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A methodology for assessing the vulnerability of mangroves and fisherfolk to climate change

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Abstract. Mangroves are putatively vulnerable to climate change, especially sea level rise, depending on factors such as coastal topography and the presence of barriers to landward migration. Usage patterns of mangrove resources can also affect their ability to respond to change. Brazilian artisanal fisherfolk are highly dependent on mangrove resources and services, which makes them also vulnerable to climate change. These populations have to cope with high levels of uncertainty related to the availability of natural resources, and to social and political contexts, such as biodiversity conservation policies. Besides being protected by many different laws, mangroves are also included in no-take protected areas. This may contribute to their resilience as natural systems, but can enhance the vulnerability of human populations. We propose herein a research methodology for assessing the vulnerability to climate change of the social-ecological system mangroves - fisherfolk, by analyzing exposure to sea-level rise, sensitivity and adaptive capacity, and the impacts of conservation policies on these elements, particularly the effects of coastal protected areas in southern Brazil. An integrated social-ecological diagnosis may lead to more flexible policies, elaborated with stakeholders' participation, more adequate to local realities and more inclusive of strategies for mitigation and adaptation to climate change.

Keywords: adaptive capacity, sea-level rise, Brazil, protected areas, social-ecological systems

Resumo. Metodologia para análise da vulnerabilidade de pescadores e manguezais às mudanças climáticas. Os manguezais são vulneráveis às mudanças climáticas, especialmente à elevação do nível do mar. Sua capacidade de resposta depende da topografia costeira, da presença de barreiras à migração e de padrões de uso dos recursos naturais. Pescadores artesanais no Brasil são dependentes de recursos e serviços ambientais dos manguezais, sendo também vulneráveis às mudanças climáticas. Eles lidam com incertezas relacionadas à disponibilidade destes recursos, e a contextos sociais e políticos. Mesmo protegidos por diversas normas, os manguezais também são incluídos em unidades de conservação de proteção integral. Isso pode contribuir para sua resiliência, mas pode, por outro lado, aumentar a vulnerabilidade das populações humanas. Propomos nesse trabalho uma metodologia para avaliar a vulnerabilidade de manguezais e populações costeiras às mudanças climáticas, usando como estudo de caso uma área no litoral sul do Brasil. A metodologia baseia-se na análise da exposição à elevação do nível do mar, da sensibilidade e da capacidade adaptativa, e dos impactos das atuais políticas de conservação, especialmente as unidades de conservação, sobre esses elementos. Um diagnóstico sócioecológico integrado pode contribuir para políticas mais flexíveis, elaboradas com a participação de todos os interessados, mais adequadas às realidades locais e que incluam estratégias de adaptação às mudanças climáticas.

Palavras-chave: capacidade adaptativa, elevação do nível do mar, Brasil, áreas protegidas, sistemas socioecológicos

Introduction

Vulnerability of coastal populations and ecosystems is a multi-concept which includes *hazard exposure, sensitivity* (the magnitude of losses that potentially result from exposure to the hazard) and *adaptive capacity*, or the capacity to respond to impacts and prepare ahead of them, through coping strategies and long-term adaptation to a certain threat (Kelly & Adger 2000, Brooks 2003, Turner *et al.* 2003, Füssel 2007).

In projected climate change scenarios, the main threats to coastal populations and ecosystems are sea-level rise, the intensification of extreme weather events and ecosystem changes (Nicholls *et al.* 1999, Nicholls *et al.* 2007, Gilman *et al.* 2008). Other expected impacts are a rise of up to 3 ºC on sea surface temperature, changes in precipitation and fresh water input, salt water intrusion into soils and coastal aquifers, and ocean acidification (Sterr *et al.* 2000, Adger *et al.* 2005, Nicholls *et al.* 2007). These climate alterations will have varied effects on coastal ecosystems and human populations, with a likely increase on flooding and loss of wetlands (Nicholls 2004), flooding of populated areas and infrastructure, resulting in severe economic impacts (Zhang *et al.* 2004, Wu *et al.* 2008), and changes in the availability of natural resources, with consequences for the livelihoods of those that rely directly on them for survival, such as traditional or neo-traditional coastal populations, including fisherfolk (Badjeck *et al.* 2010).

Exposure to these threats is directly linked to the position of human settlements and ecosystems on which they depend in relation to the sea and to regions prone to the occurrence of sea-level rise and extreme weather events (Smit & Wandel 2006). Sensitivity, often treated as equivalent to exposure, depends on the number of people, the infrastructure and the extension of ecosystems exposed to the hazard, and on the level of dependency on natural resources of the considered population (Tuler *et al.* 2008). Adaptive capacity depends, in the case of human populations, on a series of factors linked to access to assets. In the case of ecosystems, adaptive capacity can be treated as analogous to ecological resilience, which is the capacity of a system to recover after a disturbance while maintaining its functionalities (Walker *et al.* 2004). It will be affected, among other factors, by the degree of ecosystem degradation and the exploration levels of its natural resources. In any case, adaptive capacity is a result of the system's ability to self-organize, learn and adapt (Walker *et al.* 2004, Adger 2006).

In this article we aim to present a methodology for assessing the vulnerability to climate change of both mangroves and fisherfolk, jointly conceived as a Social-Ecological System - SES (Folke *et al.* 2002, Folke *et al.* 2003).We do this by first presenting a general review of the main elements that determine the vulnerability of these ecological and social systems to the major expected effects of climate change on coastal areas. We then present a case study of the coastal region of the State of Paraná, southern Brazil, where artisanal fishing villages coexist with extensive mangrove forests. This scenario is rendered more complex by the existence of several protected areas on the region. We suggest that the strict preservation of these areas, mainly for biodiversity conservation, can have both negative and positive effects on the vulnerability of mangroves and artisanal fisherfolk to climate change. Furthermore, these varying effects can work in opposite directions, for example, enhancing the vulnerability of fishing villages, by diminishing their options for livelihood diversification, while lowering the vulnerability of mangroves, by protecting adjacent land and allowing them to adapt to sea-level rise.

Based on this case study we propose a methodology to assess the joint vulnerability to climate change of mangroves and fisherfolk, which we believe can be used in other settings and is based on the so-called vulnerability or contextual approach (Ford *et al.* 2010). In this perspective, which considers vulnerability of social-ecological systems as a starting point, studies must focus on defining the current processes related to the social construction of vulnerability. That is, how different social, economic and political characteristics, processes and trends determine, in the present, distinct levels of vulnerability. The goal is to develop policies that are able to improve future perspectives considering social and environmental changes (Kelly & Adger 2000, Van Aalst *et al.* 2008). This approach becomes more relevant if we consider that, in general, lack of adaptive capacity is the main factor contributing to increase the vulnerability of human societies, although physical exposure to hazards is also an important component of vulnerability of social and natural systems (Nicholls *et al.* 2007).

