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Recent Trends of *Zostera marina* (Eelgrass) in a Highly Eutrophic Coastal Lagoon in the Mid-Atlantic Region (USA)

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Abstract

Spatial and temporal characteristics of *Zostera marina* (eelgrass) in the Barnegat Bay-Little Egg Harbor Estuary are compared before (2004-2011) and after (2012-2013) major fertilizer legislation (Fertilizer Law A2290) was enacted in New Jersey (USA) to reduce nutrient inputs from fertilizers to water bodies in the state. A significant decrease of *Z. marina* biomass and areal cover occurred in this eutrophic estuary between 2004 and 2011 concomitantly with increasing nitrogen and phosphorus loading from the watershed. The rate of decline in aboveground and belowground biomass was significantly sharper during 2004-2006 than during 2008-2010. In 2010, *Z. marina* biomass dropped to a very low level (mean aboveground biomass = 7.7 g dry wt m^{-2}; mean belowground biomass = 27.0 g dry wt m^{-2}), persisting through the last sampling period (October-November) in 2013. Biomass and areal cover of *Z. marina* decreased even further after Fertilizer Law A2290 was enacted in January 2012, with the lowest values recorded from August to November each year. These low values are the result of ongoing eutrophication of the system. More seagrass monitoring and research are necessary in future years to determine if the fertilizer law will have a positive effect on *Z. marina* condition in the estuary over the long term.

Keywords

Barnegat Bay-Little Egg Harbor Estuary, Coastal Lagoon, Nutrient Enrichment, Eutrophication, *Zostera marina* Characteristics, Nutrient Reduction Regulation

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1. Introduction

Barnegat Bay-Little Egg Harbor (BB-LEH) Estuary, New Jersey (**Figure 1**), is a eutrophic coastal lagoon [1]-[9]. Over the past two decades, the eutrophic condition of the estuary has increased, and it is now classified as a highly eutrophic system [4]-[6] [9] [10]. This 280 km^2 estuarine water body is susceptible to nutrient loading because it is shallow, poorly flushed, and bordered by a highly developed and altered watershed (1730 km^2 area) that acts as a conduit for nutrient transport to the estuary. More than 585,000 people inhabit the BB-LEH Watershed (up from ~108,000 in 1960), which exhibits a conspicuous north-south decreasing gradient in population density and development [7] [11] [12]. About 34% of the watershed is now developed, up from ~19% in the early 1970s. Total nitrogen concentrations in the estuary are positively correlated with nitrogen loading from the watershed, which peaks in the northern segment [9] [13] [14].

Nitrogen enrichment is a major driver of ecological change in BB-LEH, as well as other coastal lagoons in the mid-Atlantic region (USA) and elsewhere, being linked to an array of adverse impacts including depleted dissolved oxygen, harmful algal blooms (HABs), heavy epiphytic growth, loss of habitat, reduced biodiversity, declining fisheries, imbalanced food webs, and diminished ecosystem services [15]-[18]. Such cascading effects can significantly alter the structure and function of these productive systems.

Total nitrogen loading to BB-LEH from the surrounding watershed ranged from ~455,000 to 857,000 kg TN yr^{-1} between 1989 and 2011, with the loading generally increasing through time [7]. Highest loading in the

