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Deforestation Scale and Farm Size: the Need for Tailoring Policy in Brazil

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Deforestation Scale and Farm Size: the Need for Tailoring Policy in Brazil

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Abstract

Once driven by large-scale clearings, Amazon deforestation now occurs mostly in small increments. Did this result from the emergence of a new group of agents or from an adaptation in the behavior of those who led deforestation in the past? We address this question using georeferenced data on private rural properties and deforestation. Results indicate that centralized policy efforts introduced starting in the mid-2000s successfully inhibited medium- and large-scale deforestation, but had heterogeneous effects on small-scale deforestation. Although the relative participation of small deforestation polygons increased in both sample states, the relative participation of smallholders in total state deforestation increased in Pará, but remained constant in Mato Grosso. The apparent similarity in scale of deforestation across states conceals relevant baseline differences between the agents engaging in forest clearing in each locality. Tailoring policy to account for such differences could strengthen Brazilian conservation policy.

Keywords: deforestation, Amazon, property size, conservation policy
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1. Introduction

Brazilian Amazon deforestation rates escalated in the early 2000s, but after peaking at over 27,000 km^2 in 2004, decreased sharply to about 4,500 km^2 in 2012 (INPE, 2015). A change in the composition of deforestation occurred alongside the reduction in the overall level of annual forest clearings. Once driven by large-scale clearings, Amazon deforestation now occurs mostly in small increments. Figure 1 illustrates this phenomenon — small deforestation polygons (defined as contiguous areas of cleared forest under 25 hectares), which accounted for under a quarter of total forest area cleared in 2002, amounted to more than half of annual deforestation in the early 2010s. The increase in the relative participation of small-scale deforestation was accompanied by a decrease in that of large and very large-scale forest clearings (deforestation polygons greater than 1 square kilometer).

[Figure 1 about here.]

The timing of this change coincides with important shifts in Brazilian conservation policy. In particular, the strengthening of Amazon monitoring and law enforcement efforts starting in 2004 was one of the main drivers of the deforestation slowdown (Assunção et al., 2013a). Central to these efforts was the implementation of the remote sensing-based Real-Time System for Detection of Deforestation (DETER). Yet, the satellite used in DETER is only capable of detecting forest clearings whose total contiguous area exceeds 25 hectares. Because DETER is used to target law enforcement activity in the Amazon, clearings smaller than this threshold are less likely to be caught by law enforcers. The recent change in deforestation composition suggests that the dynamics of Amazon forest clearings may have changed in response to DETER's technical shortcoming.

This paper aims at shedding light on the nature of the change in deforestation composition. Did it result from the emergence of a new group of agents or from an adaptation in the behavior of those who already led deforestation in the past? In the former scenario, forest clearings by large landowners, which once accounted for the bulk of deforestation, are contained, but clearing practices by small landowners continue.[1] Deforestation in large properties would have therefore declined relatively more than in small properties. In the latter scenario, large landowners are still responsible for the greatest share of deforestation, but clear forest in smaller patches to elude monitoring. In this case, despite the decrease in average deforestation polygon size, there would be

[1] We refer to agents operating within private properties as landholders or landowners throughout the paper. Although owners themselves might not be the ones actually practicing deforestation inside a given property, they are the ones responsible for registering the property in the databases we explore. In this sense, they are ultimately responsible for forest clearing activity occurring inside their property.

no reason to expect a change in the relative participation of large and small properties in total deforestation.

We address this question by exploring georeferenced data on private rural properties from the Environmental Rural Registry (CAR) and the Unique Environmental License (LAU) databases, which provide property perimeters. We combine property boundary data with georeferenced deforestation data to determine whether deforestation polygons were located inside small/medium/large properties. Due to data availability, our analysis focuses on Mato Grosso and Pará states.

Results indicate that the pattern of deforestation differed across sample states. More specifically, policy efforts introduced starting in the mid-2000s appear to have successfully inhibited medium- and large-scale deforestation in both Mato Grosso and Pará, but had heterogeneous effects on small-scale deforestation. Although the relative participation of small deforestation polygons increased in both sample states, the relative participation of smallholders in total state deforestation increased in Pará in the late 2000s, but remained constant throughout our sample period in Mato Grosso. This highlights an important finding — the apparent similarity in scale of deforestation across states conceals relevant differences between the agents engaging in forest clearing in each locality. Tailoring policy to account for such differences could strengthen Brazilian conservation policy.

