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

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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.

SUSTAINABILITY SCIENCE

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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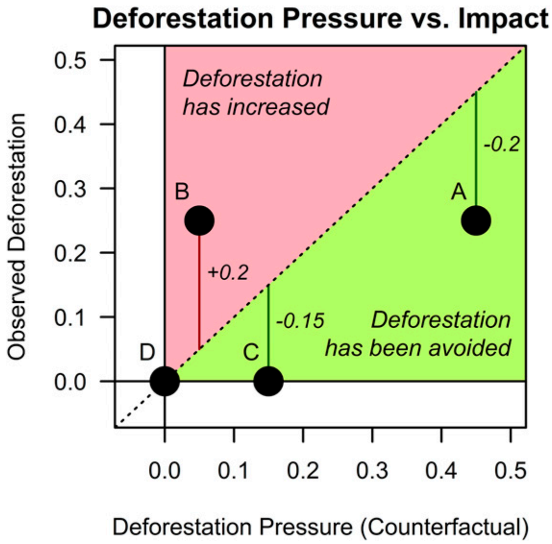

Fig. 1. Relationship between deforestation pressure (deforestation rate in the absence of protection) and impact of four imaginary protected areas: "A" has high deforestation rates, but is estimated to have avoided deforestation compared with what would have been expected in the absence of protection. "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

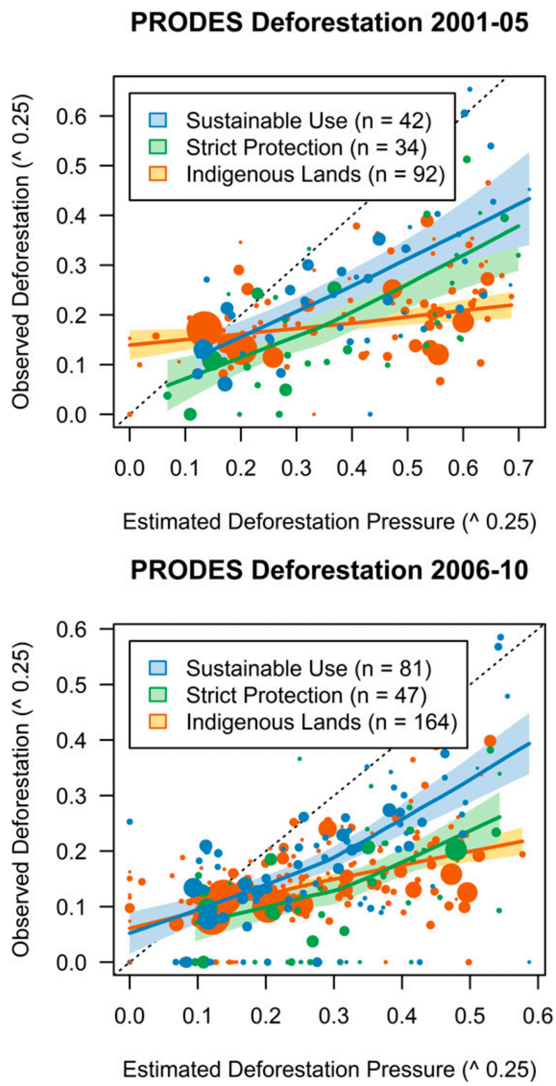

Fig. 2. Observed deforestation in different types of protected areas as a function of estimated deforestation pressure (solid lines) based on protected areas established in or before 2000 for 2000–2005 impacts (*Upper*) and in or before 2005 for 2006–2010 impacts (*Lower*). Points represent protected 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*).

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Supporting Information

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SI Materials and Methods

Data. ***Protected areas.*** We considered all protected areas included in the World Database of Protected Areas (WDPA) (1) situated in the Brazilian Legal Amazon. We used spatial data from the 2010 version of the WDPA as it included the original boundaries of protected areas that had recently been subject to downsizing as a result of their failure to stem deforestation (2). For example, the National Forest Bom Futuro had been significantly downsized in 2010 to exclude deforestation that had occurred between 2000 and 2010. We used 2012 data from the National Cadaster of Protected Areas (CNUC) of the Brazilian Ministry of the Environment to ensure that our pool of potential controls (unprotected forest parcels) did not any contain parcels situated in recently established protected areas or protected areas with expanded boundaries. We excluded from the pool of potential controls all unprotected forest parcels situated within 10-km buffers around any protected area (both the WDPA and CNUC) to reduce the vulnerability of our results to potential local spillover effects (3).

