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Coincident patterns of waste water suspended solids reduction, water transparency increase and chlorophyll decline in Narragansett Bay

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ABSTRACT

Dramatic changes occurred in Narragansett Bay during the 1980s: water clarity increased, while phytoplankton abundance and chlorophyll concentration decreased. We examine how changes in total suspended solids (TSS) loading from wastewater treatment plants may have influenced this decline in phytoplankton chlorophyll. TSS loading, light and phytoplankton observations were compiled and a light- and temperature-dependent *Skeletonema*-based phytoplankton growth model was applied to evaluate chlorophyll supported by TSS nitrogen during 1983–1995. TSS loading declined 75% from ~0.60 × 10^6 kg month^{-1} to ~0.15 × 10^6 kg month^{-1} during 1983–1995. Model results indicate that nitrogen reduction related to TSS reduction was minor and explained a small fraction (~15%) of the long-term chlorophyll decline. The decline in NBay TSS loading appears to have increased water clarity and *in situ* irradiance and contributed to the long-term chlorophyll decline by inducing a physiological response of a ~20% reduction in chlorophyll per cell.

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1. Introduction

A long-term decrease in phytoplankton (as chlorophyll) has occurred in lower Narragansett Bay (NBay), declining from ~6 μg L^{-1} (1983) to ~3 μg L^{-1} in 1995 (Li and Smayda, 1998), continuing at the reduced level through the 2000s (Fulweiler et al., 2007). The long-term decline in chlorophyll in NBay has been attributed to various processes: increased water temperature (Cook et al., 1998; Oviatt, 2004; Nixon et al., 2009), changes in light availability related to increased cloudiness (Borkman, 2002; Nixon et al., 2009), changes in ctenophore (Sullivan et al., 2001) and copepod (Keller et al., 1999; Oviatt, 2004) grazing, and long-term variations in coupled ocean–atmosphere forcing such as the NAO (North Atlantic Oscillation; Hawk, 1998; Oviatt, 2004; Borkman and Smayda, 2009a) and the Gulf Stream (Borkman and Smayda, 2009b). During the early portion of the chlorophyll decline in the 1980s, improved wastewater treatment led to a dramatic decline in suspended solid loading (TSS) into NBay from wastewater treatment plants (WWTP). From 1983 to 1995, TSS loading decreased *ca.* 75%, from *ca.* 9 × 10^6 kg year^{-1} (1983–84) to <3 × 106 kg year^{-1} (1992 to 1995) (Save the Bay, 1996; Borkman and Smayda, 1998). These solids, through their release of nitrogen and other nutrients, are a potential nutrient source no longer available to phytoplankton. Although particulate N is a relatively small portion of N loading to NBay (~5%; Hamburg et al., 2008; Nixon et al., 2008), the potential role of the 6 × 10^6 kg year^{-1} reduction in WWTP particulate loading on the 13-year decline (1983–1995) in mean annual chlorophyll has not been evaluated. The question we examine is how much of the decrease in lower NBay chlorophyll may be attributed to the decrease in TSS loading *via* two potential mechanisms, 1) nitrogen reduction and 2) increased *in situ* light. A large body of field and experimental evidence indicates nitrogen limits phytoplankton growth in NBay (Smayda, 1974; Furnas et al.,1986; Furnas, 1983; Oviatt et al., 1995; Nixon, 1997; among others). Applying dose-yield kinetics leads to the expectation that the reduction in TSS loading would decrease biomass. However, if the decline in chlorophyll is related to N availability, the relationship is paradoxical because the early phase of chlorophyll reduction (1983–1995) occurred during a period of no apparent change in nitrogen loading (Hamburg et al., 2008; Nixon et al., 2008).