In particular, we provide evidence that smallholders deforested larger patches (above 25 hectares) relatively more in Mato Grosso than in Pará. This type of forest clearing activity was more easily detected by DETER and, thus, more effectively contained by the new monitoring system. In this sense, enhanced law enforcement efforts starting in the mid-2000s targeted small, medium, and large landholders alike in Mato Grosso. This interpretation is consistent with the timing of the onset of the deforestation slowdown in Mato Grosso. In contrast, deforestation in small properties appears to have been more persistent in Pará throughout our sample period. This can be partly explained by the fact that forest clearings inside small properties in the state occurred mostly in increments smaller than 25 hectares. As this activity was not detected by DETER, smallholders in Pará were, in practice, less visible to law enforcers, and thus less likely to be targeted by them. This suggests that DETER-based improvements in monitoring and law enforcement may have been less effective in curbing deforestation in Pará, as compared to Mato Grosso. Indeed, although absolute deforestation in Pará shows a downward trend starting in the mid-2000s, the reduction in annual forest clearings is slightly more accentuated towards the late 2000s. Forest clearing activity in Pará therefore appears to have been relatively more sensitive to conservation efforts introduced in the late 2000s — particularly the targeting of priority municipalities and the conditioning of rural credit concession upon proof of compliance with environmental and land titling regulations —

than to earlier monitoring and law enforcement efforts.

These results further the ongoing debate in the literature on actor-specific contributions to Amazon deforestation. The unavailability of Amazon-wide property-level information has, however, limited the advance of this literature. Works covering the full extent of the Brazilian Amazon resort to municipality or census tract aggregations, classifying each unit of observations according to its prevailing property size (Pacheco, 2012; Godar et al., 2014). The main limitation with this approach, which does not explore individual property limits, is the inability to determine whether deforestation occurred inside or outside each property. Property-level analyses are, however, typically confined to small geographical areas (Walker et al., 2000; Aldrich et al., 2006; Michalski et al., 2010; Godar et al., 2012). Although insightful, empirical findings from studies conducted in these areas cannot easily be generalized for the entire Amazon. We, too, do not have Amazon-wide property-level data. Yet, by combining information from CAR and LAU, we are able to build a property-level database for the two states that consistently accounted for about two thirds of the forest area cleared in our sample years. Hence, even if not exhaustive, our sample is relevant.

Our work also speaks to the literature on the drivers of deforestation. The impact of socioeconomic and geographic factors on deforestation has long been documented — population, road density, climate, rural credit, and agricultural commodity prices, among others, have been shown to be important drivers of forest clearing activity (Cropper and Griffiths, 1994; Panayotou and Sungsuwan, 1994; Andersen, 1996; Barbier and Burgess, 1996; Chomitz and Gray, 1996; Cropper et al., 1997; Angelsen and Kaimowitz, 1999; Pfaff, 1999; Barbier and Burgess, 2001; Ferraz, 2001; Pfaff et al., 2007; Chomitz and Thomas, 2003; Araujo et al., 2009). More recent works have looked specifically at the 2000s Amazon slowdown, aiming at disentangling the leading causes for the decrease in deforestation (Hargrave and Kis-Katos, 2013; Assunção et al., 2013b,a; Assunção and Rocha, 2014; Assunção et al., 2015). We contribute to this literature to the extent that our findings enhance the understanding about the changing nature of Amazon deforestation and its underlying causes. We provide evidence that centralized and uniform conservation efforts had heterogeneous effects, likely due to regional heterogeneities at baseline. Although we are unable, within the scope of this work, to determine the precise reasons for these baseline differences, our results highlight the need to more finely shape conservation efforts to regional specificities.

The remainder of this paper is organized as follows. Section 2 provides an overview of the institutional context for Amazon conservation policies, and presents a state-level comparison of Mato Grosso and Pará. Section 3 details data sources and variables construction. Section 4 discusses results from descriptive and regression analyses. Section

5 interprets these results. Finally, Section 6 concludes with policy implications.

2. Institutional Context

This section starts by providing an institutional background for Amazon conservation policy in the 2000s, and follows with a descriptive comparison of Mato Grosso and Pará states. Both the overall policy and the state-level dimensions are relevant for the interpretation of our results.

