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A framework for deriving measures of chronic anthropogenic disturbance: Surrogate, direct, single and multi-metric indices in Brazilian Caatinga

Xavier Arnan[a,b,*,1], Inara R. Leal[c], Marcelo Tabarelli[c], Janete F. Andrade[b], Maria Fabíola Barros[b], Talita Câmara[b], Davi Jamelli[b], Clarissa M. Knoechelmann[b], Tatiane G.C. Menezes[b], Artur G.S. Menezes[b], Fernanda M.P. Oliveira[b], Alexandre S. de Paula[b], Sílvia C. Pereira[b], Kátia F. Rito[b,d], Julia C. Sfair[b], Felipe F.S. Siqueira[b], Danielle G. Souza[b,e], Maria J. Specht[b], Ligia A. Vieira[b], Gabriela B. Arcoverde[f], Alan N. Andersen[f]

[a] CREAF, Universitat Autònoma de Barcelona, Cerdanyola del Vallès, Spain
[b] Programa de Pós-Graduação em Biologia Vegetal, Universidade Federal de Pernambuco, Av. Prof. Moraes Rego s/no, Recife, PE 50670-901, Brazil
[c] Departamento de Botânica, Universidade Federal de Pernambuco, Av. Prof. Moraes Rego s/no, Recife, PE 50670-901, Brazil
[d] Instituto de Investigaciones en Ecosistemas y Sustentabilidad, Universidad Nacional Autónoma de México, Morelia, Michoacán 58190, Mexico
[e] Departamento de Sistemática e Ecologia, Laboratório de Ecologia Terrestre, Universidade Federal da Paraíba, Castelo Branco, João Pessoa, PB 58051900, Brazil
[f] Research Institute of Environment and Livelihoods, Charles Darwin University, Darwin, NT 0909, Australia

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ABSTRACT

The development of multi-metric indices of chronic anthropogenic disturbance (CAD) from disparate disturbance indicators represents a major challenge for understanding the impacts of CAD on biodiversity, especially in tropical dry areas where livelihoods of local populations are highly dependent on natural resources. We present a conceptual framework for deriving variably integrated, multi-metric measures of CAD from disparate disturbance indicators. Our framework has three steps: (1) identifying the main sources of CAD in the target region, and quantifying them using data of varying levels of spatial and intensity precision; (2) classifying the sources of disturbance into general disturbance pressures, and deriving an index for each; and (3) combining the individual disturbance pressure indices into a fully integrated index that characterizes the overall level of CAD. We apply this framework to Catimbau National Park in the Brazilian Caatinga, using 12 primary data sources to derive disturbance pressure indices relating to livestock, wood extraction and people pressure. The meaningfulness of pressure and overall CAD indices were validated by reference to variation in ant communities. Our analysis revealed notable findings. First, indirect measures from the geographic and socio-ecological context were poorly correlated with direct, field-based measurements, and were therefore of questionable reliability. Second, the three main disturbance pressures were largely independent of each other, which points to complex patterns of resource use by local communities. Third, different weightings of component disturbance pressure indices had little influence on the Global index, making our Global CAD index somewhat insensitive to assessments of the relative importance of different disturbance pressures. Finally, our results caution against a reliance on multivariate ordination to derive integrated indices of disturbance from disparate data sources. Our multi-scale integration of disturbance data can facilitate the analysis of the resource use effects on biodiversity, contributing to effective conservation management and sustainable livelihood development.

