Governance regime and location influence avoided deforestation success of protected areas in the Brazilian Amazon

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Edited by Philip M. Fearnside, National Institute for Amazonian Research (Instituto Nacional de Pesquisas da Amazônia), Manaus, Brazil, and accepted by the Editorial Board February 4, 2013 (received for review August 28, 2012)

Protected areas in tropical countries are managed under different governance regimes, the relative effectiveness of which in avoiding deforestation has been the subject of recent debates. Participants in these debates answer appeals for more strict protection with the argument that sustainable use areas and indigenous lands can balance deforestation pressures by leveraging local support to create and enforce protective regulations. Which protection strategy is more effective can also depend on (*i*) the level of deforestation pressures to which an area is exposed and (*ii*) the intensity of government enforcement. We examine this relationship empirically, using data from 292 protected areas in the Brazilian Amazon. We show that, for any given level of deforestation pressure, strictly protected areas consistently avoided more deforestation than sustainable use areas. Indigenous lands were particularly effective at avoiding deforestation in locations with high deforestation pressure. Findings were stable across two time periods featuring major shifts in the intensity of government enforcement. We also observed shifting trends in the location of protected areas, documenting that between 2000 and 2005 strictly protected areas were more likely to be established in high-pressure locations than in sustainable use areas and indigenous lands. Our findings confirm that all protection regimes helped reduce deforestation in the Brazilian Amazon.

Terrestrial protected areas, an integral component of biodiversity conservation policy, have also become a centerpiece of global efforts to reduce carbon emissions from tropical deforestation (1). In the past decade, governments across the tropical biome have continued to expand their protected area networks (2), and international donors have pledged billions of dollars for forest-based climate change mitigation (3, 4). Situated at the overlap between multiple global and local interests (5, 6), protected areas are managed under a wide range of governance regimes to achieve better ecological and social outcomes. Although all these regimes establish some form of spatially explicit restrictions on land use and resource extraction, such restrictions can vary substantially (7).

A common distinction between governance regimes is that between strictly protected areas that discourage consumptive resource use or even physical access and sustainable use areas that allow for controlled resource extraction, land use change, and in many instances human settlements (8). Indigenous lands, established primarily to safeguard the rights and livelihoods of indigenous people, are put forward as a third type of protected areas with considerable potential to contribute to climate change mitigation (9). Recent prospects of international carbon payments tied to avoided deforestation have reignited the interest of donors and governments to understand the extent to which each of these governance arrangements are effective in helping conserve tropical forest carbon (10, 11).

Keen theoretical debates surround the extent to which controlled resource use in protected areas can reduce deforestation. Proponents of strict conservation have long argued that ruling out resource extraction coupled with enforcement by protected area guards is more likely to be effective at achieving conservation than more inclusionary approaches (12–15). Other contributors highlight that such enforcement has often proved insufficient to inhibit extraction in tropical parks (16–18) and that forest-dependent communities, including indigenous people, can have stronger incentives than disinterested or understaffed government agencies to protect their livelihood base against externally driven deforestation pressures (19–21). From this latter perspective, allowing controlled resource use in protected areas can help leverage local support for creating and enforcing regulations against such pressures (22, 23). Supporting indigenous communities in their efforts to demarcate and manage their territories promises similar synergies (24).

Although these lines of argument differ, authors commonly identify two contextual factors as influencing the advantages of one protection regime over the other: (*i*) the willingness and capacity of government agencies to enforce conservation regulations and (*ii*) the intensity of deforestation pressures to which a given area is exposed. Whether and how the relative effectiveness of protection regimes varies along these contextual dimensions, however, remains poorly understood. High-pressure locations, for example, may prove particularly challenging for strict protected areas that lack local constituencies (25), but could facilitate external enforcement because of greater accessibility and lower travel costs (26). Indigenous actors have been characterized as both weak (27) and strong (9, 23, 28) in avoiding deforestation in high-pressure areas. Similarly, strengthening government enforcement and other regulatory policies could improve the performance of strictly protected areas. However, positive effects could be offset if enforcement displaced deforestation into less accessible parks (29) or increased subsistence deforestation in sustainable use areas and indigenous lands.

