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Introduction

Recent intensification of existing anthropogenic drivers and the emergence of new ones suggest that impacts derived from environmental changes upon mangroves, coral reefs, seagrass beds and other less conspicuous, but nevertheless important, ecosystems along tropical and subtropical coasts are still far from being understood. Also, most literature deals with the response of the biological component of these ecosystems to regional or global changes. In our view, however, there is still a large gap regarding these ecosystems' geochemical and biogeochemical responses. Also, approaches taking into consideration the continuum between watersheds and the ocean and the processes involved in their continuity are particularly underdeveloped. This scenario calls for a joint effort to spread multidisciplinary research encompass the mosaic of natural ecosystems spreading the tropical belt worldwide to provide a comprehensive view of major alteration on the fluxes, transformation and the cycle of substances, with particular emphasis on the continent-ocean interface, but linking watershed processes and the oceanic receptor, which underlies the onset of environmental changes leading to eutrophication, minimum oxygen zones, pollution and biological crises.

Of particular significance are the studies regarding the fate of carbon, nutrients and persistent pollutants ; involving their biogeochemical cycles in estuaries, coastal waters and the continental shelf; the anthropogenic influence on the interaction between drainage basins and the continent-ocean interface and the impacts on the continental shelf; implications of global change to ecosystems functioning, conservation and sustainable development; the vulnerability of the continent-ocean interface and threats to society through food security and human occupation of the coastal zone.

Mangrove biogeochemical response to climate change

Over 1,200 publications between 1990 and 2018 refer to “Mangrove & Climate Change”. Most however, discusses eventual impacts and scenarios that might occur in the future, based on projections and modelling. Unfortunately, however, this approach inherits two major constrains that make them extremely difficult to support local and regional scale governance aiming adaptation and mitigation of climate change impacts to coastal regions. First, these scenarios and modeling exercises are based on scarce empirical data. Even worst, most data supporting them are generated from mangroves located near their latitudinal limits or obtained under greenhouse-controlled conditions, far from nature’s reality. Second, they consider impacts that may occur in the future, whereas they are actually happening today in many significant mangrove-dominated areas. Less than 5% of those 1,200 publications actually discuss observed, quantified impacts, even considering among them the nearly half that deals with controlled laboratory or greenhouse experiments. This present discussion deals with these 5%. For a general appraisal of the mangrove *vs* climate change issues one is referred to at least four recent, outstanding reviews summarizing future scenarios and aspects of climate change impacts on mangroves (Alongi, 2015; Ward et al., 2016; Jennerham et al., 2017; Makowski, 2018).

A summary of observed responses of mangroves to climate change pressures

Global climate changes result ultimately from increasing heat accumulation in the atmosphere due to anthropogenic emissions of greenhouse gases, CO_2 in particular. Major direct pressures affecting mangrove physiology are the buildup of atmospheric CO_2 proper and augmenting air and sea temperature. Indirectly, climate change also acts upon sediment equilibrium, hydrology and hydrochemistry, causing changes in rainfall quantity and distribution and thus of the amount and quality of the continental runoff to the ocean. Storminess and frequency of extreme climate events and sea level rise have also been observed and quantified worldwide. In general, these pressures associated with climate change tend to be more intense in extreme environments, such as the Poles, oceanic islands and semiarid coasts (Jennerjahn et al., 2017).

Increase of atmospheric CO_2 improves mangrove growth rates and this is an adaptive advantage to cope with competing species. Seedlings of *A. germinans* increased growth under higher CO_2, but only when grown alone. Its growth was strongly suppressed when grown in mixture with the C-4 grass, *Spartina alterniflora* (McKee and Rooth, 2008). This implies that biological interactions such as competition and herbivory modify the potential effects of higher CO_2. How this scenario would work, if at all, in natural stands growing mixed with and array of other C-3, as well as C-4 plants, is however far from comprehension. Unfortunately, the scarcity of quantitative data avoids a more profound evaluation of this biological response to the carbon stocking in mangroves.

