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Spatial and temporal variability of carbon budgets of shallow South African subtropical estuaries

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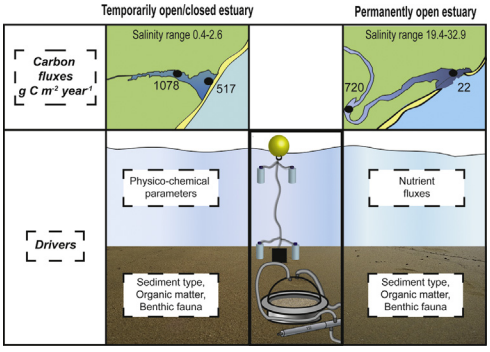
HIGHLIGHTS

- Subtropical estuarine communities are net heterotrophic during the year.
- Emissions vary significantly between seasons and sites.
- Estuarine mouth status (permanently open or prolonged closure) influences magnitude of carbon fluxes.
- First comprehensive direct estimation of carbon and nutrient fluxes in South African estuaries

GRAPHICAL ABSTRACT



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ABSTRACT

Estuarine carbon fluxes constitute a significant component of coastal CO_2 emissions and nutrients recycling, but high uncertainty is still present due to the heterogeneity of these areas. Although South Africa has nearly 300 estuaries, very little is known about their contribution to carbon emissions or sequestration. This study aims to provide a first estimation of the carbon emissions and nutrient fluxes of South African sub-tropical estuaries through a direct quantification of respiration, primary production and nutrient regeneration of benthic and planktonic communities. In order to account for the extreme variability in subtropical estuarine areas, due to seasonality in rainfall, two estuaries with opposite characteristics were studied; the temporarily open/closed Mdloti Estuary subjected to strong anthropic pressure, and the permanently open Mlalazi Estuary located in a natural reserve. Field deployment of benthic chambers and clear/dark bottles assessed oxygen, ammonia and phosphate fluxes of both benthic and planktonic communities. An inverse pattern between benthic and pelagic primary production was found in both estuaries. Different drivers related to mouth status and sediment characteristics were identified in the two estuaries. The annual average carbon emission indicates that the two systems are heterotrophic over the year releasing substantial CO_2 emissions into the atmosphere. Results show that carbon fluxes in subtropical estuaries are extremely variable in space and time. Future up-scaling carbon estimations need to account for those small scale and regional dynamics.

1. Introduction

Estuarine areas are recognized as important carbon reservoirs able to sustain high burial rates and act as net carbon storages (Kuwae et al., 2016). However, this is only one aspect of the estuarine carbon

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budget since the intense mineralisation and respiration activities, promoted by terrestrial inputs, generally lead to a net heterotrophic state (Chen and Borges, 2009; Herrmann et al., 2015). Carbon budgets in estuarine systems are therefore a delicate balance between carbon burial and CO_2 emissions strongly dependent on the environmental conditions and on anthropic pressure (Kuwae et al., 2016).

Several anthropogenic activities such as nutrient inputs, water abstraction and wetland degradation, together with climate change pressures have been known to affect estuarine carbon fluxes and enhance CO_2 degassing (Bauer et al., 2013; Dai et al., 2006). Estuaries constitute a crucial link between terrestrial and oceanic ecosystems propagating human impacts through the global carbon cycle (Bauer et al., 2013). Therefore, the study and monitoring of these areas is fundamental for the understanding of both land-ocean and ocean-atmosphere CO_2 fluxes.

The Intergovernmental Panel on Climate Change (IPCC) recognized that estuaries could constitute a significant component of coastal CO_2 emissions, but there is still great uncertainty due to the high heterogeneity of these areas (IPCC, 2013). While in the last few decades several studies focused on coastal carbon budgets and dynamics, still little information is available on subtropical estuarine systems (Chen and Borges, 2009; Eyre et al., 2011; Maher and Eyre, 2012). Furthermore, the majority of studies on estuarine carbon budgets have been performed on macro-tidal estuaries and very little information is available on other types of estuarine ecosystems (Borges et al. 2005).

Although South Africa has nearly 300 estuaries, very little is known about their contribution to carbon emissions or sequestration (Anandraj et al., 2007; Froneman, 2002). South African estuaries are highly heterogeneous in term of biotic, hydrodynamic and physico-chemical characteristics and numerous systems are subjected to strong anthropic pressures (Van Niekerk et al., 2013; Whitfield, 1992). In the subtropical area, primary production and biomasses have been shown to vary significantly between estuaries but also within the same system depending on the hydrodynamic conditions (Anandraj et al., 2007; Anandraj et al., 2008; Ortega-Cisneros et al., 2014).

