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Land-use changes and the expansion of biofuel crops threaten the giant anteater in southeastern Brazil

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Land-use changes impact biodiversity, and biofuel crop production and its expansion pose as an important driver of negative effects in the tropics. Understanding the influence of land-use changes on suitable habitats for species is a worldwide conservation challenge, particularly on large-sized mammals. We modeled habitat suitability of the threatened giant anteater (*Myrmecophaga tridactyla*) in the Brazilian State of São Paulo. The region is the most populous and economically developed of the country and is the world's main sugarcane production area. We aimed to 1) map habitat suitability for the giant anteater population in the State; 2) assess the contributions of selected landscape and anthropogenic predictors to species habitat suitability; and 3) quantify suitable habitats in environmental protection areas and in areas threatened by the sugarcane expansion. We used a two-step analysis: First, we created a suitability map in the species' distributional range (Drange); from this map, we extracted the results for São Paulo State. Second, we built a regional model to predict the current scenario of São Paulo using the following environmental layers: 1) the resulting distributional range map for giant anteater (Drange); 2) landscape metrics; and 3) anthropogenic factors that might affect anteaters. The State of São Paulo presented, in general, very low values of habitat suitability. The following predictors made the greatest contribution: Drange, vegetation connectivity and distance to protected areas. Suitable habitats for anteaters within strictly protected areas are very scarce (1.6% of the total area), and 22% of the suitable areas are expected to be altered by future sugarcane expansion. Suitable habitats on private lands must play a role in conserving biodiversity.

Mudanças no uso da terra têm impactos na biodiversidade e a produção e a expansão de biocombustíveis representam um importante fator de efeitos negativos nos trópicos. Compreender a influência das mudanças no uso da terra em hábitats adequados para as espécies é um desafio conservacionista mundial, particularmente para mamíferos de grande porte. Para avaliar tal influência, modelamos a adequabilidade de hábitat do ameaçado tamanduá-bandeira (*Myrmecophaga tridactyla*) no Estado brasileiro de São Paulo. A região é a mais populosa e economicamente desenvolvida do país e é a principal área de produção de cana-de-açúcar do mundo. Nossos objetivos foram: 1) mapear a adequabilidade de hábitat para a população de tamanduás-bandeira no estado de São Paulo; 2) avaliar a contribuição dos principais preditores à adequabilidade de hábitat para a espécie; e 3) quantificar hábitats adequados em áreas de proteção ambiental e em áreas ameaçadas pela expansão da cana-de-açúcar. Usamos uma análise em duas etapas: primeiro, criamos um mapa de adequabilidade na área de distribuição da espécie (Drange); a partir dele, extraímos os resultados para o estado de São Paulo. Segundo, construímos um modelo regional para predizer o cenário atual de São Paulo usando as seguintes camadas ambientais: 1) mapa resultante da adequabilidade na distribuição geográfica da espécie para o recorte estadual, 2) métricas de paisagem e, 3) camadas antrópicas. O estado de São Paulo apresentou, em geral, valores muito baixos de adequabilidade de hábitat. Os seguintes preditores deram as maiores contribuições: Drange, conectividade de vegetação e distância às áreas protegidas. Hábitats adequados para tamanduás-bandeira dentro de áreas estritamente protegidas são muito escassos (1,6%), e 22% das áreas adequadas devem ser convertidas futuramente em cana-de-açúcar. Hábitats adequados em terras privadas devem desempenhar um papel na conservação da biodiversidade.

Key words: bioethanol, mammals, Pilosa, protected areas, species distribution modeling

In the 21st century, anthropogenic activities dominate ecosystems at multiple scales through agriculture and animal grazing, deforestation, mining, biofuel production, infrastructure development (roads, dams, railroad, power lines), human settlements, and urbanization (McGill et al. 2015; IEA 2016). These land-use changes have their drivers in complex political and socioeconomic features (Nelson et al. 2006) and have impacts on biodiversity (McGill et al. 2015). Modeling studies have shown that land-use changes strongly decrease the local terrestrial biodiversity (Newbold et al. 2015) and historical land-use changes are estimated to have caused vertebrate communities to lose 11% of species compared with pristine habitats (Newbold 2018). The human population is still growing (IEA 2016); thus, the trends expected for biodiversity are continuing depauperization and biotic homogenization.

An important driver of multiscale land-use change is energy crop production and its expansion (Verdade et al. 2015). Conversion of natural habitats into biofuel crop plantations has negative environmental consequences on biodiversity due to habitat loss, the intense use of agrochemicals that could cause soil, water, and biota contamination, and the rise of road-kill risks, pollution, and bioinvasions (Campbell and Doswald 2009; Rudorff et al. 2010; Verdade et al. 2015). The world's largest producer of sugarcane (*Saccharum* spp.) is Brazil, having its core production area in São Paulo State, a region originally covered by Cerrado and Atlantic Forest biomes and currently the most populous and economically developed state of the country, where most of the sugarcane mills and industrial plants are located (Goldemberg et al. 2008; Rudorff et al. 2010).

Landscapes dominated by sugarcane fail to provide resources needed by a large assemblage of mammals, although many species are still recorded (Dotta and Verdade 2011; Magioli et al. 2016; Beca et al. 2017). The giant anteater (*Myrmecophaga tridactyla*, hereafter simply anteater) is one of the mammals that has its environment affected by the establishment and expansion of sugarcane crops (Superina et al. 2010). This species is a large-sized Neotropical mammal considered by the International Union for Conservation of Nature (IUCN) as threatened (Miranda et al. 2014), and is also considered threatened in Brazil (Miranda et al. 2015) and in São Paulo specifically (Chiquito and Percequillo 2009). Their population is declining across the country, and many regional populations are small or have been extirpated (Miranda et al. 2014), mainly due to habitat loss. Current ecological and behavioral knowledge about the species comes from studies conducted in well-preserved or protected areas (Camilo-Alves and Mourão 2006; Vynne et al. 2011), with their ecology and habitat use in anthropogenic and nonprotected areas relatively unevaluated (Superina et al. 2010). Nonetheless, the "2010 Anteater Assessment" clearly states that the conversion of suitable habitat to plantations is affecting the Brazilian populations (Superina et al. 2010).

Environmentally protected areas are a common strategy to limit biodiversity decline and species extinction (Joppa et al. 2009). However, alone they are insufficient to ensure the species' maintenance (Jenkins and Joppa 2009) because only 12% of the globe's land surface is currently under environmental protection. An increase in the proportion of natural environments protected within reserves is needed to strengthen this conservation strategy; future biodiversity may depend on the ability of those reserves to protect it (Jenkins and Joppa 2009). Therefore, it is essential to understand how agricultural expansion threatens endangered species to better assess environmental protection and develop effective conservation strategies and actions.

