Role of Brazilian Amazon protected areas in climate change mitigation

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Protected areas (PAs) now shelter 54% of the remaining forests of the Brazilian Amazon and contain 56% of its forest carbon. However, the role of these PAs in reducing carbon fluxes to the atmosphere from deforestation and their associated costs are still uncertain. To fill this gap, we analyzed the effect of each of 595 Brazilian Amazon PAs on deforestation using a metric that accounts for differences in probability of deforestation in areas of pairwise comparison. We found that the three major categories of PA (indigenous land, strictly protected, and sustainable use) showed an inhibitory effect, on average, between 1997 and 2008. Of 206 PAs created after the year 1999, 115 showed increased effectiveness after their designation as protected. The recent expansion of PAs in the Brazilian Amazon was responsible for 37% of the region's total reduction in deforestation between 2004 and 2006 without provoking leakage. All PAs, if fully implemented, have the potential to avoid 8.0 ± 2.8 Pg of carbon emissions by 2050. Effectively implementing PAs in zones under high current or future anthropogenic threat offers high payoffs for reducing carbon emissions, and as a result should receive special attention in planning investments for regional conservation. Nevertheless, this strategy demands prompt and predictable resource streams. The Amazon PA network represents a cost of US$147 ± 53 billion (net present value) for Brazil in terms of forgone profits and investments needed for their consolidation. These costs could be partially compensated by an international climate accord that includes economic incentives for tropical countries that reduce their carbon emissions from deforestation and forest degradation.

Amazon Region Protected Areas | effectiveness | reducing emissions from deforestation and forest degradation | simulation model | opportunity cost

Tropical forests play a major role in the world's climate system by storing large stocks of carbon (1) and by regulating energy and water fluxes (2). The release of this carbon to the atmosphere through deforestation and forest degradation is the second largest source of greenhouse gas emissions (3) but was omitted from the Kyoto Protocol. The 13th Conference of Parties of the United Nations Framework Convention on Climate Change produced the Bali Action Plan that stressed the need to pursue incentive mechanisms for developing countries to reduce carbon emissions from deforestation and forest degradation (REDD). As nations finalize negotiations of REDD (4), funds are already flowing into REDD pilot programs. In one of the greatest environmental conservation challenges in history, Brazil has established a target for reducing Amazon deforestation by 80% below the historical baseline of 19,500 $\mathrm{km}^2\ \mathrm{year}^{-1}$ by 2020. To finance this effort, Brazil established the Amazon Fund, to which Norway already has committed US$1 billion (5). An essential component of a basin-wide conservation strategy, protected areas (PAs), play a major role in this effort, given their potential to avoid the emission to the atmosphere of a large portion of the 47 ± 9 Pg of carbon stored in the Brazilian Amazon forest (5).

We broadly define PAs as all public areas under land-use restrictions that contribute to protecting native ecosystems, even if they were created for purposes other than environmental conservation (6). Under this definition, PAs in the Brazilian Amazon include strictly protected and sustainable-use conservation reserves (categories I–VI) (7) as well as indigenous lands, with their social and cultural priorities, and military areas (Table S1). These PAs cover a total area of 1.9 million km^2, encompassing 45.6% of the Amazon biome in Brazil or 54% of its remaining forest (≈ 3.4 million km^2), and this figure keeps increasing. Between 2002 and 2009, 709 thousand km^2 were designated as new PAs (Fig. 1 and Fig. S1*C*). Many of these new PAs receive financing from the Amazon Protected Areas Program (ARPA), a program launched by the Brazilian government in 2002 that aims to support a total of 600,000 km^2 of new and existing PAs, making it the most ambitious PA program in the world. This recent PA expansion partially contributed to a 75% decrease in deforestation in the Brazilian Amazon from 2004–2009, representing a 64% reduction below the 10-year average (5, 8). Thus, as political momentum builds to compensate nations that lower their carbon emissions from tropical deforestation (4), there is a timely need to measure the contribution of the Amazon PAs to Brazil's effort to mitigate climate change.

