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Nitrogen versus phosphorus limitation in a subtropical coastal embayment (Moreton Bay; Australia): Implications for management

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ABSTRACT

An approach combining nutrient budgets, dynamic modelling, and field observations of phytoplankton and nitrogen (N_2)-fixing *Lyngbya majuscula* following changes in wastewater N loads, was used to demonstrate that Moreton Bay is potentially phosphorus (P) limited. Modelling and nutrient budgeting shows that benthic N-fixation loads are high, allowing the system to overcome any potential N-limitation. Phytoplankton biomass has shown little change from 1991 to 2006 in the sections of Moreton Bay most impacted by wastewater effluents, despite a large reduction in wastewater N loads from 2000 to 2002. This is consistent with modelling that also showed no reduction in primary productivity associated with reduced N loads. Most importantly, there have been rapid increases in the occurrence of N-fixing *L. majuscula* in Moreton Bay as wastewater P loads have increased relative to wastewater N loads. This is also consistent with modelling. This work supports the premise that there may be fundamental differences in nutrient limitation of primary production between subtropical and temperate coastal systems due to differences in the importance of internal nitrogen sources and sinks (N-fixation and denitrification). These differences need to be recognised for optimum management of coastal systems.

1. Introduction

Since Ryther (1954) first suggested that Moriches Bay on Long Island might be nitrogen (N) rather than phosphorus (P) limited there has been much debate over N versus P limitation of primary production in coastal systems (mostly focused on temperate systems; see Nixon et al., 1986; Howarth, 1988; Howarth and Marino, 2006; Conley et al., 2009 for reviews). In a recent review, Howarth and Marino (2006) concluded that many temperate coastal systems are N-limited mostly because they are unable to replenish nitrogen via N-fixation. Exceptions to this paradigm are the low salinity regions of temperate systems that support planktonic cyanobacteria (e.g. Lukatelich and McComb, 1986; Larsson et al., 2001). This contrasts with Smith's (1984) view that P is the limiting nutrient in marine systems based on nutrient budgets in subtropical and temperate systems that showed large nitrogen inputs via N-fixation. These contradicting views raise the question, "are there fundamental mechanistic differences in nutrient limitation of primary production between subtropical and temperate systems, mostly because of their ability to replenish N via N-fixation?"

On the basis of whole ecosystem scale nutrient budgets Eyre and McKee (2002) argued that Moreton Bay, a sub-tropical coastal embayment, was P limited. Extending the N versus P limitation debate from temperate to tropical coastal systems, Glibert et al. (2006) have argued that Moreton Bay is N limited, on the basis of small-scale bottle incubation experiments, ambient water column dissolved and particulate nutrient concentrations, and new estimates of N-fixation. In contrast, the results from other batch and continuous culture studies on *L. majuscula* by Elmetri and Bell (2004) suggested that the growth of these benthic cyanobacteria is P limited. The fundamental difference between these studies is the scale at which the evaluations of nutrient limitation were undertaken. Glibert et al. (2006) failed to recognise that the interpretation and extension of their work should be restricted to the spatial and temporal scale of their experiments (Fisher et al., 1995; Eyre and McKee, 2002). For example, the use of small-scale experiments by Glibert et al. (2006) excluded critical larger spatial and temporal scales of nitrogen recycling and benthic N-fixation pathways, in particular benthic-pelagic coupling in the bay, which is a critical link for the P-limitation paradigm (see Eyre and McKee, 2002).

To demonstrate that Moreton Bay could be P limited we have used a combined approach of nutrient budgets, dynamic modelling, field observations of phytoplankton biomass (chlorophyll-a concentrations), and the behaviour of N-fixing *L. majuscula* within the context of changes in wastewater loads to the bay. This work

