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# Effects of land use changes on eutrophication indicators in five coastal lagoons of the Southwestern Atlantic Ocean

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## ABSTRACT

Five catchment areas in Uruguay were selected to conduct a nutrient exportation analysis and to evaluate the effects of current land use on the eutrophication of coastal lagoons. Satellite images and national agriculture censuses were used for a quantitative analysis of land use changes from 1974 to 2005, and a nutrient export coefficient approximation was used to determine long-term changes in annual loads. Several eutrophication indicators (water, sediment and autotrophic communities) were assessed seasonally in the lagoon basins during 2005 and 2006. The areal annual load of nutrients exported to the lagoons increased over time. Population and extensive livestock ranching were the most important nutrient sources, while agriculture is increasing in importance. Buffer effects of riparian forests on eutrophication indicators were observed in contrast to the wetlands surrounding the lagoons, which seem to be acting as a source of nutrients. Catchment size was inversely related to most eutrophication indicators. Afforestation and agriculture were found not to directly impact eutrophication indicators, however, catchments with larger agricultural areas showed higher concentrations of suspended solids, which may indicate the export of particulate nutrients. Salinity was inversely related to most eutrophication indicators, suggesting that the manipulation of the sand bar of the lagoons is a critical management issue. Sediment-related eutrophication indicators were more sensitive to changes in land uses and covers, in contrast with the more variable water column indicators, suggesting their potential use as enduring indicators. This research provides a rapid and integral assessment for qualitatively linking catchment changes with eutrophication indicators in coastal environments, which can easily be replicated to track pollutants in locations that lack standardized monitoring programs needed for more complex catchment modeling approaches.

## 1. Introduction

Coastal waters are becoming increasingly eutrophic and coastal lagoons are among the most affected ecosystems (Gaertner-Mazouni and De Wit, 2012). Human activities in catchment areas are the primary sources of the nutrients that cause eutrophication. Despite the worldwide importance of this detrimental cultural phenomenon, its scientific understanding is still in progress (Ferreira et al., 2011 and references therein). Much effort has been expended to establish methods to assess eutrophication in coastal and transitional waters, which generally integrate physicochemical and biological indicators into different indices (Cañedo-Argüelles et al., 2012; Christia et al., 2014). Indicators have to be able to reflect the effects of the increase in the human-induced impact, and it is desirable to combine indicators that reflect direct and indirect effects of nutrient increases (Ferreira et al., 2011). In freshwater and

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marine waters, simple and clear relationships exists among eutrophication indicators (i.e., nutrients and the chlorophyll *a* (Chl *a*) concentration), but in highly dynamic ecosystems such as coastal lagoons, these relationships becomes blurred due to other processes that operate simultaneously at the interchange of saltwater and freshwater, including resuspension, among others (Abreu et al., 2010).

Under such dynamic conditions it might be relevant to distinguish between enduring from non-enduring indicators (Valesini et al., 2010), whose sensitivity to environmental changes may in turn affect the assessment of eutrophication. Furthermore, to assess the influence of human activities in the catchment area on water quality, the knowledge of the relationships among water and catchment area indicators has to be improved. While determining point-source inputs of nutrients to surface waters is relatively easy, nonpoint sources have remained elusive and more difficult to identify, quantify, target and remediate (Dodd and Sharpley, 2015). Thus, attention on nonpoint sources is increasingly being considered worldwide. Generally, agricultural lands export higher levels of nutrients than natural forests and grasslands (Ryding and Rast, 1992; Reckhow et al., 1980; Jeje, 2006). Aquatic ecosystems located in agricultural catchment areas tend to be more eutrophic than those in natural landscapes. However, mechanisms exist at the scale of the catchment area to buffer upland runoff that enters surface waters. Riparian vegetation and wetlands can improve stream water quality through a combination of physical, chemical and biological processes. This vegetation stabilizes river banks and protects them from fluvial and runoff erosion, at the same time that filters and traps upland sources of sediments, nutrients and other chemicals (Mitsch and Gosselink, 2000; McKergow et al., 2003; Fisher and Acreman, 2004; Aguiar et al., 2015). Wetlands can also act as important sinks for nutrients and suspended solids, showing specific roles for each system according to the hydrological regime.

