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MANGROVE RESTORATION IN NE BRAZIL: A UNIFIED CONTRIBUTION TO ADAPTING TO GLOBAL CLIMATE CHANGE

Restauração de manguezais no NE do Brasil: uma contribuição unificadora para adaptação à mudança climática

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ABSTRACT

The decade 2021-2030 was defined by the UN as the decade of *'Ecosystem Restoration'* and of '*Ocean Science for Sustainable Development*', aiming to restore ecosystems and protect the Oceans. Among target ecosystems, mangroves are fundamental wetlands, since they support a lively, biologically dynamic frontier between land and sea, furnishing many goods and services in relation to their extension, like fisheries, timber, biodiversity conservation and climate change mitigation, among others. Regarding climate change, mangrove restoration helps mitigate GHG emissions, by sequestering carbon in biomass and sediments for long periods of time and increases shore protection facing sea level rise and extreme climate events. The possibilities and conditions for mangrove restoration are many, and their rehabilitation/restoration is possible as provided by evidence form many experiments worldwide. Notwithstanding, there are still many steps in methodology and governance decisions to place mangrove restoration as a globally effective mitigation and adaptation measure to climate change.

Keywords: global changes, ecosystem services, ecological rehabilitation, mitigation.

RESUMO

A década 2021-2030 foi definida pelas Nações Unidas como a década da "Restauração Ecossistêmica" *e da* "Ciência Oceânica para o Desenvolvimento Sustentável"*, com o objetivo de restaurar ecossistemas e proteger os oceanos. Entre os ecossistemas-alvo, os manguezais são áreas úmidas fundamentais, uma vez que suportam uma viva e biologicamente dinâmica fronteira entre o mar e a terra, fornecendo muitos bens e serviços em relação à sua extensão, como recursos pesqueiros, madeira, conservação da biodiversidade e mitigação das mudanças climáticas, entre outros. Em rela-*

ção às mudanças climáticas, a restauração de manguezais ajuda a mitigar as emissões de GEE, através do sequestro de carbono em biomassa e sedimentos por longos períodos, além de aumentar a proteção da costa diante do aumento do nível do mar e eventos extremos. As possibilidades e condições para a restauração de manguezais são muitas, e sua reabilitação/restauração é possível, conforme evidenciado por muitos experimentos em todo o mundo. Não obstante, ainda existem várias etapas metodológicas e decisões de governança para colocar a restauração de manguezais como uma medida efetiva de mitigação e adaptação à mudança climática.

Palavras-chave: *mudanças globais, serviços ecossistêmicos, reabilitação ecológica, mitigação.*

INTRODUCTION

The decade 2021-2030 was defined by the UN as the decade of *'Ecosystem Restoration'* and of *'Ocean Science for Sustainable Development'*. Both aiming to restore life support ecosystems (LSEs) and protect the Oceans to face the current state of degradation of the Planet. Among target ecosystems, mangroves are extremely important wetlands since they support a lively biologically dynamic frontier between land and sea. They furnish a high provision of goods and services in relation to their extension, like fisheries, timber and other products, and services like biodiversity conservation and coastal protection (Alongi, 2002; McLeod & Salm, 2006).

In the reality of global warming and its consequences, mangroves play a significant role in coastal protection and sequestering of GHG (Greenhouse Gases). Mangroves are significant sinks of atmospheric carbon, stocking several times more carbon than other terrestrial forests. Indeed, they account for around 3% of carbon sequestered by tropical forests, although mangroves represent only around 1% of these forests. This relatively significant contribution is not only due to high productivity rates, but to the large accumulation of carbon in anoxic sediments, protecting organic matter from oxidation and so contributing to counteract global warming (Alongi, 2014; Donato *et al*., 2011). Notwithstanding their important ecological and social roles, between 2000 and 2016, anthropogenic activities reduced 62% of the global mangrove area, with shrimp, rice and oil palm cultivation responsible for close to half of this loss (Goldberg *et al*., 2020). Despite a slight reduction in forest loss rates mainly in the Americas, Africa and Australia, mangrove clearing, and fragmentation continues, mainly in Southeast Asia (Friess *et al*., 2019).