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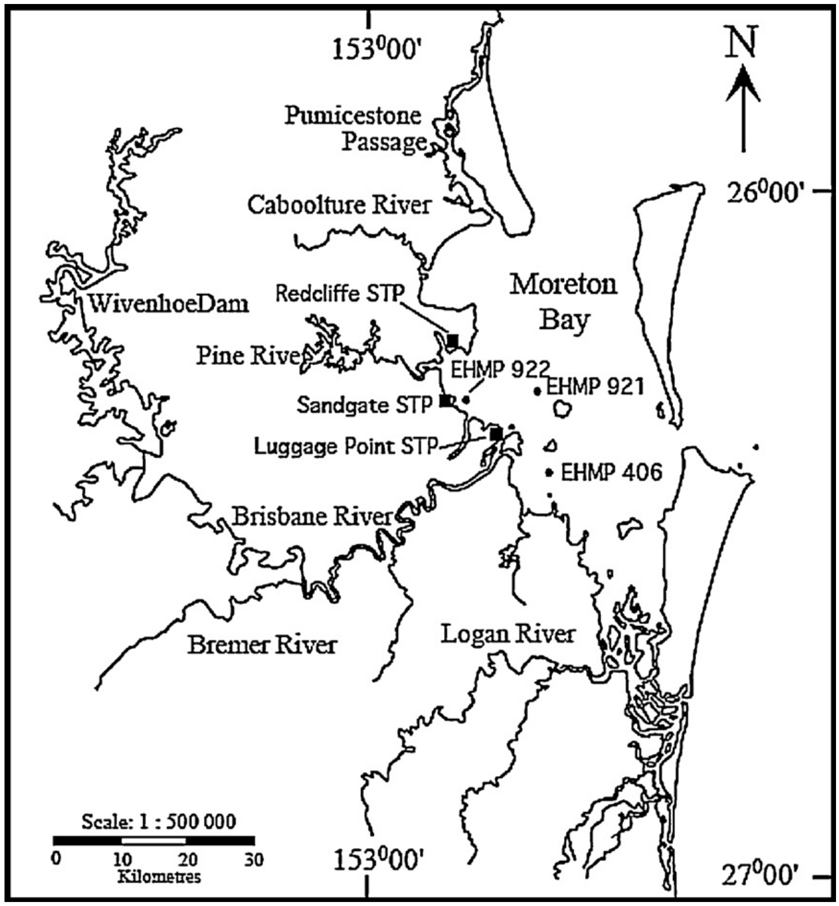

Fig. 1. Map of Moreton Bay, Queensland, Australia.

supports the premise that there may be fundamental differences in nutrient limitation of primary production between sub-tropical and temperate coastal systems, and that these differences need to be recognised for the optimum management of such sub-tropical coastal systems.

2. Materials and methods

2.1. Study area

Moreton Bay borders Brisbane, the third largest city in Australia, and is a subtropical bay exposed to intensive human use. The bay supports major shipping facilities, a large commercial fishery, and extensive tourism, and encompasses important nature conservation areas. Accordingly, sustainable management of the bay is essential for the economic and ecological sustainability of the region.

Moreton Bay covers 1845 km^2 and has a mean depth of only 6.3 m. It contains extensive seagrass beds, is fringed by mangroves along much of its coast, and is enclosed by large sandy barrier islands towards the sea in the east (Fig. 1). The average water residence time is 44 days and the catchment area is approximately 14 times larger than the Bay. Characteristic of most Australian estuaries, substantial climate variability leads to low freshwater inputs during most of the year interrupted by short, intense rainfall events. For Moreton Bay these pulsed inputs have been substantially dampened over the last 40 years as the four major rivers entering the bay have become regulated. There has also been a net decrease in inputs from the catchment associated with a decline in average annual rainfall in the last 10 years. Evaporation exceeds rainfall annually in this subtropical part of the continent. Oceanic swell, tidal and wind mixing, and the lack of consistent freshwater inputs keep this shallow estuary well mixed.

The warm water and low nutrient East Australian Current (EAC) dominates the offshore waters outside the bay. Clear waters characterize the eastern and northern sections of Moreton Bay, whilst the western and more southern parts generally receive elevated levels of silt and humic substances from river runoff and sediment re-suspension. Whilst both areas of the bay experience algal blooms, the total biomass and duration of blooms appears to differ for the clearer waters and the more turbid western areas of the bay (EHMP Report, 2008). There is a high ecological diversity in the bay with habitat types including soft muddy sediments, mobile high-energy sandy substrates, seagrass meadows, mangrove forests, hard-packed sandy bottoms, rocky outcrops, and even coral reefs. The ecological characteristics of the Bay are extensively summarized and described in Dennison and Abal (1999).

Southeast Queensland has been among the fastest growing regions in the world over the past half century (Dennison and Abal, 1999). The population of greater Brisbane is currently approximately 1.6 million, and approximately 2 million people live in the wider Moreton Bay drainage basin. The land used for agriculture in the catchment is now decreasing as it is converted to peri-urban and urban development. The amount of fertilizer used continues to increase with intensified cultivation of agricultural land, and this is clearly seen in the nutrient concentrations of the rivers. Nitrate concentrations in the Brisbane River, for example, have increased 22-fold and phosphate concentrations 11-fold since the 1950s. Three quarters of the sewage and industrial point sources