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Atmospheric nitrogen deposition from a remote source enriches macroalgae in coral reef ecosystems near Green Turtle Cay, Abacos, Bahamas

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Abstract

Over the past several decades, the fixation of "new" nitrogen to the biosphere has doubled. For the early 21st century, the most significant rate increases in atmospheric nitrogen deposition are predicted for developing nations. Wet nitrogen deposition was assessed on the remote island of Green Turtle Cay, Bahamas in a dry and wet season from January to July 2000. Episodic deposition of nitrate (~1–137 μM) and ammonia (~2–122 μM) represented a mean deposition rate of ~0.2 mg DIN m^{-2} yr^{-1}. Wet deposition of nitrogen to the climatologically-linked east coast of Florida is ~4 times greater than the estimated annual wet nitrogen deposition value at Green Turtle Cay, suggesting the continental US as a principal airshed for this loading source. Short-term bioassays of macroalgal productivity with a 5% rainfall solution caused depressed net productivity and increased dark respiration, well known "transient metabolic" responses by nutrient-limited tropical macroalgae. Wet deposition of inorganic nitrogen from episodic rainfall events may provide up to 20% of the "new" nitrogen necessary to meet growth demands of macroalgae on coral reefs near Green Turtle Cay.

Keywords: Atmospheric deposition; Nitrogen; Macroalgae; Coral reefs; Bahamas

1. Introduction

Within the past two decades, the fixation of "new" nitrogen to the biosphere has doubled as a result of human activities (Vitousek et al., 1997a). This biogeochemical modification has altered patterns of primary productivity throughout the global environment, because most ecosystems on land and in the sea tend to be nitrogen-limited (Vitousek and Howarth, 1991). Coastal marine ecosystems, in particular, are typically limited by nitrogen (Ryther and Dunstan, 1971; Howarth, 1988; Nixon, 1995) and may be one of the more impacted environments on earth as a result of increased nitrogen loadings from coastal watersheds and airsheds (NRC, 2000).

Like the oligotrophic seas they have evolved in, hermatypic coral reef ecosystems are adapted to nutrient limited conditions where natural nitrogen fixation is the dominant source of "new" nitrogen (Wiebe et al., 1975). Alternatively, reefs with high water column nitrogen and phosphorus concentrations are more favorable for fleshy opportunistic algae (Lapointe, 1997) and are less favorable for calcifying macroalgae (Delgado and Lapointe, 1995; Lapointe and Thacker, 2002) and hermatypic corals (McConnaughey et al., 2000). Saturating concentrations of DIN for growth of tropical marine macroalgal are ~0.5–1 μM (see Lapointe, 1999). Because of this adaptation to low nutrient conditions, coral reefs are particularly susceptible to eutrophication via anthropogenic nutrient loading (Lapointe, 1997,

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1999). Macroalgal blooms are becoming more conspicuous on hermatypic coral reefs throughout their circumtropical distribution (Done, 1992; Hodgson, 1999). As a result, macroalgal dominated reefs (see Lighty, 1982; Hughes, 1994; Lapointe, 1997; NRC, 2000) may represent an alternative "stable-state" in the era of increased anthropogenic domination of ecosystems (Vitousek et al., 1997b). Oceanic islands, such as Jamaica, with high topography and carbonate geology are particularly prone to mobilization of sewage, fertilizers and other sources of nitrogen to adjacent reef systems (Marsh, 1977; Rawlins et al., 1998; Lapointe and Thacker, 2002).