On a second level of analysis we propose specific indicators to analyze the impact of the protected areas on the elements that compose vulnerability. Most protected areas in the world were established based on availability of space or political viability, without considering climate, or based on a static view of climate issues. Even though climate change will probably affect the distribution of species, so that many of them may move out of protected areas, these will continue to be an important tool for biodiversity conservation. However, in this new context, it becomes more urgent to integrate conservation policies with other general strategies for management of landscapes and natural resources. And it also becomes essential that the selection of areas to be protected and the management of them and of the landscapes in which they are inserted are done with climate change as an explicit parameter (Hannah *et al.* 2002, Hannah *et al.* 2007).

Conservation actions should not be limited to protecting large tracts of ecosystems, but should also consider dynamics of change and adaptation of social-ecological systems and the building of adaptive capacity in human communities, including actions aimed at diversifying income sources so that these populations become less dependent on natural resources and are better able to cope with and adapt to the expected and unexpected impacts of climate change (McClanahan *et al.* 2008). For this to be achieved, there is a need to identify which elements of climate change will bring the most important effects on each ecosystem and human population, and what will these effects be (Sterr *et al.* 2000, Hulme 2005). Thus, it is of great importance to understand how social and natural systems currently respond to climate-related disturbances, in order to provide a basis for the development of these new adaptive strategies capable of achieving biodiversity conservation, both inside and outside of protected areas, together with the social and economic sustainability of human populations.

Mangroves and their vulnerability to climate change

Among coastal ecosystems, mangroves are of great ecological, economic and social importance. Occupying most of the protected and semi-protected coasts in tropical and subtropical regions, they stabilize coastlines, prevent erosion and function as a barrier to storms. They provide refuge, feeding and reproduction sites for a great variety of animals, including commercially important species, and ultimately help to sustain and restore fishing stocks. Mangroves are also a source of organic matter for other coastal ecosystems; they provide adequate sites for aquaculture; their sediments are sinks for pollutants and terrigenous sediments; and they have aesthetic and spiritual value for many human groups. Besides these functions, many mangrove products are directly explored by coastal populations, especially wood, used as fuel and building material, but also tannins and other plant extracts (Lacerda 2002, Agrawala *et al.* 2003, Walters *et al.* 2008, Valiela *et al.* 2009).

Mangroves are amongst the most threatened coastal ecosystems. In the Americas, an estimated 38% of mangrove areas have already been lost, at an annual rate of 3.62% (Valiela *et al.* 2009). However, South America had the lowest rate of mangrove loss among all world regions, only 0.18%, or 4,000 hectares, in the 2000 - 2005 period (FAO 2007). Threats to mangroves have two main origins: on the one hand human occupation and unsustainable patterns of resource usage threaten their existence and limit available space for migration, besides affecting factors such as sediment supply, the volume of groundwater and the discharge of nutrients and pollutants. On the other hand, the effects of global climate change, especially sea-level rise, pressure the frontward margin of mangroves, causing erosion, tree mortality and loss of forest area. As active contributors to the degradation of mangroves, coastal populations may end up eliminating the very ecosystem that provides them resources and protection against the impacts of climate change (Taylor & Sanderson 2002).

The ability of mangroves to respond to sea-level rise depends on many factors, including coastal topography and the presence of barriers to landward migration. This response depends on their ability to accumulate sediments and promote accretion, a process which is regulated by a series of geomorphological, climatic and hydrological controls over sediment supply, primary production, decomposition, subsidence and autocompaction, all of which are extremely variable from one site to another (Cahoon & Hensel 2006). Vulnerability also depends on their ability to migrate, following sea-level variations. Though significant increases in total mangrove area have been recently reported for the northeastern Brazilian coast (Maia *et al.* 2006, Lacerda *et al.* 2007, Lacerda 2009), migration and colonization of new areas may be limited by human occupation of adjacent areas, which restricts this ecosystem's capacity to adapt to new conditions (Scavia *et al.* 2002). Mangroves are unable to follow sea-level rise when the surface elevation rate is lower than the relative sea-level elevation rate. This has been observed in some recent studies (Gilman *et al.* 2008), although some other studies have shown the opposite (Alongi 2008), indicating there is a need for more long-term observations in a larger number of sites.

Mangroves will probably suffer a combination of positive (rise in atmospheric temperature and CO_2 concentration) and negative (rise in saline intrusion and erosion) effects of climate change, and the balance between the two will largely depend on site-specific factors (Saenger 2002). Because of the multiplicity of expected responses of mangroves to these changes, a more realistic approach would be to categorize and delimitate forests according to their level of vulnerability.

Less vulnerable mangroves would be those located in areas with high tidal range (> 5 meters), in humid tropical coasts and/or in areas close to the mouths of large rivers or on their margins, in remote areas with little human occupation, in areas with large nutrient supply, those growing on deep soils, with available space for landward migration and in regions with large extensions of well developed mangrove stands, which are a source for propagules and seeds. These conditions are found, for example, on the northern coast of Brazil. Highly vulnerable mangroves would be those situated on small islands, growing on calcareous soils, in regions without large rivers, in arid regions, in places subject to ground subsidence, in areas with low tidal range and with no sediment supply, and mangroves whose expansion is blocked by human occupation or a steep slope (McLeod & Salm 2006, Alongi 2008, Lovelock & Ellison 2007). Therefore, the main variables that should be considered for the analyses of mangrove responses to relative sea-level rise are: topography, sediment sources, rate of sediment supply, area of the drainage basin, tidal range, coastal dynamics and the mean rate of sea-level rise (Soares 2009).

Even though the predicted impacts of climate change on mangroves will vary between different ecosystems and regions, it is important to consider that they will combine with, and even intensify, other stress factors, potentially aggravating overall conditions. Thus, the survival of these ecosystems in a climate change scenario depends on their adaptive capacity, but also on the intensity with which human activities are undermining this capacity (Scavia *et al.* 2002). For example, in comparison with prior sea-level rise events in Earth´s history, nowadays most coastal regions are affected by human activities, including cities and infrastructure, which limit the possibility of mangroves migrating towards the continent in response to climate change. In addition, if we consider the large number of people living close to mangroves and depending directly on them for survival, and at the same time functioning as a source of impact and contributing to lower their resilience, it becomes of surmount importance to analyze these systems together, hence our SES approach. The development of management policies and strategies for land occupation and resource use in coastal environments must consider these multiple elements, or otherwise, there is a risk that both mangroves and human populations will lose (Walters *et al.* 2008).

Fisherfolk and their vulnerability to climate change

Among coastal populations, those that depend on the direct use of natural resources, such as fisherfolk, are especially vulnerable to climate change. Worldwide, an estimated 120 million people depend directly on fishing for their survival, 95% of which live in developing countries, where the great majority is engaged in artisanal fisheries (Allison & Ellis 2001). Artisanal fisherfolk in tropical and subtropical regions are usually highly dependent, directly or indirectly, on resources and services provided by mangroves, which makes them jointly vulnerable to climate change, since those that depend on marine resources as a source of food are highly vulnerable to its impacts, both in terms of health and food security, and in economic terms (Nicholls *et al.* 2007).

