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

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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

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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

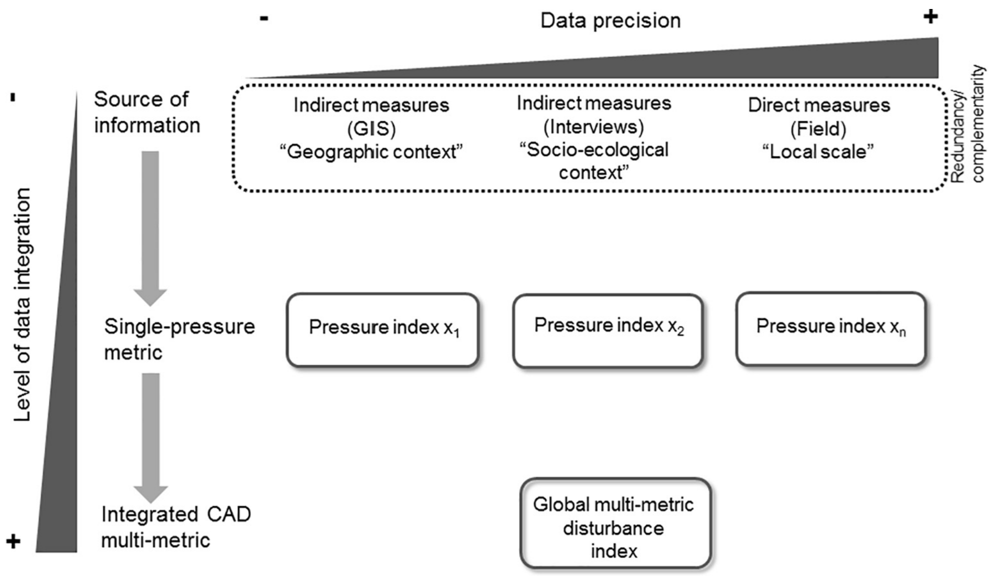

Fig. 1. Conceptual framework for calculating a Global multi-metric CAD index (the maximum level of disturbance data integration) from available sources of information that vary in their level of data precision. The available sources of information are first used to derive a metric for each of the main disturbance pressures, which are then combined to form an integrated metric that characterizes the overall level of CAD.

Table 1
List of original disturbance metrics for each group of direct (taken at field) and indirect (not taken at field) primary sources of information used to measure CAD intensity. The higher the values, the higher the disturbance intensity.

Metric	Unit	Relevant disturbance pressure index
Geographic context (indirect sources of information)		
Proximity to house (PNH)*[,1]	1/x in metres	A, B, C
Proximity to village (PNV)	1/x in metres	A, B, C
Proximity to road (PNR)*[,1]	1/x in metres	A, B, C
Socio-ecological context (indirect sources of information)		
Number of people (NP)*[,1]	No units[3]	A, B, C
Number of goats (NG)	No units[3]	A
Number of cattle (NC)	No units[3]	A
Firewood use (FWU)	No units[3]	B
Direct sources of information		
Goat trail length (GTL)*[,2]	metres	A
Goat dung (GD)*[,2]	n/0.1ha	A
Cattle dung (CD)*	n/0.1ha	A
Live wood extraction (stem cuts) (LWE)*	cm^2/0.1ha	B
Fire-wood collection (litter) (FWC)*	1/(Kg litter/Kg total biomass)	B

* Variables used to calculate the Global multi-metric CAD index.
[1] Variables integrated into the "People pressure" index.
[2] Variables integrated into the "Goat usage" index.
[3] since the original values were divided by the distance between each house and the plot, these variables have no units. A = Livestock pressure; B = Wood extraction; C = People pressure.

types (Table 1). (2) Wood extraction. This disturbance type refers to extraction of both live and dead wood, and relevant metrics are also included in all three information types (Table 1). (3) People pressure. This disturbance type refers to all other resource use by people, and relevant metrics come only from indirect measures related to the geographic and socio-ecological contexts (Table 1).