Over the last two decades in Uruguay, agriculture expanded and afforestation (sensu Farley et al., 2005) with exotic trees for wood and pulp production have been established. These activities replaced natural grasslands that belong to priority areas for global conservation (Hoekstra et al., 2005) and sustain one of the most important economic activities - livestock ranching. To sustain this intensification, total fertilizer imports almost doubled (DIEA, 2013). As a result, water quality deteriorated and algal blooms have become a frequent phenomenon in freshwater and brackish ecosystems (Bonilla et al., 2015). The government took several measures to overcome these environmental impacts, developing actions to improve the treatment plants for point sources, implementing best practices in the agricultural sector, and reformulating the legal framework of soils to prevent erosion, among others. However, the reformulation of water-quality policies is pending, and the identification of suitable eutrophication indicators and their references values for different kinds of ecosystems is under discussion. Therefore, many national research efforts are devoted to the evaluation of the state of eutrophication of surface waters and to the elucidation of the relationships among land uses and the eutrophication process.

Even though many modeling methods have been developed to assess nutrients load exported form catchment areas to aquatic ecosystems and their relationships with eutrophication indicators, they are not always available in many countries and situations, due to the lack of technical capacities, systematic monitoring programs and their relatively high cost. Therefore, alternative methods must be used to obtain a first, rapid and integral assessment that may help managers to take more informed decisions. This research provides an approach for qualitatively linking catchment changes with eutrophication indicators in coastal environments. The approach can easily be replicated to track pollutants in other locations that lack standardized monitoring programs. The aims of this study were: 1) to assess land use changes in the basin of five Uruguayan coastal lagoons, 2) to estimate the annual nutrient loads to surface waters and 3) to analyze the effects of the current land use on eutrophication indicators.

## 2. Materials and methods

### 2.1. Study area

On the Atlantic coast of Uruguay, there is a series of coastal lagoons that periodically connect with the ocean (Fig. 1, Table 1). Such natural dynamics drive steep salinity gradients and determine the ecological functioning of the entire ecosystem (Conde et al., 2000), affecting the abundance and composition of aquatic communities (Bonilla et al., 2005; Meerhoff et al., 2013; Rodríguez-Gallego et al., 2015). The connection with the ocean occurs directly through a breach that opens on the sand bar of Laguna de Rocha, Garzón and José Ignacio, but in Castillos, the connection occurs through the Valizas stream. The connection between the ocean and these lagoons is often mechanically forced by local municipalities in order to reduce flooding, mainly of unplanned buildings and cattle fields and to improve fisheries. In Diario, the natural connection was replaced by a permanent outlet of freshwater discharge into the ocean when a coastal route was built in the 1950s, impeding marine intrusions.

The catchment area of the coastal lagoons is dominated by grasslands mixed with patches of riparian and hilly forests. Large areas of freshwater and saline wetlands surround the lagoons, and sand dunes are abundant in the coastal zone (Fig. 1). These lagoons belong to Ramsar sites, a Biosphere Reserve and are high priority areas for biodiversity conservation in Uruguay. The population is relatively low (Table 1) and it is mostly urban (91.6% of the total population) (Table 1). The most important land is livestock ranching on natural prairies, agriculture, afforestation and urbanization for tourism development (Table 1). In the 1990s, intense land use changes began to occur. Agriculture started to expand and afforestation with exotic species (eucalyptus and pine) was established as a new economic activity. Eutrophication is among the most important threats to these lagoons. Diario is almost completely covered with submerged aquatic vegetation (SAV) and exhibits anoxic and organic sediments (Kruk et al., 2009). The other coastal lagoons are in the initial phases of cultural eutrophication. Phosphorus appears to be increasing in Rocha (Aubriot et al., 2005) and blooms of potentially toxic cyanobacteria have already been observed in Rocha and Castillos (Bonilla et al., 2015).

### 2.2. Land use classification and the estimation of a nutrient budget

We quantified the land use changes over a 31-year period by comparing Landsat satellite images from 1974 (Path/Row 222-084, resolution of 70 $m^2$), 1997 (Path/Row 222-084, resolution of 25 $m^2$) and 2005 (Path/Row 222-084, resolution of 25 $m^2$). All images were taken in the summer. The land cover and land use were determined using a combination of automatic and supervised techniques. To do so, first the catchment area of each lagoon was separated into two or three homogeneous zones, and then an automatic classification in 8 classes was conducted with the Categorize tool of ArcView. Finally, all classes were visually inspected and assigned to a land cover category (Table 1), and polygons that were wrongly classified were manually reclassified. Agriculture also included artificial prairies, tilled lands, fallow land and recently fertilized grasslands and oversowed areas. Grasslands were mainly natural and were under extensive livestock ranching, but may also include abandoned agricultural fields. The classification was checked in the field