It is important to discriminate the different dimensions that compose the vulnerability of fisheries systems. This vulnerability is dynamic over time due to changes in the characteristics of threats, the exposure to them, the sensitivity of the system and the adaptation actions. A "fisherfolk-mangroves" SES may be exposed to different kinds of threats (environmental, economic and political), may have distinct sensitivities to these threats and may also be more or less resilient (Tuler *et al.* 2008).

Small-scale fisheries face a permanent state of uncertainty, due to the natural variability of fish stocks and because these stocks are declining as a result of overfishing, bad management practices, and other factors (Jackson *et al.* 2001, Mullon *et al.* 2005, Pauly *et al.* 2005). For these populations, which usually have lower adaptive capacity, social and biophysical resilience are closely connected and climate change can increase the uncertainties regarding the availability of natural resources (Dolan & Walker 2004), and, as a consequence, threaten their biological survival and social reproduction. Climate change will bring direct impacts on marine biodiversity, such as changes in reproduction and migration periods of several species, an increase in diseases, changes in latitudinal and longitudinal distribution patterns, changes in population size and community composition and changes in the hydrological cycle, with effects on biodiversity and environmental services (Gitay *et al.* 2002). Much of this is already evident in different ecosystems and biomes all over the planet (e.g. Walther *et al.* 2002, Parmesan & Yohe 2003, Parmesan 2006). These changes can alter seasonal and distributional patterns of fish species that are explored by artisanal fisheries, potentially impacting local livelihoods. Faced with the restrictions imposed on them by the natural environment, these fisherfolk are forced to adapt to the seasonal distribution and the ecology of fish, both strongly influenced by climate (Iwasaki *et al.* 2009).

Climate change will also bring greater variability and uncertainty regarding weather conditions, which impact directly on artisanal fisherfolk, whose fishing gear limit their mobility and ability to operate in adverse conditions. In face of these changes in the environment, traditional knowledge accumulated by these populations, which used to guide them during their fishing activities in an efficient and safe way, may become useless (Ford & Smit 2004).

Uncertainties also derive from political, economic and social contexts. Market variations and changes and inadequacies of the rules that regulate fishing activities are sources of variability and stress that constantly threaten the livelihoods of fisherfolk (Marschke & Berkes 2006). Other factors such as the lack of external institutional support and erosion of traditional resource use systems can lead to a rise in the vulnerability of these livelihoods (Kalikoski *et al.* 2010). In addition to fisheries management rules, small-scale fishermen are also subject to the effects of other types of rules, such as those concerned with biodiversity conservation. For the sake of biodiversity, many restrictions are imposed on the access to and usage of coastal environments and resources. These actions may function as factors that increase the vulnerability of the system by making it more sensitive or by limiting its capacity to respond.

These factors (environmental laws, environmental degradation, increase in variability and uncertainty related to climate and fish stocks) may result in a reduction of the adaptive capacity of coastal populations, potentially aggravating the effects of climate change. As an example, fishing villages that depend on a small number of species, and that have few options for diversifying their income sources, tend to be very vulnerable to changes in fish stocks. On the other hand, the consequences of climate change can make the implementation of biodiversity conservation policies ever more difficult, if they fail to take into account this new scenario, and if they fail to include in their elaboration and implementtation processes those that are directly affected by them.

A case study: the coast of Paraná State, southern Brazil

With environmental problems and land occupation patterns partially similar to other developing countries, the coast of Brazil is also exposed to extreme climatic events, such as storm surges and flooding, with risks for natural systems, infrastructure and human settlements. The rise of mean sea-level in Brazil, which is already occurring in most measuring sites, although still small, tends to add to the effects of these other phenomena, bringing such consequences as an acceleration of coastal erosion, a magnification of flooding events, the rise of water tables and increased salinization of rivers, estuaries and aquifers (Szlafsztein 2005).

Most human occupation on the Brazilian coast derives from urbanization and the expansion of activities such as tourism, ports, commerce and industry, which are concentrated on the roughly 55% of the coast which are more densely populated (Neves & Muehe 2008). In these areas, the impacts of extreme events and climate change tend to be economically and socially important, as they affect great concentrations of infrastructure and human populations. On the remaining parts of the coast, there is a predominance of SES in which human populations, such as artisanal fisherfolk, depend directly on the exploration of natural resources, with many of them still using traditional practices.

A fundamental interface between the social and the ecological components of a fisheries system is the relation between fishing populations and the coastal environments from which they extract the resources that sustain their livelihood. In Brazil, mangroves play an important role on supporting both coastal ecosystems and human populations. Mangroves occur along most of the Brazilian coast, from the extreme north (Cabo Orange, Amapá, 04º30’ N) to the city of Laguna, in the southern state of Santa Catarina (28º56’ S), covering most intertidal areas (Schaeffer-Novelli *et al.* 1990). Coastal populations in Brazil who rely on the direct exploration of marine resources are highly dependent on mangrove ecosystems. As an example, in the northern state of Pará, at the estuary of the Caeté River, in the city of Bragança, over 80% of the population base their livelihoods on mangroves, and around 68% obtain income directly from mangrove products (Glaser 2003).

In spite of their importance for human populations, there are few studies dealing with the vulnerability to climate change of coastal ecosystems in Brazil. Even less common are studies that analyze both biophysical and socioeconomic aspects in an integrated manner. Some studies focused on observing changes in the distribution of mangroves as a response to relative sea-level rise (Almeida *et al.* 2008). Gathering results from this and other studies, Soares (2009) has proposed a conceptual model for the study of the response of mangroves to climate change, but it focuses, fundamentally, on biophysical aspects.

In the extensive mangrove forests of the northern coast of Brazil, many long-term studies have been developed, especially as part of the MADAM project (Berger *et al.* 1999). Some of these focused on biophysical dynamics, such as the temporal analysis of mangrove distribution by Cohen & Lara (2003), who concluded that mangrove stands are losing area in the seaward margin and migrating landward, possibly as a response to relative sea level rise, but that this migration is limited by local topography. Other studies analyzed the dependency of local populations on mangrove resources (Glaser 2003), while there were also studies that related the response of mangroves to sea-level rise to socioeconomic matters such as land use and occupation (Lara *et al.* 2002). In other regions of the Brazilian coast, studies have measured extension, retraction and migration of mangrove forests, but without relating them directly to climate change (*e.g.* Lacerda *et al.* 2007).

