Impacts of a large-scale titling initiative on deforestation in the Brazilian Amazon

Benedict Probsta, Ariel BenYishaybc, Andreas Kontoleon\*a, Tiago N. P. dos Reisde

a Department of Land Economy, University of Cambridge, United Kingdom; b Department of Economics, The College of William & Mary, United States; c AidData, United States; d Earth and Life Institute, Université catholique de Louvain, Belgium; e Associate-researcher, Instituto de Pesquisa Ambiental da Amazônia (IPAM), Brazil.

\* Corresponding author, email: [ak219@cam.ac.uk](mailto:ak219@cam.ac.uk), +44 1223 339773, Fax: +44 (0)1223 337130

**Abstract:**

Across carbon- and biodiversity-rich tropical forests, titling initiatives are implemented with the goal of regularising land tenure and decreasing deforestation. However, the effect of tenure security on deforestation is theoretically ambiguous while credible empirical evidence is lacking. We analyse the response of 10,647 landholders between 2011-2016 to a large-scale land-titling programme called Terra Legal in the Brazilian Amazon, set to regulate an area as big as Germany and France combined. Using a fixed-effects regression modelling strategy and property-level data we managed to explore the causal chain between land titling and deforestation. Contrary to expectations, we find evidence that small and medium landholders increased deforestation in response to the programme, whereas large landholders remained largely unaffected. Landholders with property titles deforest more as crop and cattle prices increase, indicating greater market integration at the expense of conservation. Our results suggest that titling alone without greater coordination with other policies will not yield the expected environmental benefits.

**Keywords**: Land tenure, forest cover, impact evaluation, agricultural prices, Amazon.

1. Background

Slowing deforestation in the Amazon rainforest has been a central environmental issue for decades, driven by concerns about declining eco-system services, biodiversity loss and growing carbon emissions1. With increasing worries in particular over catastrophic climate change, scientists and policymakers have intensified their attention on forest conservation as a mean to advance climate goals. Several studies suggest that forest conservation could contribute up to 40% of the needed greenhouse gas (GHG) emissions reduction to mitigate climate change, with particular importance attributed to Brazil, which has 13% of global remaining forests2–4.

In order to address these concerns, several policies have been implemented in Brazil to curb deforestation on private and public properties, including enhanced satellite monitoring5, zero-deforestation supply chain agreements by the private sector6, credit restrictions for municipalities with high deforestation7 and more stringent enforcement of Brazil’s Forest Code8,9. These efforts have focused primarily on reducing deforestation on large properties and have played an important role in lowering deforestation rates since their peak in 2004. Nonetheless, deforestation has been recently increasing again at a worrying pace rate, reaching a 10-year high in 201810. One important reason for this renewed negative trend is that deforestation on smallholdings (relative to larger properties) has gone up substantially over time 11,12. Overlapping or inexistent tenure rights in the Brazilian Amazon, particular on smaller properties, is seen as a central catalyser for high deforestation, yet this empirical hypothesis remains largely under-investigated.

Addressing this research gap is crucial (discussed in detail in the SI) as many tenure right programmes are partly justified on the grounds of yielding beneficial environmental outcomes. Yet, there are compelling theoretical reasons whereby under different institutional and market settings, altering tenure arrangements may lead to countervailing impacts with respect to deforestation rates16. Also, the mediating role of other plot specific characteristics, most notably the size of land holdings in the affected area, can sway the impact of changing tenure arrangements on deforestation in ambiguous directions2. Such countervailing effects are poorly understood, and hence the often-held default ‘conservation presupposition’ that promoting individual private tenure arrangements will lead to greater ecological benefits must be taken with caution.

We analyse the causal link chain connecting forest land tenure, property size and observed deforestation rates in the Brazilian Amazon. In particular, we examine the impacts on deforestation associated with the Brazilian Terra Legal Programme (TLP), one of the largest land titling programmes in the world, which since 2009 has been assigning property rights to undesignated public lands in the Legal Amazon (comprising all nine Brazilian states in the Amazon basin) corresponding to an area of France and Germany combined13. The programme focuses on so-called ‘undesignated public areas’ which are *de jure* public plots of land but on which private landholders have lived and farmed on. Under the TLP landholders receive a conditional title if they can prove effective cultivation of the land before July 2008 (the latter condition was set in order to avoid incentives for land-grabbing and legalisation through the programme). In addition, the title remains conditional for ten years, where landholders need to show that they follow the requirements of the Forest Code, which prescribes that 80% of the forest in the Amazon is set aside for nature protection. If landholders comply with these stipulations for the provisional period, then they receive the final title which grants full property rights over the land in question. Importantly, farmers are not allowed to sell the land during the provisional period, but can use it as collateral for loans.

