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Collective property rights reduce deforestation in the Brazilian Amazon

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In this paper, we draw on common-pool resource theory to argue that indigenous territories, when granted full property rights, will be effective at curbing deforestation. Using satellite data, we test the effect of property rights on deforestation between 1982 and 2016. In order to identify causal effects, we combine a regression discontinuity design with the orthogonal timing of homologation. We find that observations inside territories with full property rights show a significant decrease in deforestation, while the effect does not exist in territories without full property rights. While these are local average treatment effects, our results suggest that not only do indigenous territories serve a human-rights role, but they are a cost-effective way for governments to preserve their forested areas. First, obtaining full property rights is crucial to recognize indigenous peoples' original right to land and protect their territories from illegal deforestation. Second, when implemented, indigenous property rights reduce deforestation inside indigenous territories in the Amazon rainforest, and could provide an important positive externality for Brazil and the rest of the world in terms of climate change mitigation.

deforestation | property rights | indigenous | Brazil | Amazon

The Amazon rainforest accounts for half of the remaining tropical forest on our planet, is an important source of biodiversity, and has a major influence on the world's climate and hydrological cycles (1). As such, its preservation is key in the fight against climate change. However, with forest fires and illegal logging and mining surging in recent years, the Amazon has seen unprecedented levels of deforestation according to Brazil's National Institute for Space Research (Instituto Nacional de Pesquisas Especiais [INPE]). Further degradation of the Amazon could lead to faltering rain, increased drought, increased carbon dioxide emissions, increased flooding, loss of biodiversity, loss of medical possibilities, increased fires, and poverty (2).

Sixty percent of the Amazon rainforest is located in Brazil's Legal Amazon. From January to August 2019, INPE reported over 40,000 fires—77% more than the same period in 2018—and a 278% increase in deforestation in the Legal Amazon (3, 4). Deforestation is the leading cause of these fires, as burning forests is the most effective way to clear land quickly for agricultural purposes.

While recent trends in deforestation and forest fires in Brazil are cause for concern, the country's system of protected areas (PAs) aimed at ecological preservation and curbing deforestation can be an example of effective policy. Securing and expanding PAs has become an essential component of global and national conservation policies, as they represent key areas in carbon sequestration (5, 6). In 2014, 57% of carbon stock in the Legal Amazon was held in PAs, most of this being stored in indigenous territories (7). We can outline two reasons for this preservation role of indigenous territories. First, indigenous traditional land use, based on collective ownership, has been associated with the preservation of a land's biodiversity (8, 9). Second, as forests are a common-pool resource (CPR), indigenous peoples have been found to fulfill the necessary requirements for successful common-property resource management (10) with clearly defined boundaries, collective management, the recognition of rights to organize, monitoring systems, sanctions, and conflict resolution mechanisms (11–13). However, we argue that only those territories that have gained full property rights fulfill these requisites (14–20). This can help explain why the effectiveness of indigenous territories in forest preservation remains contested in existing literature. While some findings highlight the very effective role of these territories in curbing deforestation (5, 6, 14, 21–26), others find no effect (14, 27, 28).

In this paper, we draw on CPR theory (11–13) to argue that indigenous territories will only be effective at curbing deforestation when they are granted full property rights. Indigenous territories in Brazil gain their full property rights through a legal process called demarcation. Demarcation consists of a four-step process involving 1) an anthropological study to identify the physical boundaries of the territory, 2) the approval of FUNAI (Fundação Nacional do Índio [National Foundation for the Indigenous Peoples]), 3) the approval of the Minister of Justice, and 4) the homologation by presidential decree and registration in the national land registry. This process further holds that, prior to the presidential homologation, any third party can contest the demarcation of a territory, and nonindigenous parties living on said territory will be resettled and financially compensated. Once homologated, indigenous territories gain their full property rights as enumerated in the 1988 Brazilian Constitution. The Constitution states that indigenous peoples' sociopolitical rights and original right to land is incumbent upon the Union's demarcation of these territories (Article 231) and recognizes these homologated territories as "those indispensable for the

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Significance

Deforestation in the Amazon has reached record highs in 2019 and poses a serious threat to climate change. In Brazil, about 2 million hectares of indigenous land are still awaiting homologation, and thus do not have their full property rights. We find that granting property rights significantly reduces the levels of deforestation inside indigenous territories, and the results are of significant orders of magnitude. Our local effects indicate that areas of land right inside a territory with full property rights experience significantly less deforestation than those right outside of the border. Collective property rights might thus provide an effective way to reduce deforestation in the Brazilian Amazon.

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The authors declare no competing interest.

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preservation of environmental resources necessary for their well-being" (29). Article 231 poses that indigenous peoples have "the exclusive usufruct of the riches of the soil, rivers and lakes existing thereon" (29), while exploitation rights of the subsoil remain vested in the State. Additionally, the Union has the constitutional "responsibility to delineate these lands and to protect and ensure respect for all their property" (29).