The coast of the Brazilian southern state of Paraná is dominated by the Paranaguá Estuarine Complex (PEC), whose physical, chemical and biological properties were described by Lana *et al.* (2001). It has extensive intertidal flats, which totalize around 295 km^2, mostly covered by mangroves (Fig. 1). The whole region is part of a Biosphere Reserve and of the Atlantic Rainforest Biome. Around 70% of the region's surface area is still covered by this type of forest and associated ecosystems, in stark contrast with most of the Brazilian coast, where this ecosystem has been largely destroyed (SOS Mata Atlântica/INPE 2009).

The study case site (Fig. 1) is centered around the northern part of the PEC, in the municipality of Guaraqueçaba, where there are two coastal protected areas (PAs), managed by the Brazilian Federal Government: Guaraqueçaba Ecological Station (created in 1982, it encompasses

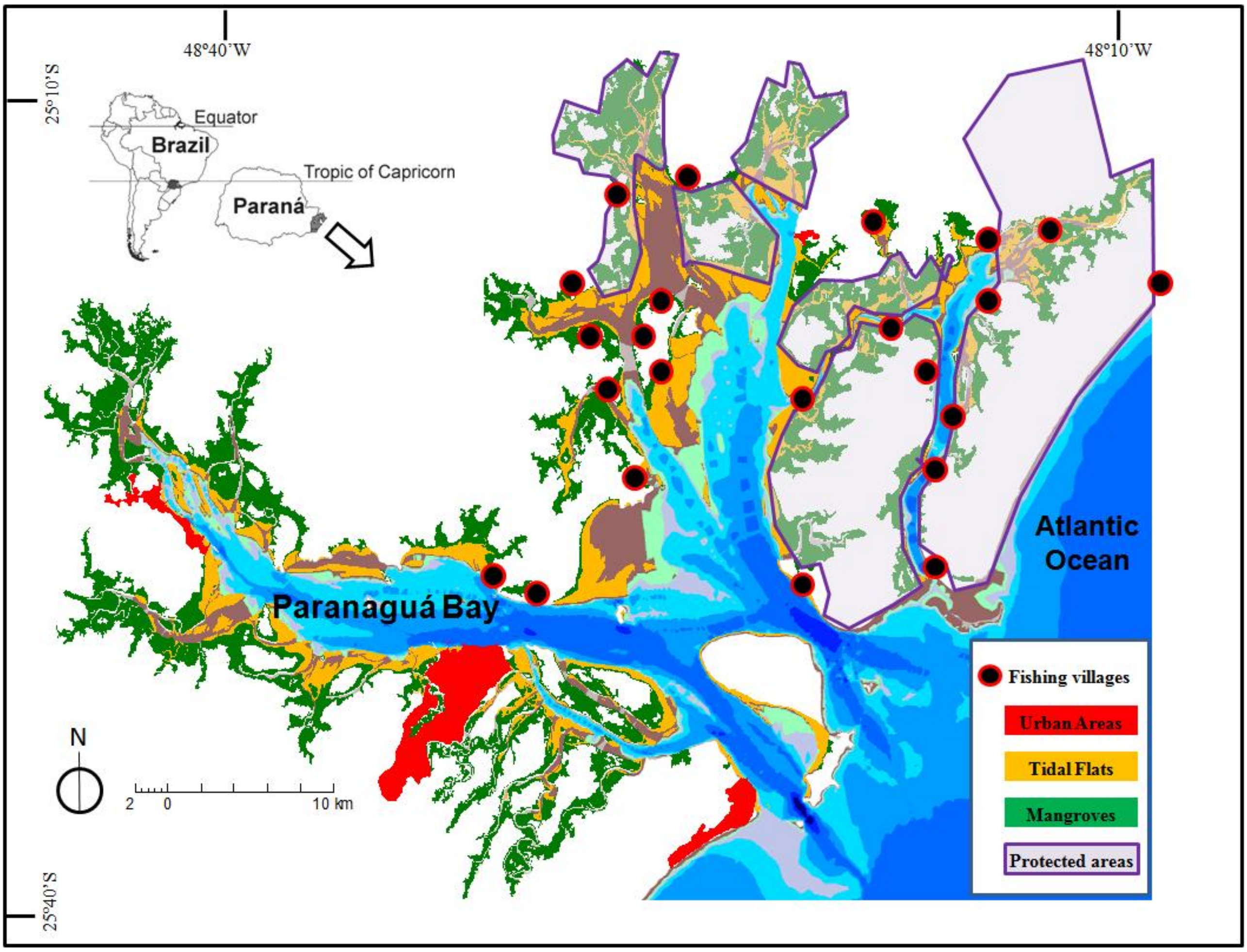

Figure 1. The Paranaguá Estuarine Complex, its extensive mangroves, numerous fishing villages and the no-take protected areas that dominate the northern part of the estuary. Source: Adapted from an original map designed by Prof. Mauricio A. Noernberg, CEM/UFPR.

around 11,500 hectares of mangroves around the Bays of Laranjeiras and Pinheiros) and Superagüi National Park (created in 1989, it protects around 34,000 hectares in the islands of Superagüi and Peças, which include a variety of coastal ecosystems).

Guaraqueçaba is a sparsely occupied area with a population of 7,890 inhabitants distributed over 2,315 km^2. It is one of the poorest municipalities in the state of Paraná, with a Human Development Index of 0.659 (IPARDES 2010). Fishing is the main activity in around 40 villages located on the margins of the estuary where there are an estimated 2,100 families of artisanal fisherfolk, most of them living close to mangroves and the aforementioned PAs (Martin & Zanoni 1994, IPARDES 2010). Although of little regional economic importance, fishing is locally of high social and economic importance (Borges *et al.* 2006).

Artisanal fisheries in this area have been changing over time due mainly to factors such as market changes, demographic dynamics (immigration) and technical innovation, which led part of the local fisheries to more intensified and market-oriented practices, while some of the other practices have disappeared (Andriguetto-Filho 2003, Andriguetto-Filho *et al.* 2009).

Environmental problems in the coasts of Brazil and Paraná affect fisherfolk in diverse ways, causing a series of conflicts, such as the displacement of these populations to inappropriate areas, disputes over fishing grounds among artisanal and industrial fisheries and aquaculture, contamination and depletion of fishing stocks, among others. Cleavages are also observed among artisanal fisherfolk, between those that are traditionally linked to fishing and the opportunists, and between those that use predatory techniques and those that avoid them (Andriguetto-Filho 1999). These problems threaten the survival and socioeconomic reproduction of these populations.

Besides environmental degradation and the disputes with industrial fisheries, there are evidences of conflicts between environmental regulations and the economic activities of local populations, especially those engaged in small-scale fishing and agriculture. Many studies point to environmental conflicts associated with the creation of PAs in the coast of Paraná, especially in the municipality of Guaraqueçaba (Andriguetto-Filho 1993, Martin & Zanoni 1994, Zanoni & Miguel 1995, Pedroso Jr. 2002, Cunha *et al.* 2004, Miranda 2004, Teixeira 2004).

