading. Protracted water residence times in the estuary result in the retention of nutrient elements within the estuarine basin. These conditions threaten the ecological integrity of the system.

Nutrient enrichment and organic carbon loading are particularly problematic in coastal lagoons which are often moderately to highly eutrophic. These shallow enclosed systems typically exhibit a range of ecological and biogeochemical responses that signal a shift in the balance of selective forces shaping biotic communities and habitats. An array of cascading biotic and environmental problems is coupled to progressive eutrophication of coastal bays, and the net insidious effect of these problems is the potential for permanent alteration of biotic communities, major shifts in food web structure, marked decline in ecosystem services, and the decrease of human uses of the affected waterbodies. Shifts in plant subsystems associated with eutrophy can have serious long-term detrimental effects on higher trophic levels. Changes in phytoplankton communities from diatom/dinoflagellate dominants to greater abundances of microflagellates, raphidophytes, and bloom forming pelagophytes (e.g., *Aureococcus anophagefferens*, the causative agent of brown tides) often lead to dramatic losses of shellfish resources (e.g., hard clams, *Mercenaria mercenaria* and bay scallops, *Argopecten irradians*). Effective management strategies must be formulated to reduce nutrient loading and institute effective mitigation plans to remediate the biotic and habitat impacts.

Seagrass subsystems, which are excellent indicators of estuarine sediment and water quality conditions, have been on the decline not only in estuaries in the mid-Atlantic region but also in many other regions worldwide due to nitrogen and phosphorus loading associated with human activities (Nixon, 1995; Rabalais, 2002; Orth et al., 2006; Valiela, 2006). Concurrently, nuisance and toxic algal blooms have been on the rise, directly impacting seagrass beds and other habitats. Both macroalgal and phytoplankton blooms are problematic because they cause severe shading and attenuation of light transmission, thereby hindering benthic photosynthetic processes. According to Lamote and Dunton (2006), more than 70% of the large-scale decline in seagrass habitats reported in recent studies is ascribed to eutrophication. Over two-thirds of U.S. estuaries are experiencing moderate to high eutrophic conditions as a result of nutrient over-enrichment (Bricker et al., 1999, 2007).

Most of the seagrass beds in New Jersey (~75%) occur in the Barnegat Bay-Little Egg Harbor Estuary. While more than 6,000 ha of seagrass habitat have been reported in this system (McLain and McHale 1997), some studies indicate that significant losses of seagrass have taken place during the past 30 years, possibly reducing the beds by 30-60% (Bologna et al., 2000). A GIS spatial comparison analysis of SAV surveys by Lathrop et al. (2001) suggests that a contraction of the seagrass beds to shallow subtidal areas (< 2 m) may have occurred during this period due to a decrease in available light in response to phytoplankton and macroalgal blooms as well as epiphytic attenuation. Eutrophy has progressively increased in the estuary. Designated as moderately eutrophic in the early 1990s, the estuary was later classified as highly eutrophic by application of NOAA's National Ecosystem Assessment Model and Nixons's Trophic Classification (Nixon, 1995; Bricker et al. 2007; Kennish et al. 2007).

Increased nutrient loading to the Barnegat Bay-Little Egg Harbor Estuary has raised concern over potential impacts on seagrass, as well as biotic communities and other habitats in the system (Kennish, 2001). In this study, we examine the demographics of *Zostera marina* in the estuary over the 2008 study period to determine its status and trends. We also discuss the environmental factors responsible for changes in the structure and function of the seagrass beds. Assessment of the distribution, abundance, and biomass of seagrasses is important for tracking escalating eutrophic problems. To this end, comprehensive *in situ* sampling of seagrass beds was conducted in the estuary during the spring-fall period in 2008, similar to surveys of the same beds conducted from 2004-2006.

STUDY AREA

Barnegat Bay-Little Egg Harbor is a lagoonal estuary located along the central New Jersey coastline (Figure 1). It forms an irregular tidal basin ~70 km long, 2-6 km wide, and 1.5 m deep. The surface area amounts to 280 km^2, and the volume, 3.54 x 10^8 m^3 (Kennish, 2001a). The location of the barrier island complex (Island Beach and Long Beach Island) restricts exchange of water with the coastal ocean; therefore, flushing times of the estuary are protracted, ~74 days in summer. Exchange of bay and ocean water occurs through Barnegat Inlet, Little Egg Inlet, and the Pt. Pleasant Canal.

The adjoining Barnegat Bay watershed covers an area of 1730 km^2, and the watershed:estuary areal ratio is 6.5:1. A total of 562,493 people live in the surrounding watershed year round, but the population exceeds 1,000,000 people during the summer tourist season. A north-to-south gradient of decreasing population density occurs in the watershed. As a result, nutrient loading is highest in the northern segment of the estuary (Seitzinger et al. 2001).

The principal objectives of this investigation are to determine: (1) the demographic characteristics and spatial habitat changes of seagrass in the estuary over annual growing periods; (2) development of seagrass indicators of condition; (3) the relative abundance, spatial distribution, and potential impacts of macroalgae on the seagrass beds; (4) the determination of nitrogen concentrations in seagrass blades and the calculation of a Nitrogen Pollution Index; and (5) the effectiveness of seagrass transplantation experiments (i.e., plant survival) in the estuary. Although two species of seagrass occur in the estuary, eelgrass (*Zostera marina*) and widgeon grass (*Ruppia maritima*), eelgrass is overwhelmingly more abundant. Ground surveys yielded few widgeon grass samples.

MATERIALS AND METHODS

Sampling Design

Quadrat-and-transect sampling was conducted over the June to November period in 2008, targeting the same seagrass beds and sampling stations in Barnegat Bay (~1550 ha) and Little Egg Harbor (~1700 ha) that were sampled during the 2004-2006 period (Kennish et al., 2007b, 2009). The purpose of this work was to determine if the status (i.e., characteristics) of seagrass habitat has changed since the detailed SAV surveys conducted during the 2004-2006 period. A total of 120 sampling sites along 12 transects (see Transects 1-12; Figure 2) in four disjunct seagrass beds (1-4) in Barnegat Bay and Little Egg Harbor were sampled during a 6-month sampling period (June-November) in 2008. During each sampling period (June-July, August-September, and October-November), 80 of the 120 field sites (total n = 240 for all sampling periods) were randomly selected and sampled to determine seagrass density, biomass, and blade length. Areal cover measurements of seagrass and macroalgae were also made at all 120 sampling sites during each sampling period. In addition, diver observations were made at these sampling sites to determine the occurrence of epiphytic infestation and bay scallops. The following demographic data were recorded on all sampling dates: presence/absence of seagrass and macroalgae, aboveground and belowground biomass of seagrass, density of seagrass, percent cover of seagrass and macroalgae, seagrass blade length, and occurrence of bay scallops (*Argopecten irradians*).

In addition to data collected on the biotic parameters (presence/absence of seagrass and macroalgae, aboveground and belowground biomass of seagrass, shoot density of seagrass, percent cover of seagrass and macroalgae, and seagrass blade length), physicochemical data (temperature, salinity, pH, dissolved oxygen, turbidity, and depth) were also measured using either a handheld YSI 600 XL data sonde coupled with a handheld YSI 650 MDS display unit, an automated YSI 6600 unit (equipped with a turbidity probe), or a YSI 600 XLM automated datalogger. Secchi disk measurements were likewise collected in the survey area together with measurements of several nutrient parameters (i.e., nitrate plus nitrite, ammonium, total dissolved nitrogen, phosphate, and silica). More than 1000 biotic and abiotic measurements were obtained during the study period.

Three seagrass transplantation sites were also established during this study (Figure 3). The purpose of these sites was to conduct a seagrass cross-transplant experiment within the study area to assess growth response. In addition, it provided an opportunity to calculate a Nitrogen Pollution Index on the seagrass blades using the approach of Lee et al. (2004).

Sampling stations along each transect and at the transplantation sites were permanently located with a Differential Global Positioning System (Trimble®GeoXT™

handheld unit). Sampling periods (N = 3) commenced in June, August, and October and continued until all targeted stations were sampled. No samples were collected after November. The *in situ* sampling methods used in this study followed the standard protocols of Short et al. (2002).

Quadrat Sampling

Following the field methods of Short et al. (2002), a 0.25-m^2 metal quadrat was haphazardly tossed at the sampling sites to obtain measurements of seagrass and macroalgae areal coverage. The percent cover of seagrass and macroalgae was estimated in the quadrat by a diver using a scale of 0 to 100 in increments of 5. Subsequently, the length of a subset of seagrass blades was measured, and the mean values were recorded. The diver then visually inspected the seagrass bed within the quadrat for evidence of grazing, boat scarring, macroalgae, epiphytic loading, and wasting disease.

Core Sampling

Coring methods also followed those of Short et al. (2002), with a 10-cm (.00785 m^2) diameter PVC coring device used to collect the seagrass samples with care taken not to cut or damage the aboveground plant tissues. The diver-deployed corer extended deep enough in the sediments to extract all belowground fractions (roots and rhizomes). Each core was placed in a 3 x 5 mm mesh bag and rinsed to separate plant material from the sediment. After removing the seagrass sample from the mesh bag, the sample was placed in a labeled bag and stored on ice in a closed container prior to transport back to RUMFS. In the laboratory, the samples were carefully sorted and separated into aboveground (shoots) and belowground (roots and rhizomes) components. The aboveground and belowground fractions were then oven dried at 50-60 ºC for a minimum of 48 hours. The dry weight biomass (g dry wt m^{-2}) of each fraction was then measured to the third decimal place.

Water Quality Sampling

Water quality parameters (temperature, salinity, dissolved oxygen, pH, and turbidity) were measured at all sampling stations using a handheld YSI 600 XL data sonde coupled with a handheld YSI 650 MDS display unit, an automated YSI 6600 unit (equipped with a turbidity probe), or a YSI 600 XLM automated datalogger as noted above. The data were obtained prior to biotic sampling at each sampling site. Water quality data will be collected at a uniform depth (~10 cm) above the sediment-water interface.

Water samples were also collected and analyzed for nutrient concentrations during each sampling period. Nitrate plus nitrite, ammonium, total dissolved nitrogen, phosphate, and silica concentrations were measured at sampling sites within the seagrass beds. Laboratory analysis of the nutrients followed standard methods. Nutrient samples (N = 72) were collected at all 12 transects in the estuary over the study period.

Results

Physicochemical Conditions

Table 1 provides the mean water temperatures recorded at the sampling sites in the estuary during the three sampling periods in 2008. The mean water temperature for the June-July sampling period (23.37 ºC) was slightly lower than that for the August-September sampling period (23.99 ºC). However, it decreased markedly (19.08 ºC) for the October-November sampling period.

Salinities were in the polyhaline range, with mean values of 26.39‰ and 28.22‰ registered at the sampling sites during the June-July and August-September sampling periods, respectively (Table 2). Mean salinity decreased slightly to 26.17‰ for the October-November sampling period. Salinity variation was greatest during this last sampling period.

Mean dissolved oxygen (DO) values amounted to 7.33 mg/l during the June-July sampling period and 6.55 mg/l during the August-September sampling period (Table 3). Intermediate DO levels (mean = 7.27 mg/l) were recorded for the October-November period.

The pH values were consistent across the survey area in 2008. Mean pH measurements amounted to 8.09 for the June-July sampling period and 7.95 for the August-September sampling period (Table 4). A slightly higher mean pH value of 8.00 was registered for the October-November sampling period.

Secchi measurements were consistent across sampling periods (Table 5). In June-July, the mean Secchi readings amounted to 1.21 m. Slightly lower Secchi values (mean = 1.09 m) were recorded for the August-September sampling period. Highest Secchi recordings (mean = 1.28 m) were compiled during the October-November sampling period.

There was no significant difference in mean temperature, salinity, dissolved oxygen, pH and Secchi disk depth over the course of the study period. However, mean salinity was higher, and dissolved oxygen, pH, and Secchi disk depth lower, during the August-September sampling period compared to the June-July and October-November sampling periods. These trends were not consistent for all previous years of water quality sampling (Kennish et al., 2007b).

Nutrient concentrations in the water column were similar to those recorded in previous years, with low concentrations recorded for dissolved inorganic nitrogen and phosphorus components (nitrate, nitrite, ammonium, and phosphate) (Kennish et al., 2007). Table 6 lists the nutrient concentrations registered in this study. Nitrate plus nitrite levels were low, ranging from a mean of 0.04-0.32 µM, with highest values observed in the October-November period when plant growth was on the decline. These low concentrations reflect the effect of autotrophic uptake during the late spring to summer period. A wider range of ammonium values was recorded, with mean values ranging from 0.30-1.48 µM. Once again, the highest values were observed in the October-November period. These values were consistent with those documented by Seitzinger et al. (2001). The mean total dissolved nitrogen concentrations ranged from 12.73-16.50 µM. Similar to nitrate plus nitrite and ammonium measurements, the mean phosphate values were low, ranging from 0.73-0.78 µM; the highest values were again recorded in the October-November period. Silica ranged from a mean of 8.51-22.0 µM, with the peak levels once again observed in the October-November period.

Seagrass Demographics

Random seagrass samples were collected three times over the June-November period at 80 of the 120 sampling sites to determine seagrass density, biomass, and blade length. In addition, areal cover of seagrass was documented at all 120 sampling sites during all three sampling periods. Diver observations were also made on epiphytic overgrowth on seagrass, as well as macroalgae abundance and areal cover in the seagrass habitat at all sampling sites. Observations were likewise made on occurrence of bay scallops and other epifauna.

Seagrass Distribution

Eelgrass (*Zostera marina*) was far more abundant than widgeon grass in the Barnegat Bay-Little Egg Harbor Estuary, especially in higher salinity areas. Widgeon grass (*Ruppia maritima*) was most abundant in lower salinity areas north of Toms River. Abundance, biomass and areal coverage of *Z. marina* varied considerably both in space and time during the entire study period.

Density

Counts were made of *Zostera marina* density (shoots m^{-2}) over the June-November period. The highest density measurements in 2008 were recorded during the August-September sampling period (mean = 466 shoots m^{-2}). Significantly lower densities of *Z. marina* were registered during the June-July and October-November sampling periods. The lowest mean density value was 239 shoots m^{-2} during the study period.