This study aims to 1) map habitat suitability for the giant anteater in the State of São Paulo, in southeastern Brazil; 2) assess the contribution of selected landscape and anthropogenic predictors for habitat suitability of the species; and 3) quantify suitability within protected areas and in areas threatened by sugarcane expansion. We predicted that 1) factors at the landscape level (such as connectivity) would play a determinant role in predicting habitat suitability, 2) areas identified as suitable habitat for anteaters would converge with protected areas, and 3) suitable areas in nonprotected lands would overlap with areas of the sugarcane expansion zone that are mostly natural remnants.

Materials and Methods

Study area.—The current study was developed in two steps, at two spatial extents. First, we modeled the anteater's habitat suitability within its distributional range (Drange), aiming to produce a bioclimatic and topographic layer (see details in subsection "Predictor variables"). We based our analyses on the geographic range map for giant anteaters defined by the IUCN, from Honduras to southern South America, comprising a total area about 13 million km^2 (Fig. 1). The distribution of the anteater is dominated by the equator-to-pole thermal gradient, where the average temperature is 20°C within the Tropical Belt (20°N to 20°S). Our second step, and our main goal, was to focus on the state of São Paulo, which has one-quarter of its territory covered by sugarcane crops, with an additional 11% planned to become sugarcane plantation (Fig. 2).

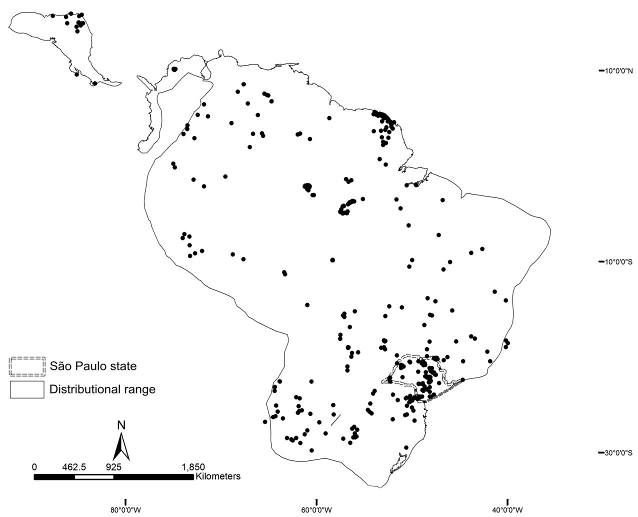

Fig. 1.—Giant anteater (*Myrmecophaga tridactyla*) records in the distributional range (from Honduras to southern South America), used to build the species distribution model.

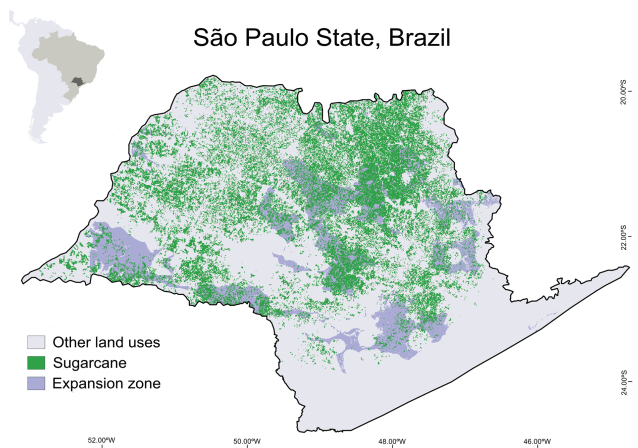

Fig. 2.—Sugarcane plantations in São Paulo State, Brazil, and the area susceptible to the expansion of sugarcane plantations.

A sugarcane field resembles an open area in its first stage of succession (leaves up to 1 m tall); it subsequently appears as a dense block of gramineous vegetation with long leaves (1–3 m tall) during the middle and the preharvest stages. We obtained the boundaries of São Paulo from Instituto Brasileiro de Geografia e Estatística (IBGE, http://www.ibge.gov.br) and used this shape to extract the São Paulo region from the distributional range model. The extent of the São Paulo model was 221 thousand km^2.

Anteater occurrence records.—We obtained occurrence data from different sources (details in Supplementary Data SD1; Fig. 1) through the journal *Edentata* (http://xenarthrans.org/newsletter), including records found in cited publications; the Species Link database (http://www.splink.org.br); the Red Book of the State of São Paulo (Chiquito and Percequillo 2009); and records from our own field surveys. The records date back to the 1980s. Because we share the philosophy of open data and open science, all data used in this study were already incorporated in the Neotropical Xenarthrans data set (access the following Github repository: https://github.com/LEEClab/Neotropical_Series and select Neotropical Xenarthrans).

Spatially rarefying occurrence data.—The data set of occurrence records indicated that some areas were sampled more intensively than others, which could result in a model with overfitting. Therefore, we spatially rarefied the records to reduce spatial autocorrelation; however, to avoid a subjective exclusion, we chose a filtering procedure based on the size of the anteater's home range. We selected only studies that described home ranges using the Minimum Convex Polygon method, because they are most numerous in the literature (Supplementary Data SD2); we found an average home range size of 6 km^2. Assuming a circular home range, we applied a buffer of 1.38-km radius (the radius of a 6-km^2 circle) around grouped records and only kept the most central one. This procedure is recommended to improve the calibration and evaluation of models (Fortin and Dale 2005; Boria et al. 2014; Brown 2014).