To assess the impact of this program on deforestation rates we make use of a unique dataset that covers 10,647 landholders over a period of six years (63,882 observations). To our knowledge, this is the first study that uses detailed panel data to investigate whether such improved tenure rights actually lead to greater conservation of forest or to increased investment and deforestation. Our data complements previous studies in several important ways. First, prior studies have primarily focused on land rights of indigenous communities14,15. However, these communities differ markedly from small farmers in a variety of ways, as do the property rights conferred on them. For example, indigenous community lands in the Brazilian Amazon are held in common ownership and may not be transferred or used as collateral. In addition, the territory covered by indigenous community land tends to be more remote, and therefore less subject to deforestation pressure. Further, previous analysis (focusing mostly on indigenous communities) have used mostly small sample sizes covering a limited time period.

By focusing on specific timescale, geographical region and population our analysis is a highly policy relevant and informative complement to prior studies for exploring the impact of property right reforms on deforestation in the Amazon. Further, our main question is of great interest to other developing and emerging countries with high levels of tropical forest and deforestation pressures, such as Indonesia. Property right reforms come with financial, social and political costs while they have ambiguous consequences on deforestation16. Hence, it is imperative to augment our understanding of the impacts of introducing such reforms through robust empirical analyses. In addition to contributing to the literature on the environmental consequences of tenure regularisation, our paper also speaks to more broader strand of literature on whether secure tenure can act as a catalyst for economic development and social reforms17. For example, previous studies show that regularising land tenure supports the rule of (forest) law, enabling the development of land, labour and commodity markets as well increase in taxation revenues18. Emerging evidence also suggests that it could lead to positive social impacts such as on gender equality and conflict resolution17,19.

The central empirical challenge in studying the effect of land rights on deforestation is finding a credible counterfactual. It is common in titling studies to use untreated land as a counterfactual (i.e. land not subjected to land right changes). However, such land is commonly untreated for non-random reasons, while it might differ to treated land in ways that are not readily measurable. The data used in this paper allow us to address these challenges. Our sample includes 10,647 properties whose land tenure was regularised under the Terra Legal Programme between 2011-2016. By exploiting plausibly exogenous variations in the timing of tenure formalization, we use a panel approach that controls for landholder specific fixed effects and time-varying covariates. In addition, our study offers the first quasi-experimental evidence on the effect of private land rights on deforestation outcomes in Brazil and complements studies on the effect of environmental registries such as the Cadastro Ambiental Rural (CAR)2, 8, 20,21.

1. Results

Our empirical analysis suggests that landholders that received the land title increased deforestation rates as a response to the programme. First, as our event study in Figure 1 shows (full table in SI), the effect of the title only fully materialised between 2-4 years after the title was received. After two years, a significant 1.7% increase in deforestation and a 4.6% increase after four years can be observed after the title was received. Second, it is important to underline that anticipatory behaviour (farmers who might deforest less in the year prior to receiving the title not to jeopardise receiving the title) is also influencing our estimates as farmers reduce deforestation – on average – by 1.6% the year prior to receiving the title. Hence, we likely slightly overestimate the impact of receiving a title on deforestation if this anticipatory behaviour is considered. We further decompose this effect for different sizes of plots in Table 3 and Figure 2 to show that this overestimation holds only true for small properties.

Figure : Event study of the effect of receiving a title on deforestation. Full table in the SI



In order to explore the mechanism behind the uptick on deforestation on registered plots, we compose detailed price indices for crop and beef to study whether formalising land tenure also leads to greater access and integration into agricultural markets. Our results from Table 1 and 2 indicate that farmers with a regularised land title respond more strongly to market signals once their land becomes regularised. It shows that the effect of titling on deforestation is mediated strongly – and very significantly – by cattle price. As Table II indicates, a 10% increase in the cattle price index leads to a 0.2% increase in deforestation, but only on properties with a title but not on those without a title. Hence, it appears that it is not the existence of a title per se that leads to deforestation, but it is the effect of changes in commodity prices (particularly, beef) that mediates the effect of titling on deforestation in our sample.

As we only compare farmers to themselves using fixed-effects regression, we control for time invariant characteristics, such as slope, area, state and other variables that do not vary over time. Yet, we include interaction effects of time-invariant characteristics such as agricultural suitability and distance to roads to account for heterogeneous effects of temporal shocks on plots with different characteristics

Table I: Fixed effects model I with cattle and crop price interaction effects



Table II: Fixed effects model II with cattle and crop price interaction effects



Our results contradict the conservation hypothesis, which posits that greater tenure security will lead to lower deforestation. Our data suggests that cattle prices (but not crop prices) have a stronger positive effect on deforestation for titled properties. One possible mechanism driving this effect is the greater integration with agricultural markets, possibly via the greater uptake of credit and investment in the land, which has been documented in case study evidence22.

