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Discriminating between natural and human-induced shifts in a shallow coastal lagoon: A multidisciplinary approach

Hugo Inda[a,*], Felipe García-Rodríguez[a], Laura del Puerto[a], Silvina Stutz[b], Rubens Cesar Lopes Figueira[c], Paulo Alves de Lima Ferreira[c], Néstor Mazzeo[a]

[a] Centro Universitario Regional Este, Universidad de la República, Maldonado and Rocha, Uruguay
[b] Laboratorio de Paleoecología y Palinología y Ecología y Paleoecología de Ambientes Acuáticos Continentales, IIMyC, CONICET-UNMdP, Mar del Plata, Argentina
[c] Institute of Oceanography – University of Sao Paulo, Pca do Oceanografico, 191 – Cid. Universitaria. Sao Paulo, SP, Brazil

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ABSTRACT

Coastal lagoons across the globe are increasingly experiencing undesired and sudden changes caused by human disturbances. Nevertheless, little is known about how long-term natural dynamics and anthropogenic impacts interact to drive the systems to their current state. This study discriminated natural- and human-induced changes in a shallow coastal lagoon near Punta del Este, Uruguay, using a multidisciplinary approach. The genesis of the water body resulted from a Middle Holocene marine transgression circa 6000 yr cal BP. From this time to about 4400 yr cal BP, a comprehensive set of proxies revealed a highly variable scenario, with alternating lagoon states linked to climatic variability. A Late Holocene hiatus was also identified in the sediment profile, linked to the barrier and inlet formation that caused a predominance of erosion over net deposition. Results showed that anthropogenic disturbances modified the landscape substantially and shifted the entire watershed to a previously unknown and undesired state. A freeway constructed in 1955 AD subsequently closed the lagoon's natural inlet and transformed the coastal water body into an artificial reservoir. After such significant human impact, the lagoon experienced a sharp decrease in water surface area along with an intensification of the siltation/eutrophication processes, as inferred from multiproxy data. Findings of this study are useful to identify early signals of human disturbances in pristine or less impacted coastal systems to assist mitigation measures and/or restoration actions.

1. Introduction

Coastal environments and coastal lagoons in particular are among the most productive ecosystems of the planet, as they provide a wide array of key ecosystem services, including food from fisheries, wild fauna and plants, construction materials out of trees and reeds, freshwater reservoirs, and recreational areas (Kennish and Paerl, 2010; Rodríguez-Gallego et al., 2012). This asseveration is valid for the time span from the appearance of modern humans on Earth up to present times (Bonomo, 2011). Nevertheless, such a strong link between humans and coastal lagoons has implied that anthropogenic impacts have followed an escalating trend over these systems because of population growth, changes in land use and other associated disturbances (Chin et al., 2014; Elmqvist et al., 2013). Furthermore, some of these anthropogenic impacts and their consequences are at the center of current debates on the chronological starting point for the Anthropocene to be included as a new epoch in the geological timescale (Bradje and Erlandson, 2013; Crutzen and Stroermer, 2000).

The relationship between humans and natural systems is highly complex, as it comprises the interaction of natural drivers acting within a range of both spatial and time frames (from El Niño events to Milankovitch cycles; Emile-Geay, 2008; Fairbridge, 1984; Schwarzacher, 1993) with anthropogenic disturbances that vary in intensity and extension. In order to overcome such inherent difficulties, we have developed a multidisciplinary approach aimed to distinguish natural from anthropogenic processes, the consequences of these coupled mechanisms and the chronological frame of the human trace on a coastal lagoon near Punta del Este, Uruguay. The underlying aim was to evaluate in what ways anthropogenic impacts affected the lagoon and its watershed beyond its resilience threshold, therefore compromising key ecosystem services by forcing this socio-ecological system into a

* Corresponding author.
E-mail addresses: hugoboss@paysandu.com, hinda@cure.edu.uy (H. Inda).

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new undesired state (Bidegain et al., 2013; Chin et al., 2014; Scheffer et al., 2001).

So as to achieve the above-mentioned objectives, we tried a multidisciplinary approach that combined paleolimnological techniques (lithological, geochemical, opal phytolith, diatom, chrysophyte cysts and pollen analyses) and C-14 dating with archaeological and historical methods, including historical chronicles and cartography consultation, the interpretation of archaeological findings and the memories of local stakeholders.

Laguna del Diario (*Del Diario Lagoon*) was selected for this study as it has experienced a recent and dramatic shift into a clear-water phase characterized by the dominance of aquatic plants (submerged and emergent vegetation) that interfered with multiple ecosystem services mainly related to recreation, landscape perception and real estate value. For instance, during the last summer periods sporadic blooms of cyanobacteria created odor problems due to intense decomposition processes and the volatilization of cyanotoxins (Pérez et al., 1999). In addition, as a coastal lagoon, it could contain a detailed record of Holocene sea level fluctuations, water body evolution and human disturbances.