Yet, climate change represents an increasing direct threat to mangroves, whereas indirectly it can potentializing impacts from local anthropogenic activities (Gilman *et al*., 2008; Moomaw *et al*., 2018). Even though, in some places, mangrove migration inland or poleward following increasing sea level and saline intrusion, could favor mangrove expansion (Gilman; Ellison & Coleman, 2007; Godoy & Lacerda, 2015), worldwide mangroves are vulnerable to the effects of global changes. Sea level rise can increase soil and pore-water salinity and contamination of biological resources through remobilization of pollutants (*i.e.,* trace metals), and of carbon, causing eutrophication (Lacerda; Borges & Ferreira, 2019; Lacerda; Marins & Dias, 2020). Drowning and erosion of coastal forests and burying of basin forests are also expected effects, along with decreasing extension and biodiversity of stands (Godoy; Meireles & Lacerda, 2018; Lacerda; Borges & Ferreira, 2019).

Notwithstanding the rising severity of environmental impacts on mangroves, the necessary levels of their conservation are insufficient. Brazil, Indonesia and Mexico have the largest extensions of mangrove protected areas (PAs) (Worthington & Spalding, 2018). Only about 39% of the remaining mangroves globally are inside PAs, mainly in the American continent and South Asia. Unfortunately, this does not necessarily mean full protection, but at least lowers the level of degradation, since coastal-marine PAs are governed centrally by the state, their effectiveness is limited by poor interinstitutional collaboration, which promotes conflicts among several management authorities, jurisdictional and regulatory ambiguities, and pressures from economic sectors (Rotich; Mwangi & Lawry, 2016; Ferreira & Lacerda, 2016). This frequently results in varying degrees of degradation, which makes restoration and rehabilitation fundamental to restore mangrove ecosystem's functioning and adaptability and migration capacity to climate change.

Variation in global mangrove area estimates (Lacerda *et al.,* 2021) affects the dimensioning of their functions and services and causes misappraisal of mangrove importance and restoration needs. Indeed, in the last four decades, it was estimated that only 2,000 km^2 of mangroves have been restored worldwide. Yet, 8,120 km^2 of lost mangroves are considered restorable, an extension 33% higher than the worldwide mangrove losses in last 25 years. Some large-scale restorations have been successful, like in the Mekong River, East Africa and the Philippines (IUCN, 2004; Nam *et al*., 2016; Barnuevo *et al*., 2017), as well as many small to medium-scale rehabilitation, planting, and restoration projects worldwide supported by Institutions, like the International Society for Mangrove Ecosystems (ISME, 2021), all showing that such endeavors are possible.

In general, coastal and shelf ecosystems are rather a source than a sink of GHG; mangroves are the only forest ecosystem occurring along estuaries and lagoons to attain high biomass, rich in recalcitrant lignin and woody matter, which protects mangrove organic matter from rapid decomposition. Other mangrove-associated vegetation formations, like salt-marshes and seagrass beds, are carbon reservoirs dynamically connected with mangroves by dissolved and particulate carbon fluxes. Also, most non-mangrove coastal vegetation is seasonal, therefore, decreasing its carbon sequestering capacity (Cragg *et al*., 2020). Conservation of world mangroves would keep locked in the ecosystem a large amount of carbon, an average of 856 ± 32 MgC/ha, approximately 11.7 PgC globally (Kauffman *et al*., 2020), which is close to 30 times the carbon emissions from Brazil in 2018 (IEA, 2020). If released, this carbon, as CO_2, would accelerate atmospheric warming. On the other hand, if the totality of the restorable degraded mangrove area is rehabilitated, 69 million tons of atmospheric carbon could be sequestered (equivalent to the annual emissions of 25 million US homes), in addition to enhancing small-scale fisheries and increasing coastal protection (Worthington & Spalding, 2018). Some projects supported by international conservation institutions and/or funds and NGOs, and sometimes governments, have advanced in mangrove restoration. Adversely, carbon accumulated in mangrove sediments over hundreds and sometimes thousands of years, when mobilized through erosion, conversion, dredging and other threats to the integrity of mangrove sediments, may release vast amounts of GHG to the atmosphere, like fossil fuel burning. Therefore, to restore mangroves contributes both to the recovering of a fundamental coastal LSE and to the preservation of the most important Earth's LSE, the Oceans, in whose coasts live around 60% of world population.

