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BENTHIC MACROALGAL BLOOMS AS AN INDICATOR OF SYSTEM EUTROPHY IN THE BARNEGAT BAY–LITTLE EGG HARBOR ESTUARY

MICHAEL J. KENNISH, BENJAMIN FERTIG, AND GREGG P. SAKOWICZ

INSTITUTE OF MARINE AND COASTAL SCIENCES, RUTGERS UNIVERSITY, NEW BRUNSWICK, NJ 08901, KENNISH@MARINE.RUTGERS.EDU

ABSTRACT: *Macroalgal blooms develop during the spring-summer period in the Barnegat Bay–Little Egg Harbor Estuary, a highly eutrophic coastal lagoon in New Jersey, and these blooms are detrimental to seagrass habitat in the system. Recurring blooms of drifting red and green macroalgae (e.g.,* Gracilaria tikvahiae *and* Ulva lactuca*) attenuate or block light transmission to seagrass beds and also produce extensive organic mats that can alter biogeochemical processes in bottom sediments. Investigations of macroalgal blooms in the estuary over a six-year period documented 55 occurrences (2.23 blooms m^{-2}) of Early Bloom (70%–80% macroalgal cover) and Full Bloom (>80% macroalgal cover) events, which resulted in increased mortality of seagrass leading to reduced biomass and bare-bottom areas within the beds.*

KEY WORDS: Coastal lagoon, eutrophication, macroalgal blooms, seagrass impacts

INTRODUCTION

More than 110 benthic macroalgal species have been identified in Barnegat Bay–Little Egg Harbor, a highly eutrophic lagoonal estuary in New Jersey (Kennish, 2001; Kennish et al., 2010). Both perennial forms and ephemeral, bloom-forming species occur in the estuary, with many comprising a drift community unattached to any substrate. Sheet-like masses of some species (e.g., *Ulva lactuca* and *Enteromorpha intestinalis*) are particularly problematic because they grow rapidly when light and nutrient conditions are favorable, outcompeting seagrasses and other vascular plants that constitute essential benthic habitat in the system (Coffaro and Bocci, 1997; Nelson and Lee, 2001). In the nutrient enriched waters of this coastal lagoon, bloom-forming macroalgal species have been observed to form dense canopies more than 25 cm thick overlying seagrass beds, which block light transmission to the beds (Twilley et al., 1985; Kennish et al., 2010). As the algal standing stocks increase, shading reduces the photosynthetic oxygen production of the seagrass plants causing diebacks (Lee et al., 2007; Ralph et al., 2007). In addition, the accumulation and decomposition of decaying plant matter and ooze in bottom sediments can result in high concentrations of sulfide in the rhizosphere that decrease nutrient uptake and contribute to additional reduction in photosynthesis, growth, leaf density, and an increase in ammonium, oxygen depletion, and seagrass mortality (Holmer and Bondgaard, 2001; Burkholder et al., 2007; McGlathery et al., 2007).

We surveyed macroalgal blooms at 120 sampling stations in Barnegat Bay–Little Egg Harbor over the 2004 to 2010 period as part of an overall assessment of the condition of seagrass habitat in the estuary. The objective of this study was to determine the frequency of occurrence of macroalgal blooms, their spatial and temporal variation, and their impact on seagrass beds in the estuary. The composition of the bloom-forming macroalgal species was investigated during 2004 and 2005.

STUDY AREA

Barnegat Bay–Little Egg Harbor Estuary is 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 × 10 m^8 (Kennish, 2001). The location of the barrier island complex (Island Beach and Long Beach Island) greatly limits the exchange of estuarine water with the coastal ocean; therefore, the water residence time of the estuary is protracted, ~74 days in summer. The low flushing rate promotes nutrient enrichment of the estuarine basin. Exchange of bay and ocean water occurs through