Thus, without homologation, indigenous territories do not have the legal rights needed to protect their territories, their territorial resources are not considered their own, and the government is not constitutionally responsible for protecting them from encroachment, invasion, and external use of their resources. Once homologated, a territory becomes the permanent possession of its indigenous peoples, no third party can contest its existence, and extractive activities carried out by external actors can only occur after consulting the communities and the National Congress. Thus, homologation enables indigenous territories to fulfill three of the CPR management requisites: "clearly defined boundaries," "collective management," and "recognition of rights to organize" (11–13, 30). The three other CPR management requisites regard environmental law enforcement. While these methods are not outlined in the Constitution, INPE, IBAMA (Brazilian Institute for the Environment and Renewable Natural Resources), and FUNAI are responsible for monitoring and enforcement activities that aim to curb deforestation and protect indigenous territories. Monitoring and enforcement activities have proven to be extremely productive in deterring deforestation (31, 32) and are necessary in providing tenure security to indigenous territories (33).

Full property rights are an important requirement for indigenous territories to fulfill the CPR environmental law enforcement requisites. When law enforcement agencies can catch deforesters red-handed, legal sanctioning tools are productive in achieving deterrence goals, as they involve a system of fines, embargoes, and seizures of equipment and material. INPE's environmental monitoring system "Real-Time System for Detection of Deforestation" (DETER) is a satellite-based system that captures change in forest cover (FC) in 2-wk intervals, enabling a real-time response by law enforcement agencies which has a significant deterrent effect on deforestation (31). FUNAI utilizes data from DETER to strengthen its monitoring and enforcement activities on indigenous territories through its Remote Monitoring Center. By partnering with IBAMA, FUNAI can respond to real-time deforestation threats, which is crucial for the protection of indigenous peoples and their territories. For example, FUNAI partnered with IBAMA and the military police of Mato Grosso in May 2019 to combat illegal deforestation on the homologated territory of Urubu Branco. In this operation, 12 people were charged with federal theft of wood and fined 90,000 R$, and multiple trucks and tractors were seized; the wood seized was then donated to the municipality. Through its monitoring system, FUNAI continues to carry out similar operations with IBAMA on indigenous territories. However, data provided by their monitoring center solely includes territories that have been homologated (granted full property rights). Public policy on the protection of indigenous territories only regards those with full property rights, while ignoring the threats nonhomologated territories face. Indigenous territories awaiting homologation find themselves struggling to be recognized by the nation while combatting illegal extractive activities without support from enforcement agencies.

Our paper builds on previous literature which finds strong effects of indigenous territories on deforestation (5, 6, 14, 21–26) and some papers which find no effects (14, 27, 28). Our paper's main contributions with regard to the existing literature are threefold. First, we use Hansen and Song (34) data to assess the question of the efficacy of indigenous land rights at curbing deforestation. This provides us with an unprecedented time span (1982–2016) and a more accurate measure of deforestation than papers that use Normalized Difference Vegetation Index (NDVI), giving us the ability to test the efficacy of homologation of territories since the beginning of the process of demarcation of indigenous lands in Brazil. As Fig. 1 shows, in 1985, most of the indigenous territories had not received full property rights. By 1995, about 50% of the territories had been homologated. Due to data constraints, most of the existing literature focuses on the period after 1995, and thus misses the effects of over half of the indigenous territories in Brazil. Second, we are able to look at all indigenous territories for which there is geographic information, bringing us to a total of 245 territories. Not using all territories, as some papers have done, may lead to selection on unobservables. Finally, while we are able to confirm the results found in Soares-Filho et al. (22), Blackman et al. (25), and Nolte et al. (5) on the effectiveness of indigenous territories at curbing deforestation, our regression discontinuity design (RDD), which includes the timing of homologation to differentiate the effects, provides us with the ability to establish causal claims, even though the estimated effects are local in nature. By exploiting the orthogonality of the timing of homologation, we are able to compare the effects of granting property rights by comparing deforestation before and after, inside and outside of the territory. The RDD ensures that we are comparing pixels that are almost identical to each other, other than for the fact that some are inside homologated territories while others are not. By comparing pixels that are so similar, we are able to isolate the actual effects of property rights, reducing concerns that the effects are driven by unobservables.