Predictor variables.—All the layers we used in our models have a resolution of 30 arc-seconds (approximately 1 km^2). Before running the analysis, we evaluated the redundancy in environmental layers through principal component analysis (PCA) and Pearson correlation (r). Only the most informative and less-correlated layers were kept (Angelieri et al. 2016). First, to assess the response of giant anteaters to climate and topographic predictors, we modeled habitat suitability in the species' distributional range. Then, we extracted from the resultant model the boundaries of São Paulo (Drange; Table 1). The Drange layer was a necessary step in the modeling procedure because of the response of giant anteaters to all climate and topographic features, as proposed by Barve et al. (2011), Sánchez-Fernández et al. (2011), and Raes (2012). The layers applied in the distributional range were temperature (Bio02, Bio05, Bio06), precipitation (Bio13 and Bio14), elevation, and slope (Table 1). In the São Paulo model, we included landscape and anthropogenic predictors (Table 1), in addition to Drange, to predict the current scenario of the species in the state. We generated landscape predictors of the amount of functionally connected habitat (Ribeiro et al. 2009; Martensen et al. 2012) available to the species, based on its ability to cross a 240-m gap between patches (Shaw et al. 1985). We accomplished this using the vegetation map of the Forest Institute of São Paulo (Instituto Florestal de São Paulo—Kronka 2010), which featured three land cover types: savanna, forest (native remnants), and forestry (commercial timberland of *Eucalyptus* spp. and *Pinus* spp.). Bearing in mind the gap-crossing ability and the three land cover types, we clustered habitat patches that were connected within 240 m to calculate functional connectivity as follows: 1) forest plus forestry connectivity (Forcon240); and 2) native vegetation plus forestry connectivity (savanna, forest, and forestry; Natcon240). These procedures were performed in 6.4.3 GRASS software (Neteler et al. 2012) using the package LSMetrics—https://github.com/LEEClab/ls_metrics. The land cover types were given by Kronka (2010) at 30-m resolution; after the geoprocessing techniques in GRASS using the "clump" metric, we resampled them at 1-km^2 resolution. The anthropogenic predictors were the 2010 human population

Table 1.—Predictors used in the habitat suitability model for the giant anteater (*Myrmecophaga tridactyla*) in São Paulo State, the most populous and economically developed State of Brazil and the world's main sugarcane producer. All the layers have a resolution of 30 arc-seconds (approximately 1 km^2). * refers to the distributional range extent and ** to the São Paulo State extent.

Predictors	Description and source
Environmental variables	
Mean diurnal range (mean of monthly (max temp – min temp)) (Bio02)*	Bioclimatic variables derived from the monthly temperature or rainfall values. Data were generated through interpolation. From WorldClim (www.worldclim.org—Hijmans et al. 2005).
Maximum temperature of warmest month (Bio05)*	
Minimum temperature of coldest month (Bio06)*	
Precipitation of wettest month (Bio13)*	
Precipitation of driest month (Bio14)*	
Elevation*	Map of digital elevation model. From Atlas of the biosphere (www.sage.wisc.edu/atlas).
World relief slope*	Slope percentage rise calculated from Elevation map. From SRTM spatial mission (project www2.jpl.nasa.gov).
Distributional range model (Drange)**	The distributional range model cropped to São Paulo State boundaries. This model used the variables listed above.
Landscape variables	
Forest + forestry connected (Forcon240)**	Functional connectivity based on a 240 m gap-crossing built on São Paulo vegetation types (Kronka 2010). Layers generated by us.
Native vegetation + forestry (Natcon240)**	
Anthropogenic variables	
Human population density (HPD)**	Human population density in 2010. From Socioeconomic Data and Applications Center (www.sedac.ciesin.columbia.edu/gpw).
Road density (Roaden)**	Kernel density of roads in São Paulo State with respect to the length per square map unit in 100 km^2 neighborhood (m/m^2), based on state and federal highways. From Brazilian Ministry of the Environment (http://mapas.mma.gov.br/geonetwork).
Distance to protected areas (PAdist)**	Euclidean distance (m) between all municipal, state, and federal protected areas. From Brazilian Ministry of the Environment (http://mapas.mma.gov.br/i3geo/datadownload.htm).

density (HPD), road density (Roaden), which is the density of roads in the State of São Paulo, and distance to protected areas (PAdist), the Euclidean distance between all municipal, state, and federal protected areas (Table 1). To summarize, we applied Drange, Forcon240, Natcon240, HPD, Roaden, and PAdist to model the habitat suitability of the giant anteater in São Paulo State.

Modeling procedures.—We used the maximum entropy (Maxent version 3.3.3k) approach to develop a species distribution model for giant anteaters at both extents (Elith et al. 2010). This method has been shown to perform better than other modeling methods using presence-only data due to its capacity to fit complex responses and to choose an appropriate set of predictors (Elith and Leathwick 2009). We ran Maxent using a maximum of 500 iterations, with a convergence threshold of 0.00001 and 10,000 randomly generated background localities. We modeled 20 bootstrap replicates, randomly selecting 70% of the points to generate models and using the remaining 30% for accuracy assessment. We used the testing points to calculate the area under the curve (AUC). The AUC considers the proportion of correct and incorrect predictions over the possible thresholds, and its values range from 0.5 to 1. Values close to 0.5 indicate a fit no better than that expected randomly, while a value of 1 indicates a perfect fit (Elith et al. 2006). The habitat suitability map was composed of pixels whose quantitative values ranged from 0 to 1, where higher values signify more suitable areas.

Post-modeling analysis.—The anteater habitat suitability map is the average model of the 20 bootstrap replicates. To generate the final maps, we used a 10% training presence threshold (distributional range value = 0.251; São Paulo value = 0.245), which predicts unsuitable habitat for the 10% most extreme observations (e.g., Morueta-Holme et al. 2010), resulting in a binary map (0 = unsuitable; 1 = suitable). Then, we overlaid the São Paulo model with the protected area and sugarcane polygons. For the protected area, we considered the two major categories of Brazilian protected areas: full protection (labeled as strictly protected) and sustainable use. The former does not allow human interference in maintaining the ecosystems; the latter allows human presence, because it aims to balance conservation with a reasonable use of resources (Rylands and Brandon 2005). For the sugarcane production, we used the polygons of São Paulo's sugarcane crops in 2013 (CANASAT Project using techniques of Rudorff et al. 2010) and the state's agroecological zoning for sugarcane expansion (www.ambiente.sp.gov.br/etanolverde/zoneamento-agroambiental) to delineate current areas with the crop and its expansion. Those two polygons were merged into a single sugarcane layer (Fig. 2). Then, we compared the values of habitat suitability inside and outside protected areas, and also inside and outside sugarcane crops using Kruskal–Wallis tests. These analyses were performed using ArcGis 10.2 (ESRI 2014) and R software (R Development Core Team 2016).

Results

We collected 461 records of anteaters in the distributional range; 149 of those records were from the State of São Paulo (Fig. 1; Supplementary Data SD1). However, after our spatially rarefying procedure, we used 359 and 90 occurrence records, which were used to model habitat suitability for the anteater within the distributional range and within the state, respectively.

The distributional range model was statistically significant (AUC = 0.80 ± 0.02, omission error = 0.1, $P < 0.001$), predicting environmental suitability for about 47% of the species' range (Supplementary Data SD3). The predictors Bio06 (Minimum temperature of coldest month) and Bio14 (Precipitation of driest month) were the most important in the habitat suitability model, accounting for 55% of its explanatory power (Supplementary Data SD3). Visual inspection of the predictor Drange found environmental suitability for more than 50% of the state's total area (Supplementary Data SD3), which is consistent with the prediction that the state could support a greater distribution of anteaters in the absence of anthropogenic pressures.

