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Identification of Areas in Brazil that Optimize Conservation of Forest Carbon, Jaguars, and Biodiversity

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Abstract: *A major question in global environmental policy is whether schemes to reduce carbon pollution through forest management, such as Reducing Emissions from Deforestation and Degradation (REDD+), can also benefit biodiversity conservation in tropical countries. We identified municipalities in Brazil that are priorities for reducing rates of deforestation and thus preserving carbon stocks that are also conservation targets for the endangered jaguar (*Panthera onca*) and biodiversity in general. Preliminary statistical analysis showed that municipalities with high biodiversity were positively associated with high forest carbon stocks. We used a multicriteria decision analysis to identify municipalities that offered the best opportunities for the conservation of forest carbon stocks and biodiversity conservation under a range of scenarios with different rates of deforestation and carbon values. We further categorized these areas by their representativeness of the entire country (through measures such as percent forest cover) and an indirect measure of cost (number of municipalities). The municipalities that offered optimal co-benefits for forest carbon stocks and conservation were termed REDDspots (n = 159), and their spatial distribution was compared with the distribution of current and proposed REDD projects (n = 135). We defined REDDspots as the municipalities that offer the best opportunities for co-benefits between the conservation of forest carbon stocks, jaguars, and other wildlife. These areas coincided in 25% (n = 40) of municipalities. We identified a further 95 municipalities that may have the greatest potential to develop additional REDD+ projects while also targeting biodiversity conservation. We concluded that REDD+ strategies could be an efficient tool for biodiversity conservation in key locations, especially in Amazonian and Atlantic Forest biomes.*

Keywords: corridors, multicriteria decision, prioritization, PROMETHEE, REDD+

Identificación de Áreas en Brasil que Optimizan la Conservación del Carbono del Bosque, Jaguares y la Biodiversidad

Resumen: *Una gran pregunta en la política ambiental global es si los esquemas para reducir la contaminación de carbono por medio del manejo forestal, como la Reducción de Emisiones de la Deforestación y la Degradación (REDD+), también pueden beneficiar la conservación de la biodiversidad en países tropicales. Identificamos municipalidades en Brasil que son prioridades para la reducción de tasas de deforestación y así preservan cantidades de carbono que también son objetivos de conservación para el jaguar (*Panthera onca*), que se encuentra en peligro de extinción, y la biodiversidad en general. El análisis estadístico preliminar mostró que las municipalidades con alta biodiversidad estuvieron asociadas positivamente con cantidades altas de carbono forestal. Usamos una decisión multi-criterio para identificar a las municipalidades que ofrecían las mejores oportunidades para la conservación del carbono forestal y la biodiversidad bajo un*

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rango de escenarios con diferentes tasas de deforestación y valores de carbono. Categorizamos estas áreas por su representatividad de todo el país (por medio de medidas como el porcentaje de cobertura forestal) y una medida indirecta del costo (número de municipalidades). Las municipalidades que ofrecían co-beneficios óptimos por el carbono forestal y la conservación se denominaron puntos REDD (n =159) y su distribución espacial se comparó con la distribución de proyectos REDD actuales o propuestos (n = 135). Definimos los puntos REDD como las municipalidades que ofrecen las mejores oportunidades para co-beneficios entre la conservación del carbono forestal, jaguares y otra vida silvestre. Estas áreas coincidieron en un 25% (n = 40) de las municipalidades. Identificamos además 95 municipalidades que pueden tener el mayor potencial para desarrollar proyectos REDD+ adicionales a la par de enfocarse en la conservación de la biodiversidad. Concluimos que las estrategias de REDD+ pueden ser una herramienta eficiente para la conservación de la biodiversidad en localidades clave, especialmente en los biomas del Amazonas y el Bosque Atlántico.

Palabras Clave: Corredores, decisión multi-criterio, priorización, PROMETHEE, REDD+

Introduction

Tropical forest biomass contains an estimated 323 billion ton of carbon (Gibbs et al. 2007) and approximately two-thirds of the world's terrestrial biodiversity (Gardner et al. 2010). Deforestation contributes around 12% to global annual CO_2 emissions, the second largest emitter by sector (Van der Werf et al. 2009) and causes habitat fragmentation and biodiversity loss (Gardner et al. 2010). Reducing Emissions from Deforestation and Degradation (REDD) is topical and it is hoped that REDD+ might benefit biodiversity conservation (Laurance 2008) (the + in REDD+ refers to strategies that also consider the role that conservation, sustainable forest management, and enhancement of forest carbon stocks have in reducing emissions). Furthermore, the addition of a biodiversity component to REDD+ may offer mechanisms to conserve key species (Venter et al. 2009). A major policy question is whether this mechanism can be adapted to deliver these diverse goals.

We explored whether a REDD+ like scheme has the potential to deliver protection of forest carbon and the conservation of a top predator, the jaguar, *Panthera onca*, and associated other biodiversity. Although we acknowledge that REDD+ offers many diverse opportunities for conservation, in this analysis we were primarily concerned with preserving existing jaguar habitat and thus we focused on the avoided deforestation aspect of REDD+.

Jaguars are listed as near threatened on the International Union for Conservation of Nature's (IUCN) Red List of Threatened Species (Caso et al. 2008), but their numbers are decreasing and their regional status varies in the different Brazilian biomes (Paula et al. 2010; Desbiez & Paula 2012). Jaguars occupy about 46% of their historical range (Sanderson et al. 2002), and in past decades Brazil has lost more jaguar habitat than any other country (Cavalcanti et al. 2010). Although jaguars are not obligate forest dwellers, they rely on vegetation cover (Crawshaw & Quigley 1991), so deforestation poses a major threat (Haag et al. 2010) and increases their vulnerability to human persecution (Nowell & Jackson 1996). Additionally, because of their large home range sizes (34.1–262.9 km^2) (Cavalcanti & Gese 2009) jaguars are potential umbrellas for wider biodiversity conservation, whereas their absence might indicate simplification of the ecosystem and trigger trophic cascades (Estes et al. 2011). Finally, jaguars are charismatic but controversial; consequently, they exert disproportionate leverage in international and local communities (Cavalcanti et al. 2010).

Jaguar conservation units (JCUs) are a network of priority areas for jaguar conservation, defined by Sanderson et al. (2002) and subsequently refined to include a network of corridors (Rabinowitz & Zeller 2010; Nijhawan 2012). The Brazilian Jaguar Action Plan (PAN: Plano de Ação Nacional para Onça-pintada) promotes the concept of JCUs connected by dispersal corridors as the basis of jaguar conservation in the country (Nijhawan et al. 2010; Paula et al. 2010; Desbiez & Paula 2012). The PAN assigned levels of conservation priority to JCUs: urgent protection, conservation and research, conservation, and exploratory research. In addition, it included 2 models of corridors, one taking account of natural and human-made barriers (barrier corridors) and another, hypothetical, assuming these barriers do not influence jaguar dispersal (no barrier corridors).

