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SPREADING EUTROPHICATION AND CHANGING CO_2 FLUXES IN THE TROPICAL COASTAL OCEAN: A FEW LESSONS FROM RIO DE JANEIRO

Propagação da eutrofização e mudanças nos fluxos de CO_2 no oceano costeiro tropical: algumas lições do Rio de Janeiro

Gwenaël Abril[1,2,3], Luiz C. Cotovicz Jr.[4], Aguinaldo Nepomuceno[2], Thais Erbas[2], Suzan Costa[3], Vinicius V. Ramos[2], Gleyci Moser[5], Alexandre Fernandes[5], Eduardo Negri[5], Bastiaan A. Knoppers[3], Nilva Brandini[3], Wilson Machado[3], Marcelo Bernardes[3], Vincent Vantrepotte[6]

[1] Laboratoire de Biologie des Organismes et Ecosystèmes Aquatiques (Borea), Muséum National d'Histoire Naturelle, UMR 8067, CNRS, MNHN, IRD, SU, UCN, UA, Paris, France. E-mail: gwenael.abril@mnhn.fr
[2] Programa de Pós-Graduação em Biologia Marinha e Ambientes Costeiros, Universidade Federal Fluminense, Niterói, RJ, Brazil
[3] Programa de Geoquímica, Universidade Federal Fluminense, Niterói, RJ, Brazil
[4] Instituto de Ciências do Mar, Universidade Federal do Ceará, Fortaleza, Ceará, Brazil
[5] Faculdade de Oceanografia, Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
[6] Laboratoire d'Océanologie et de Géosciences (LOG), Université de Lille, Université du Littoral Côte d'Opale, UMR 8187, Wimereux, France

ABSTRACT

In Brazil and in many other tropical countries, large urban cities and populations are still growing on the coast and coverage in terms of sewage treatments is far from desirable. Cultural eutrophication is not solely a threat for the coastal ocean; it is now acting as one of its major biogeochemical and ecological driver. Along the littoral of the state of Rio de Janeiro, semi-enclosed marine bays and lagoons show clear spatial and temporal pattern of increasing concentrations of chlorophyll *a* (Chl *a*), organic carbon, and nutrients in their waters and sediments in urbanized regions. Acting as a buffer, the nearshore ecosystems have turned highly eutrophic and their autotrophic metabolism has been enhanced creating strong carbon dioxide (CO_2) sinks. We compile here data of CO_2 fluxes recently gathered in four coastal marine ecosystems in the state of Rio de Janeiro: the Guanabara Bay and the Araruama, Saquarema and Jacarepagua lagoons. We observed intense CO_2 sources in restricted areas at the vicinity of sewage loads, where microbial degradation of organic matter predominates, and large CO_2 sinks in confined and nearshore brackish, marine and hypersaline waters, where phytoplankton blooms occur. We also report a correlation across the four ecosystems between the partial pressure of CO_2 in waters and the Chl *a* concentration. Chl *a* satellite data all along the Brazilian coast suggest that the CO_2 sink induced by eutrophication probably occurs in many coastal ecosystems including bays, lagoon and shelf waters, and could contribute to an additional blue carbon. Part of the additional organic carbon is stored in sediments, and part is exported offshore. However, this additional blue carbon has dramatic environment impacts as it would evolve toward the formation of marine dead zones, and could contribute to a production of methane (CH_4) a more powerful greenhouse gas. We emphasize an urgent need for multidisciplinary research to promote simultaneously the storage of atmospheric carbon, and the preservation of biodiversity and socio-economic goods in the eutrophic tropical coastal ocean.

Keywords: tropical coastal ecosystems, cultural eutrophication, phytoplankton blooms, marine dead zones, blue carbon.