Deforestation. We used two different deforestation datasets to draw on their respective strengths in detecting tropical deforestation. The fine-grained PROgrama de Cálculo do DESflorestamento na Amazonia (PRODES) dataset published by the Brazilian Institute for Space Research (Instituto Nacional de Pesquisas Espaciais) is based on ~30-m resolution LandSat imagery and thus capable of detecting deforestation in relatively small patches of forests (4). However, the low temporal resolution of LandSat imagery (biweekly images) hampers the detection of deforestation due to frequent cloud cover. PRODES' particularly high rate of error in early years (up to 2000) prompted us to use only 2001–2005 data for our first period of analysis. Our second deforestation measure, the Gross Forest Cover Loss (GFCL) published by South Dakota State University (5), is based on data from the Moderate Resolution Imaging Spectroradiometer (MODIS). With daily return rates, MODIS satellites are more likely to encounter cloud-free conditions. However, the lower resolution of their sensors (~250 m) reduces their ability to detect small-scale deforestation patches (6). We ran separate analyses with both datasets and contrasted their respective results throughout.

Covariates. Probabilities of deforestation pressure and protection are influenced by a number of location-specific characteristics, most notably the suitability of a given plot for agriculture, ease of access, and distance to markets (3, 7, 8). We use the following covariates to control for differences in deforestation pressure:

- Agricultural suitability: Elevation and slope influence a forest parcel's suitability for agriculture (7). Similarly, the occurrence of seasonal flooding has been shown to influence agricultural suitability and the probability of forest conversion (9). We extracted average slope and average elevation from data provided by the International Institute for Applied Systems Analysis (10) and identified seasonally flooded areas using the GlobCover 2005 dataset based on the European Space Agency's Envisat platform (11).
- Forest cover: At ~1-km resolution, low average tree cover on a forest parcel can indicate existing forest fragmentation and deforestation. Furthermore, the probabilities of forest conversion detected by GFCL are a function of baseline tree cover (12). We used tree cover estimates provided by the MODIS-based Vegetation Continuous Fields (VCF) dataset (collection 3) to control for this covariate (13).
- Distance to forest edge: Strongly influencing physical accessibility, the distance to the forest edge has been shown to be strongly associated with deforestation (3). We computed distance to forest edge as the shortest Euclidian distance of a given forest parcel to (i) parcels with less than 25% forest cover (VCF), (ii) rivers (ESRI hydropolygons), and (iii) major roads (14).
- Travel time to major cities: Accessibility to markets is an important predictor of deforestation patterns (7). We used the algorithm, datasets, and assumptions of an existing travel time dataset from the European Union's Joint Research Center (15) to compute our own travel time estimates using (i) improved and more detailed Brazilian road data (14) and (ii) a land cover map that reflected baseline land cover conditions in the year 2000 (MODIS Land) (16).
- State: Brazil's federal states can exercise considerable autonomy in devising state-level policies that can influence deforestation pressure and its spatial distribution. We used state boundaries provided by the Global Administrative Areas database (www.gadm.org) to control for this covariate.

We did not include distance to roads as a covariate in our analysis. Roads facilitate physical access to forest parcels and the transport of timber and agricultural products to markets. However, in the Brazilian Amazon, roads are only one element of transport infrastructure, with river travel being the main means of travel and transport in remote areas of the basin. We argue that (*i*) our estimates of travel time to major cities capture such interactions between road and river travel better than an estimate of distance to roads and that (*ii*) our estimates of distance to forest edge, with forest edge including major roads and rivers, capture the remainder of local-level variation in physical accessibility.

Methods. ***Estimating deforestation pressure.*** Matching is a quasi-experimental method that seeks to mimic random assignment of treatment by identifying artificial control groups of untreated units that differ from treated units in all relevant aspects but the treatment itself. Matching estimators rely on the assumption that treatment selection is on observables, i.e., that the observable covariates used in the matching procedure account for all differences between treatment and control units that are associated with both the probability of treatment (protection type) and the outcome (deforestation). Given the absence of randomly controlled trials of the assignment of protection to forest parcels, an explicit test of the validity of this assumption is not possible. Assessments of the validity of matching estimators therefore have to rely on (*i*) a sound theoretical and empirical argument for the choice of covariates and an (*ii*) assessment of the extent to which matching was able to balance covariates between control and treatment groups.