Previous studies have quantified the effectiveness of these PAs in reducing deforestation (9–11), but the methods adopted to measure PA performance are somewhat controversial (12). We reviewed nine studies (9–17) of PA effects on tropical deforestation, summarizing their methods, assumptions, and main conclusions (Table S2). The methods of these studies vary from simple comparisons of deforestation rates in zones inside and outside groups of PAs [all PAs of a region or groups of PAs, wall-to-wall data, high or low spatial resolution, time-period or annual deforestation rates (9–11, 14, 15)] to more sophisticated statistical approaches that attempt to resolve differences in deforestation probability in samples used for comparison (12, 13, 16, 17). The well-supported argument against using buffer zones for pairwise comparison made by this second group of studies is that landscape characteristics in sampled areas are not the same: areas in the interior of PAs usually are more remote (18) and thus are less likely to be deforested than areas in their exterior (12, 16, 17). Conclusions from these studies regarding the inhibitory effect of PAs on deforestation also vary, from a positive effect (9, 10, 15) that, however, is not seen in all PA groups (11) or a positive but modest effect (12, 13, 16, 17) to no effect (14). As a result, the terms "*de jure*" and "de facto" have been used to qualify PA effects (11); the latter simply expresses a bias toward

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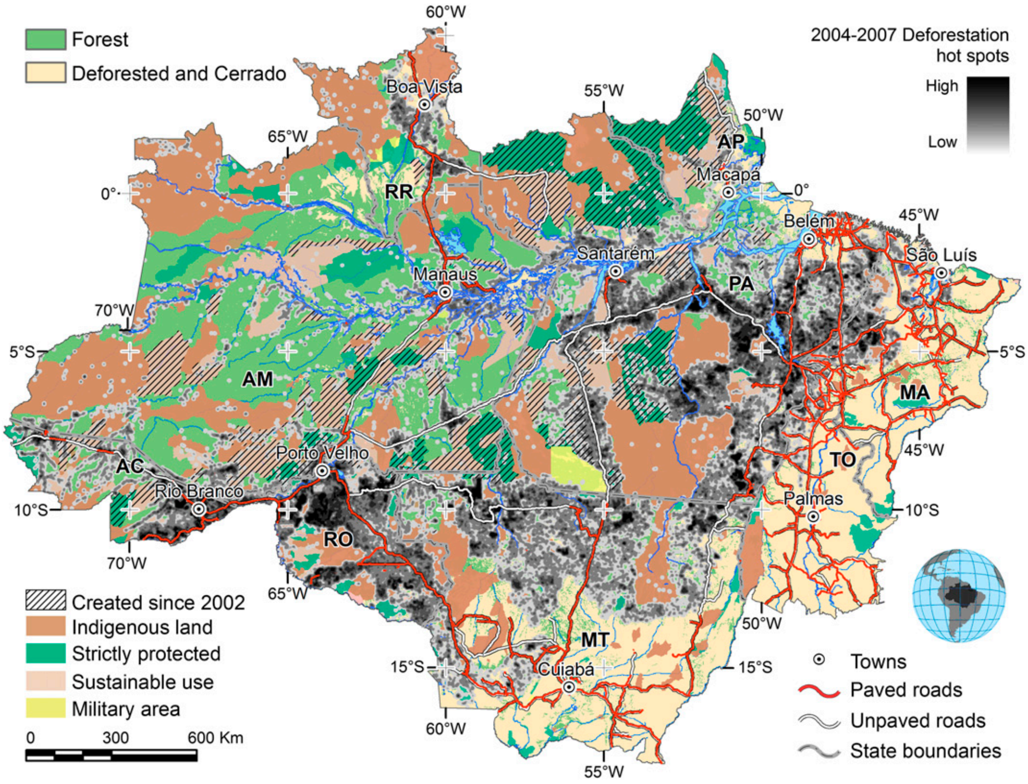

Fig. 1. Brazilian Amazon PAs and 2004–2007 deforestation hot spots. The Arc of Deforestation comprises eastern, southern, and southwestern Amazon. AC, Acre; AM, Amazonas; AP, Amapá; MA, Maranhão; MT, Mato Grosso; PA, Pará; RO, Rondônia; RR, Roraima; TO, Tocantins.