RESUMO

No Brasil e em muitos países tropicais, os grandes centros urbanos estão em crescimento na zona costeira, porém a cobertura das Estações de Tratamento de Esgoto ainda está muito longe do ideal. A eutrofização cultural não é somente uma ameaça ao oceano costeiro; a eutrofização é atualmente uma das maiores forçantes de processos biogeoquímicos e ecológicos. Ao longo da zona costeira do estado do Rio de Janeiro, baías e lagunas costeiras semienclausuradas mostram um padrão espaçotemoral muito claro de concentrações crescentes de clorofila a (Chl a), carbono orgânico, nutrientes em suas águas e sedimentos de regiões urbanizadas. Atuando como uma região tampão, os ecossistemas costeiros se tornaram altamente eutrofizados e o seu metabolismo autotrófico tem sido estimulado, criando fortes sumidouros de dióxido de carbono (CO_2) da atmosfera. No presente trabalho, compilamos dados de fluxos de CO_2 recentemente coletados em quatro ecossistemas marinhos costeiros do estado do Rio de Janeiro: a Baía de Guanabara e as lagunas de Araruama, Saquarema e Jacarepaguá. Observamos fontes intensas de CO_2 para a atmosfera em áreas restritas nas proximidades de descargas de esgoto doméstico, onde predomina a degradação microbiana da matéria orgânica, e grandes sumidouros de CO_2 em águas rasas e confinadas, salinas e hipersalinas, onde ocorrem florações de fitoplâncton. Também relatamos uma correlação entre a pressão parcial de CO_2 nas águas e a concentração de Chl a nos quatro ecossistemas analisados. Os dados de satélite de toda a costa brasileira sugerem que o sumidouro de CO_2 induzido pela eutrofização provavelmente ocorre em muitos outros ecossistemas costeiros, incluindo baías, lagunas e águas de plataforma continental e pode contribuir com um estoque adicional de carbono azul. Parte do carbono orgânico adicional é armazenada nos sedimentos e parte é exportada para o oceano costeiro adjacente. No entanto, esse carbono azul adicional tem impactos ambientais dramáticos, pois evoluiria em direção à formação de zonas marinhas mortas e poderia contribuir para a produção de metano (CH_4), um gás de efeito estufa mais poderoso. Enfatizamos a necessidade urgente de pesquisas multidisciplinares para promover simultaneamente o armazenamento de carbono atmosférico e a preservação da biodiversidade e dos bens socioeconômicos no oceano costeiro tropical eutrofizado.

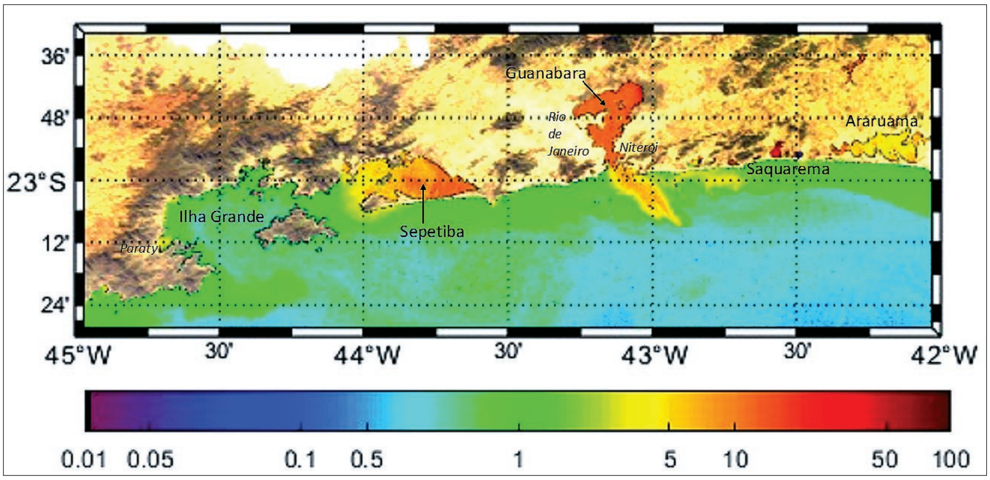
Palavras-chave: *ecossistemas costeiros tropicais, eutrofização cultural, florações de fitoplâncton, zonas marinhas mortas, carbono azul.*

INTRODUCTION

Eutrophication, defined by Nixon (1995) as "*an increase in the rate of supply of organic matter to an ecosystem*", is a major threat to the coastal ocean (Walsh, 1988; Turner & Rabalais, 1994). Other authors prefer to define coastal eutrophication as an enrichment of the aquatic ecosystem by inorganic and organic nutrients (Jessen *et al.*, 2015). In fact, in the definition of Nixon (1995), the additional supply of organic matter can come from external sources on the watersheds, and/or from the enhancement of aquatic primary production created by the additional supply of nutrients. Although simple indices, based on a combination of physicochemical parameters measured *in situ*, can been used to describe the trophic state (*e.g.* Cotovicz *et al.*, 2013), eutrophication is a process, rather than a state parameter (Nixon, 1995; Richardson & Jørgensen, 1996; Jessen *et al.*, 2015). The symptoms of eutrophication are well documented: formation of dense and sometimes harmful algal blooms, spectacular events of colored tides, severe hypoxia in bottom waters, loss of biodiversity, reduction of light and loss of benthic habitats and, finally, loss of natural resources. However, the process of eutrophication itself, that is, the way the equilibria between the forms of carbon and nutrients and the living organisms in the ecosystem are being modified, remains partially understood, particularly in tropical coastlines. In temperate and boreal regions, management strategies could be deployed, consisting mainly of a reduction of nutrient loads, and have enabled to limit and sometimes to revert the process of coastal eutrophication (Duarte & Krause-Jensen, 2018). In contrast, eutrophication continues to spread massively in the tropics where big cities are growing along the coast and where the sewage treatment plants are still lacking or inefficient (Fistarol *et al.*, 2015; Costa; Pessoa & Carreira, 2018). In addition, the tropical coastal zone has climatic, hydrodynamical, geomorphological and biological properties that generate specific responses to eutrophication. Environmental changes are in general faster than in other climatic regions, primarily because of the high temperature and solar radiation that enhances productivity (Carmouze & Vasconcelos, 1992; Knoppers & Kjerfve, 1999).