Aboveground Biomass

Aboveground biomass of *Zostera marina* in the Barnegat Bay-Little Egg Harbor Estuary peaked during the August-September sampling period (mean = 30.83 g dry wt m^{-}

^{2}), with lowest values (mean = 22.91 g dry wt m^{-2}) recorded during the October-November sampling period. Intermediate aboveground biomass values (mean = 25.01 g dry wt m^{-2}) were documented during the June-July period (Table 7). An Analysis of Variance (ANOVA) test used to compare the aboveground biomass values of *Z. marina* among the three sampling periods showed no statistically significant differences (F = 0.48; P = 0.6189) in biomass values among sampling periods (Table 8). These results agreed with a separate non-parametric Kruskal-Wallis test (Table 8.) (Chi square = 4.32, pr > chi = 0.12).

Median biomass values during the three sampling periods were much lower than the mean values because few samples were collected relative to the total number of stations examined for seagrass occurrence. Figure 4 shows box plots of aboveground seagrass biomass values for the three sampling periods. Highest biomass values were observed during the August-September sampling period. Of the 240 stations surveyed for from June to November, only 125 aboveground biomass measurements were recorded. The high percentage of sites with no biomass measurements for all three sampling periods might cause a type II error (fail to reject null hypothesis that there is no difference between aboveground biomass between sampling periods). This is likely due to a systematic decline in seagrass habitat for the entire 2008 sampling period.

The median values of the aboveground and belowground biomass during the June-July sampling period were 0 (Table 9). Very few seagrass samples were collected in Little Egg Harbor during June sampling. The highest median values were found during the August-September sampling period when the median aboveground biomass amounted to 12.49 g dry wt m^{-2} and the median belowground biomass amounted to 27.21

g dry wt m^{-2}. Median aboveground and belowground values during the October-November sampling period amounted to 2.67 g dry wt m^{-2} and 2.26 g dry wt m^{-2}, respectively (Table 9).

During the 2008 study period, the mean aboveground biomass of *Zostera marina* was highest for transect 3 (65.1 g dry wt m^{-2}), transect 7 (54.2 g dry wt m^{-2}), and transect 9 (51.2 g dry wt m^{-2}). The lowest mean aboveground biomass value (1.4 g dry wt m^{-2}) was recorded for transect 12 (Table 10). Figure 5 shows the mean aboveground biomass values for all transects during the six-month survey period.

The biomass data were also assessed on the basis of values recorded at interior transect sites (3, 4, 5, 6, 7, and 8) versus exterior transect sites (1, 2, 9, and 10). The mean aboveground biomass values for the interior transect sampling sites were substantially greater than those recorded at the exterior transect sampling sites (Figure 6). This pattern was consistent with that observed for previous survey years (2004-2006) (Kennish et al., 2007b).

Belowground Biomass

Sampling for belowground biomass was likewise conducted during the three sampling periods between June and November 2008. Belowground biomass decreased sharply during the October-November sampling period, after a period of relatively consistent levels during the June-July and August-September sampling periods. The highest mean belowground biomass of *Z. marina* samples was observed during the June-July sampling period (81.31 g dry wt m^{-2}), and the lowest mean belowground biomass was found during the October-November sampling period (39.86 dry wt m^{-2}). An intermediate mean belowground biomass value was obtained during the August-September sampling period (76.12 g dry wt m^{-2}) (Table 7).

Figure 7 shows box plots of belowground *Z. marina* biomass values for the three sampling periods. Similar to the aboveground biomass values, the highest belowground biomass values were observed during the August-September sampling period. The belowground biomass measurements of *Z. marina* were markedly higher than the aboveground biomass measurements during all three sampling periods in 2008, being two-fold higher during sampling periods 1 and 2 and nearly 50% higher during sampling period 3. An ANOVA test was used to compare belowground biomass values of *Z. marina* between the three sampling periods, and the test showed a statistically significant difference (F = 3.18; P = 0.0434) (Table 11). This result disagreed with a separate non-parametric kruskal wallis test (Table 11) (Chi square = 4.36, pr > chi = 0.11). The high percentage of sites with no biomass for all three sampling periods might cause a type II error (fail to reject null hypothesis that there is no difference between belowground biomass between sampling periods). This is likely due to a systematic decline in seagrass habitat for the entire 2008 sampling period.

Belowground biomass of *Zostera marina* was also investigated in respect to spatial distribution, with mean values determined for the 12 transects in the study area (Table 10, Figure 8). The highest mean belowground biomass (115.5 g dry wt m^{-2}) was recorded for transect 11, with lower but similar levels for transects 3, 4, 5, and 9. The lowest mean belowground biomass values were registered for transects 12 (1.4 g dry wt m^{-2}) and 1 (4.2 g dry wt m^{-2}). As in the case of aboveground biomass values, belowground biomass values were much greater at interior than exterior trasnsect sampling sites, especially during the first two sampling periods (Figure 9).

The aboveground to belowground biomass ratio for *Z. marina* was less than 1.0 for all transects except transects 1 and 12. The ratios ranged from 0.13 (transect 10) to 1.5 (transect 1). These values indicate that the aboveground biomass was consistently less than the belowground biomass along all but two of the transects (Table 10).

Seagrass Blade Length

Table 12 lists the mean length of *Zostera marina* blades recorded during the study period. The highest mean length (19.88 cm) was observed during the October-November sampling period. The mean length of the blades was lowest (14.57 cm) during the August-September sampling period, and slightly higher (15.35 cm) during the June-July sampling period. Blade length values were not significantly different during the sampling periods.

Percent Cover: Seagrass and Macroalgae

The mean percent cover of seagrass during period 1 (June-July), period 2 (August-September), and period 3 (October-November) in 2008 was 23%, 36%, and 27%, respectively (Table 13). Figure 10 shows a box plot of seagrass percent cover for the three sampling periods, with the highest percent cover recorded during the August-September period. Figure 11 shows the percent cover of seagrass by transect. The percent cover was considerably higher at interior transect sampling sites than exterior transect sampling sites for all sampling periods (Figure 12). By comparison, the mean percent cover by macroalgae during these periods was substantially less, averaging 20% (June-July), 10% (August-September), and 5% (October-November) for the study period (Table 13). Figure 13 shows a box plot of macroalgae percent cover for the three sampling periods. The highest percent cover was observed during the June-July sampling period. Considerable variation of macroalgal cover was evident among the transects, particularly between the interior and exterior transect sites. Macroalgal cover was greater at interior than exterior transect sites for the June-July and August-September sampling periods (Figure 14).

Seagrass Experimental Transplantation Plots

Reciprocal transplanting of *Zostera marina* plants was performed between three sites located in the northern, central, and southern segments of the estuary on May 29, 2008 (Figure 3). Two of the sites (northern and central segments) were located in Barnegat Bay, and one site (southern segment), was located in Little Egg Harbor. These sites were selected based on similar physicochemical characteristics (i.e., depth, light penetration, sediment composition, etc.). At each site, nine seagrass samples were extracted from the estuarine bottom sediment using the aforementioned coring device, yielding a total of 27 plugs. Intact plugs were extracted at each site containing complete leaf, root, rhizome, and sediment components with minimal disturbance. All of these samples were inserted into peat pots measuring 8 cm on a side and then placed in coolers. The three sites were subsequently visited the same day in reverse order from north to south (sites 3 – 2 – 1), and the pots were transplanted within hours of collection. At each site, a denuded area was chosen within the seagrass beds and marked with a Garmin

GPSmap 530s. Three plants from each site were then planted in a rigid 1 x 1 m PVC frame designed to demarcate the samples.

The transplantation sites were revisited on September 16, 2008. However, no peat pots were found at sites 1 and 2, having been lost to weather events, high currents, or anthropogenic factors. The peat pots were found only at site 3 on this date, and a subset of the blades were sampled from the peat pots at this location. This site was later visited again on November 12, 2008, and plant blades in five of the peat pots were sampled and measured in the laboratory for length, leaf mass, and nitrogen content. A Nitrogen Pollution Index (NPI) was calculated based on these later measurements (Table 14).

Nitrogen Pollution Index

Seagrass samples were collected at transplantation site 3 to develop a Nitrogen Pollution Index (NPI). The following expression was applied to develop the index:

$$NPI = \frac{\text{Leaf N}}{\text{Normalized Leaf Mass (mg dry wt cm}^{-1}\text{)}}$$

The ratio of leaf nitrogen to leaf mass has been shown to provide an accurate integrated measure of environmental nitrogen exposure by eelgrass in other estuarine systems (Lee et al., 2004).

After removing the subset of seagrass blades from the peat pots, they were placed in a labeled bag, stored on ice in a closed container, and transported back to the Rutgers University Marine Field Station in Tuckerton. In the laboratory, the samples were carefully sorted and separated. Morphometric measurements were made in the laboratory on the plants. Epiphytes were removed from the eelgrass blades, which were then dried. The dried leaf material was subsequently ground and passed through a 40-mesh screen. The tissue from the samples was used to determine leaf N content employing an elemental analyzer. A matrix of values was developed for the eelgrass leaf nitrogen content and assessed for environmental nitrogen exposure which the plants experienced. The NPI values for site 3 are listed in Table 14.

DISCUSSION

The Barnegat Bay-Little Egg Harbor Estuary has been classified as a highly eutrophic system (Bricker et al., 2007; Kennish et al., 2007). Eutrophy of the estuary has been linked to an array of adverse biotic responses, including declining seagrass habitat. Altered biotic community composition and habitat conditions of the estuary associated with progressive eutrophication signal increasing ecosystem disturbance and impairment that must be tracked in order to implement effective remedial measures and circumvent the decline in human use of estuarine resources and amenities. To this end, a seagrass demographic survey was conducted during 2008 to collect data on the following parameters: presence/absence of seagrass and macroalgae, aboveground and belowground biomass of seagrass, density of seagrass, percent cover of seagrass and macroalgae, and seagrass blade length. The same parameters were measured at the same field sites in comprehensive seagrass surveys conducted in the estuary from 2004-2006, enabling comparisons to be made.

A major goal of this long-term work is to examine seagrass responses to nutrient enrichment of the system. In order to achieve this goal, it is important to determine the demographic characteristics as well as the spatial and temporal habitat change of seagrass in the estuary over an annual growing period. Data collected on seagrass demographics in the system are vital for devising remedial plans to restore seagrass habitat in the estuary.

Aboveground and belowground biomass of seagrass beds in the estuary decreased by 50-87.7% over the 2004-2006 period (Kennish et al., 2007b, 2008). Areal coverage, density, and blade length of seagrass also declined markedly over this period. Blooms of drifting macroalgae (e.g., *Ulva lactuca*) periodically produced extensive benthic canopies during this period that posed a serious danger to the seagrass beds by blocking sunlight transmission to the estuarine floor. Rapid growth of other macroalgal species in the estuary, such as the rhodophytes *Ceramium* spp., *Champia parvula*, *Gracilaria tikvahiae*, and *Spyridia filamentosa*, also formed mats of vegetation that appeared to be detrimental. The decomposition of thick macroalgal mats is problematic because it can promote sulfide accumulation and the development of hypoxic/anoxic conditions in bottom sediments that are hazardous to benthic faunal communities.

The decrease in seagrass areal coverage in recent years has eliminated habitat for bay scallops (*Argopecten irradians*), hard clams (*Mercenaria mercenaria*), and other benthic organisms. Blooms of the sea nettle (*Chrysaora quinquecirrha*) have likewise occurred in the estuary since 2000, seriously impairing some areas for human use. In addition, this invasive species has been shown to disrupt estuarine food webs by grazing heavily on zooplankton, thereby truncating energy flow to upper trophic level organisms. It is a species that also thrives in eutrophic estuaries, such as tributary systems of Chesapeake Bay and the Barnegat Bay-Little Egg Harbor Estuary (especially north of

Toms River). Nitrogen over-enrichment, when unchecked, causes significant deterioration of sediment and water quality, loss of biodiversity, and disruption of ecosystem health and function (Nixon, 1995; Nixon et al., 2001; Kennish et al., 2007a). There is growing concern that escalating eutrophication can lead to severe, long-term degradation of the structure and function of the Barnegat Bay-Little Egg Harbor system. Hence, seagrass surveys were continued in 2008 because seagrass beds are an important indicator of overall water and sediment quality conditions.

Results of the 2008 seagrass survey in the estuary yielded a number of important findings. Data collected on seagrass demographics indicate that the beds in 2008 have yet to recover from the marked decline of seagrass abundance and biomass observed in 2006. Seagrass in the estuary has decreased significantly since 2004 when seagrass beds exhibited much greater abundance and biomass. In 2008, seagrass was found at less than 50% of the survey sites (46.3%) during the June-July sampling period when the median aboveground and belowground biomass values were 0. The fewest number of seagrass samples were recovered in Little Egg Harbor.

The biomass of *Zostera marina* in the estuary typically peaks during the June-September period as evidenced by data collected during the 2004-2006 and 2008 years of sampling. In 2008, the mean aboveground biomass was highest in August-September (30.93 g dry wt m^{-2}), and the mean belowground biomass was highest in June-July (81.31 g dry wt m^{-2}). Over the entire June-November sampling period, the mean aboveground biomass declined slightly from 25.01 g dry wt m^{-2} to 22.91 g dry wt m^{-2}, while the mean belowground biomass decreased markedly (by 51%) from 81.31 g dry wt m^{-2} to 39.86 g dry wt m^{-2}. The aboveground biomass values were low throughout the 2008 study period, and this explains in part only a modest decline in aboveground biomass (9.2%) recorded at this time.

A progressive reduction of seagrass biomass was evident over the 2004-2006 sampling periods, with the losses being most acute during 2006 (Kennish et al., 2007b). Thus, conditions of diminished seagrass abundance appear to have continued through 2008, although the levels of decline were greatest in 2006. Between 2004 and 2006, the mean aboveground biomass of *Zostera marina* along six transects (1-6) in Little Egg Harbor decreased 87.7% from 59.62 g dry wt m^{-2} to 7.31 g dry wt m^{-2}, and the mean belowground biomass declined 59.4% from 75.60 g dry wt m^{-2} to 30.69 g dry wt m^{-2}. Similarly, along six transects (7-12) in Barnegat Bay between 2005 and 2006, the mean aboveground biomass of *Z. marina* declined 50% from 32.04 g dry wt m^{-2} to 16.03 g dry wt m^{-2}, and the mean belowground biomass decreased 52.4% from 84.59 g dry wt m^{-2} to 40.25 g dry wt m^{-2}. The decline in seagrass biomass was estuary-wide in 2006. The mean biomass values of *Z. marina* in 2006 rank among the lowest mean annual biomass values ever recorded for this species in the estuary. They appear to be linked to increasing eutrophic impacts in the system associated with nuisance algal blooms, shading, and bottom disturbances.