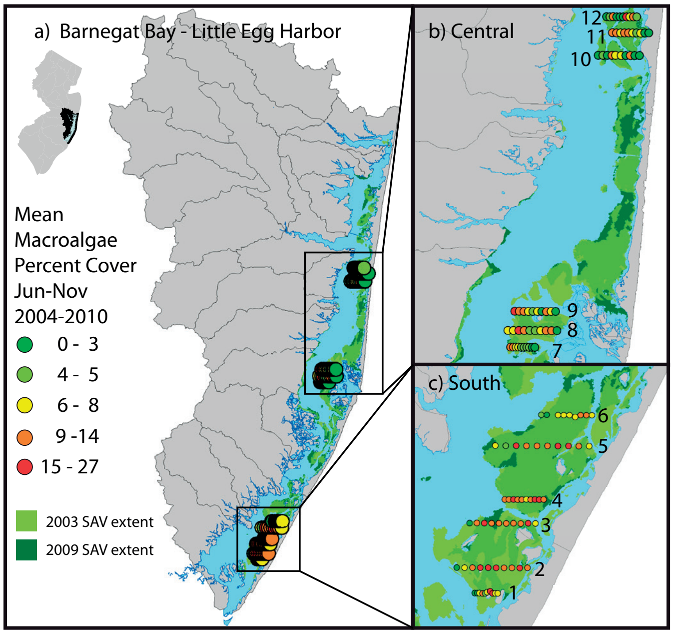

Figure 1. Map of the Barnegat Bay–Little Egg Harbor Estuary study site. Note 12 transects and 120 sampling stations along the transects. Inset shows the location of the estuary with respect to the state of New Jersey.

the Pt. Pleasant Canal in the northern perimeter, Barnegat Inlet in the mid-bay, and Little Egg Inlet in the southern extremity.

MATERIALS AND METHODS

Quadrat and hand sampling was conducted in four disjunct seagrass beds of Barnegat Bay (~1550 ha) and Little Egg Harbor (~1700 ha) to examine macroalgal bloom occurrence and effects on seagrass habitat. We established 10 sampling stations spaced at equal intervals along each of 12 transects spanning the width of the seagrass beds (0.63 km to 2.57 km) along the east-west axis of the estuary (Figure 1), conducting sampling during three successive periods (June–July, August–September, October–November) each year. These stations were permanently located with a Differential Global Positioning System (Trimble®GeoXT™ handheld unit). Macroalgae sampling was conducted at 60 stations in Little Egg Harbor (Transects 1–6) during 2004 and at 60 stations in Barnegat Bay (Transects 7–12) during 2005. Taxonomy surveys were conducted during 2004 and 2005 to determine the composition of macroalgae in the four seagrass beds. Macroalgae sampling was expanded to 80 stations in 2006 (40 in Little Egg Harbor and 40 in Barnegat Bay), and all 120 stations in 2008, 2009, and 2010. No sampling was conducted in the estuary in 2007. The sampling protocols consisted of haphazardly tossing a 0.25-m^2 metal quadrat at each station and having a diver estimate the areal cover of macroalgae within the quadrat using a scale of 0 to 100 in increments of 5. The diver then visually inspected the seagrass bed surrounding the quadrat for additional evidence of macroalgal blooms and their spatial distribution. Areal percent cover of macroalgae (%) was recorded for each sampling station. Macroalgae areal cover of 60-70% was considered 'Pre-Bloom', 70-80% was considered 'Early Bloom', and > 80% was considered 'Full Bloom' conditions. Bloom occurrences at all levels were reported as # blooms m^{-2} to account for changes in sampling effort.

Spatial patterns were identified across transects and between Little Egg Harbor and Barnegat Bay by mapping (ArcMap 9.2) mean macroalgae percent cover (June–November, 2004–2010) at each of the 120 stations overlaid on the extent of seagrass (2003 and 2009) in Barnegat Bay, as determined by remote sensing (Kennish et al. 2010). Tukey-adjusted ANOVAs (Proc Mixed, SAS Inc.) tested for spatial differences in macroalgae percent cover. Regression analysis (Proc Reg, SAS Inc.) of macroalgae percent cover was conducted across years for each time period to determine long-term trends and across time periods for each year to determine seasonal patterns. Correlations (Proc Corr, SAS Inc.) between macroalgae percent cover and seagrass metrics (biomass, shoot density, blade length, percent cover) were analyzed on the complete dataset.