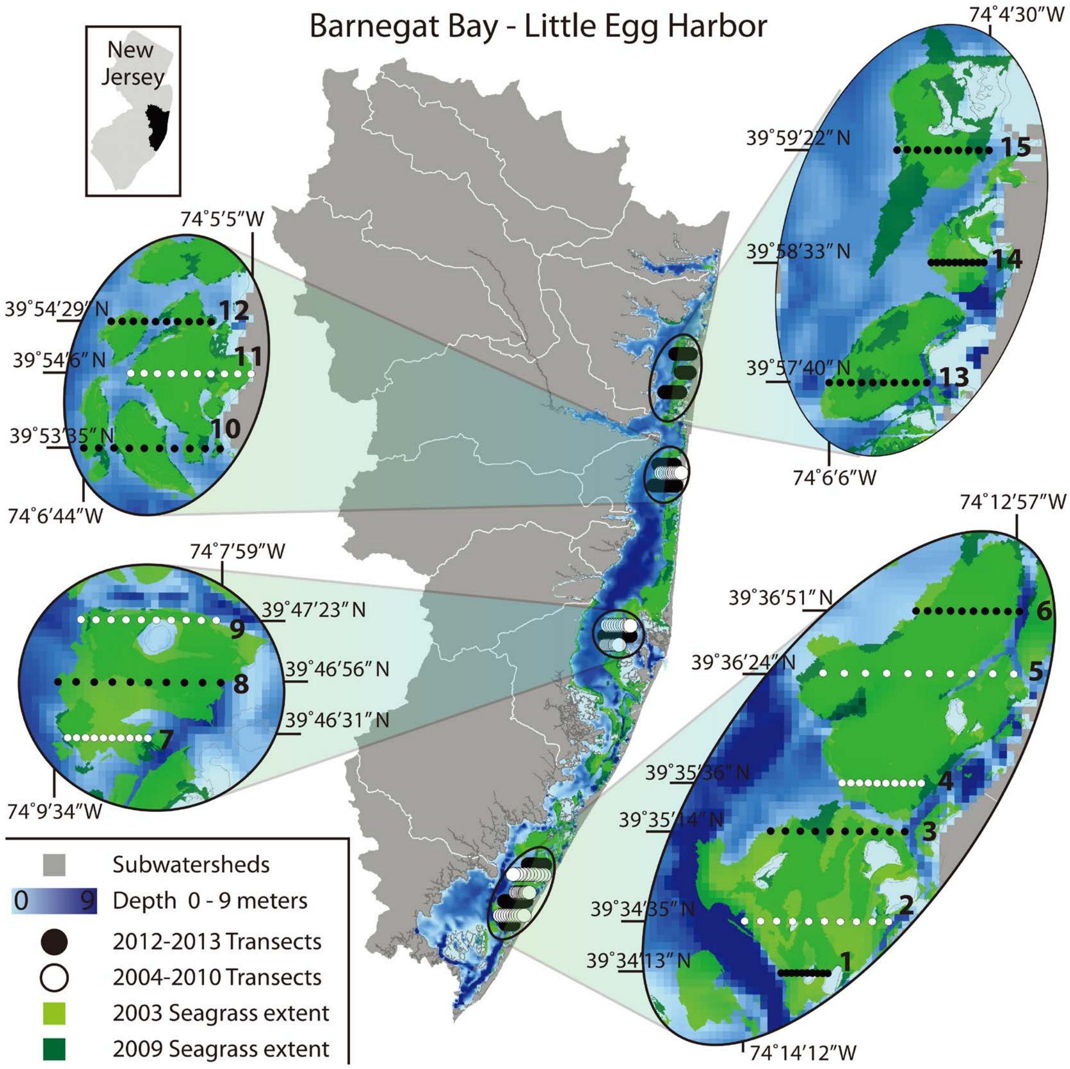

Figure 1. Map of Barnegat Bay-Little Egg Harbor Estuary showing sampling transects and stations used in this study.

northern segment of the estuary occurred in closest proximity to the most heavily developed areas of the watershed. Elevated total nitrogen levels were also detected in the southern segment of the estuary [7] [9]. Nutrient enrichment elicits negative responses in seagrass habitat due to accelerated algal growth, epiphytic infestation, light attenuation, and shading of the estuarine floor. Seagrass plays a major ecological role in the estuary, but has declined significantly in recent years [6] [8] [9] [19] [20]. Eutrophication left unabated can lead to permanent alteration of biotic communities and habitats, as well as greater ecosystem-level impacts [18].

The decline of seagrass beds is a serious concern in any estuary because of the multiple ecosystem services that they provide, notably major sources of primary production, food for waterfowl and other organisms, essential habitat and nursery areas for numerous fish and invertebrates, filters of chemical substances, agents in biogeochemical cycling, and buffers against wave and current action as well as sediment erosion [21]-[23]. These vascular plants are also important indicators of overall ecosystem health of an estuary because they integrate water quality and benthic attributes [23]-[26].

In this study, *Zostera marina*'s (eelgrass) characteristics (*i.e.*, shoot density, aboveground and belowground biomass, blade length, and areal cover) and water quality conditions (*i.e.*, temperature, salinity, pH, dissolved oxygen, and depth) were measured during 2012 and 2013 along 9 transects (10 stations each, 90 sampling stations total) in BB-LEH (**Figure 1**, **Table 1**). The measurements of *Z. marina*'s characteristics were compared with those of previous years (2004-2011). More specifically, spatial and temporal trends of *Z. marina*'s characteristics were compared for years before and after major fertilizer legislation (Fertilizer Law A2290) was enacted in New Jersey in January 2012 to protect surface and ground waters in the state from impairment due to nitrogen and phosphorus loading derived from fertilizers [27].

2. Background

Nitrogen loading stimulates algal growth and epiphytic loading which cause light attenuation and shading of seagrass in the estuary [8] [9] [28]. Blooms of drifting, ephemeral macroalgae (e.g., *Ulva lactuca*, *Enteromorpha intestinalis*, *Gracilaria tikvahiae* and other species) produce thick canopies over the estuarine floor that pose a potential danger to seagrass beds by smothering the plants, blocking light penetration, and reducing photosynthesis [5] [13] [19] [28]. Additionally, the accumulation of these macroalgal mats on the estuarine floor can increase sediment sulfide concentrations due to microbial decomposition in anoxic, organic-rich sediment; this process is often detrimental to seagrasses and benthic infauna [17] [26]. Seagrass photosynthesis, metabolism, and growth are negatively affected by sulfide build up in bottom sediments, frequently leading to a decrease in the depth penetration of seagrasses in eutrophic systems [26] [29] [30].

