



Systematic Planning and Ecosystem-Based Management as Strategies to Reconcile Mangrove Conservation with Resource Use

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About 120 million people worldwide live within 10 km of large mangrove forests, and many of them directly depend on the goods and services provided by these ecosystems. However, it remains unclear how to synchronize ecological definitions and legal conservation strategies regarding mangroves, especially in developing countries, such as Brazil. The influence of human populations' socio-economic context in mangrove conservation policies, as well associated challenges in incorporating this influence, are underestimated or, often, largely ignored. Considering the recent threats emerging from changes in legislation and the lack of spatial and social-ecological integrated data to plan mangrove conservation in Brazil, this paper aims to answer the following questions: (1) What suitable measures could managers and other decision makers adopt for efficient mangrove conservation planning?; (2) What are the site-specific, social-ecological aspects that need to be taken into account when deciding on conservation and management strategies?; and (3) How could science contribute to the development of these measures? In order to achieve an ecosystem-based management approach, mangrove ecosystems should not be divided into sub-systems, but instead treated as an integrated system. Furthermore, interconnections with other coastal ecosystems must be assessed and taken into account. This is crucial for effective systematic conservation planning. Also, most of the particular social-ecological aspects in the different types of mangrove ecosystems along the Brazilian coast, and how those differences might be considered while planning for conservation, remain poorly understood. Based on similar drivers of change, geological features, and likely impacts of climate change, a macro-unit approach is proposed to group mangrove systems along the Brazilian coast and guide national policies. This paper draws parallels with management approaches worldwide to find common points and hence lessons to be applied in other regional realms. It considers the issues of legal vulnerability and needs for social-ecological data on mangroves, contributing toward systematic conservation planning and ecosystem-based management for these ecosystems.

Keywords: coastal-marine spatial planning, social-ecological system, marine protected area, ecosystem service, GIS-based data, Brazil

INTRODUCTION

About 120 million people worldwide live within 10 km of mangrove forests (UNEP, 2014). Many of them largely depend on the goods and services provided by coastal ecosystems, such as food and timber provision, fuel wood and shoreline protection (Spalding et al., 2010; Barbier et al., 2011). Mangroves also indirectly deliver farther-reaching benefits, such as serving as habitat for terrestrial and marine species (Nagelkerken et al., 2008). At least 776 species of birds, fish, mollusks, arthropods and plants are associated with these ecosystems in Brazil (Schaeffer-Novelli, 1999), with even larger numbers in Indo-Pacific mangroves (Latham and Ricklefs, 1993). On a global scale, they function as important carbon-sequestering systems (Donato et al., 2011; Ray et al., 2011; Murdiyarso et al., 2012).

In some developing countries, mangroves are estimated to contribute to national economies with US\$33–57 thousand per hectare per year (e.g., Sathirathai and Barbier, 2001). Some coastal human populations are directly dependent on mangroves, such as in north Brazil, where 83% of rural households harvest natural resources from mangroves, which also provide 68% of their cash income (Glaser, 2003). However, mangroves have been largely affected by land conversion, pollution, and overexploitation, leading to a loss 3–5 times faster than that in other forest types (Alongi, 2002). Clearing of these forests is usually due to aquaculture, agriculture, and urban land uses (Spalding et al., 2010). The deforestation of coastal vegetated ecosystems corresponds to up to nearly 20% of total emissions from deforestations on the planet, with economic damages of US\$6–42 billion per year (Pendleton et al., 2012).

Brazil has between 75 and 83% of its mangrove coverage within some category of protected area (Magris and Barreto, 2010; Prates et al., 2012). This represents a much larger cover than the global average (~ 28%) (Juffe-Bignoli et al., 2014). The total protected extension of Brazilian mangroves kept increasing in recent years: since 2014, the country holds the largest extent of protected mangrove in the world: 322 thousand hectares inside 11 “*extractive reserves*”—a sustainable-use category (Plataforma Brasil, 2015). Similar protected area models have been shown to offer good conservation results elsewhere (Aheto et al., 2016). In Brazil, however, these reserves have not yet been systematically assessed. Moreover, around 58% of the total protected mangrove areas are within the category of *environmental protection areas*, a sustainable-use category of protected areas considered to deliver low levels of protection (Prates et al., 2012).

Despite having already lost 10–20% of its mangroves (FAO, 2007), Brazil still holds a total mangrove area of over one million hectares (Magris and Barreto, 2010), spread out along 6,786 km of coastline (Schaeffer-Novelli et al., 2000). Contrary to the trend in other countries, the total mangrove area in Brazil even increased in the first decade of the millennium (Aide et al., 2013).

Recent changes in conservation policy in Brazil, however, such as the new Brazilian Forest Code (BRASIL, 2012), will likely have negative impacts on mangroves and other vegetation types (Silva et al., 2011; Medeiros et al., 2015; Ferreira and Lacerda, 2016b; Oliveira-Filho et al., 2016). This federal law, strongly biased toward agribusiness interest (Oliveira-Filho et al., 2016),

disaggregates from the mangrove the salt flats (“*apicuns*”), which are of special interest to shrimp farming, but also an important component of the mangrove ecosystem (Schmidt et al., 2013). The new law admits the “sustainable use” of these areas, including aquaculture and salt production ponds.

Negative impacts on coastal and marine processes and on social-economic activities are predicted consequences of this change in legislation (Rovai et al., 2012) because it fails to adopt an ecosystem-based approach when defining mangroves and the interactions between its components. Ecosystem-based management is here understood as “an integrated approach to management that considers the entire ecosystem, including humans” (McLeod et al., 2005), where the complexity and relationship within close ecological systems are acknowledged, together with social and governance objectives of mangrove management (Barbier, 2006; Aswani et al., 2012; Carter et al., 2015; Long et al., 2015). The ecosystem-based management approach is an opportunity to maximize ecosystem services while promoting ecological resilience and appropriate productive activities (Lithgow et al., in press).

