Seagrass Demographic and Spatial Habitat Characterization in Little Egg Harbor, New Jersey, Using Fixed Transects

Authors: Kennish, Michael J., Haag, Scott M., and Sakowicz, Gregg P.

Source: Journal of Coastal Research, 2008(10055) : 148-170

Published By: Coastal Education and Research Foundation

URL: https://doi.org/10.2112/SI55-0013.1

Journal of Coastal Research	SI	55	148–170	West Palm Beach, Florida	Summer 2008

Seagrass Demographic and Spatial Habitat Characterization in Little Egg Harbor, New Jersey, Using Fixed Transects

Michael J. Kennish[†], Scott M. Haag[‡], and Gregg P. Sakowicz[§]

[†]Institute of Marine and Coastal Sciences
Rutgers University
New Brunswick, NJ 08901, U.S.A.
E-mail: kennish@marine.rutgers.edu

[‡]Center for Remote Sensing and Spatial Analysis
Rutgers University
New Brunswick, NJ 08901, U.S.A.

[§]Rutgers University Marine Field Station
800 Great Bay Boulevard
Tuckerton, NJ 08087, U.S.A.

ABSTRACT

KENNISH, M.J.; HAAG, S.M., and SAKOWICZ, G.P., 2008. Seagrass demographic and spatial habitat characterization in Little Egg Harbor, New Jersey, using fixed transects. *Journal of Coastal Research,* SI(55), 148–170. West Palm Beach (Florida), ISSN 0749-0208.

A detailed submerged aquatic vegetation (SAV) study was conducted in Little Egg Harbor (39°35′N, 74°14′W), New Jersey, a lagoonal estuary located within the boundaries of the Jacques Cousteau National Estuarine Reserve, to assess the demographic characteristics and spatial habitat changes of *Zostera marina* beds over an annual growing period and to determine the species composition, relative abundance, and potential impacts of benthic macroalgae on seagrass habitat in the system. Two disjunct seagrass beds in Little Egg Harbor, covering an area of ~1700 ha, were sampled at 10 equally spaced points along six, east–west-trending transects in spring, summer, and fall (June–November) of 2004. During this period, 180 seagrass samples were collected at 60 transect sites, together with an array of water quality measurements. Results of this investigation indicate that both aboveground and belowground biomass of seagrass peaked during June–July and declined significantly into the fall months. Mean aboveground biomass ranged from 18.22 to 106.05 g dry wt m^{-2}, and mean belowground biomass from 50.48 to 107.64 g dry wt m^{-2}. Biomass values were higher along the northernmost sampling transects than along those farther to the south. They were also higher at interior sampling sites within the seagrass beds than along the bed margins for two of the three sampling periods. Mean seagrass blade length was consistent throughout the study period, averaging 31.83–34.02 cm. The percentage of cover by seagrass, which ranged from 21% to 45%, peaked in June–July at the time of maximum seagrass biomass. The percentage of cover by macroalgae was lower than that of seagrass, averaging 13%–21%, with maximum cover occurring in August–September. Most of the macroalgal species collected in the seagrass beds were red algae, although the dominant species was typically the green seaweed, *Ulva lactuca.* During the 6-month study period, no brown tide (*Aureococcus anophagefferens*) blooms were recorded, and phytoplankton abundance did not appear to cause shading problems for seagrass in the system. However, benthic macroalgal blooms were observed in the seagrass beds, most notably *U. lactuca.* These blooms blanketed parts of the seagrass beds and appeared to degrade them over extensive areas. Nutrient enrichment, elevated turbidity levels, and prop scarring are anthropogenic factors that may significantly influence seagrass beds in Little Egg Harbor during the growing season.

ADDITIONAL INDEX WORDS: *Little Egg Harbor, seagrass beds, Zostera marina, Ruppia maritima, macroalgae, demographics, habitat change.*

INTRODUCTION

The Jacques Cousteau National Estuarine Research Reserve (JCNERR) encompasses a wide range of terrestrial and aquatic habitats within a 45,000-ha area in southern New Jersey (Figure 1) (KENNISH, 2004). Among the most important aquatic habitats in the reserve are seagrass beds within shallow waters of the Barnegat Bay–Little Egg Harbor Estuary, a lagoonal system located along the central New Jersey coastline. More than 2000 ha of eelgrass (*Zostera marina*) and 5 ha of widgeon grass (*Ruppia maritima*) occur in distinct areas of Little Egg Harbor (Figure 2), and they are important indicators of water quality conditions (LATHROP *et al.,* 2001). Human activities, such as recreational boating (prop scarring), shoreline development, and nonpoint-source nutrient inputs, affect seagrass structure and function in the system.

Seagrasses have been the target of a wide range of studies in the Barnegat Bay-Little Egg Harbor Estuary during the past three decades (KENNISH, 2001). GOOD *et al.* (1978) examined the areal coverage of the dominant seagrass species in the estuary, noting that *Z. marina* was by far the most abundant form, except in areas of low salinity, where *R. maritima* predominated. MACOMBER and ALLEN (1979) surveyed and mapped the distribution of seagrasses in the system, as did MCLAIN and MCHALE (1997) and BOLOGNA *et al.* (2000). LATHROP *et al.* (1999) and LATHROP and BOGNAR (2001) compared the results of previous seagrass mapping projects in the estuary to delineate historical trends in the abundance and distribution of seagrass beds. FITENI (1981) recorded the macroalgal epiphytes associated with *Z. marina* in the estuary. VAUGHN (1982) also documented seagrass epiphytes as well as the production of *Z. marina* in Little Egg Harbor. OHORI (1982) compiled data on the biomass of aboveground components of *Z. marina* in the central part of Barnegat Bay, whereas WOOTTON and ZIMMERMAN (1999) investigated the relationship between aboveground and belowground seagrass biomass in this area. SOGARD and ABLE (1991) discussed the

DOI: 10.2112/SI55-0013.1.

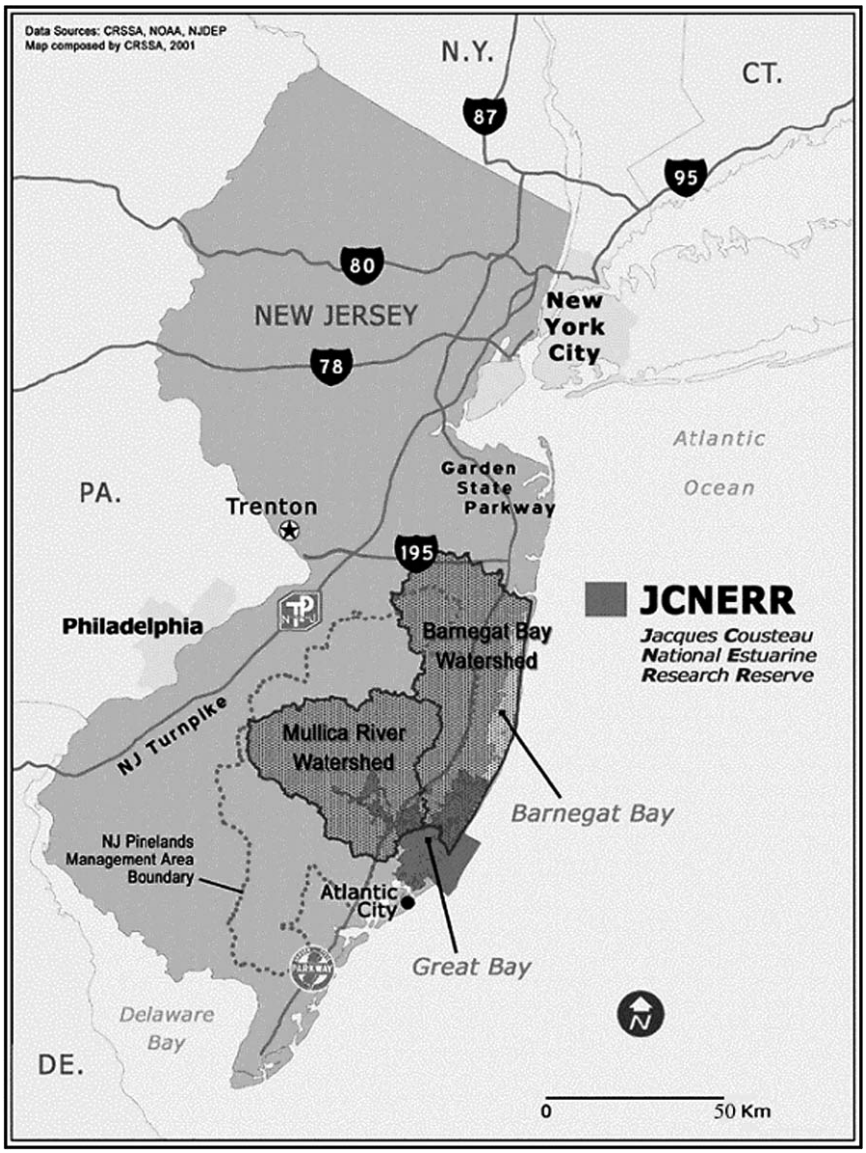

Figure 1. Map of New Jersey showing the location of the Jacques Cousteau National Estuarine Research Reserve and surrounding coastal watersheds that drain into the Barnegat Bay–Little Egg Harbor Estuary and Mullica River–Great Bay Estuary.

importance of seagrass beds in Little Egg Harbor as habitat for epibenthic fish and decapods. BOLOGNA (2006) determined the faunal density and secondary production of *Z. marina* beds in the embayment.

Approximately 75% (6,083 ha) of the seagrass beds in New Jersey occur in the Barnegat Bay–Little Egg Harbor Estuary (LATHROP *et al.,* 2001; MCLAIN and MCHALE, 1997). LATHROP *et al.* (1999), BOLOGNA *et al.* (2000), and LATHROP and BOGNAR (2001) indicate that a significant loss of seagrass may have occurred in the deeper waters of the estuary during the period between the 1960s and 1990s, resulting in the contraction of the beds to shallower subtidal flats. However, more data on the distribution and demographics of seagrass beds in the estuary are needed to establish the status and trends of this vital habitat.

LATHROP *et al.* (2001) examined four historical surveys of seagrass conducted in Barnegat Bay between 1968 and 1999. These surveys were imported into a Geographic Information System database and analyzed for changes in the area and boundaries of the seagrass beds through time. A loss of ~2000 ha of seagrass was noted between 1987 and 1999, representing a ~25% reduction of seagrass habitat in the bay. However, because of differences in sampling methods between the surveys, this loss could not be directly attributed to any change in spatial coverage of seagrass in the bay. To further define seagrass bed boundaries, the Barnegat Bay

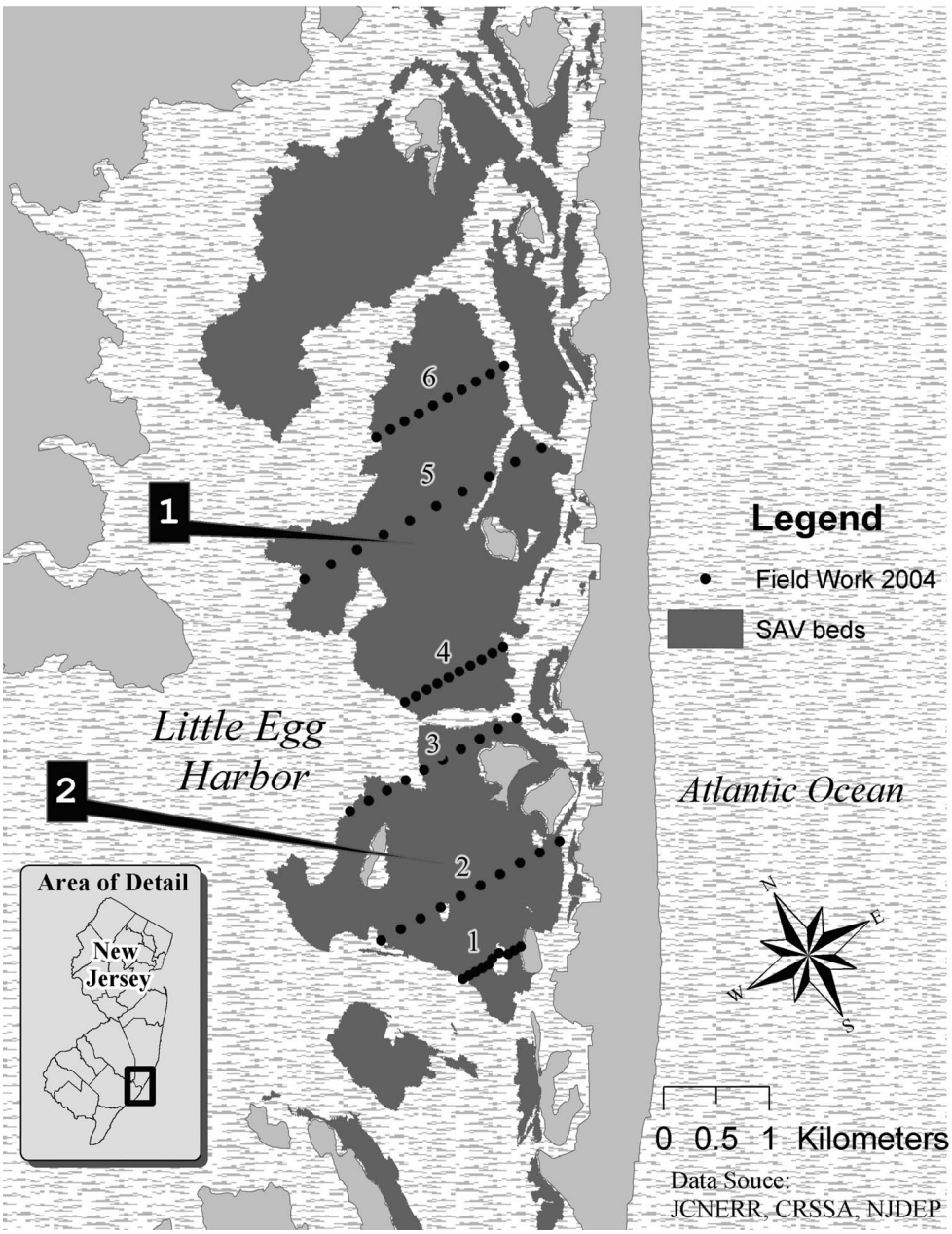

Figure 2. Map of the Little Egg Harbor study site. Note two disjunct seagrass beds, transects (1–6), and sampling sites along transects. Inset shows the location of the study area with respect to the state of New Jersey.

Table 1. *Physicochemical measurements*[1] *recorded at the seagrass survey sites in Little Egg Harbor, New Jersey, during three sampling periods*[2] *in 2004.*

Sample Period	Mean Temperature (°C)	Mean Salinity (ppt)	Mean Dissolved Oxygen (mg L^{-1})	Mean pH	Mean Turbidity (NTU)
1	20.97 (2.87)	30.01 (0.38)	7.91 (1.53)	7.64 (0.15)	1.88 (1.50)
2	24.79 (1.11)	30.42 (1.12)	8.53 (1.42)	7.63 (0.21)	2.23 (1.99)
3	11.29 (1.52)	29.59 (1.27)	10.49 (1.48)	7.70 (0.13)	1.09 (0.64)

[1] Standard deviation in parentheses.
[2] Sample period 1 = June–July; sample period 2 = August–September; and sample period 3 = October–November.