As a stronghold of carbon and biodiversity with a high deforestation risk, Brazil has been at the forefront of the international REDD debate (Kapos et al. 2008; Laurance 2008; Parker et al. 2009). Consequently, REDD initiatives are flourishing in Brazil (May & Millikan 2010). The locations of REDD+ programs might be based on a range of factors including high carbon stocks and deforestation risk (Harris et al. 2008), opportunity costs (Olsen & Bishop 2009), and the congruence of high carbon stocks and biodiversity (Kapos et al. 2008; Venter et al. 2009). We used a multicriteria decision analysis to identify municipalities where REDD+ projects might yield protection against deforestation and the combined conservation of carbon stocks, jaguars, and overall biodiversity. We are the first to suggest prioritization schemes considering optimal areas based on carbon stocks and deforestation risk (ideal areas for REDD), conservation initiatives for jaguars, and overall biodiversity. We called these co-benefit areas REDDspots (REDDspots are defined as the municipalities that offer the best opportunities for co-benefits between the conservation of forest carbon stocks, jaguars and wider wildlife conservation).

We identified municipalities in Brazil that represented REDDspots (i.e., priority areas for REDD+ that simultaneously deliver the greatest benefits for the conservation of jaguars and wider biodiversity and reduce deforestation and consequently conserve carbon stocks) and municipalities where current or proposed REDD projects overlapped REDDspots and where new REDD+ could be initiated to target jaguar and biodiversity conservation.

Methods

First, we quantified how carbon stocks and annual deforestation rates (ADefR) relate to the importance of each municipality for jaguars and for biodiversity conservation. We tested the hypothesis that municipalities with high carbon stocks have greater potential for jaguar and biodiversity conservation than municipalities with low carbon stocks.

Second, we analyzed key variables (carbon stocks, ADefR, and importance for jaguars and biodiversity) and measures of their representativeness (in relation to Brazilian totals) and cost (number of municipalities [NM]) in the context of a number of different scenarios of varying forest carbon stocks and deforestation rates. These scenarios were generated by applying varyingly inclusive threshold criteria to all municipalities for both forest carbon stocks and ADefR, which we then compared in a decision matrix to identify which municipalities delivered the greatest benefits for jaguar and wider biodiversity conservation for any carbon and deforestation risk targets. Having identified candidate scenarios for our REDDspots, we tested their sensitivity to the NM involved (as a proxy for cost) and recent deforestation rates (surrogate for deforestation risk). Because each scenario identified a number of municipalities, the sensitivity analysis was preferred to the alternative approach of simply selecting the top few municipalities in each group (i.e., top 100, 200, etc; Olson & Dinerstein 2002). The least sensitive scenario was chosen to represent our REDDspot priorities. The final areas identified as REDDspots were then compared with current and planned REDD-related activities to identify areas where prospective REDD+ projects could best target jaguar and biodiversity conservation as collateral benefits.

Data Sets

Detailed information on all data sources is in Supporting Information. Data sets were analyzed at the scale of Brazilian municipalities (n = 5565) (IBGE 2008) (Supporting Information) in a single nation-wide database (Fig. 1). Municipalities are the functional administrative

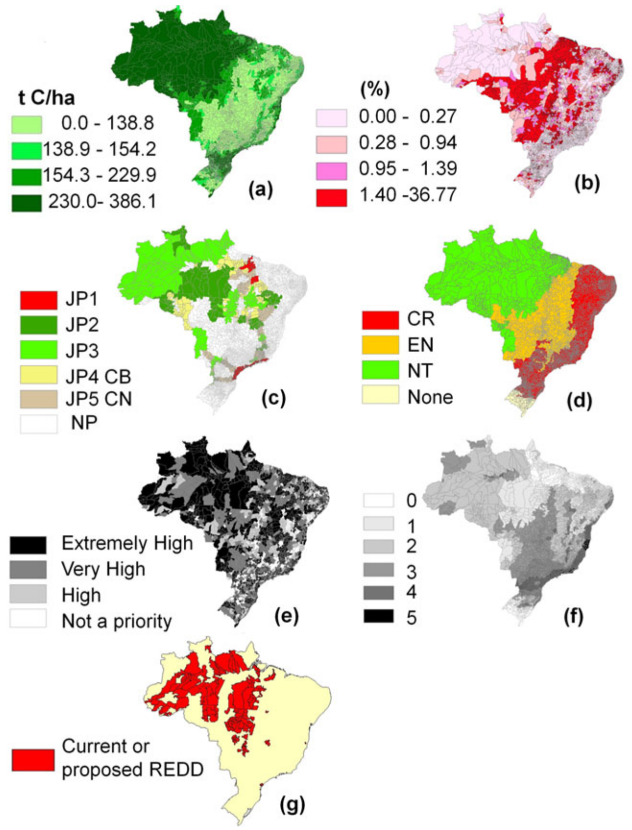

Figure 1. Maps showing, at the municipality level (n = 5565) (IBGE 2008), (a) forest carbon stock, (b) annual deforestation rate (2002–2008), (c) Jaguar conservation units and corridors (JCUs) (JP1, urgent action; JP2, research and conservation; JP3, research or conservation; JP4CB, barrier corridors; JP5CN, no barrier corridors; NP, no priority), (d) jaguar status in the biome (CR, critically endangered; EN, endangered; NT, near threatened; none, jaguars absent or extirpated), (e) Brazilian Ministry of Environment (MMA) biodiversity priorities, (f) international biodiversity priorities (IBPs) (absence of priority areas [0] to overlap of 5 distinct biodiversity priority areas [5]), (g) current or proposed REDD projects in Brazil. Scale values of carbon storage and annual deforestation rate correspond to the thresholds used for the analysis (Fig. 2). More details about data sets are in Table 1 and Supporting Information.

units in Brazil and compatible with available information on REDD projects.

The original carbon storage layer from UNEP/WCMC (Kapos et al. 2008; Ruesch & Gibbs 2008) (Supporting Information) was combined with a remnant vegetation layer from 2008 (National Institute for Space Research: INPE 2009; Brazilian Ministry of Environment: MMA/IBAMA 2010) (Supporting Information). The resultant grid file provided an estimate of total carbon stock per hectare within forest remnants. Forest carbon values varied from 0 to 386.13 tC/ha per municipality (Fig. 1a). Whenever we refer to carbon or a derived term in the context of our analysis, we are always referring to this value of forest carbon stock per municipality. To validate our use of Ruesch and Gibbs (2008) data set, we compared it with Saatchi et al. (2011).

We used recent deforestation data as a surrogate for deforestation risk. Recent deforestation (INPE 2009; MMA/IBAMA 2010) (Supporting Information) was calculated as the difference in forest remnants between 2002 and 2008, converted into a raster layer (1-ha resolution), and expressed as an ADefR (%) (Puyravaud 2003) for each municipality. The ADefR varied from 0% to 36.77% per municipality (2002–2008) (Fig. 1b).

To identify areas of importance for Jaguars, we followed the PAN and used the JCU priority classifications and the IUCN jaguar extinction risk categories for jaguars in different biomes (Nijhawan et al. 2010; Paula et al. 2010; Desbiez & Paula 2012). In Amazonia and the Pantanal, jaguars are near threatened, in the Cerrado they are endangered, whereas in the highly fragmented Atlantic Forest and Caatinga biomes jaguars are critically endangered. JCUs are designed to identify priority areas for jaguar conservation that consider factors such as density, prey availability, vegetation cover, and threats. Corridors are the routes that a jaguar is most likely to use for dispersal between populations.