We then integrated these original sources of information into the first level of data integration as multi-metric indices of single-disturbance pressures. We first conducted Spearman rank correlations among the original disturbance metrics in order to remove redundancy. We considered metrics as too strongly correlated when their coefficients of correlation were $r \geq 0.71$ (Cohen, 1988), given that such metrics share at least 50% of their base information content (i.e. $R^2 \geq 0.5$). We also used correlations with direct field data to assess the reliability of indirect metrics. Field data related to livestock and wood extraction pressures were not highly correlated with the socio-ecological metrics, and so the latter were discarded when calculating the pressure indices for livestock and wood extraction. Since metrics with a large range are often better than metrics with a very small range for assessing disturbance condition (Stoddard et al., 2008), all our selected variables for multi-metric computations, once standardized in order to be comparable and integrated in multi-metric indices, displayed a large range of values of disturbance intensity (see Results).

For the Livestock pressure index, we first integrated the two measures of goat usage (trail length and dung counts) into a single measure by means of PCA. Both variables were highly ($r > 0.90$) and positively correlated with the first PCA axis, which explained 88% of variance, and so we used its coordinates to obtain a single measure of goat usage. The Livestock pressure index was then calculated as the sum of goat usage and cattle dung frequency, using the following formula proposed by Legendre and Legendre (1998) and subsequently by other authors (Herzog et al., 2006; Blüthgen et al., 2012): $I = \frac{\sum_{i=1}^{n} (y_i - y_{min})/(y_{max} - y_{min})}{n} \times 100$, where I is the overall pressure index, y_i is the observed value for one disturbance metric in plot i, y_{min} is the minimum observed value for the disturbance metric considering all plots, y_{max} is the maximum observed value for the disturbance metric considering all plots, and n is the number of individual disturbance metrics considered in the index. Thus, this formula first standardizes the values of each component disturbance metric between 0 and 1, and so they are weighted equally. The overall index I varies from 0 (zero values for all component metrics) to 100 (maximum values of all component disturbance metrics).

The Wood extraction pressure index was calculated by adding the field measurements of live wood extraction and fire-wood collection using the above formula. Finally, the People pressure index was calculated entirely from two indirect sources of information related to geographic distances (we discarded 'distance to village' because it was highly correlated to 'distance to house', see Results) plus the indirect source of information related to the socio-ecological context 'number of people' (Table 1). We integrated these into a single metric by two means. First, we added the source information using the above formula. Second, we used the variables to ordinate sites using PCA, and calculated a People pressure index as the weighted (by variance explained; 48.2% and 32.0% for axis 1 and 2 respectively) mean of the coordinates of the first two axes. All variables were positively correlated with one of these axes. The values of the two People pressure indices were very