Mean air temperature increase has led to a poleward migration at mangroves geographical distribution limits. Mangroves are expanding their latitudinal range on the Atlantic US coast (Zomlefer et al., 2006) and the east coast of Australia and this expansion corresponds to the poleward extension of mild temperature zones in the past half century (Canavaugh et al., 2014). However, this poleward movement of mangroves do not occur in a global scale and latitudinal expansions are inhibited by barriers to dispersal in some locations, e.g., *A. marina* in Australia and New Zealand (de Lange and de Lange 1994), and is not occurring, at all, in other coasts latitudinal limits, such as in the western South Atlantic, due to unknown reasons (Soares et al., 2012). To what extent poleward migration will be hampered by a local mix of environmental variables and settings? On the other hand, out of their colder distribution limits, how peak of high temperature will affect mangroves?

Increasing or decreasing the frequency of extreme events result in sudden growth or dieback of mangroves, which are followed by significant fluctuations in the sedimentation/erosion equilibrium. In the Mississippi River Delta, USA, a combination of drought and low river outflow led to wide-spread dieback of the salt marsh dominant *S. alterniflora*. More drought-tolerant *A. germinans* was unaffected, and the absence of killing freezes during this period fast expanded *A. germinans* cover (McKee et al., 2004). On the other hand increasing storminess, although potentially threatening, has not been faced vis-à-vis mangrove resilience. Again, most observed abrupt changes in mangrove cover have been studied close to their latitudinal limits, although important information resulted from the evaluation of mangrove recovery after hurricanes, in particular the abundant literature following the 2004 Indian Ocean tsunami (Gedan et al., 2011). Therefore, a reliable resistance/resilience appraisal is still far from possible.

By far, change in sea level is the best studied pressure on mangroves, since dated sediment cores ranging in extension from decades to millennia, provide insightful templates of mangrove response to this pressure. Rising sea level, much earlier than any catastrophic stage, strongly affects hydrology, surface and groundwater salinity and soil stability, creating new competitive requirements from natural animals and plants (Jennerjahn et al., 2017). Declining of terrestrial vegetation by tree mortality responding to increasing groundwater salinity in low elevation areas and partial replacement by *A. germinans* was reported in Sugarloaf Key, Florida, USA (Ross et al., 2009). Along the equatorial margin of northeastern Brazil, location of the largest continuous stretch of mangroves in the world (Kjerfve and Lacerda, 1992); extensive pasture lands on low lying islands and river margins have been substituted by mangroves (Souza Filho & Pardella, 2003). This landward migration is the most and better documented response of mangroves to sea level rise (see Godoy & Lacerda (2015) for a review). Although, observed worldwide, it is consistently more intense along semiarid coasts, associated with lower annual rainfall and fluvial fluxes, e.g. NE Brazil (Godoy et al., 2018). Unfortunately, few studies (Lacerda et al., 2013) discuss the biogeochemical consequences of expanding mangroves not only in terms of vegetation changes properly, but on impacts of typical mangrove biogeochemical processes on the regional cycles of sulphur, carbon, nutrients and trace elements of the new colonized areas.