Since carbon cycling in estuaries can vary tremendously both spatially and temporally, within and between estuaries, there is a strong need for systematic flux estimations on small and local spatial scales (Bauer et al., 2013; Eyre et al., 2011). Oxygen and nutrient community fluxes are good indicators of critical ecological processes such as photosynthesis and remineralisation of organic matter (Pratt et al., 2015). Moreover, incubation-based estimations can provide direct and detailed information on the contribution of the various communities to the global processes (Hopkinson and Smith, 2005; Maher and Eyre, 2012).

For these reasons, this study aimed to provide an estimation of carbon fluxes of two South African subtropical estuaries through a direct quantification of nutrient, respiration and primary production fluxes. In situ fluxes were measured simultaneously in the benthic and pelagic communities on a seasonal basis together with the main biotic and abiotic parameters in order to explore the drivers affecting the metabolic fluxes.

We hypothesize that, due to high organic matter and nutrient fluxes, the communities will be net heterotrophic predominantly during the rainy season (Ortega-Cisneros et al., 2016). We also expect that areas submitted to stronger anthropogenic pressure will exhibit higher carbon emissions (CO_2) than the other sites and that spatial and temporal change in the environmental conditions will lead to changes in the balance between benthic and pelagic productivity.

2. Material and methods

2.1. Experimental sites and set up

This study focused on two subtropical estuarine areas with opposite characteristics, both located to the north of Durban on the KwaZulu-Natal coast, South Africa. The Mdloti Estuary is a temporarily open/closed system generally shallow with a low salinity (Deale et al., 2013). The estuary has been classified as largely modified with fair health (Van Niekerk et al., 2013). The Mlalazi estuary is a permanently open system that may only close during major droughts. The estuary is located within the protected area of the Mlalazi Nature Reserve and is classified as largely natural and in good condition (Van Niekerk et al., 2013). Experiments were conducted seasonally (September 2015, November 2015, April 2016 and July 2016) at two sites in each estuary to account for differences between upstream and downstream communities (Fig. 1).

At each site, two benthic chambers were installed approximately 5 m apart to minimize sediment disturbance resulting from installation of the first chamber. The benthic chamber module consisted of a polyvinyl chloride base of 35 cm diameter that was inserted into the sediment for about 10 cm and a clear acrylic dome of 35 cm diameter. The chamber design has a recirculation pump that takes water from the benthic chamber via a multiparameter probe (YSI 6600 and YSI 6920) through a closed circuit (Fig. 2).

In proximity of the chambers, four 1.5 l polyethylene terephthalate (PET) incubation bottles were attached to a buoy system allowing to keep two bottles at the sub-surface and two close to the bottom (Fig. 2). Each bottle was integrated with an oxygen sensor spot readable by an optical fluorescence-based oxygen meter (Fibox 4, Presens, Germany). A second buoy system was installed in proximity to allow the deployment of two light-meters to quantify irradiance at the sub-surface and near-bottom (Fig. 2).

2.2. Oxygen and nutrient fluxes

Net community primary production (NPP), community respiration (CR), ammonia (NH_3) and ortho-phosphate ($O\text{-}PO_4$) fluxes were measured during short-term incubations (~1 h).

NPP is defined as the balance between the production of organic carbon through photosynthesis (gross community primary production, GPP) and the consumption of organic matter used for respiration (CR). When the net production of organic matter exceeds respiration and calcification, the community is considered “autotrophic”. Conversely, when community respiration outweighs gross primary production, the system is defined as “heterotrophic”. Nutrient fluxes accounted for any oxidation, reduction, biological release or uptake in the water column or in the benthic chamber.

Firstly, a dark incubation was performed with black material covering the incubation bottles and chambers to measure respiration fluxes. Thereafter, three clear incubations were made to account for photosynthesis at different irradiance levels. Both types of incubations lasted for ~1 h.

Water sampled for nutrient analysis was filtered through a GF/C filter directly in the field and kept in 100 ml LDPE (Low Density Polyethylene) acid washed bottles. Bottles for nutrient analysis were kept in a cool and dark container until the end of the experiments. Once in the laboratory nutrient samples were kept in a freezer (−20 °C) until further analysis. All samples were analysed within three months. Nutrient analyses were performed by the Council for Scientific and Industrial Research (CSIR, Durban, South Africa) using a Skalar San++ Automated Wet Chemistry Analyzer.

At the beginning of the experiment, the incubation bottles were filled with water from the sub-surface and near-bottom and attached to the buoy system. Simultaneously, additional bottles were filled to quantify the initial nutrient concentration (two bottles for each depth). Nutrient fluxes were calculated as a difference between those initial concentrations and the concentrations measured at the end of the experiment on the incubated water. Oxygen consumption of the planktonic community was calculated as the difference between the beginning and the end concentrations (average of three readings over 1 min for each).