Empirical evidence also continues to be inconclusive. Recent studies find evidence that sustainable use areas and indigenous lands tend to be situated in locations with higher deforestation pressure compared with strictly protected areas (8, 30–32), giving the former a greater potential to avoid deforestation (Fig. 1). In line with this observation, three studies have found that sustainable use areas and indigenous lands, in the aggregate, have avoided more deforestation and forest fires than strictly protected areas in the Brazilian Amazon and globally (8, 31, 32). Another study from Brazil suggests that strictly protected areas, in the aggregate, blocked deforestation pressures more successfully than did sustainable use areas, whereas indigenous lands were even more effective (36). Taken together, these studies seem to suggest that sustainable

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Author contributions: C.N. and A.A. designed research; C.N. performed research; B.S.S.-F. contributed new reagents/analytic tools; C.N. analyzed data; and C.N., A.A., K.M.S., and B.S.S.-F. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission. P.M.F. is a guest editor invited by the Editorial Board.

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1214786110/-/DCSupplemental.

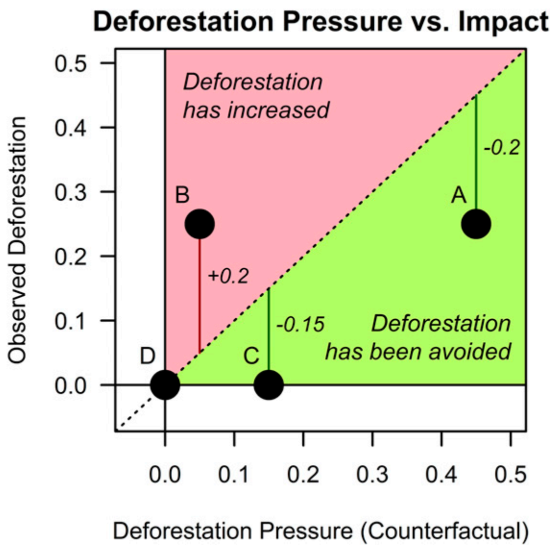

Fig. 1. Relationship between deforestation pressure (deforestation rate in the absence of protection) and impact of four imaginary protected areas: "A" has high deforestation rates, but is estimated to have avoided deforestation compared with what would have been expected in the absence of protection. "B" has deforestation rates identical to those of "A," but due to its location in a low-pressure area is estimated to have increased deforestation (see note below). "C," although perfectly untouched by deforestation, is estimated to have a lower absolute impact than "A." Located in an area of extremely low deforestation pressure, "D" is "passively protected" (10) and will thus never be able to claim avoided deforestation, regardless of its observed deforestation rates. Note: Global protected area assessments have identified countries whose protected areas exhibit higher rates of land use change than the counterfactual of no protection (33). Although this phenomenon is poorly understood, which may point to methodological weaknesses, protected areas can have undesired negative effects, e.g., if resource users engage in environmentally degrading activities as a form of protest against protection (34, 35).

use areas and indigenous lands are more successful by virtue of location, whereas strictly protected areas and indigenous lands are more successful by virtue of successfully enforced regulations. However, more systematic empirical examination is necessary to understand the joint functional relationships between avoided deforestation, governance regimes, deforestation pressures, and government enforcement in tropical protected areas.

We examined whether and how the effectiveness of 292 strictly protected areas, sustainable use areas, and indigenous lands in the Brazilian Amazon covaried with differences in deforestation pressure and federal government enforcement. Covering an area of more than 5 million km^2, the Brazilian Amazon exhibits significant spatial differences in terms of agricultural potential, transport infrastructure, and market access; as a result, deforestation pressures vary widely across the region. In addition, Brazil's federal enforcement efforts underwent a major shift in recent history: Having made international headlines for a historical high in Amazon deforestation rates between 2000 and 2005, Brazil achieved radical reductions in deforestation rates in the second half of the past decade (37). Although part of these reductions were attributed to price declines of agricultural commodities, recent analyses also show that regulatory government policies—including a drastic increase in enforcement activities, embargoes on soy and beef markets in selected municipalities, and the expansion and strengthening of protected area networks—all contributed significantly to the observed reductions (36, 38, 39). By examining the relationships between avoided deforestation, protection type, and deforestation pressure in both the first and the second half of the past decade, our analysis sheds analytical and empirical light on how governance regime, location, and government enforcement jointly influence conservation outcomes in protected areas.

Results

We considered all forested protected areas in the Brazilian Amazon that had been declared in or before 2005 and contained at least 200 km^2 of humid tropical rainforest (Fig. S1). Strictly protected areas include state and national biological stations, biological reserves, and national and state parks; sustainable use areas include state and national forests, extractive reserves, and sustainable development reserves. We included indigenous lands as a third protection type of interest; although governed through different regulatory frameworks than other protected areas, indigenous lands in Brazil are subject to restrictions on development and resource use that are devised through joint planning processes involving governments and indigenous communities.

