Collective Property Rights Lead to Secondary Forest Growth in the Brazilian Amazon

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Forests serve a crucial role in our fight against climate change. Secondary forests in the form of forest restoration provide important potential for conservation of biodiversity and climate change mitigation. In this paper, we explore whether collective property rights in the form of Indigenous Territories (ITs) lead to higher rates of secondary forest growth on previously deforested areas. We exploit the timing of granting of property rights, the geographic boundaries of ITs and two different methods, regression discontinuity design and difference-in-difference, to recover causal estimates. We find strong evidence that Indigenous territories with secure tenure not only reduce deforestation inside their lands, but also lead to higher secondary forest growth on previously deforested areas. After receiving full property rights, land inside ITs displayed higher secondary forest growth than land outside ITs, with an estimated effect of 5% using our main RDD specification, and 2.21% using our difference-in-difference research design. Furthermore, we estimate that the average age of secondary forests was 2.2 years older inside ITs with secure tenure using our main RDD specification, and 2.8 years older when using our difference-in-difference research design. Together, these findings provide evidence for the role that collective property rights can play in the push to restore forest ecosystems.

Collective Property Rights, Secondary Forest Growth, Amazon, Indigenous Lands, Brazil

Significance Statement

Forest restoration has become a popular instrument in the climate change toolkit. Indeed, secondary forests are a highly productive source of carbon uptake, with an estimated average rate of 3.05 Mg C ha\(^{-1}\)yr\(^{-1}\) in neotropical regions (1). Secondary forest regrowth can also mitigate biodiversity loss (2) and provide habitats for endangered and threatened species. With all these benefits to be paid to when and where secondary forest growth occurs, and what policies can lead to successful regeneration of native forests.

Secondary forest growth can be a crucial part of a successful, long-term climate policy. In fact, countries across the globe have committed to the restoration of about 350 million hectares of land by 2030 under recent international agreements like the Bonn Challenge and the Paris Agreement (7, 8). Brazil, for its part, has committed to growing 4.8 million ha of native vegetation in the Amazon by 2030 (8). Unfortunately, many of these commitments rely on the expectation of growing areas covered by plantations (7). Plantations store less carbon than native forests (7, 9, 10), and also have been shown to be problematic when they are not planned in conjunction with local communities (11, 12).

However, when done right, forest restoration has potential to regenerate natural forests, restore ecosystems and support local communities (13). Collective property rights, rights over land devolved to Indigenous communities, fulfill several of the requirements that have been identified for successful secondary forest growth policy (13). Secondary forest growth in these territories is driven by local stakeholders (14) and their preferred land use practices, the forests are managed and allowed to grow in a natural state such that species diversity is encouraged and valued, and Indigenous knowledge of local conditions is at the heart of the regeneration process. In this paper, we seek to causally identify whether collective property rights lead to higher rates of secondary forest growth in previously deforested areas of the Brazilian Amazon. We focus on secondary natural forests, such that plantations and monocultures are not included in our definition of secondary forests based on (15). Rather, our measure focuses on the regeneration and natural restoration of forests.

The Brazilian Amazon is home to 726 Indigenous territories which cover 13.8% of Brazil (and 23% of the Legal Amazon territory) (16). In order to gain recognition of their lands, Indigenous peoples have to go through a four step process called demarcation. The final step of the demarcation process is homologation - meaning that the President officially declares the territory as belonging to an Indigenous peoples. Once homologated, a territory becomes the permanent possession of

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its Indigenous peoples, contestation is limited and extractive
activities carried out by external actors can only occur after
consulting the communities and the National Congress. As
such, we argue that secondary forest regrowth is more likely to
take place when full property rights are granted to the community.
This allows for long term planning, and also provides the
legal backing for decisions on land use and prevention of
encroachment by third parties. We thus expect secondary
forest growth to be higher within homologated ITs compared to
non homologated territories and non-Indigenous, neighboring
lands. In what follows of the paper, we refer to ITs that have
been homologated as ITs with full property rights or ITs with
secure tenure interchangeably, and those which have not yet
been homologated as ITs without full property rights or secure
tenure.