An abundant literature has described the decadal changes of nutrient and organic carbon fluxes in waters and sediments of coastal ecosystems during eutrophication (e.g. Turner & Rabalais, 1994), including the region of Rio de Janeiro (Souza *et al.*, 2003; Cerda *et al.*, 2013, 2016; Ramos, 2016; Fistarol *et al.*, 2015). In addition, changes in the phytoplankton biomass and the spreading of eutrophication can be inferred from ocean color satellite data, which now allow for a synoptic monitoring of coastal waters Chl *a* concentration continuouly since 1997 (Groom *et al.*, 2019, and references therein). Much less is known on the impact of eutrophication on the other side of the carbon cycle, that is, the carbonate system and the CO_2 exchanges, as well as the potential interaction between coastal eutrophication, ocean warming and ocean acidification (Borges & Gypens, 2010; Cai *et al.*, 2011). The state of Rio de Janeiro (Figure 1) hosts many coastal ecosystems of high ecological value such as mangroves, meso-haline lagoons (Jacarepagua Lagoon Complex, Saquarema) and hyper-saline lagoons (Araruama, Vermelha), large semi-enclosed bays such as Guanabara, Sepetiba and Ilha Grande, and the continental shelf, which belongs to the Santos Basin and is influenced by resurgence of South Atlantic Central Water (SACW), particularly in the region of Cabo Frio city (Knoppers *et al.*, 2009). The population of the state has been increasing continuously during the last 80 years to reach 17.2 million of inhabitants in 2018 (Figure 2). This population is concentrated around the "marvelous city" of Rio de Janeiro, surrounding the Guanabara Bay. Satellite Chl *a* data reveal that the Guanabara Bay, the Sepetiba Bay, together with the urbanized lagoons of the *Região dos Lagos* toward the Northeast, are the most eutrophic regions, whereas the *Costa Verde* region in the South-West remains relatively well preserved (Figure 1). The impact of urbanization on the trophic level and water quality is not limited to the coastal bays but can also significantly affect the adjacent shelf waters as illustrated in the Figure 1 by the presence of a high Chl *a* water plume spreading out of the Guanabara Bay. The impact of such export of Chl *a* rich water (and more globally of the associated organic carbon and nutrient fluxes) within the coastal ecosystem of the Rio de Janeiro area should be more deeply investigated (spatial extension and temporal dynamics) through the analysis of regional ocean color archives.

Figure 1 – Example of the spatial distribution of the surface Chl *a* concentration (µg.L^{-1}) estimated from Sentinel-3 OLCI (300 m spatial resolution) over the coastal area of Rio de Janeiro illustrating the eutrophication of the Sepetiba and Guanabara bays



The clear spatial gradient of eutrophication and morphological diversity makes the state of Rio de Janeiro a perfect region in order to describe decadal trends and micro- to meso-scale processes induced by the massive loading of untreated wastewater. With respect of cultural eutrophication, the littoral of the state of Rio de Janeiro is representative of the situation found in many developing tropical countries in South America, Africa and Asia. The population of the state of Rio de Janeiro is still growing very fast (Figure 2) and a scenario of reduction of sewage loads is very unlikely, all the more since seawater will penetrate deeper in the urban sewage network in the future with sea level rise, making the management of wastewater even more difficult. We present here a short synthesis of some recent works in the region, showing the spatial distribution patterns of air-sea CO$_2$ fluxes and their links with chlorophyll *a* concentration. We also attempt to analyze the potential changes in the properties of the carbon cycle in tropical coastal systems with eutrophication, based on our experience in Rio de Janeiro. Finally, we describe a situation where uncontrolled coastal eutrophication creates a CO$_2$ sink in the tropics, thus mitigating climate change, but at the same time has dramatic environmental effects on ecosystem health and resources.

CO$_2$ fluxes in eutrophic waters of Rio de Janeiro

Data on CO$_2$ fluxes in tropical coastal ecosystems are scarce, and the contribution of tropical regions to the global coastal ocean carbon balance is uncertain, except for the plumes of world largest rivers such as the Amazon, the Yangtze and the Mekong (Dai *et al.*, 2008; Borges & Abril, 2011; Chen *et al.*, 2013; Lefèvre *et al.*, 2017; Borges; Abril & Bouillon, 2018). In the region of Rio de Janeiro, measurements started in 2013 in the Guanabara Bay (Cotovicz *et al.*, 2015), followed by the estuary of the Paraiba do Sul river (Cotovicz *et al.*, 2020), the Jacarepagua lagoon complex (Cotovicz *et al.*, 2021a), the Araruama lagoon (Cotovicz *et al.*, 2021b) and the Saquarema lagoon (Erbas; Marques Jr. & Abril, 2021). The flux data are based on direct measurements of the partial pressure of CO_2 (pCO_2) at various seasons and the calculation of the gas transfer velocity on the basis of wind speed data. These results are summarized in Table I and Figure 3.