We defined deforestation pressure as the rate of deforestation that would have been expected within the boundaries of a protected area had it not been protected (counterfactual). Following earlier quasi-experimental assessments of protected area impacts (8, 33, 40, 41), we nonparametrically estimated deforestation pressure as the rate of deforestation observed on artificial control groups of forest parcels. Unlike previous matching studies, we estimated deforestation pressure for each protected area individually, which later allowed us to include pressure as an explanatory variable in regression-based comparisons of protected area effectiveness. We identified control groups by repeatedly sampling forested parcels from within the boundaries of each protected area and matching them to forested parcels that had never been protected up to 2010 but were similar in terms of key covariates associated with the likelihood of protection and deforestation. We dropped forest parcels for which no sufficiently similar control parcels could be found. Estimates of deforestation rates came from two datasets: Brazil's official PROgrama de Cálculo do DESflorestamento na Amazonia (PRODES) dataset, based on ~30-m resolution LandSat imagery (42), and the coarser Gross Forest Cover Loss (GFCL) dataset based on ~500-m Moderate Resolution Imaging Spectroradiometer (MODIS) imagery (43). We report deforestation rates as the total ratio of deforestation observed within a given time period on control and treatment parcels, averaged across 30 repetitions (*Materials and Methods*).

To verify whether results are consistent with earlier matching studies (8, 31, 32), we first aggregated estimates of pressure and impact by protection type, weighting estimates for each protected area by its number of matched forest parcels (Table 1). For protected areas declared in or before 2000, results allowed conclusions similar to earlier analyses: First, protected areas of all types exhibited less deforestation on average than similar unprotected areas. Second, sustainable use areas were, on average, situated in locations with higher deforestation pressure than strictly protected areas. Third, sustainable use areas were estimated to have avoided more aggregate deforestation than strictly protected areas despite higher aggregated deforestation rates in the former. Fourth, indigenous lands were consistently estimated to face the highest levels of deforestation pressures and to have achieved the greatest avoided deforestation.

Comparisons across time periods revealed new patterns. As expected, estimated deforestation pressure dropped considerably between the first and the second half of the past decade as a result of a decrease in deforestation rates on unprotected forest parcels in the Amazon. Despite this reduction, the relative ordering of protection types in terms of pressure and impact remained similar in both time periods for protected areas declared in 2000 or earlier. However, when the sample for the second time period included protected areas established in or before 2005, the ordering of protection types changed. Strictly protected areas in the extended sample were estimated to be exposed to higher average pressure than either sustainable use areas or indigenous lands

Table 1. Estimates of deforestation pressure and impact, aggregated by protection type

Sample, time period, and dataset	Measure	Strict protection	Sustainable use	Indigenous lands
Protected areas established in or before 2000				
PRODES deforestation: 2001–2005 (%)	Pressure (estimated)	2.40	3.04	4.47
	Observed	0.39	0.91	0.21
	Impact (estimated)	−2.00	−2.13	−4.26
Gross Forest Cover Loss: 2000–2005 (%)	Pressure (estimated)	2.16	2.44	4.29
	Observed	0.28	0.62	0.11
	Impact (estimated)	−1.88	−1.82	−4.18
[No. of protected areas]		[34]	[42]	[92]
[No. of pairs of matched forest parcels]		[5,852]	[7,541]	[24,432]
Protected areas established in or before 2000				
PRODES deforestation 2006–2010 (%)	Pressure (estimated)	0.87	1.51	1.61
	Observed	0.16	0.64	0.10
	Impact (estimated)	−0.71	−0.87	−1.51
Gross Forest Cover Loss: 2005–2010 (%)	Pressure (estimated)	0.63	1.23	1.51
	Observed	0.08	0.50	0.13
	Impact (estimated)	−0.54	−0.73	−1.38
[No. of protected areas]		[34]	[42]	[92]
[No. of pairs of matched forest parcels]		[5,846]	[7,538]	[23,566]
Protected areas established in or before 2005 (includes in or before 2000)				
PRODES deforestation 2006–2010 (%)	Pressure (estimated)	1.85	0.96	1.32
	Observed	0.17	0.37	0.13
	Impact (estimated)	−1.68	−0.58	−1.19
Gross Forest Cover Loss: 2005–2010 (%)	Pressure (estimated)	1.80	0.73	1.24
	Observed	0.15	0.27	0.12
	Impact (estimated)	−1.65	−0.46	−1.11
[No. of protected areas]		[47]	[81]	[164]
[No. of pairs of matched forest parcels]		[9,187]	[15,017]	[39,415]