Indigenous territories (ITs) have been shown to reduce
deforestation inside their borders (17–21), especially after
receiving secure tenure (17)∗. As such, Indigenous territories
produce significant positive externalities to non-Indigenous
populations by providing forest and eco-system conservation
while also achieving a human rights role. Although much has
been written on the conservation effects of ITs, we know far
less about the secondary forest growth dynamics inside these
lands. Secondary forest growth may have differing patterns
inside ITs given the different land use dynamics which occur
inside these territories. Indeed, scholars have found that land
use within ITs tends to be less centered around intensive
agriculture and cattle grazing, with decreased deforestation
(17, 18, 21) and forest fires (25) when compared to land outside
ITs. Additionally, Indigenous knowledge and culture regarding
land use also plays an important role as it aims to ensure
the long term use of the soil, directly enabling the regrowth
of secondary forests. Furthermore, as Indigenous peoples
protect their land, existing secondary forests will be allowed
to continue growing through time, and so the average age of
secondary forest extents inside these lands should also be
higher than the average age of secondary forest extents outside
Indigenous lands.

In this paper, we use a geographic regression discontinuity
design and exploit the timing of homologation (receiving secure
tenure rights) of ITs (17) in order to estimate the effects
of secure tenure on secondary forest growth on previously
deforested areas. We find strong effects of IT secure tenure on
secondary forest growth. Once secure tenure is granted, pixels
right inside ITs display 5% higher secondary forest growth
rates compared to pixels right outside an ITs border. This
effect is not present in ITs which never gain full property rights
(non-homologated ITs) or in ITs which eventually receive full
property rights before they are granted (before homologation).
We also find that the average age of secondary forest trees
inside ITs is about 2.2 years older than that of trees right
outside ITs, suggesting that forests are allowed to grow for
longer without being cut down inside ITs.

Additionally, we use a staggered difference-in-difference
design (26) to ensure robustness of our results. Our results

* Although some papers find no effect of ITs on deforestation (22–24)
remain strong with this alternative method. Using this methodology, our results suggest that secure tenure leads to about a 2% increase in secondary forest growth and an increase of 2.8 years in the average age of secondary vegetation². Taken together, these results suggest that providing full property rights to Indigenous peoples has a positive effect on secondary forest growth, not only on the conservation of previously standing forests.

1. Indigenous Territories in the Brazilian Amazon

Brazil is home to 252 Indigenous peoples who speak more than 150 distinct languages. Indigenous peoples live in 726 Indigenous territories which are at different stages of demarcation - the legal process by which ITs gain their full property rights (16). The final step of demarcation involves a homologation by Presidential decree and registration of the land in the national land registry. The Constitution states that Indigenous peoples’ socio-political 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 preservation of environmental resources necessary for their well-being” (27). Article 231 poses that Indigenous peoples have “the exclusive usufruct of the riches of the soil, rivers and lakes existing thereon” (27) 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” (27). This process further holds that, prior to presidential homologation, third parties could contest the demarcation of a territory in court, and non-Indigenous 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 (27).

As of today, 487 of these lands have gone through the final stages of the demarcation process, while the rest are at earlier stages and awaiting their final homologation. Figure 1 shows the map of ITs and their homologation status in the year 2000 (roughly half-way through our study time). Secondary forest growth outside ITs is mapped in shades of green while secondary forest growth inside ITs is mapped in shades of red. Figure S3 (in the SI) shows how in 1990 most of the territories were not homologated compared to 2019, where most territories have gained their full property rights.

Indigenous Territories and Secondary Forest Growth. Land use dynamics and deforestation trends differ inside versus outside ITs, consequently affecting the likelihood of secondary forest growth. Inside ITs, deforestation can be driven either by external actors encroaching on the lands of Indigenous peoples, or by Indigenous peoples themselves who may clear forestry in order to build villages, engage in agricultural activities or simply to make profits from logging. Deforestation driven by external encroachment is often driven by agriculture, logging, mining and by the incentive to show there is a “productive” use of the land thereby opening up the possibility of contesting territorial borders.