We disaggregate these effects (see Table III) to check for differences between property class sizes (small, medium and large, see SI for definitions). Receiving a title increased the likelihood that clearing occurred on a property by 0.8% p.a. relative to untitled properties (column 1 in Table III). Yet, this effect is particularly pronounced for small and medium landholders. The likelihood that clearing occurs on small landholdings increase by 0.9% and by 1.9% on medium-size properties on average p.a. compared to those without title. The extent of clearing also increases with land titling, with this effect being most pronounced in medium properties with an increase by 4.3% in the extent of deforestation compared to other medium properties without title. Large properties, in contrast, remained completely unaffected by the programme, with none of these coefficients showing consistent and significant signs. The fact that the weighted regression – which weighs the effect of each intervention by the size of the property – is not significant indicates that large farmers (who hold most of the forest area) do not respond to the intervention.

Table II: Effect of titling on annual deforestation



Our central robustness check of anticipatory behaviour – which we discussed for Figure 1 – is undertaken via an event study disaggregated for different property sizes (Figure 2a-c). Our results show that particularly farmers that possess smaller properties deforest substantially less (-1.8%) in the year prior to receiving the title, potentially due to interaction with forest authorities. It takes four years for the full effect of the title to materialise, potentially because it takes time to secure a loan and invest in the land. For farmers that hold medium-sized plots, there are little anticipatory effects and deforestation increases substantially in the two years after receiving the title (5-9% and 7-9%). Famers with medium-sized plots might already be better integrated into agricultural markets (as they likely substantially produce above the level of subsistence) and therefore the response to receiving the title is more immediate and sizeable than for the other two property types. In contrast, the deforestation pattern of large properties appears to be unaffected by the programme, both before and after receiving the title. This could be due to central government’s past efforts to curb deforestation on large properties, which are easier to monitor and to sanction.

Figure : Time-specific effects of titling for (a) small, (b) medium and (c) large plots



1. Discussion

We return to the main question on whether increased tenure security leads to greater conservation or to the contrary effect of higher rates of deforestation. The TLP may have contributed to a change in the behaviour of small and medium landholders, although in the opposite way to which it was intended. Large landholders, in contrast, remained largely unaffected by the programme. Yet, as our analysis indicates the effect of property titles on deforestation is likely mediated by changes in agricultural commodity prices, particularly beef.

The effects of behaviour change with respect to deforestation, however, were different across time and property classes. Small landholders were the only property class that significantly altered their behaviour before they received the official title, potentially due to the contact with forest authorities. Famers with medium-sized properties substantially increased deforestation one to two years after the title was received, whereas this ‘ramp-up’ time took up to four years for farmers with small properties (likely because it takes more time for the latter farmers to secure credit for agricultural or cattle expansion). These results are in line with other studies on the effects of titling on agricultural investment. For example, Keswell and Karter 23 investigate the impacts of the land reform in South Africa, and found a time lag in recipients’ increases in income between 3-4 years, due to the time it took to get a return on the investment in the title. A recent randomised control trial from Benin also suggested substantial increases in agricultural investment as a result of greater tenure security 24.

Our findings are also consistent with the limited number of studies in Latin America that have investigated the effect of land rights on deforestation. Liscow25, using an instrumental variable approach, found that Nicaragua's agrarian reform has significantly increased deforestation. The underlying mechanisms he proposes of tenure security leading to increasing investment, agricultural productivity and increased returns to deforestation are also echoed in case study evidence. Wood and Walker22 found that farmers with land titles were three times as likely to have access to credit than untitled farmers. In Brazil subsidized loans and micro-credit policies are commonly used as mechanism to achieve development goals. For instance, Assunção et al.7 have shown that credit restrictions played a vital role in slowing deforestation in the Amazon, indicating that access to credit may analogously increase deforestation.

Our findings stand in contrast to L'Roe et al.26 who study the impacts of the environmental registry CAR enrolment in Brazil and its effect on properties roughly the same size as those studied in our paper. They find that CAR registration, when paired with being registered in the TLP process, lead to sizeable reduction effects of deforestation. As CAR is a mechanism of environmental monitoring, and although it could be a first step towards tenure security, it appears to induce different behaviour than Terra Legal.

As with many studies comparing early and late enrolees in a program, our results do not necessarily extend to farmers who never enrolled in the programme (and who may not have been interested in receiving a land title in the first place). We offer evidence on impacts among a large swath of the farming population who enrolled in the program. Understanding drivers of deforestation among non-enrolees is an important topic for further research.

It is also clear that one of the channels that is commonly assumed to lower deforestation – namely, increased formal regulatory pressure – has not (yet) yielded a significant effect on deforestation. This is not necessarily surprising given that many of the studied areas are remote. In addition, the TLP should be seen as the foundation for increased environmental monitoring in the future. Apart from budget constraints, TLP staff might also be worried that harsh sanctioning mechanisms (e.g., expropriation) might yield lower cooperation from landholders.

Holders of larger properties did not alter their behaviour as a consequence of the titling programme. This is not unexpected given that large properties have faced increasing scrutiny since 200412. Larger landholdings are also easier to monitor through the DETER system, which uses remote sensing technology to detect deforestation in real time. It allows for quicker law-enforcement measures and has contributed to deforestation reductions in the past5. Recent empirical evidence from the Brazilian state Mato Grosso do Sul shows that larger farms showed a higher compliance with the Forest Code than smaller properties27. It could also be a result of more intensive agriculture instead of the historically dominant extensive agriculture due to better technology access and improved forest governance28.