1. Introduction

Disturbance is a key factor influencing the structure of ecological assemblages and evolution of species within ecosystems (Dornelas, 2010; Ponge, 2013). Over recent decades, increasing levels of anthropogenic disturbance have been a major driver of biodiversity loss at local, regional and global scales (Sala et al., 2000; Fahrig, 2003; Fischer and Lindenmayer, 2007; Chazal and Rounsevell, 2009). In turn, biodiversity loss is jeopardizing the sustainability of ecological processes and the provision of ecosystem goods and services (Cardinale et al., 2012; Mitchell et al., 2015). There is thus an urgent need to quantify and predict the ecological effects of anthropogenic disturbance to guide

* Corresponding author at: CREAF, Universitat Autònoma de Barcelona, 08193 Cerdanyola del Vallès, Spain.
E-mail address: x.arnan@creaf.uab.cat (X. Arnan).
[1] *Permanent address*: Programa de Pós-Graduação em Biologia Vegetal, Universidade Federal de Pernambuco, Av. Prof. Moraes Rego s/no, Recife, PE 50670-901, Brazil.

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conservation efforts and the management of ecological resources.

Chronic anthropogenic disturbance (CAD) involving activities such as grazing by livestock, firewood collection and exploitation of non-timber forest products is the most widespread form of environmental change in developing countries (Singh, 1998; Gunderson, 2000; Ribeiro et al., 2015, 2016; Ribeiro-Neto et al., 2016). It is especially prevalent in dry areas of the tropical world because ecosystems typically support dense and low-income rural populations that depend on forest resources for their livelihoods (Singh, 1998; Davidar et al., 2010; Specht et al., 2015; Rito et al., 2017). Areas with a long history of past and present human occupancy usually result in a complex mosaic of differently disturbed patches, such that measurements of CAD often need to integrate very different and uncorrelated sources of disturbances (Martorell and Peters, 2005; Ribeiro et al., 2015; Rito et al., 2017). The development of multi-metric CAD indices from disparate disturbance indicators represents a major challenge for understanding the impacts of CAD.

Ideally, CAD metrics would be based on direct measurements of land-use intensity in the field (Martorell and Peters, 2005), especially when we are interested in spatially-explicit impacts. However, this is often not feasible, and so a range of indirect metrics have been used as surrogates (Sagar et al., 2003; Martorell and Peters, 2005; Leal et al., 2014, 2015; Ribeiro et al., 2015, 2016; Ribeiro-Neto et al., 2016; Schulz et al., 2016), usually focusing on single types of disturbances (Ribeiro et al., 2015; Rito et al., 2017). Such metrics can be based on locally-derived socio-economic and socio-ecological information (Medeiros et al., 2012a), or from distance-based geographic and population data with the assumptions that higher population densities and closer distances to towns and roads equate to higher intensity of land-use (Ahrends et al., 2010; Leal et al., 2014; Ribeiro et al., 2015). Socio-ecological data can provide a robust indication of disturbance intensity at the landscape level (Ostrom and Cox, 2010), but lack spatial precision. Geographic data are more spatially explicit, but provide a very imprecise measure of disturbance intensity (Rogan et al., 2007, Barlow et al., 2016).

CAD metrics can be used for different purposes that require different levels of data integration. Some studies aim to analyze the role of a particular disturbance (e.g. grazing by livestock or firewood collection), or the relative importance of different disturbances, as a contribution to a mechanistic understanding of the drivers of ecosystem dynamics (e.g., Specht et al., 2015; Eldridge et al., 2016; Schulz et al., 2016; Zhou et al., 2016). This requires metrics that are specific to particular disturbances. Other studies are more interested in the overall impact of human disturbance on ecosystems, and so require a fully-integrated index that provides a metric of overall CAD (Schoolmaster et al., 2012).

The serving of multiple objectives using both indirect and direct sources of information requires a hierarchical framework that uses multi-level integration of data of varying precision (Schoolmaster et al., 2012). We propose a conceptual framework for deriving multi-metric measures of CAD that serves this purpose (Fig. 1). Our framework uses a three-step process. The first step is to identify the main sources of chronic disturbance and classify them into general disturbance pressures (Pressure index x_1 to Pressure index x_n in Fig. 1). The second step is to use available sources of information to derive a metric for each disturbance pressure. We focus on metrics that are proxies of disturbance pressure intensity ('universal metrics', *sensu* Schoolmaster et al., 2012) rather than measures of disturbance impact (e.g., Stoddard et al., 2008; Miller et al., 2016). The available information follows a gradient of data precision, from less-precise but more traditionally-used indirect measures based on geographic and socio-ecological surrogates, to more-precise and spatially explicit field-based measurements of disturbance intensity. A single metric may be based on a single source of information, or integrate multiple sources. Finally, the individual disturbance pressure metrics are then combined to form an integrated metric that characterizes the overall level of CAD (Fig. 1).