Studies have focused on comparing deforestation on ITs and non-ITs in the Amazon, highlighting that deforestation, forest degradation and fires are more intensive on land that does not belong to Indigenous peoples (28). These areas tend to be more prone to clearings and agricultural activities. Specifically, pastures and croplands are more likely to be on land not inhabited by Indigenous peoples.

Deforestation negatively affects land quality by provoking soil erosion, decreasing the fertility of soil, drying springs and bodies of water, damaging habitats, and endangering local species (29). Fires and degradation have negative effects on the structure of forests and their ecological compositions. Similarly, using land for agriculture and livestock reduces the availability of water, the quality of the soil and biodiversity itself. As the regeneration of secondary forests depends on various factors including the previous intensity of land-use, its management and duration, the negative consequences of deforestation, agriculture, and livestock challenge the possibility of regrowth (29, 30).

While the growth of secondary forests may be less likely on non ITs due to more intensive land use and land management practices, the opposite is true within ITs, where Indigenous peoples are found to actively facilitate secondary forest growth (30). Indigenous knowledge and management practices are recognized as instrumental for the protection of biodiversity

Table 1. RDD Results for Secondary Vegetation

<table>
<thead>
<tr>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
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<tbody>
<tr>
<td>Non Homologated</td>
<td>Before Homologation</td>
<td>After Homologation</td>
</tr>
<tr>
<td>RDD Coefficient</td>
<td>1.021</td>
<td>0.155</td>
</tr>
<tr>
<td>Mean.Control</td>
<td>13.317</td>
<td>17.791</td>
</tr>
<tr>
<td>Kernel Bandwidth</td>
<td>Triangular</td>
<td>Triangular</td>
</tr>
<tr>
<td>N</td>
<td>3325</td>
<td>18758</td>
</tr>
<tr>
<td>BW</td>
<td>1333</td>
<td>1575</td>
</tr>
</tbody>
</table>

NOTE: Significance levels: *10%, **5%, ***1% and Std. Errors in brackets. The Table shows robust coefficients from a RDD where the cut-off is the border of the IT. Panel A shows results for secondary vegetation proportion (in %) as the dependent variable. Panel B shows results for secondary vegetation age (in years) as the dependent variable. Column (1) shows the results of running the RDD on non homologated ITs, while column (2) shows the results for homologated territories before homologation and column (3) after homologation. All models use linear polynomials on either side of the cut-off, optimal bandwidth selection procedure that minimizes mean square error, triangular kernels and standard errors are clustered at the IT level.
and are central to international conventions and summits as shown by the Convention on Biodiversity (31). These practices emphasize adaptive management strategies, utilize deeper understandings of ecological processes, rely on social and cultural norms and rules, and have as a goal the promotion of nature recovery and regeneration (30). As the natural regrowth of secondary forests requires “the alignment of ecological and social factors” (32), scholars emphasize that promoting secondary forest growth is of specific importance to Indigenous peoples and local communities whose well-being is negatively affected by the degradation of forestry, biodiversity, and soil (33).

Forest recovery has been at the forefront of the Indigenous movement, along with forest conservation. Active restoration initiatives in Indigenous lands abound (8, 34, 35). Many of these initiatives consist of the collection and management of different seeds for restoration of biologically diverse biomes. In fact, some of this has been supported by FUNAI, which between 2012 and 2019 has invested more than R$2.5 million in the acquisition of seedlings for restoration projects inside Indigenous Lands (34, 36).

A successful example of an Indigenous led forest recovery project is Rede Sementes do Xingu, a non-governmental organization led by Indigenous peoples and local family farmers whose dual objectives consist of “forest restoration through the collection and commercialization of seeds of different species, and the appreciation of the autonomy of the peoples and traditional cultures that are part of the Xingu Seeds Network” (Rede Semente Xingu). In their more than 15 years of existence, the Rede Sementes do Xingu has collected seeds for more than 220 native species, recovered 7.4 thousand hectares and planted about 25 million trees with their seedlings. Additionally, this work provides an important source of sustainable income for the local communities, representing about R$5.3 million directly to the seed collectors. This type of initiative, led by Indigenous peoples, represents a prime example of secondary forest growth efforts in the Amazon and the contributing role of Indigenous territorial rights.

