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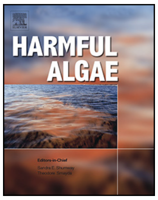

Research paper

Spatial and temporal variability in macroalgal blooms in a eutrophied coastal estuary

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ABSTRACT

All three macroalgal clades (Chlorophyta, Rhodophyta, and Phaeophyceae) contain bloom-forming species. Macroalgal blooms occur worldwide and have negative consequences for coastal habitats and economies. Narragansett Bay (NB), Rhode Island, USA, is a medium sized estuary that is heavily influenced by anthropogenic activities and has been plagued by macroalgal blooms for over a century. Over the past decade, significant investment has upgraded wastewater treatment from secondary treatment to water-quality based limits (i.e. tertiary treatment) in an effort to control coastal eutrophication in this system. The goal of this study was to improve the understanding of multi-year macroalgal bloom dynamics through intensive aerial and ground surveys conducted monthly to bi-monthly during low tides in May–October 2006–2013 in NB. Aerial surveys provided a rapid characterization of macroalgal densities across a large area, while ground surveys provided high resolution measurements of macroalgal identity, percent cover, and biomass.

Macroalgal blooms in NB are dominated by *Ulva* and *Gracilaria* spp. regardless of year or month, although all three clades of macroalgae were documented. Chlorophyta cover and nutrient concentrations were highest in the middle and upper bay. Rhodophyta cover was highest in the middle and lower bay, while drifting Phaeophyceae cover was patchy. Macroalgal blooms of >1000 g fresh mass (gfm)/m^2 (max = 3510 gfm/m^2) in the intertidal zone and >3000 gfm/m^3 (max = 8555 gfm/m^3) in the subtidal zone were observed within a heavily impacted embayment (Greenwich Bay). Macroalgal percent cover (intertidal), biomass (subtidal), and diversity varied significantly between year, month-group, site, and even within sites, with the highest species diversity at sites outside of Greenwich Bay. Total intertidal macroalgal percent cover, as well as subtidal *Ulva* biomass, were positively correlated with temperature. Dissolved inorganic nitrogen concentrations were correlated with the total biomass of macroalgae and the subtidal biomass of *Gracilaria* spp. but not the biomass of *Ulva* spp. Despite seasonal reductions in the nutrient output of wastewater treatment facilities emptying into upper Narragansett Bay in recent years, macroalgal blooms still persist. Continued long-term monitoring of water quality, macroalgal blooms, and ecological indicators is essential to understand the changes in macroalgal bloom dynamics that occur after nutrient reductions from management efforts.

1. Introduction

Macroalgal blooms are a worldwide hazard that damage coastal habitats and economies by outcompeting perennial macrophytes and phytoplankton for light and nutrients (McGlathery et al., 1997, 2001; Valiela et al., 1997; Hauxwell et al., 1998), creating hypoxic or anoxic conditions through nightly respiration and eventual decomposition (Valiela et al., 1992; Diaz, 2001), producing toxic

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chemicals (Nelson et al., 2003a; Eklund et al., 2005), and interfering with boat traffic, fishing, and tourism by clogging waterways and fouling beaches (Lee and Olsen, 1985; Thomsen and McGlathery, 2006; Leliaert et al., 2009). Through their environmental impacts, blooms can result in reduced macrophyte, invertebrate, and vertebrate diversity and abundance (Valiela et al., 1992; Hauxwell et al., 2001; Thomsen and McGlathery, 2006; Berezina et al., 2007; Tyler, 2007; Wennhage and Pihl, 2007; Schein et al., 2012). Consequent herbivore reductions can exacerbate bloom conditions by initiating a feedback loop where reduced herbivory leads to increased macroalgal biomass, which further reduces herbivore abundance (Engelsen et al., 2010).

Laboratory culturing, mesocosm studies, and field studies have demonstrated a strong positive relationship between macroalgal bloom formation and nutrient enrichment, particularly when algae are grown at optimal temperatures and light conditions (Valiela et al., 1992, 1997; Taylor et al., 2001; Bintz et al., 2003; Nelson et al., 2003b; Cohen and Fong, 2004; Sousa et al., 2007; Teichberg et al., 2010). Field observations support these findings and highlight the additional importance of the complex physical characteristics of a local geographic site, including geographic orientation in relation to prevailing winds, currents, tidal dynamics, and bathymetric features (Aldridge and Trimmer, 2009; Lyons et al., 2009; Lee et al., 2011; Liu et al., 2013; Hu et al., 2014). Herbivory can also limit bloom biomass (Geertz-Hansen et al., 1993; Williams and Ruckelshaus, 1993; Korpinen et al., 2007), though this influence varies by bloom species, herbivore species, and abiotic conditions and is often insufficient to prevent bloom formation in highly eutrophic areas (Horne et al., 1994; Hauxwell et al., 1998; Morgan et al., 2003; Worm and Lotze, 2006; Fox et al., 2012; Guidone et al., 2015).