Brazilian mangroves are also included in no-take PAs, besides being protected by many different laws (Martin & Lana 1994). This may contribute to the resilience of natural systems, but can also affect the vulnerability of human populations. Large tracts of Atlantic Rainforest and mangroves in Paraná compose an area of high priority for biodiversity conservation, being classified as of extremely high biological importance by the Brazilian Ministry of Environment (MMA 2007). A great variety of ecosystems and species of interest for conservation is reflected in the existence of many PAs in this region. These areas have been created here since the 1980s and include no-take reserves as well as “sustainable use” ones. They cover a large portion of the region: around 76% of the northern coast of Paraná is included inside PAs, of which 13% (59,440 hectares) in no-take reserves such as National Parks and Ecological Stations. There are also specific rules to protect the Atlantic Rainforest, which also limit the possibilities for occupation of the land and usage of natural resources. This stands in stark contrast with the process of rapid destruction of natural ecosystems that characterized the first centuries of human occupation of the Brazilian coast (SOS Mata Atlântica/INPE 2009).

In no-take PAs, and especially on those that include mangroves, there is a prevalence of strict conservation rules, which aim at completely banning the direct use of natural resources. Mangroves were the first ecosystem in the region to be included in a no-take PA (the above mentioned Guaraqueçaba Ecological Station is composed mainly of mangroves). For this ecosystem, strict no-take rules applied equally to all mangroves represent a simplistic view of the ecosystems structural and functional characteristics, because they are based on the misconception that all mangrove stands are equally productive, that resources are equally distributed and even that human groups access and explore all areas in the same way and with the same intensity. This last assumption also ignores territoriality relations between human groups and even the community conservation mechanisms that may be in use by them. All of this makes these rules not only inadequate but also inefficient, and even unfair, paradoxically resulting in open-access situations and in the environmental degradation of these ecosystems. Extensive discussions on the novel conflicts created by environmental legislation, mainly in the northern sector of the Paranaguá Estuarine Complex, were provided by Martin & Zanoni (1994), Lana (2003) and Raynaut *et al.* (2007).

In spite of the fact that most mangroves in this region are located inside no-take PAs, local populations use mangrove fishing resources on a regular basis. Although mangrove products, such as crabs (*Ucides cordatus*), oysters (*Crassostrea rhizophorae*) and shrimp (*Penaeus schmitti*), account for a relatively small percentage of total artisanal fish production, there are some communities that rely on crab extraction and oyster semicultivation as their main economic activities. It is also evident that a practical situation of open access to these resources has lead to overexploitation. Additionally, a general crisis in fisheries in the region has led to an increase in these activities in local mangroves. In some areas there is a direct relation between the fishing village and the nearby mangrove, with examples of locally established rules of access. But in many cases mangrove resources are explored by people coming from distant places, which is a source of conflicts between different groups of fisherfolk in this region (Miranda 2004).

Even when they are not included in no-take PAs, the direct exploration of mangrove resources, except fishing resources, is considered illegal in Brazil, which is also a source of conflicts with those populations that traditionally explore them (Glaser & Oliveira 2004). In the end, this situation of permanent illegality experienced by those that explore mangrove resources results in a normative insecurity and in a reduction of acceptance of environmental rules, with growing hostility between local populations and environmental authorities. It results also in the adoption of economically inefficient, ecologically inappropriate and socially unequal practices by these populations (Glaser *et al.* 2003).

Therefore, although they might have contributed for the conservation of natural resources in this region, land management and biodiversity conservation policies also generate conflicts when they restrict occupation of certain areas and prohibit exploration of resources. The impacts of these rules are unevenly distributed among different social groups. This situation results in negative impacts on the livelihoods of the populations that inhabit areas considered important for conservation. This is one of the reasons why official management actions are, more often than not, inefficient in protecting natural resources, especially common pool resources such as fishing and mangrove ones.

In a context such as the one observed in the coast of Paraná, one of the poorest regions in the state (Pierri *et al.* 2006), this scenario becomes even more problematic, as local small-scale fishing populations have limited access to political, financial and social assets, which aggravates the impacts that even small fluctuations in natural resources availability, or restrictions on the access to these resources, can have on their livelihood and survival. Therefore, environmental regulations become one of the sources of variability and disturbance for these livelihoods, acting together with other environmental (variations in fish stocks, environmental degradation, extreme weather events) and economic (market fluctuations, low income, lack or inadequacy of support mechanisms) factors, and contributing to increase the vulnerability of populations and ecosystems to climate change. The vulnerability of the SES of small scale fisheries in this context puts at risk the survival conditions of thousands of people, compromising their social reproduction.

As we recognize the connections between coastal ecosystems and human populations, there is a growing need for interdisciplinary research on the effects of climate change and to translate research results into better policies. It is important to comparatively understand these dynamics, analyzing how this multitude of factors affects the livelihoods and adaptive capacity of coastal populations and ecosystems, in order to better adapt conservation strategies, with an eye to both biodiversity conservation and social reproduction of human populations. Research in this domain must find ways to influence the making of environmental policies and rules.

A methodology for assessing vulnerability to climate change and the impacts of protected areas

The development of conservation policies for coastal zones must consider the need to understand the different systems - socioeconomic, geomorphologic and ecologic - in an integrated manner, so that vulnerability can be analyzed for the coastal area as a whole. Although climate is one of the main sources of hazards for the coastal zone, it is not the only source of change and vulnerability. It needs to be considered together with other factors so that management instruments are useful for integrated coastal management. Thus, while developing methodologies for analyzing vulnerability, the components of this analysis must provide information about all the processes that define the behavior of the whole system (McFadden & Green 2007).

A research framework aiming to analyze the relations between social and ecological systems has to face the challenge of understanding cross-scale interactions between phenomena and processes. Nevertheless, considering that responses to the impacts of climate change will consist primarily of individual responses to day-to-day changes on a local scale, there is a need for this type of study to have a multiscale perspective which can be applied to the analysis of adaptive capacity on the level of the communities (Dolan & Walker 2004).

Therefore, the proposal for working with a local case study as the starting point is based on the idea that the information to be collected can form the basis for a bottom-up analysis aimed at elucidating some of these interactions, contributing with studies of global change, which have usually focused on global scale models as the starting point, then extrapolating to the regional and local levels (Wilbanks & Kates 1999). With a focus on the local context, extrapolations could work on the opposite direction, emerging from comparisons between different communities – for example, using proximity to no-take protected areas as the independent factor – or even between different societies, comparing the results of the small-scale study with similar realities in other countries – for example, where artisanal fisherfolk and mangroves may coexist under different conservation policies.