RESULTS

The absolute percent cover of macroalgae at the sampling stations during all years ranged from 0–100%, and the mean percent cover of macroalgae ranged from 2–21%. Table 1 shows the area normalized frequency of occurrence of macroalgal bloom conditions in the estuary for each survey year. There were 10 occurrences (0.45 blooms m^{-2}) of Pre-Bloom conditions (60–70% macroalgae cover), 19 occurrences (0.67 blooms m^{-2}) of Early Bloom conditions (70–80%), and 36 occurrences (1.57 blooms m^{-2}) of Full Bloom conditions (80–100%), indicating that macroalgal blooms developed relatively frequently in

Table 1. Area normalized occurrences of macroalgal blooms (# blooms m^{-2}) in the Barnegat Bay–Little Egg Harbor Estuary over the 2004–2010 study period.

	Pre-Bloom (60–70%)			Early Bloom (70–80%)			Full Bloom (80–100%)		
	Jun–Jul	Aug–Sep	Oct–Nov	Jun–Jul	Aug–Sep	Oct–Nov	Jun–Jul	Aug–Sep	Oct–Nov
2004	0.00	0.07	0.00	0.00	0.00	0.00	0.13	0.27	0.13
2005	0.13	0.00	0.00	0.00	0.00	0.00	0.13	0.00	0.00
2006	0.00	0.05	0.00	0.00	0.05	0.05	0.00	0.05	0.05
2008	0.00	0.00	0.00	0.27	0.10	0.00	0.23	0.13	0.00
2009	0.07	0.03	0.07	0.03	0.03	0.13	0.07	0.00	0.10
2010	0.00	0.03	0.00	0.00	0.00	0.00	0.03	0.13	0.10

Table 2. Regression analysis of macroalgae areal percent cover: (a) over 2004–2010 for each of three time periods; and (b) over the three time periods for each year.

a)

Time Period	n	Slope	Intercept	R^2	F	P
June–July	600	-0.66	1,338	0.00	2.91	0.09
Aug.–Sept.	600	-1.50	3,015	0.03	19.60	**<0.01**
Oct.–Nov.	600	-0.37	760	0.00	1.40	0.24

b)

Year	n	Slope	Intercept	R^2	F	P
2004	180	0.46	15.03	0.00	0.06	0.80
2005	180	-6.04	19.86	0.11	21.61	**<0.01**
2006	360	2.28	0.66	0.03	9.76	**<0.01**
2008	360	-7.56	26.76	0.08	32.02	**<0.01**
2009	360	3.11	1.22	0.02	7.74	**<0.01**
2010	360	-0.52	5.60	0.00	0.29	0.59