Under these circumstances, if territorial rights are fully granted to Indigenous peoples, thereby limiting the possibility of contestation, we should expect to see a rise in the secondary forest extent, especially if the prior deforestation was driven by outside forces rather than by the Indigenous peoples themselves. Given that prior research has shown steep declines in deforestation rates inside Indigenous territories after homologation (17), indicating that Indigenous peoples in general have a preference for preserving their forests, we should also expect to see a recovery of the forest once the land rights are granted back to Indigenous peoples.

We thus present the following hypotheses:

Hypothesis 1: given prior deforestation, pixels inside homologated ITs (territories with secure tenure) are more likely to display secondary forest growth than those outside ITs.

Given our expectation that forests are more likely to grow inside homologated ITs (territories with secure tenure) compared to outside ITs.

Hypothesis 2: the average age of secondary forests is expected to be higher inside homologated ITs (territories with secure tenure) compared to outside ITs.

2. Analysis and Results

In order to test our hypotheses, we rely on a grid of points at a 0.05° resolution (about 4km X 4km) (17) which cover the area known as the Legal Amazon in Brazil 1. We draw a 1km buffer around the centroid of each point and calculate the value of different geographic outcomes for the area inside these buffers. Our main dependent variables are the proportion of secondary forest extent and the average age of the secondary forest inside a pixel, based on (Silva Junior et al. 2020)(15).

Our treatment is the homologation (granting of secure tenure) of an Indigenous territory and we include covariates which contribute to deforestation and secondary forest growth rates. These control variables include elevation, rainfall, population, and proximity to roads, mines, and rivers.

We rely on two distinct methodologies in order to identify causal effects of granting ITs secure tenure on secondary forest growth. First, we rely on a geographic regression discontinuity design, following the methods in (17) described in Materials and Methods. By using a geographic discontinuity design, we focus on observations very close to the IT borders, on the outside and inside of ITs (21, 37, 38) (see Figure S1 in the SI for reference on how we compute our buffers and select the pixels in our sample). This helps us to identify local average treatment effects, such that we are comparing plots of land which are almost identical to each other but for the fact that they lie on opposite sides of the border.

By exploiting the orthogonality of the timing of homologa-

tion, we are able to compare the effects of granting property rights by comparing deforestation before and after, inside versus outside the territory (17). The timing of homologation follows no clear pattern, as can be seen in SI Appendix, Figure S2. The number of territories homologated in any given year varies between 0 and 70. All presidents except for President 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 prior deforestation and timing of homologation.

We see no statistical significance in the correlation between deforestation rates at the timing a territory is declared and 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 the following year. 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. 8

Second, to ensure that the results are robust to different methodologies and also to get estimates of treatment effects in time we use a difference-in-difference method proposed by (26), which relies on the staggered entry into treatment, as is the case with the homologation of ITs in the Brazilian context where ITs were homologated at different points in time throughout the study period.

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1 The Legal Amazon covers 60% of the Amazon Rainforest and includes nine Brazilian states: Amazonas, Pará, Roraima, Rondônia, Acre, Mato Grosso, Amapá, Tocantins and Maranhão.

8 BenYishay et al. (2017) 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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Regression Discontinuity Design Results. We find strong effects of Indigenous land rights on secondary forest growth and secondary forest age. Table 1:Panel A shows the results from running the regression in Equation 1, where the dependent variable is the proportion of secondary forest extent as measured by (15). Column (1) displays the results of the RDD on non-homologated territories while columns (2) and (3) show the results for homologated territories before homologation and after homologation, respectively.

Table 1:Panel B shows the results of running the regression in Equation 1. For all specifications, we used the first-degree polynomial on either side of the cut-off with bandwidths selected by the method proposed in (37). The coefficient plots can be found in Figure 2, where the left panel presents the results for secondary forest extents and the right panel presents the results for an average age of secondary forests.