Table 2. *Range of nutrient values recorded in the seagrass survey area of Little Egg Harbor, New Jersey, during the June–September period, 2004.*[1,2]

NO_3^- plus NO_2^-	NH_4^+	TDN	PO_4	Si
0.1–0.3	0.0–2.1	8.2–15.3	0.03–1.21	9.8–26.4
0.0–0.8	0.0–1.5	0.0–24.2	0.67–0.89	0.0–18.7

[1] Values are in micromolars.
[2] Sample period 1 = June–July; sample period 2 = August–September.

National Estuary Program and JCNERR funded a remote-sensing survey in 2003, which was conducted by the Center for Remote Sensing and Spatial Analysis at Rutgers University. This comprehensive survey from aerial platforms generated an extensive database on the broad-scale distribution of seagrass habitat in the estuary (LATHROP, MONTESANO, and HAAG, 2006). KENNISH, HAAG, and SAKOWICZ (2006) later employed high-resolution underwater videography to document the abundance and spatial coverage of seagrasses in localized areas.

The apparent decline of seagrass beds in New Jersey's estuarine waters is a major concern because seagrasses are critically important as habitat and as a source of nutrition for many fish and invertebrates (BOLOGNA, 2006; HECK and VALENTINE, 2006; HILY *et al.,* 2004; LARKUM, ORTH, and DUARTE, 2006; LINK, PLATELL, and POTTER, 2001). Various recreationally and commercially important estuarine and marine species (*e.g., Argopecten irradians, Mytilus edulis, Callinectes sapidus,* and *Cynoscion nebulosus*) use the beds extensively during at least a part of their lives (BOLOGNA, 2006; BOLOGNA *et al.,* 2005). Seagrass beds also play a significant role in biogeochemical cycling and filtering of essential elements (CAFFREY and KEMP, 1990; MOORE, 2004). In addition, seagrass beds are major primary producers and, hence, are greatly affected by nutrient levels as well as other environmental factors, such as turbidity and light intensity (BORTONE, 2000; CUMMINGS and ZIMMERMAN, 2003; KENNISH, 2001; LARKUM, ORTH, and DUARTE, 2006; LATHROP *et al.,* 2001; MOORE, 2004; MOORE, NECKLES, and ORTH, 1996; ORTH *et al.,* 2006). Finally, seagrass beds serve as indicators of overall ecosystem health, thereby influencing coastal management decisions (LEE, SHORT, and BURDICK, 2004). Therefore, by assessing the condition of seagrass beds over time, it may be possible to establish trends in estuarine health.

The study reported here was conducted to assess the condition of seagrass beds in Little Egg Harbor (39°35′N, 74°14′W) and to provide baseline data for further work on

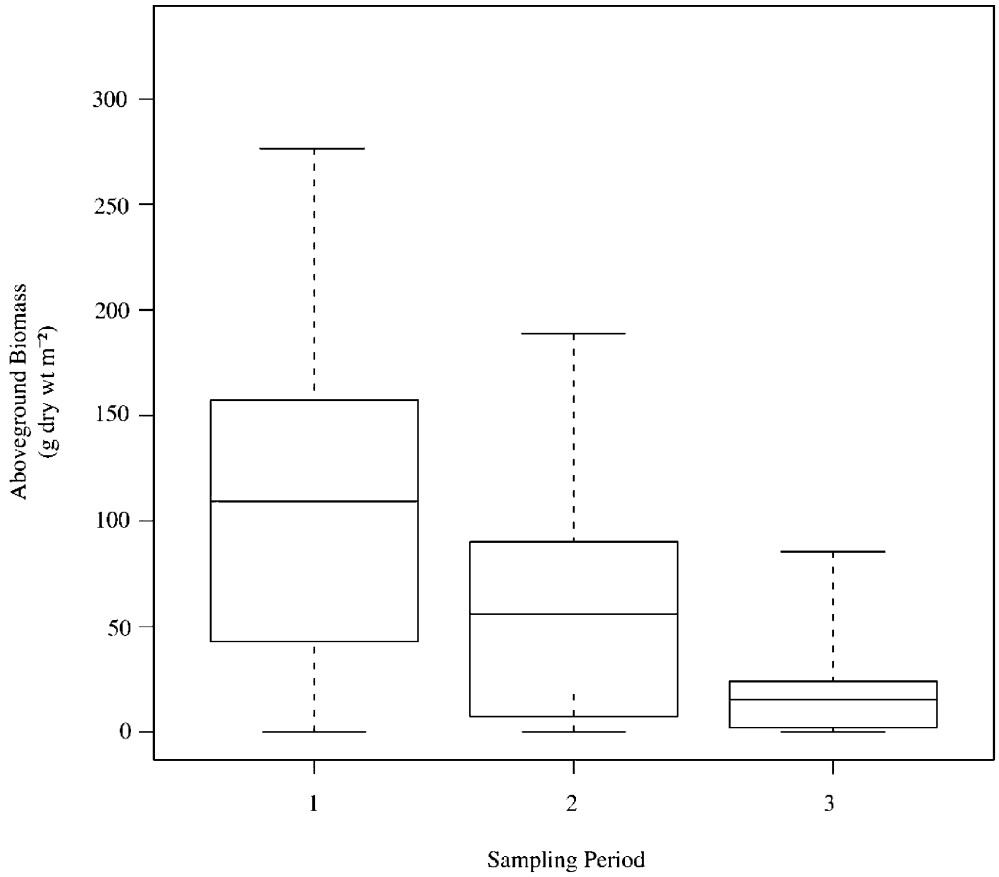

Figure 3. Mean aboveground biomass of all seagrass samples collected in Little Egg Harbor, New Jersey, during three sampling periods in 2004. Sampling period 1, June–July; sampling period 2, August–September; and sampling period 3, October–November.

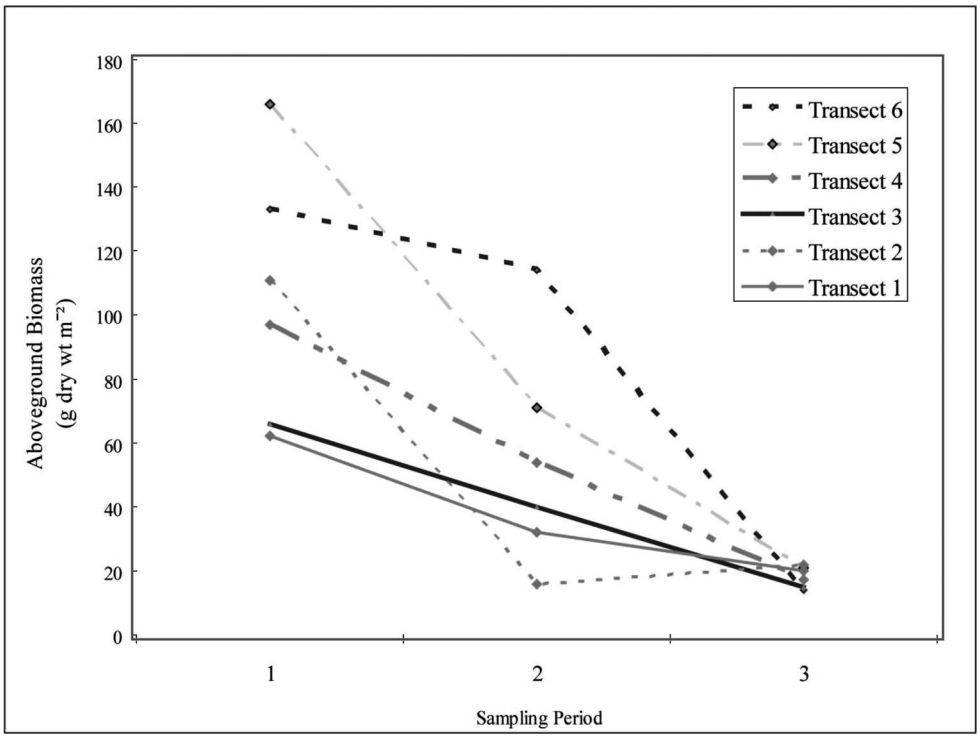

Figure 4. Mean aboveground biomass at six transects in Little Egg Harbor, New Jersey, during three sampling periods in 2004. Sampling period 1, June–July; sampling period 2, August–September; and sampling period 3, October–November.

seagrass distribution in the system. The principal objectives were (1) to determine the demographic characteristics and spatial habitat changes of seagrass (*Z. marina* and *R. maritima*) in Little Egg Harbor over an annual growing period; (2) to assess the species composition, relative abundance, areal coverage, and potential impacts of benthic macroalgae on the seagrass beds; and (3) to ascertain the occurrence and impacts of brown tide (*Aureococcus anophagefferens*) on the beds. Although two species of seagrass occur in the estuary, eelgrass (*Z. marina*) and widgeon grass (*R. maritima*), relatively few *R. maritima* samples were recovered during this investigation. Hence, the main focus was to examine more comprehensively the demographics of eelgrass within estuarine waters of the JCNERR.

Some of the specific questions that were addressed by this research effort include the following:

- What quantitative changes take place in aboveground and belowground biomass, as well as maximum canopy height, of seagrass beds in Little Egg Harbor over a growing season? Is it possible to link these changes to specific environmental factors?
- Where and when are the maximum seagrass biomass values observed in the study area?
- How variable is seagrass coverage in the system? Are shifts in spatial distribution of the seagrass significant within a growing season?
- What changes occur in the percentage of cover by macroalgae from spring to fall, and do these changes affect the seagrass beds?

METHODS

Sampling Design

Two disjunct seagrass beds in Little Egg Harbor, covering a total area of ~1700 ha, were sampled at 10 equally spaced points along six, east–west-trending fixed transects in the spring, summer, and fall of 2004 (Figure 2). Quadrat and transect sampling was conducted during three sampling periods: (1) June–July, (2) August–September, and (3) October–November. Each bed was divided into equal segments based on the total north to south length divided by four (Figure 2). For each segment, a randomly placed sampling station was located on the eastern boundary of the seagrass bed delineated by a remote-sensing (aerial) survey in 2003 (LATHROP, MONTESANO, and HAAG, 2006). From this initial station, the seagrass bed was divided into nine equally spaced sampling stations along a transect from east to west until the western edge of the bed was reached based on the remote-sensing survey of the area. Thus, 180 samples were collected at 60 transect sites during the 6-month study period. At each site, the following demographic data were obtained on each sampling date: aboveground and belowground biomass of seagrass, average blade length, percentage of cover by seagrass, and percentage of cover by macroalgae. Physicochemical data (tem-

Table 3. *Mean aboveground and belowground biomass of* Zostera marina *in Little Egg Harbor, New Jersey, during the June–November period in 2004.*[1]

Sample Period[2]	Aboveground Biomass[3]	ANOVA Values	Belowground Biomass[3]	ANOVA Values	Aboveground : Belowground Biomass Ratio
1	106.05 (A)		107.64 (A)		0.99
		$F = 45.02$		$F = 6.89$	
2	54.61 (B)		68.69 (B)		0.80
		$p = <0.0001$		$p = 0.0013$	
3	18.22 (C)		50.48 (B)		0.36

[1] Values are in grams of dry weight per square meter.
[2] Sample period 1 = June–July; sample period 2 = August–September; and sample period 3 = October–November.
[3] Tukey groupings are in parentheses.

perature, salinity, pH, dissolved oxygen, turbidity, and depth) were also collected at each sampling site. In addition, Secchi disk readings were taken in the study area. Several nutrient parameters (nitrate plus nitrite, ammonium, total dissolved nitrogen, phosphate, and silica) were likewise measured along the seagrass beds. Finally, sediment composition (percentage of sand, silt, and clay) was determined at all sampling sites.

Sampling stations along each transect were permanently located with a Differential Global Positioning System (Trimble GeoXT handheld unit) and marked with a polyvinyl chloride (PVC) pipe. Sampling periods commenced on June 1, August 1, and October 1 and continued until all stations were sampled. During each sampling period, therefore, seagrass samples were collected at 10 stations *per* transect, one transect *per* segment, and three segments *per* seagrass bed.

Quadrat Sampling

Following the sampling method of SHORT *et al.* (2002), a 1-m-long by 2-cm-diameter PVC stake was driven into the bay bottom to a depth of 0.5 m at each sampling site, thereby providing a permanent location for the entire growing season. A metal quadrat, measuring 0.5 m on each side with an area of 0.25 m^2, was placed on the south side of the PVC pipe, and a photograph was taken for later analysis of the quadrat area. The percentage of cover by seagrass and macroalgae was then estimated *in situ* by a diver using a scale of 0 to 100 in increments of 5. The diver also visually inspected the seagrass bed within the quadrat for evidence of grazing, epiphytic loading, boat scarring, and wasting disease. Subsequently, the length of a subset of seagrass blades was measured, and the mean values of the plants were calculated.

Table 4. *Mean aboveground and belowground biomass of* Zostera marina *along six sampling transects in Little Egg Harbor, New Jersey, during the June–November period in 2004.*[1]

Transect	Mean Aboveground Biomass	Mean Belowground Biomass	Aboveground : Belowground Biomass Ratio
6	87.20	131.01	0.67
5	86.24	104.48	0.82
4	55.69	52.41	1.06
3	40.13	44.80	0.90
2	49.72	72.24	0.69
1	38.76	48.67	0.78

[1] Values are in grams of dry weight per square meter.

Macroalgae Sampling

A diver also collected macroalgae samples at each sampling site. The samples were removed from the seagrass bed by hand and placed in 1-L Nalgene bottles containing formalin adjusted to approximate ambient salinities. They were subsequently transported to the Rutgers University Marine Field Station (RUMFS) for taxonomic identification.

Core Sampling

Coring methods, likewise, followed those of SHORT *et al.* (2002). At all sampling sites and on all sampling dates, a 10-cm (0.00785 m^2) diameter core was collected, with care taken not to cut or damage the aboveground seagrass tissues. Because of the destructive nature of seagrass biomass sampling, coring was not performed within the quadrat nor was it repeated at the same location during the same season. Areas similar to the quadrat area in percentage of seagrass cover were sampled within 1 m and to the south of each PVC stake. The core extended deep enough to extract all belowground fractions (roots and rhizomes). Each core was placed in a 3 $\times$ 5-mm mesh bag and rinsed to separate plant material from 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 before 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 °C for 24–48 hours. The dry weight biomass (g dry wt m^{-2}) of each fraction was subsequently measured to the third decimal place.

Sediment Sampling

Sediment samples were collected at all sampling sites to a depth of ~15 cm using a 10-cm-diameter coring device. The samples were taken within 1 m of the PVC pipe at each site during October 2004. These samples were analyzed in the laboratory for the percentage of composition of sand and silt (dry sieving) as well as clay (wet sieving through a 63-μm sieve). The sand component was further analyzed for five component size classes.

