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Strict protected areas are essential for the conservation of larger and threatened mammals in a priority region of the Brazilian Cerrado

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ABSTRACT

Assessing protected area (PA) effectiveness is key to ensure the objectives of habitat protection are being achieved. There is strong evidence that legal protection reduces loss of natural vegetation, but biodiversity loss can still happen without significant changes in vegetation cover. Here we use data from a specifically designed camera trap survey to conduct a counterfactual assessment of PA effectiveness at safeguarding local biodiversity in the Brazilian Cerrado. We surveyed the mammal community in 517 locations at the Sertão Veredas-Peruaçu mosaic, distributed across five strict PAs (264 survey sites in five arrays) and two multiple-use PAs with low management levels (253 survey sites in four arrays). We adopted a multi-species occupancy framework to analyse our dataset while also controlling for confounding factors not directly related to protection. Of the 21 species assessed, nine had higher occupancy in strict PAs, one had higher occupancy in multiple-use PAs, and ten did not respond to protection level. Site species richness was nearly twice as large in areas under stricter protection, with even greater differences for species richness of globally threatened and larger mammals (> 15 kg). Overall we demonstrated that the strict PAs surveyed support higher mammal diversity than similar areas under less restrictive management, with a particular strong effect on larger and threatened species. Given that strict PAs cover only 3% of the Cerrado, our results suggest that expanding the area under strict protection is likely to benefit iconic species of the Brazilian savanna, such as the maned wolf and giant anteater.

1. Introduction

Measuring protected area (PA) effectiveness is not a simple task. Due to the number of metrics that could be used and, most importantly, to the challenge of obtaining accurate data on these metrics there is a limited understanding of the extent to which PAs deliver positive biodiversity outcomes (Coetzee et al., 2014; Ferraro and Pattanayak, 2006). Most PA performance evaluations have focused on Management Effectiveness assessments (usually questionnaire-based evaluations on how PAs are managed; e.g. Coad et al., 2015) or on remote sensing data to estimate deforestation levels inside and outside PAs (e.g. Carranza et al., 2014; Ament and Cumming, 2016). Although Management Effectiveness assessments can be useful in adaptive management of PAs, their subjective nature does not allow for robust evaluation of the effects of protection on safeguarding habitats and species (Coad et al., 2015). On the other hand, the amount of deforestation avoided due to habitat protection is clearly a direct conservation outcome and a valid measure of PA success (Geldmann et al., 2013).

Biodiversity loss, however, can still happen without a significant change in vegetation cover. Poaching and bushmeat hunting can severely deplete populations of vertebrates (Corlett, 2007; Peres, 2001; Redford, 1992) and habitat degradation – an impact not easily detected by remote sensing – can have strong negative effects on biodiversity (Barlow et al., 2016; Ribeiro et al., 2015). Therefore reliable measures of conservation outcomes based on local biodiversity metrics are paramount to investigate PA effectiveness and could complement

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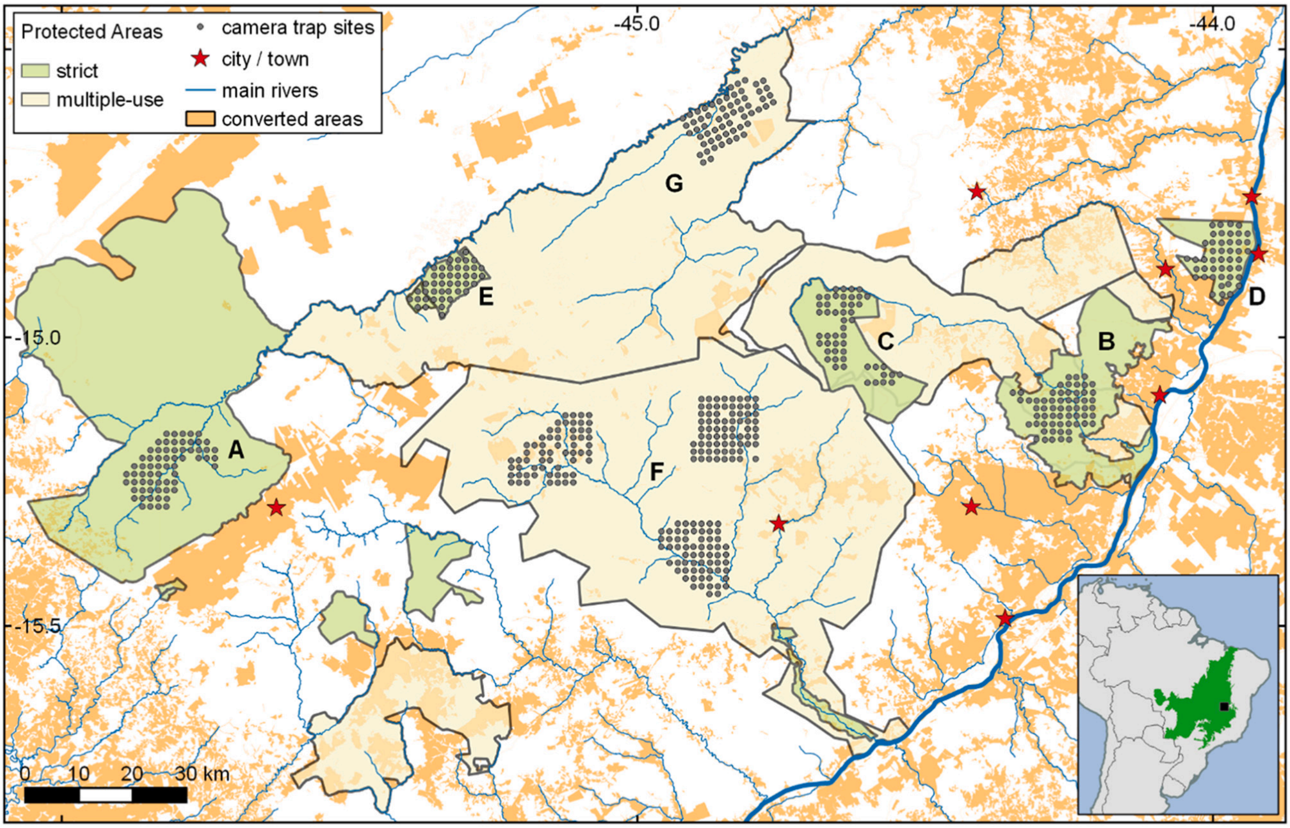