Detailed investigations of *Z. marina* in BB-LEH have revealed significant declines in plant characteristics (shoot density, aboveground and belowground biomass, and areal cover) during the 2004 to 2011 period in response to nitrogen enrichment [6] [8] [9] [19], when up to 150 stations were sampled each year in the estuary

Table 1. Mean water temperature, salinity, dissolved oxygen, pH, and Secchi depth recorded in the Barnegat Bay-Little Egg Habor Estuary during three sampling periods in 2012 and 2013.

Parameter	Sampling Period		
	June-July	August-September	October-November
Temperature (˚C)			
2012	25.78 (2.63)	24.69 (2.15)	16.01 (0.34)
2013	27.99 (2.93)	23.83 (0.94)	18.21 (1.65)
Salinity (ppt)			
2012	23.59 (5.42)	22.92 (5.91)	24.34 (5.16)
2013	24.67 (8.84)	24.10 (5.08)	27.79 (3.07)
pH			
2012	8.08 (010)	8.00 (0.17)	7.93 (0.10)
2013	8.00 (0.20)	7.98 (0.24)	8.05 (0.11)
Dissolved Oxygen mg·L^{-1}			
2012	7.82 (0.77)	7.70 (1.08)	9.41 (7.73)
2013	7.58 (1.59)	7.66 (0.69)	9.48 (1.26)
Secchi Depth			
2012	114.42 (29.76)	87.46 (31.39)	126.20 (18.15)
2013	94.26 (17.01)	93.01 (15.94)	117.38 (21.31)

Standard deviation values in parentheses.

(**Table 2**). The mean shoot density of *Z. marina* during 2004-2011 (~160 - 495 shoots m^{-2}) decreased substantially compared with earlier measurements (~650 - 1150 shoots m^{-2} in 1999 [31]; ~500 - 1000 shoots m^{-2} in 1982 [32]). In addition, after an extended progressive decline, *Z. marina* mean aboveground and belowground biomass values in 2010 fell to very low levels in the estuary, being more than 85% and 65% lower, respectively, in October-November 2010 than in June-July 2004. For example, the lowest aboveground and belowground values over the decade of study occurred during 2011-2013 (**Table 2**). The lowest aboveground biomass of *Z. marina* was recorded in the estuary in October-November 2010 (Mean = 2.7 g dry wt m^{-2}); the lowest belowground biomass of *Z. marina* was found in August-September 2013 (Mean = 7.8 g dry wt m^{-2}).

Other impacts were delineated in the estuary concomitant with the decline of *Z. marina* over the 2004-2011 period. For example, macroalgal blooms increased significantly during 2004-2010, with 55 (2.23 blooms m^{-2})

Table 2. Mean (±standard deviation) aboveground and belowground biomass, shoot density, blade length, and percent areal cover of *Zostera marina* recorded in the BB-LEH Estuary during sampling periods in 2004-2013.

Sampling Period	Aboveground Biomass	Belowground Biomass	Shoot Density	Blade Length	Areal Cover
Months	g dry wt m^{-2}	g dry wt m^{-2}	Shoots m^{-2}	cm	%
2004					
June-July	109.5 (67.6)	110.2 (118.8)	297.8 (414.7)	34.0 (10.9)	44.8 (27.6)
August-September	54.6 (48.8)	68.7 (58.8)	108.2 (282.1)	32.3 (7.2)	37.6 (31.3)
October-November	18.2 (19.8)	50.5 (66.0)	0.0 (0.0)	31.8 (8.4)	21.4 (23.3)
2005					
June-July	52.1 (71.4)	142.7 (197.1)	494.4 (614.5)	32.7 (17.6)	36.9 (33.1)
August-September	28.8 (48.0)	69.0 (101.8)	163.4 (220.0)	25.9 (14.9)	23.1 (35.1)
October-November	15.7 (26.6)	42.8 (64.0)	233.4 (284.4)	28.5 (14.7)	11.3 (12.9)
2006					
June-July	11.8 (26.4)	55.5 (70.7)	170.3 (263.3)	22.2 (24.6)	23.5 (35.8)
August-September	13.7 (21.7)	46.5 (112.6)	156.0 (311.2)	3.7 (9.8)	13.5 (20.6)
October-November	12.8 (25.4)	31.6 (64.7)	163.5 (299.4)	4.6 (9.8)	16.4 (24.0)
2008					
June-July	22.3 (63.6)	72.4 (158.6)	241.7 (435.3)	28.6 (12.2)	22.2 (29.9)
August-September	24.7 (39.4)	60.9 (89.3)	414.2 (570.4)	22.4 (13.6)	29.6 (36.3)
October-November	18.1 (40.6)	31.6 (51.8)	264.4 (464.6)	31.4 (17.7)	22.3 (31.1)
2009					
June-July	15.1 (31.2)	43.0 (60.3)	346.7 (536.3)	22.3 (13.2)	31.3 (35.5)
August-September	8.0 (17.1)	37.2 (51.7)	265.0 (406.9)	24.5 (11.6)	27.2 (34.8)
October-November	3.0 (7.2)	17.1 (34.5)	154.8 (325.0)	21.5 (10.8)	14.6 (19.0)
2010					
June-July	13.3 (24.3)	32.6 (47.0)	664.5 (459.6)	22.2 (12.5)	28.2 (35.7)
August-September	6.6 (15.3)	29.6 (52.8)	376.9 (379.8)	19.9 (10.6)	21.0 (34.5)
October-November	2.7 (8.0)	17.9 (37.5)	439.8 (708.3)	22.7 (13.4)	9.2 (21.0)
2011					
June-July	7.2 (19.9)	21.4 (43.3)	157.0 (304.3)	25.3 (15.7)	19.7 (30.0)
August-September	9.4 (37.6)	15.7 (37.8)	149.4 (443.2)	29.1 (12.3)	17.9 (32.9)
October-November	17.4 (51.0)	15.5 (33.4)	179.1 (395.8)	31.5 (13.3)	16.1 (30.3)
2012					
June-July	21.4 (38.8)	27.3 (47.2)	327.0 (575.1)	24.5 (9.7)	22.7 (33.6)
August-September	9.7 (25.4)	15.2 (34.1)	138.7 (344.6)	20.1 (7.6)	13.7 (28.2)
October-November	5.6 (14.0)	17.3 (36.6)	158.5 (387.3)	21.2 (8.1)	10.3 (23.7)
2013					
June-July	21.3 (49.0)	16.7 (46.6)	195.3 (483.6)	22.6 (10.5)	15.8 (28.8)
August-September	8.1 (31.3)	7.8 (21.9)	120.3 (322.6)	20.6 (11.2)	9.9 (22.4)
October-November	9.2 (27.9)	15.2 (35.5)	117.5 (328.7)	23.1 (8.7)	12.4 (27.0)