Summary of the general findings from observed impacts on mangroves

Based on published observations and results, there is a certain agreement on some aspects with enough consistency regarding the response of mangroves to climate change to allow a certain degree of generalization. Inter-related and spatially variable climate change pressures including sea level rise, increased storminess, altered precipitation regime and increasing temperature are impacting mangroves at regional scales (Ward et al., 2016); but the intensity of the response seems site-specific (Godoy & Lacerda, 2015). Biological interactions such as competition and herbivory modify the mangrove response to some environmental pressures from climate change, particularly those involving plant physiology (McKee & Rooth, 2008). Interactions with local anthropogenic drives, in particular damming and basin diversion, and eutrophication also modify the intensity of the mangrove response either favoring or hampering adaptability (Mounier et al 2018). Mangroves are resilient and can adapt progressively to global climate change, provided some environmental settings (Godoy & Lacerda, 2015). Even these agreements, however, have to be taken with caution since most reported observed impacts were derived from limited time series and in general performed on less representative mangrove areas, mainly close to their latitudinal limit. Also, the great majority of the studies on the response of mangroves to climate change have taken into consideration the vegetation proper, and a more realistic approach to assess climate change impacts on mangroves needs to consider mangroves not only as a vegetation form, but as a unique biogeochemical realm.

Some biogeochemical settings following mangrove response to climate change

The biogeochemistry of mangrove ecosystems, is affected by the interaction between multiples stressors of local, regional and global origins. On the other hand, estuarine and adjacent coastal areas are directly influenced by what occurs in these forests, mostly related to changes in sedimentology and hydrology, but also with drastic alterations in water, pore water and sediment chemistry. Erosion of margin mangroves resulting from sea level rise and reinforced by diminishing average annual rainfall increases suspended solids load; favors the oxidation of reduced minerals (sulfides) present in the now exposed mangrove sediments; including the mobilization of accumulated pollutants (Lacerda & Miguens, 2013). In areas with a strong legacy of pollution, this “resuscitated” contamination can reach alarming levels. Increase CO_2 emission also occurs as a result of the aerobic respiration of partially degraded sedimentary organic matter (Cavalcante et al., 2018; Mounier et al., 2018). Expansion over newly formed sedimentation areas, as well as migration inland, follows saline intrusion and increases the trapping of continental sediments, including pollutants; enlarging the mangrove redox realm, dominated by dissimilatory sulfate reduction, upriver (Godoy et al., 2018). Sulfate reduction is unable to fully degrade deposited organic matter and thus exports large quantities of dissolved organic complexes from waters increasing metal mobilization through organic-complexation (Lacerda et al., 2013, Mounier et al 2018) and bioavailability (Moura & Lacerda, 2018), resulting in more efficient and fast bioaccumulation rates and augmenting human exposure to pollutants (Costa & Lacerda, 2014).

Sediment accretion rates (SAR), which include sediment build up by trapping continental runoff plus carbonate production, up also increases carbon preservation and the efficiency of the CO_2 sink. Although existing results are preliminary and lack long-term monitoring, SAR value suggests that most mangroves, free of other constrains, will eventually adapt to sea level rise (SRL) by migrating inland, as observed in many arid and semiarid coastlines with SLR higher or similar to SAR. On the other hand, the reduction of excess nutrient fluxes from continental sources results from trapping of suspended particles and this may be more significant under eutrophication.

There may be, however, constrains to mangrove adapting to climate change. Intensification of sand dune displacement, associated with extended drought periods, results in encroaching of mangroves, a phenomenon already recorded in some arid and semiarid environment and directly related to climate change (Maia et al., 2005; Lacerda, 2018). It is still uncertain if the sediment accretion rate/carbonate production rate measured apply for all mangrove sub-environments relative to continental runoff (basin, fringe and island forest types, for example). Additionally, inland natural processes and human activities along most coastlines may act as a barrier to mangrove migration inland.

This described sequence of biogeochemical events primarily triggered by a response of mangroves to global climate change may, unfortunately, be occurring worldwide, particularly along broad coastal plain littorals, but has been virtually neglected. Some questions considering mangrove migration and export inland of its biogeochemical characteristics remain unanswered: Will there occur remobilization or changes in bioavailability of deposited pollutants in the new colonized areas? If so, will these processes be significant relative to environmental health, as reported in some semiarid regions ? These gaps and questions regarding the biogeochemical impacts related to the mangrove responses to global climate change need urgent assessment, in order to achieve the necessary conservation and sustainable utilization of mangrove forests in the Anthropocene.

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