The recent developments and discussions on sub-systems, such as the salt flats, and the uniqueness of mangroves as ecosystems illustrate the discussion that directly affects mangrove conservation. It remains unclear how to synchronize the ecological definitions and legal conservation strategies regarding mangroves. As observed for other countries where mangrove forests are found, laws and policies in Brazil are rarely designed for the specific management requirements of mangroves. As illustrated by the Forest Code, mangroves are usually regulated under legal frameworks created originally for forests in general, environment, water, land, or marine fisheries (Rotich et al., 2016).

Mangrove management requires attention to the multidimensional benefits they provide, both ecologically and socially (Rotich et al., 2016). However, incorporation of social-ecological aspects, such as people’s perception and traditional uses in conservation policies, is deficient (McConney and Charles, 2008). As pointed out by Benessaiah and Sengupta (2014), one challenge is that many ecologists and managers tend to define ecosystems in a localized sense, rather than adopting a broader understanding of ecosystems as self-organizing units comprised of interacting ecological and social components operating at different scales. Adopting a social-ecological system approach explicitly defines issues as an integrated system of people and environment (Benessaiah and Sengupta, 2014; Nayak and Berkes, 2014). The term social-ecological is used throughout this paper in the sense of the integration of humans and nature in complex, adaptive systems (Berkes and Folke, 1998).

Systematic conservation planning requires explicit goals and criteria for implementing conservation action, besides mechanisms for maintaining the conditions within reserves that are required to foster the persistence of key natural features (Margules and Pressey, 2000). It is based on the extent to which conservation goals have already been met in existing reserves and clear methods to locate and design new reserves to complement existing ones (Margules and Pressey, 2000).

Considering the recent threats from changes in legislation and the lack of spatial, social-ecological data integration to

plan for conservation of mangrove systems, this paper aims to answer the following questions: (1) What suitable measures could managers and other decision makers adopt for efficient mangrove conservation planning?; (2) What are the site-specific, social-ecological aspects that need to be taken into account when deciding on conservation and management strategies?; and (3) How could science contribute to the development of these measures?

This is the first review to consider the issues of legal vulnerability and lack of integrated social-ecological data, using Brazil as a study case and systematic planning and ecosystem-based management as backbones to discuss the following suggested approaches to tackle the apparent paradox of reconciling mangrove conservation and sustainable use: (1) mangrove as a social-ecological system; (2) mangrove as an integrated system; (3) multi-scale planning; (4) standardized, GIS-based information and synthesis work; and (5) assessment of the protected area system.

LINKING SYSTEMATIC PLANNING AND ECOSYSTEM-BASED MANAGEMENT TO GUIDE FURTHER STRATEGIES

The Mangrove as a Social-Ecological System

The involvement of stakeholders in environmental management, when underpinned by a focus on empowerment, equity, trust and learning, can (1) improve environmental decision making by considering more comprehensive information inputs (Reed, 2008) and (2) increase public trust in decisions and civil society, if participatory processes are perceived to be transparent and consider conflicting claims and views (Richards et al., 2004). Stakeholder participation can increase the likelihood that environmental decisions are perceived to be holistic and fair, accounting for a diversity of values and needs and recognizing the complexity of human-environmental interactions (Richards et al., 2004). It can also empower stakeholders through the co-generation of knowledge with researchers and through increased participants' capacity to use this knowledge (Stephenson et al., 2016). To be successful, the involvement of actors must be institutionalized, creating organizational cultures that can facilitate processes where goals are negotiated and outcomes are uncertain (Reed, 2008).

Scientific research can indicate concrete measures to enhance stakeholder participation and develop strategies to help involve local actors in a more efficient way. As emphasized by Ferreira and Lacerda (2016a), in order to promote mangrove conservation, besides government enforcement of the protection legislation, people need to be aware of the goods and services provided by mangroves. Unfortunately, population awareness usually only arises after the consequences of mangrove degradation (Barbier, 2006), so providing people with information about similar cases and the consequences of mangrove degradation elsewhere through experience exchange could be a shortcut to avoid human-promoted mangrove degradation by lack of knowledge. However, science often fails

to translate knowledge to decision makers and the general public (Granek et al., 2010).

In the case of fisheries, which is an important human activity developed in mangrove areas (UNEP, 2014), engaging community leaders has been shown to be essential to achieve successful co-management (Gutiérrez et al., 2011). Native populations, especially those directly dependent on mangrove goods and services, as well as other societal sectors, need to be integrated through community-based management (Ferreira and Lacerda, 2016a). In addition, when considering the effectiveness of protected areas, besides creating more and larger reserves, it is important to concomitantly invest in education, economic incentives, and community-based enforcement (Rife et al., 2013).

Regarding fisheries management, successful outcomes of community-based initiatives benefit from (1) effective information sharing, (2) harvesting rules that merge traditional and contemporary practices, (3) strong leadership, and (4) resource monitoring (Blythe et al., 2017). There is, though, a deficiency of information on the social dimensions of mangrove management (Rotich et al., 2016), necessary to promote these aspects. Local and scientific knowledge can be integrated to provide a more comprehensive understanding of complex and dynamic socio-ecological systems and processes (Reed, 2008).

Local people often have a symbolic relationship with the mangrove forest, so the socio-cultural dimension of mangrove services needs to be considered by policy makers to tackle challenges in coastal ecosystems conservation (Queiroz et al., 2017). To tackle the financial dependency on mangroves it is vital to provide all stakeholders with the capability to influence the political aspects of governance, support institutions which foster accountability, encourage civil society to participate in decision making processes, and ensure that views from the local level feed into the multi-level governance process (Orchard et al., 2015).