Water Quality

Water quality parameters (temperature, salinity, dissolved oxygen, and pH) were measured at all sampling stations us-

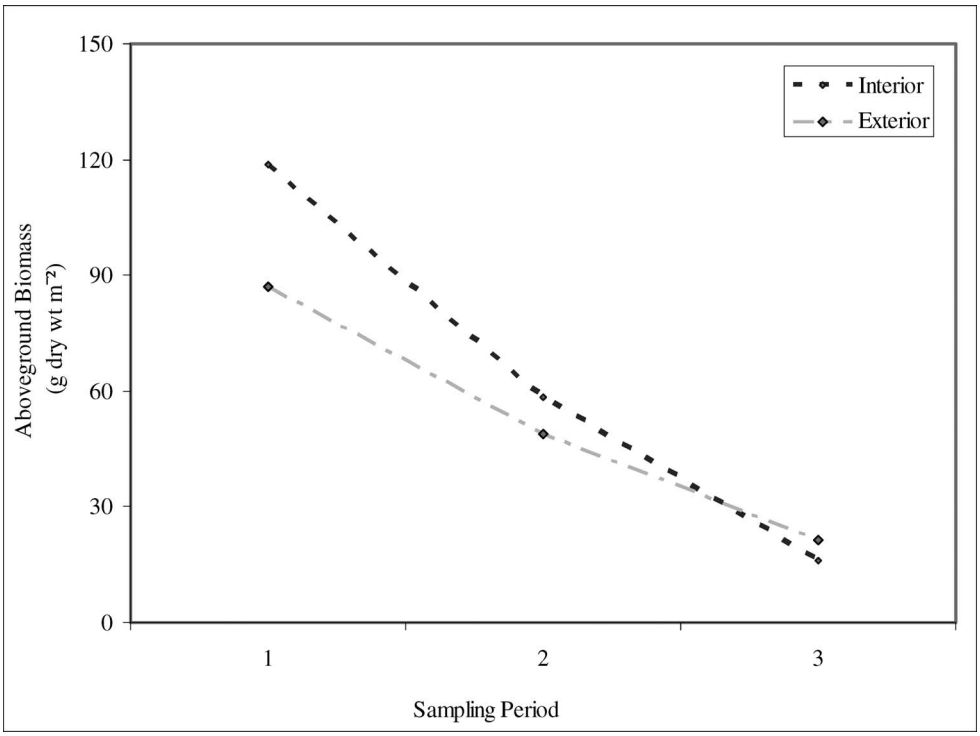

Figure 5. Mean aboveground biomass at interior sampling sites (sites 3, 4, 5, 6, 7, and 8) and exterior sampling sites (sites 1, 2, 9, and 10) on transects in Little Egg Harbor, New Jersey, during three sampling periods in 2004. Sampling period 1, June–July; sampling period 2, August–September; and sampling period 3, October–November.

ing a handheld YSI 600 data sonde coupled with a handheld YSI 650MDS digital display unit. These data were obtained before biotic sampling at each sampling site. Turbidity was determined by collecting a whole water sample, placing it on ice, and transporting it back to the laboratory. Turbidity of the sample was then measured with a YSI data sonde equipped with a YSI 6163 turbidity probe. Water quality data were collected at a uniform depth (~10 cm) above the sediment–water interface and adjacent to the PVC stake.

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.

RESULTS

Physicochemical Conditions

Table 1 provides the measurements of key physicochemical parameters recorded at the sampling sites during the three sampling periods. The mean water temperature ranged from 11.29 °C to 24.79 °C, with the highest value recorded during the August–September sampling period and the lowest value during the October–November sampling period. Salinity was much less variable; mean salinity was lowest during the October–November period (29.59‰) and highest during the August–September sampling period (30.42‰). The range of mean dissolved oxygen values varied from 7.91 mg/L for the June–July sampling period to 10.49 mg/L for the October–November sampling period. The lowest mean pH measurement (7.63) was registered during the August–September sampling period, and the highest mean pH measurement (7.70), during the October–November sampling period. The mean turbidity level increased from a low of 1.88 Nephelometric Turbidity Units (NTUs) during the June–July sampling period to a high of 2.23 NTUs during the August–September sampling period.

Nutrients

Table 2 lists the range of nutrient concentrations found in the seagrass survey area during the June–September period. Nitrate plus nitrite levels were low, ranging from 0–0.8 μM. These low concentrations reflect the effect of autotrophic uptake during the late spring and summer months. A wider range of ammonium values was recorded (0–2.1 μM), although these values were consistent with those documented by SEITZINGER *et al.* (2001). Total dissolved nitrogen ranged from 0–24.2 μM. Similar to nitrate plus nitrite measurements, phosphate values were low, amounting to 0.03–1.21 μM. Silica ranged from 0–26.4 μM.

Seagrass Distribution

Few *R. maritima* samples were collected during this study, and therefore, demographic analysis focused on *Z. marina,*

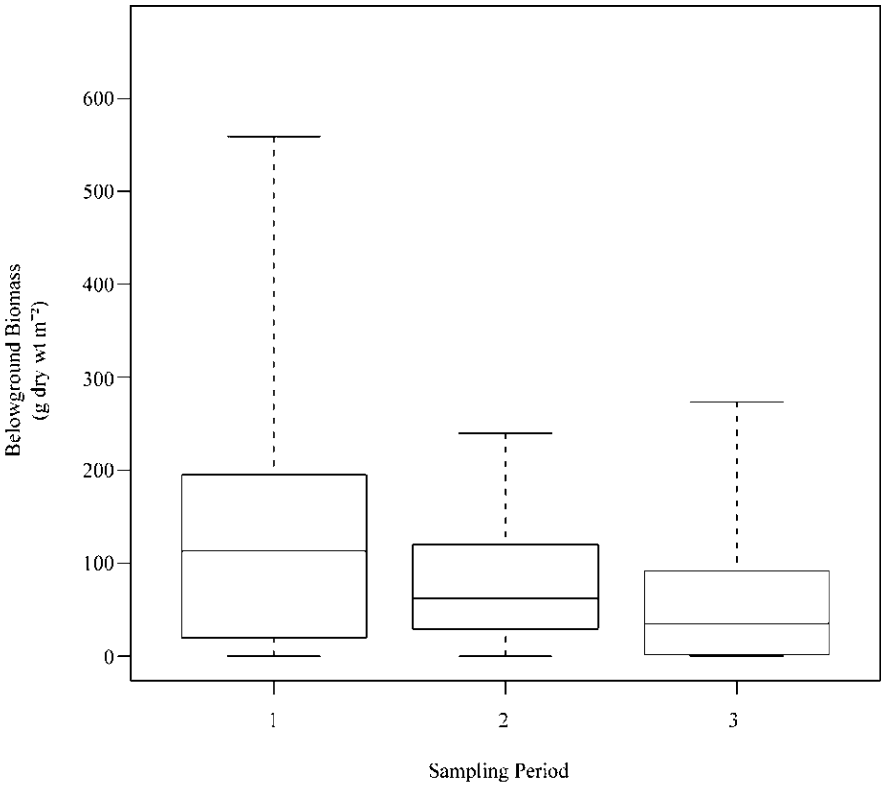

Figure 6. Mean belowground biomass of all seagrass samples collected in Little Egg Harbor, New Jersey, during three sampling periods in 2004. Sampling period 1, June–July; sampling period 2, August–September; and sampling period 3, October–November.

the dominant seagrass species in Little Egg Harbor. Seagrass was found along all transects during each sampling period at depths ranging from <1 to 2 m. However, the biomass and areal coverage varied considerably both in space and time. Conspicuous trends in the data were evident, with the highest biomass and percentage of cover by seagrass occurring during the June–July period and gradually declining values observed through November. Seagrass distribution was clearly depth limited as noted by LATHROP *et al.* (2001); it became very patchy at depths below 1 m.

Aboveground Biomass

Aboveground biomass of seagrass peaked during the June–July sampling period and then declined during the succeeding sampling periods (Figure 3). This pattern held for all transects except transect 2 (Figure 4). For example, the mean aboveground biomass of the seagrass samples collected during the June–July sampling period (106.05 g dry wt m^{-2}) was nearly twice that collected during the August–September (54.61 g dry wt m^{-2}) period and more than five times that collected during the October–November (18.22 g dry wt m^{-2}) period (Table 3). An analysis of variance (ANOVA) test was used to compare aboveground biomass values between the three sampling periods. This test showed statistically significant differences ($F = 45.02$; $p < 0.0001$). A Tukey honestly significant difference (HSD) test applied to the data revealed that all mean aboveground biomass values *per* sampling period were significantly different.

During the entire study period, the aboveground biomass of seagrass was higher along transect 6 than along each of the other five transects. The highest mean aboveground biomass value (87.20 g dry wt m^{-2}) was recorded for transect 6, and the lowest mean aboveground biomass value (38.76 g dry wt m^{-2}) was registered for transect 1, the southernmost transect (Table 4). The biomass measurements were not only higher for all transects during the June–September period, they were more variable than those obtained during the October–November period, when the biomass was consistently low at all transects (Figure 4). This pattern indicates that the seagrass responds uniformly across the study area to decreasing photoperiod, light intensity, and temperature late in the growing season. These major controlling factors are more favorable for seagrass growth between June and September; however, other factors, such as macroalgal abundance, nutrient concentrations, and turbidity, may be more locally variable at that time, accounting for the greater range of biomass values found along the transects.

Each transect was also divided into exterior and interior sampling sites (exterior sites: sites 1, 2, 9, and 10; interior sites: sites 3, 4, 5, 6, 7, and 8). The mean biomass values of seagrass for the interior sampling sites of the transects exceeded those for the exterior sampling sites, except during

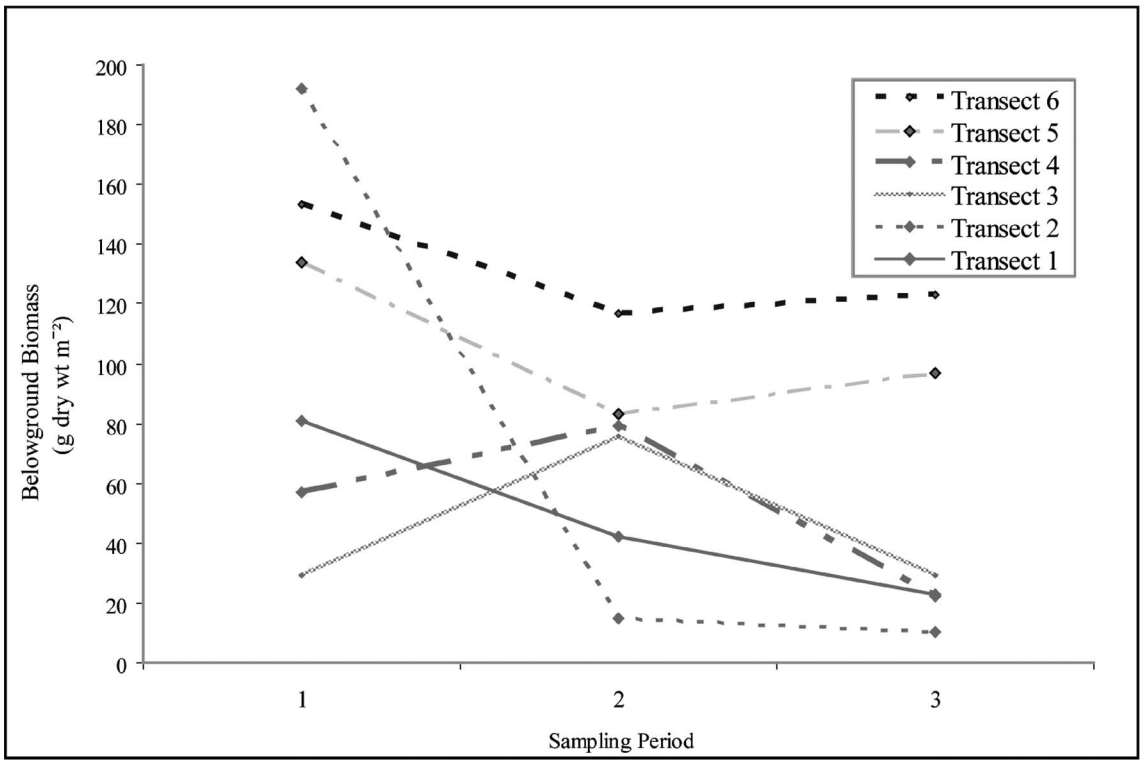

Figure 7. Mean belowground biomass at six transects in Little Egg Harbor, New Jersey, during three sampling periods in 2004. Sampling period 1, June–July; sampling period 2, August–September; and sampling period 3, October–November.

the fall sampling period (October–November) (Figure 5). These data suggest that environmental conditions are generally more favorable for seagrass growth in the interior of each bed than in more marginal areas.

Belowground Biomass

Sampling for belowground biomass of seagrass was likewise conducted during three periods between June and November 2004. A distinct trend of decreasing biomass was evident during the entire 6-month period, consistent with that of declining aboveground biomass (Figure 6). For example, the highest mean belowground biomass of seagrass samples was recorded during the June–July sampling period (107.64 g dry wt m^{-2}), and the lowest mean belowground biomass was registered during the October–November sampling period (50.48 dry wt m^{-2}). An intermediate mean belowground biomass value was obtained during the August–September sampling period (68.69 g dry wt m^{-2}). The mean belowground biomass calculated for the June–July sampling period was nearly equal to that of the mean aboveground biomass, as evident by the aboveground : belowground biomass ratio (0.99). The mean belowground biomass was significantly greater than the aboveground biomass during the August–September and October–November periods, when the aboveground : belowground biomass ratios decreased to 0.80 and 0.36, respectively. The declining ratio from late spring to fall signals a substantial loss of the aboveground portion of the plants because of foraging/grazing, wasting disease, or mass leaf detachment. The greatest difference was documented for the October–November sampling period when the belowground biomass was nearly three times higher than that of the aboveground biomass (Table 3). An ANOVA test was used to compare belowground biomass values between the three sampling periods. This test showed statistically significant differences ($F = 6.89$; $p = 0.0013$). A Tukey HSD test applied to the data revealed that the mean belowground biomass values in Little Egg Harbor were significantly different between sampling periods 1 and 2 and sampling periods 1 and 3.