Our work is most similar to that of BenYishay et al. (27) and Bonilla-Mejía and Higuera-Mendieta (23). The former is most similar in scope, while the latter is most similar in methods. BenYishay et al. (27) study the effects of indigenous land demarcation on deforestation in Brazil and finds no effects. They focus on territories that were part of the Geospatial Impact Evaluation of the Demarcation of Indian Territories Project (Projeto Integrado de Proteção ás Populações e Terras Indígenas da Amazônia Legal [PPTAL]), a program that ran between 1995 and 2008 which sought to finalize the demarcation process of a select group of indigenous territories in the Amazon. Their sample is therefore smaller than ours; they look only at communities existing in 1995 and studied by PPTAL for potential formalization, thus limiting their sample size to only 106 indigenous territories (27). Additionally, they use a different data source for their dependent variable, which spans only until 2010 and consists of an NDVI which captures on-the-ground biomass. However, this index cannot differentiate between tree cover and short vegetation, making it difficult to identify differences between forested areas and areas which have been deforested and used as graze lands (34). We use a new dataset (35) which provides a measure of FC derived from tree cover measures, thus making it possible to identify deforestation in a more accurate way. Additionally, our data are available between 1982 and 2016, and, since we do not have the restriction of looking only at PPTAL territories, we can include observations for all years between 1982 and 2016 for all indigenous territories for which we have geographic information. Finally, while they focus on the third step of the demarcation process, the approval of the Minister of Justice, which they call "demarcation," we focus on the fourth stage when the process is finalized and de jure rights are granted, what we call "homologation" and they call the "approval" stage. We believe the final stage should be the one that makes the difference, since it is when actual property rights are granted, no more contestation can happen, and enforcement is undertaken by the government agencies. Our results are robust to testing only on their sample; we report the results in *SI Appendix*, Table S5 and Fig. S14.

Bonilla-Mejía and Higuera-Mendieta (23) analyze the effects of PAs on deforestation in Colombia. They find strong effects of national PAs, indigenous reserves, and Afro-Colombian lands,

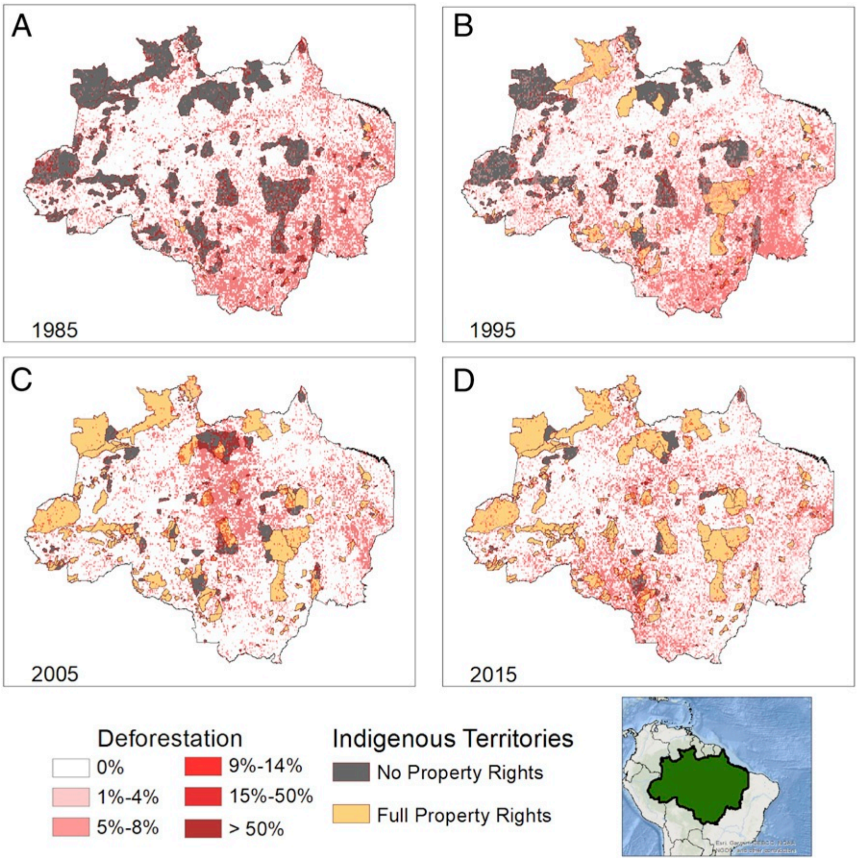

Fig. 1. Indigenous territories and deforestation in Brazilian Amazon for (*A*) 1985, (*B*) 1995, (*C*) 2005, and (*D*) 2015. Gray plots represent indigenous territories which have not received full property rights, while yellow plots represent plots which have received full property rights.

and find no effects for regional PAs. Their paper is most similar to ours in the methods used. Both use regression discontinuity design to assess the effects of land demarcations on deforestation. Their results are similar to ours and provide evidence that the findings of this paper may be generalizable to other settings. However, their paper also has a shorter time frame. They use Hansen et al. (36) data which span only between 2001 and 2016. They are thus limited by their dependent variable. Additionally, our results are made stronger by the fact that we have the plausibly orthogonal timing of homologation, which allows us to test the effects before homologation versus after homologation, and to also use nonhomologated territories as a placebo.