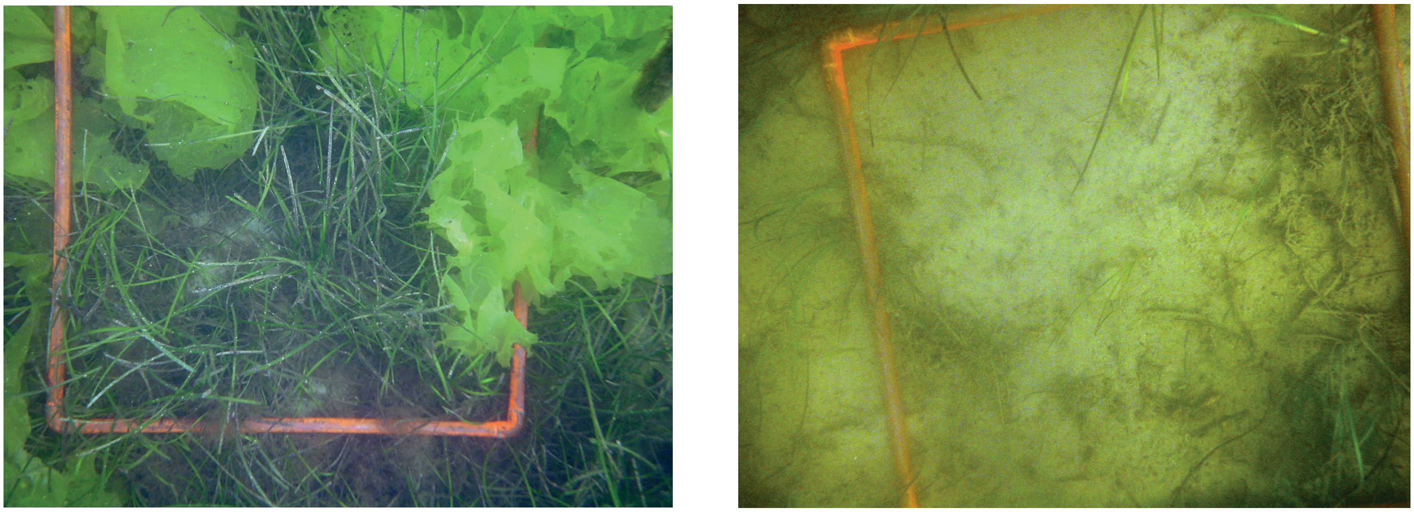

Figure 2. (a) Sampling quadrat showing the early formation of a green macroalgal bloom, *Ulva lactuca*, on an eelgrass, *Zostera marina*, bed in Barnegat Bay. (b) Sampling quadrat showing the loss of eelgrass due to light attenuation by the macroalgal bloom. Note only bare bottom area remains within the quadrat.

the estuary. Blooms were more frequent during June–July (27 occurrences, 1.10 blooms m^{-2}), and August–September (22 occurrences, 0.95 blooms m^{-2}), than October–November (16 occurrences, 0.63 blooms m^{-2}). The majority of the blooms occurred during the 2008–2010 period. There were 6 occurrences of Pre-Bloom conditions (0.20 blooms m^{-2}), 17 occurrences of Early Bloom conditions (0.57 blooms m^{-2}), and 24 occurrences of Full Bloom conditions (0.80 blooms m^{-2}) during the 2008–2010 time period. Only 18 Pre-Bloom, Early Bloom, and Full Bloom conditions (1.12 blooms m^{-2}) occurred during the 2004–2006 period. This indicates that the frequency of macroalgal blooms may be increasing in recent years in the estuary.

Yet despite the increased number of macroalgae blooms of multiple intensities, the areal percent cover of macroalgae actually exhibited a significant negative trend (-1.5% yr^{-1}, $R^2 = 0.03$, $F = 19.6$, $p < 0.01$) over 2004–2010 during the August–September time period, but did not change over the years during either June–July or October–November time periods (Table 2a). Although macroalgal blooms did not cover the entire area of the seagrass beds at any time during this study, the cumulative impact of the blooms across multiple locations within the beds resulted in acute loss of vegetation and the genesis of extensive bare bottom areas. *Ulva lactuca* blooms were particularly damaging in this regard (Figure 2a,b). Little Egg Harbor had significantly higher macroalgae percent cover than Barnegat Bay during 2009 (12.4% and 2.5% respectively, $F = 31.10$, Tukey-adjusted $p < 0.01$) and 2010 (7.8% and 1.3% respectively, $F = 17.74$, Tukey-adjusted $p < 0.01$), but there was no difference during 2006 or 2008. Little Egg Harbor had significantly higher macroalgae percent cover than Barnegat Bay during August–September (10.9% and 5.4% respectively, $F = 16.42$, Tukey-adjusted $p < 0.01$) and October–November (11.8% and 2.3% respectively, $F = 61.94$, Tukey-adjusted $p < 0.01$), but there was no difference between these areas during June–July.

In most years (2005, 2006, 2008, 2009), macroalgae areal percent cover significantly varied ($p < 0.01$) over the course of the year but did not do so consistently across years (Table 2b). Macroalgae areal percent cover significantly increased by time period in 2006 and 2009, decreased by time period in 2005 and 2008, and did not significantly change during 2004 and 2010 (Table 2b).