The results show that the area of secondary forests is significantly larger inside ITs only for homologated ITs, and that the average age of secondary forests inside homologated ITs compared to outside is also significantly higher. In particular, the results in column (3) of Table 1:Panel A show a statistically significant increase in the extent covered by secondary forest of about 5%. This represents a 23% increase compared to area outside homologated ITs. This is compared to the results for non homologated (column (1)) and homologated territories before homologation (column (2)), both of which are statistically indistinguishable from 0.

Similarly, when looking at the results for the age of secondary forests in Table 1:Panel B, we can see that pixels inside homologated ITs have secondary forests that are on average 2.334 years older than those right outside. This represents a 23.3% increase in the average age of secondary forests. This is compared to the results for non homologated (column (1)) and homologated territories before homologation (column (2)), both of which are statistically indistinguishable from 0.

These results are in line with our expectations and indicate that once forests are cleared, for whatever reason this may be, the land inside Indigenous territories with full property rights recovers its forests at a higher rate than the land outside Indigenous territories. Furthermore, secondary forests inside homologated ITs are allowed to grow for longer, as is evidenced by the higher average age of the forests inside homologated ITs.

Event Study Design Results. The event study using CSDiD provides further evidence for the effects of IT secure tenure on secondary forest growth dynamics. In line with the RDD results, we find a robust effect of Indigenous land rights on secondary forest growth and age. Table (2) illustrates group-
time ATTs using CSDiD method. We present multiple types of results using a flexible arrangement of group-by-time combinations to estimate ATT across the simple, dynamic, calendar, and group (cohort) interpretations.

Table 2 presents the results, which are robust to different group-by-time aggregations. Our main results are presented in terms of the ‘dynamic’ event study design, where the ATT is presented in column (1), and the event study estimates are shown in Figure 3. We find that the secondary forest proportion grew by 2.21% more in treated units compared to the control. The dynamic ATT reiterates that there are more extensive secondary forests inside homologated ITs. The average age of the secondary forest is higher by 2.78 years inside homologated ITs.

3. Discussion

Our results show that in Brazil, ITs with full property rights not only reduce deforestation but allow for natural forest regrowth. Below, we highlight three important takeaways from our findings and what they mean for the future of forests: 1) collective property rights can be a tool for conservation and forest restoration, 2) collective property rights can’t exist in an institutional vacuum - in order for these rights to be enforced and effective there needs to be a clear rule of law and an institutional framework willing and capable of ensuring respect for these rights, and 3) some recent trends in the political landscape provide reason for hope.

First, we provide evidence that conservation and restoration can stem from collective property rights. The recent push to “plant one trillion trees” could be used as a positive policy momentum if done right. Attention must be placed on local communities, their needs and knowledge, as well as on the natural environment. Secondary forest growth should focus on allowing and aiding natural forest regrowth, rather than plantations of monocultures (9). In line with previous research, our work suggests that the trade-off between forest conservation and livelihood promotion could be ameliorated by the regrowth of secondary forests (39–41). Moreover, protection and regrowth of secondary forests could open novel paths for emerging benefits for the Indigenous communities which are producing this public good. As Brazilian carbon markets take form (PL 528/21), there is a timely possibility of including secondary forest growth inside ITs and beyond as a form of carbon credit, thus providing environmental conservation and poverty alleviation.

Notably, the logic of secure property rights enabling forest recovery could be extended to private lands, although it is uncertain whether results would hold for private versus collective, Indigenous lands. Future work should delve deeper into the link between property rights and secondary forest growth inside privately held land. In this case, smallholders’ role in protecting secondary forests could offer some unique opportunities for livelihood diversification. While most forest conservation policies, such as land registration programs like Cadastro Ambiental Rural-CAR, focus on conservation inside privately held lands, they give limited attention to landholder’s livelihood opportunities via recovery of ecosystems. Like (40), we contend that a comprehensive impact assessment of forest conservation on private landholdings should consider social, human, and financial capital in post-CAR interventions. We suggest that integrating environmental regularization with secondary forest restoration would provide robust benefits to forest conservation and livelihood promotion options for smallholdings.