The São Paulo model had a reasonable goodness of fit (AUC = 0.70 ± 0.06, omission error = 0.1, $P = 0.008$), predicting that 161.3 thousand km^2 has some degree of suitability for the occurrence of anteaters (Fig. 3). The model showed habitat suitability in the central to eastern regions of the state, with a conspicuous strip of inadequate habitat in the west of the state (Fig. 3). The average suitability value was about 0.26. Pixels with suitability values higher than 0.5 were present in only 10% of the state. The predictors Natcon240, Drange, and PAdist made the greatest individual contributions to the model (31%, 23%, and 17% gain, respectively; Fig. 4).

The suitable areas for anteaters were located far from human population densities greater than 5,000 per km^2 (Fig. 5). A pattern emerged in which the regions with low concentrations of humans are more suitable for the species. Additionally, the predictor Roaden made only a minor contribution to our model (only 8% gain). However, this variable gave the map a distinctive visual scenario of channels connecting the nonsuitable areas (Fig. 3); in fact, these channels are the greater part of São Paulo State's road network.

Habitat suitability within protected areas corresponded to only 1.6% of the area within the strictly protected category and 11.5% within the sustainable use category, showing that only 21.1 km^2 of the state's protected environment is suitable habitat for anteaters. We compared the values of habitat suitability outside protected areas and within protected areas from both strictly protected and sustainable use categories by a Kruskal–Wallis test ($H = 42034$, $d.f. = 2$, $P < 0.01$; Fig. 6A), and we found lower values of suitability inside of the strictly protected areas. In addition, about 22% of the areas that have some degree of suitability for anteaters are potentially threatened by sugarcane plantations; 15% are already occupied by sugarcane, and the other 7% are expected to be converted in the near future (Fig. 2). Habitat suitability values were lower inside the sugarcane areas (Kruskal–Wallis test, $H = 4099$, $d.f. = 2$, $P < 0.01$; Fig. 6B).

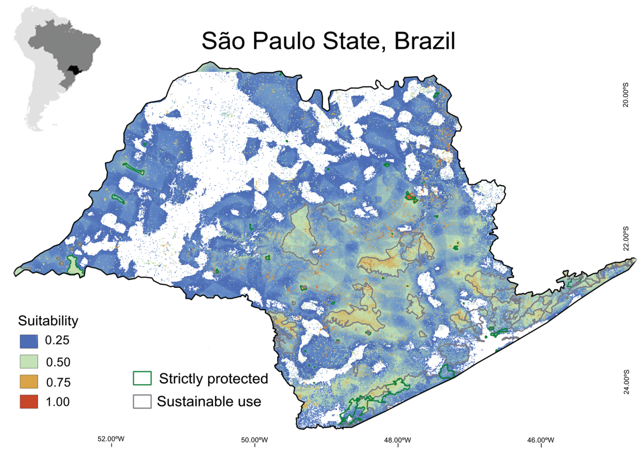

Fig. 3.—Giant anteater (*Myrmecophaga tridactyla*) habitat suitability in São Paulo State, Brazil. Categories of protected areas (strictly protected and sustainable use) are highlighted in the map. Most of the areas corresponding to the lowest suitability are a reflection of Sao Paulo State's road network.

Discussion

Although the anteater habitat suitability model for São Paulo State had an intermediate AUC value, it was statistically significant ($P = 0.008$), and its predictive performance resulted in a reliable map of habitat suitability for the giant anteater (Fig. 3). Elith et al. (2006) proposed that an AUC around 0.75 has a useful amount of discrimination to predict suitable areas. We compiled 149 locations (from published literature, museum collections, and our own field work) of giant anteaters in the state, a large data set for this scale, and our background predictors represent the species' abiotic requirements and the current scenario in São Paulo.

The suitable habitats for anteaters in São Paulo generally had low suitability values and were dispersed throughout the territory. This may indicate that the species is under a suboptimal condition in the state. Low suitability areas are not able to provide all conditions and resources needed for the species' long-term persistence (Diniz and Brito 2013), and this could be a driver of local extinction in the near future. Probably, habitat suitability and hence anteater distribution will likely decline further as more naturally vegetated land is converted to other land uses (Venter et al. 2014). The sugarcane crop expansion will result in patchier remnants and more matrix cover; consequently, anteater populations may be isolated. Additionally, the sugarcane expansion will not act alone, and other land-use changes will probably act in synergy. Our map indicates that the areas with medium to high habitat suitability values are isolated remnants of native vegetation. This highlights the need for decision-makers to define more effective conservation strategies beyond protected areas. Also, our map shows that most suitable areas are in the central to southern regions of São Paulo State and near protected areas (Fig. 3), possibly because those areas are acting as a reservoir for resources and conditions that the species requires.

Vegetation connectivity as a proxy for suitability.—Native vegetation plays an important role in anteater occurrence, mainly because it provides heterogeneous conditions and resources for the species (Camilo-Alves and Mourão 2006; Vynne et al. 2011). However, the anteater has been described in the past as an open-habitat mammal (Einsenberg and Redford 1999). Here, the layer Natcon240 made a strong contribution to