2.1. Novel Conservation Efforts

The Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm), the pivotal conservation policy effort of the mid-2000s, marked the beginning of a novel approach towards combating deforestation in the Brazilian Legal Amazon.[2] Launched in 2004, it integrated actions across different government institutions and proposed innovative procedures for monitoring, environmental control, and territorial management. Henceforth, all changes to Brazilian forestry and conservation policy happened within the plan's framework. The operational project for the PPCDAm consisted of a large set of strategic conservation measures to be implemented and executed as part of a new collaborative effort between federal, state, and municipal governments, alongside specialized organizations and civil society.

One of the pillars of the PPCDAm was the strengthening of Amazon monitoring and law enforcement. The main driving force behind this was the adoption of DETER in 2004. Developed and operated by the National Institute for Spatial Research (INPE), DETER is a satellite-based system that captures and processes georeferenced imagery on forest cover in 15-day intervals. These images are used to identify deforestation hot spots and target law enforcement efforts. Prior to the activation of the satellite-based system, Amazon monitoring depended on voluntary reports of threatened areas, making it very difficult for law enforcers to identify and access deforestation hot spots in a timely manner. With the adoption of DETER, law enforcers were able to better identify and more quickly act upon areas afflicted by illegal deforestation.

Yet, the monitoring system suffers from an important technical limitation — the satellite used in DETER is only capable of detecting forest clearings whose total contiguous area is greater than 25 hectares. Any clearings smaller than this are, essentially, invisible to the monitoring system, and are therefore less likely to be caught by law enforcers.

[2] The Legal Amazon is a socio-geographic division of Brazil. It is composed of the western territory of the state of Maranhão and the entire territory of the states of Acre, Amapá, Amazonas, Mato Grosso, Pará, Rondônia, Roraima, and Tocantins.

In addition to the implementation of the DETER system, the PPCDAm promoted improved qualification of law enforcement personnel via stricter requirements in the recruitment process for the environmental police, as well as more specialized training of law enforcers. The new plan also introduced institutional changes that brought greater regulatory stability to the administrative processes for dealing with environmental crimes. New directives for the investigation and punishment of environmental infractions regulated the use of sanctions including fines, embargoes, and seizure of production goods, tools, and materials. Law enforcement efforts were also strengthened with the creation of the priority municipalities policy in 2008, which singled out municipalities with intense deforestation activity and took differentiated action towards them. These municipalities, selected based on their recent deforestation history, were classified as in need of priority action to prevent, monitor, and combat illegal deforestation. In addition to being more closely monitored, priority municipalities became subject to a series of other administrative measures that did not necessarily stem from law enforcement policy. Examples include harsher licensing and georeferencing requirements for private landholdings, compromised political reputation for mayors of priority municipalities, and economic sanctions applied by agents of the commodity industry.

Parallel to the PPCDAm's monitoring and law enforcement efforts, the creation of protected areas gained momentum in the mid-2000s. From 2004 through 2009, the area covered by conservation units of integral protection and sustainable use in the Legal Amazon increased by over 520,000 km^2. By the end of the 2000s, nearly half of Legal Amazon territory was under protection as either conservation units or indigenous lands.

Finally, a novel approach towards the concession of rural credit was adopted to restrict financial resources for those who did not abide by environmental and land titling regulations. Starting in 2008 the concession of rural credit for use in the Amazon biome became conditioned upon presentation of proof of borrowers' compliance with environmental legislation and legitimacy of land claims. Small-scale producers, however, benefited from both partial and complete exemptions to the policy's requirements.

2.2. A State-Level Comparison

Combined, Mato Grosso and Pará occupy over two fifths of the Brazilian Legal Amazon, but accounted for more than half of total Amazon forest area cleared annually from 2002 through 2012 (see Table 1 and Figure 2).[3] Thus, although not representative of the Legal Amazon in its entirety, Mato Grosso and Pará cover not only a substantial fraction of Amazon territory, but also concentrate a significant share of its recent

[3] The share of annual Amazon deforestation attributable to Mato Grosso and Pará remained above 65% from the early 2000s through 2010, but fell to 64% and 55% in 2011 and 2012, respectively.

deforestation activity.

[Table 1 about here.]