A central question that emerges from this research is how the requirements that the programme entails – particularly environmental conditions – can be more clearly communicated to landholders, while increasing the perceived regulatory pressure with the limited budget of $0.12 per hectare available to the programme29. Clearly, a closer collaboration with the environmental police and other departments would be warranted.

Given the response of different landholders to the programme, a need arises to tailor the policy to these different class sizes. It also underlines that interventions might need to start even before the title is awarded to curb anticipatory clearing as was observed in the small landholder group. Here it seems important that in the initial steps, which include geo-referencing, to make participants aware of the requirements of the programme (e.g., 80% of the property needs to remain forested as prescribed by the Forest Code). Given the low funding of the programme and the remoteness of many of those communities, this poses a substantial challenge to the administration. However, low-cost interventions, including various informational, design and content nudges, which have been successfully applied in other contexts, such as taxation, might serve as an appropriate measure here as well30.

Lastly, it should be noted that part of the clearing could be completely legal since the Forest Code allows for 20% clearing of forest cover in the Amazon on private properties. In addition, some amnesties were granted, which could have further intensified the perception amongst landholders that broader clearing is not sanctioned. These amnesties might have particularly increased incentives to deforest for landholders of smaller and medium properties, whereas large landholders were unaffected. Larger landholders are likely more aware of the requirements of the Forest Code given that in the past they have been the focus of stringent monitoring and enforcement through the DETER programme.

A number of limitations of our study should be underscored. First, the study period is limited to 2011-2016 and hence effects of the TLP, particularly with the continuing rollout, can change in the future. Second, while we show (see Data and Methods Sections) that titling across different years display relatively constant characteristics, in the absence of randomisation or a viable instrumental variable, we cannot fully eliminate the possibility of omitted variable bias. Nonetheless, as noted in the pre-trend analysis (Data and Methods), we have strong reasons not to believe that this is the case. Third, in the absence of credit uptake data, which unfortunately is not collected by the programme, our hypothesis that increased deforestation is mainly explained through the greater uptake of credit cannot be fully explored and is based on evidence from other studies7,22. Nonetheless, we show that deforestation on titled properties reacts more strongly to changes in market prices, indicating a greater integration into agricultural – and potentially credit – markets. Fourth, other factors apart from forest conservation, such as poverty alleviation and conflict reduction, are goals that are being pursued by the Brazilian government with the TLP programme. Declarations by former President Michel Temer that parts of protected areas might be opened up for agriculture yielded the worst land-related killings in 21 years and give a sense of the ferocity of environmental conflicts in the absence of clearly defined land rights31. Fifth, our study does not evaluate deforestation outside of the rural property and whether landholders comply with legislation by restoring or offsetting native vegetation elsewhere if not in compliance with the minimum required by the Forest Code. Sixth, it is important to note that the TLP only converts a relatively small share of undesignated areas to private land, with the rest being assigned to conservation units and indigenous reserves. Hence, our analysis only extends to the effect of the TLP on these farmers, not the entire policy.

In sum, our results underline that titling initiatives *per se* should not be seen as a mechanism to reduce deforestation. If titling increases the access to credit and agricultural markets, then increased tenure security can have the opposite effect of the original policy goal. Our results suggest that particularly cattle prices play an important role in informing land use decisions. Hence, stronger integrating the TLP with other policies is warranted to counter the negative environmental consequences that increased tenure security may entail. Given that many landholders are credit-constrained and a greater integration between credit programmes is a worthwhile starting point. Also, studying the impact of integration between land titling and other environmental policies warrants further investigation. In addition, livelihood impacts that ensued the TLP programme remain unclear and could also be the focus of future work.

1. Methods
   1. Data

Data of the geo-referenced properties was provided directly by the Secretariat for Land Title Regularisation in the Legal Amazon (SERFAL) responsible for the programme. Deforestation data (PRODES) was downloaded from the Instituto Nacional de Pesquisas Espaciais32. Given the frequent case of 0 for deforestation, we transformed the deforestation variable by adding half of the minimum value of deforestation in the dataset to each observation of deforestation. It is likely that some deforestation takes place on most plots, but these are below the minimum value that the deforestation detection programme PRODES can pick up. In our case, we transform annual deforestation in hectares with an inverse hyperbolic sine (IHS) transformation, which has emerged as a suitable alternative to taking the log in cases with zeros in the data 33. Climate data was downloaded from WorldClim and the monthly data was converted to yearly mean values34. Similarly, distance to roads was analysed with Open Street Map, representing highways circa 2010.Agricultural suitability and slope data was downloaded from the Centro De Sensoriamento Remoto35.