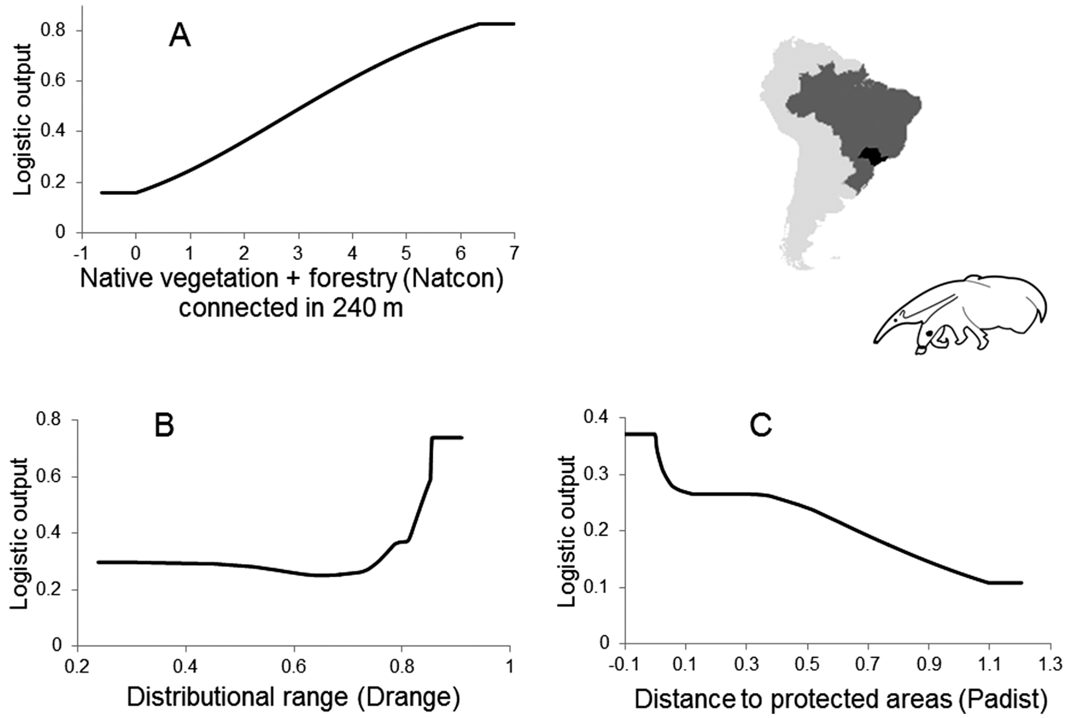

Fig. 4.—Response curves showing the logistic prediction of each of the variables that contributed the most (% values are indicated using the logistic output of probability of presence) to the habitat suitability model for the giant anteater (*Myrmecophaga tridactyla*) in São Paulo State: native vegetation + forestry connected within 240 m (Natcon, 31%; A); distributional range model (Drange, 23%, B), and distance to protected areas (PAdist, 17%, C).

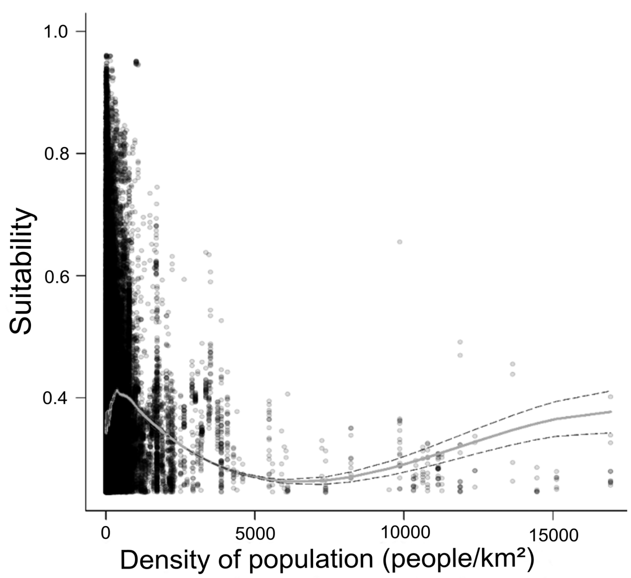

Fig. 5.—The influence of human population density (HPD) on habitat suitability for the giant anteater (*Myrmecophaga tridactyla*) in São Paulo State, Brazil.

the model; the layer is a combination of savannas, from open grassland to shrub savanna, and includes habitats types as such as forests and timberlands. This layer's contribution suggests the anteater's suitable areas are situated within a mosaic of vegetation. Past and recent studies have shown the anteater's preference for heterogeneous habitats (Vynne et al. 2011; Quiroga et al. 2016). Typically, anteaters rest and shelter in forests and are active in grasslands and shrub savannas (Camilo-Alves and Mourão 2006).

Functional habitat connectivity is essential for the species' maintenance, as it forms a corridor that enables access to resources from different patches (Venter et al. 2014). Conversely, biofuel plantations, such as sugarcane, entail a process of habitat simplification that impacts the fauna (Verdade et al. 2015; Magioli et al. 2016; Beca et al. 2017; Giubbina et al. 2018).

Distributional range contribution to the model.—Drange is a mix of climate and abiotic predictors, and it was the second-best predictor in the São Paulo habitat suitability model, indicating the importance of both in achieving conditions suitable for anteaters. A visual inspection of Drange (Supplementary Data SD3) indicates that more than 50% of the state has a high degree of suitability for anteater occurrence, considering only abiotic conditions, without accounting for current anthropogenic impacts. In the near future, however, climate change may cause a contraction of the anteater's range, mainly in forest biomes such as the Amazon (Zimbres et al. 2012). The species' ability to persist mainly in drier environments such as savanna and semiarid areas will mostly depend on the available suitable habitats.

Contribution of protected areas and human population density to the model.—A study of the effectiveness of protected areas to maintain viable anteater populations showed that small protected areas are not able to sustain wild populations because of the risks of loss of individuals due to demographic stochasticity, genetic stability, and road-kills (Diniz and Brito 2015). To properly protect the species, we need to immediately

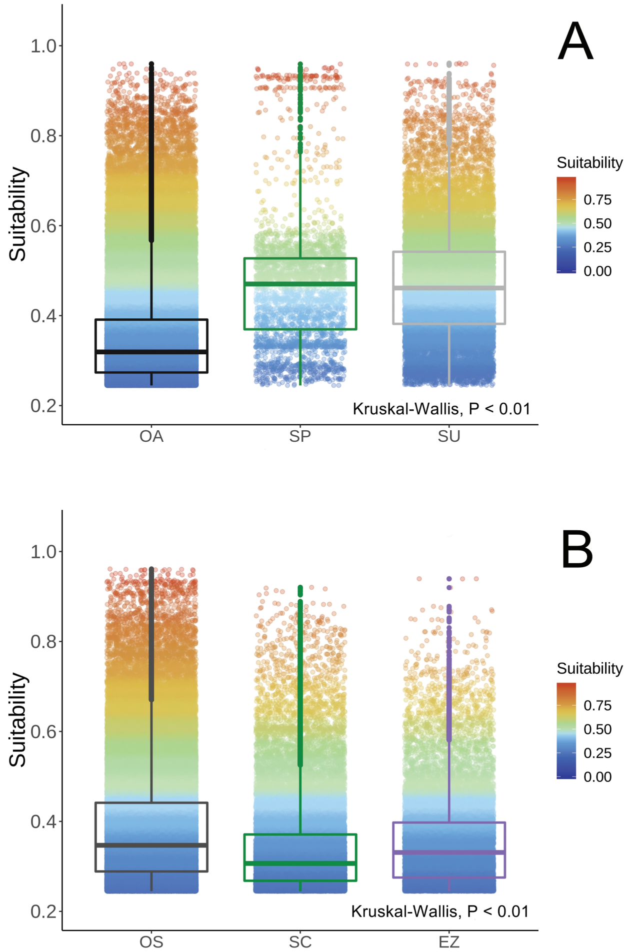

Fig. 6.—Values of habitat suitability for the giant anteater (*Myrmecophaga tridactyla*) of São Paulo State, Brazil. (A) The suitability of habitats outside protected areas (OA) in contrast to protected areas of strictly protection (SP) and sustainable use (SU) categories, and (B) suitability in areas outside of sugarcane plantations in contrast to sugarcane crop plantations (SC) and its expansion zone (EZ).

increase the size of protected areas and habitat patches (in São Paulo State, 90% of native habitat remnants are smaller than 20 ha) and increase the functional connectivity between the most suitable areas (Vynne et al. 2011). The additional amount of area that is required needs to be estimated, and this is a topic for future research.