The biomass of *Zostera marina* generally peaked during the June-July sampling period. For example, the maximum mean aboveground and belowground biomass of *Z. marina* in Little Egg Harbor in 2004 (the sampling year exhibiting best seagrass conditions) occurred during the June-July period, amounting to 106.05 g dry wt m^{-2} and 107.64 g dry wt m^{-2}, respectively. The biomass values subsequently declined during the ensuing August-September period (mean aboveground biomass = 54.61 g dry wt m^{-2};

mean belowground biomass = 68.69 g dry wt m^{-2}) and October-November period (mean aboveground biomass = 18.22 g dry wt m^{-2}; mean belowground biomass = 50.48 g dry wt m^{-2}).

In 2005, the maximum mean aboveground biomass (51.69 g dry wt m^{-2}) and belowground biomass (141.95 g dry wt m^{-2}) of *Zostera marina* in Barnegat Bay were also recorded during the June-July period. Lower mean aboveground and belowground biomass measurements were found during the August-September period, amounting to 28.79 g dry wt m^{-2} and 69.03 g dry wt m^{-2}, respectively. Even lower mean aboveground and belowground biomass measurements were recorded during the October-November period, equaling 15.66 g dry wt m^{-2} and 42.78 g dry wt m^{-2}, respectively. Over the 2005 study period, both the aboveground and belowground biomass values of *Z. marina* decreased by more than 69%.

The mean aboveground biomass of *Zostera marina* in Barnegat Bay-Little Egg Harbor in 2006 peaked during the August-September period (mean = 13.77 g dry wt m^{-2}). In contrast, the mean belowground biomass was a maximum during the June-July period (51.54 g dry wt m^{-2}). A consistent seasonal decline in belowground biomass was evident in 2006 from a mean of 51.54 g dry wt m^{-2} in June-July, 36.08 g dry wt m^{-2} in August-September, and 24.23 g dry wt m^{-2} in October-November. The aboveground biomass did not exhibit a similar seasonal decline in 2006.

An Analysis of Variance (ANOVA) and a separate non-parametric Kruskal-Wallis test was used to compare aboveground biomass values of *Zostera marina* in Little Egg Harbor for sampling years 2004, 2006, and 2008. This test showed statistically significant differences ($F = 35.44$; $P < 0.0001$) among years. Results of the Kruskal

Kruskal-Wallis non-parametric test corroborate the ANOVA results (Chi-Square = 77.30 and pr > ch = 0.00001). A Tukey HSD test applied to the data revealed that all mean aboveground biomass values per sampling year were significantly different (Table 15). Application of a Wilcoxon Rank Sum Test revealed significant differences (P < 0.95) in aboveground biomasses between sampling years 2004 and 2006, 2006 and 2008, and 2004 and 2008 (Table 15).

An Analysis of Variance (ANOVA) test was used to compare belowground biomass values of *Zostera marina* in Little Egg Harbor for sampling years 2004, 2006, and 2008. This test showed statistically significant differences (F = 5.93; P < 0.0029) among years. Results of the Kruskal-Wallis non-parametric test concur with the ANOVA results (Chi-Square = 30.30 and pr > ch = 0.0001). Application of a Wilcoxon Rank Sum Test revealed significant differences (P < 0.95) in belowground biomasses between sampling years 2004 and 2006, 2006 and 2008, and 2004 and 2008 (Table 16).

An Analysis of Variance (ANOVA) test was used to compare aboveground biomass values of *Zostera marina* in Barnegat Bay for sampling years 2004, 2006, and 2008. This test showed statistically significant differences (F = 4.63; P < 0.0104) among years using the ANOVA test. A separate non-parametric Kruskal-Wallis test failed to reject the null hypothesis (Chi-Square = 3.74 and pr > ch = <.154). The non-parametric test weighs all sites equally, including sites which have no seagrass across the entire sampling period. We believe the result is too conservative, causing a type II error failure to reject the null hypothesis. Application of a Wilcoxon Rank Sum Test revealed significant differences (P < 0.95) in aboveground biomasses between sampling years

2005 and 2006, and 2006 and 2008. No statistically significant differences were found between aboveground biomass values for 2005 and 2008 (Table 17).

An Analysis of Variance (ANOVA) test was used to compare belowground biomass values of *Zostera marina* in Barnegat Bay for sampling years 2005, 2006, and 2008. This test showed statistically significant differences ($F = 5.52$; $P < 0.0044$) among years. A separate non-parametric Kruskal-Wallis test failed to reject the null hypothesis (Chi-Square = 4.58 and pr > ch = <.10). The non-parametric test weighs all sites equally including sites which have no seagrass across the entire sampling period. We believe the result is too conservative, resulting in a type II error failure to reject the null hypothesis. Application of a Wilcoxon Rank Sum Test revealed significant differences ($P < 0.95$) in belowground biomasses between sampling years 2005 and 2006, but no significant differences between sampling years 2005 and 2008, and sampling years 2006 and 2008 (Table 18).

The density of *Zostera marina* ranged from 239-466 shoots m^{-2} during 2008. Peak density of *Z. marina* occurred during the August-September period when the aboveground biomass also peaked. The density range of the plants was similar to that in 2005 (163-479 m^{-2}) but greater than that in 2006 (171-378 shoots m^{-2}).

The blade length of *Zostera marina* was relatively consistent during 2008, with mean values amounting to 15.35 cm in June-July, 14.57 cm in August-September, and 19.88 cm in October-November. By comparison with the previous years of sampling from 2004-2006, the blade lengths during 2008 were the shortest on record, even when compared to the heavily impacted year of 2006. For example, the mean blade length of *Z. marina* in Little Egg Harbor during 2004 was 34.02 cm in June-July, 32.21 cm in

August-September, and 31.83 cm in October-November. The mean blade length of *Z. marina* in Barnegat Bay during 2005 amounted to 32.71 cm in June-July, 25.89 cm in August-September, and 28.47 cm in October-November. In 2006, the mean blade length of *Z. marina* in the estuary was 19.37 cm in June-July, 18.65 cm in August-September, and 18.61 cm in October-November. The reduced growth during 2006 correlated with lower shoot density and biomass measurements at this time as well.

The nitrogen content of *Zostera marina* blades measured at field transplantation sites ranged from 2.97% to 4.33%. These values are similar to those measured by Lee et al. (2004) in seagrasses of Waquoit Bay and two other estuaries systems. Nitrogen Pollution Index values calculated for the *Z. marina* in the Barnegat Bay-Little Egg Harbor Estuary based in part on the leaf nitrogen content ranged from 0.58 to 2.55.

The percent cover of seagrass was similar to that observed in previous years of sampling. For example, the percent cover of seagrass in the study area progressively declined over the June-November period for all years of sampling except 2008, dropping from 45% to 21% in 2004, 43% to 16% in 2005, and 32% and 19% in 2006. In 2008, however, the percent cover of seagrass was lowest in June-July (23%), highest in August-September (36%), and intermediate in October-November (27%).

Seagrass biomass, density, and areal cover in 2008 were higher at exterior transect sampling sites (1, 2, 9, and 10) than at interior transect sampling sites (3, 4, 5, 6, 7, and 8). These values are consistent with those recorded during 2004, 2005, and 2006. This pattern indicates that seagrasses located near the margin of their distribution are more likely to be exposed to less optimal conditions for growth and survival.

The percent cover of macroalgae in 2008 was significantly lower than that of seagrass, declining markedly from June to November. The mean percent cover of macroalgae declined from 20% during the June-July period to 10% during the August-September period and 5% during the October-November period. By comparison, the percent cover of macroalgae in Little Egg Harbor in 2004 increased from 13% to 21% from June to September and then decreased to 14% in November. In Barnegat Bay during 2005, macroalgal areal coverage dropped from 14% in June-July to 2% in October-November. In 2006, the percent cover of macroalgae in the estuary increased from 2% during the June-July period to 7% during the October-November period. Macroalgae completely covered extensive areas of the bay bottom during blooms, particularly when comprised of sheet-like forms such as *Ulva lactuca*, as was the case in Little Egg Harbor in 2004. These blooms appear to cause significant dieback of seagrass in some areas of the estuary. Although macroalgae coverage of bay bottom is less than seagrass coverage over an entire season, blooms of macroalgae can form spikes in the database completely blanketing seagrass beds over extensive areas during specific times of the year.

SUMMARY AND CONCLUSIONS

Barnegat Bay-Little Egg Harbor Estuary is a highly eutrophic lagoonal estuary. Symptom expressions of eutrophication include low dissolved oxygen, particularly in the northern perimeter, declining seagrass habitat, epiphytic overgrowth, nuisance/toxic algal blooms, and markedly reduced fisheries (i.e., hard clams). Seagrass beds in this coastal lagoon have exhibited degraded conditions for years (Bricker et al., 1999, 2001; Kennish, 2001, 2007a), and based on surveys conducted in 2004-2006 and 2008, declining conditions appear to be worsening. Extensive areas of the northern estuary have recently (2008) experienced low dissolved oxygen levels. The aboveground and belowground biomass of seagrass in the estuary decreased by 50-87.7% over the 2004-2006 period, underscoring the ongoing degradation. Seagrass density, blade length, and areal cover also showed statistically significant reductions over this three-year period (Kennish et al., 2007b). Accelerated growth of drifting macroalgae (e.g., *Ulva lactuca*) has periodically caused extensive benthic mats that have attenuated light, leading to detrimental conditions for seagrass growth and survival. Acute events were observed in 2004 as well as in other years. Aside from sea lettuce impacts, rapid growth of other macroalgal species in the estuary, such as the rhodophytes *Ceramium* spp., *Champia parvula*, *Gracilaria tikvahiae*, and *Spyridia filamentosa* also appear to be detrimental. The decrease in seagrass areal coverage has eliminated essential habitat for bay scallops, hard clams (*Mercenaria mercenaria*), and many other benthic organisms. Blooms of the sea nettle (*Chrysaora quinquecirrha*), possibly coupled to increasing eutrophic conditions, have likewise occurred in the estuary since 2000. The aforementioned changes signal ongoing disruption of ecosystem structure and function.

The biomass of seagrass beds in the Barnegat Bay-Little Egg Harbor during 2008 sampling exhibited important temporal and spatial patterns similar to those reported for the 2004-2006 period. The density as well as the aboveground and belowground biomass of seagrass varied considerably during the spring to fall period, but were generally highest during the June-September period as in previous seagrass demographic surveys.

In 2008, the mean aboveground biomass was highest in August-September (30.93 g dry wt m^{-2}), and the mean belowground biomass was highest in June-July (81.31 g dry wt m^{-2}). Over the entire June-November sampling period, the mean aboveground biomass declined slightly from 25.01 g dry wt m^{-2} to 22.91 g dry wt m^{-2}, while the mean belowground biomass decreased markedly (by 51%) from 81.31 g dry wt m^{-2} to 39.86 g dry wt m^{-2}. The aboveground biomass values were low throughout the 2008 study period. Seagrass was found at less than 50% of the survey sites (46.3%) sampled during the June-July sampling period in 2008 when the median aboveground and belowground biomass values were 0. The fewest number of seagrass samples were recovered at the Little Egg Harbor sampling sites. These data indicate that seagrass habitat conditions have not recovered from the devastating losses in 2006.

The density of *Zostera marina* ranged from 239-466 shoots m^{-2} during 2008. Peak density of *Z. marina* occurred during the August-September period when the aboveground biomass also peaked. The density range of the plants was similar to that in 2005 (163-479 m^{-2}) but greater than that in 2006 (171-378 shoots m^{-2}).

The blade length of *Zostera marina* was relatively consistent during 2008, with mean values amounting to 15.35 cm in June-July, 14.57 cm in August-September, and 19.88 cm in October-November. By comparison with the previous years of sampling from 2004-2006, the blade lengths during 2008 were the shortest on record, even when compared to the heavily impacted year of 2006. For example, the mean blade length of *Z. marina* in Little Egg Harbor during 2004 was 34.02 cm in June-July, 32.21 cm in August-September, and 31.83 cm in October-November. The mean blade length of *Z. marina* in Barnegat Bay during 2005 amounted to 32.71 cm in June-July, 25.89 cm in

August-September, and 28.47 cm in October-November. In 2006, the mean blade length of *Z. marina* in the estuary was 19.37 cm in June-July, 18.65 cm in August-September, and 18.61 cm in October-November. The nitrogen content of eelgrass blades measured during the surveys in 2008 ranged from 2.97% to 4.33%.

The percent cover of seagrass in the study area gradually declined over the June-November period for all years of sampling except 2008, dropping from 45% to 21% in 2004, 43% to 16% in 2005, and 32% and 19% in 2006. In 2008, the percent cover of seagrass was lowest in June-July (23%), highest in August-September (36%), and intermediate in October-November (27%). The June-July period in 2008 was much different than previous years of sampling (2004-2006) with much less aboveground seagrass being present.

Seagrass grow best away from the bed border areas. For example, seagrass biomass, density, and areal cover in 2008 were higher at exterior transect sampling sites (1, 2, 9, and 10) than at interior transect sampling sites (3, 4, 5, 6, 7, and 8). These values are consistent with those measured during 2004, 2005, and 2006. This pattern indicates that seagrasses located near the margin of their distribution are more likely to be exposed to less optimal conditions for growth and survival.

Macroalgae percent cover decreased significantly from June to November in 2008. For example, the mean percent cover of macroalgae declined from 20% during the June-July period to 10% during the August-September period and 5% during the October-November period. During bloom conditions, macroalgae completely cover extensive areas of the estuarine floor, which can impact seagrass abundance and distribution due to the attenuation of sunlight.

REFERENCES

Bologna, P. A. X., R. Lathrop, P. D. Bowers, and K. W. Able. 2000. Assessment of the Health and Distribution of Submerged Aquatic Vegetation from Little Egg Harbor, New Jersey. Technical Report, Contribution #2000-11, Institute of Marine and Coastal Sciences, Rutgers University, New Brunswick, New Jersey. 30 pp.

Bricker S. B., C. G. Clement, D. E. Pirhalla, S. P., Orlando, and D. R. G. Farrow, D. 1999. National Estuarine Eutrophication Assessment: Effects of Nutrient Enrichment in the Nation's Estuaries. NOAA, National Ocean Service, Special Projects Office and National Centers for Coastal Ocean Science, Silver Spring, Maryland, USA.