Fig. 1. Location of camera trap sites surveyed at the Sertão Veredas-Peruaçu mosaic, Brazil. Inset shows study area within the Brazilian Cerrado (green). See Table 1 for names and characteristics of protected areas surveyed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

assessments quantifying habitat conversion. Despite the limited amount of data comparing communities and populations in sites under contrasting levels of protection, recent global studies have shown that PAs are to some extent effective in conserving biodiversity, supporting higher species richness and abundance (Coetzee et al., 2014; Gray et al., 2016; but see Venter et al., 2014 and Oliveira et al., 2017 for examples on how the current PA coverage fails to include many species). However, data available for such studies are not homogeneously distributed across the planet, resulting in poor geographic coverage of some regions. A case in point is the Brazilian Cerrado, a global biodiversity hotspot where little information exists about the effectiveness of PAs in conserving local biodiversity.

Given that half of the Cerrado has been converted to anthropogenic land uses (MMA, 2014a) and that just 8% is under PAs (MMA, 2018), it is critical that we obtain information allowing us to understand the effectiveness of habitat protection in safeguarding species. Furthermore, of the already reduced area under protection less than half is within strict PAs (only 3% of the original Cerrado extent – MMA, 2018), making it essential to establish the role of these stricter levels of protection in conserving local biodiversity. However, except for a few assessments showing that Cerrado PAs are effective in avoiding land conversion (Carranza et al., 2014; Françoso et al., 2015) little is known about the effect of habitat protection on this ecosystem, and to our knowledge no counterfactual studies focusing on local biodiversity have been conducted so far. This paucity of evidence is a cause of concern in a time when the very existence of some Brazilian PAs is under threat (Bernard et al., 2014; Silveira et al., 2018) and there is a global trend of weakening the legal protection conferred to natural areas (Mascia and Pailler, 2011).

Here we use data gathered from a large network of camera traps deployed in a priority region for conservation in the Brazilian Cerrado as a counterfactual case study to assess PA effectiveness at safeguarding local biodiversity. Our study was conducted in the Sertão Veredas-Peruaçu mosaic and specifically designed to answer the question: What is the effect of stricter levels of protection on mammal diversity in this landscape? We adopted a multi-species occupancy framework that allowed us to estimate species' probability of occupancy and species richness in two contrasting management regimes while controlling for confounding factors that are not directly related to protection level. We focused our assessment on mammals > 1 kg as they include species that can greatly benefit from effective habitat protection. This is because larger mammals tend to have higher extinction risk than smaller species of this taxonomic group (Cardillo et al., 2005; Cooke et al., 2019) and are negatively affected by anthropogenic pressure (Benítez-López et al., 2019; Chiarello, 1999; Morrison et al., 2007; Ripple et al., 2016). Moreover, this group of species can be effectively surveyed with camera traps, which allows for standardisation of data collection and coverage of large survey areas in a cost-effective manner (Rovero and Ahumada, 2017) – two important features in assessing PA effectiveness based on local biodiversity metrics. Overall, we expected a positive effect of strict PAs on the local mammal community, although we anticipated variation in species' response due to differences in their biology, natural history and conservation status. More specifically, because body size and extinction risk can influence the effect of habitat protection and anthropogenic pressure on terrestrial mammals (Barnes et al., 2016; Boron et al., 2019; Rich et al., 2016; Wearn et al., 2017), we predicted that larger and threatened species would tend to benefit from stricter protection, whereas non-threatened and smaller species would generally show a neutral response to protection level.