Partnerships with mangrove research groups need to be created and strengthened (Ferreira and Lacerda, 2016a). Scientific research can contribute, for example, with the development of methods to incorporate local ecological knowledge, through bottom-up social studies that shed light on how to apply this knowledge to the development of conservation strategies for mangroves. This is especially relevant to assess monetary and non-monetary values of ecosystem goods and services. With such a valuation at the local level, policy makers can be made aware that the profit coming from the shrimp market, for example, is considerably smaller than the environmental damage caused, as exposed in the case of some intensive shrimp farms in NE Brazil (Ferreira and Lacerda, 2016a). {One exception could be, for example, organic farms in NE Brazil and traditional "tambacs" in Asia, which may have a mutual benefit for adjacent mangrove forests (Lacerda et al., 2002).}

A lack of understanding of the values associated with wetlands is largely due to the complexity and "invisibility" of spatial relationships between groundwater, surface water, and wetland vegetation (Turner et al., 2000). Following a global pattern (Walters et al., 2008), the values associated with Brazilian mangrove ecosystems are not taken into account by policy makers, when, for example, shrimp farming is considered more

valuable than mangrove preservation. Despite pressure and consequent damages over mangroves, little is known about their unique value in terms of ecosystem services, since local variation can be high due to site specificities along the Brazilian coast (Souza and Ramos e Silva, 2010; Estrada et al., 2015; Ferreira and Lacerda, 2016a). But even these few accurate studies are not taken into consideration by decision makers or environmental authorities. The largest mangroves in the world, the Sundarbans, for example, lack a specific protection agenda or policy (Roy and Alam, 2012).

More integrated studies to assess ecosystem services and vulnerability to environmental impacts have to be conducted for Brazilian mangroves. Integrated wetland research combining social and natural sciences can help to partly solve the information problem and provide consistency among various government policies (Turner et al., 2000). While global (Martínez et al., 2007) and local scale (Saint-Paul and Schneider, 2016) integrated approaches have been applied, the regional level might be the best starting point to identify cross-scale interactions which shape coastal and marine social-ecological dynamics and outcomes (Glaser and Glaeser, 2014).

In order to make progress, further and intensified co-operation is needed between social and natural scientists (Turner et al., 2000). It is also imperative to collect and integrate data from different disciplines, which are essential for sustainable development and management, particularly in developing countries (Dahdouh-Guebas, 2002). Including models and values of ecosystem services and vulnerability in marine spatial planning, for example, can help achieve multiple benefits for nature and people (Arkema et al., 2015). Böhnke-Henrichs et al. (2013) provide a framework for such an ecosystem service approach in marine spatial planning. Given the peculiarities of transitional ecosystems such as mangroves, however, an even more specific typology and sets of indicators for coastal areas could be useful to assess ecosystem services. Additionally, stakeholders at different spatial scales can have very different interests in ecosystem services (Hein et al., 2006), so it is important to consider the scales of these services when valuation is applied to support the formulation or implementation of spatial plans.

In fisheries, for example, management systems are starting to value fishers' knowledge, considered part of the "best available information." Fishermen are able to provide information that can integrate ecological, economic, social, and institutional considerations of future management. Fishers' knowledge can be added to traditional assessment with appropriate analysis and explicit recognition of the intended use of the information and, if implemented in a participatory process designed to receive and use it, this knowledge can facilitate the participation of fishers in assessment and management, considered as best practice in fisheries governance (Stephenson et al., 2016).

The view of mangroves and contiguous coastal ecosystems as an assembly of interconnected exchanging matter and energy flux means that the conservation and use of such ecosystems requires integrated management (Ferreira and Lacerda, 2016a). Indeed, countless fishery resources recruit and grow in different coastal ecosystems, which also share mutual buffer effects (Walters

et al., 2008; PEDRR, 2010). An integrated, ecosystem-based management should account for the complexity and relationship within close ecological systems (Macintosh and Ashton, 2005; Long et al., 2015; Lithgow et al., in press). It should also account for social and governance objectives of mangrove ecosystem management, like community-based management and social decisions, effective use of scientific knowledge, stakeholder involvement, appropriate monitoring, applying of precautionary approach and others (Macintosh and Ashton, 2005; Walters et al., 2008; Granek et al., 2010; Aswani et al., 2012; Carter et al., 2015; Long et al., 2015; Schmitt and Duke, 2015). Such an approach has been rarely applied worldwide, mainly due to land tenure issues, lack of interdisciplinary research and of incorporation of native populations' knowledge, weak law compliance, and ineffective governance structures (Aswani et al., 2012; Carter et al., 2015; de Almeida et al., 2016; Ferreira and Lacerda, 2016a).

Standardized, GIS-Based Information and Synthesis Work

Brazil holds the world's largest nearly uninterrupted mangrove belt, between the cities of Belém and São Luís: a 6,516-km² tract that, as a unitary system, corresponds to 4.3% of the total global mangrove area and over 80% of Brazilian mangroves (Spalding et al., 2010). The Bragança peninsula is the data-richest area in this mangrove belt, due to intensive research work developed through the MADAM Project and subsequent projects (Saint-Paul and Schneider, 2016). Geomorphological and hydrographic conditions (Souza Filho and Paradella, 2002) as well as vegetation patterns (Menezes et al., 2008), are likely similar throughout the northern mangrove region. Research gaps remain, however, as to whether data and assessment applied to the local level could be scaled up to support a regional approach to management.