By 2012, the registration of private rural properties was relatively advanced in Mato Grosso and Pará, as compared to other Legal Amazon states. Table 1 shows that nearly half of Mato Grosso's unprotected territory (or 40% of state territory) was registered. In Pará, although registered properties amounted to only 18% of total state territory, they covered 40% of its unprotected area.[4] Both states therefore had comparable shares of registered unprotected territory. Given the sheer size of Mato Grosso and Pará, these shares imply that our sample area is not only sizable, but also of relevance to our topic of interest.

The composition of registered areas differed across states. While large properties accounted for 81% and small properties for only 3% of Mato Grosso's total registered area, the equivalent figures for Pará were 68% and 14%, respectively. Indeed, the average size of a registered property in Mato Grosso was more than three times that of its counterpart in Pará. Considering that the size of fiscal modules is similar in the two states, the difference in average property sizes suggests that the agrarian structure in Mato Grosso differs significantly from that in Pará. Section 5 explores this further.

[Figure 2 about here.]

The two states also exhibited different deforestation trends during the sample period. The rate of forest clearings decreased in both Mato Grosso and Pará in the second half of the 2000s, accompanying the overall Amazon deforestation slowdown. Yet, deforestation proved to be more persistent in Pará, as shown in Figure 2. In 2002, each state accounted for approximately 35% of total Amazon forest cleared, but after overtaking Pará's share of annual deforestation in the first half of the 2000s, Mato Grosso's share gradually fell. In contrast, starting in 2006, Pará systematically accounted for at least two fifths of annual deforestation. In 2012, Mato Grosso was responsible for 17% and Pará for 38% of total forest area cleared in the Amazon.

Despite its persistence, it's interesting to note that deforestation in Pará appears to have decreased at a slightly faster pace starting in 2009. Considering that the PPCDAm was implemented in the mid-2000s and that forest clearings had been slowing down substantially in Mato Grosso since 2005, this stylized fact suggests that Pará was

[4] Note that the regulation regarding forest clearing activity within protected areas is stricter than that referring to unprotected areas. Thus, protected areas in the Amazon do not typically contain private rural properties.

somewhat more susceptible to conservation measures adopted in the late 2000s, namely, the priority municipalities policy and the conditioning of rural credit. This might have resulted from a combination of historical and geographical factors that gradually shaped the productive structure of each state. We return to this discussion in Section 5.

Unlike state deforestation, forest clearings happening within registered properties followed similar trends in Mato Grosso and Pará. About half the forest area cleared in each state was located inside registered properties in the early 2000s; by 2012, this fraction had decreased to less than a quarter. Most of the forest clearing activity in unregistered areas in the late 2000s and early 2010s therefore occurred either in public land or in unregistered private land. Combined, these stylized facts suggest that enrollment in the registry was not uniformly distributed across rural agents. As registration was not mandatory during our sample period (see Section 3.1 for details), it is likely that agents who were more inclined to deforest were also the ones who refrained from registering their properties (at least until forced to do so). After all, compliance with registry regulation required landowners to document legal reserves and areas of permanent protection within their properties — precisely the areas that must be preserved inside private landholdings under Brazilian environmental regulation.

Although these descriptive statistics do not allow us to determine the underlying reasons for the different trends, they highlight the fact that there was heterogeneity between rural landowners in Mato Grosso and Pará in the early 2000s. This heterogeneity will be central to our interpretation of the change in Amazon deforestation composition.

3. Data

We use georeferenced data on annual deforestation inside private rural properties in Mato Grosso and Pará to build a 2002 through 2012 property-by-year panel data set. This section describes data sources and details the construction of our key variables.

3.1. Private Rural Properties

Private property boundaries were obtained from the CAR database, via the State Secretariats for the Environment. To obtain the CAR, landowners must georeference (record the geographical coordinates for) their properties' perimeters, as well as delimitations for legal reserves, areas of permanent protection, remaining native vegetation, consolidated rural areas, and areas of social or public interest. Upon inputing this information into the CAR system, landowners hold a temporary CAR; permanent CARs are only issued after the State Secretariat for the Environment validates the information. In this study, we make no distinction between properties holding temporary and permanent CARs — all are considered registered properties.[5]

The CAR system was created to serve as an instrument for the environmental regularization of rural properties in Brazil. Although its origin dates back to the second half of the 2000s, it was not until the approval of the new Brazilian Forest Code in 2012 that registration in CAR became compulsory for all private rural properties in the country. At the time of writing, the deadline for registration in CAR is May 2015, but registry coverage is still incomplete. Our sample does not, therefore, include all private rural properties in Mato Grosso and Pará. As there is currently no available data that allows us to differentiate unregistered private properties from public lands, these private properties are not considered in our analysis.