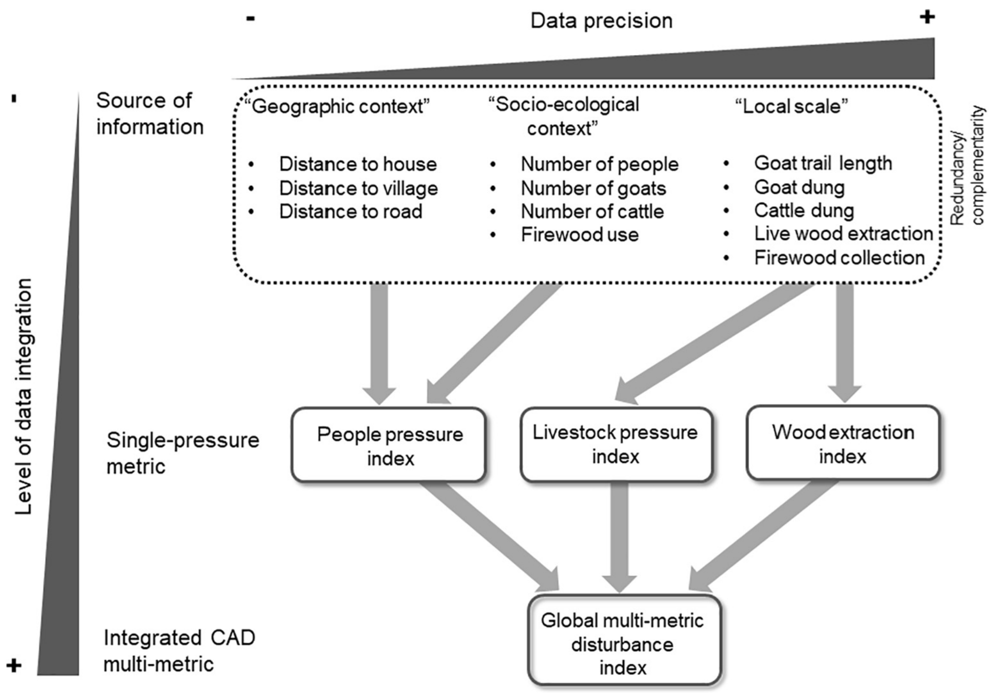

Fig. 2. Populating our CAD index framework for Catimbau N.P. We used available information sources to calculate single-disturbance pressure indices for livestock, wood extraction and people. The indices for livestock and wood extraction pressures were calculated from direct field measures, whereas the people pressure index was calculated from indirect geographic and socio-economic measures (Table 1). Finally, the three single-disturbance pressure indices were integrated into a Global multi-metric CAD index.

highly correlated (Pearson $r = 0.95$, $p < 0.0001$), and so we just used the sum approach (i.e. using the above formula) values for further analyses.

2.2.3. Global multi-metric CAD index

The three single disturbance pressure indices were then integrated into a fully-integrated Global multi-metric CAD index (Fig. 2) using the formula described above for single disturbance pressure indices. The overall CAD index varied from 0 (zero values for all disturbance pressure metrics) to 100 (maximum values of all disturbance pressure metrics).

2.3. Validating the disturbance indices

We used data for ants collected from a 4 × 5 grid of pitfall traps (4.5 cm diameter, partially filled with a mixture of water, ethylene–glycol and soap) with 10-m spacing established in each plot. Traps were operated for a single 48-hr period in March 2015. All ants collected in traps were sorted into species level, and vouchers deposited at the Universidade Federal Pernambuco in Recife. We used non-metric multidimensional scaling (NMDS) to characterize variation in overall ant species composition, based on frequency of occurrence data (i.e., number of pitfall traps out of 20) and Bray–Curtis dissimilarity. We then conducted Spearman rank correlations between the coordinates of each of the two NMDS axes and (1) the original disturbance metrics, (2) the three single-disturbance pressure indices, and (3) the Global multi-metric CAD index. We also correlated each of the disturbance metrics and indices with the abundances of each species ($n = 16$) that occurred in at least 10 plots.

2.4. Analyzing the different disturbance indices

We performed correlations between each of the four indices (three disturbance pressure indices and the Global index) and each of the 12 primary sources of information (original disturbance metrics). We also performed PCA in order to see how plots distribute in relation to the indices characterizing people pressure, goat usage, cattle usage, live-wood extraction and fire-wood collection. The statistical significance of PCA axes was tested by means of the broken-stick model (Legendre and Legendre, 1998). If all variables are highly correlated to significant PCA axes, and different variables go in the same direction within an axis, PCA might also be an alternative tool to integrate (as previously done with the new 'goat usage' and 'people pressure' metrics) very different and uncorrelated sources of disturbance in a Global multi-metric index (Martorell and Peters, 2005).