We apply a proximate, mass balance approach to quantify the linkages between the long-term (n = 13 years during 1983 to 1995) decline in wastewater TSS loading and chlorophyll concentration in lower NBay in an effort to explain the 1980s to 1990s decline in chlorophyll concentration. The model integrates the light and temperature-dependent growth rate of the dominant diatom (*Skeletonema costatum* s.l.) in NBay (Karentz and Smayda, 1984; Borkman and Smayda, 2009a) and

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the time series data available for WWTP TSS loading, incident irradiance, water clarity, temperature, chlorophyll, and *Skeletonema* abundance during 1983–1995.

2. Methods

2.1. Geographic setting and data sources

Narragansett Bay (*ca.* 327 km^2) is a well-mixed, relatively shallow (mean depth 9 m), estuary located southwest of Cape Cod along the eastern U.S. coast (*ca.* 41°30′N, 71°20′W), and is contiguous with Rhode Island Sound and Long Island Sound. Nutrient-enriched freshwater flowing into the upper NBay produces a pronounced salinity - nutrient gradient over the length of its 30 km axis, progressing from an upper region of low salinity (*ca.* 20) and elevated nutrients to a region of high salinity (*ca.* 33), and decreased nutrient at its entrance (Smayda and Borkman, 2008). The mean residence time of NBay water is 26 days, varying from 10 to 40 days dependent on the volume of freshwater input and wind conditions (Pilson, 1985). A detailed description of the geographic setting and the biological, physical and chemical oceanography of NBay is available in Desbonnet and Costa-Pierce (2008).

Water temperature, water clarity, incident and *in situ* irradiance, chlorophyll concentration and numerical abundance of *S. costatum* s.l. were measured weekly at a long-term monitoring station in unpolluted lower NBay (41°32′N × 71°23′W) from 1983 to 1995. Methodological details for measurement of water temperature, irradiance and water clarity are described in Smayda (1984, 1998) and Borkman and Smayda (1998); chlorophyll methods are available in Li and Smayda (1998), and *Skeletonema* numerical abundance methods are in Borkman and Smayda (2009a, 2009b). The 1983 to 1995 data used in our study are a subset from the long-term (1959 to present) Narragansett Bay Plankton Time Series. We analyze only the 1983 to 1995 portion of the data set because it is the only portion of the time series for which synchronous measurements of phytoplankton, chlorophyll concentration, irradiance, water clarity and TSS loading data are available. Incident solar irradiance during the time series initially was measured in the non-SI units of Langley day^{-1} (Pratt, 1965; Hitchcock and Smayda, 1977). We converted those data into Watts using the conversion 1 Langley day^1 = 0.485 W m^{-2} day^{-1} (National Institute for Standards and Technology, 2008). Incident irradiance was recorded using an Eppley pyrheliometer installed at the URI-GSO campus in Narragansett, RI (~10 km south of the long-term sampling site) during 1983 until 1987. From 1988 until 1995 incident irradiance was recorded using an Eppley pyrheliometer installed at Eppley Laboratories in Newport, RI (~11 km southeast of the long-term sampling site). The mean weekly *in situ* irradiance ('I bar') at the monitoring station was calculated from the daily *in situ* irradiance during the 1983 to 1995 period using the equation of Riley (1957) as modified by Hitchcock and Smayda (1977):

$$\text{I bar} = \frac{\text{Io}}{kz\left(1-e^{-kz}\right)} \tag{1}$$

where Io is incident irradiance, k is the extinction coefficient (calculated from Secchi disk depth (D) after the formula of Holmes (1970): k = 1.44/D) and z is the mixed layer depth equivalent to the depth (8 m) of the long-term sampling station.

The collective monthly and annual WWTP TSS loading levels during 1983 to 1995 from 17 waste water treatment plants that discharge into NBay were compiled from reports issued by Save the Bay (1996). Locations of the main WWTP and the long-term loading history of metals, nitrogen and other pollutants to Narragansett Bay are shown in detail by Nixon and Fulweiler (2012). Some plants provided only total annual discharge data. For those, the total annual TSS discharge was seasonally adjusted based on the mean monthly pattern of TSS discharge at the three largest treatment plants during 1994 and 1995, *i.e.*, Fields Point, Fall River and Blackstone (Worcester) Facilities. The nitrogen content of sludge from a representative RI treatment plant (located in Cranston, RI) was 2.5% of dry sludge weight (Oviatt et al., 1987). Monthly TSS loading was multiplied by this nitrogen content to approximate monthly nitrogen loading into NBay from sewage plant TSS.