A model for Brazil in the year 2000 showed that the suitable habitat for anteaters represented 9% of the area within strictly protected areas and 17% of the area within sustainable use areas (Zimbres et al. 2012). This result is similar to our findings of the gap in anteater protection within strictly protected areas, and of the low representation of protected areas in the species' distributional range. Thus, private landowners and the government should work together toward inventing a system to augment the areas intended for biodiversity conservation, and also to find a path to reconcile economic activities with the maintenance of biodiversity. We need to be careful in assuming that the species is protected in sustainable use areas. This category of protection allows human presence, but the anteater avoids sites with high human disturbance (Diniz and Brito 2013; Quiroga et al. 2016); suitable areas for anteaters were far from sites of high human population density (Fig. 5). This is a pattern that applies to other large-sized mammals that are sensitive to land-use change. Recently, the lowland tapir (*Tapirus terrestris*) was rediscovered, after being considered locally extinct, in the largest protected area of Cerrado in the State of São Paulo (Rodrigues et al. 2014). The tapir and collared peccary (*Pecari tajacu*) also are locally extinct within sugarcane areas with less than 40% forest cover (Beca et al. 2017). The occurrence of the marsh deer (*Blastocerus dichotomus*) is restricted to a few protected areas in the state (Chiquito and Percequillo 2009), and those areas are responsible for maintaining the species, which has been declining since 1994 (Weber and Gonzalez 2003). Conversely, the puma (*Puma concolor*), a large-sized carnivore, seems to have adapted to highly fragmented areas and low-quality native habitats (Dotta and Verdade 2011). However, there are still few studies assessing faunal diversity in biofuel crop plantations (Verdade et al. 2015; Medeiros et al. 2016; Beca et al. 2017), not only because of legal issues involved in the survey those areas, but also because the topic is a recent specialty within the field of conservation biology.

Road density as a threat.—Roads have been described as unreliable modeling predictors (Vynne et al. 2011; Di Blanco et al. 2015), corroborated by the results presented here. However, visual inspection of the anteater habitat suitability map for São Paulo (Fig. 3) shows a pattern of roads being nonsuitable areas (Fig. 3). It is well-known that road-kill incidents are frequent and severe throughout the anteater's range (Miranda et al. 2014). A recent study estimated that anteater road-kills total 4.5 individuals/year in two regions in southeastern Brazil (Freitas et al. 2014). Besides this obvious impact, there are indirect effects such as the isolation of populations and loss of connectivity (Freitas et al. 2014). A study on road-kills within fragmented landscapes embedded within sugarcane and other land use in São Paulo State reports that, after road widening, there was an increase of anteater road-kills (Ciocheti et al. 2017). Nevertheless, the effect of roads may be context dependent, since the effect of roads on habitat selection by giant anteaters could not be firmly established by a study in Argentina, or by a study in the Brazilian Cerrado (Vynne et al. 2011; Di Blanco et al. 2015). Regardless of these findings, roads are needed to connect biofuel plantations to industry (Campbell and Doswald 2009); as expected, sugarcane plantations are surrounded by both dirt and paved roads, increasing the probability of faunal mortality (Freitas et al. 2015).

Sweet opportunities to face the threats of sugarcane and biofuel expansion.—When a sugarcane plantation extends onto adjacent lands, as is the plan in São Paulo (state's agro-ecological zoning for sugarcane expansion; Fig. 2), suitable areas for the anteater near the sugarcane plantations become even more threatened. In this scenario, the anteater population, which is already classified as "Vulnerable," will probably be restricted to a few individuals isolated in the few remnants of suitable habitat. Although anteaters have been recorded in anthropogenic areas, such as soy plantations in central Brazil

(Vynne et al. 2011) and timberland surrounding native remnants (Kreutz et al. 2012; Miretzki and Braga 2014; Timo et al. 2015), the proportion of anteater occurrences in forest strips surrounded by crops is much lower when compared to native habitat (Nunez-Regueiro et al. 2015).

Species composition in landscapes dominated by sugarcane monocultures is very different from those regions with large amounts of native habitats, as is the case in São Paulo (Beca et al. 2017). Typically, a generalist species can adapt, while specialist species decline in population size or become regionally extinct (Dotta and Verdade 2011). Thus, two questions arise: 1) Are anteater populations adapting to the current scenario in São Paulo? 2) Are anteaters facing a regional process of disappearance in the midterm? Extinction of wildlife populations seems to occur either in areas of high human population density, or in areas severely affected by intensive agriculture, overgrazing, and hunting (Ceballos and Ehrlich 2002). All these factors are found in our study site.

The Brazilian sugarcane industry is historically supported by economic incentives prescribed by government policies (Goldemberg et al. 2008). Sugarcane plantations have a very high environmental cost; thus, policies that promote them need to include best practices related to feedstock production, refining practices (see Groom et al. 2008, item 12 of policy recommendations), and planning of sustainable strategies (Duarte et al. 2013). If the expansion of this biofuel crop occurs at the expense of Brazil's natural habitats, the consequences will be disastrous not only for carbon emissions but also for the country's biodiversity (Fargione et al. 2008; Verdade et al. 2015).

With respect to the role of nonprotected areas in large-mammal conservation, future work should focus on the following possibilities for low suitability areas: 1) the creation of functional habitat corridors protected by environmental law, 2) environmental restoration, and 3) establishment of a Private Natural Heritage Reserve that is a category of Brazilian protected area in which a reserve is held as private property and is legally considered untouchable. Additionally, we suggest future research to analyze the habitat simplification process caused by biofuel crops, such as palm (*Elaeis* spp.), jatropha (*Jatropha* spp.), and sweet sorghum (*Sorghum vulgare*) in other tropical countries, to understand its effects on medium- and large-sized mammals.

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Supplementary Data

Supplementary data are available at *Journal of Mammalogy* online.