Our Global multi-metric CAD index was calculated by weighting each disturbance pressure index equally. However, the different disturbance pressures might have differential importance. We assessed how different weightings influence the Global CAD index by re-calculating it on the basis of: (1) double weight to the Livestock pressure index; (2) double weight to the Wood extraction index; (3) double weight to both the Livestock pressure and Wood extraction index; (4) double weight to the Livestock pressure index and x1.5 weight to the Wood extraction index: (5) double weight to the Wood extraction index and x1.5 weight to the Livestock pressure index; and (6) double weight to the People pressure index. We then performed Pearson correlations between each of these weighted Global CAD indices and the unweighted Global CAD index.

3. Results

3.1. Populating the CAD Indices Framework

3.1.1. Sources of information

Most of the 12 original sources of information, and especially the seven that were selected for integration in multi-metric indices, showed large variability among plots (Appendix S3 and S4), and were poorly correlated with each other (Table 2). We did not find strong correlations between original variables from different types of information (i.e. geographic context, socio-ecological context, and direct field data). Significant correlations occurred only within each of the three types of sources of information (i.e., geographic context, socio-ecological context and direct field data), and the strongest of these were: Geographic context – proximity to house and proximity to village; Socio-ecological context – number of people and number of goats, number of people and firewood use, and number of goats and firewood use; Direct field data – goat trail length and goat dung (Table 2).

Table 2
Spearman rank correlation coefficients (r) for relationships among the original single disturbance metrics. $*P < 0.05$; $**P < 0.01$; $***P < 0.001$; in grey, disturbance metrics from the same source of information (indirect: geographic context and socio-ecological context based metrics, and direct: measures taken at field, local scale); in bold, $r \geq 0.71$). For abbreviations, see Table 1.

	Geographic context			Socio-ecological context				Local scale				
	PNH	PNV	PNR	NP	NG	NC	FWU	GTL	GD	CD	LWE	FWC
PNH		**0.88*****	0.23	0.18	0.18	−0.22	0.31	0.69**	0.67**	0.00	0.53*	0.00
PNV			0.12	0.17	0.12	−0.31	0.26	0.49*	0.46*	0.00	0.61**	0.00
PNR				0.38	0.26	0.00	0.40	0.34	0.34	0.19	0.00	0.00
NP					**0.89*****	0.54*	**0.94*****	0.20	0.28	0.15	0.00	−0.19
NG						0.60**	**0.80*****	0.32	0.42	0.16	0.00	0.01
NC							0.32	0.01	0.00	0.36	−0.15	0.35
FWU								0.36	0.43	0.00	0.01	−0.37
GTL									**0.90*****	−0.08	0.25	−0.19
GD										0.00	0.22	−0.19
CD											−0.31	0.00
LWE												0.39

3.1.2. CAD pressure indices

The different single-disturbance pressure indices displayed a wide range of values (Appendix S4). Most indices showed values from 0 to 50–65, except the Wood extraction index that had one plot with a value of 100 (corresponding to maximum values for both live wood extraction and fire-wood collection).

3.1.3. Global multi-metric CAD index

The Global multi-metric CAD index also displayed a wide range of values, from 2 to 58 (Appendix S4).

3.2. Validating the different disturbance indices

NMDS1 coordinates were not correlated with any of the disturbance metrics or indices (Table 3). However, the coordinates of NMDS2 showed several significant correlations, the highest of which (Spearman $r = 0.70$) was with the Global multi-metric index. NMDS2 was significantly correlated with the Livestock pressure and People pressure indices, and with one each of the original disturbance metrics used to construct these pressure indices (Goat-trail length and Proximity to nearest house respectively).

The Global multi-metric index was significantly correlated with the abundances of five of the 16 most common ant species (Table 3). The highest correlations were with *Camponotus crassus* (Spearman $r = 0.68$) and *Dorymyrmex thoracicus* (Spearman $r = 0,63$). The abundances of these species were significantly correlated with only one of the 12 original disturbance metrics (Firewood collection), but were significantly correlated with both the Livestock and Wood extraction pressure indices. The significant correlations between the Global multi-metric index and the abundances of *Brachymyrmex* sp. A and *Pheidole* sp. D were due primarily to correlations with the Livestock pressure index; notably in both cases there were no significant correlations with either of the two metrics used to calculate the Livestock pressure index, or with any of the original Geographic or Socio-ecological metrics (Table 3).