We assigned scores to each municipality based on their JCU priority and status. In cases where municipalities contained more than one JCU category, we assigned the higher score to the whole municipality (Table 1). Because this analysis aimed to highlight areas that benefit both jaguar and carbon conservation, we focused on the most important areas for jaguars and excluded those municipalities without JCUs or corridors (NP in Table 1). The JCUs include 2 classes of corridor: those that account for natural and human-made barriers (barrier corridors) and a hypothetical class based on the assumption that these barriers do not influence jaguar dispersal (no barrier corridors). We included both models of corridor in our analysis, but because barrier corridors were deemed to be more realistic, we assigned these a higher score.

This municipality scale data set was then assessed on how the binary presence or absence of JCUs correlated with deforestation and carbon values (generating probabilities of occurrence); how carbon and deforestation varied across different JCU priorities; and how carbon and deforestation values correlated with the jaguar index (I), which combined JCU priority and jaguar status calculated as (Table 1 & Figs. 1c–d):

$$I = \frac{(J + S)}{2} \times O, \tag{1}$$

where J is JCU priority score, S is jaguar status, and O is proportion of a municipality occupied by JCUs (calculated by dividing the JCU area within a municipality by the area of the municipality). The jaguar index controlled for area and varied from 0 to 4.5.

We used 2 data sets of biodiversity priority areas (Supporting Information). First, Kapos et al.'s (2008) synthesis of international biodiversity priorities (IBPs) and, second, a Brazilian Ministry of Environment's map of biological priority areas based on research and expert opinion (MMA 2007). The original scale of the IBP data was retained in our analysis, whereas the categorical biodiversity MMA data (scaled from not important to extremely important) were converted into an ordinal scale (Table 1 & Fig. 1). Where a municipality included more than one category, it was assigned to the category that occupied the largest area. Biodiversity data were analyzed at municipality level to understand how the presence or absence of biodiversity spots correlated with deforestation and carbon values, how carbon and deforestation varied across different biodiversity priorities, and how carbon and deforestation values correlated with the biodiversity indices, which were generated by multiplying the value of the ordinal scale (for each of the biodiversity maps) by the proportion of a municipality designated as a priority site. The IBP index varied from 0 to 5, and MMA index varied from 0 to 3.7. These ranking differences were subsequently accounted for with the Promethee method (Brans & Mareschal 2005).

Data on current or proposed REDD projects were gathered from CIFOR (May & Millikan 2010), the Brazilian Forestry Services (SFB-MMA 2009), and IDESAM (Cenamo et al. 2010) (Supporting Information). We identified 35 REDD-related initiatives at varying stages of implementation distributed across 135 municipalities (Fig. 1g). The initiatives varied considerably in size from small private areas <100 ha, to a proposed project covering more than 20 municipalities representing indigenous territories in Brazil. Spatially explicit information was unavailable for most REDD sites so we used presence or absence within municipalities. We used Ministry of Environment data sets on Brazilian Biomes (MMA 2005) and Protected Areas and Indigenous Territories (MMA&FUNAI 2010) (Supporting Information).

Data Analyses

We used binomial logistic regression to investigate whether the presence or absence of jaguar or biodiversity priority areas was related to forest carbon stocks (Ruesch & Gibbs 2008) or ADefR.

We also investigated whether forest carbon or ADefR were related to a specific JCU priority and biodiversity category using box-plots and Kruskal-Wallis tests (Supporting Information).

To identify the municipalities that offered the greatest opportunities for co-benefits, we applied thresholds for JCU priority, amounts of carbon, ADefR, and forest cover

Table 1. Data sets used in the statistical and multicriteria decision analyses which defined the REDDspots. References and categories are included.

	Criterion[a]						
	REDD	*Jaguar Conservation Units & Corridors (JCUs)*		*International Biodiversity Priorities (IBPs)*	*MMA Biodiversity Priorities*		*IBP, MMA, and Jaguar Indices*[c]
	current or proposed (occurrence in municipality)	priority for action	jaguar status	(number of priorities overlapping municipality)	(biological priority categories)	Occurrence of JCUS, IBPS, and MMA (biodiversity priorities in municipality)	priority categories and% area occupied in municipality
	Reference[a]						
Score[b]	*SFB, CIFOR, Idesam, Supporting Information*	*CENAP/ ICMbio Supporting Information*		*UNEP-WCMC, Supporting Information*	*MMA, Supporting Information*	*CENAP, MMA, IBGE, Supporting Information*	*UNEP-WCMC, Supporting Information*
0	absent	Other municipalities (NP)	least concern	0	insufficient data or not important	absent	calculated[c]
1	present	No barrier corridors (JP5CN)	not threatened	1	high	present	calculated[c]
2	-	Barrier corridors (JP4CB)[d]	vulnerable	2	very high	-	calculated[c]
3	-	Exploratory Research or conservation (JP3)[e]	endangered	3	extremely high	-	calculated[c]
4	-	Research and conservation (JP2)	critically endangered	4	-	-	calculated[c]
5	-	Urgent (JP1)	-	5	-	-	calculated[c]

[a] *Abbreviations: MMA, Brazilian Ministry of Environment; SFB, Brazilian Forestry Service; CIFOR, Center for International Forestry Research; Idesam, Institute for the Conservation and Sustainable Development of Amazonas; CENAP/ICMbio, National Research Center for the Conservation of Natural Predators/Chico Mendes Institute; UNEP-WCMC, United Nations Environment Programme's World Conservation Monitoring Centre; IBGE, Brazilian Institute of Geography and Statistics.*

[b] *In cases where the original data were presented in a categorical format (e.g., JCUs or the presence or absence of current or proposed REDD projects), we converted each category into an ordinal score as shown here.*

[c] *Jaguar index was calculated by adding the score for priority for action and jaguar status. This value was divided by 2 and the quotient was multiplied by the proportion of area occupied in the municipality (see Methods). Biodiversity priority indices were calculated independently for IBPS and MMA biodiversity priorities in each municipality by multiplying the ordinal scores by the proportion of area occupied.*

[d] *The category barrier corridors (JP4B) was judged to be more realistic than the no barrier corridors category (JP5CN) and was therefore assigned a higher score.*

[e] *The category exploratory research or conservation (JP3) includes 2 of the original priority categories for jaguars (Nijhawan et al. 2010): exploratory research and conservation.*

within municipalities. Only municipalities that met the relevant threshold criteria were included in subsequent steps of the analyses.

For jaguars, we considered only municipalities that contained JCUs or corridors (Fig. 1c). JCUs occurred in 23% (1281) of Brazilian municipalities. Of these, 96% (1229) contained IBP sites and 82% contained (1052) MMA biodiversity sites.

We took the 1281 municipalities where JCUs occurred and examined them in the context of varyingly inclusive scenarios generated by applying threshold criteria for forest carbon (Ruesch & Gibbs 2008) and ADefR. The threshold values were no threshold and median, mean, and high threshold. All municipalities that failed to meet the relevant threshold criteria for either forest carbon or ADefR were excluded from that scenario. Median and mean values were calculated for all Brazilian municipalities including those that were not priority areas for jaguars (forest carbon: median = 138.86 tC/ha, mean = 154.26 tC/ha; ADefR: median = 0.28%, mean = 0.95%). For the high carbon threshold, we used a carbon density above 230.00 tC/ha (Harris et al. 2008). The threshold for high ADefR was set at 1.4% because it was between the high-rate intervals obtained by Griscom et al. (2009) (0.8% to 1.5%) and above the 0.22% global average used by da Fonseca et al. (2007). Thus, 16 scenarios were created encompassing all combinations of these thresholds (Fig. 2).