PA's more remote location. All these studies focused on the proximate effects of PAs on deforestation, but none attempted to model their effects on the overall trajectory of deforestation. Here, we present analyses that help fill this gap by using a set of methods that assess the local effects of Brazilian Amazon PAs, individually or by category, and model the historical and future roles of these PAs in reducing the overall deforestation trajectory and associated carbon emissions in the Brazilian Amazon biome. We complement this assessment by analyzing the possibility for leakage and presenting an estimate of the costs of such a conservation initiative.

Results and Discussion

The most advanced method of PA comparison is propensity score matching, which selects paired samples inside and outside PAs with equivalent deforestation probabilities (16). This technique could not be used for the Brazilian Amazon PAs. First, statistical tests show that most pairs of 10-km adjacent internal and external buffers have different distributions of deforestation probability (453 out of 571, according to both Kolmogorov-Smirnov and Kruskal-Wallis tests, $P < 0.05$). This result suggests that we should look for potential matching samples at a distance from PA boundaries, both inside and outside the PA. However, the distribution of PAs in the Brazilian Amazon forms a complex and interlocking mosaic (Fig. 1), making it very difficult to find sufficient paired samples (that could yield statistically significant results) with equivalent deforestation probabilities, which tend to increase with distance from PAs and toward major roads and towns. To overcome this limitation, we adapted a Bayesian method known as the "odds ratio" to assess the local effect of PAs on deforestation. This method, termed here "adjusted odds ratio of deforestation," compensates for differences in probability of deforestation in areas used for pairwise comparison without requiring matching samples. Also, because this method accounts for differences in the probability of deforestation in both forested and deforested cells of areas of pairwise comparison, independent of cell location, it enables the use of wall-to-wall data and can be used to assess the effect of a single PA or many PAs together, incorporating tests for statistical significance and assumptions associated with the nonparametric methods used. The adjusted odds ratio of deforestation is sensitive to variations in size of areas used for pairwise comparison as well as to their locations with respect to the Arc of Deforestation (Fig. 1). Moreover, the adjusted odds ratio of deforestation allows us to compare the local effect of a PA independent of variation in the overall deforestation rate (Fig. S2 *A* and *B*), thereby making this metric a robust indicator of a PA's inhibitory effect.

We applied this metric to compare deforestation from 1997–2000 and from 2000–2008 on an annual basis (8) in adjacent internal and external 10-km buffer zones for each of 595 Brazilian Amazon PAs. An adjusted odds ratio <1 indicates an inhibitory effect, which becomes stronger in magnitude as this value approaches zero. We found that three of the four major categories of PAs (indigenous land, strictly protected, and sustainable use) showed inhibitory effects, on average, after they were designated as protected, with mean odds ratios <1 (Table 1 and Fig. S3). The most effective category consists of indigenous lands (Kolmogorov-Smirnov and Kruskal-Wallis tests; $P < 0.05$), of which the Xingu/Jarina/Menkragnotí/Kayapó/Baú complex is worthy of mention because of the degree to which it inhibits deforestation within a very active agricultural frontier (Fig. S3). Only the military areas showed on average no inhibitory effect. However, when the inhibitory effect of a PA is weighted by its areal extent, military areas, as a group, become effective because of the Serra do Cachimbo reservation, a large forest reserve that acts as a major barrier against deforestation on the border of Mato Grosso and Pará states (Fig. S3). (Results for all Brazilian Amazon PAs can be found in Dataset S1.) To test whether the

Table 1. Mean and SD of odds ratios of deforestation (1997–2008) for categories of PAs after they were designated as protected