The abundances of four species were significantly correlated with one of the original disturbance metrics but not with any of the indices, and the abundances of the remaining seven species showed no significant correlations with any of the disturbance metrics or indices (Table 3).

3.3. Analyzing the different disturbance indices

The three single-disturbance pressure indices were generally poorly correlated with the original sources of information other than those from which they were directly calculated (Table 4). The only exceptions were that the People pressure index was significantly correlated with the two original field measurements relating to goats, and the Livestock pressure index was significantly correlated with proximity to house. The Global multi-metric CAD index was significantly correlated with one of the three geographic original sources of information, three of the five original field sources, but none of the four original socio-ecological sources (Table 4). It was significantly correlated with each of the three single-disturbance pressure indices, with Spearman r ranging from 0.53 to 0.71 (Table 4).

The broken-stick model applied to the PCA analyses of the five disturbance metrics used to compute the disturbance pressure indices indicated three significant axes, which together explained 88% of the total variation (Appendix S5, Fig. 3). The indices of People pressure and goat usage were positively correlated to the first axis, that of fire-wood collection was positively correlated with the second axis, and the third axis was negatively correlated with cattle dung and positively with live wood extraction.

Finally, all the eight weighted Global indices were extremely highly correlated (Pearson $r = 0.94 - 0.98$) with the unweighted Global multi-metric CAD index.

4. Discussion

We have developed a conceptual framework for deriving variably integrated, multi-metric measures of CAD from disparate disturbance indicators varying in their levels of data precision. This framework has three steps: (1) identifying the main sources of chronic disturbance in the target region, and quantifying them using data of varying levels of precision in relation to both space and intensity; (2) classifying the sources of disturbance into general disturbance pressures, and deriving an index for each; and (3) combining the single disturbance pressure indices into a fully integrated, multi-metric index that characterizes the overall level of CAD. We have successfully illustrated how to apply this conceptual framework to Catimbau National Park in the Caatinga domain of Brazil, using sources of information that follow a gradient of data precision, from indirect measures related to geographic and socio-ecological contexts (Sagar et al., 2003; Leal et al., 2014; Ribeiro et al., 2015, 2016), to measures taken from direct field assessment (Martorell and Peters, 2005; Miller et al., 2016).

Our approach provides disturbance indices at different levels of data integration that can be used for multiple purposes, including investigating the roles of different disturbance pressures, and analyzing responses to overall CAD. The use of data at different levels of integration depends on the research aims. Assessments of overall impacts of human disturbance, require the top level of data integration (i.e., the Global multi-metric CAD index). Single-pressure metrics are suitable for analysing the impacts of any particular disturbance type of interest, or the relative importance of different disturbance types (Schoolmaster

Table 3
Spearman rank correlation coefficients (*r*) between each disturbance metric and index and ant community composition (NMDS1 and NMDS2) and the abundance of the most common species. Abbreviations: Bra spA, *Brachymyrmex* sp. A; Cam cra, *Camponotus crassus*; Cam vit, *Campotonus vittatus*; Din qua, *Dinoponera quadriceps*; Dor goe, *Dorymyrmex goeldii*; Dor tho, *Dorymyrmex thoracicus*; Ect mut, *Ectatomma muticum*; Phe rad, *Pheidole radszkowskii*; Phe spB, *Pheidole* sp. B; Phe sp.D, *Pheidole* sp. D; Sol spB, *Solenopsis* sp. B; Sol spC, *Solenopsis* sp. C; Sol spF, *Solenopsis* sp. F; Sol tri, *Solenopsis* tridens; Sol vir, *Solenopsis virulens*; Tap spA, *Tapinoma* sp. A. In bold, significant correlations ($^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$); in italics, marginally significant correlations.