We used the following forest cover thresholds for our classification: >60% forest cover (Oliveira Filho &

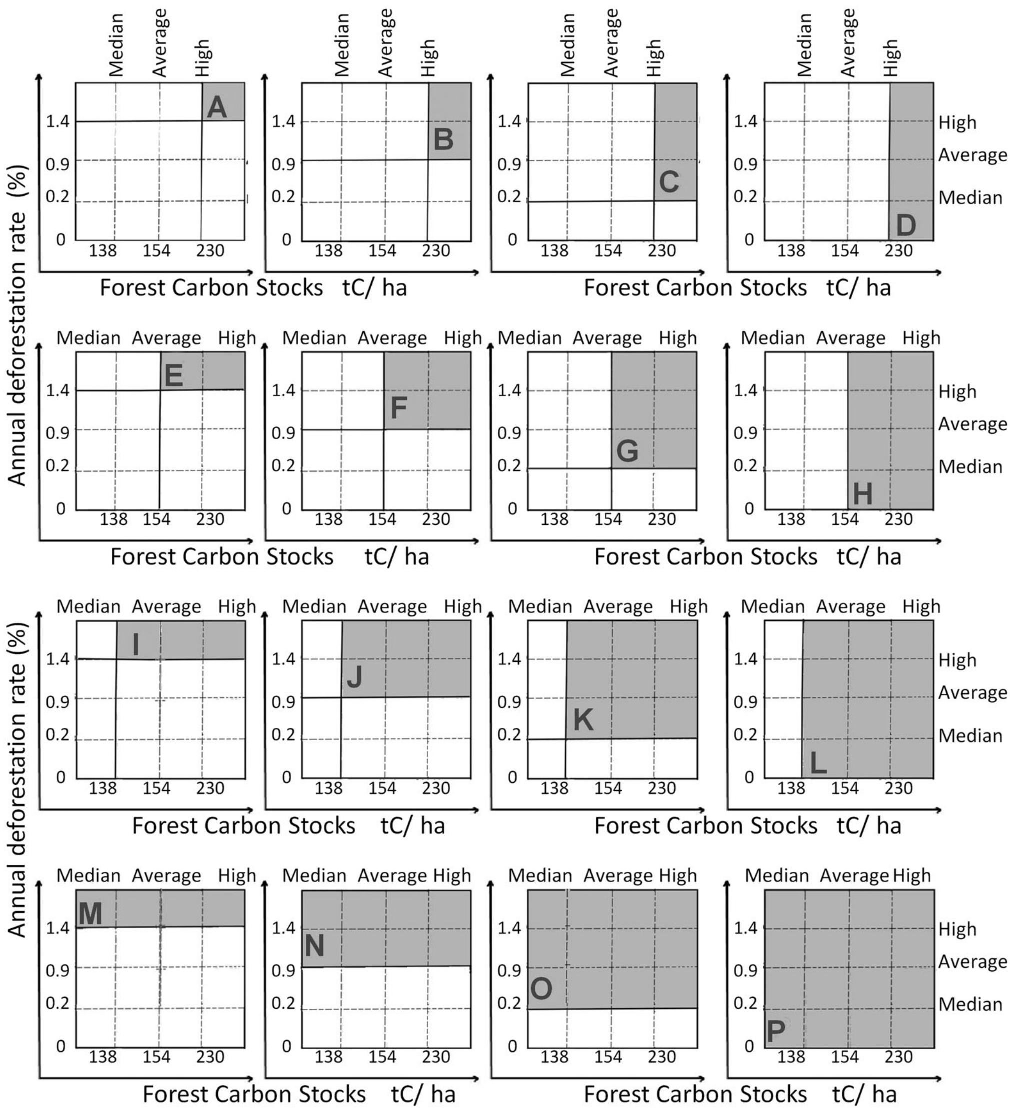

Figure 2. Sixteen scenarios (A–P) generated by combining threshold values (no threshold, median, average, and high threshold values) for forest carbon stocks and annual rate of deforestation 2002–2008. The most restrictive scenario included only municipalities that contained both high carbon stocks and high deforestation rate (scenario A, n = 86), whereas the least restrictive scenario imposed no threshold for either carbon stock or deforestation rate and thus included all municipalities (scenario P, n = 1281). Descriptions of threshold values used are in Methods. These scenarios were compared in the Promethee analyses.

Metzger 2006), >30–60%, >20–30% (Pardini et al. 2010), ≤20% but >10000 ha, and <5000 ha (approximately the size of a single jaguar home range, below which jaguar conservation may be ineffective due to insufficient habitat to support viable populations).

Decision Matrix Criteria

The 16 scenarios for varying forest carbon and deforestation thresholds were compared in a multicriteria decision analysis against 17 criteria (Table 2) in a 2-step comparison. Scenarios that scored highest for all criteria were defined as the preferred options for decision making. First, we compared all scenarios against 6 fundamental criteria (directly associated with carbon, deforestation, and amounts of vegetation cover or to probabilities of occurrence of jaguars and biodiversity priority areas). We then selected the top 4 scenarios and compared them with reference to another 11 representativeness criteria (Table 2). To consider their representativeness, each scenario was compared to the total value of a criterion for the whole country (e.g., percent total forest cover in Brazil) as well as the cost (NM, used on the assumption that more municipalities would

Table 2. Criteria used in the PROMETHEE program for comparing 16 scenarios of varying forest carbon stocks and annual deforestation rate.

*Criterion**	*Criteria type*	*Used as a threshold*	*Data type compared*	*Preference factor*
Forest carbon stocks (tC/ha)	FC	Yes	Median	0.25
Annual deforestation rate 2002–2008 (%)	FC	Yes	Median	1.00
Probability of JCU occurrence	FC	Yes	Median	0.30
Probability of IBP occurrence	FC	No	Median	0.10
Probability of MMA Biodiversity occurrence	FC	No	Median	0.10
Proportion of Forest Remnant	FC	Yes	Median	0.20
Jaguar index	RC	No	Median	0.30
IBP index	RC	No	Median	0.25
MMA index	RC	No	Median	0.30
Proportion of protected areas within JCUs (km^2)	RC	No	Median	0.50
Total annual deforestation rate (2002–2008) in Brazil (%)	RC	No	Total	2.00
Total forest cover in Brazil (%)	RC	No	Total	2.00
Total carbon in Brazil (%)	RC	No	Total	2.00
Total JCU and corridors area in Brazil (%)	RC	No	Total	2.00
Total IBP biodiversity area in Brazil (%)	RC	No	Total	2.00
Total MMA biodiversity area in Brazil (%)	RC	No	Total	2.00
Number of municipalities	Cost	No	Total	2.00

**Abbreviations: FC, fundamental criteria (eliminatory and classificatory use); RC, representativeness criteria (classificatory use); cost, number of municipalities as a proxy for cost (classificatory use); median (median values of a criterion for all municipalities within a scenario); total (sum of values of a criterion for all municipalities within a scenario expressed as a percentage of the sum of that criterion for all Brazilian municipalities); preference factors, relative preference factors (proportions) used in the Promethee matrices. Methodologically, these preference factors should be smaller than maximum and minimum values (Mareschal 2011) and were adjusted accordingly. A v-shape preference function (Brans & Mareschal 2005; Mareschal 2011) and equal weights were adopted. All criteria were maximized, with exception of number of municipalities, which were minimized.*

increase the cost of conservation strategies targeting that scenario). The highest scoring scenarios for most criteria were ultimately submitted to a sensitivity analyses with respect to the NM and representativeness to give a balanced selection of the least sensitive scenario for REDDspots.