Benthic macroalgae are powerful drivers of change in water quality and seagrass habitat. During bloom conditions, benthic macroalgae formed a dense canopy over extensive areas of the seagrass beds. Macroalgae areal percent cover significantly correlated with seagrass properties, most frequently during the June–July time period throughout 2004–2010 (Table 3). For example, during June–July 2004–2010, macroalgae areal percent cover positively correlated with *Zostera marina* aboveground and belowground biomass ($r = 0.19$, $p < 0.01$, $n = 571$ and $r = 0.16$, $p < 0.01$, $n = 571$, respectively) and *Z. marina* blade length ($r = 0.22$, $p < 0.01$, $n = 440$). These relationships did not remain significantly throughout the year. Only *Z. marina* blade length continued to be significantly correlated by August–September ($r = 0.10$, $p < 0.05$, $n = 449$), and none were significantly correlated during October–November (Table 3). Conversely, while no significant relationships between macroalgae percent cover and *Ruppia maritima* aboveground and belowground biomass were observed during June–July 2004–2010 or August–September 2004–2010; these variables were positively correlated during October–November 2004–2010 ($r = 0.38$, $p < 0.01$, $n = 60$ and $r = 0.27$, $p < 0.05$, $n = 60$) (Table 3).

A total of 39 species were recorded over 2004–2005, with bloom-forming red and green algae dominating the assemblages (Kennish et al., 2010). In 2004, the sea lettuce *Ulva lactuca* was the most abundant species, occurring in 59% of the samples collected (Figure 2a). Three red macroalgal species were also abundant, notably *Spyridia filamentosa* (55%), *Gracilaria tikvahiae* (30%), and *Champia parvula* (23%). In 2005, four red and one green macroalgal species predominated: *G. tikvahiae* (present in 70% of the samples), *Bonnemaisonia hamifera* (56%), *Spyridia filamentosa* (46%), *U. lactuca* (26%), and *C. parvula* (19%).

DISCUSSION

Nutrient enrichment promotes rapid algal growth and algal blooms in shallow estuaries leading to light attenuation and shading of the benthos (Nixon, 1995; Cloern, 2001; Bricker et al., 2008). Heavy macroalgal blooms, including events documented in Barnegat Bay–Little Egg Harbor Estuary (Table 1), cause light attenuation, which in extreme cases may result in total light extinction. Therefore, a shift in the

Table 3. Correlation analysis between macroalgae areal percent cover, eelgrass (*Zostera marina*) and widgeon grass (*Ruppia maritima*), during three time periods over 2004–2010. Sample size (n), correlation coefficient (r), and p value (p) are reported.

	VARIABLE	UNITS	JUNE–JULY			AUGUST–SEPTEMBER			OCTOBER–NOVEMBER		
			r	p	n	r	p	n	r	p	n
SEAGRASS BIOMASS	*Zostera* aboveground biomass	$g\ m^{-2}$	0.19	0.00	571	0.04	0.28	621	0.03	0.52	540
	Ruppia aboveground biomass	$g\ m^{-2}$	0.12	0.34	60	-0.18	0.16	60	0.38	0.00	60
	Zostera belowground biomass	$g\ m^{-2}$	0.16	0.00	571	0.04	0.28	621	0.04	0.31	540
	Ruppia belowground biomass	$g\ m^{-2}$	0.10	0.46	60	-0.20	0.13	60	0.27	0.04	60
SEAGRASS DEMOGRAPHICS	*Zostera* shoot density	shoots m^{-2}	-0.02	0.65	463	-0.04	0.38	500	-0.05	0.33	404
	Ruppia shoot density	shoots m^{-2}	-0.05	0.38	289	-0.08	0.13	336	-0.06	0.30	332
	Zostera blade length	cm	0.22	0.00	440	0.10	0.04	449	0.05	0.37	349
	Zostera areal % cover	%	-0.04	0.30	609	-0.00	0.93	680	0.10	0.01	560
	Ruppia areal % cover	%	-0.04	0.31	609	-0.07	0.07	680	-0.11	0.01	560
	Other areal % cover	%	0.08	0.40	120	-0.03	0.74	120			

dominance of benthic macrophyte communities may occur through time in a eutrophied estuary from seagrasses to ephemeral macroalgae (Kennish, 2009).