Figure 2 – Temporal evolution of the population of the state of Rio de Janeiro

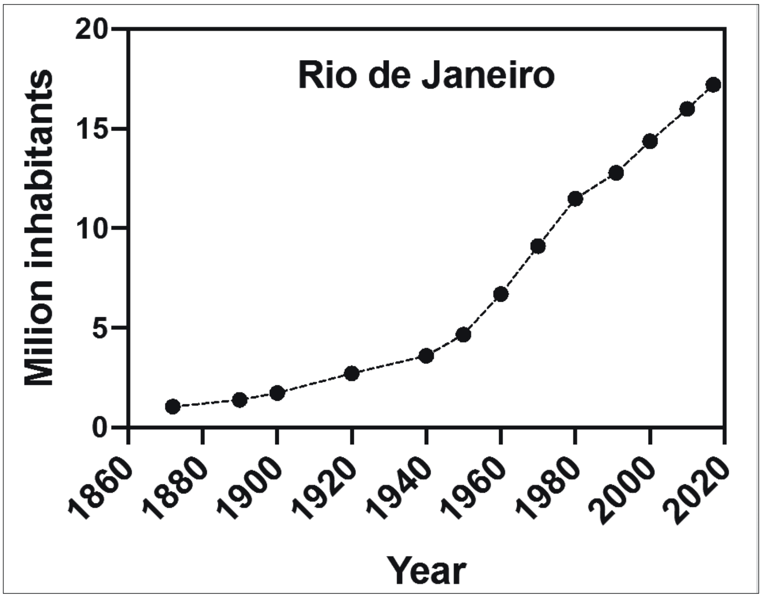


Figure 3 – Summary of available data on CO_2 fluxes in nearshore waters of the state of Rio de Janeiro (except Paraíba do Sul Estuary). Red zones are strong CO_2 sources (>10 mmol m^{-2} d^{-1}), green zones are moderate CO_2 sinks or sources (between -10 to +10 mmol m^{-2} d^{-1}), and cyan zones are CO_2 sinks (>-10 mmol m^{-2} d^{-1}) (see Table I for numerical values)

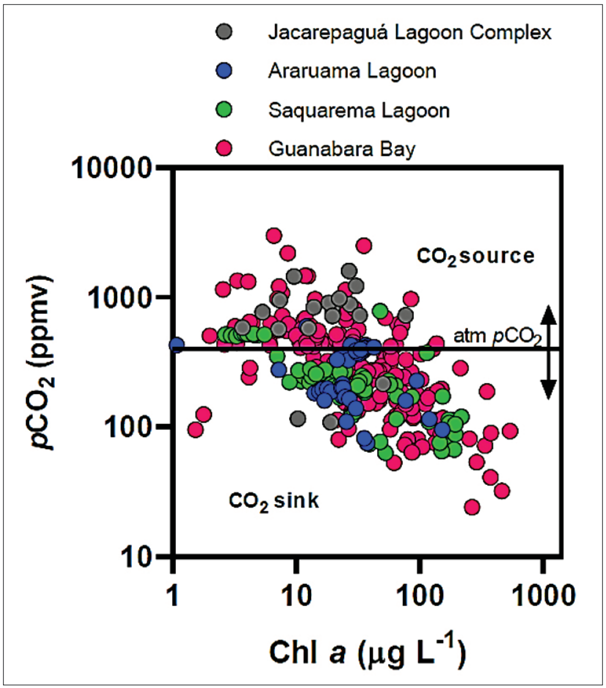
Table I – Surface areas, ranges of salinity, Chl *a*, and average air-sea CO_2 fluxes (± SD) in diverse coastal waters of Rio de Janeiro. Data from Cotovicz *et al.* (2015, 2021a, 2021b); Erbas; Marques Jr. & Abril (2021)

	Region	Area km^2	salinity	Chl *a*	CO_2 flux mmol m-2 d-1
Guanabara bay	Urban	32	30.3 ± 2.4	46.2 ± 51.4	+109.0 ± 63.1
	Confined	231	27.1 ± 5.5	78.1 ± 147.9	-67.5 ± 22.0
	Marine	47	32.2 ± 2.1	19.1 ± 22.0	-9.1 ± 4.0
Araruama lagoon	Urban/marine	32	48.5 ± 8.9	25.6 ± 26.0	-1.6 ± 8.8
	Confined	188	58.8 ± 2.7	40.3 ± 49.8	-11.9 ± 5.6
Saquarema lagoon	Confined	16	21.9 ± 5.7	93.3 ± 61.8	-101.2 ± 64.2
	Marine	7	30.9 ± 2.3	14.9 ± 11.2	-25.9 ± 49.7
Jaquarepagua lagoon	Urban	12.08	22.0 ± 9.7	22.3 ± 37.8	+11.3 ± 5.16