	NMDS1	NMDS2	Bra spA	Cam cras	Cam vit	Din qua	Dor goe	Dor tho	Ect mut	Phe rad	Phe spB	Phe spD	Sol spB	Sol spC	Sol spF	Sol tri	Sol vir	Tap spA
Geographic context																		
Proximity to house	*−0.41*	**−0.54***	−0.29	−0.33	−0.04	**0.53***	*−0.39*	*0.39*	−0.11	0.26	0.31	0.05	0.19	−0.14	−0.09	−0.25	−0.13	−0.22
Proximity to village	−0.36	*−0.40*	−0.10	−0.17	−0.28	*0.39*	*−0.42*	*0.40*	0.00	0.11	0.35	0.15	0.21	−0.31	−0.07	−0.20	0.02	−0.11
Proximity to road	−0.02	−0.26	0.22	−0.05	0.07	0.10	0.09	0.24	*−0.41*	*0.44*	−0.03	−0.14	0.12	−0.14	0.08	−0.05	−0.29	−0.16
Socio-ecological context																		
Number of people	−0.04	*−0.40*	0.11	−0.14	0.21	0.27	−0.14	0.17	0.03	−0.04	**0.49***	0.09	−0.15	−0.11	−0.07	−0.23	−0.28	−0.10
Number of goats	0.22	−0.28	0.02	−0.12	*0.41*	0.11	−0.03	0.27	0.04	0.03	0.30	0.08	−0.28	0.05	0.04	−0.10	−0.07	0.09
Number of cattle	0.32	−0.29	0.03	−0.31	*0.44*	0.01	0.17	0.15	*0.43*	*−0.39*	0.14	−0.36	**−0.63****	0.02	0.14	0.28	0.18	0.23
Firewood use	−0.25	−0.31	0.19	0.00	0.18	0.24	−0.13	0.01	−0.11	0.11	**0.55***	0.21	−0.18	−0.16	−0.12	−0.38	−0.31	−0.08
Field data																		
Goat trail length	−0.15	**−0.51***	−0.36	−0.36	0.13	0.25	−0.17	*0.40*	−0.29	0.36	−0.01	−0.21	−0.20	−0.27	0.07	−0.18	−0.22	0.00
Goat dung	0.09	*−0.43*	*−0.39*	−0.32	0.14	0.27	−0.24	0.36	**−0.46***	**0.58****	0.09	−0.14	−0.03	−0.05	−0.09	−0.10	−0.19	−0.08
Cattle dung	0.19	−0.33	−0.01	−0.10	0.38	0.02	0.25	0.06	0.21	−0.22	−0.09	−0.32	−0.20	0.04	*0.38*	−0.02	0.36	0.15
Live wood extraction	−0.24	−0.33	−0.16	−0.34	*−0.38*	*0.40*	−0.33	0.33	−0.14	0.15	*0.39*	0.01	0.32	0.00	−0.34	−0.02	−0.30	−0.27
Fire − wood collection	0.35	−0.27	**−0.48***	**−0.59****	−0.06	0.23	−0.25	**0.54***	0.04	−0.16	−0.15	*−0.40*	0.11	0.17	−0.26	*0.39*	0.08	−0.07
Pressure indices																		
Livestock	0.05	**−0.66****	**−0.55***	**−0.57****	0.21	0.35	−0.25	**0.53***	−0.16	0.10	−0.09	**−0.46***	−0.24	−0.31	0.03	−0.12	−0.09	0.00
Wood extraction	0.19	*−0.44*	*−0.39*	**−0.65****	−0.15	*0.41*	−0.38	**0.59****	0.09	−0.23	0.04	−0.33	0.18	0.09	−0.32	0.29	−0.01	−0.16
People	−0.32	**−0.47***	−0.20	−0.19	0.12	0.31	−0.01	0.11	−0.33	0.32	0.26	−0.18	−0.09	−0.18	−0.07	−0.38	−0.36	−0.16
Global multi-metric index																		
Global	0.04	**−0.70****	**−0.58****	**−0.68****	0.02	**0.48***	−0.28	**0.63****	−0.13	−0.02	0.03	**−0.45***	0.00	−0.20	−0.20	−0.06	−0.11	−0.11

Table 4
Spearman rank correlation coefficients (*r*) for relationships between the original disturbance metrics and the single disturbance pressure and Global CAD indices. * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$. For abbreviations, see Table 1.