(Table 1 and Fig. S2). Closer examination revealed that these changes in average pressure estimates were driven by the creation of only a small number of large strictly protected areas in locations with high deforestation pressure (e.g., Terra do Meio, Serra do Pardo, Nascentes da Serra do Cachimbo) and the declaration of large numbers of sustainable use areas and indigenous lands in areas with very low deforestation pressure [mostly located in the state of Amazonas (Fig. S1)]. These shifts in average pressure induced similar shifts in impact estimates: Despite protection types retaining their relative ordering in terms of observed deforestation rates in the second period, strictly protected areas were estimated to have avoided *more* deforestation on average than indigenous lands and sustainable use areas.

Table 1 highlights the importance of differences in deforestation pressure as a driver of the average impact of protection types. It also demonstrates how aggregate estimates of average impact can be vulnerable to the addition of only a small number of protected areas in high-pressure locations. However, it does not provide insights into the effectiveness of protection types in inhibiting *given* levels of deforestation pressure, nor whether such effectiveness varies with high or low pressure. To illuminate these more complex relationships, we used scatterplot smoothers to nonparametrically examine observed deforestation as a function of deforestation pressure, conducting this analysis separately for each protection type and each time period. We then tested the significance of the observed differences using multiple linear regressions. As most protected areas were found to be located in low-pressure locations and to exhibit low deforestation rates (Figs. S2 and S3), we transformed both variables to allow for a more detailed examination of differences in low-pressure contexts (Fig. 2).

Results suggest that strictly protected areas had been more effective than sustainable use areas at avoiding deforestation, regardless of the level of deforestation pressure. Across the gradient of estimated deforestation pressures, deforestation in strictly protected areas was consistently observed to be lower than in sustainable use areas—for the most part, well below the 95% confidence interval around the mean (Fig. 2). We observed similar patterns in both time periods, whether we used PRODES or GFCL as the measure of deforestation (Fig. S4), whether we applied areal weighting or not (Fig. S5), and whether we excluded protected areas declared between 2000 and 2005 from the second time period (Fig. S6). Linear regressions confirmed the significance of these differences (Table S1).

Indigenous lands followed a less consistent pattern (Fig. 2). At lower levels of deforestation pressure, they exhibited deforestation rates similar to those of sustainable use areas and, between 2001 and 2005, higher deforestation rates than in strictly protected areas. However, they appeared at least as effective as strictly protected areas at moderate levels of pressure and more effective than any other protection type at high levels of pressure. Indeed, the comparatively flat slopes of the estimated functions suggest that deforestation rates in indigenous lands seemed to be less influenced by external deforestation pressure than in other types of protected areas. Linear regressions with interactions confirmed that indigenous lands differed from strict protection and sustainable use areas in their response to deforestation pressure (Table S1). The relationship seemed less pronounced when using the coarse-resolution GFCL as the measure of deforestation (Fig. S4), providing indication that deforestation rates in low-pressure indigenous lands may largely reflect small-scale subsistence deforestation.

Discussion

Our analysis confirms that all types of protected areas have contributed to avoiding deforestation in the Brazilian Amazon