Second, our research illustrates that securing Indigenous property rights may restore erstwhile forest lands. However, two current trends in Brazil threaten the potential for secondary forest growth on Indigenous territories. First, there has been a progressive dismantling of environmental institutions over the past few years. After his election, President Bolsonaro then shifted the responsibilities of FUNAI to the Ministry of Agriculture. Environmental agencies such as IBAMA (Brazilian Institute of the Environment and Renewable Natural Resources) and FUNAI have experienced a decrease in budget and personnel cuts. Numerous bills have been proposed in-

![Fig. 3. Event Study for A) Proportion of Secondary Forest Extent and B) Secondary Forest Age. Treatment=Inside Homologated IT. Lines represent 95% confidence intervals, standard errors are clustered at the IT level. Red coefficients represent pre-treatment periods while blue coefficients represent post-treatment periods.](Image)
Materials and Methods

We create a panel dataset based on a grid of points at a 0.05° resolution, draw 1km buffers around these points and calculate the proportion of different geographic outcomes inside this area. First, we use the data from Silva Junior et al. (2020) to calculate the proportion of secondary forest extent. The authors construct the annual area under secondary forest cover calculated using land-use classification using MapBiomas annual land use images. The authors’ method is then used to produce monthly area conversion in order to get annual estimates of the secondary forest extent.

Because secondary vegetation, by definition, can only happen on previously degraded areas or areas not already containing primary vegetation, the measurement of this variable is somewhat complicated. We know from previous work that deforestation is lower inside Indigenous territories, and that the proportion of land covered by primary forests inside ITs is higher than it is outside ITs. This means that there is less land which can potentially experience secondary forest growth inside ITs. Under this scenario, taking absolute secondary forest extents, for example, measured in hectares or km², will provide an incomplete account of secondary forest growth dynamics.

In order to ameliorate these concerns and make secondary forest growth data outside Indigenous territories comparable to that inside Indigenous territories, our main dependent variables are measures of the proportion of land that can potentially experience regrowth that actually saw secondary forest growth. We define land that can potentially experience regrowth as land that did not contain primary forests in t − 1 and was not covered by water.

Our main dependent variable for each pixel is thus:

$SV_{extent,t} = \frac{SVarea}_{t} \times Pixel Area - (Primary Forest_{t-1} + Water)$

Where the denominator reflects the land area that does not already hold primary forests in t − 1 or water (like a river or lake), and can thus not be converted into secondary forests. This allows us to capture secondary forest growth as a proportion of the possible land that could be converted into secondary forests. We construct this variable using secondary forest extents based on Silva Junior data and MapBiomas.

Second, to evaluate the trend in age-wise secondary forest recovery, we use (15) estimates of secondary forest age in order to calculate average secondary forest age within each pixel. (15) provide estimates of the area (in square km) for each age group from 1-36. We rely on this information to calculate the average age of secondary forests inside a pixel. We thus calculate the following equation:

$MEANage_{i,t} = \frac{\sum_{j=1}^{36} AGEarea_{i,j,t} \times j}{Pixel Area - (Primary Forest_{t-1} + Water)}$

Where $j$ is the age of the secondary forest which can go from 1 to 36, and $AGEarea_{i,j,t}$ is the variable identifying the amount of area inside each pixel, $i$, in period $t$, which was of age $j$. $SVarea_{i,t}$ represents the extent of secondary forest inside the pixel $i$ in period $t$, in hectares km. Thus, $MEANage_{i,t}$ represents an area weighted average of the age of secondary forests inside each 1 km² pixel.