Choice of covariates. In the section *Covariates* above, we list the covariates included in our matching estimator, together with an empirical and theoretical rationale for the inclusion of each. Controlling for baseline forest cover, political boundaries, agricultural suitability, accessibility, and distance to markets has been considered both necessary and sufficient by a large number of matching studies that assess the impact of protection on deforestation and/or forest fires (3, 7, 17–19). One study from Costa Rica tests the sensitivity of matching estimates to using an extended set of covariates, including poverty, population density, and immigration, and finds results to be similar (3). Although we cannot explicitly test the extent to which matching successfully mimics random assignment, we consider the existing theoretical and empirical support for our choice of covariates sufficient to trust in the extent to which our estimator successfully controls for the most relevant joint bias in treatment assignment and deforestation outcomes.

Covariate balance. Matching relies on the existence of a pool of control units whose covariates are sufficiently similar to the pool of treatment units to qualify as matches (statistical support). Whether matching has been successful can be assessed by comparing covariate distributions between treated units and control units both before and after matching. A commonly used indicator to assess such similarity is the mean difference of empirical quantile-quantile (eQQ) plots of covariates in the treatment and control group (3). To obtain an aggregate balance indicator for each of the 292 protected areas, we averaged the standardized mean difference of eQQ plots across 30 repetitions and our six continuous covariates (matching was exact for categorical covariates). We then examined the distributions of the 292 estimates using Kernel density estimators, weighting each balance indicator by the number of matched forest parcel pairs (*Density Estimation*). We also examined distributions for each protection type separately.

Our results indicate that matching dramatically improved covariate balance for all protected areas in our sample (Fig. S7). Matching reduced the mean of our 292 balance estimates from 6.13 to 0.07. Furthermore, matching achieved similar improvements in covariate balance for all protection types (Fig. S8), suggesting that the remaining differences in covariates were not biased toward either protection type. We therefore consider our matching estimator to have successfully controlled for differences in observable covariates between forest parcels in control and treatment groups.

Dropped forest parcels. Causal inference through matching relies on the existence of control units that are sufficiently comparable to the pool of treated units to qualify as observations of counterfactual outcomes (statistical support). We followed earlier matching studies in removing protected forest parcels if no control parcels could be found within 1 SD of each covariate (calipers). Calipers retained 91.5% of forest parcels from the treated sample, distributed roughly equally among protection types (strict protection: 91.7%; sustainable use: 92.6%; indigenous lands: 90.9%). Visual inspection of the results suggests that protected areas with a high rate of dropped forest parcels are situated in both high- and low-pressure areas for all three protection types. The counterfactual outcome (deforestation pressure) cannot be observed for these dropped parcels. However, the large percentage of retained pixels and their distribution among protection types suggests that our results are likely to hold for the full sample of forest parcels.

Leakage. Leakage occurs when treatment influences the outcomes on untreated units. If protection of a given set of parcels leads to increased (or decreased) deforestation in unprotected parcels, a comparison of protected and unprotected units will overestimate (or underestimate) the effects of protection. A recent study did not find evidence for leakage occurring as the result of the creation of protected areas in the Brazilian Amazon (20). Nevertheless, we limited the risk of an influence of differences in local leakage on our findings by excluding from our pool of potential control parcels a 10-km buffer around all protected areas and military areas that had been created up to 2010. Although protection types may differ in the extent to which they engender leakage, the fact that our pool of control parcels covers a vast region reduces the probability that controls of different protection types may be differently affected by the leakage problem. Although we cannot rule out the possibility that leakage is occurring, we do not consider its possible existence to alter our findings about the differential impacts of protection types.

Density Estimation. We used Kernel density estimators to assess the skewness of the protection-type specific distributions of estimated deforestation pressure and to examine the shift in these distributions that occurred between 2000 and 2005 as a result of newly designated areas in all categories. We used *R*'s *density* function with a Gaussian kernel and default bandwidth computation and weighted observations by the number of matched forest parcels. We estimated density for each protection type separately (Fig. S2).

