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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 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 in 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 y older inside ITs with secure tenure using our main RDD specification, and 2.8 y 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

Forests serve a crucial role in our fight against climate change. Although much of the literature has focused on primary forest loss, secondary forests in the form of forest regrowth and restoration provide critical potential for the conservation of biodiversity and climate change mitigation. Indeed, secondary forests are a highly productive source of carbon uptake, with an estimated average rate of 3.05Mg C $ha^{-1}y^{-1}$ 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 from secondary forest growth (3–6), more attention needs 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 the 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 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 ref. 15. Rather, our measure focuses on the regeneration and natural restoration of forests.

The Brazilian Amazon is home to 726 indigenous territories (ITs) 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.

Significance

Forest restoration has become a popular instrument in the climate change toolkit. Indeed, secondary forests are a highly productive source of carbon uptake and can be an important tool to reduce biodiversity loss. Countries across the globe have committed to the restoration of millions of hectares. However, not every tree standing is equal. Externally led plantation efforts have been shown to sometimes be problematic for the climate, local environments, and local communities. Here, we show that collective property rights provide a policy solution not only for human rights and conservation but also for successful forest restoration. Future restoration efforts should target projects driven by local stakeholders, promoting regrowth of natural forests and allowing ecosystem restoration while improving livelihoods of local communities.

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The final step of the demarcation process is homologation—meaning that the President officially declares the territory as belonging to indigenous peoples. Once homologated, a territory becomes the permanent possession of its indigenous peoples, contestation is limited and extractive activities carried out by external actors can occur only after consulting the communities and the National Congress. As such, we argue that secondary forest regrowth is more likely to happen 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 nonhomologated territories and nonindigenous, 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.

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 nonindigenous populations by providing forest and ecosystem 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 play 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 IT border. This effect is not present in ITs which never gain full property rights (nonhomologated 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 y 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 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 y in the average age of secondary vegetation†. 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' 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 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 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 (27).

As of today, 487 of these lands have gone through the final steps of the demarcation process, while the rest are at earlier stages and awaiting their final homologation. Fig. 1 shows the map of ITs and their homologation status in the year 2000 (roughly halfway 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. *SI Appendix*, Fig. S3 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.

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[*] Although some papers find no effect of ITs on deforestation (22–24).

[†] The difference in the size of the effects could be explained by: i) the different time samples, where the RDD uses a limited number of years before and after homologation while the staggered difference-in-difference utilizes the entire panel of data, and ii) the fact that the RDD recovers a local average treatment effect, limiting the sample to observations within an optimally selected bandwidth, while the staggered difference-in-difference utilizes the full sample of observations within the 20k bandwidth. In *SI Appendix*, Fig. S11 and Table S3 of SI file, we show the results of rerunning the RDD analysis on the full time sample (without limiting years before and after). Using this method, we find that the effect for secondary vegetation is 3.212 (s.e. 0.208), while the effect for secondary vegetation average age is 4.25 (s.e. 0.093).