Temporal variations in area normalized macroalgal bloom frequencies and percent cover (Table 1, 2a, 2b) have contributed in part to the marked decline of seagrass biomass in the Barnegat Bay–Little Egg Harbor Estuary over the 2004–2010 period (Kennish et al., 2008, 2010). Orth et al. (2006) documented that seagrasses have high light requirements that approach 25% of the incident surface radiation (Dennison et al., 1993; Orth et al., 2006). Light extinction by macroalgae mats during bloom development threatens seagrass integrity. Macroalgae require lower light intensities than seagrass for survival (Hily et al., 2004; McGlathery et al., 2007). Hence, reduced light transmission to the estuarine floor can lead to the replacement of seagrass by rapidly growing macroalgae (e.g., *Ulva lactuca* and *Enteromorpha* spp.).

Similar bloom events in the estuary have been previously reported. For example, in 1998, Bologna et al. (2000, 2001) documented heavy benthic macroalgal blooms in the Barnegat Bay–Little Egg Harbor Estuary consisting of *Ulva*, *Gracilaria*, and *Codium*. Algal-detrital loading rates of ~400 g ash free dry weight m^{-2} derived from these blooms persisted throughout the summer and into the fall burying extensive areas of *Zostera marina* beneath a thick algal canopy. The positive correlations between *Z. marina* biomass (aboveground and belowground) and blade length in June–July reported here (Table 2b, Table 3) likely happen because larger seagrass blades trap more floating macroalgae, but once at full size later in the year, this relationship is no longer significant, and shading results in the rapid loss of aboveground and belowground biomass at several locations in the estuary (Bologna et al., 2001). Seitzinger et al. (2001) showed that benthic algal dynamics can significantly influence sediment-water nutrient fluxes, particularly ammonium, in Barnegat Bay–Little Egg Harbor, which may sustain system eutrophy.

The loss of seagrass due to the reduction in light availability from macroalgal blooms is likely accelerated by altered biogeochemical conditions in bottom sediments associated with the accumulation and decomposition of the increased algal standing stocks (Hauxwell et al., 2001, 2003; Nixon et al., 2001). The decomposition of the macroalgae causes higher nutrient efflux from the sediments to the water column enhancing eutrophication in eutrophied systems (Eyre and Ferguson, 2002). It also results in sulfide production in the rhizosphere which decreases nutrient uptake, seagrass photosynthesis, metabolism, and growth, while increasing the development of hypoxic/anoxic conditions hazardous to benthic communities (Goodman et al., 1995; Erskine and Koch, 2000; Holmer and Bondgaard, 2001; Ralph et al., 2006). Seagrass mortality can also significantly increase in response to oxygen depletion and high pore-water ammonium concentrations (McGlathery et al., 2007).

Eutrophication of the Barnegat Bay–Little Egg Harbor Estuary has persisted over the past decade with increased nitrogen loading from the Barnegat Bay Watershed. Between 1998 and 2007, the total nitrogen load from surface water of the watershed increased from 390,000 kg N yr^{-1} to 431,000 kg N yr^{-1} (Wieben and Baker, 2009). During 2004–2010, key indicators of ecosystem condition degraded, including seagrass biomass, algal bloom occurrence, and dissolved oxygen levels (Barnegat Bay Partnership, 2011). In 2010, the mean aboveground seagrass biomass decreased to less than 10 g dry wt m^{-2}, which is the lowest recorded for the estuary (Kennish et al., Manuscript Submitted). Macroalgal blooms appear to be an important driver of change in seagrass habitat of the estuary.

SUMMARY

Benthic macroalgae, such as *Gracilaria tikvahiae* or *Ulva lactuca*, can outcompete seagrass for nutrients, resulting in attenuation or blocked light transmission to seagrass beds, increased organic matter, and degraded seagrass condition. Macroalgae areal cover of 60-70% was considered 'Pre-Bloom', 70-80% was considered 'Early Bloom', and > 80% was considered 'Full Bloom' conditions. In Barnegat Bay–Little Egg Harbor Estuary, there were 10 occurrences (0.45 blooms m^{-2}) of Pre-Bloom conditions, 19 occurrences (0.67 blooms m^{-2}) of Early Bloom conditions, and 36 occurrences (1.57 blooms m^{-2}) of Full Bloom conditions. The majority of these blooms occurred during 2008–2010. Macroalgae areal precent cover significantly correlated with seagrass properties. This pattern indicated that macroalgae blooms in the estuary developed relatively frequently and impacted seagrass beds.

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