Category	No. of PAs	Before adjustment*		After adjustment*		Effectiveness increased	
		Odds ratio	Area-weighted odds ratio	Odds ratio	Area-weighted odds ratio	Yes	No
Strictly protected	90	0.40 ± 0.59	0.38	0.42 ± 0.60	0.43	14	12
Sustainable use	176	0.48 ± 0.86	0.33	0.58 ± 0.86	0.86	30	25
Indigenous land	318	0.74 ± 1.99	0.24	0.28 ± 0.65	0.69	71	54
Military reserve	11	4.40 ± 7.99	0.20	2.74 ± 5.31	0.50	—	—
All PAs	595	0.67 ± 1.93	0.29	0.43 ± 1.06	0.68	115	91

*Before and after adjustment to compensate for differences in deforestation probability in areas of pairwise comparison.

inhibitory effect of a PA is *de jure* (i.e., the result of its designation as a PA), we compared the mean adjusted odds ratio before and after designation of 206 PAs created after 1999. Of these, 115 showed lower mean adjusted odds ratios after their designation. Among these, Parque Estadual (PE) do Cristalino, PE dos Igarapés do Juruena, Estação Ecológica (ESEC) da Terra do Meio, Parque Nacional (PARNA) da Serra do Pardo, PARNA do Juruena, and Reserva de Uso Sustentável (RDS) do Juma are noteworthy examples. However, this analysis must be viewed with caution because of the short time span of comparison and the proportionally larger reduction in deforestation rates that took place in some regions outside PAs, which may have contributed to higher odds ratios of deforestation within PAs (Fig. S2*B*).

The causes of the recent, steep decline in deforestation rates in the Brazilian Amazon still are poorly understood and may include the declining profitability of agriculture and ranching (19), expansion of the PA network, and other factors, such as increased government enforcement of environmental law (5). To shed light on this debate, we developed an econometric model that predicts deforestation based on changes in the socioeconomic conditions (*Methods* and *SI Text*) and ran the model for 2004 (the year of highest deforestation) to 2006 (when deforestation already had started to plummet). We separated out the contribution of new PAs by running the model without and with the recent PA network expansion (i.e., replacing PA data from 2006 with data from 2004; Fig. S1*C*). Similarly, the effect of the decline in the agriculture sector was quantified through a model run that used the rates of agricultural growth (cattle herd and crop area expansion) in 2006 and, alternately, the much higher rates in 2004 (Fig. S1 *A* and *B*). All other variables were held constant. Finally, from the 2006 deforestation rates predicted by each model run (Fig. S4 *C* and *D*), we subtracted the rates obtained by running the model with the real-life PA and agricultural growth data. The total difference in area of deforestation was 5,900 km^2 for the run that excluded the agricultural downturn and 5,000 km^2 for the run without PA expansion. The sum of both differences (10,900 km^2) accounted for all but 2,500 km^2 of the 13,400-km^2 decline in deforestation measured from 2004–2006 (8). Using these values, we estimate that 44% of the 13,400-km^2 decline was caused by the agricultural slowdown, 37% by new protected areas, and 18% by factors not included in the model. Prominent within this third category are the development of a rapid deforestation-detection system (20) in support of command and control campaigns (21), which may have curbed illegal deforestation in areas outside PAs, and other investments in greater enforcement of environmental laws (5).

One criticism of the PA approach to reducing deforestation is that PAs simply deflect deforestation elsewhere, causing leakage (22). We investigated this assertion by performing a series of tests for leakage from the recent PA expansion in the Brazilian Amazon. First, if "in-to-out" leakage (23)—i.e., the displacement of people who lived inside the newly created PA to its neighboring vicinity—were occurring, there should be a spatial relationship between new PAs and deforestation. We tested for a spatial dependence between the occurrence of local increases in deforestation outside PAs from 2002–2004 to 2005–2007 and the location of the newly created PAs. The tests we used (K12, Cramer's coefficient and contingency) found no spatial dependence between regions where PAs expanded and the few regions in the Amazon where deforestation rates increased in contrast to the overall declining trend (Fig. S5 *A–D*). Second, if "out-to-out" leakage—i.e., land-grabbers entering the general area and redirecting their attention to forest areas outside the newly created PA (23)—were occurring, the ratio between the deforestation rates outside and inside PAs should increase independent of the overall trend. A trend of increase in odds ratios of deforestation within PAs between 2000 and 2007 rules out this possibility, showing that the reduction of deforestation rates outside PAs was proportionally higher than that of their interior (Fig. S2*B*). Moreover, the measured contribution of PA expansion to the recent decline of deforestation rates in the Brazilian Amazon after deducting the effect of the agricultural downturn and the pervasive and continued reduction in deforestation rates outside of PAs across almost all Brazilian Amazon municipalities (Fig. S5*D*) provides additional arguments against out-to-out leakage. Hence, these findings demonstrate the role of PAs both in deterring deforestation locally and in influencing a reduction in regional deforestation rates, because their creation may discourage action of illegal land-grabbers in their vicinities (23). Nevertheless, although PA expansion might mitigate current pressures on forests, it also might result in indirect and more diffuse leakage by contributing to the scarcity of land available for production and, in turn, through an increase in cleared land values, to higher crop and timber prices. In this respect, the role of logging concessions to be established in national and state forests is central in taming the advance of the timber industry into the inner region of the Amazon (24).