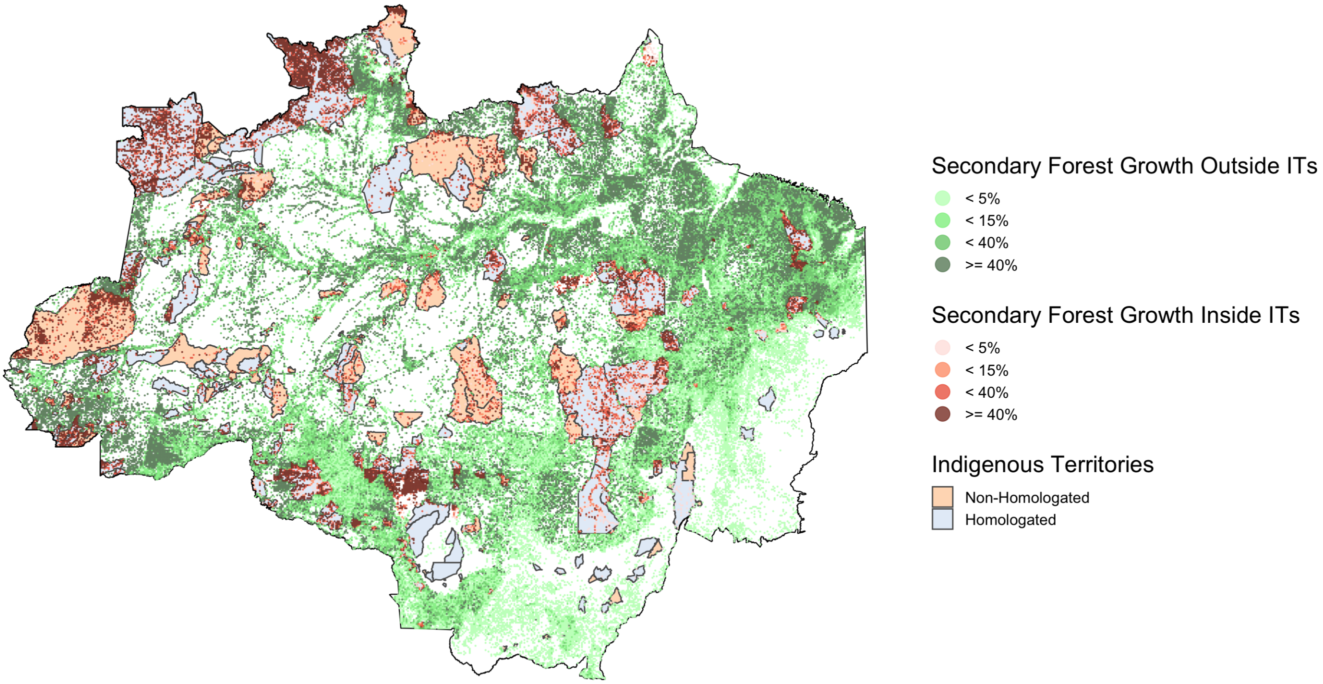

Fig. 1. Map of secondary forest growth dynamics in the Brazilian Legal Amazon in the year 2000. Green dots represent secondary forest growth outside of ITs. Red dots represent secondary forest growth inside of ITs. Orange polygons represent ITs without secure tenure while blue polygons represent ITs with secure tenure.

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 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 nongovernmental 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 y 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 back inside ITs and that they are also less likely to be cut down once they have begun recovering, we also expect secondary forests to be older, in terms of age, inside ITs. This leads to our second hypothesis:

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 4 km × 4 km) (17) which cover the area known as the Legal Amazon in Brazil[‡]. We draw a 1-km 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 the study by Silva Junior et al. (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 ref. 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) (*SI Appendix*, Fig. S1 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 homologation, we are able to estimate 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*, Fig. 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 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 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.[¶]

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 Callaway and Sant'Anna (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.

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 Eq. **1**, where the dependent variable is the proportion of secondary forest extent as measured by ref. 15. Column (1) displays the results of the RDD on nonhomologated 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 Eq. **1**. For all specifications, we used the first-degree polynomial on either side of the cutoff with bandwidths selected by the method proposed in ref. 37. The coefficient plots can be found in Fig. 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 the area right outside homologated ITs. This is compared to the results for nonhomologated column (1) and homologated territories

Table 1. RDD results for secondary vegetation

	(1) Non homologated	(2) Before homologation	(3) After homologation
A. The dependent variable is secondary vegetation proportion (in %)			
RDD Coefficient	1.021	0.155	4.961***
	(0.891)	(0.303)	(0.200)
Mean.Control	13.317	17.791	21.116
Kernel	Triangular	Triangular	Triangular
Bandwidth	mserd	mserd	mserd
N	3325	18758	22546
BW	1333	1575	907
B. The dependent variable is secondary vegetation age (in years)			
RDD Coefficient	−0.105	0.129	2.173***
	(0.251)	(0.080)	(0.091)
Mean.Control	1.624	1.904	2.993
Kernel	Triangular	Triangular	Triangular
Bandwidth	mserd	mserd	mserd
N	3644	12748	81973
BW	1559	1021	3575

NOTE: Significance levels: *10%, **5%, ***1%, and Std. Errors in brackets. The Table shows robust coefficients from a RDD where the cutoff 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 nonhomologated ITs, while column 2) shows the results for homologated territories before homologation and column 3) after homologation. For all models in this table we: (i) use a linear polynomial fit at either side of the cut-off, (ii) use the optimal bandwidth selection procedure which minimizes square errors proposed by, (iii) use a triangular kernel to weight observations close to the cut-off, (iii) cluster standard errors at the IT level.