Our results are also very similar to those found in Blackman et al. (25). They analyze an indigenous land titling campaign in the Peruvian Amazon and use community-level longitudinal data derived from high-resolution satellite images to estimate the effect of titling between 2002 and 2005 on forest clearing and disturbance. They find that titling reduces clearing by more than three-quarters in a 2-y period after the title is awarded (25); we find a similar 66% reduction in deforestation within our study buffers.

Analysis and Results

Without formal land titling, indigenous territories lack the CPR management requisites needed to protect their land from external deforestation. Literature has shown that PAs, such as indigenous territories, and law enforcement are the main inhibitive factors of deforestation (31, 32, 37–39). In order to test the effects of property rights, we focus on homologated territories. Before homologation, indigenous peoples do not possess the requisites needed to be successful sustainable institutional regimes. We thus expect that territories that have their full property rights will be more effective at curbing deforestation than those that have not yet been homologated. We exploit the orthogonality of the timing of homologation and a RDD in order to causally identify the effect of collective property rights on deforestation. This approach helps us reduce threats to the validity of the causal claims we argue for.

The timing of homologation follows no clear pattern, as can be seen in *SI Appendix*, Fig. S2. The number of territories homologated in any given year varies between 0 and 70. All presidents except for the last two (Presidents Michel Temer and Jair Bolsonaro) have homologated indigenous territories, regardless of party or ideology. Furthermore, election years are not associated with more or less homologations. Additionally, as *SI Appendix*, Table S2 shows, there are no significant correlations between deforestation and timing of homologation. We see no statistical significance in the correlation between deforestation rates at the time a territory is declared and the years it takes between declaration and homologation, or the likelihood of homologation. Similarly, there is no significant correlation between the deforestation rate inside a territory the year before homologation and the likelihood of getting homologated. We can thus argue that the timing of homologation and deforestation rates are statistically independent, and, as such, we can use this orthogonality to retrieve causal effects of homologation on deforestation rates by looking before and after the full property rights have been granted.*

*BenYishay et al. (27) also rely on the orthogonality in the timing of demarcation, proving that the timing of these processes seems to be somewhat random and not caused by observable characteristics of the territories.

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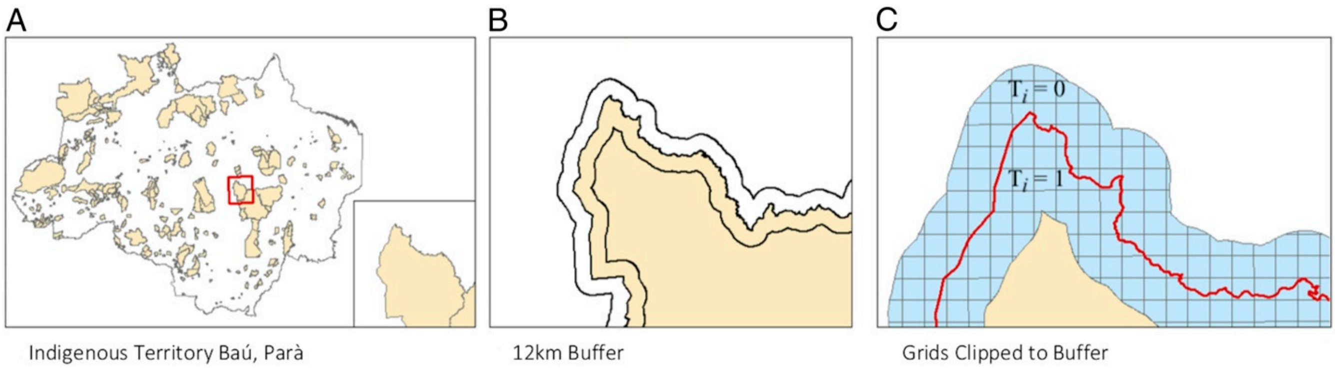

Fig. 2. (*A*) Indigenous territories in the Legal Amazon (the *Inset* shows the Baú territory in the state of Pará), (*B*) 12-km buffer inside and outside indigenous territory border, and (*C*) grids inside buffers. Grids inside are treated while grids outside are control.

We use a dataset at a $0.05°$ resolution (about 4 km $\times$ 4 km) between 1982 and 2016 to measure deforestation at yearly intervals (35). The long timespan of the data significantly expands on the time horizon that most previous literature has been able to analyze (26, 27, 31, 32, 37–39) and allows us to test for the effects of homologation since the beginning of the program to demarcate indigenous territories in Brazil. First, by using a geographic discontinuity design, we focus on observations right inside and outside of the border of the indigenous territories (23, 40, 41) (see Fig. 2 for reference on how we compute our buffers and select the pixels in our sample). This helps us to identify local average treatment effects, so we are comparing plots of land which are almost identical to each other but for the fact that they lie either inside or outside of a border. Second, by exploiting the orthogonality of the timing of homologation, we are able to compare the effects of granting property rights by comparing deforestation before and after, inside and outside of the territory. This allows us to isolate the actual effects of property rights. Finally, we can compare the effects with what we observe in territories which have not been homologated to date. Plots of land that have been demarcated but not homologated serve as good control groups for those similar plots that have been demarcated and homologated.