Bricker, S. B., B. Longstaff, W. Dennison, A. Jones, K Boicourt, C. Wicks, and J. Woerner. 2007. Effects of Nutrient Enrichment in the Nation's Estuaries: A Decade of Change. NOAA, National Ocean Service, Special Projects Office and National Centers for Coastal Ocean Science, Silver Spring, Maryland, USA.

Gastrich, M. D., R. Lathrop, S. Haag, M. P. Weinstein, M. Danko, D. A. Caron, and R. Schaffner. 2004. Assessment of brown tide blooms, caused by *Aureococcus anophagefferans*, and contributing factors in New Jersey coastal bays: 2000-2002. *Harmful Algae* 3: 305-320.

Kennish, M. J. (ed.). 2001. Barnegat Bay-Little Egg Harbor, New Jersey: Estuary and Watershed Assessment. Journal of Coastal Research, Special Issue 32, 280 pp.

Kennish, M. J., S. B. Bricker, W. C. Dennison, P. M. Glibert, R. J. Livingston, K. A. Moore, R. T. Noble, H. W. Paerl, J. M. Ramstack, S. Seitzinger, D. A. Tomasko, and I. Valiela. 2007a. Barnegat Bay-Little Egg Harbor Estuary: case study of a highly eutrophic coastal bay system. *Ecological Applications* 17(5) Supplement: S3-S16.

Kennish, M. J., S. M. Haag, and G. P. Sakowicz. 2007b. Demographic Investigation of SAV in the Barnegat Bay-Little Egg Harbor Estuary with Assessment of Potential Impacts of Benthic Macroalgae and Brown Tides. Technical Report 107-15, Institute of Marine and Coastal Sciences, Rutgers University, New Brunswick, New Jersey. 366 pp.

Kennish, M. J. 2009. Assessment of Eutrophication in the Barnegat Bay-Little Egg Harbor System: Use of SAV Biotic Indicators of Estuarine Condition. Quality Assurance Project Plan (QAPP) – Version 1.0. New Jersey Department of Environmental Protection, Trenton, New Jersey. 32 pp.

Lamote, M. and K. H. Dunton. 2006. Effects of drift macroalgae and light attenuation in chlorophyll fluorescence and sediment sulfides in the seagrass *Thalassia testudinum*. *Journal of Experimental Marine Biology and Ecology* 334: 174-186.

Lathrop, R. G., R. Styles, S. Seitzinger, and J. Bognar. 2001. Use of GIS mapping and modeling approaches to examine the spatial distribution of seagrasses in Barnegat Bay, New Jersey. *Estuaries* 24: 904-916.

Lathrop, R. G., P. Montesano, and S. Haag. 2006. A multi-scale segmentation approach to mapping seagrass habitats using airborne digital camera imagery. *Photogrammetric Engineering and Remote Sensing* 72: 665-675.

Lee, D-S., F. T. Short, D. M. Burdick. 2004. Development of a nutrient pollution indicator using the seagrass, *Zostera marina*, along nutrient gradients in three New England estuaries. *Aquatic Botany* 78: 197-216.

McClain, P. and M. McHale. 1997. Barnegat Bay eelgrass investigation 1995-96. In: Flimlin, G. E. and Kennish, M. J. (eds.), Proceedings of the Barnegat Bay Ecosystem Workshop. Rutgers Cooperative Extension of Ocean County, Toms River, New Jersey, pp. 165-171.

Nixon, S. W. 1995. Coastal eutrophication: a definition, social causes, and future concerns. *Ophelia* 41: 199-220.

Olsen, P. S. and J. B. Mahoney. 2001. Phytoplankton in the Barnegat Bay-Little Egg Harbor estuarine system: species composition and picoplankton bloom development. *Journal of Coastal Research*, Special Issue 32, pp. 115-143.

Orth, R. J., T. J. B. Carruthers, W. C. Dennison, C. M. Duarte, J. W. Fourqurean, K. L. Heck, Jr., A. R. Hughes, G. A. Kendrick, W. J. Kenworthy, S. Olyarnik, F. T. Short, M. Waycott, and S. L. Williams. 2006. A global crisis for seagrass ecosystems. *BioScience* 56: 987-996.

Rabalais, N. N. 2002. Nitrogen in aquatic ecosystems. Ambio 21: 102-112.

Seitzinger, S. P., R. M. Styles, and I. E. Pilling. 2001. Benthic microalgal and phytoplankton production in Barnegat Bay, New Jersey (USA): microcosm experiments and data synthesis. *Journal of Coastal Research*, Special Issue 32, pp. 144-162.

Short, F. T., L. J. McKenzie, R. G. Coles, and K. P. Vidler. 2002. SeagrassNet Manual for Scientific Monitoring of Seagrass Habitat. (QDPI, QFS, Cairns). 56 pp.

Valiela, I. 2006. Global Climate Change. Blackwell Publishing, Oxford, England.

Table 1. Mean water temperatures recorded at the seagrass survey sites in the Barnegat Bay-Little Egg Harbor Estuary during three sampling periods in 2008.

Sample Period	Mean Temperature (ºC)	Standard Deviation
1	23.37	3.63
2	23.99	1.06
3	19.08	2.21

Sample Period 1 = June-July
Sample Period 2 = August-September
Sample Period 3 = October-November

Table 2. Mean salinity values recorded at the seagrass survey sites in the Barnegat Bay-Little Egg Harbor Estuary during three sampling periods in 2008.

Sample Period	Mean Salinity (ppt)	Standard Deviation
1	26.39	3.38
2	28.22	2.74
3	26.17	5.56

Sample Period 1 = June-July
Sample Period 2 = August-September
Sample Period 3 = October-November

Table 3. Mean dissolved oxygen levels recorded at the seagrass survey sites in the Barnegat Bay-Little Egg Harbor Estuary during three sampling periods in 2008.

Sample Period	Mean Dissolved Oxygen (mg L^{-1})	Standard Deviation
1	7.33	1.07
2	6.55	0.98
3	7.27	1.06

Sample Period 1 = June-July
Sample Period 2 = August-September
Sample Period 3 = October-November

Table 4. Mean pH values recorded at the seagrass survey sites in the Barnegat Bay-Little Egg Harbor Estuary during three sampling periods in 2008.

Sample Period	pH	Standard Deviation
1	8.09	0.20
2	7.95	0.27
3	8.00	0.15

Sample Period 1 = June-July
Sample Period 2 = August-September
Sample Period 3 = October-November

Table 5. Mean Secchi depth (m) recorded at the seagrass survey sites in the Barnegat Bay-Little Egg Harbor Estuary during three sampling periods in 2008 when the Secchi was not unlimited.

Sample Period	Secchi (meters)	Number of Samples	Standard Deviation
1	1.21	20	0.26
2	1.09	29	0.21
3	1.28	41	0.41

Sample Period 1 = June-July
Sample Period 2 = August-September
Sample Period 3 = October-November

Table 6. Nutrient values recorded in the seagrass survey areas of the Barnegat Bay-Little Egg Harbor Estuary during the June to November study period in 2008.[1]

Sample Period	NO_3^- plus NO_2^-	Number of Samples	Standard Deviation
1	0.20	48	1.42
2	0.04	48	0.10
3	0.32	48	0.44

Sample Period	NH_4^+	Number of Samples	Standard Deviation
1	0.30	48	0.46
2	0.72	48	0.78
3	1.48	48	1.23

Sample Period	TDN	Number of Samples	Standard Deviation
1	12.73	48	2.10
2	15.72	48	3.99
3	16.50	48	2.83

Sample Period	PO_4	Number of Samples	Standard Deviation
1	0.73	48	0.41
2	0.77	48	0.36
3	0.78	48	0.20

Sample Period	Si	Number of Samples	Standard Deviation
1	8.51	48	6.86
2	13.06	48	11.50
3	22.00	48	18.08

[1]Nutrient values in µM

Table 7. Mean aboveground and belowground biomass of *Zostera marina* in the Barnegat Bay-Little Egg Harbor Estuary during the June-November 2008 period. [1]

Species	Sample Period	Aboveground Biomass	Belowground Biomass	Number of Shoots
Z. marina	1	25.01 (67.32)	81.31 (166.87)	239(436)
Z. marina	2	30.83 (41.92)	76.12 (93.88)	466(585)
Z. marina	3	22.91 (44.56)	39.86 (55.36)	297(483)

Sample Period 1 = June-July
Sample Period 2 = August-September
Sample Period 3 = October-November

[1]Nutrient values in g dry wt m^{-2}

Standard deviation values in parentheses

Table 8. Analysis of Variance (ANOVA) and Tukey test for aboveground biomass of *Zostera marina* during three sampling periods in 2008.

ANOVA F-Value	ANOVA P-Value
0.48	0.6189

Kruskal-Wallis Chi-Square	Pr > Chi
4.32	0.12

Tukey Grouping	N	Sample Period
A	80	1
A	80	2
A	80	3

Sample Period 1 = June-July
Sample Period 2 = August-September
Sample Period 3 = October-November

Table 9. Median aboveground and belowground biomass of *Zostera marina* in the Barnegat Bay-Little Egg Harbor Estuary during the June-November 2008 period.[1]

Species	Sample Period	Aboveground Biomass	Belowground Biomass
Z. marina	1	0	0
Z. marina	2	12.49	27.21
Z. marina	3	2.67	2.26

Sample Period 1 = June-July
Sample Period 2 = August-September
Sample Period 3 = October-November

[1]Values in g dry wt m^{-2}

Table 10. Mean aboveground and belowground biomass of *Zostera marina* along 12 sampling transects in the Barnegat Bay-Little Egg Harbor Estuary during the June-November period in 2008. [1]

Transect	Mean Aboveground Biomass	Mean Belowground Biomass
12	1.4 (3.4)	1.4 (4.3)
11	26.4 (26.0)	115.5 (168.5)
10	7.3 (14.1)	55.8 (154.2)
9	51.2 (77.1)	108.8 (141.6)
8	26.2 (43.3)	29.4 (50.8)
7	54.2 (53.8)	74.1 (73.2)
6	33.6 (42.8)	89.6 (68.7)
5	22.6 (30.0)	99.4 (107.9)
4	11.4 (15.3)	93.5 (130.7)
3	65.1 (115.8)	97.8 (171.4)
2	16.1 (39.5)	17.0 (36.4)
1	6.5 (20.3)	4.2 (14.6)

[1]Values in g dry wt m^{-2}

Standard deviation in parentheses

Table 11. Analysis of Variance (ANOVA) and Tukey test for belowground biomass of *Zostera marina* during three sampling periods in 2008.

ANOVA F-Value	ANOVA P-Value
3.18	0.0434

Kruskal-Wallis Chi-Square	Pr > Chi
4.36	0.11

Tukey Grouping	N	Sample Period
A	80	1
A	80	2
A	80	3

Sample Period 1 = June-July
Sample Period 2 = August-September
Sample Period 3 = October-November

Standard deviation in parentheses

Table 12. The mean length of *Zostera marina* blades measured at all sampling sites in the Barnegat Bay-Little Egg Harbor Estuary during the June-November period in 2008.

Sample Period	Blade Length (cm)	Standard Deviation
1	15.35	17.90
2	14.57	15.31
3	19.88	20.72

Table 13. Percent cover of seagrass and macroalgae on the Barnegat Bay-Little Egg Harbor estuarine floor during three sampling periods in 2008.

Sample Period	Percent Cover Seagrass (std dev)	Percent Sites with Seagrass	Percent Cover Macroalgae (std dev)
1	23% (30.4)	52%	20% (29.0)
2	36% (38.4)	62%	10% (9.6)
3	27% (32.0)	58%	5% (7.9)

Sample Period 1 = June-July
Sample Period 2 = August-September
Sample Period 3 = October-November

Table 14. Leaf nitrogen concentrations and Nitrogen Pollution Index values for seagrass at transplantation site 1 in the Barnegat Bay-Little Egg Harbor Estuary during 2008.

Site	mg	cm²	% nitrogen mean	NPI
Transplant 1(3-4)	2.1	0.88	4.33	1.82
Transplant 1(3-1)	3.2	2.06	3.92	2.52
Transplant 1(2-4)	5.2	0.83	3.62	0.58
Transplant 1(2-5)	4.3	1.76	2.97	1.22
Transplant 1(2-9)	3.6	1.07	4.11	1.22

mg = normalized leaf mass (mg dry wt cm^{-1})

% nitrogen mean = mean % nitrogen

NPI = nitrogen pollution index

Table 15. Analysis of Variance (ANOVA), Tukey Test, and Wilcoxon Rank Sum Test for aboveground biomass of *Zostera marina* in Little Egg Harbor for sampling years 2004, 2006, 2008.

ANOVA F-Value	ANOVA P-Value
35.44	.00001

Kruskal-Wallis Chi-Square	Pr > Chi
77.30	.00001

Tukey Grouping	Mean	Median	N	Sample Period
A	61.94	39.14	120	2004
B	8.25	1.19	120	2006
C	25.78	2.88	120	2008

Wilcoxon Rank Sum Test Model	P-value	Bonferroni Adjusted P-value	Significant at 95% CI
2004 ~ 2006	1.132427e-14	3.397282e-14	*
2006 ~ 2008	0.0001390108	0.0004170324	*
2004 ~ 2008	1.222440e-08	3.667321e-08	*

Table 16. Analysis of Variance (ANOVA) and Wilcoxon Rank Sum Test for belowground biomass of *Zostera marina* in Little Egg Harbor for sampling years 2004, 2006, and 2008.

ANOVA F-Value	ANOVA P-Value
5.93	.0029

Kruskal-Wallis Chi-Square	Pr > Chi
30.33	<.0001

Wilcoxon Rank Sum Test Model	P-value	Bonferroni Adjusted P-value	Significant at 95% CI
2004 ~ 2006	3.088e-10	9.265302e-10	*
2006 ~ 2008	0.001364	0.004091573	*
2004 ~ 2008	0.007416	0.02224860	*

Table 17. Analysis of Variance (ANOVA) and Wilcoxon Rank Sum Test for aboveground biomass of *Zostera marina* in Barnegat Bay for sampling years 2005, 2006, and 2008.

ANOVA F-Value	ANOVA P-Value
4.63	.0104

Kruskal-Wallis Chi-Square	Pr > Chi
3.74	<.154

Wilcoxon Rank Sum Test Model	P-value	Bonferroni Adjusted P-value	Significant at 95% CI
2005 ~ 2006	0.0002465341	0.0007396022	*
2006 ~ 2008	0.005344628	0.01603388	*
2005 ~ 2008	0.3415674	1.024702	no

Table 18. Analysis of Variance (ANOVA) and Wilcoxon Rank Sum Test for belowground biomass of *Zostera marina* in Barnegat Bay for sampling years 2005, 2006, and 2008.