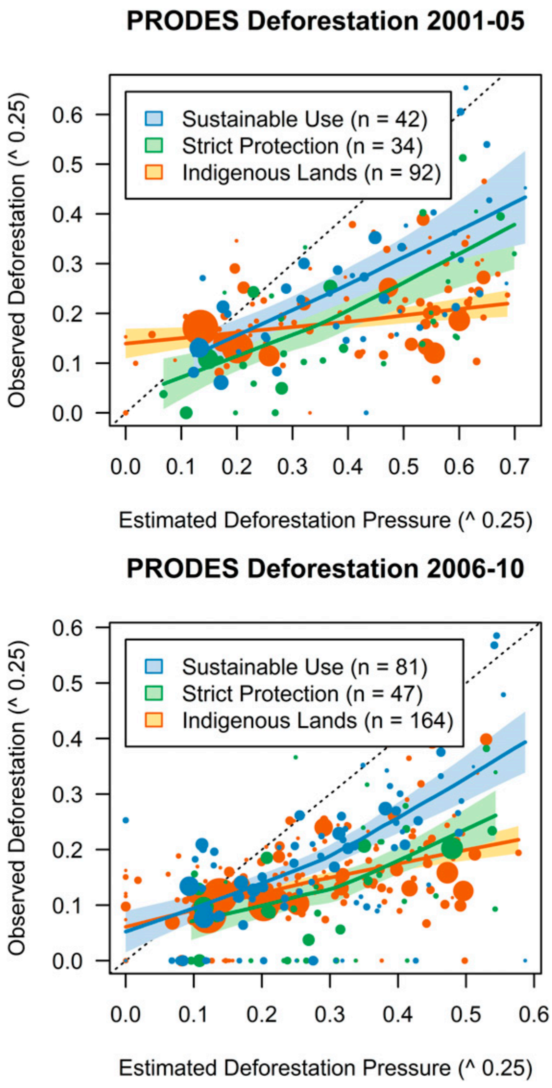

Fig. 2. Observed deforestation in different types of protected areas as a function of estimated deforestation pressure (solid lines) based on protected areas established in or before 2000 for 2000–2005 impacts (*Upper*) and in or before 2005 for 2006–2010 impacts (*Lower*). Points represent protected areas, with the area of each point corresponding to the number of matched forest parcels. Shaded areas indicate 95% confidence intervals of the nonparametric estimator. All protected areas below the diagonal (black dotted line) are estimated to have avoided deforestation.

regardless of their specific conservation objectives. Results also reaffirm the important role of strictly protected areas relative to sustainable use areas as a component of national strategies to mitigate climate change. First, we find that, in both low- and high-pressure locations, strictly protected areas in the Brazilian Amazon have consistently avoided more deforestation than sustainable use areas. Second, the observed difference between strict and sustainable use areas was robust both before and after the Brazilian government stepped up efforts to curb deforestation, indicating that strict protection was not ineffective even under conditions of limited government enforcement. Third, we observe that between 2000 and 2005 a number of strictly protected areas were established in locations with high deforestation pressure, whereas sustainable use areas seemed more likely to be declared in low-pressure locations. Reversing earlier trends of designation patterns in Brazil, this observation suggests that both strictly protected and sustainable use areas can make substantial contributions to avoiding deforestation by virtue of their location.

Indigenous lands appeared particularly effective at curbing high deforestation pressure, relative to both strictly protected and sustainable use areas. Where we estimated deforestation pressure to be low, indigenous lands exhibited slightly more deforestation than other types of protected areas between 2001 and 2005. This finding was not stable over time and across robustness checks, but may suggest that deforestation in indigenous lands is less likely to be driven by the external, market-driven pressures for which our covariates controlled, and more likely to be a result of internal, subsistence-oriented resource use.

No governance regime guarantees protection. Despite the consistency of average patterns, we observed individual cases with high and low deforestation rates for all protection types, pressure levels, and time periods. Assessments that seek to explain such remaining variance by looking at other policy variables—e.g., government vs. state designation (32, 44) or the availability of protected area management resources (45)—could benefit from applying our analytical approach to disentangle the many factors that influence success. Furthermore, our analysis does not make a distinction between illegal deforestation, which all protection types seek to reduce, and subsistence deforestation driven by the livelihood needs of indigenous and traditional people, which is legally sanctioned in sustainable use areas and indigenous lands. Incorporating protected area zonation and land rights in future parcel-based analyses could further enhance our understanding of the respective role of enforcement and sustainable resource use in reducing deforestation in protected areas.

Although our results suggest that strictly protected areas on average are more successful at counteracting location-specific deforestation pressures than sustainable use areas, this finding cannot be read as a devaluation of the latter. Indeed, the focus of our analysis on one outcome of interest—change in forest cover—precludes statements on the relative effectiveness of protected areas in reducing other anthropogenic pressures on biodiversity and carbon, such as forest degradation, hunting, fishing, mining, and infrastructure development. Our analysis neither accounts for potential positive or negative impacts on local economies and the livelihoods of forest users nor considers the political and ethical dimensions of demarcating protected areas in regions with existing communities of indigenous or traditional people. Future rigorous assessments that incorporate such diverse outcomes and carefully contrast the effectiveness of different strategies in achieving the multiple objectives of protected areas will certainly be welcomed by the global conservation community as an input for effective, efficient, and equitable strategies to mitigate global climate change.