Transformations. We found that distributions of original deforestation pressure estimates were strongly skewed toward low levels of deforestation pressure (Fig. S2, *Left*). As a result, a small number of high-pressure protected areas were able to drive the differences in the aggregate estimates of pressure and impact (see main text). We also observed a strongly skewed distribution of observed deforestation rates whose variance increased with higher estimated deforestation pressure (Fig. S3). To reduce such heteroskedasticity and to allow for an estimation of pressure-specific effectiveness of protection types that would take advantage of the full sample, we transformed both observed deforestation rates and estimates of deforestation pressure. We did not use a logarithmic transformation due to the existence of real zeros in both variables. We found that a double-square-root transformation resulted in less skewed distributions and was therefore more amenable to subsequent regressions (Fig. S2, *Right*).

Regressions. ***Nonparametric regressions.*** We used locally weighted scatterplot smoothers (LOESS, using *R*'s *loess* function, span = 1) to nonparametrically estimate observed deforestation rates as a function of deforestation pressure. We computed 95% confidence intervals based on the SEs of the LOESS prediction. We applied separate LOESS estimators for each protection type, time period (2000-05 vs. 2006–10), protected area sample (established in or before 2000 vs. in or before 2005), and deforestation dataset (PRODES vs. GFCL) and compared the resulting functions (Fig. 2 and Figs. S3–S6).

Linear regressions. We used linear regressions to test the strength of the differences in pressure-specific observed deforestation between protection types. We regressed observed deforestation rates on estimated deforestation pressure (both transformed) and included dummy variables for sustainable use areas and indigenous lands. We ran models with three distinct specifications for each dataset and time period: (*i*) without interactions between pressure and protection types, (*ii*) with interactions between pressure and protection types, and (*iii*) with interaction between pressure and indigenous lands only (Table S1). The latter corresponds to our nonparametric observation that deforestation rates in indigenous lands responded differently to deforestation pressure than deforestation rates in strictly protected and sustainable use areas (see main text).

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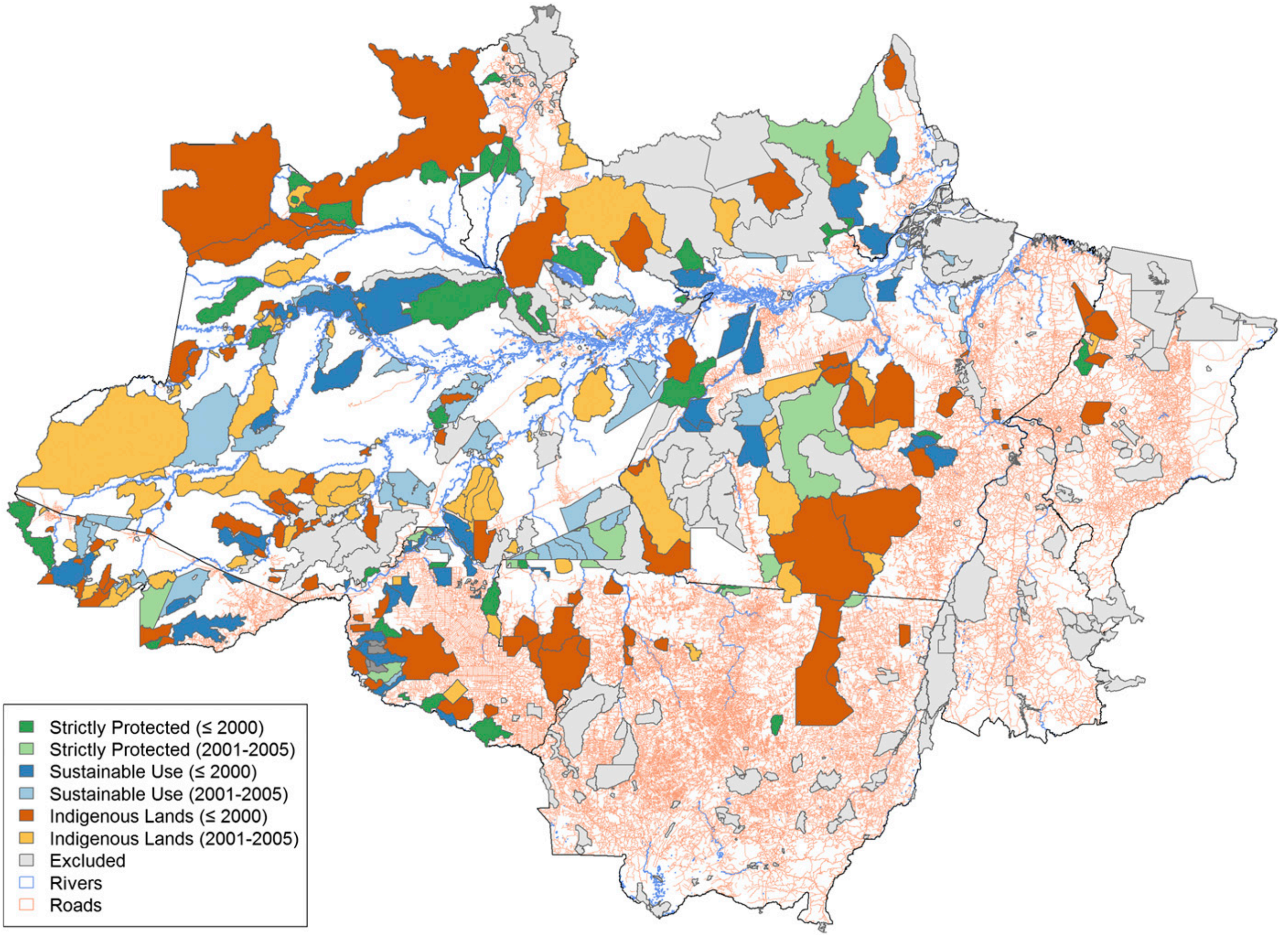