early bloom (70% - 80% macroalgal cover) and full bloom (>80% macroalgal cover) events [28]. These blooms resulted in increased mortality of *Z. marina*, leading to reduced biomass and more bare-bottom areas within the beds. Furthermore, epiphytic growth on seagrass was elevated, with the mean percent cover of seagrass leaf surfaces ranging from 10.7% to 38.3% during 2009 and 2010, and exceeding 48% in 2011. The loss of seagrass has eliminated essential habitat for hard clams, bay scallops (*Argopecten irradians*), and other benthic and demersal organisms. Seagrass beds now cover 5260-ha of the estuarine floor [20].

3. Methods

Biotic and water quality samples were collected in the estuary at 10 equally spaced stations along each of 9 east-west transects (90 stations total, **Figure 1**) sampled three times over the June-November period in both 2012 and 2013.Quadrat, core, and hand sampling was used to collect seagrass samples. We followed the standard Seagrass Net monitoring and sampling protocols of Short [33], although sampling transects were positioned perpendicular to the shore rather than parallel, to identify differences along a clearly defined depth gradient. During each sampling period in both years (June-July, August-September, and October-November), an array of abiotic data was collected in addition to the aforementioned seagrass data; Secchi depth was measured using a Secchi disk, while temperature, salinity, pH, dissolved oxygen, and depth were measured with a handheld YSI 600 XL datasonde coupled with a handheld YSI 650 MDS display unit (**Table 1**).

A 0.25-m^2 metal quadrat was randomly tossed at each sampling station to obtain measurements of *Z. marina* shoot density, biomass, blade length, and areal cover. To determine the area within the quadrat covered by *Z. marina*, a diver estimated the percentage of the quadrat area covered by this species in increments of 5 along a scale of 0 to 100. Subsequently, the diver visually examined the bottom area and vegetation within the quadrat for the occurrence of boat scarring, grazing, epiphytic loading, wasting disease, and shellfish occurrence. A digital camera was employed to image the sampling station to validate the diver observations. Subsequently, 5 replicate *Z. marina* blades were collected within the quadrat for length measurements. A 10-cm diameter PVC coring device was used to collect eelgrass samples for biomass measurements, with care taken not to cut or damage the aboveground plant tissues. The diver-deployed corer extended deep enough in the sediments to extract all belowground fractions (roots and rhizomes). Each core was placed in a 3 mm × 5 mm mesh bag and rinsed to separate plant material from the sediment. After removing the *Z. marina* blades from the mesh bag, the sample was placed in a labeled bag and stored on ice in a closed container prior to transport back to the Rutgers University Marine Field Station (RUMFS) in Tuckerton.

In the laboratory, the *Z. marina* samples were carefully sorted and separated into aboveground (shoots) and belowground (roots and rhizomes) components. The density of *Z. marina* shoots was then determined. Aboveground and belowground fractions were oven dried at 50˚C - 60˚C for a minimum of 48 hours. Dry weight of aboveground, belowground, and epiphyte biomass (g dry wt m^{-2}) was measured to the third decimal place.