2. Material and methods

2.1. Study area

We conducted our study at a mosaic of protected areas located in northern Minas Gerais state, south-eastern Brazil. The Sertão Veredas-Peruaçu mosaic (SVP; Fig. 1) extends over approximately 18,000 km^2 in a transitional area between Cerrado – a tropical savanna ecosystem – and Caatinga – a complex of thorn scrub and seasonally dry forests associated with semi-arid climate (see Supporting information 1 for detailed description of the region). Several vegetation types are found at SVP, but savannas dominate the landscape covering at least 50% of the region (data from SEMAD, 2017), while pasture and agriculture cover approximately 10% (WWF-Brasil, 2011). The climate is markedly seasonal, with well-defined wet and dry seasons, each one lasting for roughly six months; mean annual rainfall ranges from 800 to 1,400 mm and mean temperature is approximately 24 °C (MMA/IBAMA/Funatura, 2003; MMA/IBAMA/Geoclock, 2005). SVP is formed of 14 PAs – eight strict (IUCN categories I-IV) and six multiple-use PAs (IUCN categories V-VI) – and two indigenous lands. The region is a high priority area for biodiversity conservation (WWF-Brasil and MMA, 2015), and harbours 80% of all mammals > 1 kg found in the Cerrado (Ferreira and Oliveira, 2014). In this study, we surveyed seven of SVP's PAs: four national/state parks, one Natural Heritage Private Reserve (RPPN in Portuguese) and two large Environmental Protection Areas (herein referred to simply as APAs according to the Portuguese acronym) (Table 1).

The ultimate goal of parks (IUCN category II) and private reserves (IUCN category IV) is biodiversity conservation and they have strict regulations prohibiting human occupation, land conversion, and direct use of natural resources (Brasil, 2000). Due to similar restrictions to anthropogenic activity these two categories of PAs provide the same level of habitat protection allowing us to treat them as a single group of 'strict PAs'. Conversely, APAs (IUCN category V) are the least restrictive category of multiple-use PA in Brazil, where human settlements and some degree of land conversion are allowed (Brasil, 2000). For this reason, they are not as effective at avoiding Cerrado deforestation (Françoso et al., 2015) and have been described as being closer to a land-management scheme than an actual PA (Rylands and Brandon, 2005). The two APAs assessed in this study have at least 60% of their area covered with natural vegetation (WWF-Brasil, 2011), with low human density distributed across scattered villages and one small town connected by unpaved roads. Due to logistic limitations and their vast area, these APAs are under very low levels of management intervention that are mainly restricted to wildfire suppression during the dry season and localised actions to prevent illegal deforestation.

2.2. Survey design and data collection

A robust PA impact evaluation should use a counterfactual that on average is similar to the area being protected, except for the protection status (Mascia et al., 2017). Therefore, via careful study design and statistical control of confounding variables we accounted for contextual factors that could potentially affect the outcome of interest but were not directly related to protection, such as distance to towns, roads, and water sources, as well variation in vegetation. These factors have a considerable overlap with the ones used by Carranza et al. (2014) to investigate PA effectiveness in avoiding Cerrado deforestation and are known to influence the occurrence of Neotropical mammals (Ferreira et al., 2017; Nagy-Reis et al., 2017; Pinho et al., 2017). In this study, we treated strict PAs as the intervention and APAs as the counterfactual. Although APAs have legal protection status, the low levels of restrictions and management implemented (see Study area) make them an adequate counterfactual to test the effect of protection in Brazil. Furthermore, the areas we surveyed within APAs were largely covered with native vegetation but under little to no conservation intervention, which provided a suitable comparison to strict PAs.

We adapted a standardized camera trapping protocol (TEAM Network, 2011) to survey the mammal community in 517 sampling sites distributed across nine arrays (five in strict PAs and four in APAs) – covering an area of approximately 1,000 km^2 and totalling 26,367 survey days between 2012 and 2017 (Table 1; Fig. 1). Because strict PAs are more likely to be found further away from cities and towns (Joppa and Pfaff, 2009) and this may influence local biodiversity, arrays within APAs were at least 10 km from any town. Additionally, to avoid eventual spill-over of wildlife from strict PAs, arrays within APAs were again at least 10 km from the border of strict PAs. Finally, to ensure a large spatial cover of our sampling and to minimize problems of spatial non-independence, the shortest distance between neighbouring arrays was 12 km (average: 24.7; range: 12–46). Other environmental and landscape characteristics were accounted for in the statistical models (see Data analysis).

Each camera trap array consisted of 43–70 sampling sites systematically distributed at intervals of 1.5 km (Fig. 1). We deployed most camera trap units (Bushnell TrophyCam and Bushnell Aggressor) within a 50-m buffer of the sampling sites' pre-determined coordinates, aiming to select locations that we deemed most likely to record mammals (ca. 3% were 100–200 m away from the pre-determined coordinates due to access issues). Because we followed a systematic design with evenly spaced sampling sites, our survey was not biased towards specific vegetation types or human trails and roads. Cameras were always deployed in natural vegetation areas at least 200 m from smaller settlements or isolated houses, and by only four different researchers to limit variation in deployment. Each camera trap site was surveyed for no more than 74 days (average: 50.8) and only during the dry season (mid-

Table 1
Protected areas surveyed at Sertão Veredas-Peruaçu mosaic in the Brazilian Cerrado.