Such a vast area of populated coast calls for a conservation strategy consonant with community-based management (Ferreira and Lacerda, 2016a), which could be capable of safeguarding the interests of local communities while taking into consideration the already existing protected areas and indigenous territories. In co-management arrangements, for example, priorities of the various local stakeholder groups are assessed throughout the planning and management processes. In the case of an extractive reserve in North Brazil, interests of local communities have been assessed and incorporated into formal management instruments using, at least, three different strategies: (1) by researchers (Glaser, 2003; Glaser and Da Silva Oliveira, 2004), generating valuable knowledge which later on was applied by decision makers (Abdala et al., 2012); (2) by planners and managers directly (Abdala et al., 2012); or (3) as an action-research approach, where scientists facilitated co-management processes, such as participatory coastal planning (Saint-Paul and Schneider, 2016).

Additionally, the monitoring of fisheries and aquaculture activities, which varies among the different mangroves on the Brazilian coast, could contribute to the assessment of ecosystem services in mangroves. Shrimp farming as the main activity in mangrove areas can be more easily monitored, while crab catching, for instance, is not detectable by GIS imagery analyses,

what makes the latter more challenging to monitor (Santos et al., 2014).

Moreover, Walters et al. (2008) emphasize how important the availability of these data to the general public is. Satellite imagery, although in a limited format, are available on the internet at no or little cost through virtual globe programs (even though some areas of the world's surface remain poorly covered by the most easily accessible tools). In the hands of the public, these new tools could significantly change the socio-economic dynamics associated with these forests (Walters et al., 2008). Stakeholders should therefore have further and broader access to accurate and cost-effective techniques for mapping and monitoring, in order to develop and implement effective policy for the socio-economic use of mangroves (Walters et al., 2008).

Magris and Barreto (2010) highlight the need to map and make available GIS-based databases to monitor environmental changes in mangroves and, therefore, allow for efficient conservation actions. National-level organizations in Brazil need to take more serious steps toward a GIS-based databank for coastal and marine ecosystems.

Researchers in Brazil have to report their results to the federal biodiversity conservation agency for a range of field work projects. Having such results as a starting point, this agency could synthesize data produced and evaluate what information is missing, which could then be used in conservation studies. Plus, systemic and interdisciplinary studies, which include not only ecological, but also social, political and economic aspects, can provide the solution to complex problems faced by Brazilian marine protected areas (Gerhardinger et al., 2011).

Putting together pieces of information that might point to generalizations is also vital to conservation research, yet this task seems to have been left to reports and plans developed by practitioners, or are limited to a few literature reviews or meta-analyses. Research gaps do not necessarily mean lack of primary data, but spatial planning methods and case studies in similar social-ecological contexts to guide on-the-ground application can be rare. A few initiatives worldwide constitute a step-forward on the road to experience exchange, such as the Panorama platform, as an assemblage of successful examples for protected areas¹. Regarding the ecosystem service approach, groups such as the Ecosystem Service Partnership (ESP)² and The Economics of Ecosystems and Biodiversity (TEEB)³ provide case studies, which focus on the terrestrial environment, such as in the Amazon region (Rodrigo Cassola, 2010). Projects that directly apply the ecosystem service approach to spatial planning in Brazilian coastal and marine environments are rare.⁴

Compared to fully terrestrial vegetation ecosystems, such as the Amazon rainforest, and fully marine ecosystems, like coral reefs, mangroves receive little attention from mass media (Valiela et al., 2001). But contrary to the image of mangroves as smelly swamps, charismatic species are often found in many nursing

and feeding grounds offered by mangroves {a list is compiled by UNEP (2014)}, which could be used to enhance support for the conservation of these ecosystems. Indeed, important species for mangrove ecology, such as the crab *Ucides cordatus*, face overfishing and decreasing population levels in some Brazilian mangroves. This can lead to overfishing of alternative stocks, for example, the red mangrove crab *Goniopsis cruentata*, which is also a key species (Ferreira et al., 2013). Consequences of these changes for mangrove functioning remain uncertain.

Furthermore, moving from policy toward action is important to improve the protection of mangroves and of the livelihoods that depend on these ecosystems (Friess et al., 2016). Ferreira and Lacerda (2016a) urge for restoration of deforested mangroves. An inexpensive and time-saving solution would be to map and protect mangrove areas with a potential for self-recovery (Ferreira et al., 2015). Beyond specific purposes, mapping is an important tool for systematic conservation planning and ecosystem-based management (Maia et al., 2006). The zoning of protected areas in Brazil, for example, is an essential part of their management plan (BRASIL, 2000), which again highlights the importance of spatial data for mangrove management.

More Than the Sum of Its Parts: The Mangrove as an Integrated Ecosystem

In 2012 the Brazilian National Congress passed the controversial Forest Code (BRASIL, 2012). While not being the main focus of most discussions about the new law, the changes on the legal framework for mangrove protection did not go unnoticed: an important sub-system, the “apicum” {escape valve for inland migration of mangroves as an adaptive response to sea level rise (Godoy and Lacerda, 2015)}, was removed from the concept of mangrove ecosystem, being now separately attended to by this new law in a less strict level of protection. These salt flats are non-vegetated areas, essential for the maintenance of the forested area in the mangrove systems (Schmidt et al., 2013) and are the ecosystem's last resource in terms of space to persist transitional periods and sea level rise (Oliveira-Filho et al., 2016). The most protective legislation only covers the wooded component (mangrove forests) (Oliveira-Filho et al., 2016). This measure makes a large area (over 600,000 hectares) available for aquaculture development (Ferreira and Lacerda, 2016b). Making salt flats available for occupation squeezes mangroves between open waters and human activity in these salt flats, hindering them from migrating inland following sea level rise. Without these buffer areas vulnerability to climate change will be increased, and mangrove forests will be doomed in the long run.