Three-way ANOVA (transects, years, and sampling periods = class variables) was conducted to test temporal and spatial changes across all 90 sampling stations for *Z. marina* characteristics (shoot density, aboveground and belowground biomass, blade length, and areal cover). The cutoff for statistical significance was $p < 0.05$, unless otherwise noted. Seasonal differences in *Z. marina* characteristics during 2004-2011 were compared with those during 2012-2013.

4. Results

4.1. Survey Year 2012

4.1.1. Eelgrass Distribution and Abundance

The spatial distribution of *Z. marina* was similar in 2012 and 2013, being found along Transects 1, 3, 6, 8, 10, 12, and 15 during both years (see **Figure 1**). No Z. *marina* samples were collected along Transects 13 and 14 in 2012 due to low salinity levels in the northern segment limiting eelgrass distribution. The highest shoot densities of *Z. marina* in 2012 occurred at Transect 6 (Mean = 764.3 shoots m^{-2}) (**Table 3**). Excluding Transects 13 and 14, the lowest shoot densities were documented at Transect 1 (Mean = 148.6 shoots m^{-2}).

The shoot densities of *Z. marina* in 2012 were highest during the June-July sampling period (Mean = 327.0 shoots m^{-2}), which was also the time of peak plant biomass. Markedly lower shoot densities were obtained during the August-September (Mean = 138.7 shoots m^{-2}) and October-November (Mean = 158.5 shoots m^{-2}) sampling periods (**Table 2**). Shoot densities were higher during each sampling period in 2012 than in 2013.

Table 3. Mean (±standard deviation) aboveground and belowground biomass, shoot density, blade length, and percent areal cover of *Zostera marina* recorded in the BB-LEH Estuary along sampling transects during 2012 and 2013.

Sampling Transect	Year	Aboveground Biomass	Belowground Biomass	Shoot Density	Blade Length	Areal Cover
		g dry wt m^{-2}	g dry wt m^{-2}	Shoots m^{-2}	cm	%
1	2012	16.5 (41.6)	22.2 (30.3)	148.6 (229.6)	25.9 (11.1)	22.2 (29.9)
3	2012	17.8 (36.8)	31.2 (50.4)	161.4 (304.7)	23.6 (30.5)	19.2 (24.0)
6	2012	49.4 (41.4)	79.6 (61.4)	764.3 (661.5)	24.1 (57.6)	61.0 (43.3)
8	2012	11.0 (19.6)	20.2 (37.8)	152.9 (300.0)	26.7 (9.8)	11.8 (22.4)
10	2012	7.1 (15.5)	9.9 (18.5)	259.1 (564.3)	15.5 (5.6)	13.3 (24.8)
12	2012	4.1 (8.5)	11.7 (24.2)	169.9 (349.8)	13.2 (3.7)	9.0 (20.4)
13*	2012	-	-	-	-	-
14*	2012	-	-	-	-	-
15	2012	4.5 (13.7)	4.6 (12.7)	216.6 (607.9)	14.6 (2.7)	3.5 (9.8)
1	2013	28.8 (44.0)	18.5 (28.3)	199.6 (330.6)	27.5 (79.1)	32.5 (36.7)
3	2013	4.9 (18.1)	8.3 (20.4)	76.4 (223.4)	17.2 (2.4)	8.0 (14.7)
6	2013	44.1 (69.3)	62.3 (75.7)	496.8 (660.1)	19.5 (55.0)	38.3 (36.3)
8	2013	26.8 (53.9)	20.0 (40.0)	229.3 (530.4)	32.9 (110.1)	23.7 (36.7)
10	2013	10.0 (30.4)	5.3 (13.0)	182.6 (471.5)	15.8 (6.1)	6.7 (15.2)
12	2013	0.4 (1.7)	2.3 (11.0)	29.7 (123.7)	12.2 (2.8)	0.8 (2.3)
13*	2013	-	-	-	-	-
14*	2013	-	-	-	-	-
15	2013	4.9 (1.5)	4.6 (12.7)	84.9 (246.6)	14.6 (2.7)	4.3 (10.4)

*No *Z. marina* found.

4.1.2. Biomass

The biomass of *Z. marina* varied considerably both in space and time during the 2012 study period (**Table 2**). The aboveground and belowground biomass measurements were highest during the June-July sampling period; the mean aboveground biomass at this time was 21.4 g dry wt m^{-2}, while the mean belowground biomass amounted to 27.3 g dry wt m^{-2}. Progressively lower mean aboveground biomass values were recorded during the August-September and October-November sampling periods, dropping to 9.7 g dry wt m^{-2} and 5.6 g dry wt m^{-2}, respectively. The mean belowground biomass in turn decreased to 15.2 g dry wt m^{-2} in August-September and subsequently increased again to 17.3 g dry wt m^{-2} in September-October.

The highest mean aboveground and belowground measurements of *Z. marina* in 2012 (49.4 and 79.6 g dry wt m^{-2}, respectively) were recorded at Transect 6 (**Table 3**). Excluding Transects 13 and 14 where no *Z. marina* was found, the lowest mean aboveground and belowground biomass measurements were recorded at Transect 12 (4.1 g dry wt m^{-2}) and Transect 15 (4.6 g dry wt m^{-2}), respectively. The lowest aboveground and belowground biomass values were observed at northern sampling transects (Transects 10 to 15).