Our results show strong effects of collective property rights on deforestation. Homologation is responsible for about a 2-percentage point decrease in deforestation right at the border. Considering that the baseline levels of deforestation in our sample are around 3%, this represents a 66% decrease in deforestation. Given that this is a local average treatment effect, we consider this to be a very strong finding.

The plots in Fig. 3 show the regression discontinuity for our three samples. In all three plots, the cutoff at 0 represents the indigenous territory's boundary. Observations to the left of the cutoff represent grids which are located outside of an indigenous territory, while observations to the right of the cutoff represent grids which are located inside indigenous territories (details are provided in *Materials and Methods*). Fig. 3 shows the regression discontinuity for nonhomologated territories (Fig. 3*A*) and homologated territories before homologation (Fig. 3*B*) and after homologation (Fig. 3*C*). The *y* axis in all three plots is the percent of deforestation observed within a grid, while the *x* axis represents distance to the border in meters, where negative values represent grids outside of the border. The discontinuity is only clear and significant for Fig. 3*A*, showing that property rights play a major role in the effect of these territories on deforestation.

Fig. 4 shows the coefficients estimated by the RDD. For each subsample, that is, nonhomologated territories and homologated territories before and after homologation, we run the RDD with and without relevant covariates (see *Materials and Methods*). The dots represent the coefficient estimate, while the thick lines represent 90% CIs and the thinner lines represent 95% CIs. The coefficients of the RDD for territories with full property rights (After Homologation and After Hom, Cov) are significantly larger and more precisely estimated than those for observations before homologation and those in nonhomologated territories. Table 1 shows the results of running the RDD with an optimal

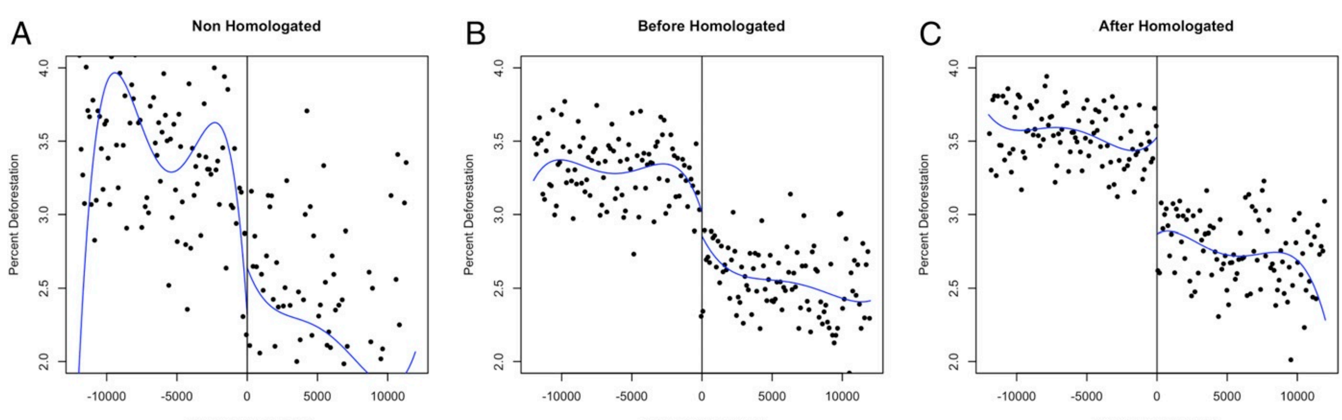

Fig. 3. Regression discontinuity plots for (*A*) nonhomologated territories, (*B*) homologated territories before homologation, and (*C*) homologated territories after homologation. Dependent variable is percent deforestation. Running variable is distance to the border. Blue lines represent fourth-order polynomial fit.

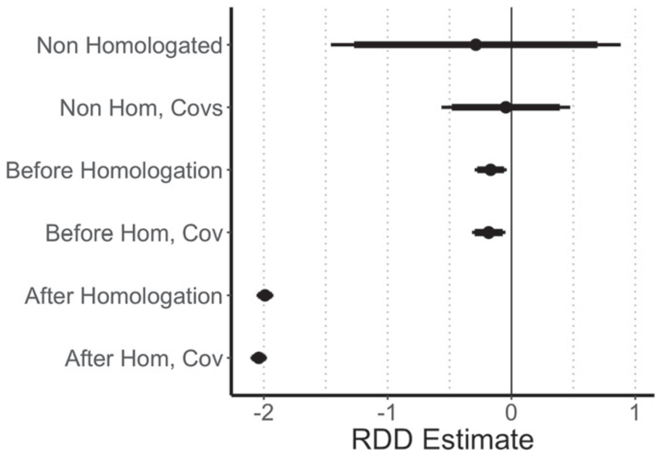

Fig. 4. RDD coefficients for nonhomologated territories and homologated territories before and after homologation, with and without covariates. Thick bars represent 90% CIs, while thinner bars represent 95% CIs.

mean-square error (MSE) bandwidth for different functional forms. We can see that the effects are robust to the choice of bandwidth and of functional form. The fourth-order polynomial results are actually the most conservative. The main estimates which are presented in Fig. 4 correspond to the fourth-order polynomials with optimal MSE bandwidths, h.