Belowground biomass of seagrass was investigated with respect to spatial distribution as well, with mean values determined for six transects in the study area (Table 4). The results were similar to those obtained for aboveground biomass in the study area. For example, the highest mean belowground biomass of seagrass (131.01 g dry wt m^{-2}) was recorded for the northernmost transect (transect 6), and the lowest mean belowground biomass (44.80 g dry wt m^{-2}) was registered for transect 3. Although the biomass values for both aboveground and belowground samples followed similar spatial distribution patterns, temporal differences were evident (see Figures 4 and 7). Belowground biomass values exhibited more variable temporal trends compared with aboveground biomass values, most notable between sampling periods 1 (June–July) and 2 (August–September), when the mean belowground biomass increased appreciably at two

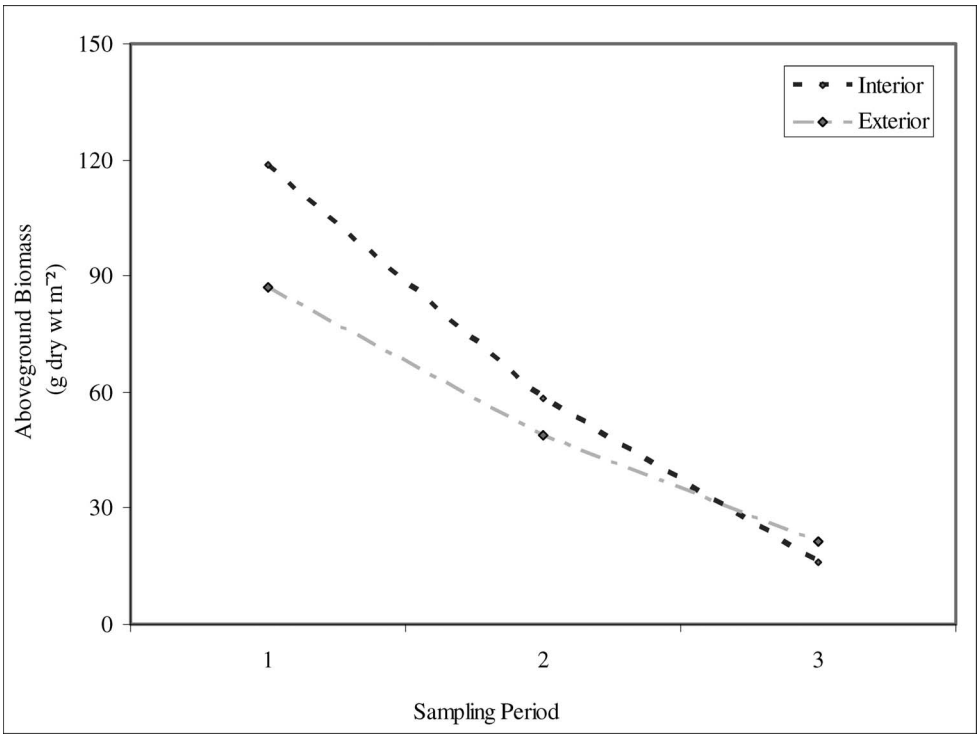

Figure 8. Mean belowground biomass at interior sampling sites (sites 3, 4, 5, 6, 7, and 8) and exterior sampling sites (sites 1, 2, 9, and 10) on transects in Little Egg Harbor, New Jersey, during three sampling periods in 2004. Sampling period 1, June–July; sampling period 2, August–September; and sampling period 3, October–November.

transects (transacts 3 and 4). Interior sampling sites (sites 3–8) along transects also had higher mean belowground biomass values during the study period than did exterior sampling sites (sites 1, 2, 9, and 10) (Figure 8).

The aboveground : belowground biomass ratios were less than 1.0 for all transects, except transect 4 (Table 4). The ratios ranged from 0.67 (transect 6) to 1.06 (transect 4). These values indicate that the aboveground biomass of seagrass was less than the belowground biomass at most sites.

Seagrass and Macroalgae Cover

The mean percentage of cover by seagrass during period 1 (June–July), period 2 (August–September), and period 3 (October–November) was 45%, 38%, and 21%, respectively (Table 5, Figure 9). The percentage of cover by seagrass by transect is shown in Figure 10. The percentage of cover by seagrass was considerably higher at interior sampling sites than exterior sampling sites (Figure 11). By comparison, the percentage of cover by macroalgae during these periods was substantially less, averaging 13% (June–July), 21% (August–September), and 14% (October–November) (Figure 12). As illustrated in Figure 13, the percentage of cover by macroalgae (trend and variation) by transect differed considerably from that of seagrass (Figure 10). Similar to seagrass cover, however, the percentage of cover by macroalgae was distinctly higher at interior transect sites (sites 3–8) than exterior transect sites (sites 1, 2, 9, 10) during the study period (Figure 14), reflecting the more favorable conditions for plant growth away from the seagrass bed margins. *Zostera marina* does not grow to depths below 2 m at low tide in New Jersey estuaries (Bologna *et al.,* 2000), and seagrass growth and areal coverage decrease as deeper waters are approached.

Table 5. *Percentage of cover by seagrass and macroalgae on the Little Egg Harbor, New Jersey, estuarine floor during three sampling periods in 2004.*

Sample Period[1]	% Seagrass Cover	% Macroalgae Cover
1	45%	13%
2	38%	21%
3	21%	14%

[1] Sample period 1 = June–July; sample period 2 = August–September; and sample period 3 = October–November.

Seagrass Blade Length

Table 6 lists the mean length of *Z. marina* blades recorded during the study period. The highest mean length (34.02 cm) was observed during the June–July sampling period. Subsequently, the mean length of the blades decreased to 32.21 cm during the August–September sampling period and to 31.83 cm during the October–November sampling period. An ANOVA test used to compare blade length values between the three sampling periods showed no statistically significant differences ($F = 0.90$; $p = 0.4078$). These data indicate that the

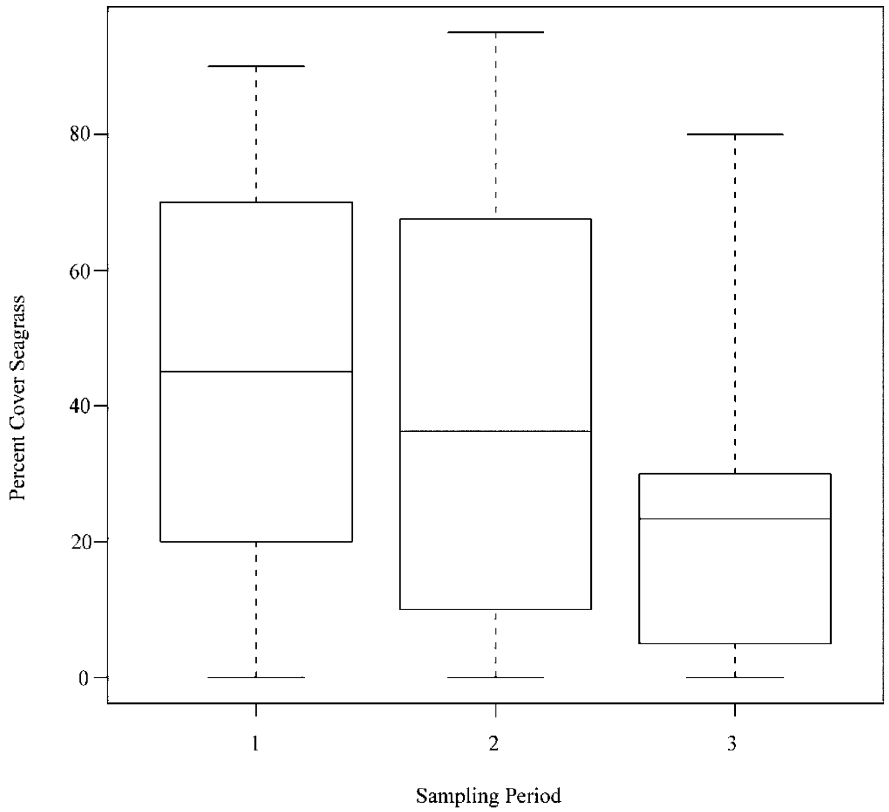

Figure 9. Mean percentage of cover by all seagrass at sampling sites in Little Egg Harbor, New Jersey, during three sampling periods in 2004. Sampling period 1, June–July; sampling period 2, August–September; and sampling period 3, October–November.

blades of *Z. marina* grew to consistent lengths from spring to fall.

Macroalgae Composition

Thirty-two macroalgae species were found during the study period, with the majority being red algae ($n = 19$) (Table 7). Fewer species of green algae ($n = 11$) and brown algae ($n = 2$) were collected. The most common species was the green seaweed (*U. lactuca*), which was found in 59% of the samples, followed by the three red seaweeds, *Spyridia filamentosa* (55%), *Gracilaria tikvahiae* (30%), and *Champia parvula* (23%). Several other species occurred in at least 10% of the samples: two greens, *Ulothrix flacca* and *Enteromorpha intestinalis;* and four reds, *Ceramium deslongchampsii, Ceramium cimbricum, Ceramium strictum,* and *Neosiphonia harveyi.* Only two species of brown algae were recovered, and they occurred very infrequently. There were several species of two red genera, *Polysiphonia* ($n = 4$) and *Ceramium* ($n = 4$); in both cases, some samples contained fragments that could not be identified to species. The average number of species *per* sample was 3.1, but there was a high degree of variability (SD = 1.6).

Because the samples were analyzed based on presence or absence of algae, no data were recorded on biomass. Thus, a small fragment of a *Ceramium* species may be equivalent to a relatively large individual of *Lomentaria baileyana* or *U. lactuca.* The vast majority of the species found were either ephemeral (*e.g.,* most of the green algae) or small epiphytic forms (*e.g.,* the majority of the red algae). There were some relatively large species. such as *Codium fragile, Gracilaria tikvahiae,* and *Lomentaria baileyana.*

Seasonal changes in the number of macroalgal species were evident *per* month, with maximum numbers observed in June and October and minimum numbers in September. However, these changes should be viewed with caution because they were associated with disparate sample sizes among the months. Figure 15 illustrates a strong (and predicted) relationship between the number of macroalgal samples and number of species found; the more samples examined, the greater the number of relatively rare species discovered.

Despite the problems with differences in sample sizes *per* month, some seasonal relationships were apparent. With the exception of an isolated sample in October, *Enteromorpha* spp. was only present in samples taken in June. The only green alga found in September was *U. lactuca,* which occurred in 29% of the samples, compared with more than 45% of the samples during the other months. The increase in ephemeral green algae might indicate the onset of summer nutrient (nitrogen) limitation. These species typically form blooms during periods of high nutrient availability, providing

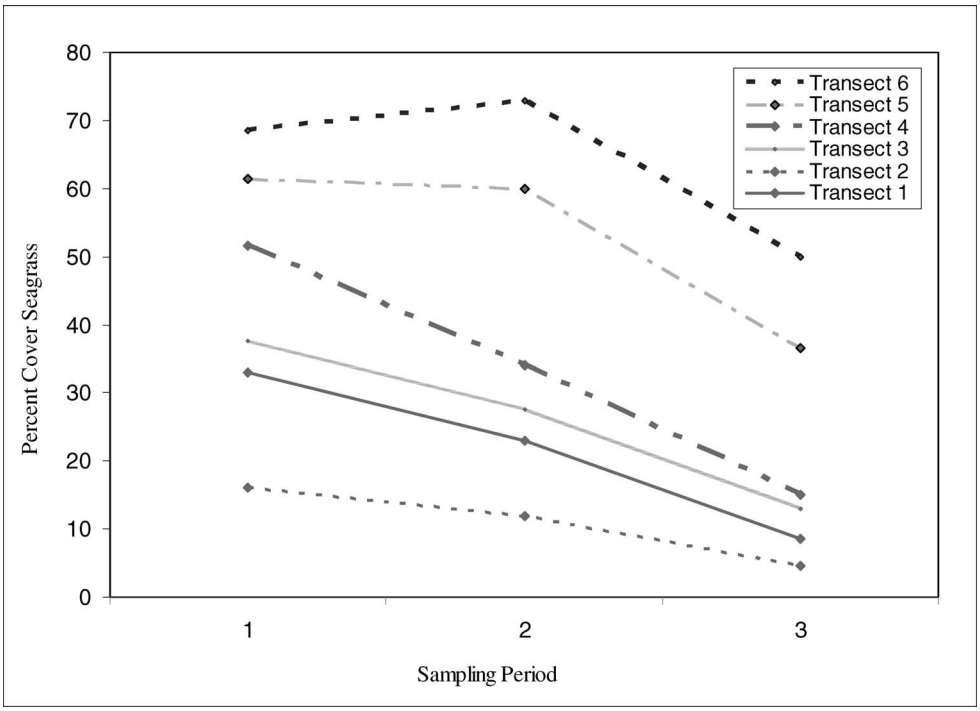

Figure 10. Mean percentage of cover by seagrass at six transects in Little Egg Harbor, New Jersey, during three sampling periods in 2004. Sampling period 1, June–July; sampling period 2, August–September; and sampling period 3, October–November.

other factors (*e.g.,* solar radiation) are also favorable. In this study, the blooms were corroborated by field observations which showed *U. lactuca* completely blanketing extensive areas of the estuarine floor during the summer (Figure 16).

No major seasonal differences were noted in the number of macroalgal species *per* sample (mean and median both ~3) (Figure 17). On average, samples contained about two species of red algae and one species of green algae. A few samples (3% of the total) contained no algae.

Brown Tide

Recurring brown tide blooms of *Aureococcus anophagefferens* have occurred in the Barnegat Bay–Little Egg Harbor Estuary since the mid-1990s. The peak numbers of *A. anophagefferens* were documented in 2000 (2.155×10^6 cells ml^{-1}), 2001 (1.883×10^6 cells ml^{-1}), and 2002 (1.561×10^6 cells ml^{-1}) (Table 8). These years of significant brown tide blooms in the estuary were also characterized by extended drought conditions, corresponding low freshwater inputs, and elevated bay salinity. The maximum abundance of *A. anophagefferens* declined markedly in 2003 (5.4×10^4 cells ml^{-1}) and 2004 (4.9×10^4 cells ml^{-1}), with no blooms reported during either year. Before 2000, brown tide blooms were observed in Little Egg Harbor during 1995, 1997, and 1999 (Olsen and Mahoney, 2001).

For the period of seagrass sampling reported here in 2004, the numbers of *A. anophagefferens* were well below the level necessary to create bloom conditions. This observation is true for stations throughout the estuary, including three stations in the seagrass study area. Thus, the probability of shading impacts on seagrass beds because of brown tide blooms was much reduced in 2004 relative to that during the 2000–02 period.

Sediment Composition

Sand predominated in the seagrass beds, exceeding 50% at most sampling sites (Figure 18). The total amount of sand and silt was greater than 80% at the transect sites, with the highest (>90%) at transect 4. The sediments in the study area were mainly classified as fine-grained to medium-grained sands.

DISCUSSION

Seagrasses are vital habitats for fish and invertebrate populations, major sources of primary production, and sensitive indicators of estuarine water quality and long-term ecosystem health (Corbett *et al.,* 2005). They serve as essential fish habitat and support many commercially and recreationally important species. The ecological and functional significance of seagrasses to estuarine environments has been clearly established by numerous studies in tropical, subtropical, and temperate waters (*e.g.,* Dennison *et al.,* 1993; Hauxwell, Cebrian, and Valiela, 2003; Heck *et al.,* 1995; Kemp, 1983, 2000; Lee, Short, and Burdick, 2004).