To assess the direct and indirect contribution of PAs to possible future reductions in deforestation in the Brazilian Amazon by 2050, we coupled the econometric projection model to Sim-Amazonia (25) and used this simulation environment to run five scenarios of progressive and cumulative increase in the PA network. To bracket a range of potential emissions for each of the five PA scenarios, we also combined these scenarios with two socioeconomic scenarios: high and moderate agricultural growth (scenario assumptions are given in *SI Text*). Hence, the potential emissions from each PA scenario represent an average of the two corresponding socioeconomic scenarios, and the range of uncertainty is the difference between these two scenarios multiplied by 1.2 to include errors in biomass estimates (26). The five PA scenarios are as follows: (*i*) Exclusion of all current PAs. (*ii*) Baseline. This scenario considers only PAs established by 2002. It serves as a basis for comparison for examining the contribution of PA expansion. (*iii*). PAs established by 2008, except for 13 areas established from 2003–2008 under the ARPA program. (*iv*). PAs established by 2008. (*v*). PAs established by 2008 plus expansion underway with support of the ARPA program.

The first scenario aims to determine which PAs face greater risk of deforestation in the near future because of their proximity to the agricultural frontier and roads slated for paving; hence their potential carbon emission reductions are higher relative to the total carbon stocks (Dataset S1). If we consider only the forest biomass within Brazilian Amazon PAs, which totals 26 ± 5 Pg of carbon, PAs hold the potential to avoid 8.0 ± 2.8 Pg of carbon emissions by 2050. In addition, the level of deforestation threat resulting from this scenario provides a vulnerability index for prioritizing PAs under an irreplaceability/vulnerability conservation framework (18, 27).

The other four scenarios depict the progressive contribution of PA expansion to reducing deforestation and the contribution of areas established with support of the ARPA program. The results showed that, by 2050, expansion of PAs during the period 2003–2008 would reduce deforestation by 272,000 ± 91,000 km^2, thereby reducing carbon emissions by 3.3 ± 1.1 Pg, of which 0.4 ± 0.1 Pg would be attributable to the 13 PAs established with ARPA support. When an additional 127,000 km^2 of new PAs currently being established under ARPA are included, the program would reduce a total of 1.4 ± 0.2 Pg in carbon emissions by 2050 (Fig. 2). This figure represents ≈16% of the current annual global anthropogenic emissions.