Original data sets presented several overlaps between properties. This might happen for one (or more) of three reasons: (i) property rights in the Amazon are not always well defined; (ii) landowners are individually responsible for georeferencing their properties, and boundary disputes induced by inconsistent georeferencing are only settled when the state regulator validates the temporary registry; and (iii) selling/buying and changes in boundaries of registered properties are not adequately documented — when a property is purchased, for example, the new owner must register the property, but the old registry remains in the state database. We deal with these overlaps by assigning the duplicate area to the most recently registered property and removing it from the others. Registered area in the original data set totaled about 630 thousand km^2; after addressing overlaps, our sample amounted to 586 thousand km^2 of private land.

The final data set contains 23,731 properties in Mato Grosso and 47,412 in Pará. As we do not have full information about changes in properties' borders during our sample period, our analysis assumes they are constant from 2002 through 2012.

We follow Brazilian law and classify property sizes based on fiscal modules. A fiscal module is defined as the minimum area needed to ensure the economic viability of exploring a rural establishment in any given Brazilian municipality. The average size of a fiscal module is 0.88 in Mato Grosso, and 0.70 in Pará (see Table 1). Property size is determined as follows: small properties are smaller than 4 fiscal modules; medium-sized properties are larger than 4 but smaller than 15 fiscal modules; and large properties are larger than 15 fiscal modules. Note that, because fiscal modules are municipality-specific, thresholds for small/medium/large properties differ across sample municipalities.

[5]For Mato Grosso, we complement CAR data with information from LAU, which served as a registry for private rural properties in the state before the adoption of CAR. Again, we make no distinction between properties registered under CAR or LAU.

3.2. *Deforestation*

We use publicly-available information from INPE to determine the location of forest clearings at an annual basis. Through its Program for Calculation of Amazon Deforestation (PRODES), INPE processes satellite imagery covering the full extent of the Brazilian Legal Amazon to identify and map deforestation activity. Both automated and human-based interpretation of satellite imagery are used to locate forest clearings. For a given year, PRODES measures deforestation that happened from August of the previous year through July of that year. This is done to ensure that remote sensing occurs at a time when visibility of Amazon land cover is typically at its best. To maximize potential visibility, images from the Amazon dry season (typically July, August, and September) are used.[6]

The PRODES dataset suffers from three technical limitations that potentially affect our results. First, cloud coverage during the period of remote sensing may prevent the satellite used in PRODES from capturing land cover imagery. Forest areas that were cleared in a given year, but were blocked from view by clouds during remote sensing, are not incorporated into that year's deforestation increment figure — these areas are only accounted for when they eventually show up on PRODES imagery. Although we cannot address this issue in our descriptive results, we include variables indicating PRODES cloud coverage and unobservable areas, both of which are made publicly available by INPE, in all regressions to control for measurement error. Second, deforestation data is missing for some regions of Pará in one or all sample years. A total of 210 properties are affected by this, and are dropped from our sample. Third, the satellite used in PRODES can only detect contiguous areas of cleared forest that are greater than 6.25 hectares. Hence, our analysis does not consider deforestation polygons that are smaller than this.

3.3. *Combining Georeferenced Data*

Georeferenced data on deforestation from PRODES/INPE and on private rural property from the environmental registries are overlapped as shown in Figure 3. This allows us to not only identify forest clearings happening inside private property, but also calculate the area of such clearings.

[Figure 3 about here.]

[6] PRODES only accounts for the clearing of tropical forest, and it does not detect deforestation of areas covered by secondary forest. See Câmara et al. (2006) for a detailed account of PRODES methodology.