ANOVA F-Value	ANOVA P-Value
5.52	0.0044

Kruskal-Wallis Chi-Square	Pr > Chi
4.58	0.10

Wilcoxon Rank Sum Test Model	P-value	Bonferroni Adjusted P-value	Significant at 95% CI
2005 ~ 2006	7.852718e-05	0.0002355815	*
2006 ~ 2008	0.1195	0.358749	no
2005 ~ 2008	0.0503	0.1509	no

Figure Captions

Figure 1. Map of New Jersey showing the location of the Barnegat Bay-Little Egg Harbor Estuary. Inset shows the location of the estuary with respect to the State of New Jersey.

Figure 2. Map of the estuarine study area. Note disjunct seagrass beds, Transects (1-12), and sampling sites along transects. Inset shows the location of the study area with respect to the State of New Jersey.

Figure 3. Seagrass transplantation sites (1-3) in the Barnegat Bay-Little Egg Harbor Estuary during the 2008 study period.

Figure 4. Box plots showing aboveground biomass values of *Zostera marina* samples collected in the Barnegat Bay-Little Egg Harbor Estuary during all three sampling periods in 2008. Highest values were observed during the August-September sampling period. Sampling period 1, June-July; sampling period 2, August-September; and sampling period 3, October-November.

Figure 5. Mean aboveground biomass of *Zostera marina* at 12 transects in the Barnegat Bay-Little Egg Harbor Estuary during three sampling periods in 2008. Sampling period 1, June-July; sampling period 2, August-September; and sampling period 3, October-November.

Figure 6. Mean aboveground biomass of *Zostera marina* at interior sampling sites (3, 4, 5, 6, 7, and 8) and exterior sampling sites (1, 2, 9, and 10) on transects in the Barnegat Bay-Little Egg Harbor Estuary during three sampling periods in 2008. Sampling period 1, June-July; sampling period 2, August-September; and sampling period 3, October-November.

Figure 7. Box plots showing belowground biomass of *Zostera marina* samples collected in the Barnegat Bay-Little Egg Harbor Estuary during three sampling periods in 2008. Highest values were observed during the August-September sampling period. Sampling period 1, June-July; sampling period 2, August-September; and sampling period 3, October-November.

Figure 8. Mean belowground biomass of *Zostera marina* at 12 transects in the Barnegat Bay-Little Egg Harbor Estuary during three sampling periods in 2008. Sampling period 1, June-July; sampling period 2, August-September; and sampling period 3, October-November.

Figure 9. Mean belowground biomass of *Zostera marina* at interior sampling sites (3, 4, 5, 6, 7, and 8) and exterior sampling sites (1, 2, 9, and 10) on transects in the Barnegat Bay-Little Egg Harbor Estuary during three sampling periods in 2008. Sampling period 1, June-July; sampling period 2, August-September; and sampling period 3, October-November.

Figure 10. Box plots showing percent cover of seagrass at sampling sites in the Barnegat Bay-Little Egg Harbor Estuary during three sampling periods in 2008. Highest values were observed during the August-September sampling period. Sampling period 1, June-July; sampling period 2, August-September; and sampling period 3, October-November.

Figure 11. Mean percent cover of eelgrass at 12 transects in the Barnegat Bay-Little Egg Harbor Estuary during three sampling periods in 2008. Sampling period 1, June-July; sampling period 2, August-September; and sampling period 3, October-November.

Figure 12. Mean percent cover of eelgrass at interior sampling sites (3-8) and exterior sampling sites (1, 2, 9, and 10) on transects in the Barnegat Bay-Little Egg Harbor Estuary during three sampling periods in 2008. Sampling period 1, June-July; sampling period 2, August-September; and sampling period 3, October-November.

Figure 13. Box plots showing the percent cover of macroalgae at all sampling sites in the Barnegat Bay-Little Egg Harbor Estuary during three sampling periods in 2008. Highest values were observed during the June-July sampling period. Sampling period 1, June-July; sampling period 2, August-September; and sampling period 3, October-November.

Figure 14. Mean percent cover of macroalgae at interior sampling sites (3-8) and exterior sampling sites (1, 2, 9, and 10) on transects in the Barnegat Bay-Little Egg Harbor Estuary during three sampling periods in 2008. Sampling period 1, June-July; sampling period 2, August-September; and sampling period 3, October-November.

Figure 15. Sediment composition recorded at the seagrass sampling sites in the Barnegat Bay-Little Egg Harbor Estuary during the June-November survey period of 2005 and 2006. Values are shown as percent sand, silt, and clay at each sampling site.

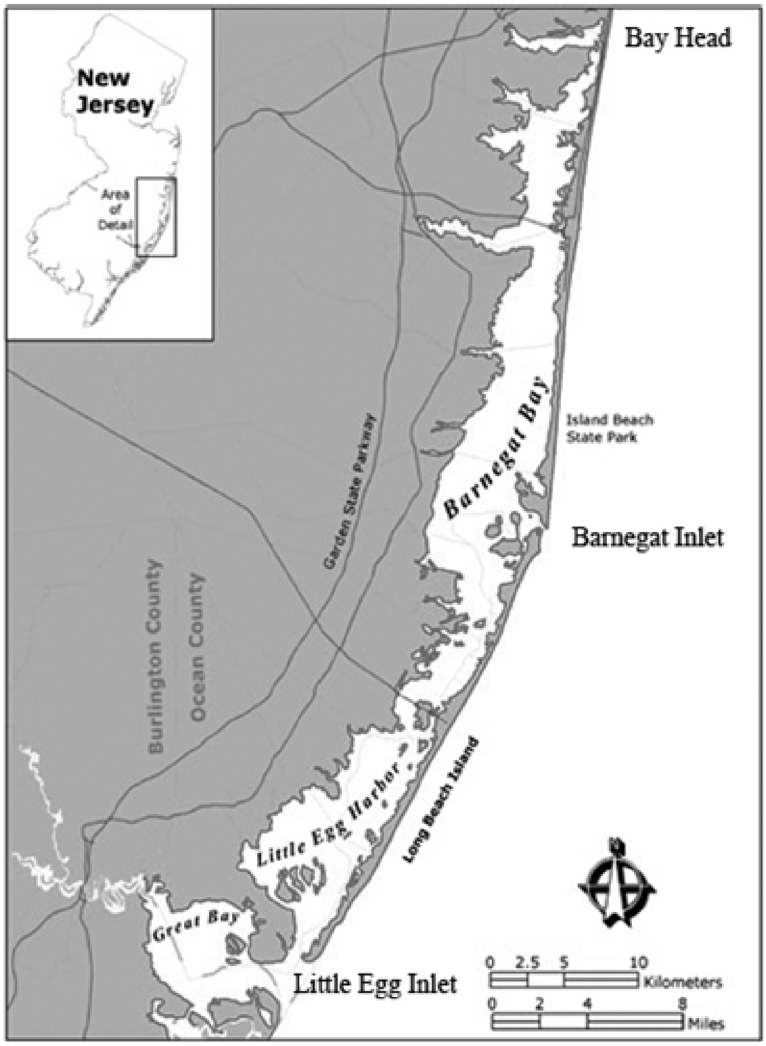

New Jersey
Area of Detail
Bay Head
Island Beach State Park
Barnegat Bay
Barnegat Inlet
Garden State Parkway
Burlington County
Ocean County
Little Egg Harbor
Long Beach Island
Great Bay
Little Egg Inlet
0 2.5 5 10 Kilometers
0 2 4 8 Miles

Figure 1

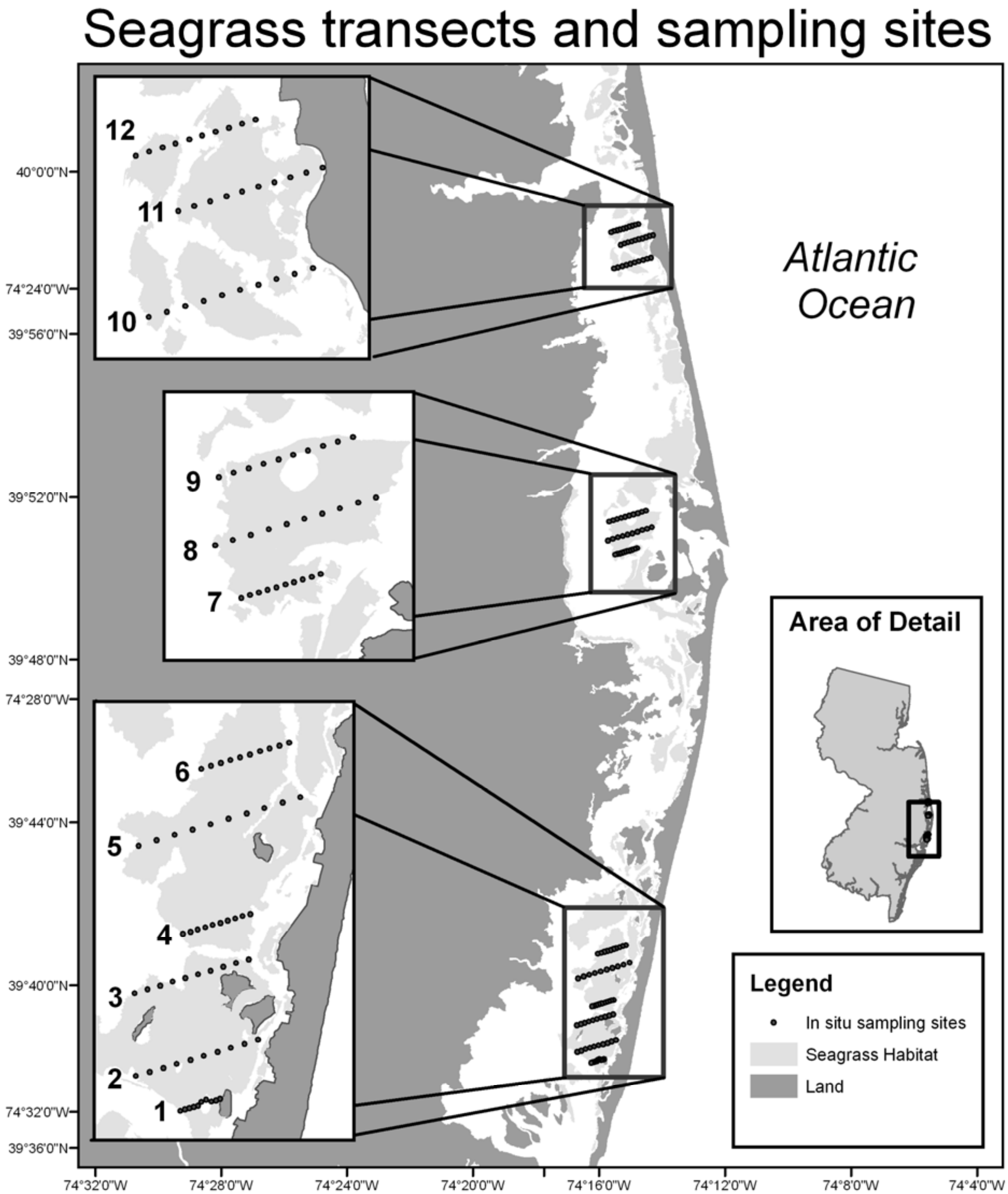

Seagrass transects and sampling sites
Atlantic Ocean
12
11
10
9
8
7
6
5
4
3
2
1
Area of Detail
Legend
In situ sampling sites
Seagrass Habitat
Land
40°0'0"N
74°24'0"W
39°56'0"N
39°52'0"N
39°48'0"N
74°28'0"W
39°44'0"N
39°40'0"N
74°32'0"W
39°36'0"N
74°32'0"W
74°28'0"W
74°24'0"W
74°20'0"W
74°16'0"W
74°12'0"W
74°8'0"W
74°4'0"W

Figure 2

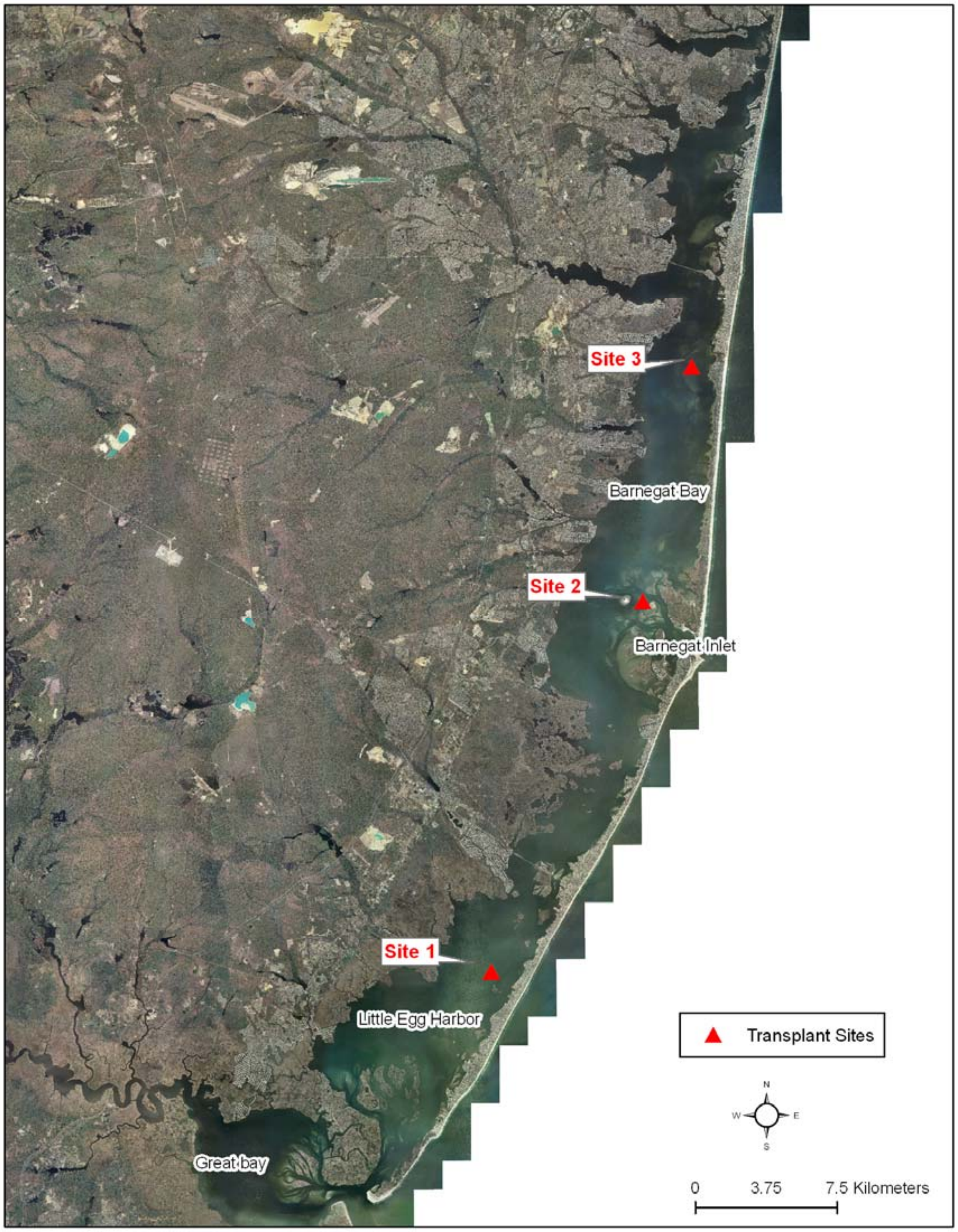

Site 3
Barnegat Bay
Site 2
Barnegat Inlet
Site 1
Little Egg Harbor
Great bay
Transplant Sites
N
W
E
S
0
3.75
7.5 Kilometers