PROMETHEE Outranking

We used the Visual PROMETHEE-GAIA (Preference Ranking Organisation Method for Enrichment Evaluations and Geometrical Analysis for Interactive decision Aid) software for multicriteria decision analysis (Mareschal 2011). This creates a matrix for each criterion in which all the alternative scenarios are compared against each other, highlighting the relative strengths of each scenario for a given criterion, and then combines the results in a final decision matrix (Drechsler 2004; Brans & Mareschal 2005).

For all the criteria, except NM, the maximum values were favored, and the software allocated a score of 1 for the highest value in each pairwise comparison between scenarios. To be considered significantly different, the value for one scenario must exceed its pair by an amount known as the preference factor (PF) (Table 2). Preference factors and the mathematical functions that best fit each criterion are determined by the user. This enables the comparison of criteria with different ranking categories or types of data because the PF and function are adjusted according to the inherent characteristics of the data corresponding to each criterion. If the difference between 2 compared scenarios is smaller to the PF, then the program automatically flags these as being estimates of weak preference. A score of zero is assigned to scenarios that are either equal or lower than their pair during the pairwise comparisons. For the criteria NM, the model favored smaller values to reflect our preference for scenarios that encompassed fewer municipalities.

After completing pairwise comparisons between the scenarios for each criterion, the scores are summed in a final matrix providing outfluxes (Φ^+; how much better one scenario is than others in relation to the overall criteria) and influxes (Φ^-; how much worse a scenario is than others in relation to the overall criteria). The difference of outfluxes and influxes provides a final net outranking flow: $\Phi = (\Phi^+)$–(Φ^-). The scenarios that have the highest net flow (Φ) are the scenarios that perform best with respect to all criteria (PROMETHEE II, with complete rank procedure) (Brans & Mareschal 2005). In this particular analysis, we kept equal weights among criteria but we attached greatest importance to the fundamental criteria (Table 2) and used them as a basis for eliminating less satisfactory scenarios. We applied the complete rank procedure in 2 phases: comparison of all scenarios against the 6 fundamental criteria to determine only the top 4 REDDspot scenarios and comparison of the top 4 scenarios against all the fundamental, representativeness, and cost criteria. For both phases, the final matrices provided outfluxes (Φ^+), influxes (Φ^-), and a final net outranking flow (Φ) for each scenario.

Assessment of the Decision Matrix Results and Suitable REDDspots

We varied the weightings for the cost (NM) and deforestation risk (ADefR) criteria to examine their effect on the final net outranking flow results. From the top 4 REDDspot scenarios (based on equal weights for all the co-benefits), we selected the scenario that was least sensitive to varying weights of cost (NM) and deforestation risk (ADefR). This scenario represented an optimal solution for jaguar and forest carbon conservation, balancing the co-benefits and the NM.

REDDspots versus Current or Proposed REDD Projects

Chi-square tests were used to compare the overlap between municipalities with current and/or proposed REDD projects and the REDDspots derived from the analysis above.

REDDspots and Use of Alternative Carbon Data Sets

We compared the carbon data set used here (Ruesch & Gibbs 2008) with another empirically derived data set (Saatchi et al 2011). Method and result details regarding this comparison are in Supporting Information.

Results

Forest Carbon and Deforestation

Presence of JCUs was positively associated with carbon and negatively associated with deforestation. The odds of a municipality including a JCU or corridor increased by 0.8% for each unit increase of carbon ($z = 13.89, p < 0.0001$) and decreased by 16% for each unit increase in deforestation ($z = -2.33, p < 0.05$).

Jaguar index varied positively with carbon stocks and negatively with deforestation. The highest jaguar conservation priority areas were mostly above 230 t C/ha of carbon storage and with an ADefR under 5% (Fig. 3a).

Municipalities containing urgent priority JCUs had higher carbon stocks ($\chi^2 = 397.03$, df $= 5, p < 0.0001$) and lower deforestation rates ($\chi^2 = 157.53$, df $= 5, p < 0.0001$) compared with municipalities containing other categories (Supporting Information).

The probability of biodiversity priorities occurring in a municipality was influenced by the negative interaction between carbon and deforestation. Consequently, when both deforestation and carbon values increased, the likelihood of a municipality containing MMA or IBPs decreased by 0.1% and 0.3%, respectively ($z = 2.66, p < 0.01$ and $z = -7.59, p < 0.0001$).

When considered separately, each unit increase in carbon increased the likelihood of occurrence of both MMA biodiversity priorities (by 0.7%, $z = 11.73, p < 0.0001$) and IBPs (by 0.2%, $z = 2.58, p < 0.01$). And for each unit increase in ADefR, the likelihood of a municipality including an IBP increased by 46% ($z = 4.72, p < 0.0001$); however, there was no significant relationship with MMA biodiversity priorities ($z = -1.687, p = 0.09$).

Municipalities with the highest IBP index were typified by either high carbon and low deforestation or by low carbon and high deforestation (Fig. 3b). Municipalities with the highest MMA indices were more evenly distributed (Fig. 3c), but still exhibited positive association with carbon stocks.

The highest IBP biodiversity categories (4 and 5) were positively associated with forest carbon stocks ($\chi^2 = 316.58$, df $= 5, p < 0.0001$, Supporting Information) and negatively associated with deforestation ($\chi^2 = 578.03$, df $= 5$, $p < 0.0001$, Supporting Information), whereas lower scores (0 and 1) exhibited the opposite trend. The MMA biodiversity medians differed significantly for carbon ($\chi^2 = 214.31$, df $= 3$, $p < 0.0001$, Supporting Information) and deforestation ($\chi^2 = 54.29$, df $= 3$, $p < 0.0001$, Supporting Information), but only category 0 differed significantly from the others.

Multicriteria Decision Matrix Analyses (PROMETHEE)

The values used to compare the 16 scenarios (Fig. 2) in the fundamental criteria matrix are summarized in Table 2 and Supporting Information. The length of the criterion axes indicated the strength of the discriminating criteria (Fig. 4a). All fundamental criteria presented a similar length, but the deforestation ADefR criterion exhibited the longest axis and thus the most influence on the overall decision.

Scenarios C and D were ranked highest, appearing close to the decision axis for all fundamental criteria π (Fig. 4a) and in particular for carbon storage, probability of JCU occurrence, probability of MMA occurrence, and proportion of forest remnant.

Probability of IBP occurrence and proportion of forest remnant showed similar orientations, but they were opposite to ADefR (indicating conflicting preferences between these criteria).