4. Results

4.1. Deforestation by Polygon Size

Figure 4 decomposes total cleared forest in each state and year into the shares attributable to each polygon size class. In Mato Grosso, small-scale clearings (< 0.25 km^2) were responsible for less than 15% of total state deforestation through the mid-2000s. An increase in their participation was accompanied by a decrease in the participation of large (1–5 km^2) and very large (> 5 km^2) polygons in the second half of the 2000s. The timing of this change in composition coincides with the introduction of the DETER system, which is unable to detect deforestation polygons that are smaller than 0.25 square kilometers (see Section 2.1 for a detailed explanation).

[Figure 4 about here.]

The rise in small-scale deforestation in Mato Grosso is, however, only timid when compared to that which occurred in Pará. Clearing forest in small increments was a more common practice in Pará already in the early 2000s, when small polygons accounted for about 25% of total state deforestation. The first half of the 2000s saw a considerable increase in the participation of small polygons in annual deforestation, but it was after 2007 that small-scale deforestation overtook medium and large clearings by a wide margin. By the early 2010s, the share of deforestation attributable to small polygons had almost tripled in only ten years. A reduction in the participation of medium, large, and particularly very large forest clearings occurred in tandem with the rise in small polygons.

Overall, deforestation became more fragmented in both states, but the much greater rise in participation of small-scale deforestation in Pará indicates relevant heterogeneity across states.

4.2. Deforestation by Property Size

The data presented so far show that the deforestation slowdown was mostly driven by the curbing of large-scale forest clearings. We now investigate if those who currently deforest in small increments are the same agents who led deforestation in the past — then in large increments — or a new set of agents who are emerging with the containment of large-scale forest clearing activity. In the first scenario, large landowners, who once accounted for the bulk of deforestation, are still responsible for the greatest share of it, but now clear forest in smaller patches. Hence, despite the decrease in average deforestation polygon size, there would be no reason to expect a change in the relative participation of large and small properties in total deforestation. In the second scenario, forest clearings by large landowners have been contained, but clearing practices by small landowners continue. Deforestation in large properties would have therefore declined relatively more than in small properties.

To see this, we again decompose total deforested area in each state, but now using property size as the basis for classification. Figure 5 shows that trends in Mato Grosso and Pará differed significantly. In Mato Grosso, the shares of state deforestation occurring within each property size remained fairly stable over the sample period, with large properties accounting for about 70% and small properties for less than 10% of total annual deforestation. In contrast, there was a reversal of roles in Pará. In 2002, large properties answered for 60% and small properties for 15% of total deforestation; over the next 10 years, the participation of small properties gradually increased, while that of large ones decreased, such that, by 2012, each accounted for about 40% of total cleared forest area.

[Figure 5 about here.]

These trends indicate that the nature of the change in deforestation composition differed across states. The evidence suggests that, in Mato Grosso, agents changed their behavior. Despite increased fragmentation of forest clearings, large properties continued to be responsible for the largest part of annual state deforestation — large properties switched from large-scale clearing practices to small-scale ones. One plausible explanation for this is that, aware of DETER's inability to detect deforestation polygons smaller than 0.25 square kilometers, landowners adapted their deforestation practices to elude monitoring.

Although large landowners in Pará may also have changed deforestation practices in response to DETER, the rise in the share of small properties indicates that another effect was also in place — namely, the curbing of forest clearing practices inside large properties was relatively stronger than that in small properties. Indeed, small properties in Pará exhibited a unique trend. From 2002 to 2012, deforestation in absolute terms decreased by more than 90% in all property categories in Mato Grosso, as well as in medium and large properties in Pará; at the same time, the reduction in forest clearings within small properties in Pará was only 69%.

[Table 2 about here.]

We conduct a descriptive regression exercise to determine how deforestation outcomes correlate with property size categories in each state over our sample period. The estimated model is:

$$d_{it} = \beta_t small_i * year_t + \delta X_{it} + \alpha_i + \lambda_t + \epsilon_{it} \quad (1)$$

where d_{it} is one of three alternative deforestation outcomes in property i and year t; $small_i * year_t$ is an interaction between a dummy variable flagging small properties and year dummy variables; X_{it} is a vector of property-level controls including cloud coverage and accumulated deforestation through 2001; α_i are municipality fixed effects; λ_t are year fixed effects; and ϵ_{it} are the idiosyncratic errors. Standard errors in all specifications are clustered at the municipality level.