Materials and Methods

Data. We obtained protected area boundaries and characteristics from the World Database of Protected Areas (46) and the National Cadaster of Conservation Units of the Brazilian Ministry for the Environment (www.mma.gov.br). Deforestation estimates were based on (*i*) a fine-scale dataset (PRODES) based on LandSat imagery and published by the Brazilian Institute for Space Research (42) and (*ii*) the coarse-resolution GFCL dataset based on MODIS imagery and published by South Dakota State University (43). Baseline forest cover in 2000 and 2005 came from the Vegetation Continuous Fields (VCF) of the Global Land Cover Facility (47). We computed travel time estimates to major cities based on the algorithm and datasets of ref. 48, supplemented by improved road datasets generated by SimAmazonia (49) and land cover estimates for 2000 obtained from MODIS Land subsets (50). Other datasets include slope and terrain from the International Institute for Applied Systems Analysis (51), floodable areas as identified by GlobCover 2005 (52), and state boundaries from the Global Administrative Areas database (www.gadm.org). We projected all datasets into MODIS' own sinusoidal projection, resampled them to ~1-km resolution, and extracted all humid tropical forest parcels with more than 25% average forest cover (VCF) into one table (*SI Materials and Methods*).

Estimating Deforestation Pressure. We used matching to create artificial control groups of forest parcels for each protected area. We considered all protected areas established in or before 2005 that had at least 50% average tree cover in 2000 (47), were located at least 60% within the humid tropical forest biome (53), and contained at least 200 forest parcels (at ∼1-km resolution). We excluded Brazil's Environmental Protection Areas from the group of sustainable use areas, as they primarily consist of private lands on which the protected area does not impose significant additional restrictions (54). We did not consider military areas. We randomly sampled 5% of the forested parcels from each of the remaining 292 protected areas and matched them to a sample of 5% of forest parcels that (*i*) had never been protected up to 2010 and (*ii*) were situated farther than 10 km away from any protected area boundary. Following related studies (8, 33, 40, 41), we controlled for elevation, slope, probability of flooding, baseline forest cover, distance to forest edge, travel time to major cities, and state. Control groups for 2000–2005 and 2006–2010 were estimated separately, the latter accounting for changes in covariates (baseline forest cover and distance to forest edge) that had occurred within the first time period. Matching was with replacement. We dropped forest parcels for which no nearest neighbor could be found within 1 SD of each covariate (caliper). We repeated the process of random sampling and matching 30 times for each protected area and averaged the resulting estimates of observed deforestation and deforestation pressure. See *SI Materials and Methods* for information on covariate choice, covariate balance, and leakage.

Comparing Effectiveness. We estimated and contrasted pressure-specific effectiveness of different protection types using both nonparametric and parametric regressions. Locally weighted scatterplot smoothers (LOESS) allowed us to flexibly examine differences in the response of observed deforestation in different protection types as a function of deforestation pressure (Fig. 2). Results from these nonparametric regressions informed the specifications of the linear regressions that we used to formally test for the strength of the observed differences (Table S1 and *SI Materials and Methods*). To reduce skewness of distributions and issues of heteroskedasticity and to allow for a more detailed examination of differences in low-pressure locations, we transformed estimates of observed deforestation and deforestation pressure before applying regressions (*SI Materials and Methods*).

ACKNOWLEDGMENTS. We thank Dan Miller, Alemayehu Negassa, Pete Newton, Alexander Pfaff, Johannes Scholl, the editor, and two anonymous reviewers for thoughtful comments on earlier versions of this article; Desirae Hoffmann and Shannon Brines for computation of travel time estimates; and the Center for Statistical Consultation and Research at the University of Michigan for helping refine the analysis. C.N. and A.A. acknowledge support from the Gordon and Betty Moore Foundation, the Rights and Resources Initiative, the Graham Environmental Sustainability Institute, and the National Science Foundation (CNH-0709545). B.S.S.-F. received support from the Brazilian National Council for Scientific and Technological Development (Conselho Nacional de Desenvolvimento Científico e Tecnológico).