We collected agricultural prices from the Agriculture and Supply Secretariat of the State of Paraná (SEAB- PR). Although Paraná is not part of the Legal Amazon, its prices are strongly correlated with local crop prices in the municipalities in the Brazilian Amazon.36 The set of agricultural commodities are rice, mandioca, cassava, corn and sugarcane, and account for circa 70% of the total harvested area in the sample municipalities.We constructed an annual municipality-specific price index for these crops. We began by averaging prices for each year and crop and deflated prices to 2011 Brazilian Reais to compute an index with base year 2011. We then calculated a weighted real price for each municipality and year:

(1)

where *PAitc* is the weighted real price of crop c in municipality *i* at time *t*. *Aic* is the area of land in the municipality *i* dedicated to crop *c*, *TAic* is the total area that is dedicated to the five investigated crops in municipality *i* in 2011, and *Pic* is the real price of crop *c* in Parana at time *t* expressed an index with base year 2011. The first term on the right-hand side represents the relative importance of the crop *c* in the agricultural production of municipality *i* at the beginning of our sample period.

We also constructed an index of cattle prices, which have been shown to act as a strong pull factor on deforestation. Using the SEAB-PR data, we derived an annual cattle price index in similar fashion to equation (1). However, since there is no information on the area dedicated to cattle, we use the number of cattle per municipal land *i* in 2011 as municipality-specific weights. We derive both indices for the 149 distinct municipalities in our sample.

It is important to underscore one peculiarity of the PRODES data, which is that annual deforestation maps run for year *t*, run from August *t-1* to July *t* (e.g., deforestation for 2014, runs from August 2013 to July 2014). Hence, we recoded all variables (such as whether the land was titled in a given year) to correspond to the PRODES timeframe. We therefore also employ beef and crop prices in the year *t-1*, which accounts for the timing of agricultural production in the Legal Amazon. Given that the regional dry season extends from June through September, crops are sown between October and December, and harvested the next year until May. For farmers to derive optimal value from their harvest, previous studies have shown that farmers likely observe prices in early *t-1* for land-use decisions, which should then be evident in deforestation rates between August *t-1* and July *t*36.

Spatial data was processed in QGIS and subsequently analysed in R and Stata. PRODES deforestation maps, temperature and precipitation data were split into yearly shapefiles/tiff-files and intersected with the geo-referenced property maps provided by SERFAL to extract the yearly amount of deforestation and climate variation on each property. For calculations involving distance measures (e.g., distance to roads of properties), equi-distant projections were used, whereas for deforestation measures projections yielding equal area were employed.

The first two years of the programme, which only account for a minor fraction of titles, were excluded due to irregularities and database issues. Until May 2011, 611 titles were granted, almost one third in Novo Progresso in Pará. Some of these titles were also migrated from another system, and therefore may represent claims that resulted prior to the programme period. In addition, these were almost six times as large as plots titled in Pará between 2011-2016, indicating irregularities in the titling procedure. Indeed, a joint operation by the federal police (IBAMA), Federal Reserve and Public Federal Ministry (MPF) in Novo Progresso captured a criminal organisation specialised in environmental crimes and land grabbing, with damages estimated to have reached R$ 500 million. Part of the scheme was to register illegally-seized properties in the TLP with falsified documents and subsequently sell the land 37.

Supplementary Table II & III shows the number of titled plots across eight Amazonian States in the period 2012–2016 (Note: data from Roraima was excluded due to data availability issues). 44% were titled between 2012–2014, whereas 56% were titled in 2015–2016 (as previously mentioned, titling dates were recoded to correspond to the PRODES deforestation data, which uses the seasonal year, e.g., 2012 runs from August 2011 - July 2012). As discussed, since properties that were officially listed as being titled in 2009 or 2010, could have been transferred from a different policy with an earlier titling date, these were excluded from the main analysis. By far the largest registration took place in 2015, where 42% were titled*.* The relative number of titles per class size also remains largely similar across different years. In addition, while more than 80% of titles were registered by small property owners, they only account for around 40% of the overall area, comparable to the area of medium property owners, even though they represent less than 20% of registered plots.

Across states, the mean area of titled plots remained relatively constant at close to 50 hectares (Supplementary Figure 7). Whereas in 2014 registered plots tended to be larger, the plot size across the studied period remained relatively constant. In addition, mean deforestation on these plots prior to the programme 2000–2009 was relatively similar across titled years, with a slightly decreasing trend over time. As we estimate the impact of the TLP by comparing earlier titled plots with those titled later, and later titled plots appear to have lower opportunity cost (e.g., due to suitability of the land for agricultural purposes) than there is a chance that the impacts of titling are slightly underestimated. Hence, if prior deforestation is used a proxy for the opportunity cost plots face, our estimates may represent the lower bound of impact given that later plots may face slightly lower opportunity costs.

This is supported by the agricultural suitability data, which shows a slightly decreasing trend. It is noteworthy, however, that agricultural suitability data shows that the titled plots are on average suitable for agriculture (with a mean around 1, which indicates ‘suitable’ but is far from the maximum value of 2 (‘very suitable’).