The three deforestation outcomes used are: (i) a dummy variable flagging whether property i cleared any patches of forest in year t; (ii) the size of the largest deforestation polygon cleared in property i and year t; and (iii) total cleared area in property i and year t as a share of total property area. Only regressions using the first dependent variable include all registered properties; all other regressions use a restricted sample that excludes properties in which there was no deforestation from 2002 through 2012. We run separate regressions for Mato Grosso and Pará.

Table 3 presents estimated coefficients for model (1) using each of the three alternative deforestation outcomes in each state. The coefficients capture the difference in correlation between the outcome variables and small properties, as compared to that between the outcome variables and medium and large properties. Results indicate that small properties were about 10% less likely to deforest than medium and large ones at the beginning of our sample period (see columns 1 and 4). Over time, however, this difference becomes insignificant — by the early 2010s, coefficients are statistically equal to zero, indicating that forest clearings were just as likely to happen in small properties as in medium and large ones. This pattern is observed in both Mato Grosso and Pará, though the difference between small and medium/large properties was greater in the latter through 2009. Considering that medium and large properties were not only more likely to deforest, but specifically deforested relatively more polygons that were visible to DETER, these properties were more likely to be targeted by law enforcers. This may have contributed to close the gap between small and medium/large properties in the probability of deforesting.

[Table 3 about here.]

Our estimations also capture the fragmentation of deforestation in both Mato Grosso and Pará. The size of the largest cleared polygon in small properties was significantly smaller than that in medium and large properties in the first half of the 2000s, indicating that larger properties were, in fact, engaged in larger-scale deforestation. Yet, this difference decreases over time, reaching zero by the 2010s (see columns 2 and 5). These results reflect the fall in medium- and large-polygon forest clearings. Moreover, they serve as evidence that deforestation practices inside medium and large properties became similar to those of small properties. Overall, this is to be expected in light of the implementation of the DETER monitoring system and its focus on medium/large polygons.

Finally, results indicate that the shift in forest clearing practices in Mato Grosso and Pará was not entirely parallel. In early sample years, small properties deforested a larger share of their total area as compared to medium and large properties (see columns 3 and 6). This difference was greater in Mato Grosso. Starting in 2006, the gap between small and medium/large properties decreased substantially in Mato Grosso — although small properties still cleared a greater share of their total area in the 2010s, the gap was about a quarter of what it had been in the first half of the 2000s. Keeping in mind that small and medium/large landowners were equally likely to deforest in the late 2000s and early 2010s, the pattern in share of total property area deforested signals that, among landowners who still cleared forest, small ones started deforesting relatively less of their properties than medium and large landholders. Considering that small properties in Mato Grosso engaged in medium- and large-scale deforestation, the change in behavior induced by DETER might have contributed to close part of the gap in share of property area that was cleared.

The same was not seen in Pará, where the gap between cleared shares in small versus medium/large properties remained roughly constant over the sample period. This result speaks to the pattern seen in Table 2, which shows that small property deforestation in Pará fell relatively less than medium/large property clearings. Thus, despite the general decrease in deforestation, small properties still saw a greater share of their areas being deforested through late sample years. Again, this might be a consequence of the nature of deforestation that occurred in small properties in Pará. Since small-scale deforestation was not as heavily targeted by law enforcers, smallholders maintained their pre-DETER practices, while medium and large ones were forced to contain deforestation — combined, these effects go against a closing of the gap between small and medium/large landowners.

5. Discussion

The evidence presented so far suggests that the stories behind the change in deforestation composition were not the same across sample states. What set Mato Grosso and Pará on different paths?

Figure 6 highlights an important component of the answer. The decomposition of total cleared forest in each state by property and polygon size shows that small properties in Mato Grosso and Pará left from different starting points in the early 2000s. In 2002, less than 25% of the area deforested inside small properties in Mato Grosso was cleared in polygons smaller than 0.25 square kilometers; in Pará this share was greater than 60%.

Starting in the mid-2000s, the bulk of small property deforestation was therefore visible to the DETER monitoring system in Mato Grosso, but remained undetected in Pará. In this sense, enhanced DETER-based law enforcement efforts, which Assunção et al. (2013a) have shown to be the leading policy driver of the recent Amazon deforestation slowdown, equally targeted small, medium, and large properties in Mato Grosso. This interpretation is consistent with the timing of the deforestation slowdown in Mato Grosso, as well as with descriptive statistics and results presented in previous sections. Overall, it points towards small, medium, and large properties alike responding to the new monitoring system by decreasing forest clearings and shifting towards smaller deforestation increments. This preserved the relative participation of each property size in annual deforestation (recall Figure 5).