These comparisons would aim on identifying those characteristics of communities and their environments that contribute to enhancing or lowering vulnerabilities, and the elements of the adaptation strategies that turn out to be more efficient (Smit & Wandel 2006). This would result in scientific explanations of the specific realities, but not necessarily on guidelines that could be universally applied to the formulation of policies, because the great variety of social and ecological contexts makes it difficult to develop homogeneous management solutions.

Supported by this logical background, we propose herein a research framework to assess the vulnerability to climate change of mangroves and fisherfolk. Using the case study of the Paranaguá Estuarine Complex in southern Brazil as an example we further include in the proposed methodology indicators to analyze the impacts of biodiversity conservation actions, especially no-take PAs, on this vulnerability. Following this perspective, the framework aims to understand how fisherfolk respond to changes in the status of the assets (biophysical, cultural, political and institutional) on which they base their livelihoods, and if this status is affected by environmental changes or changes in access and entitlements to these assets, specifically as a result of climate change and the implementation of no-take PAs.

Specific steps in the methodology include: (a) Evaluation of the vulnerability of mangroves to climate change, especially regarding their exposure and sensitivity to sea-level rise, and their adaptive capacity; (b) Evaluation of the vulnerability of fisherfolk populations to climate change, considering the exposure of villages to sea-level rise and extreme climatic events, their position in relation to no-take PAs, and the elements that enhance or diminish their adaptive capacity; and (c) Analysis of the effects of no-take PAs on these vulnerabilities, through impacts on sensitivity and adaptive capacity of both fisherfolk and mangroves. Such an approach can also be useful to analyze regional biodiversity conservation policies regarding their adequacy to deal with climate change related dynamics, aiming to identify how they can be adapted to contribute to building adaptive capacity, both of mangroves and fisherfolk, to respond to these changes.

To achieve these objectives, we propose an analysis of vulnerability in two sections, corresponding to two different scales (regional and local) and considering the main components of vulnerability: exposure, sensitivity and adaptive capacity. By analyzing the components of vulnerability in different situations we aim to understand which elements of the system are directly affected by change, being it regulatory, environmental, social or economic (Tuler *et al.* 2008), but with an emphasis on the impacts of existing PAs on the factors that condition vulnerability.

Preliminary steps in the research project should include the definition of the spatial and temporal scales for the study, considering biophysical and socioeconomic criteria, and the time scale in which management decisions are taken; collection of information on the biophysical environment and on socioeconomic and cultural characteristics of the area; identification of specific rules and policies that affect the area; and, choosing the specific sites for detailed data collection, according to the population, ecosystems and policies of interest (Harvey *et al.* 1999).

We divide the analysis according to the three components of vulnerability and the three subsystems being considered: social (fisherfolk), natural (mangroves) and social-ecological (representing the interaction between the other two subsystems; in our case study, it concerns mainly the fisheries production system, or the patterns of utilization of natural resources by coastal populations). It should also be considered that factors influencing vulnerability can be both social and ecological, and internal or external to the system (Füssel 2007).

Vulnerability should always be measured in relation to specific environmental hazards, which can vary according to the specific characteristics of the setting under consideration. For the coastal populations and environments of our case study, we defined three expected effects of climate change as the main threats: relative sea-level rise, an increase in the frequency and intensity of extreme climatic events, and an increase in uncertainty and variability related to the availability of fishing resources.

Exposure to these threats is mainly related with the characteristics of the sites where villages and mangroves are located, especially their proximity to the sea and the topography and slope of the terrain. Thus, for the analysis of this element a digital elevation model (DEM) of the coastal area needs to be constructed. This can be accomplished through the use of remote sensing, with a high-resolution satellite image of the region, or, ideally, with LIDAR (Light Detection and Ranging) data (Gesch 2009).

To improve the quality of the model, the upper boundary of mangrove forests should be delimitated and considered as equivalent to the mean high tide in the region. The DEM can then be constructed through interpolation of existing elevation data, considering this high tide line and the first topographic contour available in local maps (10 meters in the case of the Brazilian coast). To further improve the accuracy of the model, the interpolation can be fed with a series of elevation data points established along the margins of the estuary, in the area between the sea and the first topographic contour.

This digital elevation model, even if not accurate enough to produce detailed scenarios of areas prone to future flooding, especially if LIDAR data is not available, will allow a classification of the coastline in categories representing different levels of exposure to sea-level rise and flooding. The main goal is to identify the location and topography of mangroves and villages and the land-use patterns in the low-lying areas, up to 10 meters above sea-level. This focus on topography and on the existence of barriers to mangrove migration is justified by the lack of consistent data on local and regional sea-level rise. In this case, the analyzed factors work as surrogates or indirect indicators of this dynamics, producing information about the response of these ecosystems to climate change (Gilman *et al.* 2007). The last component of exposure to be measured is the magnitude and frequency of occurrence of extreme climatic events. Information on these events can be obtained both from meteorological and historical records and from interviews with local inhabitants. We suggest as a proxy for this the measurement of the number of fishing days lost due to bad weather conditions.

For the analysis of exposure, we can already identify opposite effects on the social and natural subsystems. A gentle slope means a higher exposure to sea-level rise and storm surges, increasing the vulnerability of villages, considering that the flatter the land the larger the area that would be flooded. But, for mangroves, a gentle slope in adjacent landward areas means that they have available space to migrate towards the continent, although land-use patterns may create barriers to this migration. In our specific setting, this spatial analysis of land adjacent to mangroves will also evaluate the situation of local fishing villages regarding their sensitivity to mean sea-level rise and the impacts of protected areas which exclude human occupation. In this case, the factor that will be analyzed is “coastal squeeze”, that is, if a rise in sea-level will put pressure on human occupations and if these will be able to respond. Many villages in this region are placed between the ocean and the PAs, being susceptible to coastal squeeze if sea level rises.

Still regarding sensitivity, which relates to effects that hazards can have on the systems, the general housing, health and food conditions of human populations should be measured, together with their dependency on climate-influenced resources (such as fish). For this, we propose, based on the Livelihood Vulnerability Index methodology (Hahn *et al.* 2009), to focus on water and food sources and storage capacity, the percentage of household members that lost work or school days due to health problems, and the distance to the closest health service (Table I). For mangroves, mapping of the total area occupied by the ecosystem and the forest types potentially affected are indicators of this component.

Following this analysis of exposure and sensitivity, some villages, and the mangroves associated to them, identified as potentially highly vulnerable, can be chosen for a more detailed evaluation of factors affecting their adaptive capacity. That is, besides exposure and sensitivity to biophysical risk, the other main component of vulnerability will be analyzed: the capacity of these populations and ecosystems to cope and adapt to change, the factors that contribute to it, and, in our specific case, how the existence of no-take PAs affects these factors.