Protected area	IUCN category	Area (km^2)	Year created	Camera trap sites/survey effort (days)	Human density[a] (people/km^2)	Year surveyed
Strict protected areas						
Grande Sertão Veredas National Park (A)	II	2,300	1989	65/3,767	0	2017
Cavernas do Peruaçu National Park (B)	II	568	1999	60/2,939	0.03	2014
Veredas do Peruaçu State Park (C)	II	312	1994	50/1,826	0	2012
Mata Seca State Park (D)	II	136	2000	46/2,085	0	2013
Porto Cajueiro Private Reserve (E)	IV	90	2004	43/2,048	0	2015
Environmental Protection Areas (APAs)						
Rio Pandeiros (F)	V	3,801	1995	193/10,916[b]	1.14, 2.31, 4.33	2015, 2016
Cochá Gibão (G)	V	2,844	2004	60/2,786	4.59	2017

Letters inside the parenthesis indicate protected areas location at Fig. 1.
[a] Human density at the camera trap array (see Fig. S3 for data source).
[b] Divided in three independent arrays of 60, 63 and 70 camera trap sites.

April to mid-October) to minimize equipment damage and for standardisation purposes. Camera traps sensitivity was set to 'normal', a 30-second interval between sequential triggers was observed and no bait was used to attract animals.

2.3. Data analysis

After accounting for malfunctioning and theft, we divided the survey period into 6-day intervals (survey occasions) and assembled detection/non-detection matrices at 501 camera trap sites for 27 mammal species > 1 kg (*Dasypus novemcinctus* and *D. septemcinctus* were joined under *Dasypus* spp. because they were difficult to distinguish in many images). We used a data augmentation procedure to estimate species richness (Dorazio et al., 2006), adding all-zero detection histories for seven mammal species > 1 kg that occur at SVP (Ferreira and Oliveira, 2014) but were not detected during our survey. We joined these matrices together resulting in a large array of 501 sites, 12 survey occasions of 6 days each, and 34 species.

We used a hierarchical multi-species occupancy framework that allows us to estimate species richness based on a model of species occurrence while accounting for imperfect detection during surveys (Dorazio et al., 2006). The modelling approach assumes that detection and occupancy parameters for each species are drawn from a common distribution governed by hyper-parameters representing the mean effect of covariates over the whole community, which improves precision of individual species estimates (Kery and Royle, 2016). Following Zipkin et al. (2010) approach, we modelled species-level occupancy probabilities at each management regime (strict PA and APA) independently while accounting for the following potential confounding variables: distance from main roads, distance from rivers and lakes, and mean Normalized Difference Vegetation Index (NDVI) of a 500-m buffer around the camera trap site extracted from Landsat 8 images (Table S1). Further details on the modelling approach and on the process of obtaining variables for analysis are described in Supporting information 1. A variable representing human presence at the survey area (e.g. distance from village or house) was not included because human occupation is the main legal difference between APAs and strict PAs in Brazil and, therefore, directly related to management regime. Moreover, distance from towns was accounted for in the survey design.

We assessed the effect of strict protection on 21 species with at least 15 records by taking the difference in occupancy estimates between strict PAs and APAs (both on logit scale) at each iteration of the Bayesian sampling process, where positive values indicate the species had higher occupancy in strict PAs and negative values indicate higher occupancy in APAs. We follow recommendations from MacKenzie et al. (2006) and interpret occupancy estimates as the species' probability of occurring or using the area sampled by a camera trap during our survey period, an approach commonly adopted in similar studies (e.g. Tobler et al., 2015; Rich et al., 2016). Occupancy modelling explicitly accommodates detection probability through an additional hierarchical component of the model (Kery and Royle, 2016), which in our study was modelled as a function of camera trap location in relation to trail (on or off trail) and camera trap model (based on production year) to account for eventual differences in the camera's detection sensor.

To investigate the influence of body size and threat status on the effect of strict protection we constructed two additional models that included distinct hyper-parameters for groups of species according to these two factors (size and threat). In the first model, species were divided into two groups according to body size (larger: > 15 kg; smaller: < 15 kg) and two distinct hyper-parameters governing each of these groups were specified. In the second model species were again divided into two groups, but this time distinct hyper-parameters were specified based on threat status, with nationally threatened species (vulnerable, endangered or critically endangered; MMA, 2014b) forming one group and non-threatened species forming the other. We constructed these additional models using the same formulation and variables as in the model used to obtain species-level estimates, with the exception of distinct hyper-parameters governing the response of species according to the group they belong (Kery and Royle, 2016; Rich et al., 2016). Therefore, the estimated values for hyper-parameters in these additional models represent the mean effect of covariates on a given group of species (i.e. larger vs smaller and threatened vs non-threatened). We used results from these additional models only to investigate the effect of protection on occupancy estimates of species groups and decided to use the model with a single hyper-parameter governing the whole community for species-level inferences because we considered it to be more conservative regarding our predictions.

In multi-species occupancy models, species richness per sampling site (herein site species richness) emerges naturally at each iteration of the Bayesian sampling process as the sum of species occurring at a site (Dorazio et al., 2006). We used the single hyper-parameter model (used to obtain species-level occupancy probability) to estimate mean site species richness at each management regime for all mammal species > 1 kg (overall species richness) and for five subsets of the community: globally threatened species (vulnerable, endangered or critically endangered), nationally threatened species (vulnerable, endangered or critically endangered), non-threatened species (not present in the national Red List), larger species (mean weight > 15 kg), and smaller species (mean weight < 15 kg). Global and national threat status follows IUCN (2017) and MMA (2014b), respectively, whereas species' mean weight was obtained from Marinho-Filho et al. (2002) and Paglia et al. (2012). To assess the influence of protection level on the spatial distribution of species richness, we classified each camera trap site in five distinct groups based on the 20th, 40th, 60th, and 80th percentile of species richness (from 'very low' to 'very high' richness, respectively) and plotted them on a map.