After homologation, the area of indigenous territories within the buffer used in the RDD estimation saw a decrease in deforestation of 66% (went from about 3% to about 1%). Given that this is a local treatment effect, we believe these results are extremely significant and show the importance of collective property rights in the preservation of forest lands. Our results are robust to the inclusion of covariates, different bandwidths, and different time periods—that is, selecting observations 3, 5, and 10 y before and after homologation (*SI Appendix*, Fig. S7). Additionally, we present results showing that the estimates are robust to the choice of bandwidth (*SI Appendix*, Fig. S6).

One limitation that our design cannot address is the issue of leakage. Given the local nature of our results, we cannot rule out that the reduced deforestation inside the territories is not being partially offset by an increase in deforestation somewhere else. However, evidence of leakage is limited inside our buffers. The difference in deforestation rates right outside of the borders before and after homologation is less than 0.2 percentage points, which would represent a very small amount of leakage compared to the 2-percentage point reduction in deforestation we estimate. In this sense, our results shed light on the effectiveness of property rights in ensuring that indigenous communities can reduce deforestation inside their lands, and provide some evidence that the overall effects on deforestation inside the buffers are negative.[†] Although we are not able to make causal claims on total deforestation levels in the Amazon as a whole, our results provide strong evidence for the role of collective property rights in reducing deforestation rates inside indigenous lands and the possibilities for using indigenous territories as a tool to preserve key forest areas.

[†]An alternative way of addressing the leakage concern would be to conduct a donut hole analysis (42) where observations closest to the border are deleted. Although the donut hole analysis does diminish the size of the estimated effects, which could suggest that there is some leakage, the effects remain significant. Additionally, deleting the observations closest to the border may violate the main identifying assumption of the RDD, that is, that we are comparing pixels that are identical to each other, other than for their homologation status. Finally, even if leakage is taking place, our results suggest that expanding the size and prevalence of homologated territories would likely lead to an overall reduction in deforestation.

Our results suggest that not only do indigenous territories serve a human rights role, but they are a cost-effective way for governments to preserve their forested areas. First, obtaining full property rights is crucial to recognize indigenous peoples' original right to land and protect their territories from illegal deforestation. Second, when implemented, indigenous property rights create sustainable areas in the Amazon rainforest, providing an important positive externality for Brazil and the rest of the world in terms of climate change mitigation. Our findings suggest that, if CPR management requisites are met, and indigenous peoples are provided property rights over their land, they can better manage their land and protect it from external threats. We find that granting property rights significantly reduces the levels of deforestation inside indigenous territories, and the results are of significant orders of magnitude.

The complete standstill in homologation of indigenous lands which began with the Temer administration and has continued under President Bolsonaro could be responsible for an extra 1.5 million hectares of deforestation per year. This together with the increase in violence toward indigenous peoples and Bolsonaro's claims that he will open these lands to mining and agricultural interests also highlight the importance of an institutional system which will recognize these property rights. Providing full property rights and the institutional environment for enforcing these rights is an important and cost-effective way for countries to protect their forests and attain their climate goals. Public policy, international mobilization, and nongovernmental organizations should now focus their efforts on pressuring the Brazilian government to register indigenous territories still awaiting their full property rights, strengthening the existing mechanisms that protect indigenous territories from extractive activities and providing nonhomologated territories with monitoring and enforcement support.

Materials and Methods

We use NASA's Making Earth System Data Records for Use in Research Environments Vegetation Continuous Fields (VCF) Version 1 data product (VCF5KYR) which provides remote-sensing validated historical fractional vegetation cover data at a 0.05° resolution between 1982 and 2016 to measure deforestation at yearly intervals (35). This dataset allows us to cover over 30 y of deforestation across the globe. While the spatial resolution of this dataset is significantly lower than the Hansen Global Forest Change data, the temporal resolution is much longer. Most of the other papers in this literature are analyzing short time periods, due to limited temporal resolution of older datasets; however, the long time coverage provided by VCF5KYR allows us to compare deforestation before and after the homologation of most of the indigenous territories in Brazil.