Scenarios I and E performed best in relation to the criteria for deforestation (in agreement with the thresholds for deforestation in both scenarios), and scenarios L and H performed best in relation to IBP occurrence. Overall scenarios M, N, O, and P were the least preferred scenarios (opposite to the decision axis π [Fig. 4a]). The long length of π implies that the decision axis had a strong decision power and that the preferred solutions will be oriented in that direction. Scenarios A, B, C, and D were selected as the preferred candidates considering the pairwise comparison for all fundamental criteria.

The final net outranking flow (Φ) for the top 4 scenarios in the PROMETHEE II analysis corresponded to $\Phi = D > C > B > A$. Scenarios D and C exhibited the highest scores for net flow (Φ), which is the difference between

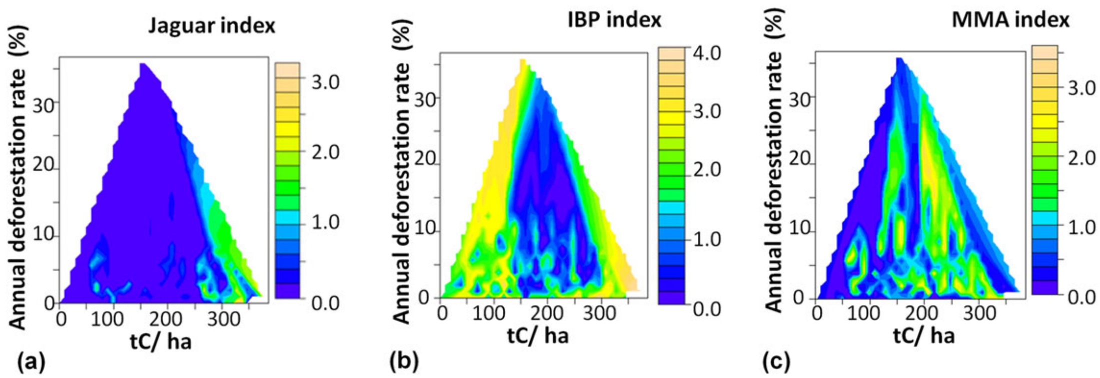

Figure 3. Relations among the variables forest carbon (0–386 t C/ha) and annual deforestation rate 2002–2008 (0–36%) and (a) priorities for jaguar conservation (jaguar index), (b) international biodiversity priorities (IBP index), and (c) Brazilian Ministry of Environment (MMA index) (the higher the index value, the higher the conservation priority of the index).

outfluxes (Φ^+; how much a scenario is preferred to all other scenarios) and influxes (Φ^-; how much all other scenarios are preferred to a given scenario). However, scenario D had the highest outfluxes whereas C had the highest score for influxes. Thus one should not assume D is better than C. We therefore compared the top 4 scenarios in another decision matrix including additional criteria (Table 2 & Supporting Information).

The top 4 scenarios compared against all 17 fundamental, representativeness, and cost criteria (Supporting Information) obtained an equivalent final net flow Φ result (D>C>B>A). These 4 scenarios had a high carbon threshold (≥230 tC/ha), but different thresholds for deforestation (Figs. 2 & 4b).

Assessment of Decision Matrix Results and Suitable REDDspots

The criteria we used as proxies for cost and deforestation risk favored scenarios A and B, which had fewer municipalities (A = 86, B = 95) and higher deforestation thresholds (Fig. 4b), whereas most of the representativeness criteria (e.g., percent total forest cover and percent total forest carbon) were maximized in scenario D (371 municipalities). Subsequent PROMETHEE-GAIA analysis confirmed this relationship but indicated the choice between C or D depended upon the weighting attributed to each criteria, with changes of 10% affecting the direction of the decision axis toward selecting either D or C. Varying the weightings by more than 65% could push the outcome toward B or A.

We explored the sensitivity of the top 4 scenarios to variations in the weights of cost and deforestation risk (Figs. 4c & d). Increasing the weighting of cost favored scenarios with fewer municipalities. Under equal weights (6%), D was the preferred scenario; however, when weights were >57% for cost and >33% for deforestation risk, scenario D became the least favorable scenario.

Scenario C was revealed as the least susceptible to weightings variations in both cost and deforestation risk (Figs. 4c & d). Scenario D was the preferred option when cost and risk were not taken into account, whereas C was a reasonable solution considering these factors, remembering that all municipalities contained in C were also contained in D (Figs. 2 & 4b). We therefore selected the municipalities highlighted in scenario C as our REDDspots.

REDDspots (scenario C) (Fig. 4b) were distributed in 3 biomes and 10 states: 5 states from Amazonia, 3 from Amazonia/Cerrado, and 2 from Atlantic Forest. The general trend was the selection of municipalities from Amazonian arc of deforestation and the Atlantic rainforest because these are the 2 high-carbon regions most affected by large scale deforestation.

A threshold for forest cover was applied to the REDDspots identified under scenario C (Figs. 5a & 5b) concerned specifically with potential jaguar conservation. From 159 REDDspot municipalities, 12 (7%) contained <5000 ha of forest cover, and these occurred in the Atlantic forest and Amazonia biomes in the states of Santa Catarina (4), Parana (6), and Maranhão (2). Of these, 8 corresponded to Jaguar corridors, 7 of which were of the less realistic no barrier corridors category. In municipalities with less than 5000 ha of forest cover, there may be fewer opportunities for successful interventions focused on jaguar conservation.

REDDspot ($n = 159$) and current or proposed REDD projects ($n = 135$) coincided in 25% ($n = 40$) of municipalities (Fig. 5d), a significantly greater level of overlap than expected by chance ($\chi^2 = 357.30$, df = 1, $p << 0.0001$). All REDD projects in Amazonia ($n = 39$) occurred in REDDspot municipalities, whereas only 1 did so in the Cerrado. Of the 119 municipalities that were identified as REDDspots but for which we were unaware of any REDD projects, 84 occurred in Amazonia and 35 in Atlantic Forest. There were 95 municipalities that contained