Supplementary Data SD1.—Data set of locations of giant anteaters (*Myrmecophaga tridactyla*).

Supplementary Data SD2.—Average of Minimum Convex Polygon home range size (km^2) of giant anteaters (*Myrmecophaga tridactyla*).

Supplementary Data SD3.—Habitat suitability for giant anteaters (*Myrmecophaga tridactyla*) in the distributional range and its response curves.

Literature Cited

Angelieri, C. C., C. Adams-Hosking, K. M. Ferraz, M. P. de Souza, and C. A. McAlpine. 2016. Using species distribution models to predict potential landscape restoration effects on puma conservation. PLoS One 11:e0145232.

Barve, N., et al. 2011. The crucial role of the accessible area in ecological niche modeling and species distribution modeling. Ecological Modelling 222:1810–1819.

Beca, G., et al. 2017. High mammal species turnover in forest patches immersed in biofuel plantations. Biological Conservation 210:352–359.

Boria, R. A., L. E. Olson, S. M. Goodman, and R. P. Anderson. 2014. Spatial filtering to reduce sampling bias can improve the performance of ecological niche models. Ecological Modelling 275:73–77.

Brown, J. L. 2014. SDMtoolbox: a python-based GIS toolkit for landscape genetic, biogeographic, and species distribution model analyses. Methods in Ecology and Evolution 5:694–700.

Camilo-Alves, C. S. P., and G. Mourão. 2006. Responses of a specialized insectivorous mammal (*Myrmecophaga tridactyla*) to variation in ambient temperature. Biotropica 38:52–56.

Campbell, A., and N. Doswald. 2009. The impacts of biofuel production on biodiversity: a review of the current literature. UNEP-WCMC, Cambridge, United Kingdom.

Ceballos, G., and P. R. Ehrlich. 2002. Mammal population losses and the extinction crisis. Science 296:904–907.

Chiquito, E. A., and A. R. Percequillo. 2009. *Myrmecophaga tridactyla* (Linnaeus, 1758), Pilosa, Myrmecophagidae. Pp. 45–45 in Mamíferos ameaçados de extinção no estado de São Paulo (P. M. Bressan, M. C. M. Kierulff, and A. M. Sugieda, eds.). FPZ-SP/Secretaria do Meio Ambiente, São Paulo, Brazil.

Ciocheti, G., J. C. de Assis, J. W. Ribeiro, and M. C. Ribeiro. 2017. Highway widening and underpass effects on vertebrate road mortality. Biotropica 49:765–769.

Di Blanco, Y. E., I. Jiménez-Perez, and M. S. Di Bitetti. 2015. Habitat selection in reintroduced giant anteaters: the critical role of conservation areas. Journal of Mammalogy 20:1–12.

Diniz, M. F., and D. Brito. 2013. Threats to and viability of the giant anteater, *Myrmecophaga tridactyla* (Pilosa: Myrmecophagidae), in a protected Cerrado remnant encroached by urban expansion in central Brazil. Zoologia 30:151–156.

Diniz, M. F., and D. Brito. 2015. Protected areas effectiveness in maintaining viable giant anteater (*Myrmecophaga tridactyla*) populations in an agricultural frontier. Natureza & Conservação 13:145–151.

Dotta, G., and L. M. Verdade. 2011. Medium to large-sized mammals in agricultural landscapes of south-eastern Brazil. Mammalia 75:345–352.

Duarte, C. G., K. Gaudreau, R. B. Gibson, and T. F. Malheiros. 2013. Sustainability assessment of sugarcane-ethanol production in Brazil: a case study of a sugarcane mill in São Paulo state. Ecological Indicators 30:119–129.

Einsenberg, J. F., and K. H. Redford. 1999. Mammals of the Neotropics - the central Neotropics: Ecuador, Peru, Bolivia, Brazil. University of Chicago Press, Chicago, Illinois.

Elith, J., et al. 2006. Novel methods improve prediction of species' distributions from occurence data. Ecography 29:129–151.

Elith, J., and J. R. Leathwick. 2009. Species distribution models: ecological explanation and prediction across space and time. Annual Review of Ecology, Evolution and Systematics 40:677–697.

Elith, J., S. J. Phillips, T. Hastie, M. Dudík, Y. E. Chee, and C. J. Yates. 2010. A statistical explanation of Maxent for ecologists. Diversity and Distributions 17:43–57.

ESRI. 2014. ArcView GIS for Desktop 10.2. Environmental System Research Institute, Inc., Redlands, California.

Fargione, J., J. Hill, D. Tilman, S. Polasky, and P. Hawthorne. 2008. Land clearing and the biofuel carbon debt. Science 319:1235–1238.

Fortin, M. J., and M. R. T. Dale. 2005. Spatial analysis - a guide for ecologists. Cambridge University Press, Cambridge, United Kingdom.

Freitas, C. H., C. S. Justino, and E. Z. F. Setz. 2014. Road-kills of the giant anteater in south-eastern Brazil: 10 years monitoring spatial and temporal determinants. Wildlife Research 41:673–680.

Freitas, S. R., N. A. Oliveira, G. Ciocheti, M. V. Vieira, and D. M. S. Matos. 2015. How landscape features influence road-kill of three species of mammals in the Brazilian savanna? Oecologia Australis 18:35–45.

Giubbina M. F., A. C. Martensen, and M. C. Ribeiro. 2018. Sugarcane and *Eucalyptus* plantation equally limit the movement of two forest-dependent understory bird species. Austral Ecology 43:527–533. doi:10.1111/aec.12589.

Goldemberg, J., S. T. Coelho, and P. Guardabassi. 2008. The sustainability of ethanol production from sugarcane. Energy Policy 36:2086–2097.

Groom, M. J., E. M. Gray, and P. A. Townsend. 2008. Biofuels and biodiversity: principles for creating better policies for biofuel production. Conservation Biology 22:602–609.

Hijmans, R. J., S. E. Cameron, J. L. Parra, P. G. Jones, and A. Jarvis. 2005. Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25:1965–1978.

IEA – International Energy Agency. 2016. Energy and air pollution – world energy outlook special report. https://www.iea.org/publications/freepublications/publication/weo-2016-special-report-energy-and-air-pollution. Accessed 8 August 2016.

Jenkins, C. N., and L. Joppa. 2009. Expansion of the global terrestrial protected area system. Biological Conservation 142:2166–2174.

Joppa, L. N., S. R. Loarie, and S. L. Pimm. 2009. On population growth near protected areas. PLoS One 4:e4279.