This analysis of adaptive capacity can be divided in two steps. The first one focuses on current vulnerability, considering exposure to risks and coping strategies observed in the present, and based in knowledge of the environment, available resources and existing strategies. A second step aims to create future scenarios by estimating changes that might occur and possible adaptation actions based on behaviors already demonstrated in the past, and their adequacy to these scenarios. What is considered is how communities have dealt with extreme events and disturbances, what conditions may change and what opportunities exist for future adaptation (Ford & Smit 2004).

This type of analysis considers current conditions in these communities, with factors and processes that contribute to enhance or diminish their capacity to respond to changes, to variations and to the unexpected. This perspective recognizes the importance of factors that are not directly connected to climate, such as sources of subsistence, assets, access to resources, institutional arrangements, etc., that condition the vulnerability of these populations. This means that vulnerability to climate change is analyzed together with other sources of stress, with emphasis on the ability of people to respond to risks, changes and threats, potentially generating adaptation proposals that diminish vulnerability to climate change through the reduction of exposure or minimization of other adverse factors. Therefore, besides identifying the most relevant matters for the adaptive capacity of communities, the aim is also to understand the importance of climatic stresses in comparison to other sources of disturbance to these livelihoods (Tschakert 2007).

McClanahan *et al.* (2008) proposed an index of adaptive capacity composed of the following variables: recognition by the population of the causalities; anticipation of changes; mobility and occupational multiplicity of the population; social capital; material assets; and available infrastructure and technology. In a similar way, Yohe & Tol (2002) developed a method to estimate adaptive capacity using eight factors linked to technological options, availability of resources and their distribution in the population, structure of institutions that are important in decision making, the stock of human and social capital, the access to risk spreading processes, characteristics and abilities of the decision makers and the perception of the public in relation to the causes of stress and the meaning of being exposed to it.

Other authors applied and discussed the pertinence of more specific and detailed methodologies such as "Community Risk Assessment" and "Participatory Rapid Appraisal" (Van Aalst *et al.* 2008), or the "Sustainable Livelihood Approach" (Iwasaki *et al.* 2009). What these methods have in common is a bottom-up approach, the direct involvement of communities and a focus in analyzing vulnerability to current events, as well as strategies and policies based on current and real experiences, in different scales.

The "Sustainable Livelihood Framework" (Adato & Meinzen-Dick 2002, Baumann 2000, Divakarannair 2007) is a widely used approach for the study of the livelihoods of these communities that depend directly on natural resources, as well as the study of the importance of biophysical, social, cultural, economic, political and institutional factors that determine the options held by these populations. This method considers that livelihoods are linked to assets composed of human capital (education, knowledge, health, nutrition, workforce), natural capital (the natural resources explored by the community), physical capital (the available infrastructure, such as fishing gear and housing), financial capital (savings, credit, income), social capital (networks, cooperation, access to opportunities, organization) and political capital (policies, institutions and processes that link the individual or group to external power structures).

It is also important to include in this analysis elements of Environmental History, through, for example, interviews with elders and analysis of aerial photographs of the region, that may indicate historical patterns of land usage and occupation. The aim is to understand how the measured factors behaved prior to the existence of PAs, and in this way, relativize the impacts of them on these factors.

Considering the studies already mentioned, and the objectives of this work, and also considering other sources that discuss indicators and criteria for the evaluation of vulnerability and resilience in SESs (Marschke & Berkes 2006, Tschakert 2007, Tuler *et al.* 2008, Hahn *et al.* 2009, Kalikoski *et al.* 2010), we selected a number of indicators, linked mainly to income sources of fishermen and their relation to mangroves. Among the indicators usually utilized in vulnerability assessments, we considered the following to be more informative and useful regarding the objectives of this work:

- Income: total income, income distribution in communities, diversification of income sources, existence of stable income sources (retirement payments, etc.), proportion of economically active population.

- dependency of communities on fishing and mangrove resources: importance of these resources for their subsistence, access conditions and tendencies of variation on their availability, considering environmental degradation, overexploitation, climate change, and the restrictions imposed by environmental rules.

- fishing strategies: types of boats and fishing gear available; number of days they are prevented of going out to sea by bad weather; safety regarding availability of assets related to their livelihood (property of means of production, natural resources and housing, including conditions of access to them); if they have experienced changes in fishing activities (diversification, dislocation of fishing grounds) in response to economic, political and climatic changes.

- Market relations: whether they trade the products they capture or produce only in local markets, only in external ones, or in both; level of dependency on middlemen.

- Organization capacity of the community: means of organization and participation in discussion forums, associations, etc.; perceptions regarding the efficacy of these forums; responses of the community to previous catastrophic events (storm surges, oil spills).

- Adaptation and learning strategies, including social cohesion mechanisms: relations of help and exchange of information inside the community and between communities, regarding livelihood activities; participation of younger members on livelihood activities (knowledge transmission).

- Environmental and fisheries management policies and institutional factors: impacts of these policies on livelihoods; existence of financial support programs (loans, unemployment insurance, fishing ban period insurance) and the level of fishermen participation in these programs.

To assess the linked elements that compose the adaptive capacity of the SES, we propose a measurable index of the stress level or anthropization level of those mangroves that are used by these populations. Estimates on the present state of mangrove forests and fishing resources, such as oyster, mussels and crabs, including the availability of resources and how, where and in what intensity they are explored, can be used as a proxy of the impacts of human activities on the ecosystem's resilience.

This information will help to characterize the main component of the relation between mangroves and fishermen: the usage patterns of mangrove resources by these human populations. Additionally, the level of human usage of a particular mangrove shows its importance for that population. If a highly explored and useful mangrove has a low resilience to current disturbances and projected climate change, it must be the object of adequate management, one that contributes to increase the resilience of the SES as a whole.

The effect of protected areas, or other factor of interest, on the vulnerability of mangroves and fisherfolk should be dealt with at a second level of analysis. For our case study, we propose four specific indicators of these effects: (a) the distance of villages to the closest no-take protected area, indicating the probability of them suffering with “coastal squeeze” and of potential conflicts with biodiversity conservation norms; (b) the proportion of the income of local fisherfolk that comes from mangroves located inside no-take PAs, indicating the impact that these areas can have on their livelihood if these strict norms are fully enforced; (c) the proportion of local inhabitants that used to have a more diversified livelihood, practicing agriculture and extractivism, and who abandoned these activities because of the prohibitions brought on them by PAs; and, (d) the proportion of inhabitants that have suffered other type of restrictions on their livelihoods, such as limitations on improvement of housing conditions, due to PAs.

These data can be obtained from a number of different sources and utilizing a variety of techniques. Part of the social and economic data is available in government agencies, from projects developed in the region by non-governmental organizations, and as published scientific literature. Primary data shall be obtained directly on fishing villages using semi-structured interviews, contacts with key informants (such as community leaders and protected area managers) and direct observation of specific forums. Biological data from mangroves can be collected directly on site, using scientific sampling techniques, or with the help of local fishermen.