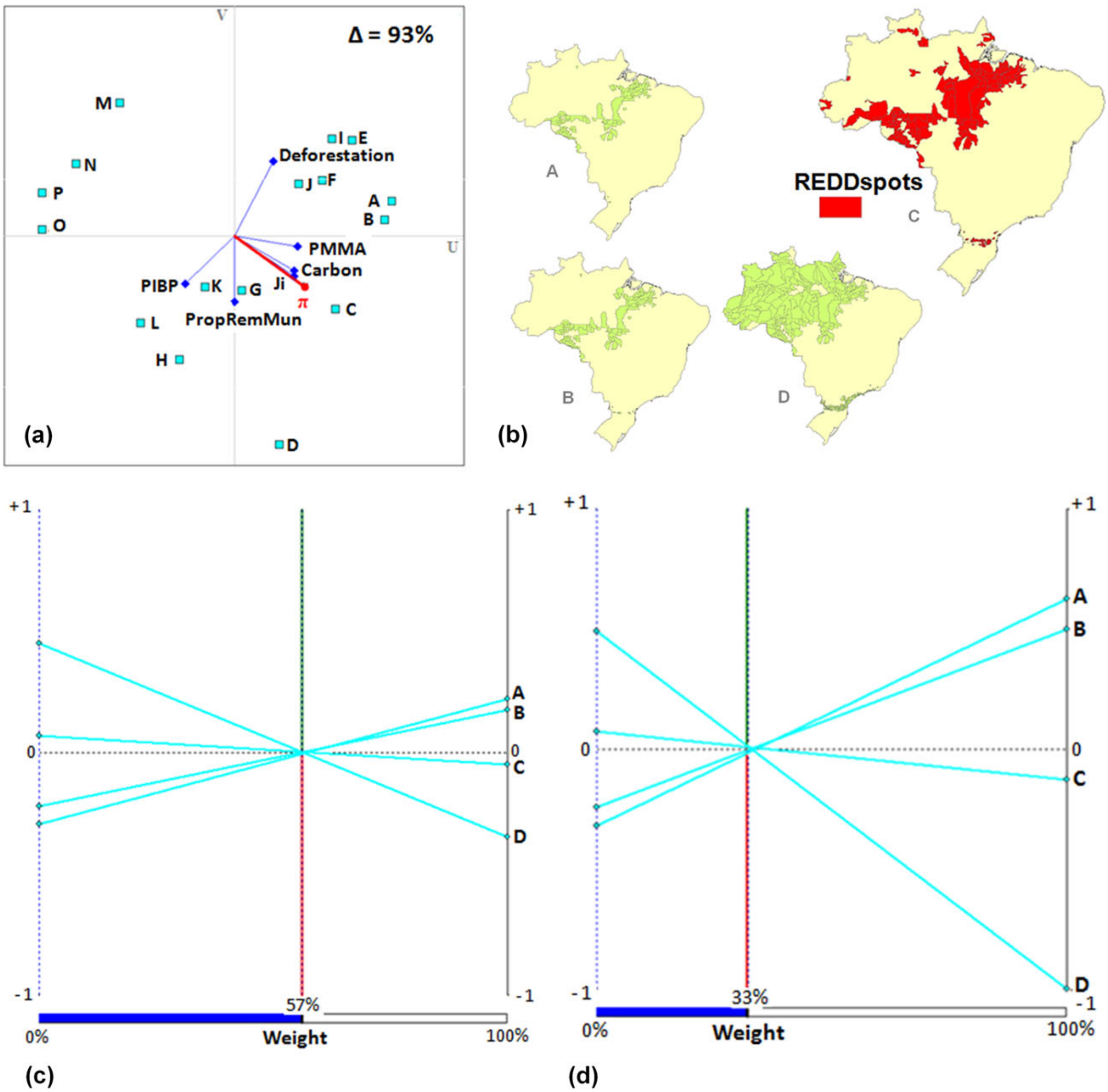

Figure 4. (a) Results of PROMETHEE-GAIA visual analyses that show how the 16 scenarios (squares A to P) (see Fig. 2) performed relative to the 6 fundamental criteria (carbon, carbon stocks in tons of C per hectare; deforestation, percent annual deforestation rate in 2002–2008; PropRemMun, median proportion of forest remnant in 2008; Pj, probabilities of occurrence for jaguar conservation priorities; PMMA, probabilities of occurrence for Brazilian Ministry of Environment biodiversity priorities; PIBP, probabilities of occurrence for international biodiversity priorities; π, optimal decision [all criteria decision axis]; Δ, amount of information explained in the GAIA projection). (b) Suitable scenarios for REDDSpots (A, B, C, and D) and their corresponding municipalities (A, n = 86; B, n = 95; C, n = 159; D, n = 371). Municipalities shown in scenario C were selected as REDDspots. (c) Stability intervals show effect of different weights on municipalities in the final net outranking flow (Φ) (scenario C is least sensitive to weight variation in the municipality criteria and D is the most sensitive to differences in cost). (d) Stability intervals showing the effect of different weights of annual percent deforestation rate (2002–2008) on the top 4 scenarios (scenario D is the lowest ranked scenario when weights are >33% and includes municipalities with no recent deforestation, which explains the low performance of scenario D relative to the deforestation risk criteria).

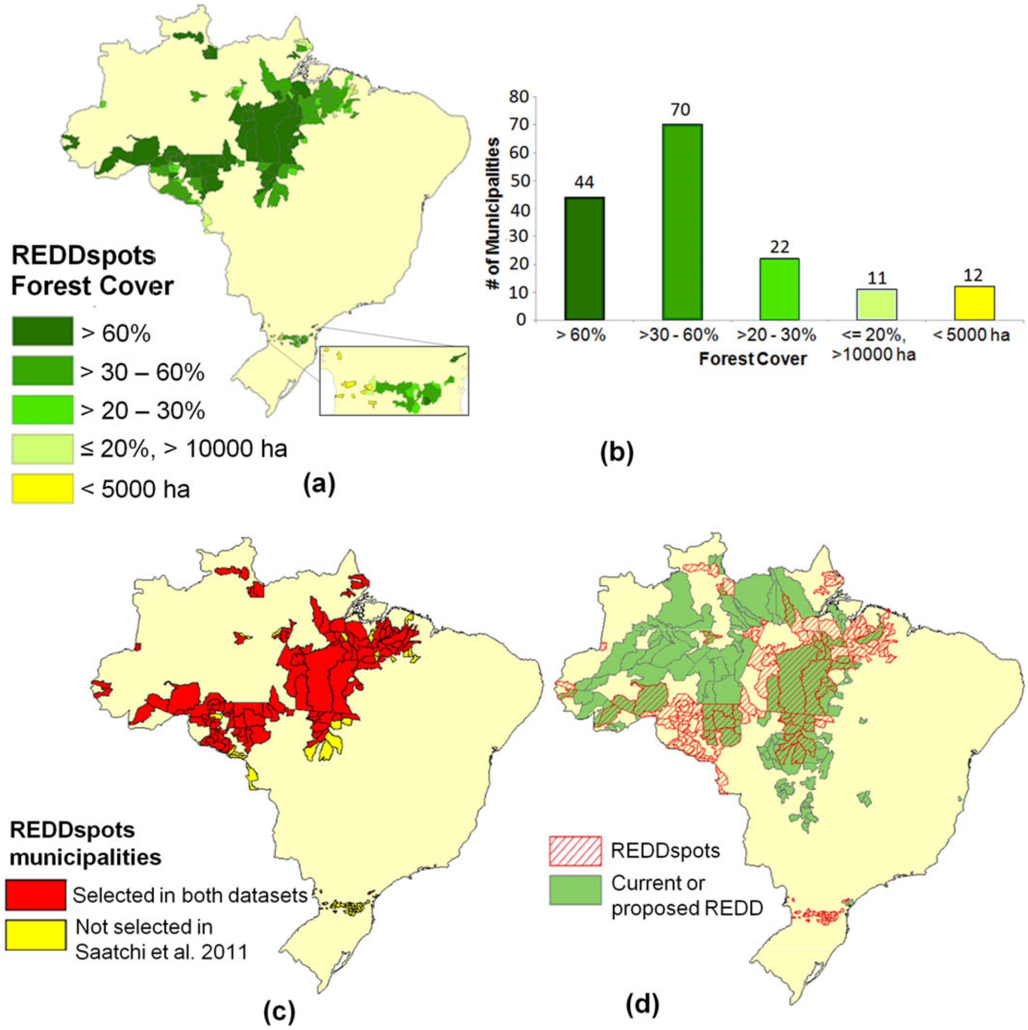

Figure 5. (a) Area of forest cover in municipalities selected as REDDspots (i.e., areas that offer the greatest opportunity for co-benefits between the conservation of forest carbon and biodiversity). Expanded region shows where most of the municipalities with <5000 ha of forest cover occur. (b) Number of municipalities associated with each class of forest cover in REDDspot municipalities. (c) Areas selected as REDDspots either in both data sets or not selected in Saatchi et al. (2011). (d) Overlap of REDDspot municipalities and municipalities containing current or proposed REDD projects (see Supporting Information for details).

current or planned REDD projects (61 in Amazonia, 31 in Cerrado, and 3 in Atlantic Forest) but which did not meet all the criteria or thresholds we used to select REDDspots. Of these, 41 failed to meet the threshold value for forest carbon, 37 failed to meet the threshold value for ADefR, 3 failed to meet the thresholds for both forest carbon and ADefR, and 14 occurred outside JCUs.