Eelgrass is far more abundant than widgeon grass in the Barnegat Bay–Little Egg Harbor Estuary, accounting for more than 99% of the total seagrass areal coverage. For ex-

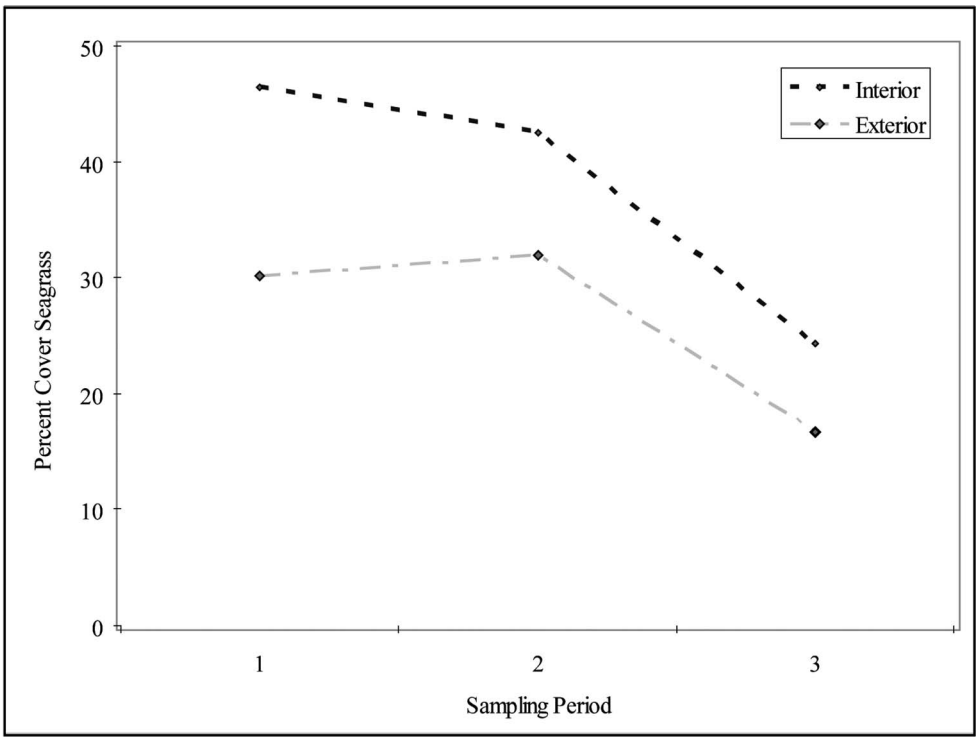

Figure 11. Mean percentage of cover by seagrass at interior sampling sites (sites 3–8) and exterior sampling sites (sites 1, 2, 9, and 10) on transects in Little Egg Harbor, New Jersey, during three sampling periods in 2004. Sampling period 1, June–July; sampling period 2, August–September; and sampling period 3, October–November.

ample, in 1998, BOLOGNA, WILBUR, and ABLE (2001) found that eelgrass covered an area of 1,299 ha in Little Egg Harbor, whereas widgeon grass only covered an area of 6.8 ha. LATHROP *et al.* (2001) reported even greater areal coverage of *Z. marina* in the estuary, amounting to ~2000 ha *vs.* 5 ha for *R. maritima.*

Water clarity and light conditions are important factors controlling the spatial distribution of seagrasses, restricting them to shallow zones (FRANKOVICH and ZIEMAN, 2005; LATHROP *et al.,* 2001; MOORE, NECKLES, and ORTH, 1996; MOORE and WETZEL, 2000). Because these vascular plants are broadly distributed in shallow estuarine or coastal marine waters, they are exposed to a wide array of natural and anthropogenic stressors that can be detrimental (BOLOGNA, 2006; BORTONE, 2000; KENNISH, 2002a, 2002b; KENNISH *et al.,* 2007; KENWORTHY *et al.,* 2001; SHORT and WYLLIE-ECHEVERRIA, 1996; VALIELA, 2006). For example, nutrient enrichment, turbidity, prop scarring by boats, sediment influx from coastal watersheds, and infection by *Labyrinthula zosterae* (*i.e.,* wasting disease) have all contributed to seagrass decline (DEN HARTOG, 1987; HAUXWELL, CEBRIAN, and VALIELA, 2003; KENNISH, 2002b; LIVINGSTON, 2002; ORTH *et al.,* 2006). Escalating coastal development and associated human activities have led to increasing impacts on seagrass meadows worldwide, resulting in their decline and retreat to shallower depths (DIXON, 2000). In some cases, human impacts have completely eliminated seagrass beds (*e.g.,* Waquoit Bay, Massachusetts) (ALFARO, 2007; KENNISH, 2004; LEE, SHORT, and BURDICK, 2004; SHORT and BURDICK, 1996).

The decline of seagrass in Little Egg Harbor during the past 25 years is not unprecedented for estuarine systems in the mid-Atlantic region. ORTH and MOORE (1983, 1984) reported a dramatic decline of *Z. marina* beds in Chesapeake Bay. They also chronicled considerable variations in the growth of eelgrass in the bay, a finding corroborated by similar studies of other estuaries (BORTONE, 2000; ORTH and MOORE, 1986). Surveys of seagrass areal coverage have revealed broadscale changes in these subsystems (LATHROP *et al.,* 2001; ROBBINS, 1997).

The Barnegat Bay–Little Egg Harbor Estuary was reclassified in 1999 from a moderately eutrophic estuary to a highly eutrophic system based on application of the National Estuarine Eutrophication Assessment model (BRICKER *et al.,* 1999). Eutrophic conditions had worsened by 2007 (BRICKER *et al.,* 2007). SEITZINGER, STYLES, and PILLING, (2001) found that nutrient levels were highest in the northern segment of the estuary because of the effects of heavy coastal watershed development in the northern sector. They reported that mean concentrations of nitrate plus nitrite were less than 4 μM. Because of biotic uptake, nitrate plus nitrite levels were lowest in the summer. Highest values were recorded in the winter when autotrophic production was at a minimum. The NEW JERSEY DEPARTMENT OF ENVIRONMENTAL PROTECTION (1996) registered more variable nitrate plus nitrite con-

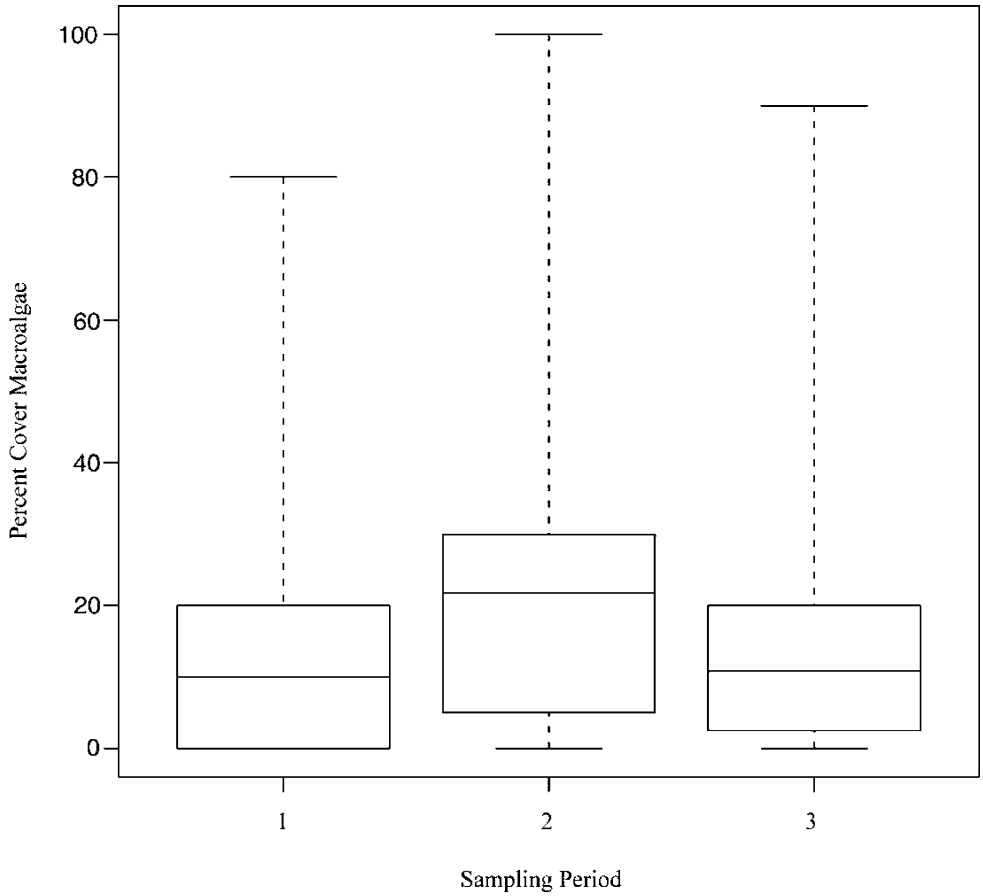

Figure 12. Mean percentage of cover by macroalgae at all sampling sites in Little Egg Harbor, New Jersey, during three sampling periods in 2004. Sampling period 1, June–July; sampling period 2, August–September; and sampling period 3, October–November.

centrations in the estuary. Mean ammonium concentrations compiled by SEITZINGER, STYLES, and PILLING, (2001) were less than 2.5 μM. Total nitrogen concentrations ranged from ~20 to ~80 μM. Most nitrogen in the estuary (87–90%) occurred in organic form. Phosphate concentrations were less than those of nitrate and ammonium, typically less that 1 μM.

Eutrophication poses a serious threat to the long-term health of seagrass beds in U.S. estuaries (HOWARTH *et al.,* 2000; KENNISH *et al.,* 2007; NIXON, 1995; RABALAIS, 2002). Nutrient loading, particularly nitrogen, has been responsible for the greater incidence of algal blooms and epiphytic growth, which have caused shading stress on seagrass beds *via* light attenuation. Macroalgal overburden can affect seagrasses by smothering the beds or by altering the sediment geochemistry. Sheet-like masses of drifting algae (*e.g., U. lactuca* and *Enteromorpha* spp.) are especially problematic because they grow rapidly when light and nutrient conditions are favorable, and their high biomasses can seriously damage seagrass habitat and associated benthic faunal communities within one growing season. For example, BOLOGNA, WILBUR, and ABLE (2001) reported significant losses of *Z. marina* habitat in Little Egg Harbor during 1998 as a consequence of macroalgal (*e.g., Ulva, Codium,* and *Gracilaria*) loading effects. They showed that large increases in algal–detrital biomass during the July–October period, which exceeded 400 g ash-free dry wt (AFDW) m^{-2}, resulted in complete elimination of the aboveground biomass of *Z. marina* in affected areas of Little Egg Harbor by October 1998. In addition, a reduction in the bay scallop (*Argopecten irradians*) population density during 1999 in these impacted areas may have been caused by the loss of eelgrass in 1998. As noted previously, the Barnegat Bay–Little Egg Harbor Estuary has been classified as a highly eutrophic system.

Other problems associated with eutrophication have surfaced in the Barnegat Bay–Little Egg Harbor Estuary. For example, brown tide blooms have commonly occurred in the estuary since 1995 (*i.e.,* 1995, 1997, and 1999–2002) (GASTRICH *et al.,* 2004a, 2004b; OLSEN and MAHONEY, 2001). Consisting of exceptionally high phytoplankton numbers, these blooms not only cause shading problems (DENNISON, MARSHALL, and WIGAND, 1989) but also discolor the estuarine waters yellowish-brown and can impact the growth of shellfish (*e.g., Mercenaria mercenaria*), the survival of bay scallops (*Argopecten irradians*), and the condition of seagrass beds (BOLOGNA, 2006; BOLOGNA, WILBUR, and ABLE, 2001; BRI-

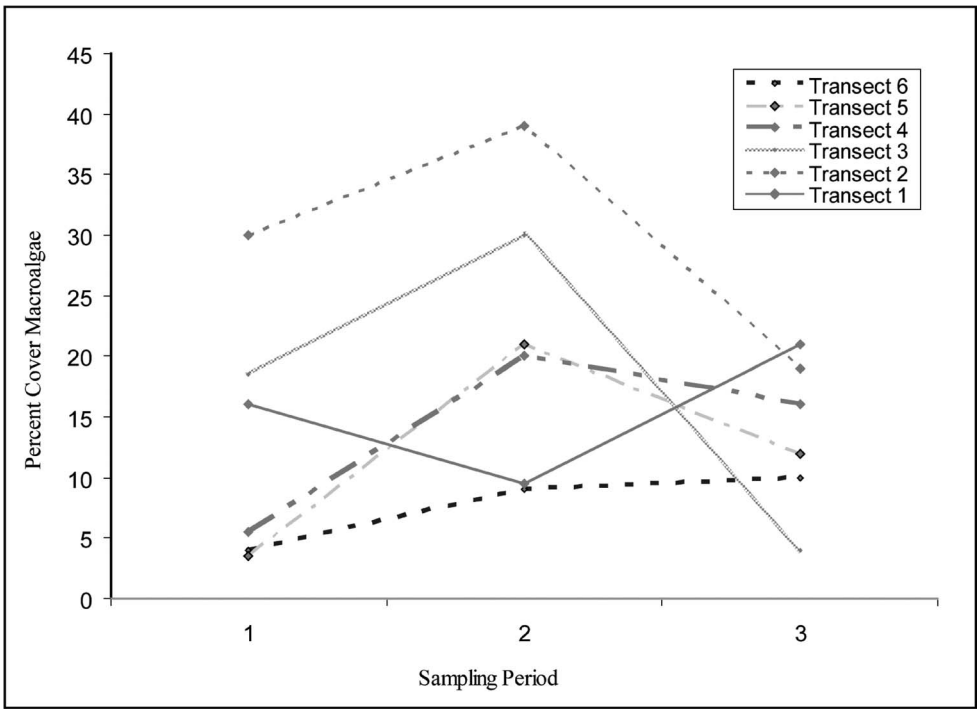

Figure 13. Mean percentage of cover by macroalgae at six transects in Little Egg Harbor, New Jersey, during three sampling periods in 2004. Sampling period 1, June–July; sampling period 2, August–September; and sampling period 3, October–November.

CELJ and LONSDALE, 1997). Brown tide blooms are caused by a minute alga, *Aureococcus anophagefferens* (Pelagophyceae), which forms spherical cells about 2–4 μm in diameter. During past years, peak numbers of *A. anophagefferens* have frequently occurred in June (OLSEN and MAHONEY, 2001). Maximum abundances of *A. anophagefferens* documented by the New Jersey Department of Environmental Protection during 2000, 2001, and 2002 exceeded 10^6 cells ml^{-1} each year. GASTRICH, ANDERSON, and COSPER (2002) and GASTRICH *et al.,* (2004a) noted that the levels of brown tide blooms in the Barnegat Bay–Little Egg Harbor Estuary were elevated relative to those in other estuaries where impacts on resources have been recorded, with the worst conditions observed in Little Egg Harbor.

When nutrient enrichment persists in estuaries, there are often shifts from large to small phytoplankton species and from diatoms to dinoflagellates that can affect benthic fauna. Additional impacts include a shift from filter-feeding to deposit-feeding benthos, and a progressive change from larger, long-lived benthic forms to smaller, rapidly growing, but shorter-lived, species (RABALAIS, 2002). The net effect is the potential for insidious and persistent alteration of biotic communities in the system associated with food-web alteration.