In addition, it is striking that distance to roads of titled plots remains relatively constant in the time period analysed, indicating that no systematic difference in accessibility between earlier and late plots exist. Properties titled in 2016 were excluded, since for our empirical strategy each property should have at least one year of deforestation data after receiving the title.

These figures indicate that plots titled early (2012-2013) present a credible counterfactual to those titled later (2014-2015). This is also tested more formally in the next section.

ddd

* 1. Pre-Trend Analysis

This section describes the methods employed in our pre-trend analysis. It tests more rigorously the integral assumption underpinning the estimation strategy, namely that properties registered later in the process can be used as a credible counterfactual to those registered earlier38. The majority of properties in the programme are relatively small and hence their occupants likely have limited political power to increase the speed and location of titling campaigns, which are organized centrally in Brasilia. In addition, farmers have to prove that they have occupied the plot of land since at least 2008 and a central federal committee in Brasilia, which remains largely uninfluenced by local politics, checks these claims.

While the assumptions remain difficult to fully prove, two different approaches were employed to formally test this assumption to complement the foregoing analysis. First, in order to check whether treatment assignment (i.e. titling) was correlated with the contemporaneous rate of deforestation in the municipality, yearly change in proportion of municipality that was deforested was regressed on the number of titles issued*.* None of the coefficients is significant, regardless whether municipality or year fixed-effects are introduced, which can be seen in Table VI in the SI.

In a second step, in line with Alix-Garcia et al.2, deforestation data prior to the programme was used to test whether the assumption would hold in the period before the programme. We ran fixed-effects regression on the deforestation data from 2007–2010, using time-effects to account for temporal shocks. As can be seen from Table VII in the SI, this was calculated using an interaction term between a time trend and a dummy variable that indicated earlier registered cohorts. The analysis was also segregated to account for year-to-year variations.

The time trend is not significant across years, suggesting trends across cohorts did not differ significantly. Even if the trends are further disaggregated into different years, the coefficients for the single years were not significant. This supports our assumptions underpinning the estimation strategy.

* 1. Main Empirical Analysis

Impact evaluation in quasi-experimental settings, as discussed earlier, commonly struggles with non-random treatment assignment. This means that treatment assignment could be spatially and/or temporally correlated with the dependent variable, deforestation rates in our study. For instance, treatment assignment could, in principle, be correlated with distance to roads, which fosters the integration with markets. This, in turn, may make the conversion to agricultural land or timber harvesting more profitable. Unless these confounding factors, both observed and unobserved, are controlled for, this could unduly alter the results. We show in our pre-trend analysis no systematic differences of the factors between across year for the titled properties.

A number of specification tests were performed in order to clarify whether fixed effects, random effects or pooled ordinary least squares (OLS) were required. First, using a Breusch-Pagan Lagrange multiplier we reject the hypothesis that a pooled OLS will produce unbiased results. Hence, this makes an individual-effects model (random or fixed-effects) necessary. Using a Hausman and Chow test, we find that year-fixed effects and property-level fixed effects are warranted39.

We therefore estimate a fixed-effects model, combined with a vector of control variables that are both time and space-variant. We estimate:

where *i* indexes the property, and *t* the years, *Y* a binary indicator whether any deforestation occurred (and in a second step, a IHS-transformed measure for the change in the amount in a specific year), *γ* are the property-level fixed effects, *δ* are the time-fixed effects, *D* is a vector of dummy variables for titling, *X* are control variables that vary over time, and are parameters to be estimated. Property-level fixed effects account for time-invariant location-specific characteristics, whereas time-fixed effects control property-invariant time effects. We estimate the equation using OLS and cluster standard errors using heteroscedasticity-consistent (HAC) standard errors, which correct for cross-sectional spatial dependence and panel-specific serial correlation. This approach therefore accounts for the dynamic nature of land use change. We account for serial correlation for the entire duration of the programme (6 years) and cluster standard errors using a distance cut-off of 10 kilometres around the property. We consider the cut-off in relation to the spatial extent of each treatment unit. Hence, for a ~5 hectare farm, with dimensions ~0.25km x 0.25km, then a 10km buffer means that we are considering effects as far away as 40x the farm size (or 40 contiguous farm plots away). Despite the dependent variable being a binary variable in the first model, we use a linear model for ease of interpretation, which for moderate levels of probability gives similar estimates while being easier to interpret than logistic probability models. In a second step the yearly amount of deforestation in hectares on the plots was IHS-transformed to indicate the change in absolute deforestation. Given the common values of zero for deforestation, we transformed the deforestation variable via an inverse hyperbolic sine transformation.



In order to consider the effect of receiving the formal property title, a dummy variable is introduced that switches from 0 to 1 once the title is received. To test whether the effect of titling changes across time (e.g., it might not be as strong after one year, since the 'perceived regulatory pressure' wanes) and anticipatory effects are present, we introduce in the event study used as a robustness check three dummy variables to capture the time the title was received. This approach is in line with similar studies 38 and accounts for possible short-term effects of titling.