The current legislation for mangroves in Brazil therefore ignores the correlate features and interdependencies between these habitat types (Moura-Fé et al., 2015). Furthermore, the total mangrove extent safeguarded in permanent protection areas, which represent another important protection instrument in Brazilian legislation, will be reduced, showing how some governmental authorities and policies purposely ignore scientific warnings about necessity and even economic advantages of mangrove conservation to favor agribusiness lobbies (Ferreira and Lacerda, 2016b).

¹<http://panorama.solutions/en>

²<http://es-partnership.org/>

³<http://www.teebweb.org/>

⁴One example is the Babitonga Ativa Project, in southern Brazil (<http://www.babitongaativa.com/>).

While the new law has been contested by the Brazilian Academy of Sciences (Silva et al., 2011), there is no unanimity about the features that constitute mangroves in Brazil, and how these ecosystems should be managed for conservation and sustainable development. Oliveira-Filho et al. (2016), for example, adopt the definition of mangrove ecosystem as “a tidally influenced wetland complex including progradational sand or mud flats, mangrove forests and salt marshes, hypersaline lagoons, intertidal flats, including salt flats, salt pans, salinas, salt barrens, apicuns, tannes and coastal *sabkhas*.” The different elements would, therefore, represent alternate states of the mangrove ecosystem (Woodroffe et al., 2016). The legislators in Brazil opted, however, for a different view of this ecosystem, assigning, through the new Forest Code, different levels of protection to the different components, and, therefore, ignoring their interdependency and interconnectedness.

In terms of applicability and monitoring, this new Forest Code also faces the issue that salt flats are not separately identified and mapped in Brazil, which leaves space for arbitrary identification of these areas during the planning and management actions at medium and large scales, moving in the opposite direction of what is required to safeguard biodiversity and the services provided by these ecosystems. Adopting such a measure reveals a national environmental policy that is dissonant with the country’s intended goals to reduce carbon emissions, which were presented just before the last United Nations Framework Convention on Climate Change—COP 21 in Paris and the zero-illegal-deforestation target for the Brazilian terrestrial Amazon by 2030 (Paulo Moutinho, 2015).

This legal backstep against mangroves in Brazil reflects how complex and dynamic features of systems allow for the emergence not only of a variety of ecological functions, but also of a diversity of social-political perspectives on these systems. While researchers see them as an integrated ecosystem, formed by sub-systems with distinct but intertwined functions, some decision makers perceive the different vegetation types as a justification to assign different degrees of protection for areas within a highly interconnected system. Interconnectivity and interdependency, of course, do not automatically translate into uniform usage of the areas. However, such fragmentation through a national regulation might set the stage for local claims for controversial use, especially by the powerful aquaculture and salt production industries.

Worldwide, authority over mangrove forest management is overwhelmingly vested in state institutions and mangrove protection is a central objective. Within the forest sector, however, mangroves normally occupy a relatively marginal role with few policies or regulations tailored to the unique needs of mangrove forests (Rotich et al., 2016).

Mangrove ecosystems in Brazil could also profit from a unifying legal instrument, which brings together a body of regulations on mangrove use and conservation, while also recognizing the uniqueness, importance, and interconnectedness of mangroves and their sub-systems. The Amazon and Atlantic Forests, for example, have national laws as specific protection instruments (BRASIL, 1953, 2006), being also recognized as biomes by both the national authority

responsible for the federal protected areas and the Ministry of Environment. A possible solution to the mangrove legal tangle would be, therefore, a unifying, national-level legislative framework for the conservation and sustainable use of mangroves in Brazil. A framework alone, however, would not be able to tackle all the legal issues regarding mangrove conservation and, if not followed by enforcement, would eventually become a useless instrument, like many other environmental laws at municipal, state, and federal levels.

Multi-Scale Mangrove Planning

In mangroves around the world, frameworks and mechanisms to enable multi-sectoral coordination across agencies and governance levels are uncommon, and where they exist, they are difficult to put into practice (Rotich et al., 2016). At the federal government scale, it is important to recognize mangroves and its subsystems as one integrated ecosystem. Concurrently, legislation needs to take into consideration regional aspects and allow for flexible management strategies related to regional or local specificities. At the municipality or state level, for instance, part of the wrongs of the new Forest Code could be at least partially overcome.

Schaeffer-Novelli et al. (1990) identified eight mangrove segments along the Brazilian coastline, according to climatic and physiographic characteristics of the mapping units. A unique combination of mangrove structure, beach characteristics, tidal regime and species composition, among others, distinguishes each of those segments. Recent studies and management plans have approached mangroves according to macro-, meso- and microtidal regimes (Magris and Barreto, 2010; MMA, 2015); creating a simpler grouping that still considers major differences among the Brazilian mangrove types, while being possibly more applicable in terms of policy-making at a national level.

Following a simplified approach, but also considering regional peculiarities relevant for management, four major mangrove regions are here proposed: North, Northeast, East, and Southeast. Such a division is based on Knoppers et al. (1999) and Godoy and Lacerda (2015), as well as on the approaches mentioned in the previous paragraphs (Figure 1).

Macro-units are thus illustrated (Figure 1 and Table 1) to guide a unified, national-level policy framework for spatial planning of mangroves. Distinctions between the macro-units are manifold (Table 1). A steep coastline in the southeast and semiarid conditions in the northeast limit a possible landward refuge of forests facing sea level increase, hence restricting them to a narrow fringe along these coasts (Ferreira and Lacerda, 2016a). These traits, summed up with strong human-use pressures (Godoy and Lacerda, 2015), might hinder mangrove survival in the face of climate change. On the other hand, mangrove areas have the chance to expand in the northern part of the coastline, following predictions related to sea-level rise, because here mangroves find landward areas for expansion, such as in the Amazon estuary (Cohen and Lara, 2003; Cohen et al., 2008; Ward et al., 2016). Along the eastern and southeastern coasts, estuaries and coastlines have suffered severe damage

(Magris and Barreto, 2010; Prates et al., 2012). In southeastern mangroves, main drivers of degradation are coastal development, urbanization, and pollution, mostly from inadequate solid waste disposal and oil spills (Ferreira and Lacerda, 2016a). In the Northeast macro-unit, mangrove loss of up to 10% is large compared to the other segments, corresponding to at least twice the country's average deforested area (Ferreira and Lacerda, 2016a). Northern mangroves, despite being relatively pristine and proportionally better included in protected areas, need to be made more resilient as social-ecological systems, in order to face severe impacts that might reach these ecosystems, as it has happened in the other segments.