Our data reveal that, in the different bays and lagoons, waters close to urban areas and sewage outlets act as CO_2 sources, whereas lagoon and bays' waters enriched in phytoplankton (Figure 1), act as strong CO_2 sinks. CO_2 fluxes in the most marine regions are one order of magnitude lower than those observed in the urban and confined regions (Table I), being slightly positive, slightly negative, or close to zero (Figure 2). Strong CO_2 degassing to the atmosphere was observed on the western region of the Guanabara Bay close to the Rio de Janeiro harbor and in the Jacarapagua Lagoon, the two most polluted sampled areas, frequently exhibiting hypoxic conditions. Strong CO_2 uptake occurred in all the confined and intermediate waters of the Guanabara Bay, Araruama lagoon and Saquarema lagoon (Figure 3). When considering the respective surface areas of these different nearshore waters, the CO_2 sinks largely predominate over the CO_2 sources.

For all the samplings during these studies, we observe a negative correlation between the pCO_2 and the Chl *a* concentration (Figure 4). Note that the majority of pCO_2 values are below the atmospheric equilibrium, showing prevalence of undersaturated conditions and CO_2 sink. The correlation was similar in all ecosystems, despite the important differences in salinity, residence time of water, depth, and other hydrographic and ecological properties. This illustrates how phytoplankton productivity overwhelms the CO_2 budget in the region, driving the CO_2 uptake.

Figure 4 – Correlation between the partial pressure of CO_2 (pCO_2) and the chlorophyll *a* (Chl *a*) concentrations in four bays and lagoons of the state of Rio de Janeiro

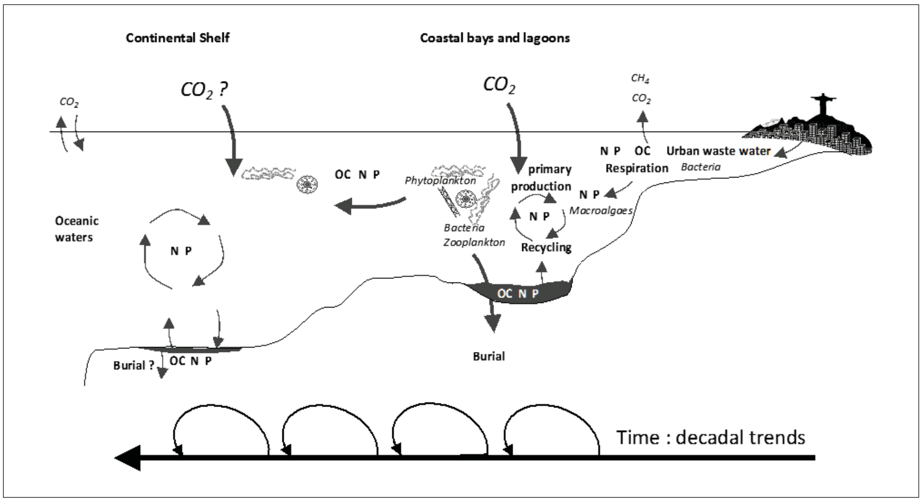


Changes in the carbon cycle in response to eutrophication

The mechanism of carbon cycling in coastal environments impacted by urban pollution has been discussed by Kubo *et al.* (2017) as the balance between the more active respiration due to the presence of sewage derived organic matter and the more active photosynthesis driven by nutrient accumulation in bays and offshore waters. This leads to a clear border between waters close to the sewage outlet that act as CO_2 sources because degradation of organic matter predominates locally, and other coastal waters that act as CO_2 sink because phytoplankton production is favoured by nutrients and light availability. This pattern is very clear in the region of Rio de Janeiro and leads to a predominant CO_2 sink in large water bodies of coastal bays and lagoons. In addition, the morphology of nearshore ecosystems, their shallowness and the predominance of naturally transparent marine waters favour autotrophy and enhance the impact of eutrophication on carbon fluxes. In general, estuaries function as heterotrophic ecosystems and CO_2 sources rather than autotrophic ecosystems and CO_2 sinks (Borges & Abril, 2011; Chen *et al.*, 2013). This paradigm was valid for the majority of river dominated temperate and boreal estuaries (Borges & Abril, 2011; Chen *et al.*, 2013). CO_2 sinks have now been documented in estuarine plumes (Borges & Abril, 2011; Dinauer & Mucci, 2017), but the $p$$CO_2$ values were not as persistent as those we observed in the Guanabara Bay, Saquarema and Araruama lagoons, with lowest $p$$CO_2$ values of 22 ppmv, 60 ppmv and 70 ppmv, respectively (Cotovicz *et al.*, 2015, 2021a, 2021b; Erbas; Marques Jr. & Abril, 2021). At these concentrations, CO_2 becomes limiting for planktonic photosynthesis, and Cyanobacteria can become predominant in these blooms, thanks to their carbon concentrating mechanisms (Shapiro, 1984; Morales-Williams; Wanamaker & Downing, 2017).