The costs of expanding and maintaining the Brazilian Amazon PA system must be taken into account, especially in a developing country with pressing social priorities. Those costs encompass two components (27): economic opportunity costs associated with the forgone profits of forest conversion, and the costs of consolidating and managing the PA system. To estimate the opportunity costs for avoiding agriculture and forestry profits, we applied a set of spatially explicit models of potential rents from soy, cattle, and timber production (5). The total opportunity costs for the Brazilian Amazon PA network is US\$141 ± 50 billion, averaging US\$5.4 ± 2.3 ton^{-1} of carbon (Dataset S1). This calculation assumes net present value (NPV) of agricultural and timber rents, using high and low price estimates, over a 30-year time horizon with a 5% discount rate. In addition, the annual budget for PA management ranges from US\$1–3 ha^{-1} (5), summing to US\$3–9 billion NPV for all current PAs over a period of 30 years. The PA costs of US\$147 ± 53 billion NPV could be defrayed in part by future REDD payments. Investments to reduce 9–23 Pg of CO_2 emissions that would be expected to occur over a period of 30 years if PAs did not exist (range of the two socioeconomic scenarios plus biomass estimation uncertainty) would amount to US\$27–84 billion NPV; these values include the entire PA network management budget and opportunity costs (high and low rent estimates) of areas that would be deforested. With annual payments representing about 1% of current global investments in clean energy (US\$148.4 billion) (28), reducing emissions with Amazon PAs would be equivalent to reducing deforestation emissions by 10% worldwide (29) but could be more cost effective, if we assume compensation of PA opportunity costs at <60%. The economic costs of PAs also are offset by the economic benefits of forest maintenance, including protection of rainfall regimes (30), reduction of fire incidence (10) and associated losses to human health, agricultural systems, and forestry potential, and the value of biodiversity itself. These benefits are difficult to quantify and generally are omitted from economic evaluations of REDD (29). In other words, assessments of the economic opportunity costs of PAs must be balanced by both the economic benefits associated with forest conservation and the programmatic costs of reducing deforestation, which can be quite small (5).

Conclusion

The expansion of the Brazilian Amazon PA network has established a conservation paradigm that not only focuses on biodiversity hotspots (31) but also seeks to set aside large blocks of forest to act as "green barriers" to deforestation. However, meeting the enormous challenge of fully implementing PAs in regions under immediate threat requires prompt and predictable inflows of resources. In short, establishing and implementing PAs in zones under a high level of current or future anthropogenic threat offers high payoffs in reducing carbon emissions and as a result should receive special attention in planning investment priorities for regional conservation. An optimal conservation strategy for the Amazon biome also should encompass PAs with high biodiversity under a low degree of threat; this strategy would increase the probability of long-term conservation of biodiversity in a scenario of climate change (32), thereby ensuring long-term protection of representative samples of biodiversity as well as reduced carbon emissions. These effects complement other roles of PAs in sustaining traditional livelihoods (33), maintaining the climate–vegetation balance (34, 35) and hydrological regimes (30, 36), and preventing forest fires (10). However, protecting the Amazon biome only with PAs is not sufficient (25). Special attention also should be paid to conservation initiatives aimed at private landholders, which should include encouraging expanding markets that value improved environmental and social performance in forestry and agricultural sectors, land-use zoning to prevent runaway expansion of agro-industry and ranching, improved monitoring and enforcement capacity among government agencies, and economic and technical incentives that will help

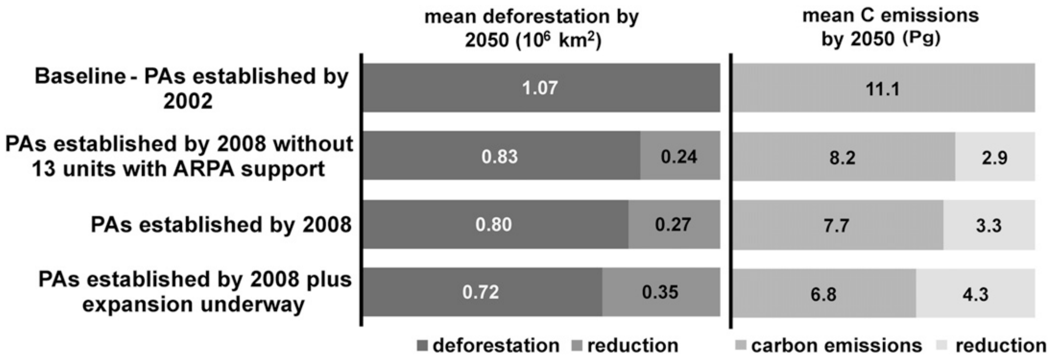

Fig. 2. Deforestation and carbon emissions in the Brazilian Amazon biome: average of two socioeconomic scenarios with simulations showing progressively increasing establishment of PAs.

landholders comply with the ambitious Brazilian forest code (19, 37). This integrated approach will be vital to REDD programs (5).