We adopted a Bayesian approach to implement all models in JAGS (Plummer, 2013) through R (R Development Core Team, 2015) using the package JagsUI (Kellner, 2017). After a burn-in of 30,000 iterations, we ran three chains of 90,000 iterations with a thinning rate of 10, and assessed convergence with R-hat statistic (Supporting information 1). We used vague priors for all parameters estimated and conducted a prior sensitivity analysis, as well as an assessment of model fit (Supporting information 1; Table S2). All inferences are based on posterior means and 95% credible intervals. R code for the multi-species occupancy model is available as Supporting information 2.

3. Results

3.1. Species occupancy

Protection level had a strong effect on almost half of the species assessed (10 of 21), of which nine had higher occupancy in strict PAs and one in APAs (Fig. 2 top panel; Table S3). As predicted, our results show that larger and threatened species tend to benefit from strict protection: seven of the eight largest species, 75% of the globally threatened and 66% of the nationally threatened species assessed had higher occupancy probability in strict PAs. It is striking that occupancy probability of large and functionally important species such as puma (*Puma concolor*), maned wolf (*Chrysocyon brachyurus*), tapir (*Tapirus terrestris*), peccaries (*Pecari tajacu* and *Tayassu pecari*) and giant anteater (*Myrmecophaga tridactyla*) was at least five times higher in SVP's strict PAs - for some the difference was tenfold (Table S3).

Conversely, hoary fox (*Lycalopex vetulus*) – a small-sized canid nationally listed as vulnerable – was the only species with higher probability of occupancy in APAs. For another 11 species, protection level did not seem to have a strong effect – although the crab-eating fox (*Cerdocyon thous*) and hog-nosed skunk (*Conepatus semistriatus*) tended to favour APAs, and ocelot (*Leopardus pardalis*) strict PAs (but credible intervals overlapped 0). As predicted, species that did not respond to protection level were generally smaller (only one species > 15 kg; grey brocket deer – *Mazama gouazoubira*) and non-threatened (only two

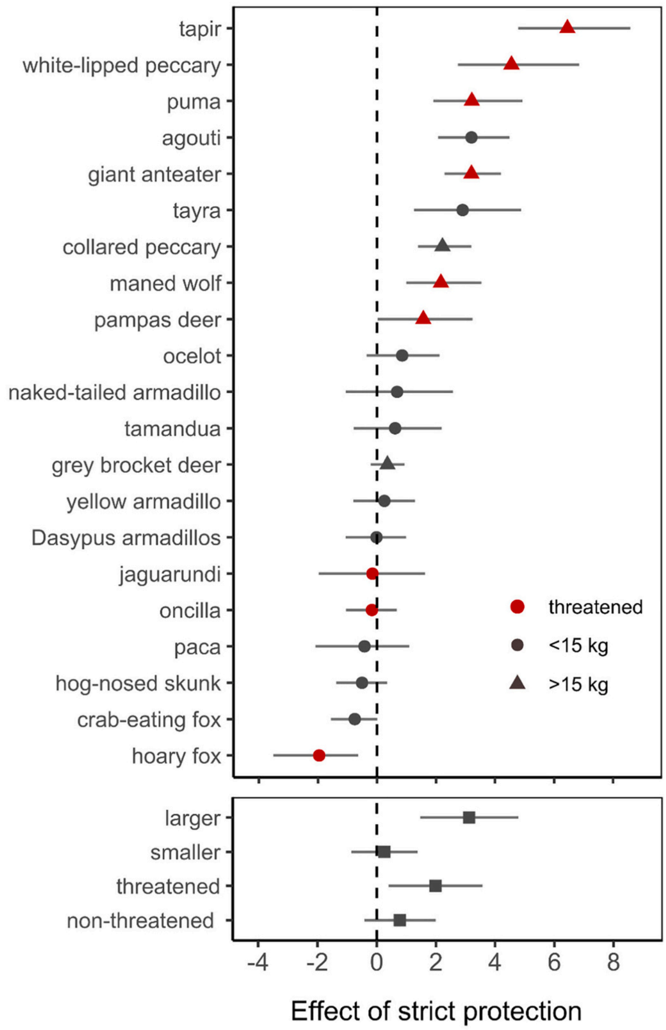

Fig. 2. Effect of strict protection on the mammal community at Sertão Veredas-Peruaçu mosaic. Symbols represent the posterior means of the effect and lines the 95% credible interval; red symbols denote nationally threatened species. Effect was estimated as the difference in probability of occupancy (logit scale) between strict protected areas and APAs, with positive values indicating higher occupancy in strict protected areas and negative values indicating higher occupancy in APAs. Top panel displays species-level estimates obtained from a multi-species occupancy model with a single hyper-parameter specification and the bottom panel displays group-level estimates from models with distinct hyper-parameters for each group (see Data analysis). Refer to Table S3 for species' Latin names and probability of occupancy at each management regime. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

threatened species, both of them small felids: oncilla – *Leopardus tri-grinus* – and jaguarundi - *Herpailurus yagouaroundi*). Confirming the patterns observed for individual species, the additional models with distinct hyper-parameters for species groups indicated that, on average, larger and threatened species benefit more from strict protection than smaller and non-threatened species (Fig. 2 bottom panel).