Figure 3

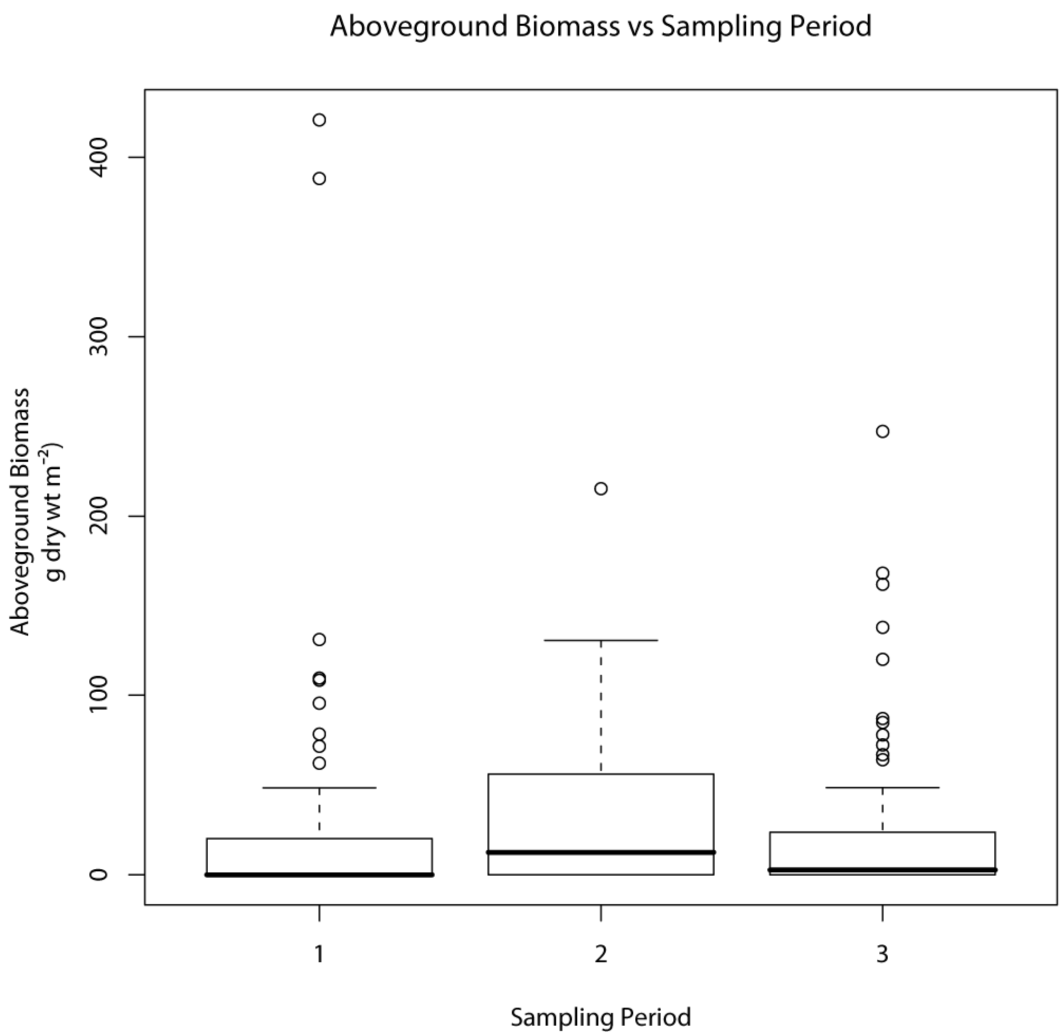

Aboveground Biomass vs Sampling Period
Aboveground Biomass
g dry wt m-2)
0
100
200
300
400
1
2
3
Sampling Period

Figure 4

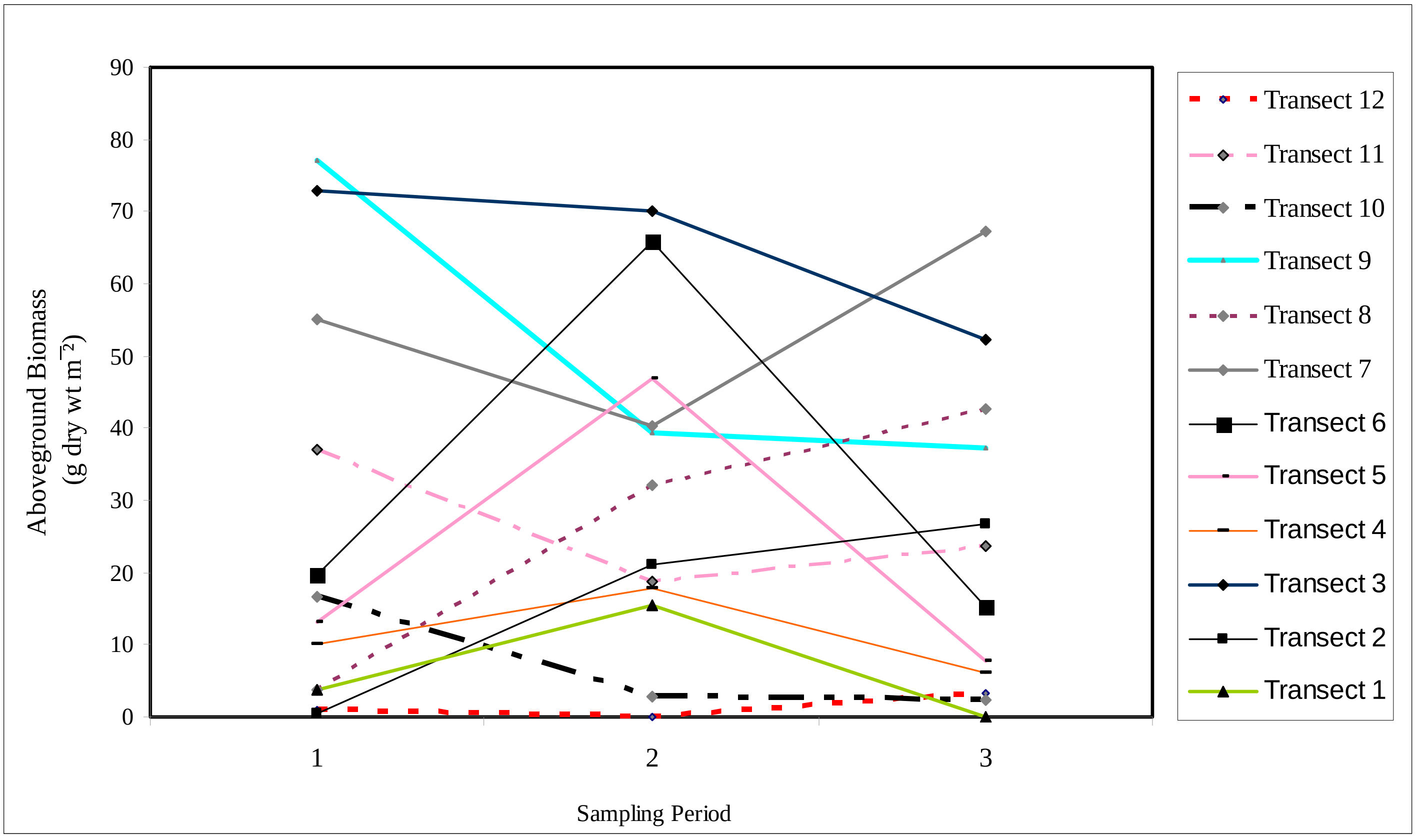

90
80
70
60
50
40
30
20
10
0
Aboveground Biomass
(g dry wt m^{-2})
1
2
3
Sampling Period
Transect 12
Transect 11
Transect 10
Transect 9
Transect 8
Transect 7
Transect 6
Transect 5
Transect 4
Transect 3
Transect 2
Transect 1

Figure 5

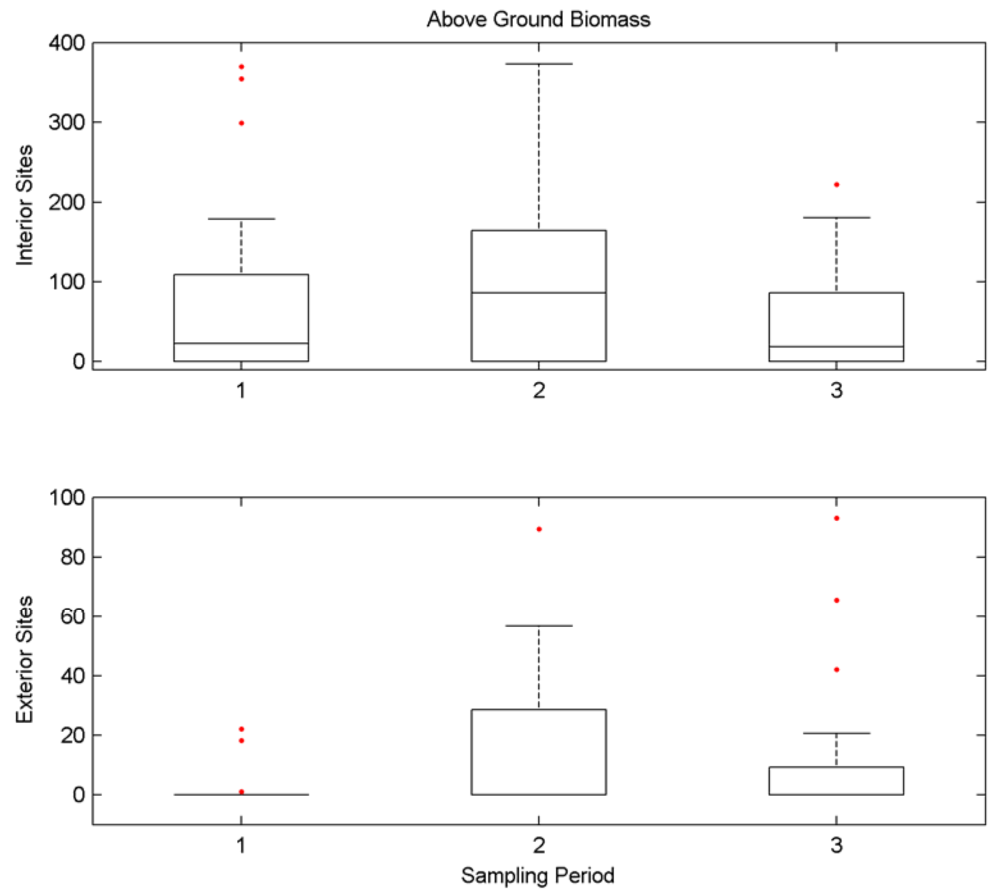

Above Ground Biomass
Interior Sites
400
300
200
100
0
1
2
3
Exterior Sites
100
80
60
40
20
0
1
2
3
Sampling Period

