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Benthic foraminifera as bioindicators of potentially toxic element (PTE) pollution: Torrecillas lagoon (San Juan Bay Estuary), Puerto Rico

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ABSTRACT

Torrecillas Lagoon, on the north coast of Puerto Rico, has experienced extensive anthropogenic influence over the past 200 years. Elevated concentrations of Potentially Toxic Elements (PTEs) in bulk sediment (Cu, Zn, Pb, Ni, Cr, Li, V, Fe, As, Se, and Mn) have been reported in surficial sediments and have relatively uniform spatial distributions. Areas with higher concentrations are associated with a higher percentage of total organic carbon (TOC) and percent mud (mud), as well as anoxic conditions. *Ammonia beccarii*, *Quinqueloculina rhodiensis*, and *Triloculina oblonga* are the dominant foraminifers in the lagoon and are characteristic of stressed coastal environments. Bulk concentrations of Cu-Zn-Fe are negatively correlated with numerous foraminiferal taxa, absolute abundances, and diversity indices, though very few correlations with the bioavailable counterparts ($F2_{Tess}$-bioavailable) are observed. Similarly, relative abundances of *Quinqueloculina* and *Triloculina* positively correlate with bulk Cu-Zn-Fe but not with $F2_{Tess}$-bioavailable. The waters in Torrecillas lagoon show strong stratification, with hypoxic/anoxic (dissolved oxygen <3 mg/L) and corrosive (pH < 7.4) conditions below 4 m depth. The presence of such strong gradients in very shallow water represents a dynamic chemical environment, with changes occurring on day-night cycles, tidal cycles, and especially with storm activity that induces mixing of otherwise highly stratified, very localized waters. Recognizing the potential for sequestered PTEs to be remobilized is an essential insight for coastal management agencies that must assess the risks of existing PTEs during coastal engineering activities (e.g., dredge and fill activities) and major storm events. Exchangeable and oxidizable fractions are likely more bioavailable than acid-soluble fractions in influencing the ecology of foraminifers under most circumstances.

1. Introduction

Estuaries are experiencing adverse changes that are influencing the natural variability of these unique ecosystems. Coastal lagoons commonly serve as sinks for a wide range of pollutants (Zaaboub et al., 2015). Rapid industrialization, overpopulation, surface-water alteration, and other factors are changing estuarine environments and biotic communities (e.g., Green-Ruíz et al., 2005; Hunter and Arbona, 1995). Estuaries receive approximately 80–90% of all waste released to marine environments (Gross, 1978) and therefore are particularly vulnerable to pollution by potentially toxic elements (PTEs). Such PTEs (see Martínez-Colón et al., 2009 for definition and further discussion) can have detrimental effects on water quality, aquatic ecosystems (i.e., reducing abundance and diversity, etc.), and human health (e.g., Laboy-Nieves, 2009).

In northern Puerto Rico, Torrecillas Lagoon (TL) has been extensively altered by anthropogenic activities (Figs. 1 and 2). From Pre-Colombian times to present, human settlements, agriculture, deforestation, landfills, dredging and urban development have affected this extensive lagoon system (Ellis, 1976; Seguinot-Barbosa, 1983). During the late 1800s, sugar cane was grown around TL (Wilson, 1899). At present, TL is influenced by a wide range of point and nonpoint sources of pollution (Table 1), coupled with localized anoxic conditions within dredged navigational channels.

Previous studies have reported that organic pollutants (PCBs, Dieldrin, DDT), as well as elevated concentrations of PTEs (As, Se, Cu, Hg, Cd Ni, Zn, and Pb) in sediments of TL are anthropogenic (Martínez-Colón and Hallock, 2010; San Juan Bay Estuary, 2000;

Abbreviations: PTE, Potentially toxic element; $F2_{Tess}$-bioavailable, Carbonate bioavailable fraction from Tessier et al. (1979)

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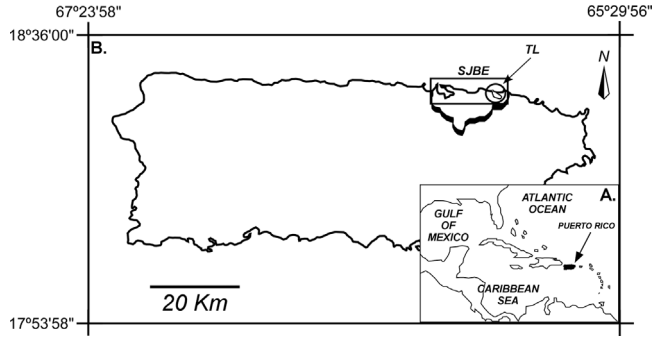

Fig. 1. A. Location of Puerto Rico. B. Map of Puerto Rico. Rectangle: San Juan Bay Estuary (SJBE). Circle: Torrecillas Lagoon (TL). Raised line: SJBE watershed.

Webb and Gómez-Gómez, 1998).

A variety of proxies has been implemented to identify pollutants in coastal waters, including macro- and micro-invertebrates, aquatic plants, and fish. Benthic foraminifers (shelled protists) were extensively used as bioindicators of pollution in coastal environments of Puerto Rico by Seiglie (1968, 1971, 1975c) and more recently by, for example, Oliver et al. (2014). Worldwide, foraminifers are known to respond to pollution through changes in assemblage makeup and abundance (e.g., Alve, 1995; Emrich et al., 2017; Yanko-Hombach et al., 2017), and to display a variety of morphological abnormalities that are considered a biological response to environmental stresses (e.g., Samir and El-Din, 2001; Yanko et al., 1998). Benthic foraminifers are likely sensitive to exposure to PTEs given the high surface-to-volume ratios of these protists and their interrelationship with sediment type and physico-chemical parameters in bottom and pore waters. Benthic foraminifers also react to changes in sediment supply, dissolved oxygen (DO), food (organic matter), pH, and other external (abiotic) and internal (biotic) factors (Alve, 1995; Alve et al., 2016; Schönfeld et al., 2012), and are often among the last eukaryotic organisms to disappear completely from polluted sites, making them exceptional bioindicators (Alve, 1991; Schafer, 2000).

This research addresses the implementation of benthic foraminifers in TL as bioindicators of PTE pollution. The objectives were to determine the distribution and bioavailability of PTEs and their possible influence on the spatial distribution and morphological deformities of benthic foraminifers.

2. Study area

Puerto Rico is the easternmost island of the Caribbean Greater Antilles (Fig. 1A). The San Juan Bay Estuary (SJBE) system, the largest estuary (Fig. 1B) in Puerto Rico, was the first tropical island estuary in the National Estuarine Program, established in 1993, and comprises ~240 km^2 of land (drainage basin), of which 25 km^2 are inundated (Webb and Gómez-Gómez, 1998). Mean annual runoff is estimated to be 185×10^6 m^3 with suspended-sediment yields exceeding 15,000 mg/km^2-yr (Webb and Gómez-Gómez, 1998). The SJBE system consists of semi-enclosed bays, lagoons (e.g., Torrecillas), and natural and dredged channels (e.g., Canal Suárez). Within the eastern subtidal portion of the SJBE system (Fig. 1B), TL (2.5 km^2) has an average depth of 2.4 m and is probably the most complex system within the SJBE due to inflow-outflow sources of salt, fresh, and brackish waters (Gómez-

Fig. 2. Sampling sites in Torrecillas Lagoon: circles = 2007; squares = 2009. Areas influenced by dredge (red) and fill (faded yellow) are indicated (from Ellis, 1976). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)