3.2. Species richness

Mean site species richness was greater in strict PAs, with nearly twice as many species as in APAs (Fig. 3; overall). The same pattern was observed for subsets of the community, with greater richness in strict PAs regardless of body size or threat level (Fig. 3). However, the effect of stricter protection was even greater for larger (> 15 kg) and globally threatened species richness, with 2.7 and 2.4 times more species per site in strict PAs than in APAs, respectively. On the other hand, the difference between management regimes on smaller species richness was more moderate, with only 1.3 times more species in strict PAs. The spatial distribution of species richness was also largely driven by protection level, with 'very low' species richness sites only found in APAs and 'very high' richness sites highly concentrated in strict PAs (Figs. 4, S1) – a pattern also found for the spatial distribution of species richness of subsets of the mammal community (Fig. S2).

4. Discussion

4.1. Biodiversity patterns in contrasting levels of protection

Using a counterfactual analysis, we provide empirical evidence that strict PAs at the Sertão Veredas-Peruaçu mosaic – a priority region for conservation in the Brazilian Cerrado – support higher levels of mammal diversity than similar areas under less restrictive management. To our knowledge this is the first counterfactual assessment of PA performance regarding local terrestrial biodiversity in the Cerrado, and one of the few in Brazil (see Coetzee et al., 2014 and Gray et al., 2016 for global assessments including data from Brazil, and Xavier da Silva et al., 2018 for a longitudinal evaluation of Iguaçu National Park in the Atlantic Forest). Our results are consistent with similar studies in Africa that found areas with stricter protection to support greater mammal diversity (Kinnaird and O'brien, 2012; Rich et al., 2016) and with research showing negative effects of anthropogenic pressure on some Neotropical mammals (Cruz et al., 2018; Michalski and Peres, 2005; Nagy-Reis et al., 2017).

We also demonstrated a strong positive impact of strict PAs on larger and threatened mammals, which seems to be part of a broader trend of large-bodied species benefitting more from strict protection than smaller species (Drouilly et al., 2018; Kinnaird and O'brien, 2012; Rich et al., 2016; Velho et al., 2016). Interestingly, size seems to have even greater influence on the effect of strict protection than threat status in the mammal community studied. The difference in occupancy between the two management regimes assessed was much greater for the larger vs smaller comparison than for the threatened vs non-threatened comparison (Fig. 2 bottom panel). Similarly, we observed a greater difference in species richness between strict PAs and APAs for larger than for smaller species, whereas the difference was more stable among threatened and non-threatened species – although still larger for globally threatened species (Fig. 3). As larger mammals are disproportionally affected by hunting (Benítez-López et al., 2019; Ripple et al., 2016) and severely threatened by habitat loss and fragmentation (Chiarello, 1999; Morrison et al., 2007), these species are likely to benefit from interventions that mitigate anthropogenic threats, such as the creation of strict PAs.

Our analyses suggest that top predators, large insectivores and large herbivores/frugivores are extremely rare in the APAs surveyed, as none of them had a probability of occupancy greater than 10% (Table S3). Moreover, larger species richness in APAs only reached one-third of the richness in strict PAs. The absence of these large and functionally important animals in extensive parts of these APAs, combined with the low occupancy of the seed-disperser agouti (*Dasyprocta azarae*), is likely to have profound impacts on the ecosystem, affecting the plant community, nutrient cycling and even carbon storage (Bello et al., 2015; Dirzo et al., 2014; Enquist et al., 2020; Terborgh et al., 2001). On the other hand, a subset of the local mammal community seems to thrive in SVP's less restrictive areas. This group of species, however, is mainly composed by smaller, non-threatened mammals, known to tolerate or favour degraded habitats, but also includes the globally threatened oncilla and two nationally vulnerable small carnivores (hoary fox and jaguarundi).

Our findings are extremely unlikely to reflect natural patterns of species occurrence that existed before the PAs were created, instead there is strong evidence that the patterns reported here reflect levels of