1. Scharlemann JPW, et al. (2010) Securing tropical forest carbon: The contribution of protected areas to REDD. *Oryx* 44(3):352–357.
2. Bertzky B, et al. (2012) Protected Planet Report 2012: Tracking progress towards global targets for protected areas (International Union for Conservation of Nature, Gland, Switzerland/United Nations Environment Programme-World Conservation Monitoring Centre, Cambridge, UK). Available at http://www.unep-wcmc.org/ppr2012_903.html.
3. Parker C, Cranford M, Oakes N, Leggett M (2012) *The Little Biodiversity Finance Book* (Global Canopy Programme, Oxford), 3rd Ed.
4. Collaborative Partnership on Forests (2012) *2012 Study on Forest Financing* (Advisory Group on Finance, Collaborative Partnership on Forests, United Nations Forum on Forests, New York).
5. Sunderland TCH, Ehringhaus C, Campbell BM (2008) Conservation and development in tropical forest landscapes: A time to face the trade-offs? *Environ Conserv* 34(4): 276–279.
6. Hirsch PD, et al. (2011) Acknowledging conservation trade-offs and embracing complexity. *Conserv Biol* 25(2):259–264.
7. Dudley N (2008) *Guidelines for Applying Protected Area Management Categories* (International Union for the Conservation of Nature, Gland, Switzerland).
8. Nelson A, Chomitz KM (2011) Effectiveness of strict vs. multiple use protected areas in reducing tropical forest fires: A global analysis using matching methods. *PLoS ONE* 6(8):e22722.
9. Nepstad D, et al. (2006) Inhibition of Amazon deforestation and fire by parks and indigenous lands. *Conserv Biol* 20(1):65–73.
10. Angelsen A (2010) Policies for reduced deforestation and their impact on agricultural production. *Proc Natl Acad Sci USA* 107(46):19639–19644.
11. Ferraro PJ, Lawlor K, Mullan KL, Pattanayak SK (2011) Forest figures: Ecosystem services valuation and policy evaluation in developing countries. *Rev Environ Econ Policy* 6(1):20–44.
12. Terborgh JW (2004) *Requiem for Nature* (Island Press, Washington, DC).
13. Oates JF (1999) *Myth and Reality in the Rain Forest: How Conservation Strategies Are Failing in West Africa* (Univ of California Press, Berkeley, CA).
14. Hilborn R, et al. (2006) Effective enforcement in a conservation area. *Science* 314(5803):1266.
15. Laurance WF, et al. (2012) Averting biodiversity collapse in tropical forest protected areas. *Nature* 489(7415):290–294.
16. Petursson JG, Vedeld P, Sassen M (2012) An institutional analysis of deforestation processes in protected areas: The case of the transboundary Mt. Elgon, Uganda and Kenya. *For Policy Econ* 26:22–33, 10.1016/j.forpol.2012.09.012.
17. Infield M, Namara A (2001) Community attitudes and behaviour towards conservation: An assessment of a community conservation programme around Lake Mburo National Park, Uganda. *Oryx* 35(1):48–60.
18. Robinson E, Kumar A, Albers H (2010) Protecting developing countries' forests: Enforcement in theory and practice. *J Nat Resour Pol Res* 2(1):25–38.
19. Gibson C, Williams J, Ostrom E (2005) Local enforcement and better forests. *World Dev* 33(2):273–284.
20. Chhatre A, Agrawal A (2008) Forest commons and local enforcement. *Proc Natl Acad Sci USA* 105(36):13286–13291.
21. Hayes T (2006) Parks, people, and forest protection: An institutional assessment of the effectiveness of protected areas. *World Dev* 34(12):2064–2075.
22. Waylen KA, Fischer A, McGowan PJK, Thirgood SJ, Milner-Gulland EJ (2010) Effect of local cultural context on the success of community-based conservation interventions. *Conserv Biol* 24(4):1119–1129.
23. Porter-Bolland L, et al. (2012) Community managed forests and forest protected areas: An assessment of their conservation effectiveness across the tropics. *For Ecol Manage* 268:6–17.
24. Schwartzman S, Zimmerman B (2005) Conservation alliances with indigenous peoples of the Amazon. *Conserv Biol* 19(3):721–727.
25. Pedlowski M, et al. (2005) Conservation units: A new deforestation frontier in the Amazonian state of Rondônia, Brazil. *Environ Conserv* 32(2):149–155.
26. Börner J, Wunder S, Wertz-Kanounnikoff S, Hyman G, Nascimento N (2011) *REDD Sticks and Carrots in the Brazilian Amazon: Assessing Costs and Livelihood Implications.* CCAFS Working Paper No. 8 (CGIAR Research Program on Climate Change, Agriculture and Food Security (Copenhagen, Denmark).
27. Vuohelainen AJ, Coad L, Marthews TR, Malhi Y, Killeen TJ (2012) The effectiveness of contrasting protected areas in preventing deforestation in Madre de Dios, Peru. *Environ Manage* 50(4):645–663.