SCHRAMM (1999) and RABALAIS (2002) described a predictable series of changes in autotrophic components of estuarine and shallow marine ecosystems in response to progressive eutrophication. For those systems that are not eutrophic, the predominant benthic macrophytes inhabiting soft bottoms typically include perennial seagrasses and other phanerogams, with long-lived seaweeds occupying hard substrates. As slight to moderate eutrophic conditions arise, bloom-forming phytoplankton species and fast-growing, short-lived epiphytic macroalgae gradually replace the longer-lived macrophytes; hence, perennial macroalgal communities decline. Under greater eutrophic conditions, dense phytoplankton blooms occur along with drifting macroalgal species (*e.g., Ulva* and *Enteromorpha*), ultimately eliminating the perennial and slow-growing benthic macrophytes, a situation that may be taking place in some areas of the Barnegat Bay–Little Egg Harbor Estuary (KENNISH, 2001). With hypereutrophic conditions, benthic macrophytes become locally extinct, and phytoplankton dominate the autotrophic communities. Excessive nitrification also influences secondary production through altered food web interactions (LIVINGSTON, 2002).

The developing eutrophication problems in the Barnegat Bay–Little Egg Harbor Estuary, manifested in part by the increasing frequency of algal blooms and decreasing shellfish resources, have raised concern regarding the long-term condition of seagrasses in the system. BOLOGNA *et al.* (2000) and BOLOGNA, WILBUR, and ABLE (2001) not only documented dramatic losses of *Zostera marina* cover in Little Egg Harbor during the summer of 1998 but also reported a 62% reduction in coverage of seagrass there between 1975 and 1999. However, color imagery, taken from planes flown in the spring (May) of 2003 and complemented with boat-based surveys by Rutgers University, throughout the estuary revealed that seagrass distribution in the Barnegat Bay–Little Egg Harbor

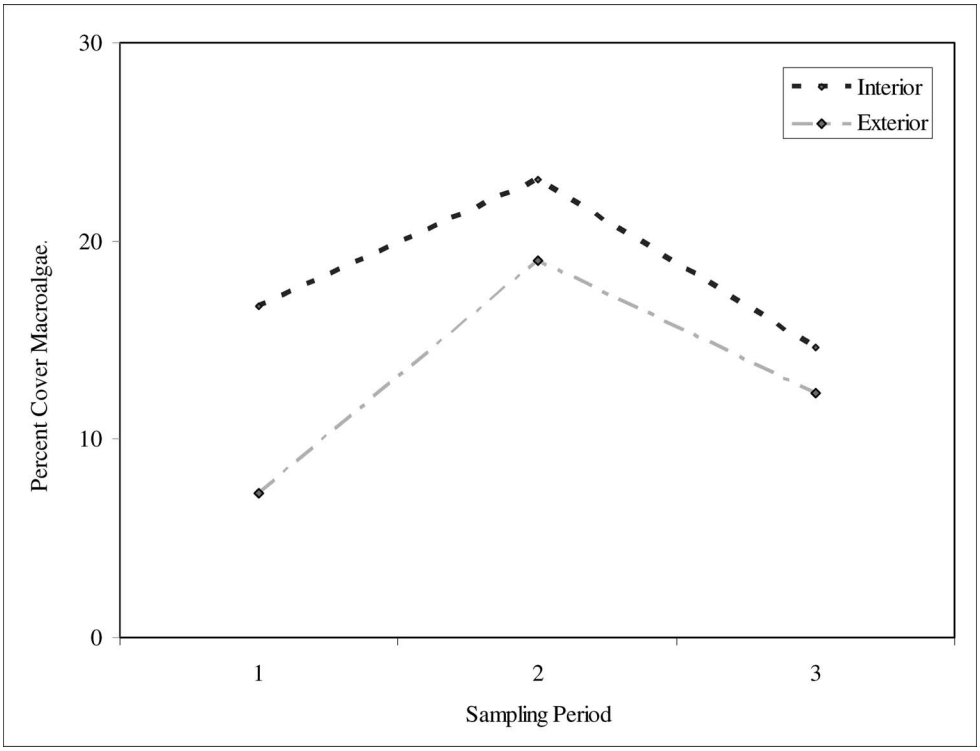

Figure 14. Mean percentage of cover by macroalgae at interior sampling sites (sites 3–8) and exterior sampling sites (sites 1, 2, 9, and 10) on transects in Little Egg Harbor, New Jersey, during three sampling periods in 2004. Sampling period 1, June–July; sampling period 2, August–September; and sampling period 3, October–November.

remained reasonably stable between 1998 and 2003 (LATHROP, MONTESANO, and HAAG, 2006). The apparent (15%) decline of seagrass beds between the late 1990s and 2003 was attributed to different mapping techniques rather than to actual seagrass losses.

There are major information gaps related to the importance of phytoplankton (brown tide) blooms on diminished water clarity and on potential impacts to seagrass beds in the Barnegat Bay–Little Egg Harbor Estuary. The significance of epiphytic algae, benthic macroalgae, wasting disease, and other disturbance factors on seagrass health and function in the estuary is also uncertain. As part of ongoing surveys in this system by Rutgers University, remote-sensing–based mapping is being complemented with *in situ* sampling to assess seagrass health and areal coverage as well as the impact of the aforementioned disturbance factors (KENNISH, HAAG, and SAKOWICZ, 2006; LATHROP *et al.,* 1999, 2001; LATHROP, MONTESANO, and HAAG, 2006).

In the current study, investigators conducted intensive

Table 6. *Mean* Zostera marina *blade length measured at all sampling sites during the June–November period in 2004.*[1]

Sample Period[2]	Blade Length (cm)	ANOVA
1	34.02 (12.00)	
		$F = 0.90$
2	32.21 (8.79)	
		$p = 0.4078$
3	31.83 (10.73)	

[1] Standard deviation in parentheses.
[2] Sample period 1 = June–July; sample period 2 = August–September; and sample period 3 = October–November.

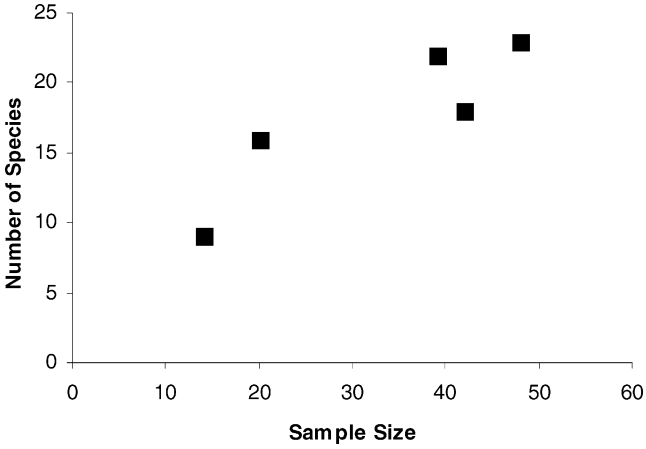

Figure 15. Plot of the number of samples collected relative to the number of macroalgal species found in Little Egg Harbor, New Jersey, during 2004.

Table 7. *Occurrence of macroalgae in bottom samples collected from the seagrass survey area in Little Egg Harbor, New Jersey, during the June–November period in 2004.*

Species	Occurrence (% of samples)
Chlorophyta	
Ulothrix flacca	10.4
Ulva lactuca	58.9
Enteromorpha intestinalis	9.8
Enteromorpha clathrata	3.7
Enteromorpha prolifera	5.5
Urospora penicilliformis	0.6
Percusaria percursa	0.6
Chaetomorpha linum	3.1
Cladophora spp.	0.6
Cladophora servica	1.8
Codium fragile	2.5
Rhodophyta	
Audouinella spp.	3.1
Gracilaria tikvahiae	30.1
Agardhiella subulata	3.1
Scinaia interrupta	2.5
Champia parvula	23.3
Lomentaria baileyana	9.2
Ceramium deslongchampsii	12.3
Ceramium cimbricum	10.4
Ceramium strictum	14.1
Ceramium diaphanum	9.2
Ceramium sp.	3.7
Spyridia filamentosa	54.6
Bostrychia radicans	0.6
Neosiphonia harveyi	11.0
Polysiphonia fucoids	0.6
Polysiphonia harveyi	1.2
Polysiphonia stricta	6.1
Polysiphonia subtilissima	5.5
Polysiphonia spp.	4.9
Phaeophyta	
Sphacelaria cirrhosa	1.8
Ectocarpus siliculosus	1.2

Table 8. *Number of* Aureococcus anophagefferens *recorded in the Barnegat Bay–Little Egg Harbor Estuary, New Jersey, during the 2000–2004 period.*[1]

Year	N[2]	Mean[3]	SD	Maximum[3]
2000	248	190,488	423,637	2,155,000
2001	148	246,540	416,598	1,883,000
2002	128	281,922	316,737	1,561,000
2003	136	8987	8616	54,000
2004	155	15,686	10,194	49,000

[1] Data from the New Jersey Department of Environmental Protection.
[2] N = Number of samples.
[3] Cells per milliliter.

sampling of *Zostera marina* beds in Little Egg Harbor during the 2004 growing season. Metric measurements of the seagrass beds showed that the maximum aboveground biomass (106.05 g dry wt m^{-2}) and belowground biomass (mean = 107.64 g dry wt m^{-2}) occurred during the June–July period. This is the time when the photoperiod peaks and nutrient levels are favorable for plant growth in the system. Seagrass biomass declined substantially during the succeeding sampling periods (August–September and October–November), and by the end of the survey, the mean aboveground biomass had decreased by 82.8% and the belowground biomass, by 53.1%.

OHORI (1982) reported biomass values of aboveground components of *Zostera marina* in Barnegat Bay amounting to 23.6 g dry wt m^{-2} in 1979 and 42.3 g dry wt m^{-2} in 1980. Working in the same region of the bay, WOOTTON and ZIMMERMAN (1999) documented decreasing seagrass biomass during the July–November sampling period, similar to our findings. At the Sedge Islands near Barnegat Inlet, the most productive of the WOOTTON and ZIMMERMAN (1999) seagrass sampling locations, aboveground biomass decreased from a mean of 141.23 g AFDW m^{-2} in July, to 25.05 g AFDW m^{-2} in August, and 0 g AFDW m^{-2} in November. Belowground biomass, which was higher, differed somewhat in trends from that of the aboveground biomass, with a mean value of 221 g AFDW m^{-2} in July and 270.69 g AFDW m^{-2} in August, and dropping to 152.69 g AFDW m^{-2} in November.

In a study of seagrass demographics in Little Egg Harbor during 1999, BOLOGNA *et al.* (2000) delineated progressively increasing monthly biomass values from May to August, followed by gradually decreasing biomass levels through October. The maximum biomass of *Zostera marina* (230 g AFDW m^{-2}) was ~50% greater than that observed by VAUGHN (1982) (149 g AFDW m^{-2}). This temporal sequence of seagrass biomass, with peak values in August 1999, differed from that reported here, with highest biomass values recorded in June–July and subsequent declining values into November. VAUGHN (1982) also ascertained an early (May–June) peak biomass of eelgrass in Little Egg Harbor in 1980–81. Hence, there appears to be significant seasonal variation in seagrass biomass from year to year in the estuary.

BOLOGNA (2006) found significant differences in habitat complexity and seagrass characteristics between the edge and interior portions of *Zostera marina* beds in Little Egg Harbor. Although the conditions in the interior zone of *Z. marina* beds were clearly better for plant growth than those at the edge, the differences in habitat structural complexity did not result in greater faunal abundance in the interior zone as reflected by the higher faunal density and secondary production observed at the edge of the *Z. marina* beds. In addition, noteworthy differences in faunal species composition were documented between the two habitat zones because of differences in plant structural features.

The decreasing biomass of seagrass in our study area during the June–November period also corresponded with a marked decrease in the percentage of cover by seagrass from 45% to 21%. However, the change in percentage of cover by macroalgae during this period was less consistent, with an increase from 13% to 21% from June to September followed by a decrease to 14% by November. The increase in the biomass and areal coverage by macroalgae from June to September was likely a major stressor on seagrass at this time and, possibly, a key factor in its decline. The frequency and magnitude of blooms of ephemeral green macroalgae, notably *Ulva lactuca,* appear to be a primary indicator of seagrass success/failure in the estuary. When both the frequency and magnitude of these blooms are high, the reduction in sea-

Figure 16. Bloom of *Ulva lactuca* in the seagrass study area in the Little Egg Harbor, New Jersey, during summer 2004. Rapid growth of *U. lactuca* covers extensive areas of the estuarine floor during bloom periods.

grass biomass and areal coverage can exceed 50% in local areas and, in extreme cases, can approach 100%. Seagrass dieback due to high nutrient availability and associated macroalgal blooms can significantly affect Little Egg Harbor ecosystem function and health.

The decrease in the abundance of bay scallops because of the loss of seagrass habitat in this system has been documented (BOLOGNA, WILBUR, and ABLE, 2001). It is likely that other benthic fauna in the study area have also been adversely affected by these acute events, but more investigations must be conducted on the benthic faunal communities to determine the overall impacts. If the benthic faunal communities in the heavily impacted areas have also been severely altered by the loss of critical habitat, then it would be useful to assess potential food-chain effects on upper trophic-level organisms. The loss of bay scallops by previous macroalgal blooms shows that resource species can be highly susceptible to seagrass decline in this system. BOLOGNA *et al.* (2005) reported that blue mussels (*Mytilus edulis*) settled in Barnegat Bay eelgrass beds in late spring at densities greater than 170,000 m^{-2}. Therefore, diminishing seagrass coverage could have a dramatic effect on the abundance of this important bivalve as well. Other resource species that use seagrass beds extensively, such as the blue crab (*Callinectes sapidus*), may also be impacted.

Several natural and anthropogenic factors create stressful conditions for seagrasses in Little Egg Harbor. For example, high water temperatures (>28 °C) in summer concomitant with increasing light attenuation caused by phytoplankton blooms (*e.g.,* brown tide) and suspended sediments can negatively affect seagrass growth and survival. Infestation of wasting disease can exacerbate these effects. BOLOGNA *et al.* (2000) determined that less than 10% of the seagrass samples collected in their surveys were infected by *Labyrinthula,* a protist responsible for wasting disease, although the infection rate varied greatly (0–50%). Early summer appeared to be the time of greatest negative impacts of wasting disease on the seagrass. They also recorded serious brown tide blooms

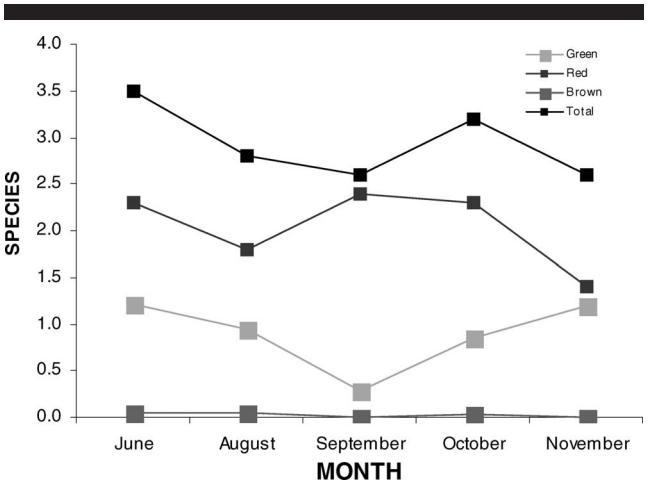

Figure 17. Number of macroalgal species collected *per* sample during the June–November study period in Little Egg Harbor, New Jersey, in 2004.

in the estuary during 1999. Only a small fraction (<10%) of the eelgrass samples collected in our study appeared to exhibit wasting disease. In addition, no brown tide blooms were observed in the estuary during 2004. The severity of wasting disease, occurrence of brown tide blooms, turbidity, and magnitude of summer temperatures all play an important role in influencing the abundance, biomass, and spatial coverage of seagrass in the estuary.