[‡] 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.

[§] We show continuity at the cut-off for these variables in *SI Appendix* Fig. S4–S6. Rainfall and population data are only available starting in 2000, so don't cover the entirety of our time frame.

[¶] 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.

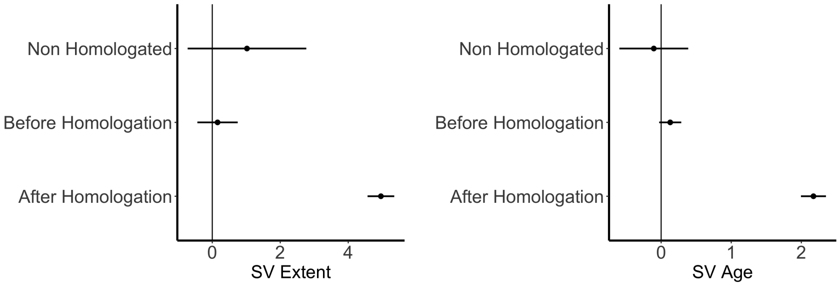

Fig. 2. Coefficients from RDD for SV secondary forest (*Left*) and age of secondary forest (*Right*) for nonhomologated territories, territories before homologation, and territories after homologation. Points show robust coefficients from RDD and lines show 95% confidence intervals. All models use linear polynomials on either side of the cutoff, optimal bandwidth selection procedure that minimizes mean square error, triangular kernels and standard errors are clustered at the IT level.

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 y 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 nonhomologated 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.

Our results are robust to different bandwidths and specifications (*SI Appendix*). They allow us to establish causal claims on the effects of collective property rights on secondary forest growth. However, caution must be exercised when interpreting them. RDD provides estimates of local average treatment effects (LATE), since it takes only observations that lie very close to the cutoff. Furthermore, our methodology based on buffers around the IT borders means we are not considering all observations in the Legal Amazon. The benefit of this is that it allows us to carefully test our hypotheses, but it also makes it difficult to extrapolate these estimates to a wider context.

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 the 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 Fig. 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 y 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 cannot 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

Table 2. Average treatment effects: Event study

	(1)	(2)	(3)	(4)
Panel A: DV is secondary vegetation proportion (in %)				
ATT	2.21 *	2.30*	1.98*	1.74*
	(0.700)	(0.559)	(0.504)	(0.459)
Num.Obs.	51666	51666	51666	51666
Std. Errors	Clustered	Clustered	Clustered	Clustered
Type	dynamic	simple	calendar	group
Periods	33	33	33	33
Panel B: DV is secondary vegetation age (in years)				
ATT	2.78*	2.20*	1.67*	1.78*
	(0.708)	(0.446)	(0.349)	(0.354)
Num.Obs.	51666	51666	51666	51666
Std. Errors	Clustered	Clustered	Clustered	Clustered
Type	dynamic	simple	calendar	group
Periods	33	33	33	33

NOTE: Significance levels: *10%, **5%, ***1%, and Std. Errors in brackets. The Table shows average treatment effects using (26) framework of estimating the dynamic event study. The estimation was done in the R CSDID package using seed number 1234 with 1000 bootstrapping iterations for the "not-yet-treated" specification. All models are clustered at the IT level.