Figure 6

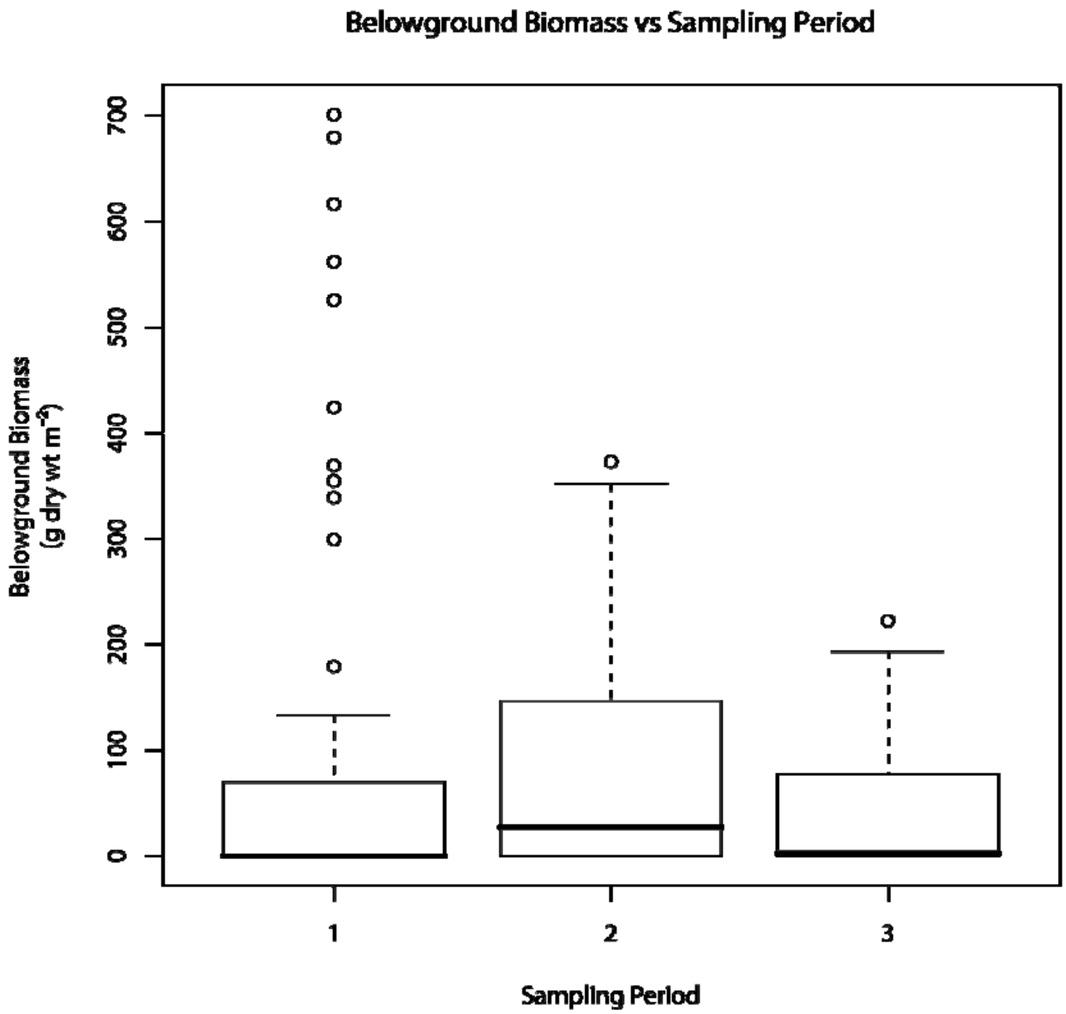
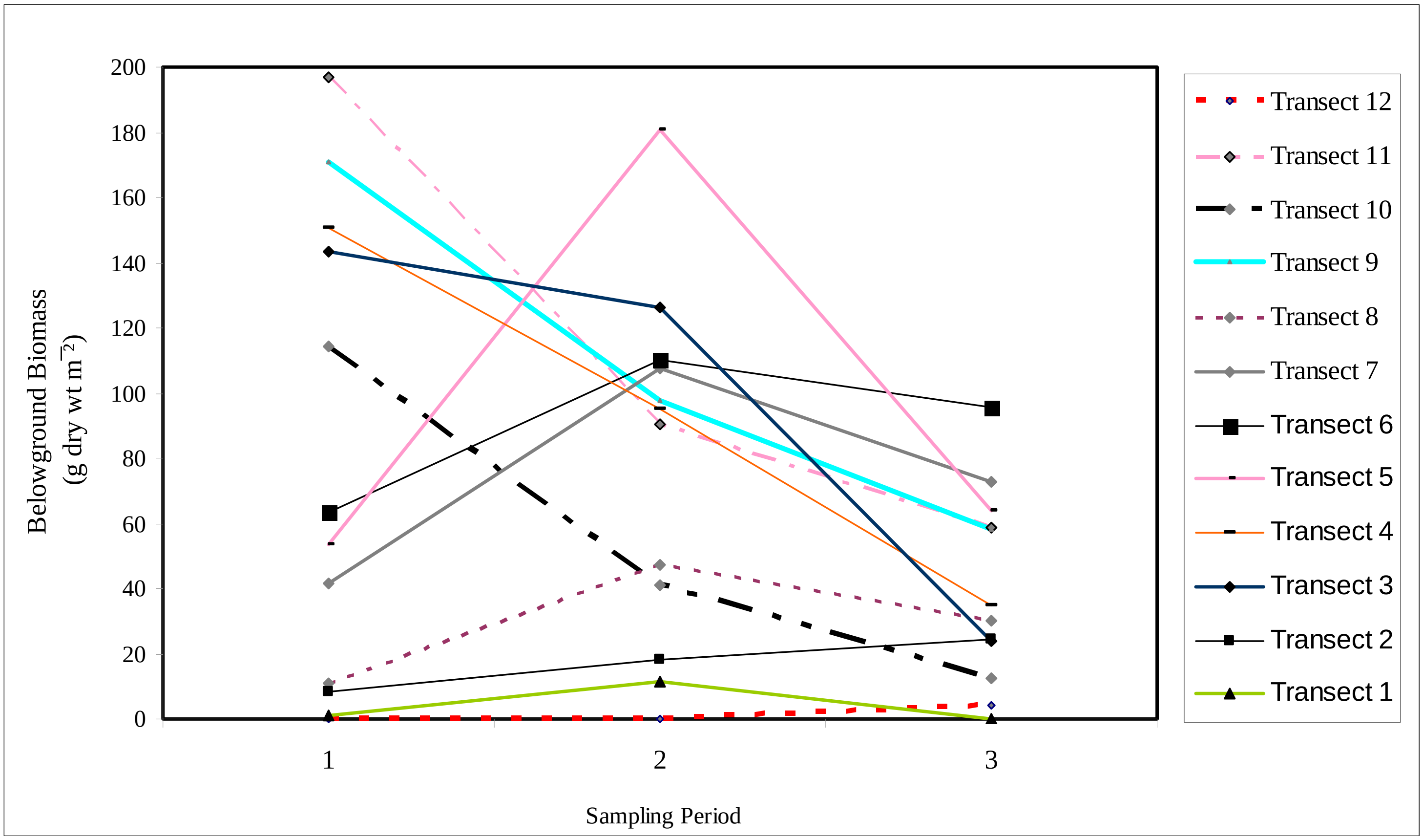

Belowground Biomass vs Sampling Period
Belowground Biomass
(g dry wt m-2)
0
100
200
300
400
500
600
700
1
2
3
Sampling Period

Figure 7



200
180
160
140
120
100
80
60
40
20
0
Belowground Biomass
(g dry wt m-2)
1
2
3
Sampling Period
Transect 12
Transect 11
Transect 10
Transect 9
Transect 8
Transect 7
Transect 6
Transect 5
Transect 4
Transect 3
Transect 2
Transect 1

Figure 8

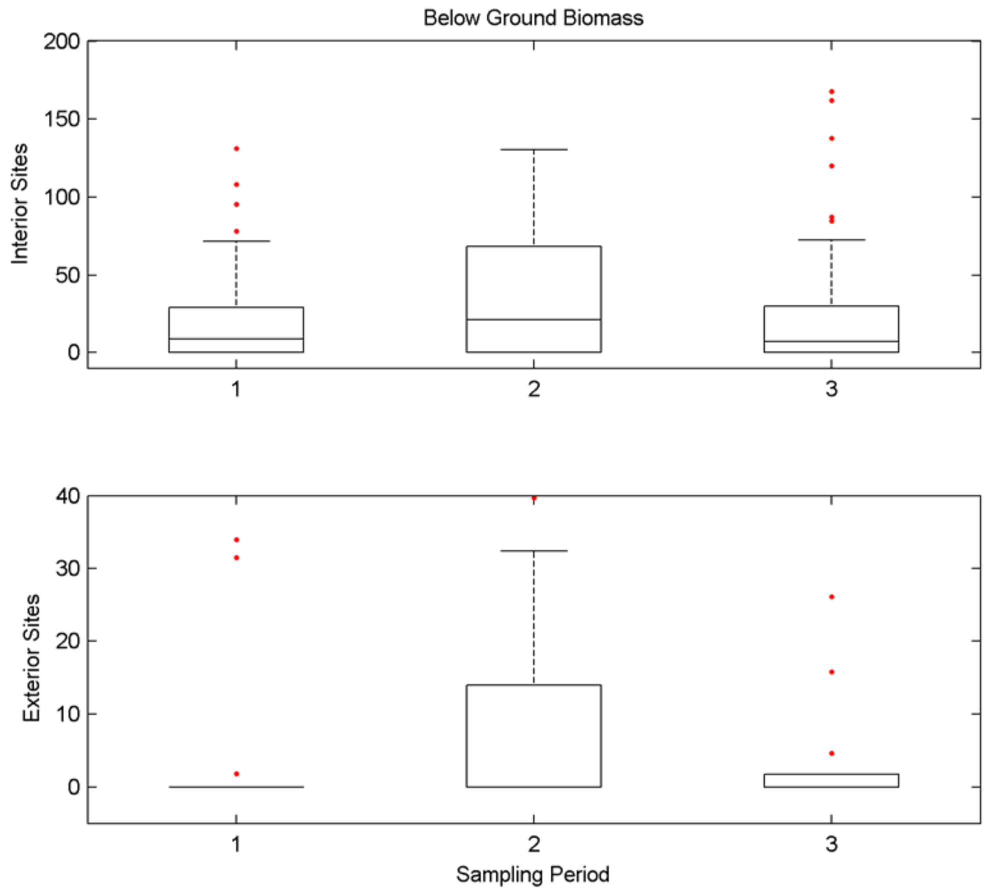

Below Ground Biomass
Interior Sites
200
150
100
50
0
1
2
3
Exterior Sites
40
30
20
10
0
1
2
3
Sampling Period

Figure 9

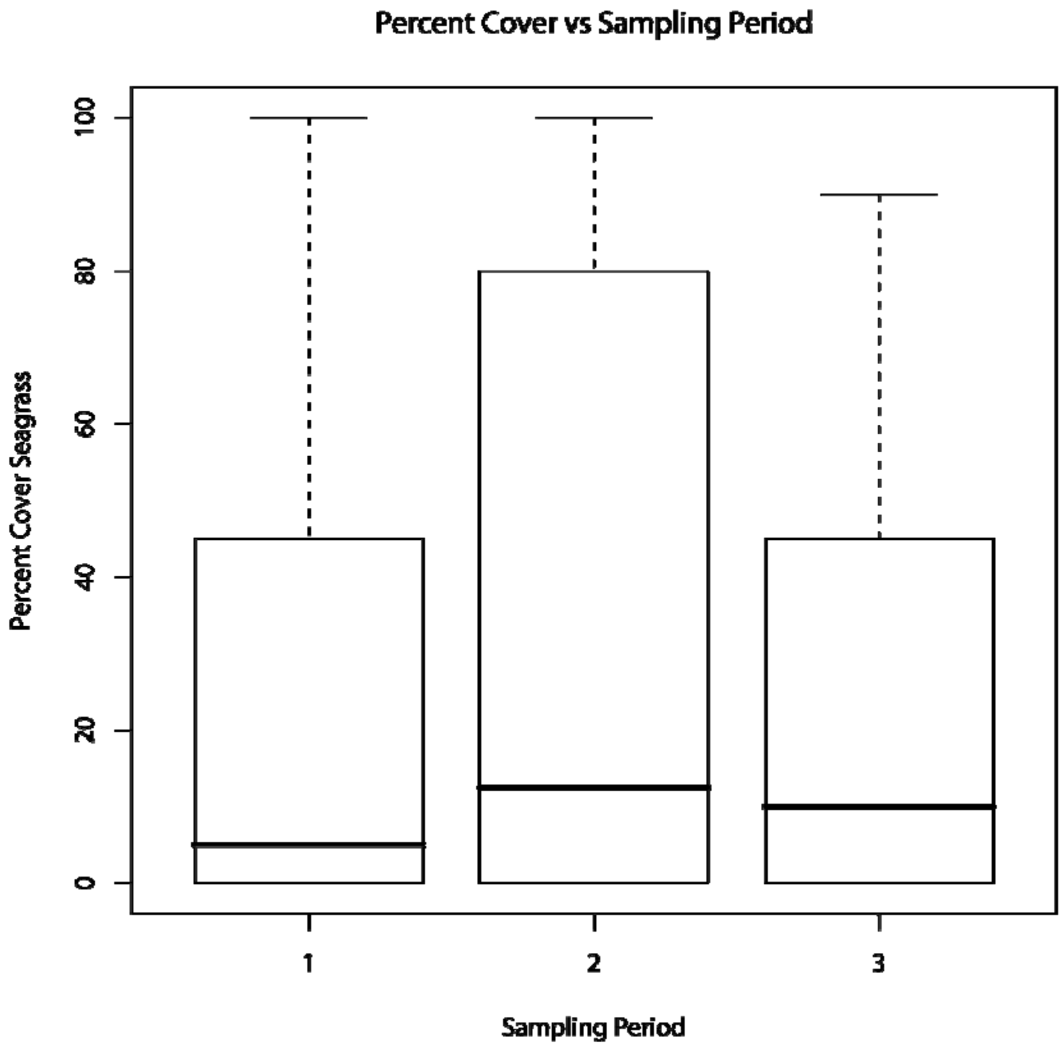

Percent Cover vs Sampling Period
Percent Cover Seagrass
0
20
40
60
80
100
1
2
3
Sampling Period

Figure 10

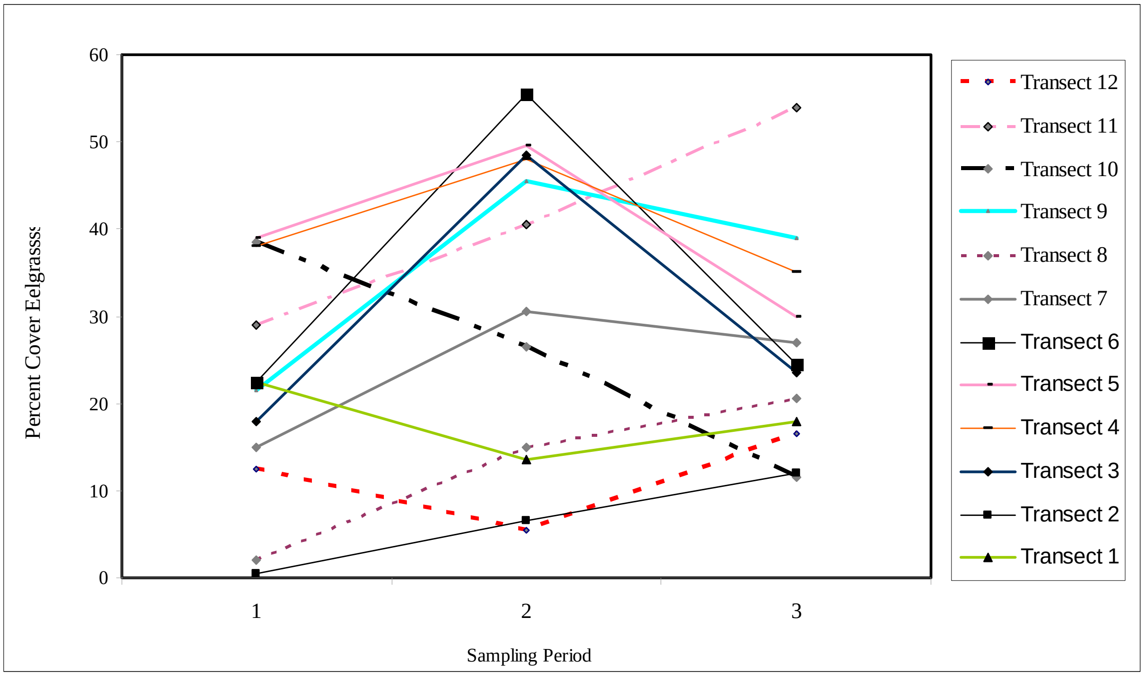

60
50
40
30
20
10
0
Percent Cover Eelgrasss
1
2
3
Sampling Period
Transect 12
Transect 11
Transect 10
Transect 9
Transect 8
Transect 7
Transect 6
Transect 5
Transect 4
Transect 3
Transect 2
Transect 1