Differences in anthropogenic impacts on mangroves ecosystems and resulting impacts are also shown for the four macro-units proposed (Table 1). A large national coverage under the denomination of protected area alone does not systematically safeguard the various mangroves segments along the coast: the extent of mangroves inside the various categories of protected

areas in Brazil varies considerably among the different macro-units, showing that the distinct mangrove systems in Brazil are unevenly protected (Figure 1).

In terms of social-economic activities developed, there is a considerable difference among these mangrove macro-units. While saltwater aquaculture is being intensively practiced in eastern (Godoy and Lacerda, 2015) and northeastern Brazil (Santos et al., 2014), artisanal fisheries and crabbing as well as harvesting of other natural resources prevail in northern mangroves (Tenório et al., 2015). Northeastern mangroves suffer from severe habitat loss due to the advance of shrimp farming (Meireles et al., 2008) and other activities such as agriculture, urban expansion, and tourism (Guimarães et al., 2010). Salt pans were also a major economic activity in northeastern mangroves, and one single state in this region reached the production of approximately 95% of the country's national consumption (Bezerra and Brito, 2001). In the eastern mangrove coastline, local shell fishing activity is now being devastated by port

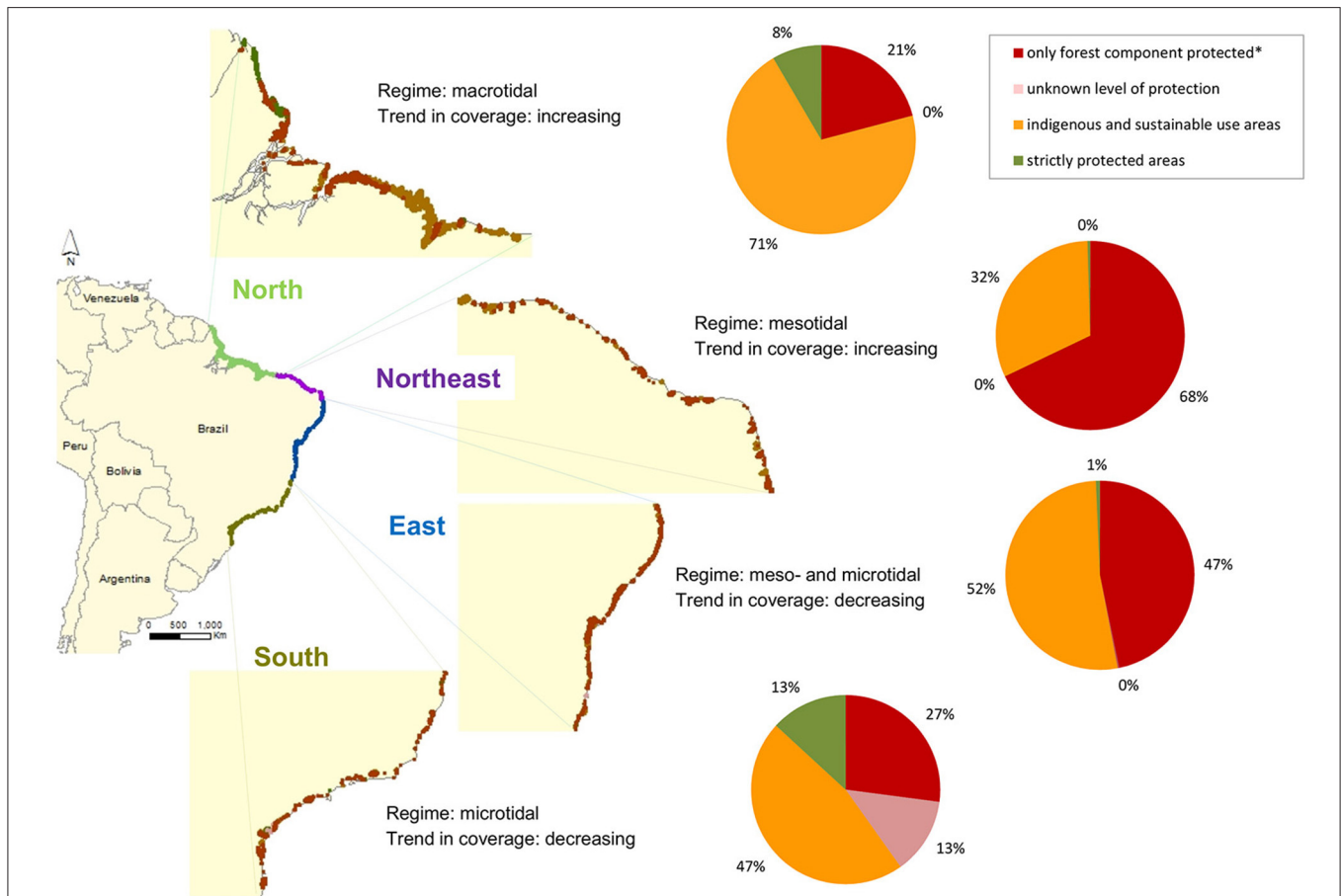


FIGURE 1 | Brazilian mangroves and formal protection level for each proposed macro-unit. Based on Knoppers et al. (1999), Godoy and Lacerda (2015). The mangrove distribution data derive from Giri et al. (2011), and the protected area data from (IUCN UNEP-WCMC., 2017). "Unknown protection" was assigned to categories whose level of protection was not declared in the UNEP-WCMC dataset. "*only forest component protected" refers to mangrove areas that are not inside a protected area or indigenous area, but are, like all forest components of mangroves in Brazil, protected under the Forest Code (BRASIL, 2012) as "permanent protection areas." Considering the states in Brazil, the division goes as follows: AP, PA, and MA (North); PI, CE, and RN (Northeast); PB, PE, AL, SE, and BA (East); ES, RJ, SP, PR, and SC (Southeast).