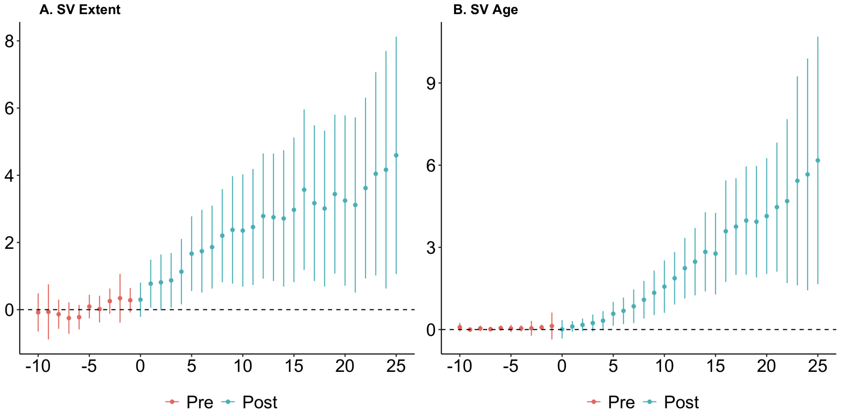

Fig. 3. Event study for (*A*) proportion of secondary forest extent and (*B*) secondary forest age. Treatment=inside homologated IT. Lines represent 95% confidence intervals, standard errors are clustered at the IT level. Red coefficients represent pretreatment periods while blue coefficients represent posttreatment periods.

of secondary forests could open 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 ref. 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 including one that aims to open indigenous territories up to mining (PL 191/2020) (42). Second, deforestation rates have been steadily increasing with illegal forest fires occurring on ITs prompted by external actors. Previous researchers have argued that effective regulatory capacity is a powerful means of protecting ecosystem service (43–45). The dismantling of environmental institutions and increased (illegal) extractive activities threaten the future of secondary forest growth on indigenous territories.

Furthermore, while international policies such as REDD+ may exist to help guide central governments in environmental policy-making, institutional strength and capacity remain the main gap in achieving these environmental outcomes (46). Our results point to the critical role of institutions such as property rights in promoting secondary forest growth. The weakening of these institutions and government agencies meant to uphold the property rights, as well as increases in deforestation may have negative consequences on the growth of secondary forestry. The protection of these agencies and institutional frameworks is necessary for the long-term success of secondary forest growth.

Finally, while these two trends have threatened the potential for secondary forest growth on indigenous territories, two recent changes may strengthen local institutions and indigenous property rights. First, at the United National Climate Change Conference in 2021 (COP26), donors committed $1.7 billion to support the tenure security and forest rights of indigenous peoples and local communities (47). These steps emphasize the international recognition that indigenous territories provide positive externalities and center property rights as a crucial element in achieving these ends. Second, the recent election of President Lula da Silva in Brazil and his first actions in office suggest there may be a reversal to the weakening of environmental and indigenous institutions observed under President Bolsonaro. Specifically, within his first month in office, President Lula da Silva signed off on six decrees which overturned some of Bolsonaro's anti-indigenous policies, reinstating the Amazon Fund and annulling mining on indigenous lands, among other actions. President Lula also created the Ministry of indigenous peoples and swore in indigenous leader Sonia Guajajara as its first minister (48).

Forest restoration has become a popular instrument in the climate change toolkit. Indeed, secondary forests are a highly productive source of carbon uptake, and can be an important tool to reduce biodiversity loss. However, not every tree standing is equal. Monocultures and plantations do not share the same carbon uptake capacity or biodiversity as native and secondary forests. Restoration and reforestation policies should take these divergences into account. In this paper, we show that collective property rights, when fully granted, provide a policy solution not only for human rights and deforestation prevention, but also for successful secondary forest growth. Indeed, our work adds to the body of research on carbon storage which suggests that indigenous territories and local communities store around 17% of the world's carbon, two-thirds of which is stored on territories with legal property rights (49) Future restoration efforts should be placed on projects driven by local stakeholders, which promote regrowth of natural forests and allow for ecosystem restoration as well as improving the livelihood of local communities.