For our treatment variable we build on the dataset provided by (17). Data with the geolocation of Indigenous territories in the Brazilian Amazon is provided by FUNAI. We complement this dataset with information on the legal status of a territory and the date it obtained this status using the Instituto Socioambiental’s database on Brazilian Indigenous territories. Throughout the paper, treated units are considered those inside ITs within a 20km

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(15) provides the annual age-wise secondary forest classification rasters that are provided on Zenodo. 2022

The project has provided annual pixel-per-pixel land use classification for the entire Brazilian territory since 1985 (51, 52). Using the Google Earth Engine (GEE) the classification is achieved in four key steps. Please refer to Algorithm Theoretical Basis Document (ATBD) Collection 6 for more details.
bandwidth from the border on the inside of the territory, while control units are those outside ITs within a 20km bandwidth from the border on the outside of the territory.

We incorporate data on various covariates which have been found to contribute to deforestation in prior literature. These control variables include elevation, rainfall, population, and proximity to roads, mines, and rivers. We calculate the average value of each covariate per individual grid cell. Data on elevation is provided by the US Geological Survey’s (USGS) Global MultiResolution Terrain Elevation Data 2010 dataset. Elevation is measured in meters at a 7.5-arcsecond resolution. Rainfall is measured in millimeters per pentad at a 0.05-arc-degrees resolution obtained from the University of California, Santa Barbara’s Climate Hazards Group’s dataset on Climatologically Important Precipitation Occurrences (with Station Data 2.0, Pentad). The Gridded Population of the World dataset provides spatial data on population in five year intervals starting in 2000. Data on roads and administrative units is provided by the Brazilian Institute of Geography and Statistics and the geolocation of mines is obtain from Mapbiomas. Additionally, the Brazilian National Agency for Water provides a dataset of the main rivers in Brazil. We also include data from Mapbiomas on initial forest cover. This data is available for the entire time span of our study.

Regression Discontinuity Design: Using Borders and Timing of Secure Tenure to Establish Causation. In order to identify the effects of Indigenous land rights on secondary forest growth, we first follow the methods used in (17). In particular, we exploit the geographic borders of Indigenous lands, as well as the times of homologation to test the effects of granting full property rights on secondary forest growth. We use a geographic regression discontinuity design, where we compare pixels that fall right inside of Indigenous lands to pixels that fall right outside of the borders, such that we are comparing pixels that are similar in every relevant way, except for the fact that those inside the border are treated with land rights while those right outside the border are not, and serve as the control group. In this design, the geographic border serves as the cut-off. Figure S1 in the SI presents a visual interpretation of the method.

Regression discontinuity relies on two important assumptions: (i) covariate smoothness at the cut-off, such that covariates that may influence our relevant outcome do not display significant jumps at the cut-off, and (ii) no sorting into treatment, such that a pixel that would be on the outside of the border can’t manipulate its way into receiving treatment. Condition (ii) is most applicable when looking at individuals as the unit of observation, since people can lie on welfare applications in order to be on the right side of the cut-off and thus receive treatment. In our case, since geography is fixed, there is no way a pixel could manipulate its position in order to be treated, so (ii) is not a big concern for our design.

Condition (i) however is a relevant concern, since we want to be comparing units that are as similar to each other except for the fact that some lie inside homologated territories and others do not. Covariate continuity at the cut-off is a way of showing that relevant covariates do not discontinuously change at the boundary. Figures S4-S6 in the SI show the continuity of covariates at the cut-off.

We thus run the following regressions:

\[ Y_{it} = \alpha + \tau_{t} + \beta_{i} f(X_{i} - c) + \epsilon_{it} \]  

Where \( Y_{i} \) is the dependent variable, \( c \) is the cut-off and \( T_{t} \) is a binary variable equal to one if \( X \geq c \) and \( -h \leq X \leq c + h \), where \( h \) is the optimal bandwidth that minimizes mean square error (38). \( f(X_{i} - c) \) is a polynomial and denotes the functional form used to fit the data.

We use a first order polynomial (53) and a bandwidth \( h \) chosen to minimize the Mean Square Error (37, 38), although results are robust to different bandwidth choices. In particular, we use the “dr0bust” package in R (37) to estimate the effects, and use the bandwidth selection option “MSERD”.