All three macroalgal clades (Chlorophyta, Rhodophyta, and Phaeophyceae) contain bloom-forming species. The largest and most frequently occurring macroalgal bloom type is the 'green tide', which is composed of one or more Chlorophyta species (Fletcher, 1996; Valiela et al., 1997; Morand and Merceron, 2005). Recurring *Ulva* blooms have been reported from around the world, including off the coast of Qingdao, China (Leliaert et al., 2009), Brittany, France (Merceron and Morand, 2004), Venice, Italy (Sfriso et al., 1992), Washington, USA (Nelson et al., 2003b), California, USA (Kamer et al., 2001), and throughout the New England region of the United States from Maine through Long Island Sound (Conover, 1958; Nixon and Oviatt, 1973; Granger et al., 2000; Vadas et al., 2004; McAvoy and Klug, 2005; Lyons et al., 2009; Guidone and Thornber, 2013; this study).

Despite the global occurrence of macroalgal blooms and extensive knowledge of how abiotic factors impact bloom species, there is a limited understanding of the long-term patterns in bloom formation, persistence, and severity, particularly within the context of management efforts and climate change. For those systems where long-term data does exist, there is evidence that management policies resulting in reduced nutrient inputs do lead to improved water quality (Deacutis, 2008; Greening et al., 2014), though whether a reduction in macroalgal biomass occurs appears to vary by algal species (Leston et al., 2008). These studies demonstrate the importance of long-term monitoring and the necessity of collecting data prior to, during, and following shifts in nutrient inputs. Moreover, because of the linkage of macroalgal growth to local nutrient levels, the thorough understanding of bloom dynamics that is gained through these monitoring programs can facilitate future management of anthropogenic nutrient loads through the development of ecological indices, as exemplified by work done in relation to the European Water Framework Directive (Scanlan et al., 2007; Sfriso et al., 2007, 2009; Wells et al., 2007; Wilkinson et al., 2007; Sfriso and Facca, 2012).

The goal of this study was to improve understanding of multi-year macroalgal bloom dynamics through intensive aerial and ground surveys of Narragansett Bay (NB), Rhode Island, USA. This estuarine system is particularly well suited to long-term study of macroalgal blooms because it is annually impacted by blooms of *Ulva* spp. and also experiences periodic blooms of *Gracilaria* spp. (Granger et al., 2000; Guidone and Thornber, 2013; this study). In addition, Narragansett Bay presents the opportunity to monitor the impacts of regulatory nutrient permit limit revisions that required wastewater treatment facilities (WWTFs) to decrease their inputs to the Bay. These regulations were implemented in stages from 2006 to 2014 and, as of 2015, they have resulted in more than a 50% decrease in nitrogen loads from WWTFs (A. Liberti, personal communication). In response to this phased decrease, it was predicted that a corresponding decrease in the observed abundance of macroalgae in the lower Providence River and Upper Narragansett Bay would occur, as these areas are closest to the sewage point sources (Deacutis, 2008). Results of these surveys provide large- and small-scale documentation of macroalgal distribution patterns in a eutrophic estuary as well as a long-term data set that can aid in distinguishing between interannual variability and management-linked decreases in bloom biomass and/or alterations in macroalgal diversity.

2. Methods

2.1. Abiotic influences in Narragansett Bay

Narragansett Bay is a medium-sized estuary (370 km^2, Ries, 1990) on the southern coast of New England, USA (Fig. 1). It has large anthropogenic nutrient loads, with the majority of nutrients coming from WWTFs (Nixon et al., 1995, 2008; Pryor et al., 2007). Low freshwater inflows (Ries, 1990), along with extensive damming of the rivers in the 1800's (Nixon et al., 1995), resulted in the majority of the estuary having polyhaline waters. A small mesohaline zone is present in the upper estuary (Providence and Seekonk tidal rivers), although the extent of this zone is dependent on river flows. Water residence time varies seasonally and among years, linked directly to river flows. Maximum residence time (~35 days) occurs during the summer months (July–September), while the minimum residence time (~20 days) occurs in spring when river flows peak (February–April; Pilson, 1985). In extremely dry summers, or with sustained winds that counteract estuarine flushing, the residence time may be up to 100 days (C. Kinkaid and W. Prell, personal communication).

Narragansett Bay has recently undergone a significant change in nitrogen loading due to management efforts that required major WWTFs to reduce their total nitrogen output by 50% in comparison to 1995–1996 levels. This target was achieved in 2015, reducing May through October baywide WWTF nitrogen inputs from 5462.6 kg/day in 2004 to 1885.6 kg/day in 2015 (A. Liberti, unpublished data). Climate change is another transformative force in NB; mean sea surface water temperature in the Bay has increased 1.4–1.6 °C since 1960 (Fulweiler et al., 2015), while precipitation has increased an average of 3.05 mm per year since 1905 (Pilson, 2008). To account for these factors, survey data were examined within the context of sampling year, region of the Bay (aerial surveys only), and available temperature, nutrient, and salinity measurements (ground surveys only).

2.2. Aerial survey

2.2.1. Data collection

Aerial oblique digital photographs of macroalgal presence were collected along the western shore of NB once a month within ±2 h of spring low tide from May through October 2007–2012.