Figure 11

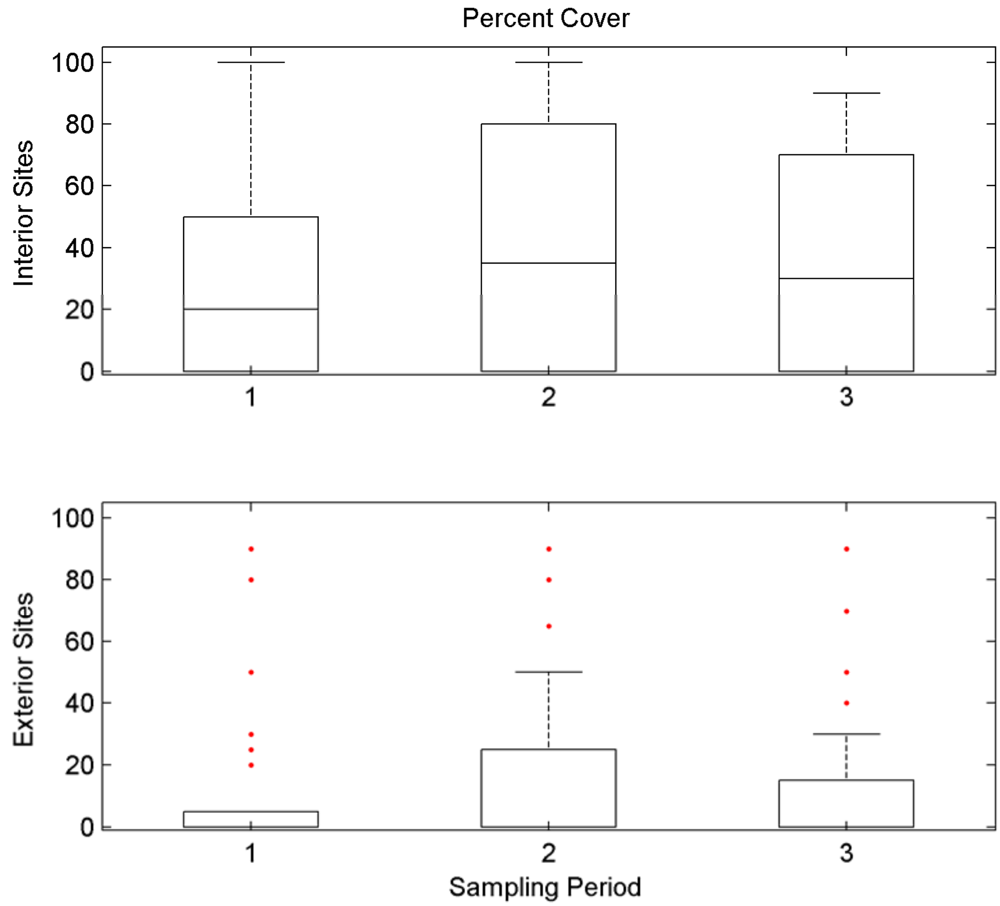

Percent Cover
Interior Sites
100
80
60
40
20
0
1
2
3
Exterior Sites
100
80
60
40
20
0
1
2
3
Sampling Period

Figure 12

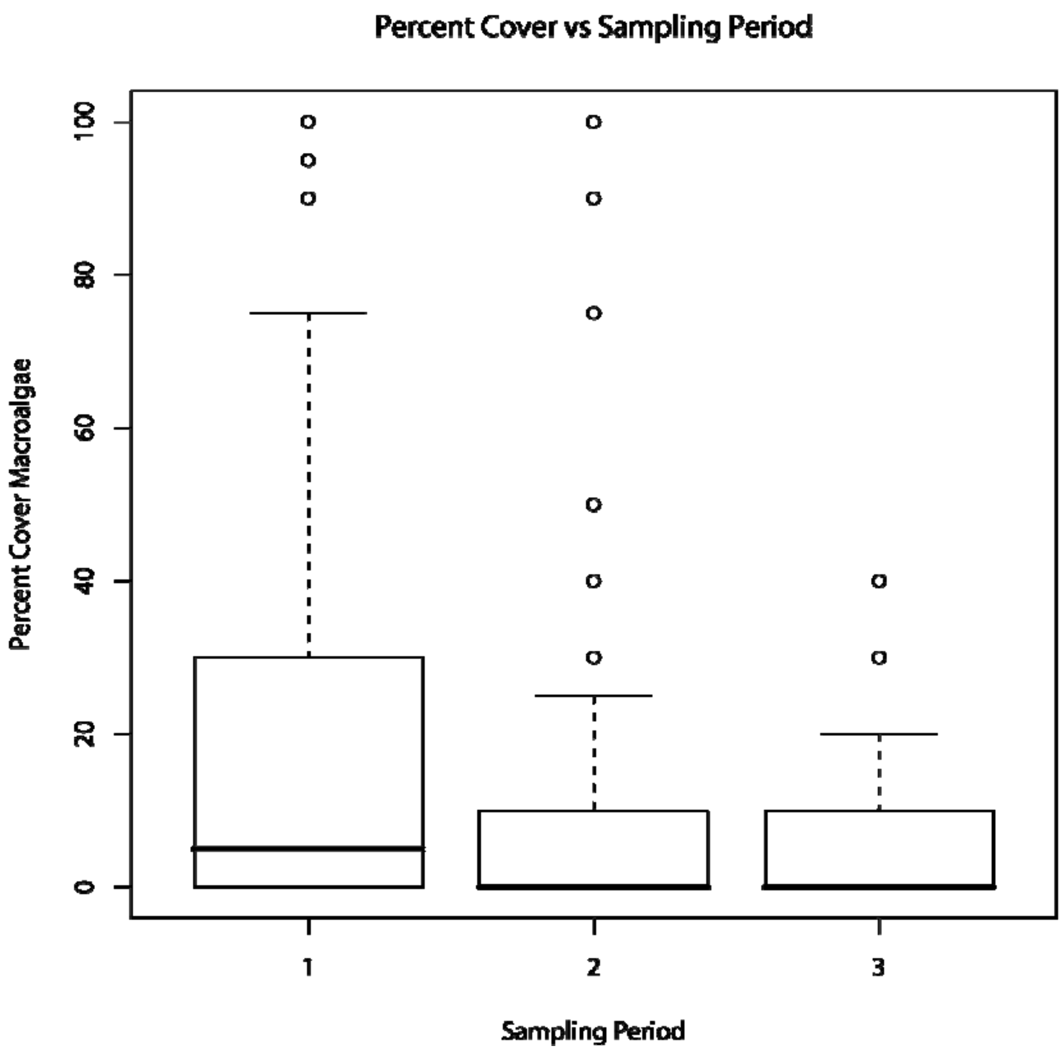

Percent Cover vs Sampling Period
Percent Cover Macroalgae
0
20
40
60
80
100
1
2
3
Sampling Period

Figure 13.

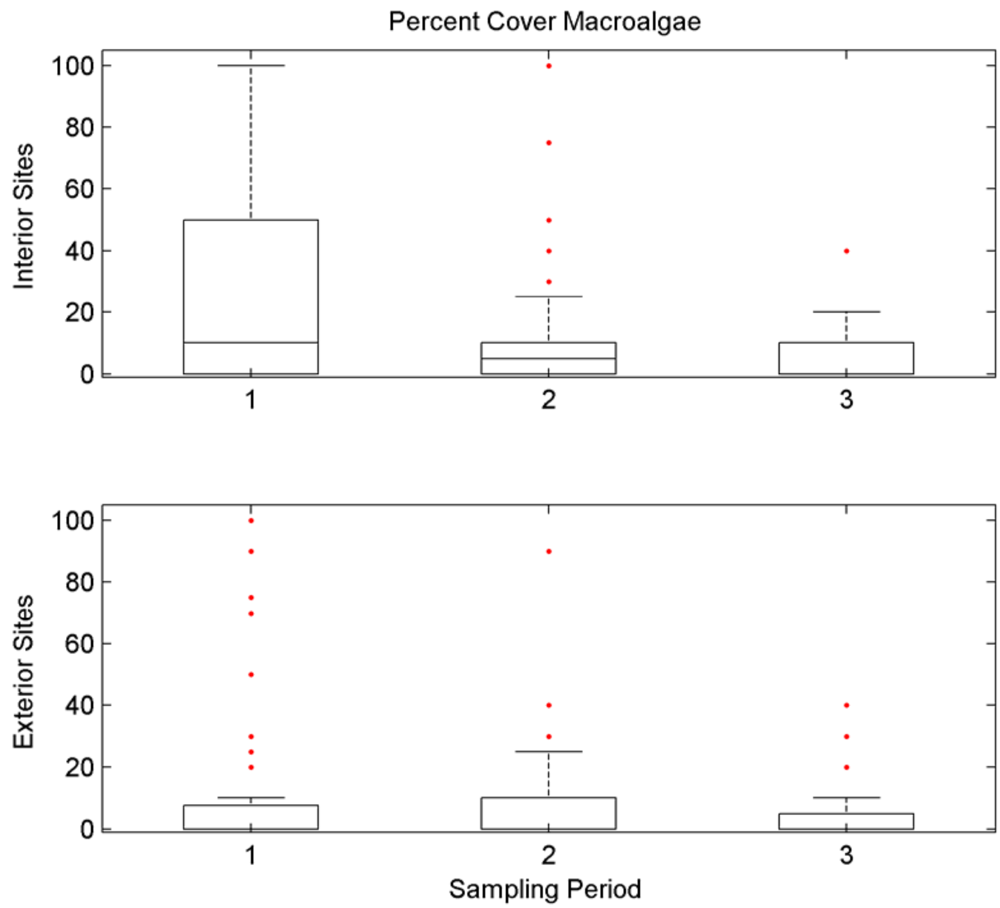

Percent Cover Macroalgae
Interior Sites
100
80
60
40
20
0
1
2
3
Exterior Sites
100
80
60
40
20
0
1
2
3
Sampling Period

Figure 14

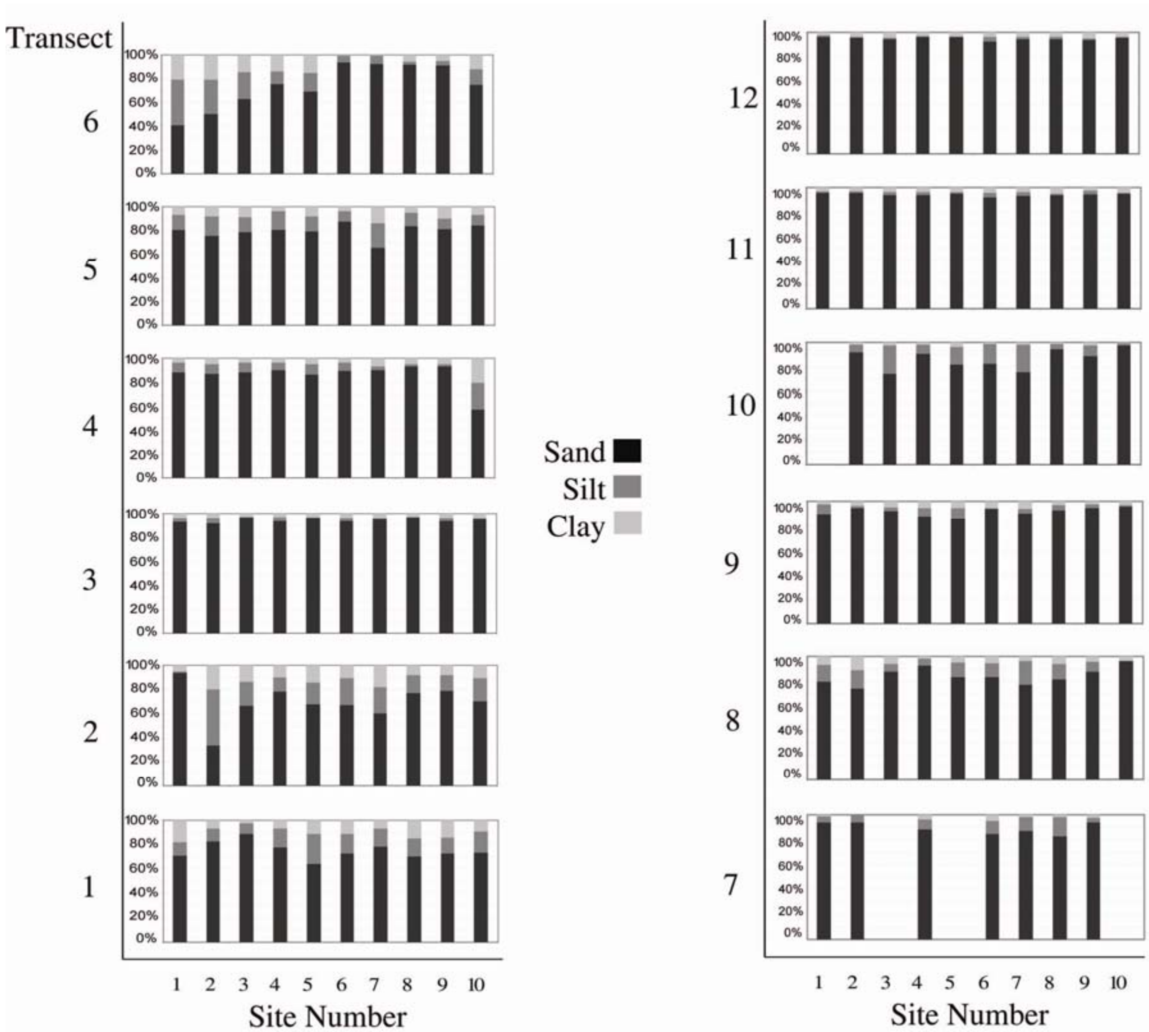

Transect
6
5
4
3
2
1
12
11
10
9
8
7
100%
80%
60%
40%
20%
0%
Sand
Silt
Clay
1 2 3 4 5 6 7 8 9 10
Site Number
1 2 3 4 5 6 7 8 9 10
Site Number

Figure 15.