MANGROVE RESTORATION FORESEEING CLIMATE CHANGE

Success of mangrove restoration efforts worldwide is diverse. Many endeavors have succeeded, despite there are still few reports on long-term observations on growth, biomass stocking, carbon accumulation in sediments, return of biodiversity and ecosystem functionality of such projects (Ferreira; Ganade & Attayde, 2015). Long-term monitoring is important to increase knowledge on sound methodologies, and to measure effective return of ecosystem functioning and the restart of their goods and ecological services, to effectively contribute with (urgent) benefits for the Planet. Several other endeavours have failed by different causes. The most common causes are the attempts to place propagules or seedlings in the wrong place in relation to the soil physico-chemical and hydrological conditions, *i.e.*, where conditions are not proper for mangrove developing or where, despite mangroves have previously existed in the area, the conditions have changed completely, or when conditions are proper for a different mangrove species (Samson & Rollon, 2008; Barnuevo *et al.*, 2017). Since climate change is already in course, mangrove restoration needs to regard geographical and environmental settings of each place to plan the methodologies with more chances of success, earliest ecosystem functionality return, and with highest chance to recover or capacity to dampen effects from climate change. This means that the trade-off between the restoring efforts and the resilience of restored forests need to be necessary addressed.

Mangrove forests are commonly assemblages of diverse tree species. At local level, Atlantic, Caribbean and East Pacific (ACEP) region stands can present 3-4 tree species (Ferreira; Ganade & Attayde, 2015), while in Indo-West Pacific (IWP) stands can have 15 species or more (Ricklefs & Latham, 1993). Monospecific restorations have been criticized due to the possible trade-off between productivity and biodiversity (and the consequent functional diversity) since forests richness can be low in comparison to natural areas (Salmo III & Duke, 2010; Lee *et al.,* 2019; Fickert, 2020). It is preferable the restoration with the maximum of native species present in each specific region, mainly in regions with high tree diversity (and consequently high faunal diversity – Ricklefs & Latham, 1993; Lee, 1998) like IWP mangroves. However, in certain sites or regions where low tree diversity stands (1-2 species) are common (e.g. Neotropical mangroves), and/or where environmental conditions are harsh (semiarid climates), restoration with one or few selected species of faster growth and higher primary production, and/or more able to facilitate other mangroves settling and return of key biological groups, can be an effective tool to hasten the return of forest functionality.

For example, cosmopolitan trees of the genus *Rhizophora* are the most commonly used for restoring mangrove stands, by their conspicuousness, easy collecting and planting, rapid growth, resistance, and high biomass and hence carbon stocking (Field, 1996; Ross *et al*., 2001; Ferreira; Bezerra & Matthews-Cascon, 2019). They can hasten organic matter and further detritus accumulation in soil, fuelling the detritivore-based food web, and allowing the settling of other mangrove species also by trapping propagules between prop roots (Menezes *et al*., 2005; Ferreira; Ganade & Attayde, 2015; Leite *et al*., 2021). This accelerates the colonization of functional groups important for mangrove functioning and restart of their biogeochemical cycles (Proffit & Devlin, 2005; Ferreira; Ganade & Attayde, 2015; Al-Khayat; Abdulla & Alatalo, 2019). The low tree diversity of Neotropical and West African mangroves, where most stands are predominantly formed by *Rhizophora mangle* (or their congeneric *R. racemosa* and *R. harrisonii*) may allow the restoration through monospecific planting, which can further promote the establishment of other tree species (Menezes *et al*., 2005; Ferreira & Lacerda, 2016; Leite *et al*., 2021). However, since mature *Rhizophora* lacks epicormic resprouting, in regions with frequent great storms and/or where they are predicted to increase, a stand of these trees could be seriously damaged and may not recover (Villamayor *et al*., 2016; Fickert, 2020), and in regions prone to extreme weather events, it is better to initially restore including also non-*Rhizophora* species. Over time, however, cyclones lead to the development of short-statured forests (Simard; Fatoyinho & Smetanka, 2019) more resilient to cyclone impacts, and promote an enhanced carbon sequestration in following years, despite reducing aboveground carbon stocks (Friess *et al*., 2020).