4.1.3. Eelgrass Blade Length

The highest mean length of *Z. marina* blades in 2012 occurred during the June-July sampling period (24.5 cm) (**Table 2**). The length of *Z. marina* blades generally decreased from south to north in the estuary. The highest mean length of *Z. marina* blades (26.7 cm) was recorded at Transect 8, and the lowest mean length of *Z. marina* blades (13.2 cm) was documented at Transect 12.

4.1.4. Areal Cover

The mean percent cover of *Z. marina* peaked during the June-July sampling period in 2012, amounting to 22.7% (**Table 3**). Progressively lower mean percent cover was found during the August-September (13.7%) and October-November (10.3%) sampling periods. The percent cover of *Z marina* was variable among the sampling transects, although it was consistently highest at sampling stations along Transect 6 (Mean = 61%).

4.2. Survey Year 2013

4.2.1. Distribution and Abundance

Similar to sampling results in 2012, the highest shoot densities of *Z. marina* in 2013 were recorded at Transect 6 (Mean = 496.8 shoots m^{-2}) (**Table 3**). The southern and central segments of the estuary exhibited the highest shoot densities in 2013. Excluding Transects 13 and 14 where no *Z. marina* was found, the lowest shoot densities were found at Transect 12 (Mean = 29.7 shoots m^{-2}) near Toms River.

Shoot densities of *Z. marina* decreased from spring to fall in 2013, amounting to mean values of 195.3, 120.3, and 117.5 shoots m^{-2} during June-July, August-September, and October-November sampling periods, respectively (**Table 2**). The highest shoot density measurements were found during the June-July sampling period at the time of maximum plant biomass, as was the case in 2012.

4.2.2. Biomass

Aboveground biomass of *Z. marina* was highest during the June-July sampling period in 2013 (Mean = 21.5 g dry wt m^{-2}), subsequently decreasing to very low levels during August-September (Mean = 8.1 g dry wt m^{-2}) and October-November (Mean = 9.2 g dry wt m^{-2}). Similarly, belowground biomass of *Z. marina* peaked during the June-July sampling period (Mean = 16.7 g dry wt m^{-2}) and then declined during the August-September sampling period (Mean = 7.8 g dry wt m^{-2}). It increased again during the October-November sampling period (Mean = 15.2 g dry wt m^{-2}) (**Table 2**).

4.2.3. Eelgrass Blade Length

The highest blade lengths of *Z. marina* in 2013 occurred during the October-November sampling period (Mean = 23.1 cm). The lowest blade lengths were recorded during the August-September sampling period (Mean = 20.6 cm). Intermediate values were documented during June-July (Mean = 22.6 cm). The length of *Z. marina* blades was highest at sampling stations along Transect 8 (Mean = 32.9 cm) and lowest along Transect 12 (Mean = 12.2 cm) (**Table 3**).

4.2.4. Areal Cover

In 2013, the mean percent cover of *Z. marina* peaked during the June-July sampling period (Mean = 15.8%). It was lowest during the August-September sampling period (Mean = 9.9%). Intermediate percent cover values were recorded during the October-November sampling period (Mean = 12.4%) (**Table 3**).

Transect 6 had the highest percent cover of *Z. marina* in 2013 (Mean = 38.3%). The lowest percent cover was documented at Transect 12 (Mean = 0.8%). The northern transects exhibited lower percent cover values than the southern and central transects (**Table 3**).

5. Discussion

Plant characteristics of *Z. marina* (shoot density, aboveground and belowground biomass, blade length, and areal cover) measured in 2004-2011 (**Table 2**) serve as a baseline for more recent changes of eelgrass characteristics in the estuary associated with ongoing eutrophication and potentially associated to some extent with nutrient loading regulations that recently came into effect. Linear decreases within and between years have been observed during this time period and are compared with plant characteristics measured in 2012-2013. Significant differences between the rate of decrease (or increase) during 2004-2010 and 2012-2013 would indicate a change in response from baseline patterns. For example, we tested for significant differences between the rate of change in aboveground biomass during 2012-2013 and that of 2004-2010 (12.5% per year) at a variety of spatial scales (*i.e.*, overall BB-LEH, within segments, and within transects) and temporal intervals (*i.e.*, intra- and inter-annually).

