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A new empirical index for assessing the vulnerability of peri-urban mangroves

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ABSTRACT

Environmental vulnerability can be understood as a function of exposure to impacts and the sensitivity and adaptive capacity of ecological systems towards environmental tensors. The present study empirically evaluated the vulnerability of forest stands that make up the subtropical Perequê River mangrove (Paranaguá Bay, S Brazil) as the basis for a more appropriate management of its resources. This mangrove is located in the coastal municipality of Pontal do Paraná (Paraná, Brazil) and is part of the Perequê River Mangrove Natural Park, which is still not under a management plan. This study aimed to contribute to the future management plan of this conservation unit through an environmental diagnosis and an empirical evaluation of its vulnerability. The primary data, collected from 51 plots of 100 m^2 each, involved the evaluation of: 1) the exposure to solid waste, deforestation, trails, landfills, and constructions; 2) the degree of sensitivity according to the environmental conditions of each plot; and 3) the adaptive capacity according to the recovery and reproductive potential and structural complexity of the forests. These data were integrated to compose the empirical index of environmental vulnerability (*VI*) expressed as $VI = (SI + EI) - ACI$ where *SI* is the sensitivity sub-index, *EI* is the exposure sub-index, and *ACI* is the adaptive capacity sub-index. Empirical indices calculated for local forests varied significantly due to differences in values of *SI*, *EI* and *ACI*. This variability defines the local mangrove as a mosaic of vulnerability conditions and suggests that the planning and implementation of local management actions consider such environmental heterogeneity. Applying or extending these actions should be based on local forest conditions at short spatial scales and should not be applied to the mangrove as a whole.

1. Introduction

Vulnerability is an analytical category used to describe conditions of susceptibility to physical damage (Adger, 2006). This concept has been applied to social, ecological, biophysical, or socio-ecological systems, with different focuses and meanings (Gallopín, 2006; Adger, 2006; Eakin and Luers, 2006; Smit and Wandel, 2006; Füssel, 2007).

Various methodological approaches have been used in the analysis of vulnerability (Eakin and Luers, 2006). Some have treated vulnerability as the opposite of ecological resilience (Holling, 2001; Holling et al., 2002), others believe that resilience or adaptive capacity can be understood only as an environmental vulnerability-reducing factor in any system (Smit and Wandel, 2006).

The lack of a unifying theory of vulnerability has led some researchers to defend more pragmatic approaches that accept the inevitable diversity of applications and the need for greater flexibility in the definition of indicators, methodology, and systematizations (Downing et al., 2004). Multiple models of analysis converge on the recognition that vulnerability depends on the exposure and sensitivity to stress vectors and on the resilience or ability to cope, adapt, and recover from the effects of adverse conditions (Smit and Wandel, 2006; Adger, 2006). Sensitivity refers to the magnitude of the damage that an individual or a group will probably suffer when exposed to any danger (Tuler et al., 2008). Resilience comprises the ability of natural systems to absorb disturbances and reorganize while undergoing changes and still preserve its structure and function (Holling, 1973; Carpenter et al., 2001; Eakin and Luers, 2006).

A recent emerging interdisciplinary understanding about vulnerability is based on the co-evolutionary and interdependent nature of social and natural systems (Tuler et al., 2008). The magnitude of the damage caused by environmental disturbances for both systems depends on their acquired or evolved ability to deal with them. This ability depends on the level of access to essential maintenance allowances in the coupled system or

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independent subsystems (Hassan et al., 2005). In this sense, environmental variables such as salinity, nutrient and fresh water intake, and oxygenation would represent to mangroves what essential subsistence resources such as sanitary conditions and food represent to socio-environmental systems.

Mangroves are located in coastal and estuarine confined tropical and subtropical areas influenced by extremely fast and marked variations of tides, temperature, salinity, freshwater supply, substrate conditions, and oxygen availability (Kathiresan and Bingham, 2001; Alongi, 2007). From an evolutionary standpoint, plants and animals in these systems have developed specific adaptations to this predictable or unpredictable environmental variability. These organisms display physiological and morphological adaptations to the extreme and highly variable conditions that commonly occur in this habitat (Alongi, 2002).

Cyclones, flooding, and major storms are common impact vectors and part of mangroves' historical evolution (Alongi, 2002). Mangroves may also become stressed by non-selective, random and of high intensity man-made impact vectors such as deforestation, landfills, salinity alterations and pollutants (Lugo and Snedaker, 1974; Kathiresan and Bingham, 2001; Alongi, 2002). The degree of a mangrove exposure to anthropic impact vectors depends on the distance from the sources of impact and nature of the vector. Measuring the distance between the affected site and urban network or vectors of specific impacts, such as solid waste, is one way to estimate the degree of exposure.