2.2. Model development

We used the diatom *Skeletonema* as the representative phytoplankton taxon to model whether the recorded decline in mean annual chlorophyll in NBay was related to the decline in TSS discharge. *S. costatum* s.l. is numerically the most abundant diatom in NBay year-round; it accounts for a mean of 42% of total phytoplankton numerically (annual mean contribution range of 11% to 69%; Karentz and Smayda, 1984; Borkman and Smayda, 2009a). There is a wealth of experimental data for *Skeletonema* strains and populations from NBay, both *in situ* and in culture, including cellular N and chlorophyll quotas, the effect of irradiance, nutrients and temperature on cellular nutrient composition and growth rate (Smayda, 1973; Yoder, 1979; Falkowski et al., 1981; Sakshaug and Andresen, 1986; Langdon, 1987; Anning et al., 2000). We used the experimentally derived linear, positive relation between growth irradiance and nitrogen content of *S. costatum* s.l. reported by Langdon (1987) for the NBay strain SK 6C:

$$\text{pg N cell}-1 = 0.028\,\text{I} + 2.97 \tag{2}$$

where I is irradiance as W m^{-2}.

Accepting that nitrogen is the nutrient that primarily limits phytoplankton growth in NBay (Smayda, 1974; Furnas, 1983; Furnas et al., 1986; Kremer and Nixon, 1978; Oviatt et al., 1995), we applied the following schematic. TSS discharge was converted to the nitrogen concentration potentially available for phytoplankton assimilation. The estimated number of *Skeletonema* cells and their chlorophyll content produced by this nitrogen accretion from TSS was calculated using the relationships reported between light, temperature and cellular nitrogen content of *Skeletonema* and between light and chlorophyll (Langdon, 1987). The lower NBay station is well-mixed over its 8 m depth through most of the year (Hitchcock and Smayda, 1977), validating the use of depth-averaged irradiance (I bar) in the model. Using I bar as input (Eq. (1)), the nitrogen content of the *in situ* concentration (cells ml^{-1}) of *Skeletonema* was estimated for each month during 1983–1995 using the weekly population densities recorded at the monitoring site (Borkman, 2002; Borkman and Smayda, 2009a). Dividing the monthly TSS nitrogen load by the light-dependent, mean monthly cellular nitrogen content yielded an estimate of the number of *Skeletonema* cells potentially supported by the monthly TSS nitrogen load. Note that this is a maximum potential estimate and that given the relatively high ambient DIN levels, the actual phytoplankton growth response stimulated by TSS-derived DIN will be less than the predicted potential response.

The model monthly nitrogen load only accounts for DIN; we have ignored the potential role of dissolved organic nitrogen (DON) in the model. DON was excluded because it was not regularly monitored during the 1983–1995 period (Nixon et al., 2005). For reference, available data indicates the percentage of total N as DON discharged into NBay by WWTP is of the order of 14% to 19% of total N discharged (Nixon et al., 2008).

The *Skeletonema* cell number estimates were converted to chlorophyll applying Langdon's (1987) equation (Eq. 3) relating chlorophyll content of *S. costatum* cells to light intensity:

$$\begin{array}{l}\text{Irradiance}<24\ \text{W m}^{-2};\ \text{Chlorophyll} = 0.72\ \text{pg cell}^{-1}\\ \text{Irradiance}>24\ \text{W m}^{-2};\ \text{Chlorophyll} = 0.41\ \text{pg cell}^{-1}.\end{array} \tag{3}$$

The estimated chlorophyll biomass supported by WWTP TSS was divided by the volume (2724 × 10^6 m^3) of Narragansett Bay (Pilson, 1985) to get a coarse monthly estimate of the potential concentration of

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