There have been a number of other investigations of seagrass habitat changes in estuaries using fixed-transect sampling designs. For example, MORRIS *et al.* (2000) conducted semiannual monitoring (summer–winter) of 76 fixed transects in the Indian River Lagoon, Florida, to measure shoot density, canopy height, and percentage of cover by multiple seagrass species (*i.e., Halodule wrightii, Syringodium filiforme, Ruppia maritima, Thalassia testudinum, Halophila johnsonii, Halophila decipiens,* and *Halophila engelmannii*). Their monitoring efforts over an extended period (1994–1998) revealed high temporal and spatial variability of seagrass abundance in the estuary from year to year. In addition, changes in seagrass cover varied greatly, exceeding 500% in some cases. Transect-site data-collection also proved to be valuable in assessing the recovery of an area following a major storm or season of drought conditions. By tracking long-term changes in seagrass abundance and cover *via* repeated field measurements along transects, the probability of separating natural variability from anthropogenic effects is increased.

PROVANCHA and SCHEIDT (2000) collected more than 8000 samples along 37 shallow-water transects in seagrass beds of the Mosquito Lagoon, Florida. They recorded the species composition and percentage of cover by seagrasses along these transects during a 13-year period. The following species were found (in declining frequency of occurrence): *Halodule wrightii* (71.9%), *Ruppia maritima* (23.7%), *Syringodium filiforme* (9.4%), *C. prolifera* (5.4%), and *Halophila engelmannii* (2.3%). The percentage of cover by each species was *H. wrightii* (35.6%), *R. maritima* (6.5%), *C. prolifera* (2.6%), *S. filiforme* (1.7%), and *H. engelmannii* (0.6%). The change in percentage of cover by these species through time was used to track the decline or expansion of seagrasses in the system. For example, *Halodule wrightii,* the dominant seagrass species, exhibited a significant decline during the study period. Shifts in *R. maritima* abundance during that period may have been responsible, in part, for the decrease in *H. wrightii.* Reduced salinity because of greater precipitation may also have been a factor. Once again, the monitoring of seagrass cover along sampling transects proved to be an effective and reliable method of tracking seagrass trends in the lagoon.

MOORE (2004) examined the relationships between seagrass-bed development and water quality in the lower region of the York River, Virginia, by sampling along transect sites across vegetated and formerly vegetated areas. Based on the analysis of water quality and macrophyte samples collected in this region of the lower Chesapeake Bay, MOORE (2004) concluded that the influence of seagrass on water quality in shallow waters of this system varied seasonally, reflecting the capacity of the seagrass beds to act as sources or sinks for suspended particulates and nutrients. The success of seagrasses in the study area may be dependent on the plants' capacity to regulate high levels of suspended particle concentrations during spring.

The aforementioned studies demonstrate the value of fixed-transect sampling in the assessment of seagrass bed condition. By conducting water quality monitoring, together with seagrass habitat measurements during extended periods, it is possible to effectively track the dynamic temporal and spatial patterns of these vital plant communities. The resulting databases are also useful in determining the factors responsible for the long-term changes in the distribution and coverage of seagrasses in shallow estuarine systems, an effort that is underway in the Barnegat Bay–Little Egg Harbor Estuary.

CONCLUSIONS

The Barnegat Bay–Little Egg Harbor Estuary, similar to other coastal bay systems in the mid-Atlantic region, is subject to an array of natural and anthropogenic stressors that pose a potential threat to the structure and function of seagrass habitat. With continued population growth and development in coastal watersheds surrounding this shallow estuary, future impacts on seagrass and other vital habitats are likely to escalate. Nutrient enrichment, elevated turbidity levels, prop scarring, and other factors coupled to anthropogenic activities are potential ongoing problems in this system, and they must be effectively addressed to mitigate future impacts. However, they require comprehensive monitoring, research, and remediation programs to meet the ecosystem-level challenges of environmental problems that have, to this point in time, eluded various management intervention strategies.

This investigation of the Barnegat Bay–Little Egg Harbor Estuary yielded a number of important findings. For example, the biomass of seagrass beds in Little Egg Harbor during the 2004 sampling period (June–November) exhibited impor-

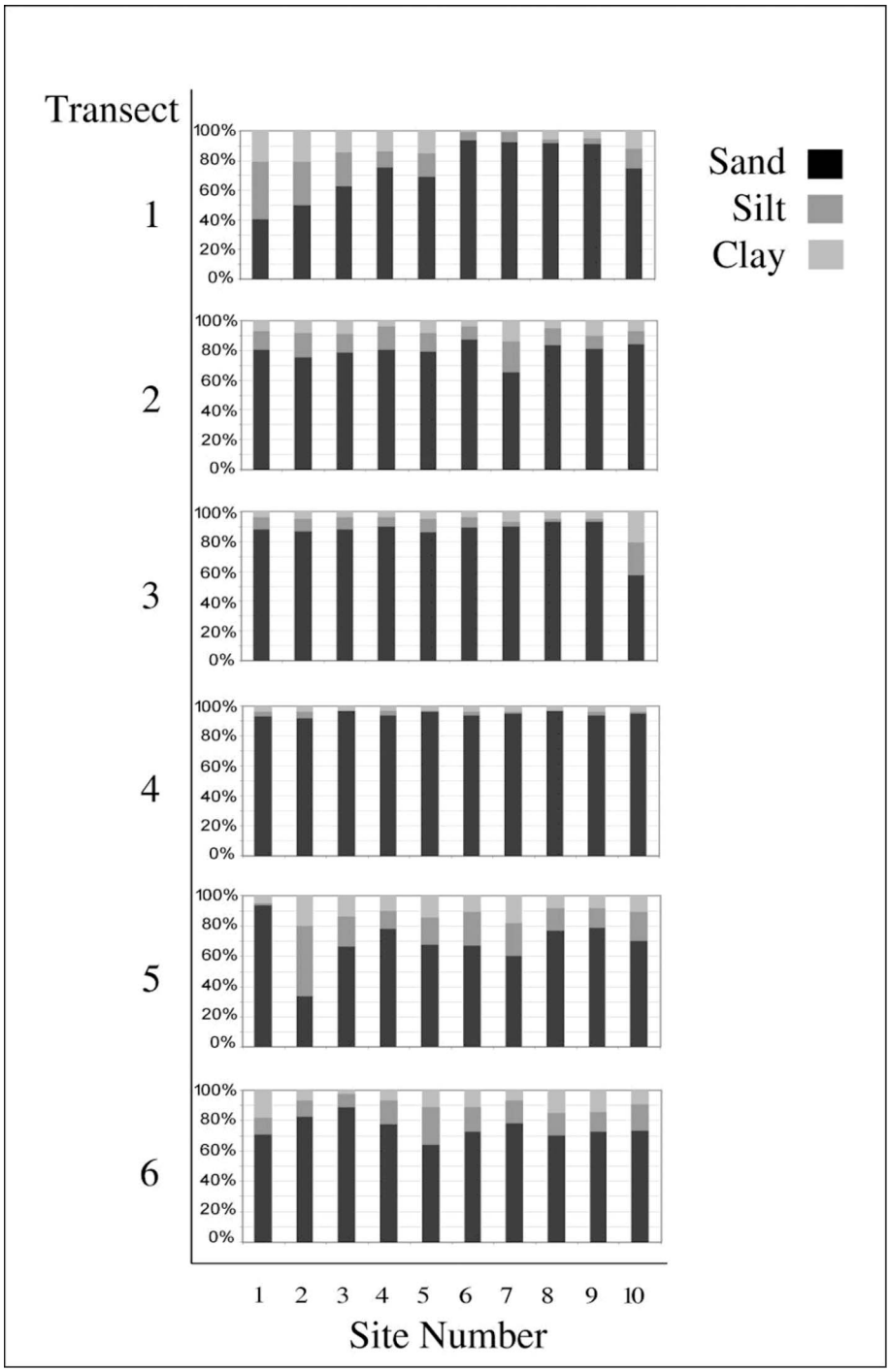

Figure 18. Sediment composition recorded at the seagrass sampling sites during the June–November study period in Little Egg Harbor, New Jersey, in 2004. Values shown as the percentage of sand, silt, and clay at each sampling site.

tant temporal and spatial patterns. Both aboveground and belowground biomass of seagrass peaked during June–July and then declined significantly during August–September and October–November. This temporal pattern is attributed to more favorable light and turbidity conditions during the late spring and early summer. A distinct spatial pattern of seagrass biomass was also evident, with highest aboveground and belowground biomass measurements recorded along the northernmost sampling transect.

Although considerable temporal and spatial variation of

eelgrass biomass was observed, eelgrass blade length was very consistent across sampling sites and sampling periods. There was only a slight decrease in mean eelgrass blade length from the June–July (34.02 cm) to August–September (32.21 cm) and October–November (31.83 cm) periods, despite the gradually declining photoperiod and variable water temperature during the 6-month study period. The maximum blade length did not vary substantially between the two different eelgrass beds.

The percentage of cover by seagrass followed biomass measurements, with gradually declining values registered from spring to fall. The highest mean percentage of cover by eelgrass in June–July (45%) was significantly greater than that in August–September (38%) or October–November (21%). In contrast, the percentage of cover by macroalgae was lower and more seasonally variable than the percentage of cover by seagrass. For example, the mean percentage of cover by macroalgae increased from 13% in June–July to 21% in August–September and then declined to 14% in October–November. The highest percentage of cover by macroalgae in August–September probably reflects the greater growth and abundance of different algal species at this time.

Most of the macroalgal species in the Barnegat Bay–Little Egg Harbor Estuary belong to a drift community. However, macroalgal blooms and patches that blanket the estuarine floor can be particularly detrimental to seagrass beds and associated benthic fauna. They hinder seagrass growth by shading or blocking sunlight and can render the estuarine floor unsuitable for regrowth of seagrass for extended periods. Hence, excessive growth of macroalgae in the estuary can be extremely damaging to seagrass habitat, a finding corroborated by studies conducted in other coastal bays in the mid-Atlantic region and elsewhere.

During the study period, 32 macroalgal species were documented in the survey area. Red algae ($n = 19$) accounted for 59% of the species collected, with green algae ($n = 11$) comprising 34%, and brown algae ($n = 2$) only 6%. *Ulva lactuca* was the most common algal species, found in 59% of the samples. Sheetlike species, such as *U. lactuca,* appear to pose the most serious threat to seagrass beds because they often form extensive patches that blanket and damage the seagrass plants.

Although brown tide (*Aureococcus anophagefferens*) blooms may be equally detrimental to seagrass beds because of their shading effects, no blooms were observed during the 2004 sampling period. The maximum cell counts of *A. anophagefferens* reported in the estuary during 2004 amounted to 4.9×10^4 cells ml^{-1}. These numbers are far less than those recorded during the bloom years of 2000–02 ($>1 \times 10^6$ cells ml^{-1}). Thus, it is very unlikely that *A. anophagefferens* had any adverse impact on the seagrass beds in Little Egg Harbor during the study period.

This investigation generated a significant database on the demographic characteristics and habitat change of seagrass in Little Egg Harbor. It also yielded valuable information on the species composition, frequency of occurrence, and potential impacts of benthic macroalgae on the seagrass beds in bay waters. The collective databases serve as a platform for improved understanding of seagrass dynamics in the Barnegat Bay–Little Egg Harbor Estuary.

ACKNOWLEDGMENTS

This work was conducted under a research award from the Estuarine Reserves Division, Office of Ocean and Coastal Resource Management, National Ocean Service, National Oceanic and Atmospheric Administration. This is contribution No. 1037-08 from the Institute of Marine and Coastal Sciences, Rutgers University.

LITERATURE CITED

ALFARO, A.A., 2007. Benthic macro-invertebrate community composition within a mangrove/seagrass estuary in northern New Zealand. *Estuarine, Coastal and Shelf Science,* 66, 97–110.

BOLOGNA, P.A.X., 2006. Assessing within habitat variability in plant demography, faunal density, and secondary production in an eelgrass (*Zostera marina* L.) bed. *Journal of Experimental Marine Biology and Ecology,* 329, 122–134.

BOLOGNA, P.A.X.; FETZER, M.L.; MCDONNELL, S., and MOODY, E.M., 2005. Assessing the potential benthic-pelagic coupling in episodic blue mussel (*Mytilus edulis*) settlement events within eelgrass (*Zostera marina*) communities. *Journal of Marine Biology and Ecology,* 316, 117–131.

BOLOGNA, P.A.X.; LATHROP, R.; BOWERS, P.D., and ABLE, K.W., 2000. Assessment of the Health and Distribution of Submerged Aquatic Vegetation from Little Egg Harbor, New Jersey. New Brunswick, New Jersey: Institute of Marine and Coastal Sciences, Rutgers University, Technical Report 2000-11. 30p.

BOLOGNA, P.A.X.; WILBUR, A., and ABLE, K.W., 2001. Reproduction, population structure, and recruitment limitation in a bay scallop (*Argopecten irradians* Lamarck) population from New Jersey, USA. *Journal of Shellfish Research,* 20, 89–96.

BORTONE, S.A. (ed.), 2000. *Seagrasses: Monitoring, Ecology, Physiology, and Management.* Boca Raton, Florida: CRC Press, 318p.

BRICELJ, M. and LONSDALE, D., 1997. *Aureococcus anophagefferens*: causes and ecological consequences of brown tides in U.S. mid-Atlantic coastal waters. *Limnology and Oceanography,* 42, 1023–1038.

BRICKER, S.B.; CLEMENT, C.G.; PIRHALL, D.E.; ORLANDO, S.P., and FARROW, D.R.G., 1999. National Estuarine Eutrophication Assessment: Effects of Nutrient Enrichment in the Nation's Estuaries. Silver Spring, Maryland: National Oceanic and Atmospheric Administration, National Ocean Service, Special Projects Office and National Centers for Coastal Ocean Science.

BRICKER, S.B.; LONGSTAFF, B.; DENNISON, W.; JONES, A.; BOICOURT, K.; WICKS, C., and WOERNER, J., 2007. Effects of nutrient enrichment in the nation's estuaries: a decade of change. Silver Spring, Maryland: National Oceanic and Atmospheric Administration, National Centers for Coastal Ocean Science, Coastal Ocean Program Decision Analysis Series 26.