Since the 90's, regional research on Holocene sea level oscillations (García-Rodríguez et al., 2001; Bracco et al., 2005; Inda et al., 2006a) –developed mainly in the Merin Lagoon basin and the Atlantic shore–identified several landforms attributed to Holocene transgressive sea levels. Radiocarbon dating of these landforms showed a remarkable consistency with existing regional sea level curves for this period (Martin and Suguio, 1992). Further paleoenvironmental and geoarchaeological studies developed since 2000 have focused on the link between marine coastal records, coastal lagoons genesis and evolution, paleoclimatic variability and the relationship with prehistoric inhabitants, generating a comprehensive multi-proxy data set (García-Rodríguez et al., 2004; Bracco et al., 2005, 2011; del Puerto et al., 2006; García-Rodríguez, 2006; Inda et al., 2006b; del Puerto, 2009; Inda, 2009) which allowed the generation of a relative sea level curve for the Uruguayan shore (Bracco et al., 2011).

Such contributions have proved that Uruguayan coastal lagoons originated after the first Holocene marine transgression (with a peak of 5.5 m above mean sea level reached 5.5 ky BP). After that, lagoons shifted from marine-brackish during positive sea levels (the already mentioned transgression and another of 2.5 m above mean sea level dating back to 2.5 ky BP) to freshwater as the sea level decreased (from 4.5 ky BP to 3.5 ky BP; García-Rodríguez et al., 2001; Bracco et al., 2005; Inda et al., 2006a,b). Paleoclimatic reconstructions have shown that climate was temperate to warm and humid in the transgressive events, shifting to temperate to cool and dry during the regressive periods, while current climate was gradually established after 2.0 ky BP (Behling, 1998; Bracco et al., 2005; Bidegain et al., 2013; del Puerto et al., 2013).

On the other hand, archaeological evidence has demonstrated that effective coastal settlement only took place after the first Holocene marine transgression, at the same time as the lagoons formation (Inda et al., 2011). Studies on such prehistoric human interaction with ecosystems were already published in other South American locations (Armesto et al., 2010; Roosevelt, 2013), but little attention was paid to the impact of colonial and modern occupation of coastal lagoons and its adjacent environments (Pauchard and Barbosa, 2003; Rodríguez-Gallego et al., 2012).

2. Materials and methods

2.1. Study area

The *del Diario* Lagoon (34° 54''s – 55° 00''W) is a water body covering a surface area of 52 ha with a watershed of 1987 ha (Fig. 1). Mean depth is 1.4 m and the maximum depth is 2.3 m. Soils are loamy sands in the northern part and aeolian sands (fixed dunes) towards the south (Marchesi and Durán, 1969). Vegetation cover is characterized by grasslands and fruit tree plantations in the north and exotic trees over the fixed dunes towards the south (mainly *Pinus, Eucalyptus* and *Acacia* genus).

The lagoon's natural connection with the estuary was artificially blocked in 1955 AD by the construction of a scenic freeway access to Punta del Este. Once the lagoon's inlet disappeared, the waterbody became a permanent freshwater reservoir which provided the cities of Maldonado and Punta del Este with drinking water for a couple of years (from 1967 to 1968). Since the late 1980's, a sudden overgrowth of aquatic vegetation over the entire water body has permanently cut drinking water supply as well as jeopardized other uses such as angling, windsurfing and sailing (Inda, 2009). Nowadays its littoral is a real estate hot spot, while in the upper part of the watershed some other activities such as stone and sand mining, cattle grazing and small fruit tree plantations still prevail, yet urban development will probably change this scenario in the near future.

2.2. Paleolimnological analysis

2.2.1. Sampling

A 110 cm-long sediment core was sampled in October 2006 at the *del Diario* Lagoon with a 6 cm diameter hand corer. It was air-sealed immediately after retrieval and kept in a dark environment at a constant temperature of 4 °C prior to laboratory processing and analysis.

2.2.2. Lithology

Lithological units were identified according to changes in sediment color (Munsell color scale), texture and presence of plant and mollusk remains along the sedimentary profile. Textural classification followed the pipette method for fine fraction while the coarse fraction was separated and classified using a sieve stack with meshes sorted in phi intervals, while sediment size frequencies were statistically assessed following Folk (1954).

2.2.3. Geochemistry

Total nitrogen and total phosphorus were determined according to DIN (Deutsches Institut fuer Normung) and ISO standards. For total nitrogen, the samples were analysed in a vario-EL-CNS elemental analyzer (ISO 25663, 1984). Total phosphorus, in turn, was measured following the DIN method (38414-S21; 1986), which oxidizes the different phosphorus compounds in phosphates, allowing the determination of their total concentrations by spectrophotometric technique (García-Rodríguez et al., 2004).

Organic matter content was determined by weight loss on ignition at 550 °C for two hours according to Heiri et al. (2001). The carbonate content, instead, was determined by LOI (loss on ignition) at 980 °C for two hours and the carbonate content was estimated by multiplying the weight loss by 1.36 (Heiri et al., 2001).

2.2.4. Dating

2.2.4.1. C-14 dating. Sediment age was determined at four intervals on bulk sedimentary organic matter (19–20 cm and 49–62 cm) and biogenic remains (*Heleobia* sp. shells; 39–40 cm and 99–110 cm). The 49–62 cm and 99–110 cm samples were dated at the *Laboratorio de ^{14}C, Cátedra de Radioquímica, Facultad de Química* in Uruguay by the conventional method, and the 19–20 cm and 39–40 cm were dated at Beta Analytic Radiocarbon Laboratory in the US by ^{14}C AMS method. For the conventional radiocarbon dating of bulk sedimentary organic matter, the sample was treated with 8% HCl for 24 h for both carbonate and humic acid removal.