In low-diversity mangroves in semiarid climates, the initial restoration with species resistant to hypersalinity and drought like *Avicennia* spp. can facilitate the return of mangrove stands (Toledo; Rojas & Bashan, 2001; Flores-Verdugo; Zebadua-Penagos & Flores-de-Santiago, 2015). *Avicennia* stands can stock relative high carbon load belowground in roots, but not aboveground (mainly in semiarid realms) like *Rhizophora* (Adame *et al*., 2021), but can be used to ameliorate soil and thermohaline stress to the colonization of other species. For example, *Avicennia* can colonize hypersaline soils in Northeast Brazil, and it is able of initially develop in salt flats and other hypersaline areas when sea level flood these areas upstream and landward (*personal communication*). *Laguncularia racemosa* is a pioneer opportunist Neotropical species that colonizes impacted/degraded areas and can be managed to primarily establish mangrove in these realms, since *Laguncularia* stands present same diversity that multispecific fragments in terms of some macrobenthic functional groups, such as fossorial and herbivore crabs and grazer gastropod snails (Ferreira; Alencar & Bezerra, 2019; Aviz; Simith & Fernandes, 2020). Fishes are another functional group indicator of mangrove restoring (Arceo-Carranza *et al*., 2016; Das, 2017).

Mangroves are efficient biogeochemical barriers to the transfer of pollutants generated in coastal landfill sites to the sea, an effect verified by restored mangroves in Australia and Southeast Brazil (Clark *et al*., 1997; Lacerda; Machado & Moscatteli, 2000). Indeed, mangroves can trap toxic metals (Fe, Mn, Zn) in the root-sediment interface, being able to colonize metal-rich sediments and hence having a great potential to minimize metal pollution, an extremely significant service in low-resources developing countries (Machado *et al*., 2002; Machado; Tanizaki & Lacerda, 2004). Mangroves sequester in sediment other heavy metals (Hg, Cd, Cu), which can be released to estuarine/deltaic waters by human activities (dredging, deforestation, alterations in river basins) and climatic driven causes (erosion, sea level rise) (Lacerda & Miguens, 2011; Lacerda *et al*., 2021).

At the Northeastern semiarid coast of Brazil, human impacts like shrimp farming, garbage, infrastructure and housing occupation, cattle breeding and river damming, are drivers of deforestation and impairment of mangrove recovering (Ferreira & Lacerda, 2016). Climate change induced drivers, like sea level rise and reduced annual rainfall, promote erosion and saline intrusion. Despite these, in several cases climate change accelerates mangrove expansion and landward migration, erosion of mangroves at the mouth of rivers and in subsiding deltaic island are locally counterbalancing this expansion (Godoy & Lacerda, 2015; Lacerda; Borges & Ferreira, 2019). To avoid occupation/use of salt flats and high intertidal fringes in estuaries can be a way to ensure grounds for mangrove establishing when pushed by sea level rise. Dynamics of estuaries and coasts driven by this factor, require that restoration endeavors can combine areas undergoing self-recovering with areas that need management to be reforested (Ferreira; Ganade & Attayde, 2015).

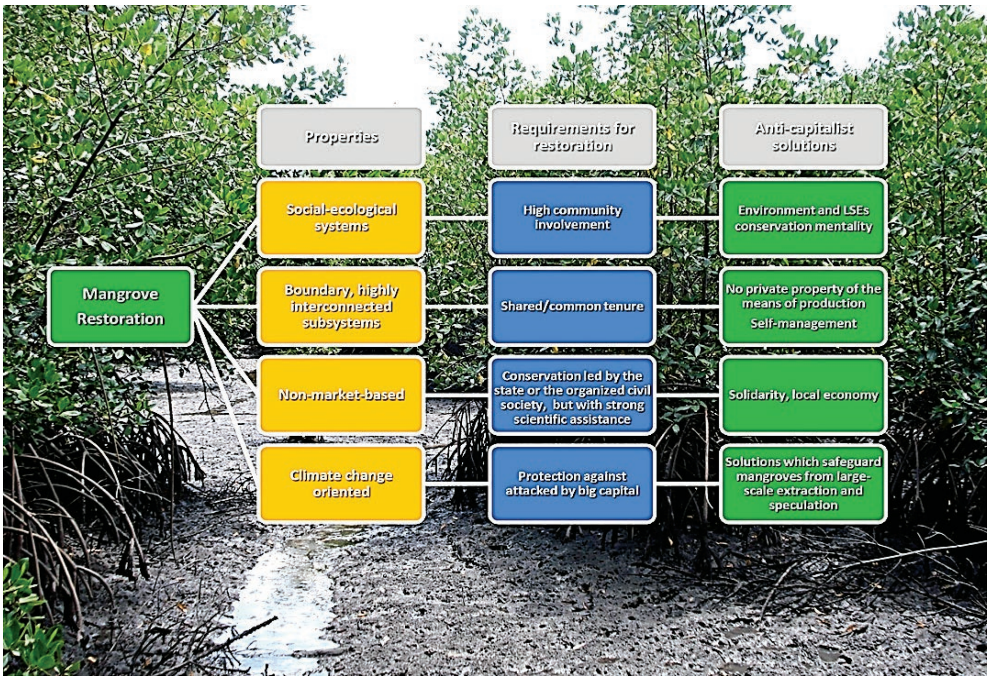
It is necessary to stress that mangrove restoration need to be integrated with a strong effort to protect and rebuild degraded marine ecosystems, aiming to increase the abundance of keystone species and key habitats. Oceans are the first LSE, and their protection is central to the biosphere's homeostasis. Notwithstanding, oceans are increasingly impacted, with 41% of their areas strongly affected by human-driven impacts (Halpern et al., 2008). Climate change affects ocean biogeochemical cycles and biodiversity, while commercial fisheries exhaust stocks, mainly of pelagic high-bycatch fishing. Coastal and benthic habitats are also being degraded by fisheries and aquaculture, mostly with locally exotic invasive species, as well as different types of pollution, threatening marine life worldwide (Halpern *et al*., 2008; Doney *et al*., 2012). A recent study demonstrates that bottom trawling can release from seabed 1.47 Pg of carbon/year, equivalent to carbon losses from farming in land (Sala *et al*., 2021). A rebuilding of marine life through extending protection to 50 % of oceans space and restoring the three-dimensional complexity of benthic ecosystems by 2050 is possible, allocating US$ 20 billion/year (Duarte *et al*., 2020), one fiftieth of the yearly military spending of USA and China together.