Materials and Methods

Details on data and methods are given in *SI Text*.

Data. The Amazon PA network comes from a database put together from various sources by the Amazon Scenarios Project (5, 25). For this study, we updated this database with information from the following sites: www.funai.gov.br and www.socioambiental.org. Annual deforestation data come from Programa de Cálculo do Desflorestamento da Amazônia (PRODES) maps in vector format (8), which were converted to a sole raster map at 0.36-ha spatial resolution. The biomass map at 100-ha spatial resolution comes from Saatchi et al. (38). Data on spatial determinants of deforestation come from a database compiled by various studies (5, 25, 37). Sources for socioeconomic data are provided in *SI Text*.

Measuring PA Effectiveness in Deterring Deforestation Locally. Adjacent internal and external 10-km buffer zones were derived specifically for each PA and overlaid with the map of deforestation for 1997–2000 and annually from 2000–2008. To test whether landscape characteristics are the same in the internal and external buffers, we integrated the effects of a series of spatial determinants [so-termed because they represent proximate causes of deforestation (e.g., the opening or paving of a road) or simply are preferable (e.g., more fertile soil, low slope) or are restricted sites (land-use zoning, such as PAs)] into a probability map of deforestation by using the weights of evidence method. This Bayesian method takes into account the differential effects of spatial determinants on the spatial prediction of deforestation. Among the various factors that influence the location of deforestation in the Amazon (25), we chose the following variables: (*i*) distance to rivers, (*ii*) distance to major roads, (*iii*) maximum net present value from soy and cattle rents (5), (*iv*) soil and terrain suitability for mechanized crops (37), (*v*) elevation, (*vi*) slope, and (*vii*) attraction by urban centers (25). First, we analyzed these variables for spatial dependence using the Crammer´s coefficient pairwise test, and then we validated the resulting probability map by applying the reciprocal fuzzy comparison method (39) to evaluate the output of a simulation of deforestation from 1997–2008 that uses this map as an input. The metric we used to assess the local effect of PAs on deforestation is the odds ratio of deforestation, which is defined as a ratio of the probability that an event will occur to the probability that it will not occur. For example, the probability of 0.5 of a person winning a contest is equivalent to odds of $0.5/(1-0.5) = 1$. Thus a PA inhibits deforestation if its odds ratio is <1, and this effect increases in magnitude as the odds ratio approximates zero. We adapted this metric to account for differences in probability of deforestation in both forested and deforested cells of the buffer zones used for pairwise comparison independent of the cell location (a detailed mathematical description of the method and its equations is given in *SI Text*). We determined the mean effect for a PA by selecting from its 1997–2008 odds ratios the odds ratios of the years after it was designated as protected. A sequence of models designed with Dinamica EGO freeware that perform these calculations, together with a demonstration dataset (25 ha spatial resolution), is available for download upon request to the corresponding author.

Analyzing Spatial Dependence Between the Creation of PAs and Deforestation. To test for spatial dependence between the observed variations in regional biennial deforestation rates from 2002–2004 to 2005–2007 outside PAs and the location of the newly created PAs, we applied a 50 × 50 km grid to calculate the percentage of PA expansion between 2002 and 2007 within each grid cell. Next, because we wanted to assess the effect of PA expansion on deforestation only outside PAs, we eliminated the grids that were completely covered with PAs (Fig. S5*A*) and then calculated the difference in total deforestation between the periods 2002–2004 and 2005–2007 in the remaining cells (Fig. S5 *B* and *C*). We carried out two analyses. First, we did a binary test for spatial dependence between the cells where deforestation increased and the cells where PAs expanded using the K12 test. In addition, we evaluated the spatial dependence between maps of percent increase in PAs versus deforestation change by applying the Cramer's Coefficient and Cramer's Contingency Coefficient pairwise tests. We repeated the latter test using Amazon municipality maps instead of 50-km cells to ensure that the spatial units of analysis represented a wide range of PA coverage (Fig. S5*D*).