In order to distinguish the effects that titling has across property sizes and time, we split the sample across "modulos fiscais" (MF). The latter is a unit of measure in hectares and, depending on the state, can be between 5 to 110 hectares for each módulo fiscal. In the Legal Amazon one MF has on average 76 hectares but size is heterogeneous across municipalities. In line with the Brazilian law, we split the sample into small properties (< 1 MF), medium properties (1-4 MF) and large properties (4-15 MF). Commonly 1-4 MF are referred to as semi-small and 4-15 as medium but for ease of interpretation and given the scope of the TLP, we chose these categories.

In our main analysis, we include the size of the property as a continuous variable but later split the sample by property sizes. Analysing the difference between property size classes is also important since landowners pay different prices to receive the land titles depending on the size. Small properties, below 1 MF, receive the property title for free. Medium properties, between 1-4 MF pay a modest fee that covers the cost of the titling process (e.g., geo-referencing and administrative costs). Large properties need to pay a higher titling fee, which commonly amounts to 20-30% of the market price of the enrolled land (this has been revised in the most recent version of the law, which was enacted after the time period we consider in this study). These differences stem from a supposed difference in income between the different classes of landowners. Another important factor is that properties in the large-size category are the only ones to be visited by the TLP to verify their claims on-site. This may incentivise some landholders to register into the programme only a proportion of their property, which is below 4 MF.

Lastly, control variables for state heterogeneity (dummies for each state, where the policy is implemented) were introduced, as well as climate controls (precipitation and temperature), agricultural suitability, slope, and crop and beef prices.

Our empirical strategy tests the assumption that titled properties display a different clearing pattern than those that are not titled yet. The original goal of the TLP is that with increased formal regulatory pressure and tenure rights, deforestation is likely to decrease. However, in principle greater integration with public and private credit programmes could also have the opposite effect if investments into extensive agriculture increase the return to deforestation as demonstrated by Liscow25 in the case of Nicaragua.

As discussed previously, a possible bias of our estimation results is that unobserved time-variant heterogeneity between properties might be driving observed results. However, as indicated we believe this is unlikely, since titling is influenced by credible exogenous factors.

7. Data and Code Availability

The data that support the findings of this study are available from SERFAL but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are however available from the authors upon request and with permission of SERFAL.

The code is available from the authors upon request.

**Competing Interest**

The authors declare no competing interests.

**Author responsibility**

BP, AB and AK contributed equally to the paper. TR was responsible for data and revision of the manuscript.

References

1. Kalamandeen, M. *et al.* Pervasive Rise of Small-scale Deforestation in Amazonia. 1–10 (2020). doi:10.1038/s41598-018-19358-2

2. Alix-Garcia, J., Rausch, L. L., L’Roe, J., Gibbs, H. K. & Munger, J. Avoided Deforestation Linked to Environmental Registration of Properties in the Brazilian Amazon. *Conserv. Lett.* **11**, e12414 (2018).

3. Baccini, A. *et al.* Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps. *Nat. Clim. Chang.* **2**, 182–185 (2012).

4. Harris, N. L. *et al.* from Deforestation in Tropical Regions. **2005**, (2012).

5. Assunção, J., Gandour, C. & Rocha, R. DETERring Deforestation in the Brazilian Amazon: Environmental Monitoring and Law Enforcement. *Clim. Policy Initiat.* 1–36 (2013).

6. Gibbs, H. K. *et al.* Brazil’s Soy Moratorium. *Science (80-. ).* **347**, 377–378 (2015).

7. Assunção, J., Gandour, C., Rocha, R. & Rocha, R. Does Credit Affect Deforestation? Evidence from a Rural Credit Policy in the Brazilian Amazon. 50 (2013). Available at: https://climatepolicyinitiative.org/publication/does-credit-affect-deforestation-evidence-from-a-rural-credit-policy-in-the-brazilian-amazon/.

8. Azevedo, A. A. *et al.* Limits of Brazil’s Forest Code as a means to end illegal deforestation. *Proc. Natl. Acad. Sci.* **114**, 7653–7658 (2017).

9. Freitas, F. L. M. *et al.* Potential increase of legal deforestation in Brazilian Amazon after Forest Act revision. *Nat. Sustain.* **1**, 3–8 (2018).

10. PRODES. Monitoramento da Floresta Amazônica Brasileira por Satélite. 2–4 (2019). Available at: http://www.dpi.inpe.br/prodesdigital/prodesmunicipal.php.

11. Godar, J., Gardner, T. A., Tizado, E. J. & Pacheco, P. Actor-specific contributions to the deforestation slowdown in the Brazilian Amazon. *Proc. Natl. Acad. Sci.* **111**, 15591–15596 (2014).

12. Rasmussen, L. V., Jung, S., Brites, A. D., Watkins, C. & Agrawal, A. Understanding smallholders’ intended deforestation behavior in the Brazilian Cerrado following environmental registry. *Environ. Res. Lett.* **12**, 094001 (2016).