We create a panel dataset between 1982 and 2016 which includes FC in each year. Summary statistics can be seen in *SI Appendix*, Table S1. We create the deforestation variable which is equal to the difference in FC between years t and $t-1$. If the difference is higher than 0, deforestation is equal to 0. Since years 1994 and 2000 are missing in the Hansen data, we impute forest in those years as the average forest in the years before and after.

Maps containing the geolocation of the indigenous territories were obtained from FUNAI (43), and maps of Brazil's administrative units (states and municipalities) and roads were obtained from the Brazilian Institute of Geography and Statistics (44, 45). Indigenous territories in the first step of the demarcation process do not have their boundaries geocoded, thereby reducing the number of territories we analyze. Additionally, we updated the data to include legal status and the year the legal status was obtained for each indigenous territory using the Instituto Socioambiental's online indigenous land database.

We also use several other sources for our control variables. Existing literature has found that proximity to roads, rivers, and mines and elevation and rainfall are significant predictors of deforestation (23, 27, 31, 32, 37–39) and are readily available in the time scope we need. Additionally, poverty and population have been found to matter as well (39); however, the time frame for which these are available in a geographically explicit manner is

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Table 1. Regression discontinuity estimates: Effect of indigenous property rights on deforestation

	Bandwidth							
	Linear		Quadratic		Cubic		4th order	
	H	*2h*	*h*	*2h*	*h*	*2h*	*h*	*2h*
Nonhomologated territories								
RDD estimate	0.077	0.14	0.233	0.22	−0.109	0.23	−0.29	0.18
	(0.409)	(0.364)	(0.394)	(0.443)	(0.542)	(0.340)	(0.598)	(0.472)
Bandwidth	2,152	4,304	4,304	8,208	4,093	8,608	5,226	10,452
n	8,165	11,998	16,532	24,536	14,161	24,536	17,697	29,914
Before homologation								
RDD estimate	−0.28**	−0.25	−0.27**	−0.29**	−0.22**	−0.29**	−0.17**	−0.32**
	(0.039)	(0.034)	(0.065)	(0.049)	(0.057)	(0.046)	(0.066)	(0.054)
Bandwidth	2,082	4,164	1,957	3,914	3,423	6,846	3,905	7,810
n	33,064	52,150	29,362	48,700	52,153	86,470	61,941	97,950
After homologation								
RDD estimate	**−2.07****	**−2.12****	**−2.66****	**−2.32****	**−2.48****	**−2.07****	**−1.99****	**−1.25****
	(0.024)	(0.027)	(0.033)	(0.038)	(0.039)	(0.034)	(0.035)	(0.023)
Bandwidth	372	744	569	1,138	1,068	2,136	2,218	4,436
n	17,969	10,574	20,188	17,506	30,716	33,384	51,123	70,328

Dependent variable is percent of deforestation. Running variable is distance to indigenous territory border in meters. Coefficients are robust RDD estimates; *h* represents the optimal bandwidth (meters) chosen to minimize square errors. Robust standard errors are clustered at the indigenous territory level and are in parentheses. Numbers in bold represent coefficient estimates for homologated territories. $^{**}P < 0.01$, $^{*}P < 0.05$.

limited. We can use nightlights (46) to proxy for development (which can capture poverty); however, these are only available from the 1990s onward (47). Additionally, population at a spatially explicit scale is only available beginning in 2000 and in 5-y intervals through the Gridded Population of the World (GPW) (48). Given these data limitations, we present our main findings using only covariates which are available for the entirety of the sample, which are mainly geological and physical characteristics. Robustness checks including nightlights and GPW indicate that our results regarding property rights are somewhat smaller, but remain statistically significant.

When the resolution of a control variable is different than that of our grids, we calculate the average value for each grid cell. We use the Global Multiresolution Terrain Elevation Data 2010 dataset provided by the US Geological Survey (USGS) (49) containing elevation data for the globe measured in meters at a 7.5-arcsecond resolution. Mean elevation is computed for each grid. The precipitation dataset (Climate Hazards Group Infrared Precipitation with Station Data 2.0, Pentad) (50) is provided by the University of California, Santa Barbara's Climate Hazards Group. This dataset consists of a gridded rainfall time series for trend analysis and seasonal drought monitoring. Precipitation is measured in millimeters per pentad at a 0.05-arc-degrees resolution; mean precipitation is computed for each grid from 1982 to 2016. Data on the main rivers in Brazil were obtained through Esri software provided by the Brazilian National Agency for Water (51). We also use NASA's USGS Earth's Resources Observation and Science Center water mask data (52) which provide a map of surface water at 250-m resolution from 2000. We compute the sum of water mask for each grid and eliminate grids that are more than 60% water.

Our final dataset is a panel dataset with 35-y observations of 30,699 pixels, coming to 1,074,465 observations. The level of analysis is at the pixel (or grid) level. We analyze 245 indigenous territories, some of which were homologated as early as 1982, while others remain to be homologated. Below, we describe the key features of our design, namely, the orthogonality of the timing of homologation which provides us with temporal identification and the RDD from which our estimates are derived.