We run Equation 1 for our two dependent variables: \( SV^{extent} \) and \( MEANage \), which represent the extent of secondary forest cover in each pixel and the average age of the secondary forests inside each pixel, respectively. Standard errors are clustered at the IT level.

Event Study using Callaway and Sant’anna (2020) (26). Following the RDD, we utilize difference-in-difference (DiD) approaches to ensure the primary results are robust to a different choice of methodology. DiD compare changes in outcomes over time between a treated and a control population in an effort to quasi-experimentally recover the effect of treatment.

A canonical DiD model relies on the critical assumption that the average outcome in the treated vs. comparison group obeys “parallel trends” (PTA) in the absence of treatment intervention. Further, the treatment is assumed to have “no anticipated” (NA) effect before the intervention. With these two assumptions, one can estimate the average effect on the treated (ATT). In the case of many independent groups from treated and comparison populations, the two-way fixed effects (TWFE) regression with clustered standard error should provide a reasonable estimation of ATT. However, with the staggered rollout of homologation of ITs, the conventional TWFE is an inefficient method to estimate ATT (26, 54–56). We thus use a novel method proposed by (26) which can resolve some of the issues that arise from the staggered rollout of treatment in classical DiD methods.

The method proposed by Callaway and Sant’anna (2020) (26), colloquially referred to as CSDiD, improves the estimation of ATT under the conditional assumptions of PTA and NA, given that the units are quasi-randomly assigned for treatment at a different time, i.e., staggered rollout. Unlike canonical TWFE, which hinges on estimating constant treatment effects (conveyed by the strict exogenous assumption), the CSDiD relies on the estimation of ATT for individual “cohorts” of units that get treated simultaneously. Therefore, the CSDiD bypasses the weighting problem (due to heterogeneous treatment effects)** in the TWFE model for staggered rollout.

Moreover, the flexible assumptions of conditional PTA and NA on the pre-treatment level of covariates, enable the group-by-year estimation of ATTs conditional on covariates. Further, the underlying estimation approach exploits (58) doubly robust difference-in-difference estimation. This approach provides consistent estimation given the well-specified outcome regression for repeated cross-sectional panel data. Finally, the approach builds the estimation of the heterogeneous treatment effect with respect to continuous covariates.

Here, we use the method proposed in (26) to estimate the following equation:

\[ Y_{it} = \alpha + \tau_{t} + \beta_{i} f(X_{i} - c) + \epsilon_{it} \]  

Equation 2 presents a dynamic specification of DiD with individual and time-fixed effects accounted for \( \alpha \) and \( \phi_{t} \) respectively. CSDiD approach considers a building block as \((g, t)\) i.e. the group-by-time, \( ATT(g, t) = \mathbb{E}[Y_{it} | g, t] - \mathbb{E}[Y_{it} | G = g] \), which gives the average treatment effect at time \( t \) for the cohort first treated in time \( g \). CSDiD further builds upon two specific options, for \( G \). The first option is only utilizing the never-treated units (\( G = \{ G \} \)) and the second uses all not-yet-treated units (\( G = \{ g' : g' > t \} \)). This unique approach in CSDiD enabled a user to estimate the ATT\((g, t)\) across event, calendar, and cohorts.

In order to make our results comparable to the RDD, and also in order to have a comparable control group, we select only grids inside the 20km buffers on either side of the border. Grids inside the Indigenous territories get assigned to treatment the year they become homologated, while grids outside the ITs act as a never treated control group. This method exploits pixel and time fixed effects, as well as clustered SEs at the Indigenous territory level, where control pixels are assigned to the IT according to what IT’s buffer they lie within. Standard errors are clustered at the IT level.

** Canonical TWFE model under staggered rollout produces higher weights for the observations with higher variance in a cross-sectional and temporal panel (26, 57). Researchers have presented that the estimated ATT may be biased due to poor comparison groupings. For instance, (57) shows that staggered rollout in multi-period DiDs illustrates that TWFE utilizes early-treated units as controls for late-treated units. Thus, producing negative weighting in TWFE setup.
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