TABLE 1 | Distinct traits about each proposed mangrove macro-unit.

Macro-units	Main human uses	Drivers of change	Likely climate change effects	Protected areas ^a	Information needed for ecosystem-based management
North	Extractivism of crab, fish, wood, and other forest products (Glaser, 2003) Very incipient shrimp farming (Tenório et al., 2015)	Climate change (Godoy and Lacerda, 2015)	Erosion of river mouths and coastline (Godoy and Lacerda, 2015) and colonization of new areas due to salt water input from ocean rising (Cohen et al., 2008; Ward et al., 2016)	Large coverage: 66% of mangroves under sustainable use; 15% in strictly protected areas (Prates et al., 2012) Corridor of protected areas currently planned for part of the mangrove belt	Areas available for mangrove landward expansion Monitoring of extractivism: stock changes, spatial patterns of resource extraction
Northeast (semiand coast)	Traditional fisheries (Vasconcellos et al., 2011) Large-scale, expanding shrimp farming (Meireles et al., 2008; Ferreira et al., 2015)	Damming of rivers, climate change (Godoy and Lacerda, 2015), and aquaculture (Guimarães et al., 2010; Santos et al., 2014; Ferreira and Lacerda, 2016b)	Mangroves pushed to migrate landward (Godoy and Lacerda, 2015);	Relatively small coverage: ca. 66% of mangroves remain unprotected (Prates et al., 2012)	Areas available for mangrove landward expansion GIS-based information on site-specific climate change impacts, e.g., on mangrove area and beach erosion Monitoring of shrimp farming, including mangrove area taken up and use of contaminants
East (meridional coast)	Traditional fisheries (Santos et al., 2017) Shrimp farming (Guimarães et al., 2010; Santos et al., 2014)	Port activities (Ferreira and Lacerda, 2016a), urbanization, industrialization, tourism, and aquaculture (Sobrinho and Andrade, 2009)	Very site-specific along the coast (Godoy and Lacerda, 2015)	Large protected coverage in sustainable use areas and comparatively very small strictly protected area: only ca. 0.5% (Prates et al., 2012)	GIS-based information on site-specific climate change impacts, e.g., on mangrove area and beach erosion Monitoring of port activities and urbanization
Southeast	Urban expansion (Ferreira and Lacerda, 2016a)	Port activities (Cunha, 2006; Ferreira and Lacerda, 2016b), urbanization (Ferreira and Lacerda, 2016a), and climate change (Godoy and Lacerda, 2015)	Erosion and drowning (Godoy and Lacerda, 2015)	More than 20% strictly protected, but ca. 33% of mangroves inside <i>environmental protected areas</i> ^b (Prates et al., 2012)	GIS-based information on site-specific climate change impacts, e.g., on mangrove area and beach erosion

^aNumbers regarding protected areas in this table differ from those presented in **Figure 1** because a national report (Prates et al., 2012) is used here, which categorizes protected areas according to the Federal Law 9985 of 2000 (BRASIL, 2000), while the UNEP-WCMC data used in **Figure 1** include other categories, such as "indigenous areas," and "world heritage sites."

^bSee Introduction section for further information on this category of protected area in Brazil.

pollution in Pernambuco (Zoe Sullivan, 2014). Due to the variety of habitats and anthropogenic pressures, changes in coverage and distribution of mangroves in this macro-unit should be more carefully assessed at the local level (Godoy and Lacerda, 2015).

Local peculiarities are also important while determining which benefits derive from mangroves in each region. Lee et al. (2014), for example, point out that effective coastal protection provided by mangroves depends on factors at landscape/geomorphic to community scales and local/species scales. It is therefore important to approach and include knowledge on local settings for mangrove management (Lee et al., 2014). Similarly, in the case of climate adaptation for protected areas, the process should be area-specific and consider ecological and social-economic conditions within and beyond the protected areas' boundaries (Rannow et al., 2014). Management strategies for mangrove conservation in Brazil, including designation and management of protected areas, and other protection instruments should therefore consider regional social-ecological peculiarities.

Assessment of the Protected Area System

In Brazil, protected areas have been shown to play a role in maintaining mangrove forest structure (Cavalcanti et al., 2009). In Indonesia, Miteva et al. (2015) concluded that protected areas reduced mangrove loss by about 14,000 hectares and avoided blue carbon emissions of approximately 13 million metric tons (CO₂-equivalent). These results were significant only for a stricter category of protected area, which does not allow for resource extraction. This highlights the importance of knowing not only *if* mangroves are under some sort of legal protection, but also *how*, i.e., what the specific regulations for protection are—not to mention whether these mechanisms are actually applied on the ground, or are just “paper rules.”

Mangroves clearly have a high value for conservation and are largely threatened ecosystems. Despite this, conservation planning for ecosystem services provided by mangroves, as well as its tradeoffs with biodiversity, remains an incipient research field. The challenges of integrating methods that are currently applied to land and marine environments into the management of transitional and highly dynamic regions such as mangroves are minimally approached by the literature. Furthermore, it remains unknown to which extent decision makers apply modeling and decision-support tools, such as InVEST and Marxan (for more information on these tools, see Ball et al., 2009; Guerry et al., 2012, respectively).