The analysis of organic carbon distribution (Kalas *et al.*, 2009; Cotovicz *et al.*, 2018; Erbas; Marques Jr. & Abril, 2021), as well as the isotopic composition of the dissolved inorganic carbon (Cotovicz *et al.*, 2019, 2021b) allow for a description of the aquatic carbon and nutrients cycles in the case of highly eutrophic tropical nearshore ecosystems. The degradation of urban organic matter nearby sewage outlet leads to a rapid degassing of wastewater carbon as CO_2 (as well as CH_4; Cotovicz *et al.*, 2016, 2021a), whereas the nitrogen and phosphorus accumulate within the system, being further assimilated by phytoplankton and recycled in waters and sediments (Figure 5). The loss of nitrogen to the atmosphere through denitrification (Souza *et al.*, 2003; Cerda *et al.*, 2013) is apparently much lower than the loss of carbon by aquatic respiration coupled to CO_2 and CH_4 outgassing. Increases in the rate of organic carbon and nutrient burial in sediments have been reported on decadal scales in Guanabara Bay (Carreira *et al.*, 2002) and Itaipu Lagoon (Cerda *et al.*, 2016). The additional organic carbon sequestered in the sediments has a predominant phytoplanktonic origin (Carreira *et al.*, 2002). Furthermore, part of the additional organic carbon loaded to and/or produced in bays and lagoons is also exported to the shelf with tidal exchanges, as revealed for example by a temporal monitoring at the mouth of the Saquarema lagoon (Erbas; Marques Jr. & Abril, 2021). Algal blooms are also occurring on the shelf, in a plume flowing from the Guanabara Bay (Figure 1). The fate of this additional organic carbon in the sea and the impact on the air-water CO_2 fluxes are currently unknown.

Figure 5 – Conceptual scheme describing the spreading mechanisms of eutrophication along the coast of Rio de Janeiro



Because of the typology of the coastline, and the complex morphological feature, the spreading of eutrophication is not occurring as a constant and linear process that impacts increasing surface area of marine ecosystems as population growths. Indeed, as they receive first a large part of the domestic sewage, nearshore ecosystems, coastal bays and lagoons, retain the nutrients and organic carbon, acting as a filter at the land-sea interface at decadal scale. One example is the Araruama lagoon, where planktonic primary production remained limited for decades after urbanization started, because the carbonated sediments could efficiently retain the excess of phosphate that remained limiting for phytoplanktonic blooms (Knoppers; Carmouze & Moreira-Turcq, 1999; Souza *et al.*, 2003). In Araruama, an important shift in the ecosystem metabolism occurred, from a heterotrophic benthic-dominated metabolism in the 1990's to an autotrophic pelagic-dominated metabolism afterwards (Souza *et al.*, 2003; Cotovicz *et al.*, 2021b).