28. Adeney JM, Christensen NL, Pimm SL (2009) Reserves protect against deforestation fires in the Amazon. *PLoS ONE* 4(4):e5014.
29. Dávalos LM, Bejarano AC, Correa HL (2009) Disabusing cocaine: Pervasive myths and enduring realities of a globalised commodity. *Int J Drug Policy* 20(5):381–386.
30. Joppa LN, Pfaff A (2009) High and far: Biases in the location of protected areas. *PLoS ONE* 4(12):e8273.
31. Pfaff A, Robalino J, Lima E, Sandoval C, Herrera LD (2013) Governance, location & avoided deforestation from protected areas: Greater restrictions can have lower impact, due to differences in location. *World Dev*, in press.
32. World Bank (2013) *Crossing Paths: Role of Protected Areas and Road Investments in Brazilian Amazon Deforestation. Economic Sector Report* (World Bank, Washington, DC).
33. Joppa LN, Pfaff A (2011) Global protected area impacts. *Proc Biol Sci* 278(1712): 1633–1638.
34. Holmes G (2007) Protection, politics and protest: Understanding resistance to conservation. *Conserv Soc* 5(2):184–201.
35. Kull C (2002) Madagascar aflame: Landscape burning as peasant protest, resistance, or a resource management tool? *Polit Geogr* 21(7):927–953.
36. Soares-Filho B, et al. (2010) Role of Brazilian Amazon protected areas in climate change mitigation. *Proc Natl Acad Sci USA* 107(24):10821–10826.
37. Tollefson J (2012) Brazil set to cut forest protection. *Nature* 485(7396):19.
38. Kis-Katos K, Gonçalves da Silva JH (2010) *Beiträge zur Jahrestagung des Vereins für Socialpolitik 2010* [Contributions to the Annual Meeting of the Association for Social Politics 2010] (Leibniz-Informationszentrum Wirtschaft, Kiel, Germany).
39. Assunção J, Gandour CC, Rocha R (2012) *Deforestation Slowdown in the Legal Amazon: Prices or Policies* (Climate Policy Initiative, Rio de Janeiro).
40. Andam KS, Ferraro PJ, Pfaff A, Sanchez-Azofeifa GA, Robalino JA (2008) Measuring the effectiveness of protected area networks in reducing deforestation. *Proc Natl Acad Sci USA* 105(42):16089–16094.
41. Gaveau DL, et al. (2009) Evaluating whether protected areas reduce tropical deforestation in Sumatra. *J Biogeogr* 36(11):2165–2175.
42. Câmara G, De Morisson Valeriano D, Vianei Soares J (2006) *Metodologia para o Cálculo da Taxa Anual de Desmatamento na Amazônia Legal (PRODES)* [Methodology for the Calculation of Annual Deforestation rates in the Legal Amazon (PRODES)] (Instituto Nacional de Pesquisas Espaciais, São José dos Campos, Brazil).
43. Hansen MC, Stehman SV, Potapov PV (2010) Quantification of global gross forest cover loss. *Proc Natl Acad Sci USA* 107(19):8650–8655.
44. Vitel CSMN, Fearnside PM, De Alencastro Graça PML (2009) *Anais XIV Simpósio Brasileiro de Sensoramento Remoto, Natal, Brazil 2009*, eds Epiphanio JCN, Galvão LS (Instituto Nacional de Pesquisas Espaciais, São José dos Campos, Brazil), pp 6377–6384.
45. Nolte C, Agrawal A (2013) Linking management effectiveness indicators to observed effects of protected areas on fire occurrence in the Amazon rainforest. *Conserv Biol* 27(1):155–165.
46. UNEP-WCMC (2011) *World Database of Protected Areas* (United Nations Environmental Programme-World Conservation Monitoring Centre, Cambridge, UK) Available at www.protectedplanet.net.
47. Hansen MC, et al. (2003) Global Percent Tree Cover at a Spatial Resolution of 500 Meters: First Results of the Modis Vegetation Continuous Fields Algorithm. *Earth Interact* 7:1–15.

48. Nelson A (2008) *Travel Time to Major Cities: A Global Map of Accessibility* (Global Environment Monitoring Unit, Joint Research Centre of the European Commission, Ispra, Italy).
49. Soares-Filho BS, et al. (2006) Modelling conservation in the Amazon basin. *Nature* 440(7083):520–523.
50. Oak Ridge National Laboratory Distributed Active Archive Center (2011) *MODIS subsetted land products* (Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, TN).
51. Fischer G, et al. (2007) *Global Agro-Ecological Zones Assessment for Agriculture* (IIASA, Laxenburg, Austria).
52. Arino O, Perez JR, Kalogirou V, Defourny P, Achard F (2009) *GlobCover 2009* (European Space Agency, Paris).
53. Olson DM, et al. (2001) Terrestrial ecosystems of the world: A new map of life on earth. *Bioscience* 51(11):933–938.
54. Verissimo A, Rolla A, Vedoveto M, Futada SdeM (2011) *Protected Areas in the Brazilian Amazon: Challenges and Opportunities* (IMAZON, Belém, Brazil).