A gap analysis to evaluate how well marine protected areas in Brazil meet conservation objectives for representation, connectivity, and risk-spreading revealed that objectives were far from fully attained (Magris et al., 2013). The protection of the marine environment was considered poor, with less than 1.9% of Brazil's marine jurisdiction within protected areas, from which only 0.14% within no-take areas. Only 23% of the ecosystems met the minimal number of replicates required by the risk-spreading objective. More positively, just over half (51%) of the no-take areas are a desirable distance apart. A systematic expansion is therefore needed to move toward an ecologically representative

and functioning system of marine protected areas in Brazil. (Magris et al., 2013).

Brazil has a 10%-target for the protection of its marine territory, which should be implemented based on a central management strategy that takes into consideration the distinct regions and local specificities. However, while the need for more protected areas is comprehensible, some questions should be considered: Are there other categories of protected areas, currently not included in the Brazilian national reserves system, which represent possible good solutions for Brazilian conflicts in the conservation of mangroves? Why is it that so many protected areas do not have a management plan yet?

Instead of addressing existing issues in the network system, the designation of more marine protected areas, in the way it is currently taking place in Brazil, could actually decrease implementation capacity and effectiveness, not achieving much beyond the fulfillment of the country's internationally established marine biodiversity targets (Gerhardinger et al., 2011). Plus, a national effectiveness monitoring scheme still lacks for marine protected areas, even though Brazil has a large number of scientists and other professional capable of performing or assisting with such a task.

The previously mentioned data banks and the national-level macro-units proposed in this paper could be used to support the development of a national spatial plan that takes into consideration existing coastal marine protected areas, while also indicating conservation priorities outside these reserves, allowing for their expansion, the creation of corridors and of new areas.

Even if salt lands were to be considered an alternative for the allocation of economic activities inside mangrove areas, some questions would have to be addressed before allowing for this type of use: How to assign activities to the different habitats inside mangroves without negatively impacting the maintenance of interconnected systems? For example, if mangroves are valued, under an ecosystem service approach, for carbon storage, and the aquaculture performed in these areas is of high economic importance, how to balance these uses, without implying that salt flats are capable of absorbing *any* damaging activities as a trade-off to preserve the more highly appreciated mangrove forests?

CONCLUSIONS

Using systematic planning and ecosystem-based management as guiding strategies, we discussed the following approaches: (1) mangrove as a social-ecological system; (2) mangrove as an integrated system; (3) multi-scale planning; (4) standardized, GIS-based information and synthesis work; and (5) assessment of the protected area system. This is, to our knowledge, the first review that shows why and how these approaches can be used to tackle the apparent paradox of reconciling mangrove conservation and sustainable use.

Complexity and extremely high economic pressure on areas such as mangroves pose a proportionally large challenge to the conservation of these ecosystems. Thorough assessment and political recognition of their social-ecological importance

can greatly contribute to a larger effort in working toward its conservation.

While environmental impacts associated with global climate change are generally expected to occur sometime in the future, many mangrove areas along the Brazilian coastline are already witnessing these impacts, and possible, future impacts have already been shown (Godoy and Lacerda, 2015). However, this is not taken into consideration in conservation strategies and legislation in Brazil, as can be easily concluded from the new Forest Code and the exclusion of salt flats from mangrove protection areas - this urgently calls for a revision of this legal instrument.

At the national level, policy-making lacks comprehensive understanding of how the various types of mangrove ecosystems along the coast function, in what social-ecological aspects they differ, and how those differences might be taken into account while planning for conservation. To support systematic conservation analyses and policy-making, mangrove ecosystems along the Brazilian coast could be grouped into planning macro-units, according to social-ecological features, geological traits and expected effects of climate change (Figure 1 and Table 1). While accounting for local peculiarities, it is important to also try and draw parallels to other mangrove ecosystems and try to learn from experiences from these ecosystems (successful restoration initiatives, co-management approaches, etc.).

Despite the widespread, mandatory reporting back of research, mangrove policy making lacks synthesized data to underpin management and conservation planning. Also, based on the deficiencies registered in the literature and the lessons learned from nearly 20 years of successes and challenges of the law that created the current national system of protected areas (BRASIL, 2000), the set of protected areas requires not only expansion but also re-structuring. Across the different countries where mangroves occur, there is a lack of evidence for the success of responses (as well as analysis of the interactions and feedbacks between different responses) in terms of their effects on declining ecological states of these ecosystems and on the services they provide.

While the need remains for more robust, unified legislation for mangrove conservation, the Brazilian experience shows that legal instruments are not enough for the effective protection of these ecosystems. Due to lack of proper evaluation of mangrove functioning, as in the case of the new Forest Code mentioned

above, anthropogenic drivers have the potential to increase threats and reduce the effectiveness of conservation legislation and possible following actions. Permanent periodical assessment of mangrove conservation status and sustainable use, long-term monitoring of rehabilitation experiments, community-based management and continuous adaptation of legislation are required to curb drivers of change and their negative impacts on mangroves.

Developing and applying methods for an ecosystem-based management that deals with and helps overcome the complexity and pressure faced by mangroves is by definition an intricate and challenging task. Needless to emphasize, though, is the urgency to address these research gaps, in hopes that filling them up will contribute to the protection of one of our most valuable and most threatened ecosystems.

AUTHOR CONTRIBUTIONS

RB designed the work, compiled literature sources, drafted, and wrote the manuscript. AF and LL helped compile literature sources, wrote parts of the manuscript, checked references, and critically revised the content of the paper. RB, AF, and LL approved the final version of the manuscript to be submitted.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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