Linear decreases within and between years were observed. Eelgrass response along linear (decreasing 2004-2010 and 2012-2013) and quadratic (decreasing 2004-2010 and increasing 2012-2013) regressions were examined for statistical significance. The rate of decline in aboveground and belowground *Z. marina* was significantly sharper during 2004-2006 than during 2008-2010. In 2010, *Z. marina* biomass decreased to a very low level (Mean aboveground biomass = 7.7 g dry wt m^{-2}; Mean belowground biomass = 27.0 g dry wt m^{-2}). The number of macroalgal blooms significantly increased from the 2004-2006 period to the 2008-2010 period, which likely contributed to this decline [28]. Biomass values of *Z. marina* did not improve between 2010 and 2013, with low levels recorded in both 2012 and 2013 (particularly from August to November each year) after enactment of New Jersey Fertilizer Law A2290 (**Figure 2**). Superstorm Sandy may have contributed to impacts on seagrass beds in the estuary during 2013. More seagrass monitoring is necessary in future years to determine if the fertilizer law will have a positive effect on plant biomass over the longer term.

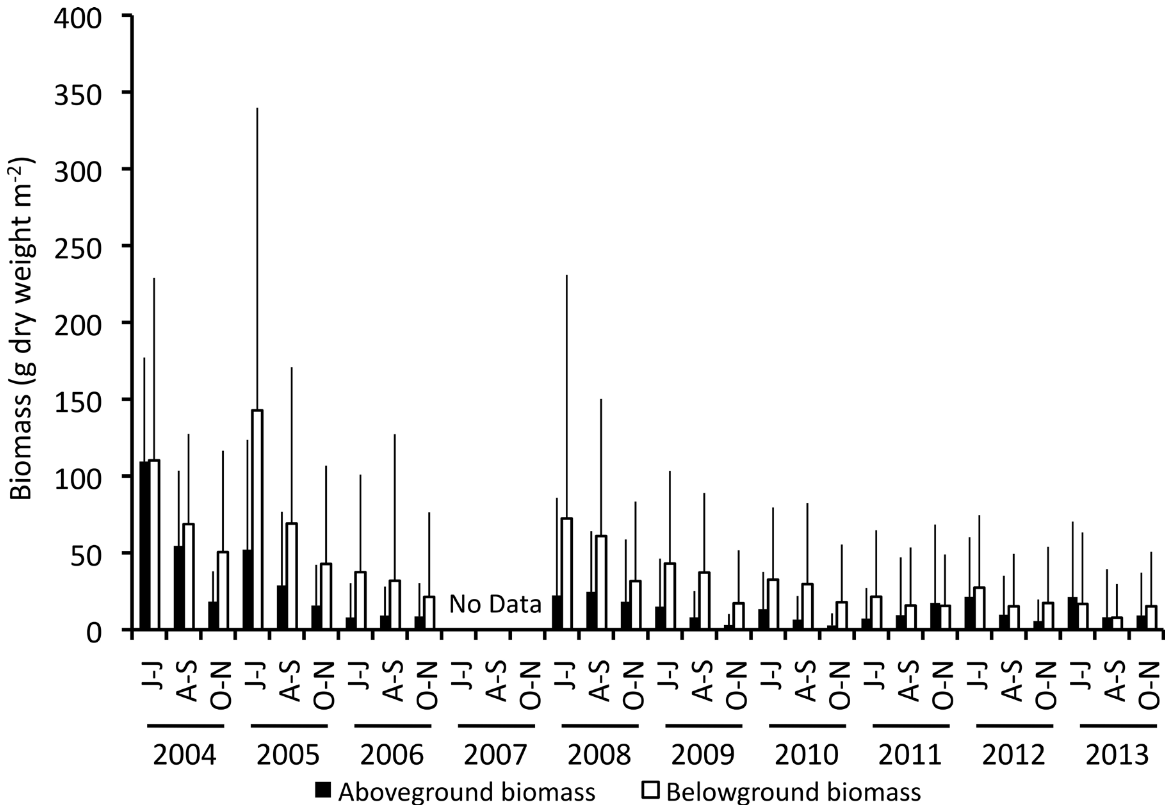

Figure 2. Long-term *Zostera marina* biomass (g dry weight m^{-2}) aboveground (black columns) and belowground (white columns) averaged for each time period (J-J = June-July, A-S = August-September, O-N = October-November) during each year from 2004-2013, except during 2007 when no data were collected.

In 2012, aboveground biomass and belowground biomass of *Z. marina* were highest during the June-July sampling period; mean aboveground biomass at this time amounted to 21.5 g dry wt m^{-2}, while mean belowground biomass amounted to 27.3 g dry wt m^{-2}. Progressively lower mean aboveground measurements were recorded for both species during the August-September and October-November sampling periods. The highest aboveground biomass and belowground biomass measurements of *Z. marina* in 2012 were found at sampling stations along Transect 6. Aboveground biomass of *Z. marina* was highest during the June-July sampling period in 2013 (Mean = 21.3 g dry wt m^{-2}), subsequently decreasing to very low levels during August-November (Mean = 8.1 g dry wt m^{-2}) and October-November (Mean = 9.2 g dry wt m^{-2}). Similarly, belowground biomass of *Z. marina* peaked during the June-July sampling period (Mean = 16.7 g dry wt m^{-2}) compared with the August-September sampling period (Mean = 7.8 g dry wt m^{-2}) and October-November sampling period (Mean = 15.2 g dry wt m^{-2}).