Modeling PA Contribution to the Recent Decline in the Amazon Deforestation Rates. Our econometric model analyses the influence of a series of socioeconomic variables on the deforestation trend (Fig. S1 *A*–*C*). Data from 1996 and 2000 Instituto Brasileiro de Geografia e Estatística (IBGE) censuses and other socioeconomic surveys carried out during this period were assembled for each Brazilian Amazon municipality together with PRODES wall-to-wall deforestation data from 1997–2001 (8), which were aggregated at the municipal level to compose the dependent variable. The model consists of a spatial lag regression ($R^2 = 0.64$) that determines the municipalities' annual net rate of deforestation based on changes in the regional socioeconomic context, as represented by five independent variables: proximity to paved roads, change in cattle herd density, change in percentage of crop areas, net migration rates, and percent of PAs, with only the last showing a negative effect (Table S3). We validated the model projecting annual deforestation rates from 2002–2006 using a set of annual series of socioeconomic data and increasingly changing the percentage of PAs (Fig. S1 *A*–*C*). The other two variables (net migration rates and proximity to paved road) were kept constant because there was no significant change between 2002 and 2006. The model replicated the overall Amazon deforestation trend under historical circumstances, with a maximum deviation of only 10%, and simulated both the rise in the deforestation rate in early part of the decade and its decline after 2004 (Fig. S1*D*).

Simulating the Future Contribution of PAs to Reducing Deforestation in the Brazilian Amazon. The econometric projection model was coupled to SimAmazonia, a spatially explicit model of Amazon deforestation (25). Integrated in this environment, which we call "SimAmazonia-2," a carbon bookkeeping model calculated emissions by overlaying annual deforestation on a map of forest carbon biomass (38) and assuming that carbon content is 50% of wood biomass (40) and that 85% of the carbon contained in trees is released to the atmosphere with deforestation (41).

Costs of Amazon PAs. To estimate the opportunity costs of avoiding forest conversion to agricultural land, we applied a set of spatially explicit dynamic models of potential rents from soy, cattle, and timber production (5). All three models are highly sensitive to changes in transportation costs. Hence, the rent of each forested parcel changes differentially through time for each competing land use, depending on the expansion of the paved highway network (25).

We incorporated uncertainty bounds in the rent estimates, running the models within a range of high and low commodity prices. Thus, these approaches account for varying production costs as well as commodity prices. For each forested parcel (400 ha), net present values (NPV) for each land use (soy, cattle, and timber) were calculated for 30 years, assuming a 5% annual discount rate. The opportunity costs of forest maintenance were estimated by choosing the maximum NPV between soybean cropping and cattle ranching and then adding the NPV of timber rent. In the national and state forests, rent from timber was excluded from the opportunity-cost calculation, because those areas can support sustainable logging. Finally, the spatial costs of carbon were obtained by dividing the map of opportunity costs by a map of forest carbon stock (38).

We applied the SimAmazonia-2 deforestation model, together with the opportunity-cost map, to simulate potential revenues from a hypothetical REDD market for Amazon PAs. A range of potential emission reductions for PAs was calculated using the maps of simulated threat level without the inhibitory effect of PAs under the scenarios of moderate and high agricultural growth. To calculate potential reduction, the model annually sums the carbon stocks of all PA cells that would be deforested under the prescribed scenarios, assuming that 85% of their forest carbon is released to the atmosphere with deforestation (41). Next, the model summed the opportunity costs of these same cells. This approach considered which areas might be more vulnerable to deforestation in the near future and therefore presents a more realistic picture of PA contribution. To calculate the minimum annual payment from REDD, we fixed a price ton $^{-1}$ of CO_2 (US\$3.47 ± 0.96) that would fully cover the total annual budget for the entire PA network plus the range of opportunity costs of areas that would be deforested under the two socioeconomic scenarios. Spatial analyses, modeling and simulations were performed with Dinamica EGO freeware.

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