Atmospheric deposition of nitrate over the past century has mirrored increases in anthropogenic fossil fuel emissions of NO_x in both North America and Europe (Brimblecombe and Stedman, 1982). Since the 1950s, for example, atmospheric deposition to the northern hemisphere has increased five-fold (Galloway et al., 1994). By the year 2020, atmospheric nitrogen deposition is predicted to increase by 25% in urbanized North America, but more significantly, may double in developing regions such as SE Asia and Latin America, and will increase by more than 50% in oceans of the Northern Hemisphere (Galloway et al., 1994). Recognition of the scope of anthropogenic atmospheric nitrogen deposition (AAND) to the global environment has expanded with reports of continental atmospheric pollution plumes reaching remote oceanic locations (e.g. Abram et al., 2003). Climatological forcing delivers anthropogenic nitrogen downwind from eastern continental regions into western oceanic environments (Miller and Harris, 1985; Levy and Moxim, 1987; Moody and Galloway, 1988). For example, the eastward flux of anthropogenic nitrogen from North America (Galloway et al., 1984a) has been monitored and reported for several decades in Bermuda (see Menzel and Spaeth, 1962; Jickells et al., 1982). On northern Pacific oceanic islands, anthropogenic continental sources from Asia are responsible for 40–70% of nitrate aerosol concentrations that represent values three times higher than background concentrations in the southern Pacific (Prospero and Savoie, 1989).

While nutrient loading from more recognizable and historically significant point and non-point sources (e.g. municipal wastewater, urban stormwater) have been subjected to management programs for reductions (e.g. EPA's Total Maximum Daily Load (TMDL) program, NOAA-Estuarine Eutrophication Survey (see Bricker et al., 2000)), increasing loads from AAND may offset the benefits of these reductions (Paerl, 1995). The symptoms of coastal eutrophication (harmful algal blooms, hypoxia) appear to have intensified despite these initiatives for reductions of traditionally important sources (Smayda, 1990; Bricker et al., 2000), leading some to point to AAND as an emerging and potentially dominant source leading to eutrophication of coastal ecosystems (Paerl, 1995; Jaworski et al., 1997). Coastal waters downwind from industrialized centers such as the Chesapeake Bay may receive greater than 50% of nitrogen loading from atmospheric deposition (Correll and Ford, 1982). Jaworski et al. (1997) estimated that 64% of the nitrogen export from NE US watersheds during 1990–1993 was derived directly or indirectly from NO_x emissions. Increased AAND to land-locked oceans such as the Baltic (Rodhe et al., 1980) and the Mediterranean (Bethoux et al., 1998) have driven broad-scale biogeochemical transitions in surface waters. Likewise, in downwind western oceanic basins Fanning (1989) attributed a shift in stoichiometric ratios of major macronutrients from nitrogen to phosphorus limitation as a result of increased AAND.

Considerable attention has been given to the role of excess nitrogen, particularly AAND, as a principal driver in the alteration of productivity patterns in terrestrial ecosystems, especially for European forests. Controversy, however, surrounds the potential role of these nitrogen additions in driving additional C fixation on the ecosystem or biome scale, particularly as a sink for the "missing carbon" from global biogeochemical budgets (Townsend et al., 1996). Clearer though, is the importance of AAND as it contributes to regional enhancement of productivity in coastal ecosystems. Nitrogen-limited coastal seas downwind of urban areas such as the Gulf Stream off of NC (Willey et al., 1988) appear particularly susceptible to enhancement of primary productivity by AAND (Paerl et al., 1990; Willey and Cahoon, 1991). A more enigmatic question is the role of AAND as its relation to primary production in marine waters remote from source production.

Beyond the obvious cases of anthropogenic nutrient enrichment from local sources, overgrowth by macroalgae has been reported on coral reefs in remote locations where sources of nutrient enrichment are not obvious (see Szmant, 2001). The Abaco Barrier Reef, near Green Turtle Cay, Bahamas (Fig. 1) has been characterized as a high-latitude reef system dominated by macroalgae (Lighty, 1982). Here, we report the significance of AAND on an oceanic coral reef environment, Green Turtle Cay, downwind from a major continental atmospheric source; and the first evidence that AAND significantly alters the productivity of coral reef macroalgae.

2. Methods

2.1. Analysis of wet deposition

Rainwater was collected from 15 rainfall events in a dry and wet season between January 18 and July 29, 2000 in clean polyethylene basins placed in an open field, <0.5 km from the meterological station on Green Turtle Cay (GTC), Abacos, Bahamas. Rainwater was