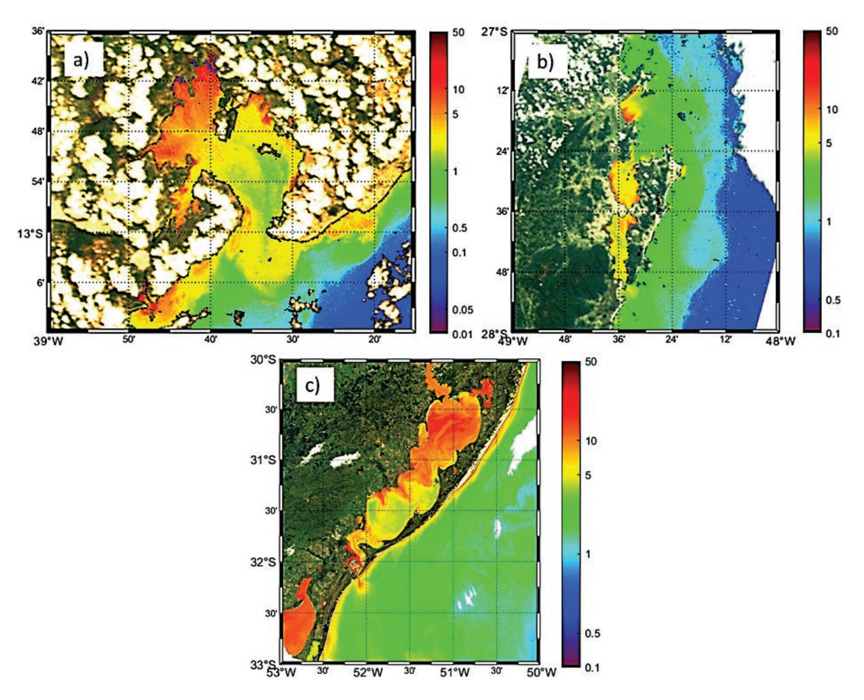
A general phenomenom

The storage of atmospheric carbon in sediments of bays and lagoons is probably the only positive environmental impact of coastal eutrophication. It is a potential contribution to blue carbon reservoir. However, eutrophication has dramatic effects on the environment and local economy and this blue carbon cannot be promoted since it creates marine dead zones (Diaz & Rosenberg, 2008). Another negative issue is that it can contribute with important emissions of CH_4 to the atmosphere (Cotovicz *et al.*, 2016, 2021a). The assessment of Chl *a* distribution from ocean color satellite observation reveals that dense blooms are occurring in many urban coastal bays and lagoons in Brazil (Figure 6). While these daily maps are only providing an instantaneous view of the phytoplankton biomass distribution (Figure 6a: Baía de Todos os Santos (BA), 6b: Baía Norte and Baía Sul de Santa Catarina and 6c: Lagoa dos Patos (RS)) they clearly illustrate the local presence of high Chl*a* levels, suggesting that our observations in Rio de Janeiro can be extrapolated to other urbanized coastal areas in Brazil. The full exploitation of the potential offered by ocean color observations for quantitatively monitoring coastal eutrophication, however, requires (Loisel *et al.*, 2013): 1) the use of adapted inversion models for improving the precision of the standard Chl *a* estimates currently delivered by spatial agencies; 2) the analysis of the whole satellite archives through adapted statistical techniques allowing the assessment of significant evolution in the Chl *a* levels; and 3) the characterization of the shape of the observed long term changes (regime shift, monotonic evolution).

We can expect all these eutrophic systems to behave as CO_2 sinks as those studied in Rio de Janeiro. Satellite data show the same connectivity between Chl *a* enriched waters and the urban areas of Salvador, Florianopolis, and Porto Alegre (Figure 6).

At the moment, no information is available on the temporal evolution of CO_2 fluxes throughout decades of eutrophication, and no precise pre-eutrophication CO_2 data are available. The only possible approach in order to apprehend past and future changes in coastal carbon cycle is to extrapolate spatial Chl *a* pattern obtained with satellite, as in the state of Rio de Janeiro (Figure 1), assuming that the preserved Ilha Grande Bay presents conditions close to those in Guanabara Bay one century ago, before eutrophication started, when the population in the marvelous city was only a few millions (Figure 2). Nevertheless, as it can be seen in Figure 1, the waters in the bay of Paraty, the only city in the region of Costa Verde, already show some signs of eutrophication.

Figure 6 – Illustration of the Chl *a* distribution (µg.l^{-1}) estimated from Sentinel-3 OLCI ocean color data (300 m spatial resolution) over a) the Baía de Todos os Santos (BA), b) the Baía Norte and Baía Sul de Santa Catarina and c) the Lagoa dos Patos (RS)



Research needs and intervention strategies

Future research cannot consist only in helpless monitoring of the degradation of the coastal ocean. How can future research help, at the same time, to store atmospheric carbon, preserve biodiversity, and create socio-economic goods in the eutrophic tropical coastal zone, is a very complicated issue. At the moment, the first objective is totally inconsistent with the second and third objectives. A huge quantity of nutrients is being accumulated, making the coastal zone a potentially highly fertile surface area for centuries. What should we do with these nutrients in the waters and stored in the sediments and can we use them to produce valuable goods? Four possible interventions may be considered as possible actions to mitigate the issue and accelerate ecosystem recovery from eutrophication and associated nutrient and organic matter fluxes: (1) reduce inputs, for instance with the implementation of wastewater treatment plants (WWTPs), (2) store, in sediments and biomass, contributing to new blue carbon, (3) remove (for instance by denitrification, by plant harvesting, or by aquaculture) and, finally, (4) export offshore (Duarte & Krause-Jensen, 2018). In Rio de Janeiro, the proportion of sewage waters that is effectively treated is unknown but probably lower than 60%, that is, the percentage of the population officially connected to WWTPs (IBGE, 2020). However, these plans are based on the principle established in other climates and not adapted to tropical rain and precarious combined sewers of a city like Rio de Janeiro (Costa; Pessoa & Carreira, 2018). As a consequence, nutrients and organic carbon are discharged in the bays and lagoons as overflow during storms. In addition, episodes of clogging and obstruction were documented in more than 80% of WWTP (IBGE, 2020). In Araruama and Saquarema lagoons, sewage is discharged without treatments from multiple points sources, individual houses, and polluted streams.

In such a context and considering the hypothesis of continuous population growth (Figure 2), it is very unlikely that organic matter and nutrient inputs will be reduced in the next future in the state of Rio de Janeiro.