Orthogonality of Timing of Homologation. We exploit the orthogonality in the timing of homologation to identify the effect of property rights. The number of homologated territories per year varies greatly, from 0 to 70 territories homologated in any given year, and seems to follow no clear pattern (more in *SI Appendix*, Table S2 and Fig. S2). We thus look at the deforestation levels right inside and right outside of a territory's borders, right before and right after the property rights were finally granted. We test using different numbers of years before and after, that is, 3 y, 5, 7, and 10 y, and find similar and robust effects for all of these specifications (*SI Appendix*, Fig. S7). We thus divide our data into three groups which are as if randomly determined due to the year of homologation variable: 1) observations that belong to territories which have not yet been homologated, 2) observations which belong to territories that have been homologated, right before homologation (i.e., main specification is 5 y before), and 3) observations that belong to territories that have been homologated, after homologation (i.e., 5 y after).

RDD. For each subgroup of data, we run a regression discontinuity for deforestation, where we include observations around a buffer of the territory's border. Our dataset includes all pixels within a 12-km buffer inside and outside of a border's territory. Observations inside a territory have a positive distance to the border, while observations right outside of a territory have a negative distance to the border. The cutoff is 0, which represents the border. By only using observations close to the borders, we are able to isolate many of the confounding effects that arise from the fact that indigenous territories might be located in systematically different lands. Observations right inside the territory are expected to be similar to observations right outside of the territory.[‡] Another way we try to alleviate these concerns is by comparing the results in homologated territories to the results in territories that have not been homologated. Many territories are demarcated, which means that their boundaries are drawn, identified as indigenous lands, and put on maps. However, they never reach the step of homologation, where the rights are actually granted to the indigenous communities. These territories serve as a useful control group. If the effect on deforestation is coming from property rights, then these territories which have been identified as indigenous lands but have not yet received the rights should show no effects.

The main results presented in the paper are computed using the following regression:

$$Def_i = \alpha + \tau T_i + \beta_1 f(X_i - c) + \epsilon_i,$$

where c is the cutoff and T_i is a binary variable equal to 1 if $X \geq c$ and $c - h \leq X \leq c + h$, where h is the optimal bandwidth that minimizes MSE (41); $f(X_i - c)$ is a polynomial and denotes the functional form used to fit the data.

‡The running variable in our RDD is the naive distance, as opposed to what Keele and Titiunik (41) call the geographic distance. We do not need the more complex geographic distance since we do not face some of the problems identified by Keele and Titiunik, such as compound treatment effects and or differential treatment at different points of the border, so we believe our simple measure of distance is appropriate. Since our outcomes of interest are environmental and geographic in nature, we also do not see sorting around the boundary, further making the more complex design unnecessary in this case.

In this paper, we use a fourth-order polynomial and a bandwidth (*h*) chosen to minimize MSE, following refs. 40 and 41. In particular, we use the "rdrobust" package in R (40) to estimate the effects, and use the bandwidth selection option "MSERD." The fourth-order polynomial is the default option in the package, and provides the most flexible functional form to fit the data. Additionally, as can be seen in Table 1, the fourth-order polynomial estimates are the most conservative. Given that our results are robust to different functional form specifications, we decided to present the most conservative estimates as our main results. However, in order to ease concerns over issues that fourth-order polynomials might create, we show that the results are robust to using linear and quadratic regressions, as proposed by Gelman and Imbens (53). With regard to the choice of the bandwidth, our results are also robust to different bandwidth choices, as can be seen in *SI Appendix*, Fig. S6.

An important assumption of the regression discontinuity model is that possible confounders should be continuous around the cutoff. In other words, assignment to treatment should rely only on the running variable, distance to border, and be orthogonal to any other variable that might be generating the outcome, in this case, deforestation. Balance tests are shown in *SI Appendix*, Figs. S3–S5. We see a jump at the cutoff for elevation, but all other geographic variables seem to be balanced. In order to ensure there is no confounding effect, we also run the regression discontinuity with covariates, and report both results in Fig. 4. The full table of estimates with covariates can be found in *SI Appendix*, Table S3. Results are robust to changing the number of years included before and after homologation, as can be seen in *SI Appendix*, Fig. S7. In order to ensure that our results are robust and build on previous literature, we test the results on the sample of territories included in the BenYishay et al. (27) study. Our results still hold, and are reported in *SI Appendix*, Table S5 and Fig. S14. Placebo tests (*SI Appendix*, Fig. S8), further robustness tests, and more on the methods can be found in *SI Appendix*.

Data Availability. Comma-separated values files and R code have been deposited in Harvard Dataverse (https://dataverse.harvard.edu/dataverse/collective_rights_amazon).

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