	Livestock pressure index	Wood extraction pressure index	People pressure index	Global multi-metric CAD index
Geographic context				
PNH	0.54*	0.12	0.50*	0.49*
PNV	0.39	0.15	0.33*	0.43
PNR	0.27	0.00	0.67**	0.30
Socio-ecological context				
NP	0.24	0.01	0.60**	0.17
NG	0.34	−0.11	0.49*	0.17
NC	0.01	0.26	0.25	0.27
FWU	0.21	−0.26	**0.75*****	0.12
Field data				
GTL	**0.80*****	−0.11	0.58**	0.47*
GD	**0.74*****	−0.15	0.60**	0.41
CD	0.42	0.00	0.27	0.34
LWE	0.01	0.60**	0.22	0.54*
FWC	0.10	**0.92*****	−0.11	0.61**
Disturbance pressure indices				
Livestock		0.11	0.59**	**0.71*****
Wood extraction			−0.01	0.67**
People				0.53*

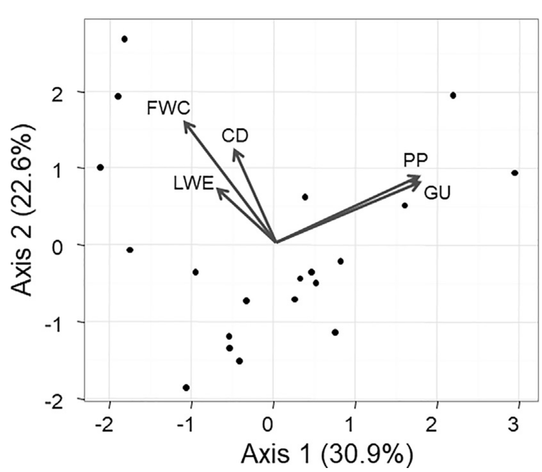

Fig. 3. Principal component analysis (PCA) of study plots (black circles) and the five disturbance metrics used to calculate CAD indices. CD, cattle dung; GU, goat usage; LWE, live wood extraction; FWC, fire-wood collection; PP, people pressure.

et al., 2012), thus providing a mechanistic understanding of biodiversity responses to disturbance.

We have demonstrated the usefulness of our indices by populating them through a case study in semi-arid Brazil, and validating their relevance for biodiversity through an analysis of variation in ant communities, which are commonly used as bioindicators of broader ecological change (Andersen and Majer, 2004). In our case study, the Global multi-metric index showed the highest correlation with overall ant species composition of all the disturbance metrics and pressures. Similarly, the Global multi-metric index was significantly correlated with the abundances of five of the most common ant species, and these correlations were typically higher than those involving any of the original disturbance metrics or with the individual pressure indices. We found significant correlations between the abundances of common species and our pressure indices in the absence of significant correlations with original disturbance metrics, and the abundance of one common species was significantly correlated with our Global multi-metric index without being correlated with any of its component pressure indices. Finally, we showed that different ant measures were correlated with different disturbance pressures; for example, overall ant species composition was correlated with Livestock and People, but not Wood extraction, pressures; the abundances of two common species were correlated with Livestock and Wood extraction, but not People, pressures; and the abundance of one common species was correlated with Livestock pressure only.