FINAL CONSIDERATIONS

The possibilities and conditions for mangrove restoration are many, and their rehabilitation/restoration is possible to stop their rampant destruction (Ferreira & Lacerda, 2016; Worthington & Spalding, 2018). A summary of major procedures on methods and governance decisions to promote rehabilitation/restoration as a globally mitigation/adaptation strategy to climate change is demonstrated in Figure 1. It would be a task of governments, with scientific/technical support, to join with civil organizations and native populations to promote and help initiatives to restore these life-supporting wetlands. Native/indigenous populations, artisanal fishers, etc., should be encouraged and assisted to restore mangroves (Borges *et al*., 2017), and even with success or failure, their attempt to restore their livelihood environment is extremely positive in terms of self-management and awareness (Primavera & Esteban, 2008). Ideally, methodologies and knowledge need to be constructed with these populations so that they can restore mangroves on their own, using sound methodologies (Ferreira & Lacerda, 2016; Borges *et al*., 2017).

When governance level fails, scientists have the obligation to help and promote restoration endeavors together with coastal communities (Ferreira & Lacerda, 2016; Borges *et al*., 2017), testing and suggesting methodologies liable of higher success. Science has been part of many actions, but their contribution needs to be more ample. Indeed, mangrove restoration has been even discouraged, with arguments that monospecific plantings are not a solution to fully restore mangroves (Walters, 2000; Salmo III & Duke, 2010; Rovai *et al*., 2012; Lee *et al*., 2019; Fickert, 2020). There is a need for better protocols to restore mangroves aiming maximum biodiversity, long-term functionality and, most important, foreseeing the effects of climate changes. However, these studies disregarded that each place have a particular setting of trees, forests characteristics, climate and present and potential impacts from humans and environment, and that sometimes the most effective restoration measures can start with a single species, particularly where this tree is a key species that can restore specific ecosystem traits and natural functions of the forest, thus increasing the chances of a successful restoration (Lewis III, 2005; Ferreira; Ganade & Attayde, 2015). The mechanistic mind of these studies has certainly contributed in discourage mangrove restorations attempts, contributing with the present situation of scarcity of well reported mangrove restoration endeavors.

Figure 1 – Major procedures on methods and governance decisions to promote rehabilitation/restoration as a globally mitigation/adaptation strategy to climate change



It is up to the Governments to link global initiatives like the UN Proposals for this decade with the resolution of their respective environmental-societal needing and with improving people environmental education, always relying in scientific but also in ancestral traditional people-based knowledge. To restore mangroves is the sole feasible, low-cost individual to regional level initiative, with directly impacting climate change by mitigating GHG emissions and protecting from sea level rise. Contrary to most technological alternatives, mangrove restoration also improves other sectors, mostly fisheries and traditional uses, and promotes protection for adjacent important coastal ecosystems.

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