13. GIZ. Land tenure regularisation in the Amazon – Terra Legal. (2014). Available at: https://www.giz.de/en/worldwide/33654.html.

14. Buntaine, M. T., Hamilton, S. E. & Millones, M. Titling community land to prevent deforestation: An evaluation of a best-case program in Morona-Santiago, Ecuador. *Glob. Environ. Chang.* **33**, 32–43 (2015).

15. BenYishay, A., Heuser, S., Runfola, D. & Trichler, R. Indigenous land rights and deforestation: Evidence from the Brazilian Amazon. *J. Environ. Econ. Manage.* **86**, 29–47 (2017).

16. Busch, J. & Ferretti-Gallon, K. What drives deforestation and what stops it? A meta-analysis. *Rev. Environ. Econ. Policy* **11**, 3–23 (2017).

17. USAID. Land Tenure and Property Rights: Tools for Transformational Development. (2008).

18. Hasan, K. M. Agricultural taxation in developing countries : a survey of issues and policy. *Agric. Econ.* **24**, (2001).

19. Ali, D. A., Deininger, K. & Goldstein, M. Environmental and gender impacts of land tenure regularization in Africa : Pilot evidence from Rwanda ☆. *J. Dev. Econ.* **110**, 262–275 (2014).

20. Araujo, C., Bonjean, C. A., Combes, J. L., Combes Motel, P. & Reis, E. J. Property rights and deforestation in the Brazilian Amazon. *Ecol. Econ.* **68**, 2461–2468 (2009).

21. Araujo, C., Combes, J. L. & Féres, J. G. Determinants of Amazon deforestation: The role of off-farm income. *Environ. Dev. Econ.* **24**, 138–156 (2019).

22. Wood, C. & Walker, R. Tenure security, investment decisions and resource use among small farmers in the Brazilian Amazon. 1–34 (2000).

23. Keswell, M. & Carter, M. R. Poverty and land redistribution. *J. Dev. Econ.* **110**, 250–261 (2014).

24. Goldstein, M., Houngbedji, K., Kondylis, F., O’Sullivan, M. & Selod, H. Formalization without certification? Experimental evidence on property rights and investment. *J. Dev. Econ.* **132**, 57–74 (2018).

25. Liscow, Z. D. Do property rights promote investment but cause deforestation ? Quasi-experimental evidence from Nicaragua. *J. Environ. Econ. Manage.* **65**, 241–261 (2013).

26. Roe, J. L., Rausch, L., Munger, J. & Gibbs, H. K. Land Use Policy Mapping properties to monitor forests : Landholder response to a large environmental registration program in the Brazilian Amazon. *Land use policy* **57**, 193–203 (2016).

27. Stefanes, M. *et al.* Property size drives differences in forest code compliance in the Brazilian Cerrado. *Land use policy* **75**, 43–49 (2018).

28. Schielein, J. & Börner, J. Recent transformations of land-use and land-cover dynamics across different deforestation frontiers in the Brazilian Amazon. *Land use policy* **76**, 81–94 (2018).

29. Kupper, B. *et al.* Protection and Sustainabe Use of Tropical Forests Need Land Tenure Regularization: Evidence from Brazil. *Annu. World Bank Conf. L. Poverty* 1–25 (2017).

30. Kettle, S., Hernandez, M., Ruda, S. & Sanders, M. Behavioral Interventions in Tax Compliance: Evidence from Guatemala. *World Bank Policy Res.* 1–40 (2016). doi:10.1103/PhysRevLett.77.4891

31. Climate Home News. Worst land-related killings in decades expose Amazon’ s lawless frontier. (2017). Available at: https://www.climatechangenews.com/2017/05/09/mass-murder-exposes-fatal-weakness-amazon-land-regulation/.

32. INPE. Instituto Nacional de Pesquisas Espaciais. 2017 Available at: http://www.inpe.br/.

33. Burbidge, J. B., Magee, L. & Robb, A. L. Alternative transformations to handle extreme values of the dependent variable. *J. Am. Stat. Assoc.* **83**, 123–127 (1988).

34. Fick, S. E. WorldClim 2: New 1-km spatial resolution climate surfaces for global land areas. **4315**, 4302–4315 (2017).

35. Centro de Sensoriamento Remoto. Centro de Sensoriamento Remoto. Available at: https://siscom.ibama.gov.br/.

36. Assuncąo, J., Gandour, C. & Rocha, R. Deforestation slowdown in the Brazilian Amazon: Prices or policies? *Environ. Dev. Econ.* **20**, 697–722 (2015).

37. Brito, B. & Barreto, P. *A regularização fundiária avançou na Amazônia?* (2011).

38. Blackman, A., Corral, L., Lima, E. S. & Asner, G. P. Titling indigenous communities protects forests in the Peruvian Amazon. *Proc. Natl. Acad. Sci.* **114**, 4123–4128 (2017).

39. Chow, C. G. Tests of Equality Between Sets of Coefficients in Two Linear Regressions. *Econometrica* **28**, 591–605 (1960).