Comparing spatial and temporal trends of *Z. marina* characteristics in BB-LEH after fertilizer legislation was enacted in New Jersey (2012-2013) to before fertilizer legislation was enacted (2004-2011) reveals the following changes:

1) Mean aboveground biomass in both June-July 2012 (21.4 g dry wt m^{-2}) and June-July 2013 (21.3 g dry wt m^{-2}) was greater than that in June-July 2006 and 2009-2011. However, the somewhat greater biomass during June-July 2012 and 2013 did not last across the seasonal sampling periods relative to prior years (2004-2011). More significantly, mean belowground biomass values in 2012 and 2013 were less than in any year 2004-2011 for all three sampling periods. Declining trends of eelgrass biomass in the estuary are well chronicled [6] [8] [9] [14] [19] [28].
2) Mean areal cover for *Z. marina* did not significantly change between 2012 or 2013 and years prior until, and including, 2006. However, mean *Z. marina* areal cover in 2005 (June-July 36.9%; August-September 23.1%) was 1.6 and 1.7 times that in 2012, and 2.3 times that in 2013, respectively. Similarly, mean *Z. marina* areal cover in 2004 (June-July 44.8%; August-September 37.6%; October-November 21.4%) was 2.0, 2.7, and 2.1

times that in 2012, respectively, and 2.8, 3.8, and 1.7 times that in 2013, respectively. Lathrop *et al*. [20], conducting remotely-sensed surveys, clearly showed that eelgrass percent cover decreased in the BB-LEH system during the first decade of the 2000s.

These findings indicate important decreases in *Z. marina* biomass and areal cover values between 2004 and 2013. Peak loading of nitrogen from the watershed to the estuary (~857,000 kg TN yr^{-1}) occurred during 2010, as did peak loading of phosphorus (~32,000 kg TP yr^{-1}) [7]. Nutrient enrichment in the estuary is a significant driver of change in eelgrass characteristics [6] [8] [9].

Studies of coastal lagoonal systems, such as BB-LEH, show that environmental impacts escalate with increases in development and the amount of impervious cover in surrounding coastal watersheds. A watershed impact threshold is exceeded when the amount of impervious surface cover is greater than 10% [34]. Development of the BB-LEH Watershed now amounts to ~34% (up from ~19% in the early 1970s), and impervious land cover exceeds 10% (Center for Remote Sensing and Spatial Analysis, Rutgers University). Land use and land cover changes in the watershed have been substantial over the past few decades [14].

The population growth in Ocean County increased from 108,241 in 1960 to 576,567 in 2010 and 586,300 in 2015. Between 1980 and 2010, the population in the county increased by more than 66%. During the summer months, the population in Ocean County increases to ~1,500,000 people as noted by the Ocean County Planning Board, and the eutrophication problems in the estuary escalate [6]. Dramatic land use and land cover changes have occurred in the BB-LEH Watershed concurrently with population growth over the past three decades. Therefore, ecological impacts in the estuary are to be expected with increasing land alteration in the watershed [5] [19] [35]. The BB-LEH Estuary is an ecologically impacted system due to eutrophication. This is manifested by declining ecological conditions such as significant loss of seagrass habitat, increasing algal blooms, and diminishing ecosystem services.

6. Conclusions

Detailed investigations of *Z. marina* in the BB-LEH from 2004 to 2013 indicate a significant decline in plant characteristics in response to ongoing nitrogen enrichment of this highly eutrophic lagoonal system. Studies conducted in the estuary from June-November in 2008 to 2010 show that the eelgrass beds had not yet recovered from a marked reduction of plant biomass recorded by earlier *in situ* surveys of seagrass beds conducted in the estuary from 2004-2006. Quadrat, core, and hand sampling of up to 150 transect stations in disjunct beds in the estuary revealed a distinct reduction in plant characteristics that are leading to significant shifts in ecosystem services. In 2010, the lowest eelgrass biomass values were recorded in the estuary (Mean aboveground biomass = 2.7 g dry wt m^{-2}; mean belowground biomass = 17.9 g dry wt m^{-2}) [8]. Low eelgrass biomass, shoot density, and areal cover continued in the estuary through the last sampling period, October-November 2013 [10].

The decline of seagrass beds is a serious concern in BB-LEH because of their multiple ecosystem services, notably major sources of primary production, food for waterfowl, essential habitat and nursery areas for numerous fish and invertebrates, filters of chemical substances, agents in biogeochemical cycling, and buffers against wave and current action as well as sediment erosion. The decline in plant parameters is evident in all eelgrass beds investigated, indicating that an estuary-wide stressor is responsible, most notably nutrient enrichment and escalating eutrophication.

As noted by Lathrop *et al*. ([20], p. 307), "Determining the causative factors for seagrass decline and expansion can be difficult in that seagrass habitat integrates the ecological signal over a multi-year period of time." Hence, a dedicated and focused monitoring program is needed to determine the long-term primary stressors and drivers of change in seagrass habitats of this coastal lagoon.

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