Our analysis of the behavior of the different disturbance indices at different levels of data integration in our case study revealed several notable findings. First, measures from indirect sources of information relating to the geographic and socio-ecological context were poorly correlated with direct field measures. For example, proximity to the nearest house or village might be expected to reflect the level of live-wood extraction and fuel-wood collection (Ahrends et al., 2010; Gonçalves et al., 2016), but we found that correlations with field measures were weak or not significant. Similarly, most of the indirect measures of land-use intensity relating to the socio-ecological context were poorly correlated with field measurements of livestock activity, live-wood extraction and fire-wood collection. This suggests that people actively select areas for use that is not a simple function of proximity, due to undocumented cultural and/or environmental factors (Soldati and Albuquerque 2012; but see Ladio and Lozada, 2000). Our interest was in disturbance at the local scale, and the generally poor correlation between socio-ecological and geographic metrics and field-based data can be attributed to the lack of spatial precision of disturbance intensity based on socio-ecological and geographic data. It raises serious questions over their reliability for analyses of CAD at the local scale, as is often done (Sagar et al., 2003; Sagar and Singh, 2004; Urquiza-Haas et al., 2007; Leal et al., 2014; Ribeiro et al., 2016; Ribeiro-Neto et al., 2016). We therefore strongly recommend the use of spatially explicit measurements taken directly in the field for calculating CAD metrics.

Our second notable finding was that the different disturbance pressures in Catimbau National Park (livestock, wood extraction and people pressures) were largely independent of each other. Such independent spatial variability in different disturbance pressures points to complex patterns of resource use by local communities, with different areas targeted for different resources. Thus, for example, although people tend to have their goats in the most accessible areas, this is not where they raise cattle or focus their wood-extraction activities. This can be at least partly attributed to variation in natural resource availability (Gonçalves et al., 2016), given that goats can be sustained throughout Caatinga vegetation because they are generalist browsers (Schlecht et al., 2006), whereas grass for cattle is very patchily distributed. It is also possible that local communities actively avoid overexploitation of areas close to where they live. The independence of the different single-disturbance pressures cautions against the use of single-disturbance measures (e.g., livestock pressure) as indices of overall disturbance in multiple-use landscapes (Stoddard et al., 2008; Schoolmaster et al., 2012).

Our third notable finding is that different weightings of the single-disturbance pressures had little influence on the Global CAD index. This makes the Global index somewhat insensitive to assessments of the relative importance of different disturbance pressures. In terms of the Global index of CAD in Caatinga, it doesn't really matter if fire-wood collection, for example, has twice the ecological impact of other land uses (Medeiros et al., 2012b; Gonçalves et al., 2016). However, we acknowledge that if one disturbance pressure were overwhelmingly dominant then the Global index would need to be appropriately modified to account for it.

Finally, our findings caution against a reliance on multivariate ordination to derive integrated indices of disturbance from disparate data sources, especially when different disturbance pressures are independent of each other. PCA was successful in combining our two metrics relating to goats (goat trail length and goat dung), as well as creating our People pressure index. However, PCA of the five metrics used to calculate the disturbance pressure and Global indices showed that they were associated with three different axes, and some of them operated in opposing directions within the same axis. The use of values from PCA axes as gradients of disturbance intensity would therefore not provide reliable measure of overall CAD, and we believe that the additive approach that we adopted is more robust for deriving a multimetric index for such areas of complex land use.

5. Conclusion

We have presented a framework for developing indices of chronic anthropogenic disturbance based on variably integrated metrics that use both indirect socio-ecological and geographic data sources and measurements taken directly in the field. The framework includes measures of original disturbance indicators, single disturbance pressures, as well as a measure of overall disturbance. We acknowledge that the our specific measurements cannot be generalized to other study systems. However, we believe that our framework for deriving the CAD index is robust and widely applicable. It is of particular relevance to arid and semi-arid areas of developing countries where people are highly dependent on the extraction of a wide range of natural resources (Davidar et al., 2010; Djoudi et al., 2015). We hope that it will facilitate the analysis of the effects of resource use on biodiversity and related ecosystem services, and therefore contribute to effective conservation management and sustainable livelihood development.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ecolind.2018.07.001.

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