Table I summarizes the steps that are proposed in this methodology. They are divided in two scales (regional and local) and categorized according to the component of vulnerability they refer to, the type of capital (human, social, political, financial, natural and physical), the type of information to be collected and analyzed, the method and the source and type (quantitative or qualitative) of data.

After gathering the data it must be decided whether they will be summarized into an index of vulnerability. Most of the indicators proposed in this methodology are quantitative and can be parameterized and used to compose such an index. Although a focus on quantitative indicators and building of a composite index can oversimplify a

Table I. Summary of the indicators that compose the proposed methodology, considering the case study described above.

Vulnerability component	Subsystem	Type of Capital	Indicator	Information collected/analyzed	Method	Data source	Data type	Scale
Exposure	Mangroves	Natural	Topography/ Slope	Surface elevation data; contour curves; upper limit of mangroves; location of PAs; relative sea-level rise scenarios	Remote sensing; spatial analysis; digital elevation model	Satellite images; LIDAR data	Quantitative	Regional
Exposure	Fisherfolk	Natural Physical	Slope; distance from village to the sea	Surface elevation data; contour curves, upper limit of mangroves; location of Pas; location of fishing villages; relative sea-level rise scenarios	Remote sensing; spatial analysis; digital elevation model	Satellite images; LIDAR data	Quantitative	Regional
Exposure	SES	Natural Physical Social	Historic occurrence of extreme climatic events	Frequency of climatic events that significantly affect the villages; number of fishing days lost due to bad weather	Collection of secondary data; interviews with local inhabitants	Government agencies; scientific publications; fisherfolk	Quantitative and qualitative	Local
Sensitivity	Fisherfolk	Social	Food and Water	Type of water source; water storage capacity; food storage capacity, percentage of food coming from own production; number of months a year when there is shortage of food	Secondary data; field observations; household surveys	Government agencies; scientific publications; fisherfolk	Quantitative and qualitative	Local
Sensitivity	Fisherfolk	Social	Health	Percentage of members of household who lost work or school days due to health problems; distance to closest health service	Household surveys	Fisherfolk	Quantitative	Local
Sensitivity	Mangroves	Natural	Mangrove type	Total area and mangrove types potentially affected by sea-level rise	Remote sensing; spatial analysis	Satellite images	Quantitative and qualitative	Regional
Sensitivity	SES	Natural Physical Social Political Human	Dependency on fishing resources/ diversity of income sources	Proportion of income derived from fishing and mangroves resources; location of exploited resources	Secondary data; household surveys	Government agencies; scientific publications; fisherfolk	Quantitative and qualitative	Local
Adaptive capacity/Ecological resilience	Mangroves	Natural	Ecosystem health	Abundance of fishing resources in mangroves and usage patterns; signs of stress in the ecosystem	Sampling of primary data	Direct measurement in mangroves	Quantitative	Local
Adaptive capacity/Ecological resilience	Mangroves	Natural	Capacity to cope with sea-level rise	Presence of barriers/patterns of occupation of landward areas; level of protection of mangroves and landward areas; proximity to rivers and size of drainage basin	Remote sensing; spatial analysis; field surveys	Satellite images; direct observations	Quantitative and qualitative	Local

Table I. Continued.

Vulnerability component	Subsystem	Type of Capital	Indicator	Information collected/analyzed	Method	Data source	Data type	Scale
Adaptive capacity	Fisher folk	Financial	Income level, distribution and diversity	Diversity of income sources; percentage of income coming from external/stable sources; dependency rate	Sampling of secondary data; household surveys	Government agencies; scientific publications; fisherfolk	Quantitative	Local
Adaptive capacity	Fisher folk	Physical	Fishing strategies diversity	Number of fisheries practiced in the village; percentage of fisherfolk that own boats and fishing gears; frequency of usage of mangrove resources	Secondary data	Government agencies; scientific publications;	Quantitative	Local
	SES	Social			Household surveys	Fisherfolk		
					Interviews with key informants			
Adaptive capacity	Fisher folk	Financial	Market connections	Number of places where fisherfolk trade their products; percentage of those that depend on middlemen	Secondary data	Government agencies; scientific publications;	Quantitative	Local
		Social			Household surveys	Fisherfolk		
					Interviews with key informants			
Adaptive capacity	Fisher folk	Social	Community organization	Existence and number of community organizations; perception of effectiveness of external help during catastrophic events; responses of community during previous catastrophic events.	Secondary data	Government agencies; scientific publications;	Quantitative and qualitative	Local
					Interviews	Fisherfolk		
		Political			Direct observation of forums			
					Focal group discussions			
Adaptive capacity	Fisher folk	Human	Adaptation and learning strategies	Frequency and type of help and exchange of information inside the community and between communities, regarding livelihood activities; percentage of inhabitants with knowledge of the threats related to climate change	Interviews; focal group discussions	Fisherfolk	Qualitative and quantitative	Local
		Social						
Sensitivity/ Adaptive capacity	Fisher folk	Political	Impacts of biodiversity conservation policies	Distance of villages to no-take protected area; proportion of income of local fisherfolk that comes from mangroves located inside no-take PAs; proportion of local inhabitants who abandoned livelihood activities and suffered restrictions because of PAs.	Interviews; focal group discussions	Fisherfolk; key informants	Quantitative and qualitative	Local
		Financial						
		Social						

complex reality, this can be useful for comparisons between villages regarding their vulnerability to climate change, the effects of protected areas and the relative importance of each vulnerability component, which can help in defining management priorities. Furthermore, qualitative information can also be used to guide interpretations of the observed situation. An important decision for composing a vulnerability index is whether each sub-component should have a different weight. This demands careful judgment of the reality being studied. We propose to follow the "balanced weighted average approach" used in composing the Livelihood Vulnerability Index (Hahn *et al.* 2009), where each sub-component contributes equally to the overall index. This allows for a clear identification of the contribution of each indicator for the composition of the overall vulnerability of a population or ecosystem, facilitating comparisons and pointing management actions towards the most relevant situations.

Conclusions

Such a complex situation as the one described requires adequate management measures, focused not only on understanding and managing of immediate sources of impact on social and ecosystem process, but also on increasing the resilience of SESs so that they can support these impacts, especially those derived from global climate change. The challenge is to develop new practices and management policies which allow for the adaptation of productive systems to change, and, therefore, their viability and sustainability. For this to be achieved we must acquire sound knowledge about the elements that compose the vulnerability to climate change of the SES formed by mangroves and fisherfolk and the effects of biodiversity conservation policies on these elements. In this context, interdisciplinary research becomes essential in the characterization and analysis of the different types of impacts, the social and economic practices of human populations, and the vulnerability of ecosystems, of the environmental services they provide and of coastal populations. A sound diagnosis may lead to more flexible policies, elaborated with stakeholders' participation, more adequate to local realities and more inclusive of strategies for mitigation and adaptation to climate change.

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