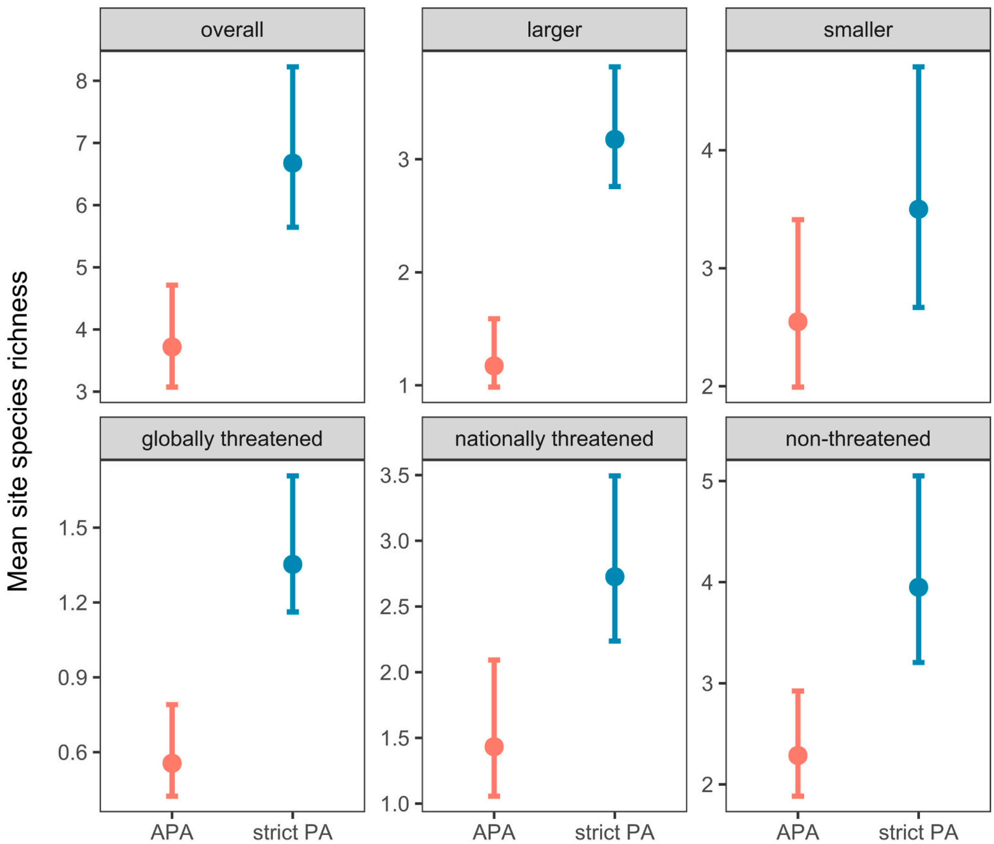

Fig. 3. Mean camera trap site species richness at the two management regimes assessed: APA and strict protected area (PA). Richness is presented aggregated over all species (overall) and for five subsets of the mammal community. Points are posterior means and lines indicate 95% credible intervals. Larger species are mammals with mean weight > 15 kg, whereas smaller species have mean weight < 15 kg.

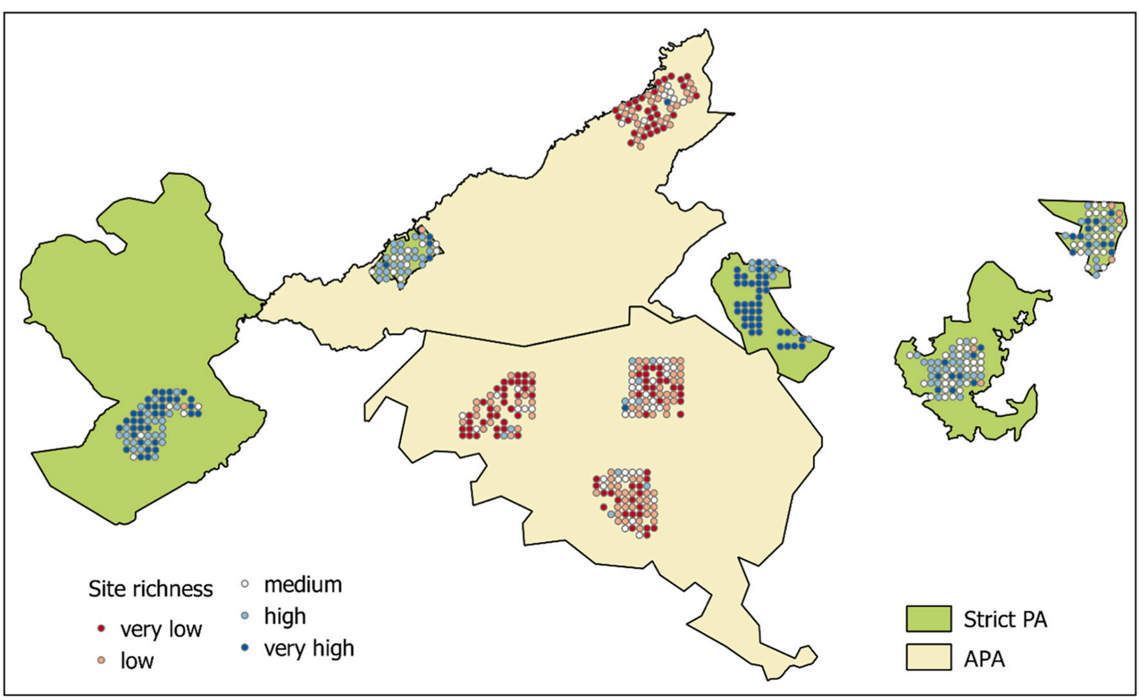

Fig. 4. Spatial distribution of mammal species richness per camera trap site at Sertão Veredas-Peruaçu mosaic, Brazilian Cerrado. Only protected areas surveyed are shown. See Fig. S2 for results on subsets of the mammal community.