Fig. S1. Schematic map of the Brazilian Amazon protected areas included in this analysis. Excluded areas include protected areas established after 2005, Environmental Protection Areas, and protected areas outside the humid forest tropical biome with less than 50% tree cover or with fewer than 200 forest parcels in 2000. Data for this figure were provided by refs. 1 and 14.

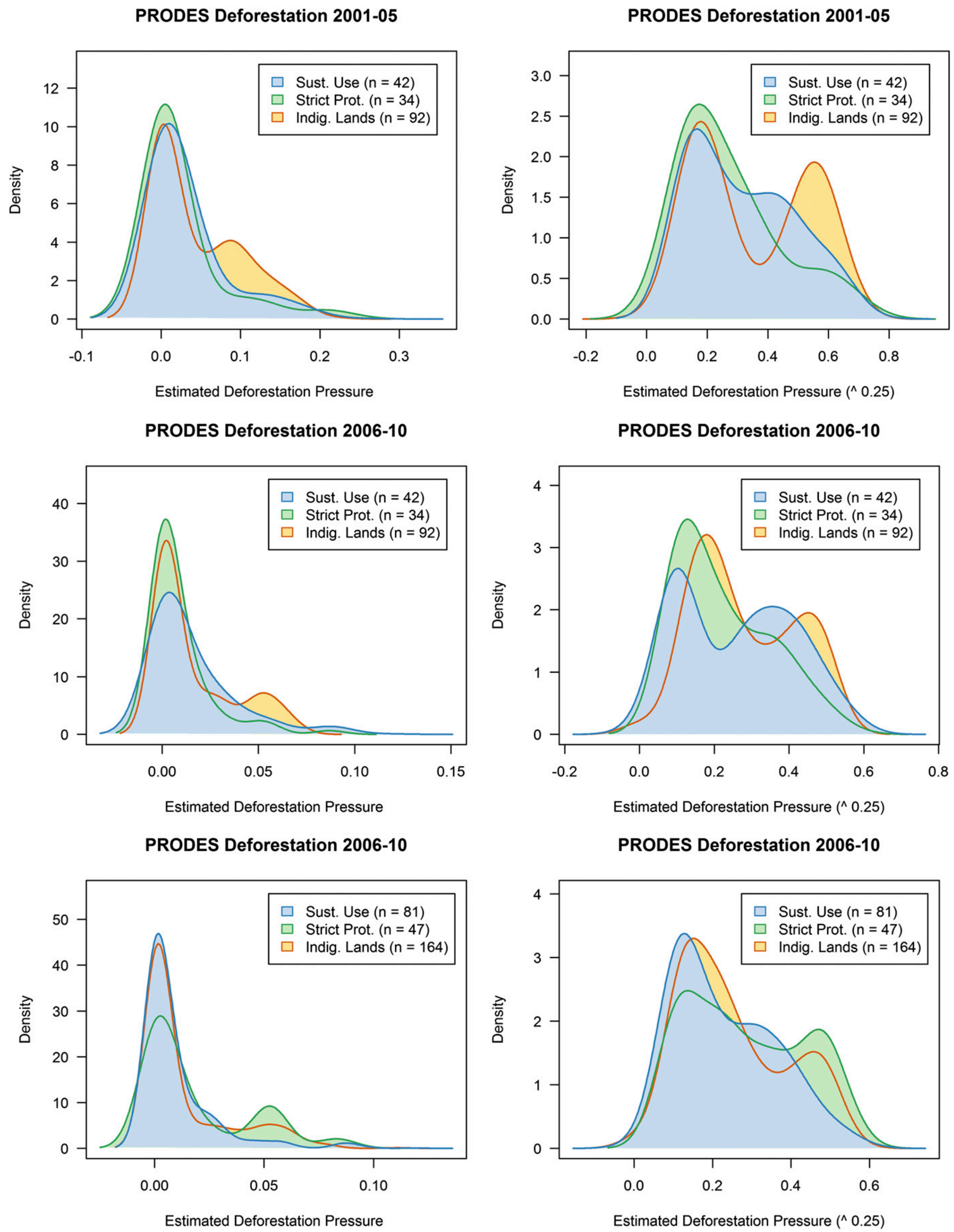