To avoid their spreading in the marine ecosystem, waters and sediments could be temporarily retained in confined marine areas inside the lagoons and bays, where some lagoon sewage treatment could be experimented as a potentially cheap and more efficient way to limit the spreading of nutrients and organic carbon offshore. Actually, entire small Lagoons like Piratininga in the municipality of Niteroi are acting as "natural" sewage treatment plants, accumulating nutrients, sedimentary organic carbon, and macrophyte biomass (Cerda *et al.*, 2016). Applied science on halophyte tropical plants and associate blue carbon geochemistry could be promoted to optimize lagoon sewage treatment as a way to store and eventually remove carbon and nutrients from the system, while valuable goods can be harvested for food, combustibles, or fertilizers. The potential for blue carbon storage should also be evaluated accounting for the potential risk for the created wetland to emit CH_4, which becomes much more limited at high salinities owing to the predominance of sulfate reduction over methanogenesis (Bartlett *et al.*, 1987). Aquaculture of suspension feeders like bivalves could be a way to remove microalgae and nutrients from the system, creating economic goods. Such potential would promote research and monitoring of other pollution issues as fecal, metallic, and organic contamination of the food. There is an urgent need for the deployment of pilot experimental sites, with support from local authorities, in order to define efficient sustainable practices with sewage waters and highly eutrophic coastal lagoons.

The last possible intervention is to favor the export of the excess of nutrients offshore. Many megacities of Brazil have chosen to discharge wastewater offshore, through submarine outfalls, as a way to preserve the nearshore ecosystems. This is obviously a risky gamble for future generations, as resources from the sea will also depend on offshore ecosystems' productivity and health. In addition, the monitoring of environmental quality around submarine outfalls is a complex operation, hampering any possibilities of future ecosystem preservation (Lamparini, 2004). A study in Rio de Janeiro 2.3 km off Ipanema and Leblon beaches reveals the presence of a stationary cloud of sewage-derive particles around the submarine outfall outlet that can remain 50 days in suspension, increasing inorganic nitrogen concentrations, phosphorus being assimilated by phytoplankton (Wagener *et al.*, 1992). Hydrodynamics is indeed of great importance for nutrients and organic matter being dispersed on the shelf and mixed in the sea, particularly in regions like the Rio de Janeiro coast that are subject to coastal upwelling influences. In the Guanabara, Sepetiba, and Ilha Grande bays, cold water events, due to bottom intrusions of the SACW, have long been observed (Kjerfve *et al.*, 1997, 2021; Signorini, 1980). The presence of these waters enhances vertical stratification in Guanabara Bay, during the intrusion events, and reduces water temperatures at surface levels, an indication of tidal stirring (Fernandes *et al.*, 2021). SACW intrusion is also likely to occur in Sepetiba and Ilha Grande Bays, to some extent. Although most frequent in summer and spring, cold water events are observed at anytime during the year and supply Guanabara Bay with cold waters for many days in a single month. As discussed by Valentin *et al.* (2021), SACW intrusions can impact food web functioning through shifts in community composition and size depending on the relative intensity and frequency of upwelling events and rainfall. Frequent SACW intrusions also dilute the highly eutrophic waters, with the potential to shift the metabolism of an estuary heavily impacted by eutrophication.

Given the scarcity of precise measurements due to economic, bureaucratic, and logistic constraints, hydrological models, coupled with remote sensing tools, can become very helpful for mass balance calculation of carbon, nitrogen, phosphorus, and contaminants. These models can be calibrated and validated at various degrees, from poorly constrained models based only on bathymetry and tide to very well constrained models validated with high frequency water current and temperature field data. Hydrodynamical models coupled with sedimentary and biogeochemical models can potentially simulate water masses exchanges and mixing with tidal and wind action, the deposition and resuspension of particles of different sizes, the photosynthesis by primary producers using different nutrients and light regimes, the decomposition of organic matter, oxygen consumption, nutrients regeneration, and greenhouse gases air-sea exchange (Regnier & Steefel, 1999; Lajaunie-Salla *et al.*, 2017). Important adaptation and calibration of models developed for temperate climates to tropical regions are probably necessary. However, modeling, remote sensing and field measurements should go ahead together, even if the biogeochemical data available to construct and validate these models are still very scarce.

CONCLUSION

Our data gathered in four nearshore marine ecosystems of Rio de Janeiro have revealed a predominant urban influence on the aquatic carbon cycle, with cultural eutrophication creating a CO_2 sink on decadal time scales. We highlight a paradoxical situation where human-impacted tropical coastal ecosystems are evolving toward marine dead zones and blue carbon reservoirs at the same time. The analysis of Chl *a* satellite data suggests that the phenomena is widespread along the Brazilian coast and probably along many tropical regions in the world. Further research is necessary in order to propose intervention strategies able to conciliate ecosystem restoration and climate change mitigation.

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