Materials and Methods

We create a panel dataset based on a grid of points at a 0.05° resolution, draw 1-km buffers around these points and calculate the value of different geographic outcomes inside this area. First, we use the data from Silva Junior et al. (15) 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 stacked pixel-level land use between 1986 and 2019 to identify pixels switching from nonforested to forested land use classification. Silva Junior et al. (15) illustrate their method using pixel-to-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 (17, 25, 50). 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, as measured in hectares or km^2, 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:

$$SV\ extent_{i,t} = \frac{SV\ area_{i,t}}{PixelArea - (PrimaryForest_{i,t-1} + Water)},$$

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 to 36. We rely on this information to calculate the average age of secondary forests inside a pixel. We thus calculate the following equation:

$$MEANage_{i,t} = \frac{\sum_{j=1}^{36} AGEarea_{j,i,t} * j}{PixelArea - (PrimaryForest_{i,t-1} + Water)},$$

where j is the age of secondary forest which can go from 1 to 36, and $AGEarea_{j,i,t}$ 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 square km. Thus, $MEANage_{i,t}$ represents an area weighted average of the age of secondary forests inside each 1-km pixel.

For our treatment variable, we build on the dataset provided by ref. 17. Data with the geolocation of indigenous territories in the Brazilian Amazon are 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 20-km bandwidth from the border on the inside of the territory, while control units are those outside ITs within a 20-km 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 are 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 precipitation (Climate Hazards Group Infrared Precipitation with Station Data 2.0, Pentad). The Gridded Population of the World dataset provides spatial data on population in 5-y intervals starting in 2000. Data on roads and administrative units are provided by the Brazilian Institute of Geography and Statistics, and the geolocation of mines is obtained 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. These data are 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 ref. 17. In particular, we exploit the geographic borders of indigenous lands, as well as the timing 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 cutoff. *SI Appendix*, Fig. S1 presents a visual interpretation of the method.

Regression discontinuity relies on two important assumptions: i) covariate smoothness at the cutoff, such that covariates that may influence our relevant outcome do not display significant jumps at the cutoff, and ii) no sorting into treatment, such that a pixel that would be on the outside of the border cannot manipulate its way into receiving treatment. Condition (ii) is most applicable when looking at individuals as the unit of observation, such that people can lie on welfare applications in order to be on the right side of the cutoff 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 cutoff is a way of showing that relevant covariates do not discontinuously change at the boundary. *SI Appendix*, Figs. S4–S6 show the continuity of covariates at the cutoff.

We thus run the following regressions:

$$Y_i = \alpha + \tau T_i + \beta_1 f(X_i - c) + \epsilon_i, \qquad [1]$$

where Y_i is the dependent variable, c is the cutoff and T_i is a binary variable equal to one if $X \geq c$ and $c - h \leq X \leq c + h$, 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 "rdrobust" package in R (37) to estimate the effects, and use the bandwidth selection option "MSERD".

We run Eq. **1** for our two dependent variables: $SVextent_i$ and $MEANage_i$, which represent the extent of secondary forest cover in each pixel and the

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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.

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 (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 SE 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 ref. 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 (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 heterogonous treatment effects)** in the TWFE model for staggered rollout.

Moreover, the flexible assumptions of conditional PTA and NA on the pretreatment 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 ref. 26 to estimate the following equation:

$$Y_{it} = \alpha_i + \phi_t + \sum_{\substack{r \neq 0 \\ -\underline{T} \leqslant r \leqslant \bar{T}}} 1\left[R_{it} = r\right] \beta_r + \epsilon_{it}. \qquad \textbf{[2]}$$

Eq. **2** presents a dynamic specification of DiD with individual and time-fixed effects accounted by α_i and ϕ_t respectively. CSDiD approach considers a building block as (g, t), i.e., the group-by-time, $\mathrm{ATT}(g, t) = \mathbb{E}\left[Y_{it}(g) - Y_{it}(\infty) \mid G_i = g\right]$, 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 $\mathcal{G}$. The first option is only utilizing the never-treated units ($\mathcal{G} = \{\infty\}$) and the second uses all not-yet-treated units $\left(\mathcal{G} = \left\{g' : g' > t\right\}\right)$. This unique approach in CSDiD enabled a user to estimate the $\mathrm{ATT}(g, t)$ 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 20-km 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.

Data, Materials, and Software Availability. CSV data have been deposited in Harvard Dataverse (https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/KZUCEA&faces-redirect=true) (59).

[**] 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 multiperiod 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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