Fig. S2. Density distributions of original (*Left*) and transformed (*Right*) deforestation pressure estimates for protected areas established in or before 2000 (*Top* and *Middle*: 2001–2005 and 2006–2010 estimates, respectively) and 2005 (*Bottom*: 2006–2010 estimates). Observations were weighted by the number of matched forest parcels.

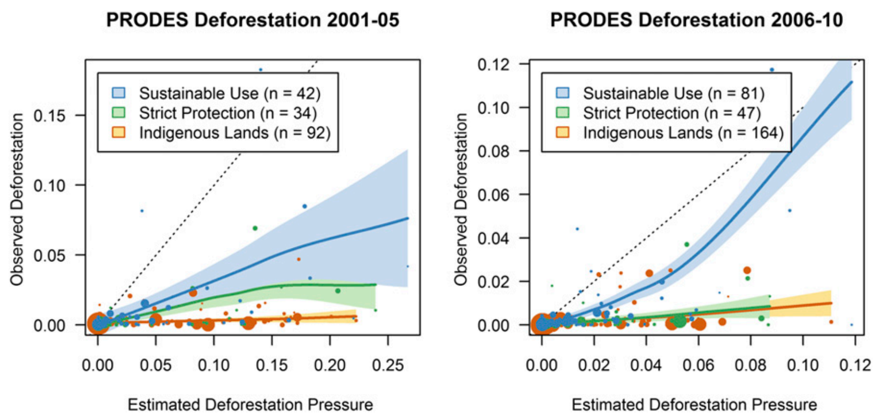

Fig. S3. As in Fig. 2, but based on original data (without transformation).

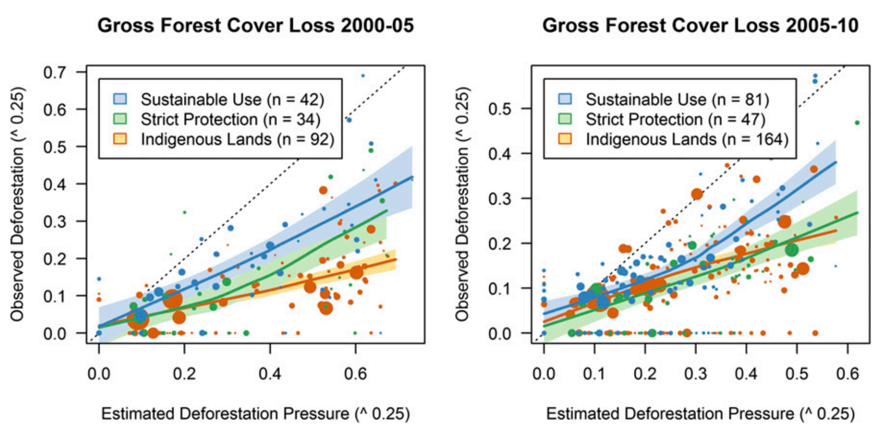

Fig. S4. As in Fig. 2, but using GFCL instead of PRODES.