CAFFREY, J.M. and KEMP, W.M., 1990. Nitrogen cycling in sediments with estuarine populations of *Potamogeton perfoliatus* and *Zostera marina. Marine Ecology Progress Series,* 66, 147–160.

CORBETT, C.A.; DOERING, P.H.; MADLEY, K.A.; OTT, J.A., and TOMASKO, D.A., 2005. Using seagrass coverage as an indicator of ecosystem condition. *In*: BORTONE, S.A. (ed.), *Estuarine Indicators.* Boca Raton, Florida: CRC Press, pp. 229–245.

CUMMINGS, M.E. and ZIMMERMAN, R.C., 2003. Light harvesting and the package effect in seagrasses *Thalassia testudinum* Banks ex König and *Zostera marina* L.: optical constraints on photoaccumulation. *Aquatic Botany,* 75, 261–274.

DE HARTOG, C., 1987. Wasting disease and other dynamic phenomena in *Zostera* beds. *Aquatic Botany,* 27, 3–14.

DENNISON, W.; MARSHALL, G., and WIGAND, C., 1989. Effect of brown-tide shading on eelgrass (*Zostera marina* L.) distributions. *In:* COSPER, E.; BRICELJ, V., and CARPENTER, E. (eds.), *Novel Phytoplankton Blooms.* New York: Springer-Verlag, pp. 675–692.

DENNISON, W.C.; ORTH, R.J.; MOORE, K.A.; STEVENSON, J.C.; CARTER, V.; KOLLAR, S.; BERGSTROM, P.W., and BATIUK, R.A., 1993. Assessing water quality with submersed aquatic vegetation: habitat requirements as barometers of Chesapeake Bay health. *Bioscience,* 43, 86–94.

DIXON, L.K., 2000. Establishing light requirements for the seagrass *Thalassia testudinum*: an example from Tampa Bay, Florida. *In:* BORTONE, S.A. (ed.), *Seagrasses: Monitoring, Ecology, Physiology, and Management.* Boca Raton, Florida: CRC Press, pp. 9–31.

FITENI, S.J., 1981. The Distribution of the Macroalgal Epiphytes of *Zostera marina* in Barnegat Bay, New Jersey. New Brunswick, New Jersey: Rutgers University, Master's thesis.

FRANKOVICH, T.A. and ZIEMAN, J.C., 2005. Periphyton light transmission relationships in Florida Bay and the Florida Keys, USA. *Aquatic Botany,* 83, 14–30.

GASTRICH, M.D.; ANDERSON, O.R., and COSPER, E.M., 2002. Viral-like particles (VLPs) in the alga, *Aureococcus anophagefferens* (Pelagophyceae), during 1999–2000 brown tide blooms in Little Egg Harbor, New Jersey. *Estuaries,* 25, 938–943.

GASTRICH, M.D.; LATHROP, R.; HAAG, S.; WEINSTEIN, M.P.; DANKO, M.; CARON, D.A., and SCHAFFNER, R., 2004a. Assessment of brown tide blooms, caused by *Aureococcus anophagefferens,* and contributing factors in New Jersey coastal bays: 2000–2002. *Harmful Algae,* 3, 305–320.

GASTRICH, M.D.; LEIGH-BELL, J.A.; GOBLER, C.J.; ANDERSON, O.R.; WILHELM, S.W., and BRYAN, M., 2004b. Viruses as potential regulators of regional brown tide blooms caused by the alga, *Aureococcus anophagefferens. Estuaries,* 27, 112–119.

GOOD, R.E.; LIMB, J.; LYSZCZEK, E.; MIERNIK, M.; OGROSKY, C.; PSUTY, N.; RYAN, J., and SICKELS, F., 1978. Analysis and Delineation of Submerged Vegetation of Coastal New Jersey: A Case Study of Little Egg Harbor. New Brunswick, New Jersey: Center for Coastal and Environmental Studies, Rutgers University, Technical Report.

HAUXWELL, J.; CEBRIAN, J., and VALIELA, I., 2003. Eelgrass *Zostera marina* loss in temperate estuaries: relationships to land-derived nitrogen loads and effect of light limitation imposed by algae. *Marine Ecology Progress Series,* 247, 59–73.

HECK, K.L.; ABLE, K.W.; ROMAN, C.T., and FAHAY, M., 1995. Composition, abundance, biomass, and production of macrofauna in a New England estuary: comparison among eelgrass meadows and other nursery habitats. *Estuaries,* 18, 379–389.

HECK, K.L. and VALENTINE, J.F., 2006. Plant-herbivore interactions in seagrass meadows. *Journal of Experimental Marine Biology and Ecology,* 330, 420–436.

HILY, C.; CONNAN, S.; RAFFIN, C., and WYLLIE-ECHEVERRIA, S., 2004. *In vitro* experimental assessment of the grazing pressure of two gastropods on *Zostera marina* L. epiphytic algae. *Aquatic Botany,* 78, 183–195.

HOWARTH, R.W.; ANDERSON, D.M.; CHURCH, T.M.; GREENING, H.; HOPKINSON, C.S.; HUBER, W.C.; MARCUS, N.; NAINMAN, R.J.; SEGERSON, K.; SHARPLEY, A.N., and WISEMAN, W.J., 2000. Clean Coastal Waters: Understanding and Reducing the Effects of Nutrient Pollution. Washington, D.C.: National Academy Press, Ocean Studies Board and Water Science and Technology Board, 391p.

KEMP, W.M., 1983. Seagrass communities as a coastal resource. *Marine Technology Society Journal,* 17, 3–5.

KEMP, W.M., 2000. Seagrass ecology and management: an introduction. *In:* BORTONE, S.A. (ed.), *Seagrasses: Monitoring, Ecology, Physiology, and Management.* Boca, Raton, Florida: CRC Press, pp. 1–6.

KENNISH, M.J. (ed.), 2001. Barnegat Bay–Little Egg Harbor, New Jersey: Estuary and Watershed Assessment. *Journal of Coastal Research,* Special Issue No. 32, 280p.

KENNISH, M.J., 2002a. Environmental threats and environmental future of estuaries. *Environmental Conservation,* 29, 78–107.

KENNISH, M.J. (ed.), 2002b. Impacts of motorized watercraft on shallow estuarine and coastal marine environments. *Journal of Coastal Research,* Special Issue No. 32, 202p.

KENNISH, M.J. (ed.), 2004. *Estuarine Research, Monitoring, and Resource Protection.* Boca Raton, Florida: CRC Press, 297p.

KENNISH, M.J.; BRICKER, S.B.; DENNISON, W.C.; GLIBERT, P.M.; LIVINGSTON, R.J.; MOORE, K.A.; NOBLE, R.T.; PAERL, H.W.; RAMSTACK, J.M.; SEITZINGER, S.; TOMASKO, D.A., and VALIELA, I., 2007. Barnegat Bay–Little Egg Harbor Estuary: case study of a highly eutrophic coastal bay system. *Ecological Applications,* 17(5) S3–S16.

KENNISH, M.J.; HAAG, S.M, and SAKOWICZ, G.P., 2006. Application of underwater videography to characterize seagrass habitats in Little Egg Harbor, New Jersey. *Bulletin of the New Jersey Academy of Science,* 51, 1–6.

KENWORTHY, W.J.; FONSECA, M.S.; WHITFIELD, P.E, and HAMMERSTROM, K.K., 2001. Analysis of seagrass recovery in experimental excavations and propeller-scar disturbances in the Florida Keys National Marine Sanctuary. *Journal of Coastal Research,* Special Issue No. 37, pp. 75–85.

LARKUM, W.D.; ORTH, R.J., and DUARTE, C.M. (eds.), 2006. *Seagrasses: Biology, Ecology, and Conservation.* Dordrecht, The Netherlands: Springer.

LATHROP, R.G., JR.; BOGNAR, J.A.; HENRICKSON, A.C., and BOWERS, P.D., 1999. Data Synthesis Effort for the Barnegat Bay Estuary Program: Habitat Loss and Alteration in the Barnegat Bay Region. New Brunswick, New Jersey: Center for Remote Sensing and Spatial Analysis, Rutgers University, Technical Report.

LATHROP, R.G. and BOGNAR, J., 2001 Habitat loss and alteration in the Barnegat Bay Region. *Journal of Coastal Research,* Special Issue No. 32, pp. 212–228.

LATHROP, R.G.; STYLES, R.; SEITZINGER, S., and BOGNAR, J., 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.; MONTESANO, P., and HAAG, S., 2006. A multi-scale segmentation approach to mapping submerged seagrass habitats using airborne digital camera imagery. *Photogrammetric Engineering and Remote Sensing,* 72, 665–675.

LEE, K-S.; SHORT, F.T., and BURDICK, D.M., 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.

LINK, T.E.; PLATELL, M.E., and POTTER, I.C., 2001. Factors influencing the partitioning of food resources among six fish species in a large embayment with juxtaposing bare sand and seagrass habitats. *Journal of Experimental Marine Biology and Ecology,* 266, 193–217.

LIVINGSTON, R.J., 2002. *Trophic Organization in Coastal Systems.* Boca Raton, Florida: CRC Press, 388p.

MACOMBER, R.T. and ALLEN, D., 1979. The New Jersey Submerged Aquatic Vegetation Distribution Atlas Final Report. Trenton, New Jersey: Department of Environmental Protection, Division of Coastal Resources, Bureau of Coastal Planning and Development, Volume 2. 25p.

MCLAIN, P. and MCHALE, M., 1997. Barnegat Bay eelgrass investigation 1995–96. *In:* FLIMLIN, G.E. and KENNISH, M.J. (eds.), *Proceedings of the Barnegat Bay Ecosystem Workshop.* Toms River, New Jersey; Rutgers Cooperative Extension of Ocean County, pp. 165–171.

MOORE, K.A., 2004. Influence of seagrasses on water quality in shallow regions of the lower Chesapeake Bay. *Journal of Coastal Research,* Special Issue No. 45, pp. 162–178.

MOORE, K.A. and WETZEL, R.L., 2000. Seasonal variations in eelgrass (*Zostera marina* L.) responses to nutrient enrichment and reduced light availability in experimental ecosystems. *Journal of Experimental Marine Biology and Ecology,* 244, 1–28.

MOORE, K.A.; NECKLES, H.A., and ORTH, R.J., 1996. *Zostera marina* (eelgrass) growth and survival along a gradient of nutrients and turbidity in the lower Chesapeake Bay. *Marine Ecology Progress Series,* 142, 247–259.

MORRIS, L.J.; VIRNSTEIN, R.W.; MILLER, J.D., and HALL, L.M., 2000. Monitoring seagrasses changes in Indian River Lagoon, Florida, using fixed transects. *In:* BORTONE, S.A. (ed.), *Seagrasses: Monitoring, Ecology, Physiology, and Management.* Boca Raton, Florida: CRC Press, pp. 167–176.

NEW JERSEY DEPARTMENT OF ENVIRONMENTAL PROTECTION, 1996.

Shellfish Growing Area 6: Manasquan River 1990–1995. Trenton, New Jersey: NJDEP, Water Monitoring Project Report.

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

OHORI, V.L., 1982. The Distribution, Abundance, and Importance of the Seagrass, *Zostera marina* L., in the Vicinity of Oyster Creek Nuclear Generating Station, Barnegat Bay, New Jersey, 1979–1980. New Brunswick, New Jersey: Rutgers University, Master's thesis.

OLSEN, P.S. and MAHONEY, J.B., 2001. Phytoplankton in the Barnegat Bay–Little Egg Harbor estuarine system: species composition and picoplankton bloom development. *Journal of Coastal Research,* Special Issue No. 32, pp. 115–143.

ORTH, R.J.; LUCKENBACH, M.L.; MARION, S.R.; MOORE, K.A., and WILCOX, D.J., 2006. Seagrass recovery in the Delmarva coastal bays, USA. *Aquatic Botany,* 84, 26–36.

ORTH, R.J. and MOORE, K.A., 1983. An unprecedented decline in submerged aquatic vegetation. *Science,* 222, 51–53.

ORTH, R.J. and MOORE, K.A., 1984. Distribution and abundance of submerged aquatic vegetation in Chesapeake Bay: an historical perspective. *Estuaries,* 7, 531–540.

ORTH, R.J. and MOORE, K.A., 1986. Seasonal and year-to-year variations in the growth of *Zostera marina* L. (eelgrass) in lower Chesapeake Bay. *Aquatic Botany,* 24, 335–341.

PROVANCHA, J.A. and SCHEIDT, D.M., 2000. Long-term trends in seagrass beds in the Mosquito Lagoon and Northern Banana River, Florida. *In:* BORTONE, S.A. (ed.), *Seagrasses: Monitoring, Ecology, Physiology, and Management.* Boca Raton, Florida: CRC Press, pp. 177–193.

RABALAIS, N.N., 2002. Nitrogen in aquatic ecosystems. *Ambio,* 21, 102–112.

ROBBINS, B., 1997. Quantifying temporal change in seagrass areal coverage: the use of GIS and low resolution aerial photography. *Aquatic Botany,* 58, 259–267.

SCHRAMM, W., 1999. Factors influencing seaweed responses to eutrophication: some results from EU-project EUMAC. *Journal of Applied Phycology,* 11, 69–78.

SEITZINGER, S.P.; STYLES, R.M., and PILLING, I.E., 2001. Benthic microalgal and phytoplankton production in Barnegat Bay, New Jersey (USA): microcosm experiments and data synthesis. *Journal of Coastal Research,* Special Issue No. 32, pp. 144–162.

SHORT, F.T. and BURDICK, D.M., 1996. Quantifying eelgrass habitat loss in relation to housing development and nitrogen loading in Waquoit Bay, Massachusetts. *Estuaries,* 19, 730–739.

SHORT, F.T.; MCKENZIE, L.J.; COLES, R.G., and VIDLER, K.P., 2002. *SeagrassNet Manual for Scientific Monitoring of Seagrass Habitat.* Cairns, Australia: Queensland Fisheries Service, Queensland Department of Primary Industries and Fisheries, 56p.

SHORT, F.T. and WYLLIE-ECHEVERRIA, S., 1996. Natural and human-induced disturbance of seagrasses. *Environmental Conservation,* 23, 17–27.

SOGARD, S.M. and ABLE, K.W., 1991. A comparison of eelgrass, sea lettuce macroalgae, and marsh creeks as habitats for epibenthic fishes and decapods. *Estuarine, Coastal and Shelf Science,* 33, 501–519.

VALIELA, I., 2006. *Global Coastal Change.* Cambridge, United Kingdom: Cambridge University Press.

VAUGHN, D., 1982. Production Ecology of Eelgrass (*Zostera marina* L.) and Its Epiphytes in Little Egg Harbor, New Jersey. New Brunswick, New Jersey: Rutgers University, Doctoral thesis, 137p.

WOOTTON, L. and ZIMMERMAN, R.W., 1999. Water Quality and Biomass of *Zostera marina* (Eelgrass) Beds in Barnegat Bay. Lakewood, New Jersey: Georgian Court College Technical Report.