The Perequê River mangrove, located in the subtropical Paranaguá Bay (Paraná, S Brazil), one of the largest and best preserved estuarine systems in the southern Atlantic (Lana et al., 2001), is formed by a set of continuous or discontinuous forests drained by the Perequê River. The Perequê River suffered various anthropic interventions over the past five decades mainly represented by touristic developments in the Pontal do Sul resort and the resulting urbanization. Dredging activities to adjust the riverbed and dislocations of sandy areas and landfills for the construction of houses and streets changed the water flow and consequently modified the local dynamics. Discharge of household and construction waste, hunting and fishing activities, and exploitation of wood are additional impact vectors.

Concern regarding degradation to the Perequê River Mangrove resulted in the creation of a Municipal Park in 2001, hereafter referred as Perequê Park that would allow, in theory, for effective resource management of this important ecosystem. Since the Perequê Park still does not have a specific management plan, the formulation of management guidelines is still a pressing need.

Few successful attempts are known to have addressed the operation and implementation of the concept of vulnerability in the management of natural areas or conservation unities. Such attempts are usually associated with socio-environmental rather than ecological studies (Villa and McLeod, 2002). The operationalization of empirical data addressing the dynamics of mangrove systems could assist managers to develop better management procedures. Based on the concepts of sensitivity, exposure, and adaptive capacity, this study developed and applied an empirical index to estimate the environmental vulnerability of the different forests that make up the Perequê River mangrove. This approach is a case study, which may be of general application to other peri-urban mangroves in developing countries.

2. Material and methods

2.1. Description of the study area

The study area is located at the Pontal do Sul resort (in the municipality of Pontal do Paraná, Paraná State, Brazil), in the Paranaguá Bay (Fig. 1).

The study area is an urban mangrove enclave with an area of 18.24 ha called Perequê River mangrove. Almost all the forests in this mangrove, continuous or discontinuous, are included in the current delimitation of the Perequê Park (Fig. 2).

The Perequê River drains a quaternary coastal plain occupied by sandbanks, marshes, and particularly mangroves that occur from intertidal areas with fine sediments, such as the margins of the main channel and internal areas of the basin, to higher areas with more sandy sediments bordering the restinga or sand-dune vegetation. The river mouth is the only site for the exchange of water and particulate matter between the local mangroves and the open sea (Fig. 2).

According to the Köeppen classification, the region of Pontal do Paraná presents a Cfa – humid-mesothermic subtropical (meteorological convention) climate with hot summers and not well-defined dry seasons (Angulo, 1992). The supply of fresh water in the region is conditioned by the upwelling of shallow groundwater (Marone et al., 1997) that provides varying amounts of water during the year and by the regular rainfall throughout the year (Angulo, 1992). The local tidal regime is semidiurnal with daily variations (Marone and Camargo, 1993). The Perequê River is often categorized as a tidal creek because its flow is mainly conditioned by tides and rainfall.

2.2. Sampling planning and data management

A pilot campaign was performed for the definition of sampling sites at the beginning of March 2010. At this time, environmental tensors such as the presence of restinga plant species and recurring anthropic impact vectors as well as the main physiographic features of the forests (structural complexity, average canopy height along the salinity gradient of the Perequê River) were identified. In this sense, the replication of this methodology in other mangrove areas should also define *a priori* what specific variables are considered most appropriate for sampling.

The Vulnerability Index (*VI*) was built considering the exposure to anthropic impact vectors, sensitivity, and adaptive capacity of the Perequê River mangrove. These three factors were obtained through mathematical calculations and presented as sub-indexes that, through equations, composed the final vulnerability index. The variables used to calculate the three sub-indexes were obtained from 51 plots of 100 m^2, sampled in a stratified random distribution, from the groundwater catchment area to the river mouth area. The sampling grid corresponded to 2.8% of the study area (Fig. 3).

2.2.1. Procedures to calculate the sensitivity, exposure, and adaptive capacity sub-indexes

The weighted average (sampling raw value divided by maximum observed value) was calculated for variables that composed the sensitivity and adaptive capacity sub-indexes. The variables considered for the exposure sub-index did not receive this treatment; the original values sampled in the field (see Section 2.2.1.2) were used for this calculation. This procedure was performed for all plots (plot 20 is presented as an example in Table 1). The variables that composed the adaptive capacity sub-index correspond to three ecological indicators obtained through calculations detailed in Section 2.2.1.3. The variable corresponding to the occurrence of restinga vegetation (see Section 2.2.1.1) was calculated using the average values from the three plant species observed (Table 1).

The sensitivity, exposure, and adaptive capacity sub-indexes were obtained through the arithmetic mean of environmental variables (sampling raw values for exposure sub-index components and weighted average values for adaptive capacity and sensitivity sub-indexes components). This was performed to avoid the multiplication of many sampling “zeros”, common in surveys of this