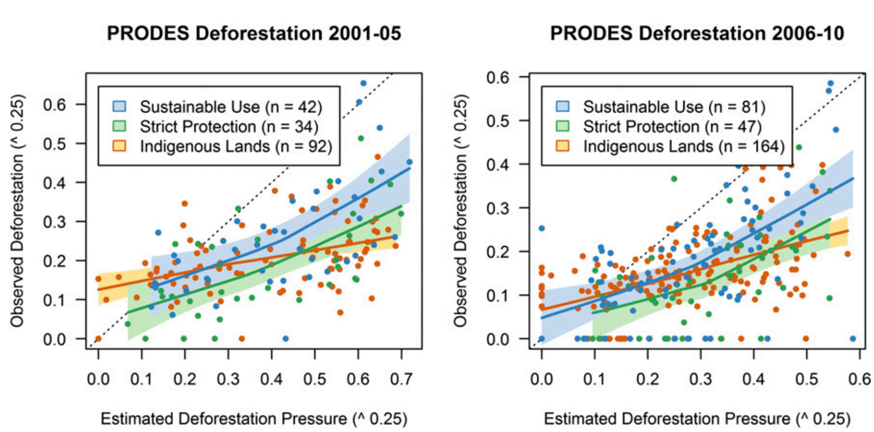

Fig. S5. As in Fig. 2, but without weighting protected areas by number of matched forest parcels.

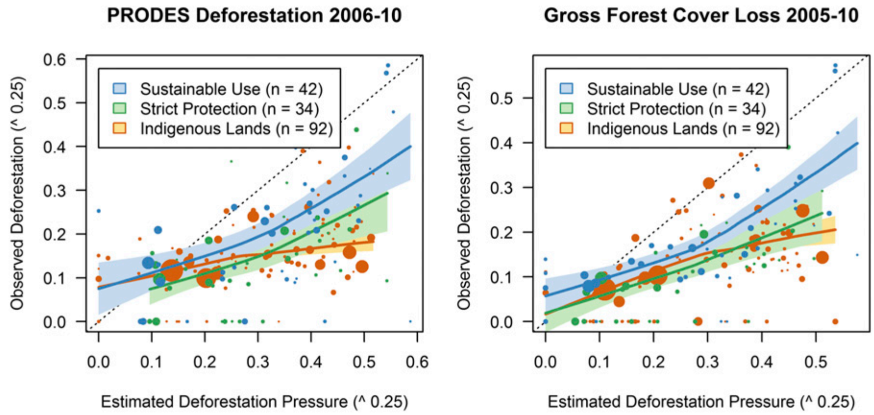

Fig. S6. As for Fig. 2 (*Right*) and Fig. S4 (*Right*), but excluding protected areas declared between 2000 and 2005 from the sample.

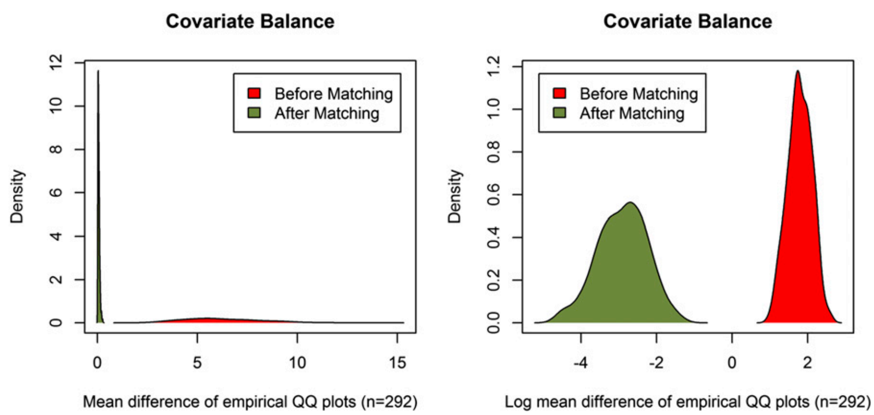

Fig. S7. Density distributions of mean standardized differences of eQQ plots (raw and log), averaged across 30 repetitions and six continuous covariates for each of the 292 protected areas considered in our analysis.