Kreutz, K., F. Fischer, and K. E. Linsenmair. 2012. Timber plantations as favorite habitat for giant anteaters. Mammalia 76:137–142.

Kronka, F. J. N. 2010. Inventário Florestal da Vegetação Natural do Estado de São Paulo: 2008–2009. Secretaria do Meio Ambiente/ Instituto Florestal, São Paulo, Brazil. https://www.iflorestal.sp.gov/sifesp/.html. Accessed 9 May 2016.

Magioli, M., et al. 2016. Connectivity maintain mammal assemblages functional diversity within agricultural and fragmented landscapes. European Journal of Wildlife Research 62:431–446.

Martensen, A. C., M. C. Ribeiro, C. Banks-Leite, P. I. Prado, and J. P. Metzger. 2012. Associations of forest cover, fragment area, and connectivity with neotropical understory bird species richness and abundance. Conservation Biology 26:1100–1111.

McGill, B. J., M. Dornelas, N. J. Gotelli, and A. E. Magurran. 2015. Fifteen forms of biodiversity trend in the anthropocene. Trends in Ecology & Evolution 30:104–113.

Medeiros, H. R., A. T. Hoshinoa, M. C. Ribeiro, and A. O. M. Junior. 2016. Landscape complexity affects cover and species richness of weeds in Brazilian agricultural environments. Basic and Applied Ecology 17:731–740.

Miranda, F., A. Bertassoni, and A. M. Abba. 2014. *Myrmecophaga tridactyla*. In: IUCN 2014. The IUCN Red List of Threatened Species. Version 2015.2. www.iucnredlist.org. Accessed 2 February 2016.

Miranda, F. R., A. G. Chiarello, F. Röhe, F. G. Braga, G. M. Mourão, and G. H. B. Miranda. 2015. Avaliação do risco de extinção de *Myrmecophaga tridactyla* Linnaeus 1758 no Brasil. Pp. 89–105 in Avaliação do Risco de Extinção dos Xenartros Brasileiros (ICMBio, ed.). ICMBio, Brasília, Brazil.

Miretzki, M., and F. G. Braga. 2014. Distribuição histórica e recente de *Myrmecophaga tridactyla* Linnaeus, 1758 (Pilosa, Myrmecophagidae) no Estado do Paraná, Brasil. Edentata 15:16–26.

Morueta-Holme, N., C. Fløjgaard, and J. C. Svenning. 2010. Climate change risks and conservation implications for a threatened small-range mammal species. PLoS One 5:e10360.

Nelson, G. C., et al. 2006. Anthropogenic drivers of ecosystem change: an overview. Ecology and Society 11:29–64.

Neteler, M., M. H. Bowman, M. Landa, and M. Metz. 2012. GRASS GIS: a multi-purpose open source GIS. Environmental Modelling & Software 31:124–130.

Newbold, T., et al. 2015. Global effects of land use on local terrestrial biodiversity. Nature 520:45–50.

Newbold, T. 2018. Future effects of climate and land-use change on terrestrial vertebrate community diversity under different scenarios. Proceedings of the Royal Society of London, B. Biological Sciences 285:20180792.

Nunez-Regueiro, M. M., L. Branch, Jr., R. J. Fletcher, G. A. Marás, E. Derlindati, and A. Tálamo. 2015. Spatial patterns of mammal occurrence in forest strips surrounded by agricultural crops of the Chaco region, Argentina. Biological Conservation 187:19–26.

Quiroga, V. A., A. J. Noss, G. I. Boaglio, and M. S. Di Bitetti. 2016. Local and continental determinants of giant anteater (*Myrmecophaga tridactyla*) abundance: biome, human and jaguar roles in population regulation. Mammalian Biology 81:274–280.

R Development Core Team. 2016. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. www.R-project.org.

Raes, N. 2012. Partial versus full species distribution models. Natureza & Conservação 10:127–138.

Ribeiro, M. C., J. P. Metzger, A. C. Martensen, F. J. Ponzoni, and M. M. Hirota. 2009. The Brazilian Atlantic Forest: how much

is left, and how is the remaining forest distributed? Implications for conservation. Biological Conservation 142:1141–1153.
Rodrigues, T. F., R. M. Paolino, N. F. Versiani, N. A. P. Salvador, E. M. Oliveira, and A. G. Chiarello. 2014. The lowland tapir *Tapirus terrestris* is back to the largest protected area of Cerrado in the State of São Paulo, Brazil. Tapir Conservation 23:5–9.
Rudorff, B. F. T., D. A. Aguiar, W. F. da Silva, L. M. Sugawara, M. Adami, and M. A. Moreira. 2010. Studies on the rapid expansion of sugarcane for ethanol production in São Paulo state using landsat data. Remote Sensing 2:1057–1076.
Rylands, A. B., and K. Brandon. 2005. Brazilian protected areas. Conservation Biology 19:612–618.
Sánchez-Fernández, D., J. M. Lobo, and O. L. Hernández-Manrique. 2011. Species distribution models that do not incorporate global data misrepresent potential distributions: a case study using Iberian diving beetles. Diversity and Distributions 17:163–171.
Shaw, J. H., T. S. Carter, and J. C. Machado-Neto. 1985. Ecology of the giant anteater *Myrmecophaga tridactyla* in Serra da Canastra, Minas Gerais, Brazil: a pilot study. Pp. 379–384 in The evolution and ecology of armadillos, sloths and vermilinguas (G. G. Montgomery, ed.). Smithsonian Institution, Washington, D.C.
Superina, M., F. R. Miranda, and A. M. Abba. 2010. The 2010 anteater Red List assessment. Edentata 11:96–114.
Timo, T. P. C., M. C. Lyra-Jorge, C. Gheler-Costa, and L. M. Verdade. 2015. Effect of the plantation age on the use of *Eucalyptus* stands by medium to large sized wild mammals in south-eastern Brazil. iForest 8:108–113.
Venter, O., et al. 2014. Targeting global protected area expansion for imperiled biodiversity. PLoS Biology 12:e1001891.
Verdade, L. M., C. I. Piña, and L. M. Rosalino. 2015. Biofuels and biodiversity: challenges and opportunities. Environmental Development 15:64–78.
Vynne, C., et al. 2011. Resource selection and its implications for wide-ranging mammals of the Brazilian Cerrado. PLoS One 6:e28939.
Weber, M., and S. Gonzalez. 2003. Latin American deer diversity and conservation-a review of status and distribution. Ecoscience 10:443–454.
Zimbres, B. Q. C., et al. 2012. Range shifts under climate change and the role of protected areas for armadillos and anteaters. Biological Conservation 152:53–61.

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