The carbon data sets used were correlated for all Brazilian municipalities (Pearson's correlation $r = 0.75$, $p << 0.0001$, df = 5563, 95% CI = 0.74–0.76) (Supporting Information); however, estimated total forest carbon per municipality was lower in Saatchi et al's (2011) data (M = 91.7 tC/ha) than in the Ruesch and Gibbs (2008) data (M = 154.3 tC/ha). The correlation and the differences between the means of the 2 data sets were variable between biomes. This is possibly related to the degree of uncertainty in Saatchi et al. (2011) or the differing NM per biome. In practice, the use of Saatchi et al. (2011) data (considering our >230 tC/ha threshold for high carbon) reduced the number of REDDspot municipalities from 159 to 103 (Fig. 5c), mainly due to Saatchi et al.'s (2011) lower carbon estimates (Supporting Information).

Discussion

REDDspots highlight areas that offer the greatest opportunity for combining the conservation of forest carbon, jaguars, and wider biodiversity. We propose that the concept of REDDspots as a useful tool for decision makers in optimizing reduced deforestation risk while targeting carbon and biodiversity conservation. Opportunity costs (Olsen & Bishop 2009) may drive REDD+ initiatives to areas of low deforestation risk; however, the greatest benefits would be to reduce deforestation risk where it is high (Harris et al. 2008). REDD+ includes biodiversity conservation only incidentally (Collins et al. 2011*b*); however, there are frameworks within which biodiversity gains could be bundled into REDD+ programs (Collins et al. 2011*a*). Furthermore, the REDDspot concept may be technically adapted with use of different scales or data sets.

High jaguar indices, the probability of a JCU occurring in a municipality, and a JCU's priority level (Fig. 3 & Supporting Information) were all positively associated with forest carbon stocks and negatively associated with deforestation. This was expected because JCUs and corridors were developed based on possible stable jaguar populations, protected areas, and indigenous territories (Nijhawan 2012). Although high-priority JCUs were associated with high forest carbon stocks and protected or indigenous areas, corridors often lay in unprotected and agricultural landscapes that are generally associated with high deforestation rates (Supporting Information).

Both measures of biodiversity priority were positively associated with forest carbon. However, although MMA biodiversity categories were more evenly distributed among biomes, IBP areas were predominantly associated with the Atlantic Forest and Cerrado (Fig. 1). The congruence between both measures of biodiversity and forest carbon stocks illustrates the potential for REDDspots to provide co-benefits, but should not diminish attention to biodiversity conservation in low carbon areas.

REDDspots balance several criteria selected alongside carbon and deforestation thresholds. The opportunity to explore combinations of cause and effect is a strength of the scenario approach (Soares Filho et al. 2006; Kass et al. 2011), and the PROMETHEE-GAIA analysis aided the selection of optimal scenarios. For fundamental criteria (Table 2) high carbon municipalities achieved the best results, in particular for jaguars and MMA biodiversity priorities (Fig. 4). Comparing the 4 high carbon scenarios, deforestation thresholds limited the selection of municipalities. Scenario D was preferred in terms of representativeness criteria, whereas scenario A was the least costly. Scenario C was the most balanced in relation to fundamental and representativeness criteria and the least sensitive to weighting changes for cost and deforestation (Fig. 4). The PROMETHEE method is a valuable tool for conservation decision making, but the final decision depends on stakeholders' goals and limitations and ultimately on discussion and judgment (Drechsler 2004).

Among the 159 municipalities highlighted as REDDspots, 12 had <5000 ha of forest (8 corresponding to potential jaguar corridors in the Atlantic Forest). Jaguar populations may not exist in such municipalities, but corridors could promote connectivity with other municipalities with small effective populations and enhance their survival (Rabinowitz & Zeller 2010). Limited forest cover, fragmentation, and road barriers could particularly affect female jaguars' mobility and dispersal (Conde el al. 2010). In addition, reduction in forest cover thresholds may negatively impact populations of forest dependent species (Oliveira Filho & Metzger 2006; Pardini et al. 2010).

The threshold values that were selected (i.e., high carbon) as well as the data set used may have major implications on the results of prioritization schemes or multicriteria decision analyses. They should therefore be considered carefully. For example, the 2 carbon data sets used here were significantly correlated; however, shifting from Ruesch and Gibbs (2008) to Saatchi et al. (2011) while maintaining the same thresholds for carbon (>230 tC/ha) would have resulted in 56 fewer municipalities being selected as REDDspots. However, because this stems from our choice of threshold value, it does not radically alter our underlying message.

REDD projects in Brazil may occur inside and outside protected areas and involve diverse stakeholders. Current or planned REDD projects ($n = 135$) overlap with REDDspots ($n = 159$) in 40 municipalities. Ninety-five municipalities contained REDD projects, but did not overlap with REDDspots. Of these, 85% were not selected as REDDspots because they did not reach the thresholds for forest carbon or ADefR, which suggests that a focus on high carbon and on deforestation risk may not have been the predominant driver of project location. The remaining 15% were sited outside JCUs and represented a potential missed opportunity for conservation.

We identified a further 119 municipalities which may have potential to develop additional REDD+ projects. These represent the areas with greatest potential for a portfolio of REDD+ projects to sensitively balance benefits to existing conservation strategies, such as the PAN, with areas of simultaneously high carbon stocks and high deforestation risk, such as the Amazon arc of deforestation. REDDspots could also be used to identify areas where avoided deforestation and reforestation projects could be combined to maintain and improve jaguar corridors. For example, in the Atlantic rainforest of southeastern Brazil, jaguar populations are perilously isolated (Haag et al. 2010). Given low forest cover and road-induced habitat fragmentation, reforestation strategies could be a useful tool in this region. Although REDDspots are a powerful tool, they are not a panacea. In the Caatinga and Cerrado the jaguar is endangered but carbon stocks are low, so REDD+ projects offer little scope for combining co-benefits for carbon and jaguar conservation.

We see great potential rewards for integrating biodiversity conservation with carbon protection and avoided deforestation, especially in the case of the jaguar which may also deliver umbrella and flagship benefits.

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Supporting Information

Additional references (Appendix S7), data sets used for GIS analysis (Appendix S1) and to compile REDD strategies in Brazil (Appendix S2), information relevant to quantitative analyses and parameters used in the Promethee analysis (Appendix S3), a list of municipalities elected as REDDspots (Appendix S4), additional spatial analyses (Appendix S5), and the results of the comparison among the quoted carbon data sets (Appendix S6) are available online. The authors are responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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