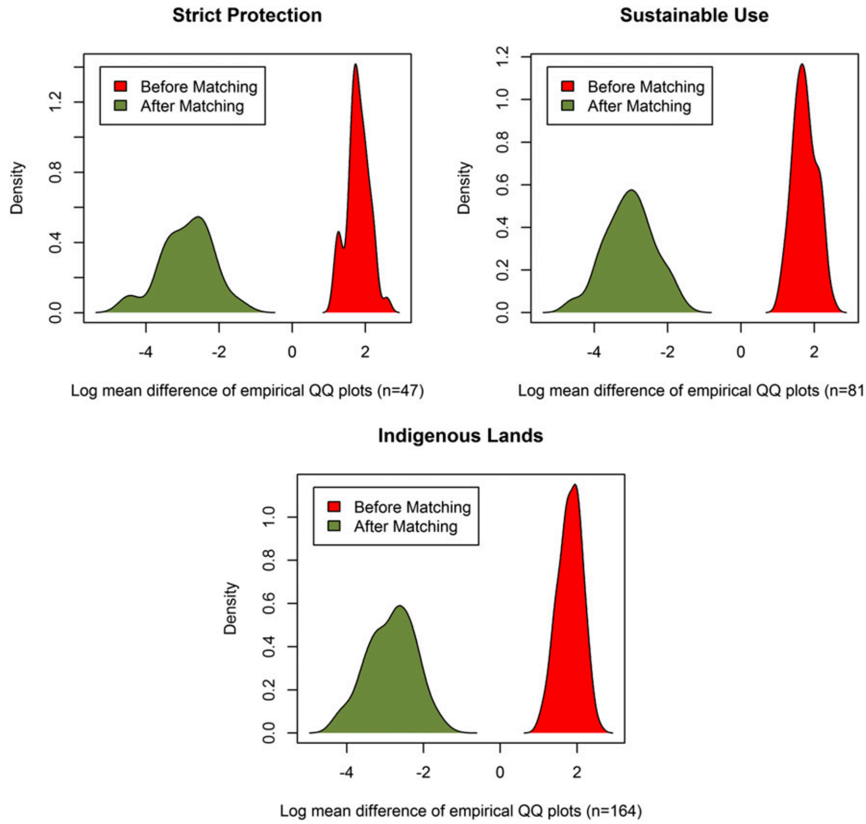

Fig. S8. Density distributions of mean standardized differences of eQQ plots (log), averaged across 30 repetitions and six continuous covariates, by protection type.

Table S1. Results of weighted regressions of observed deforestation rates on estimated deforestation pressure and protection types (transformed data)

Independent variables	Without interactions	With interactions	Interactions with indigenous lands only
PRODES deforestation 2001–2005, protected areas established in or before 2000			
Intercept	0.086***	0.014	0.010
Deforestation pressure (transformed)	0.233***	0.498***	0.515***
Sustainable use area[†]	0.056**	0.035	0.044*
Indigenous land	0.011	0.124***	0.128***
Sustainable use area × pressure		0.029	
Indigenous land × pressure		−0.382***	−0.399***
[Adjusted R^2]	[0.259]	[0.390]	[0.394]
PRODES deforestation 2006–2010, protected areas established in or before 2005			
Intercept	0.036**	0.021	−0.004
Deforestation pressure (transformed)	0.351***	0.403***	0.489***
Sustainable use area	0.043***	0.009	0.050***
Indigenous land	0.011	0.046+	0.071***
Sustainable use area × pressure		0.158+	
Indigenous land × pressure		−0.135+	−0.221***
[Adjusted R^2]	[0.351]	[0.386]	[0.381]
Gross Forest Cover Loss 2000–2005, protected areas established in or before 2000			
Intercept	0.018	−0.014	−0.023
Deforestation pressure (transformed)	0.327***	0.468***	0.510***
Sustainable use area	0.051**	0.023	0.042*
Indigenous land	−0.025	0.029	0.039+
Sustainable use area × pressure		0.075	
Indigenous land × pressure		−0.211*	−0.252***
[Adjusted R^2]	[0.478]	[0.525]	[0.526]
Gross Forest Cover Loss 2005–2010, protected areas established in or before 2005			
Intercept	0.011	0.009	−0.010
Deforestation pressure (transformed)	0.395***	0.402***	0.474***
Sustainable use area	0.037**	0.009	0.042**
Indigenous land	0.015	0.028	0.047**
Sustainable use area × pressure		0.143	
Indigenous land × pressure		−0.051	−0.124*
[Adjusted R^2]	[0.423]	[0.434]	[0.431]

***$P < 0.001$, **$P < 0.01$, *$P < 0.05$, +$P < 0.1$. Bracketed values indicate sample sizes.

[†]Protection types are dummy variables. The omitted protection type is strict protection.