protection. Firstly, spatially explicit biodiversity metrics were not available (and are still scarce) when SVP's parks and private reserves were created; their establishment was mainly driven by a mix of opportunity, scenic beauty and an attempt to protect large tracts of remaining natural vegetation. Additionally, we accounted for important confounding factors – both in study design and analysis – that could influence the occurrence of mammals in the region. In fact, we believe the pattern observed here may be found in other areas of the Cerrado, as our surveyed areas within APAs have lower human density than the average PA in the same category (Fig. S3) and SVP's natural vegetation cover of 80% (WWF-Brasil, 2011) is higher than at the biome level. However, this is likely to be the case only in regions of the Cerrado under similar or higher anthropogenic pressure than SVP and where strict PAs are relatively well implemented – the strict PAs surveyed here have lower human density than the average for state and national parks in the biome (Fig. S3).

4.2. Conservation and policy implications

Our results combined with Cerrado-wide assessments of PA effectiveness in avoiding deforestation (Carranza et al., 2014; Françoso et al., 2015) are strong arguments against attempts to downgrade or downsize PAs in Brazil (e.g. de Marques and Peres, 2014; Bernard et al., 2014) and provide scientific evidence on the value of strict PAs for mammal conservation in northern Minas Gerais. Although further investigation on the impact of strict habitat protection on local biodiversity must still be conducted in other parts of the Cerrado, we suggest that an increase in the scant coverage of strict PAs in the biome – currently at only 3% (MMA, 2018) – is likely to benefit species negatively affected by anthropogenic pressure, such as larger and threatened mammals in our study area. Furthermore, considering that the main difference between the two management regimes assessed – in practical and legal terms – is human use and occupation, it is reasonable to assume this is one of the main drivers of our results. Locally, small human settlements are known to negatively affect occupancy of a mammal species favoured by poachers (Ferreira, 2018). Therefore, we suggest that solving land tenure issues in strict PAs and adopting strategies to reduce anthropogenic pressure within these reserves should be a priority for environmental agencies and managers. This is echoed by Françoso et al. (2015) who showed deforestation rates to be higher in Cerrado PAs with unsolved land tenure problems. Indeed, adequate implementation and management of PAs, as well as increase in PA coverage, are strategic goals of the Cerrado national action plan (MMA, 2014a), one of the key conservation policies for the biome.

As a complementary approach, a sound zoning system (e.g. establishment of core areas and corridors) has the potential to improve the effectiveness of APAs in the study region. Such measures are difficult to implement on the ground, but they could be more successful if focused on large rural properties (Stefanes et al., 2018). Agencies issuing permits to convert natural vegetation within such properties should work together with APAs managers and land owners to indicate the best location for the compulsory legal reserves (proportion of land that cannot be converted according to Brazil's Native Vegetation Protection Law – Brancalion et al., 2016) and to negotiate compensations, such as the establishment of private reserves (RPPNs) in strategic areas.

Finally, our results highlight that simple metrics of overall PA coverage are unlikely to ensure that conservation end-goals will be achieved (Barnes, 2015) and that a better integration of biodiversity and deforestation monitoring initiatives (Roque et al., 2018) within a counterfactual framework (Mascia et al., 2017) is needed to provide reliable indicators of PA performance in Brazil. Only by adopting metrics that reflect conservation end-goals will it be possible to know whether PAs are reaching their objectives and to direct the actions necessary to improve effectiveness of the national PA system. This study provides a local scale example of PA effectiveness assessment using indicators directly linked to local biodiversity metrics, which could be scaled up to the biome or national level. However, our assessment still has the limitation of not providing information on population trends over time. Because declines can occur inside PAs (Craigie et al., 2010), long term monitoring of PAs over sequential years is necessary to ensure they are operating at their maximum effectiveness. The survey and analytical approach adopted here is being successfully used to monitor trends of tropical forest vertebrates across the globe (Beaudrot et al., 2019) and could be implemented over the years in selected Cerrado PAs.

4.3. Conclusion

Here we showed that conservation performance differed between areas under distinct levels of protection in a priority region of the Brazilian Cerrado, with higher mammal diversity found in strict PAs. We acknowledge that strict protection is not the only way forward and that a mix of management regimes and strategies are necessary to promote Cerrado conservation while accommodating the needs of human populations and agriculture production (MMA, 2014a; Strassburg et al., 2017). However, our work supports the conclusion that strict PAs play a vital role in maintaining larger and threatened mammal species in our study region and without them iconic animals such as maned wolves and giant anteaters will struggle to persist in this landscape.

Declaration of competing interest

GBF was part of SVP's advisory council between 2010-2016 and part of Cavernas do Peruaçu National Park's council between 2014-2016; MSP was also member of this park's council between 2016-2018. IDESE manages the private reserve (RPPN) surveyed.

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CRediT authorship contribution statement

I hereby declare that this work is all original research carried out by the authors. This manuscript has not been published or accepted for publication elsewhere, and has not been submitted to any other journal or book. All persons entitled to authorship have been named in the manuscript and all authors have seen and agreed to this submitted version. I have obtained all permits from the relevant agencies to conduct this research, and I have acknowledged all sources of funding as well as potential conflicts of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2020.108762.

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