Our study has three aims. First, we illustrate how our conceptual framework can be populated, using information on CAD in Catimbau National Park in the Caatinga domain of northeastern Brazil. Caatinga is a mix of dry forest and thorn scrub vegetation, and is the world's most diverse semi-arid biome (Leal et al., 2005; Moro et al., 2016). It is one of the most endangered ecosystems of Brazil due to historical unsustainable exploitation of natural resources by an ever-growing human population (Leal et al., 2005; Albuquerque et al., 2017). Caatinga supports very dense (26 inhabitants per km^2; Medeiros et al., 2012a) and low-income (Ab'Sáber, 1999) rural populations that are highly dependent on forest resources for their livelihoods (Davidar et al., 2010; Djoudi et al., 2015). Second, we use variation in ant communities to test of the validity of our indices in terms of biodiversity impacts. Ants are a globally dominant terrestrial faunal group, and are widely used as indicators of broader ecological change (Andersen and Majer, 2004). Finally, we analyze for our Catimbau case study how the different disturbance indices at different levels of data integration behave along the disturbance axis, and the extent to which they provide redundant or independent information.

2. Materials and methods

2.1. Study system

Catimbau National Park (8°24'00" and 8°36'35" S; 37°0′30″ and 37°1′40″ W; Appendix S1) experiences a hot semi-arid climate (Sociedade Nordestina de Ecologia, 2002). Annual rainfall ranges from 480 to1100 mm, with large inter-annual variability. The annual average temperature is approximately 23 °C. Most (70%) of the Park has sand quartzolic soils. The Park was established in 2002 and most of the residents at that time have remained, with ongoing dependence on the exploitation of natural resources.

The main land-use activities in Catimbau region are livestock (goats and cattle) production, timber extraction, fire-wood collection, hunting, and harvesting of medicinal plants (Rito et al., 2017). Together these impose a continuum of impacts, varying from relatively minor biomass reduction to severe degradation (Leal et al., 2005; Ribeiro et al., 2015).

We used our framework to quantify CAD within twenty 0.1 ha plots (20 × 50 m), separated by a minimum of 2-km, and distributed within the Park in areas dominated by old-growth vegetation exposed to chronic disturbance (Appendix S1). Human impacts in the Caatinga may date back more than 25,000 years (Heredia, 1994), and were intensified by the arrival of Europeans and Africans in 16th century. Information obtained from aerial photographs and preliminary interviews with local communities confirmed that no prior acute disturbances had affected the plots during the previous 80 years. All plots were located in areas with the same soil type (sand) and similar slope (flat terrain).

2.2. Populating the CAD indices framework

2.2.1. Sources of information

Our sources of information were 12 disturbance metrics (Table 1) from three approaches that followed a gradient of increasing data precision (Fig. 1): (a) Indirect measures based on the geographic context (3 metrics); (b) Indirect measures based on the socio-ecological context (4 metrics); and (c) Direct measures taken in the plots (5 metrics). Details of the calculation of these metrics are provided in Appendix S2. In all cases the metrics were calculated such that a higher value indicated higher disturbance.

2.2.2. Individual CAD pressure indices

Based on the 12 primary sources of information we identified three main disturbance types for characterization as individual CAD pressure indices, and representing the first level of data integration (Fig. 2): (1) Livestock pressure. This disturbance type relates to herbivore activity, as well as trampling and other physical damage in the plots caused by cattle and goats. Relevant metrics are included in all three information