[Figure 6 about here.]

In addition, the increased presence of law enforcers probably also had a spillover effect through two different channels. First, even smallholders who only deforested in small increments may have reduced deforestation in response to stricter law enforcement in neighboring areas containing larger deforestation polygons. Second, because the average property in Mato Grosso is much larger than that in Pará (recall Table 1), and considering that larger properties tended to deforest in larger polygons in the first half of the 2000s (see Figure 6), there was probably a greater chance of DETER detecting private property deforestation in Mato Grosso. State heterogeneity might also have accentuated this difference. As discussed in Section 2.2, the organizational structure differed across states. During our sample period, the leading economic activity was large-scale commercial farming of soybean in Mato Grosso, and cattle ranching in Pará. Smallholders, in particular, are typically engaged in informal cattle ranching activities in Pará. Hence, farmers in Mato Grosso might be more heavily dependent on formal relationships with banks and commodity industries than their counterparts in Pará. In this case, smallholders in Mato Grosso would be more susceptible to spillover effects from neighboring medium/large properties being targeted for illegal deforestation and, thus, more risk averse.

Smallholders in Pará, in contrast, could more easily remain unseen to DETER. The monitoring system implemented in the mid-2000s may actually have reinforced this behavior. In the same way that medium and large properties deforested relatively more small polygons than before, so did small properties — by the early 2010s, the share of small property deforestation carried out in small increments had increased to more than 85% in Pará. Interestingly, Pará trends appear to have become slightly more accentuated starting in 2008, as previously mentioned. This coincides with the introduction of the priority municipalities policy, as well as with the conditioning of rural credit concession upon proof of compliance with environmental and land titling regulations. Although the priority municipality policy does not, in and of itself, distinguish smallholders from medium and large ones, it likely contributed to the overall enhancement of law enforcement in the state (Assunção and Rocha, 2014). The conditioning of rural credit, in its turn, was subject to a series of qualifications that loosened the severity of the new credit constraints for smallholders, who benefited from partial or complete exemptions from the policy's requirements. Assunção et al. (2013b) show that the policy reduced the concession of rural credit, thereby reducing deforestation. This effect was largely driven by municipalities where cattle ranching was the main economic activity. The authors also show that the policy's impact was largest on medium and large landowners. Combined, these findings might help explain why deforestation activity by smallholders in Pará — a predominantly cattle ranching state — was relatively less impacted by conservation policy efforts at the time.

It's important to stress that our study does not allow for the identification of the underlying reasons for the baseline differences across states. Indeed, this is a topic that merits an in-depth investigation of its own. Nevertheless, our analysis serves as an illustration of how these differences have important practical consequences.

6. Policy Implications and Final Remarks

The PPCDAm brought much-needed revisions to Brazilian conservation efforts, significantly contributing to the 2000s Amazon deforestation slowdown (Assunção et al., 2013a,b, 2015). In particular, it effectively combated the bulk of deforestation during the second half of the 2000s, which was largely composed of medium- and large-scale forest clearings. The composition of Amazon deforestation has, however, changed — so must conservation efforts. Today, strengthening the control of illegal deforestation means improving the targeting of forest clearing agents who are less responsive to existing conservation efforts.

In light of this, our analysis has important implications for the design of public policy in Brazil. It has highlighted the need to effectively target small-scale deforestation, but also stressed the importance of tailoring policy to regional heterogeneities. Indeed, despite a certain degree of disaggregation — via targeting of priority municipalities, for example — the PPCDAm was, in essence, a centralized policy that treated the Amazon as a largely uniform target. In this study, we provide evidence that these uniform efforts had heterogeneous effects. Knowing how to anticipate and address heterogeneity in policy design could increase policy efficacy, to the extent that heterogeneity-based efforts could be shaped for maximum impact.

Moving forward, the challenge for conservation policy in Brazil is to account for such heterogeneities. This requires a better understanding of what these heterogeneities actually are, as well as of the underlying reasons for their being. This study takes a step towards a deeper understanding of current forest clearing practices, and thereby strengthens Brazil's capacity to combat remaining deforestation.

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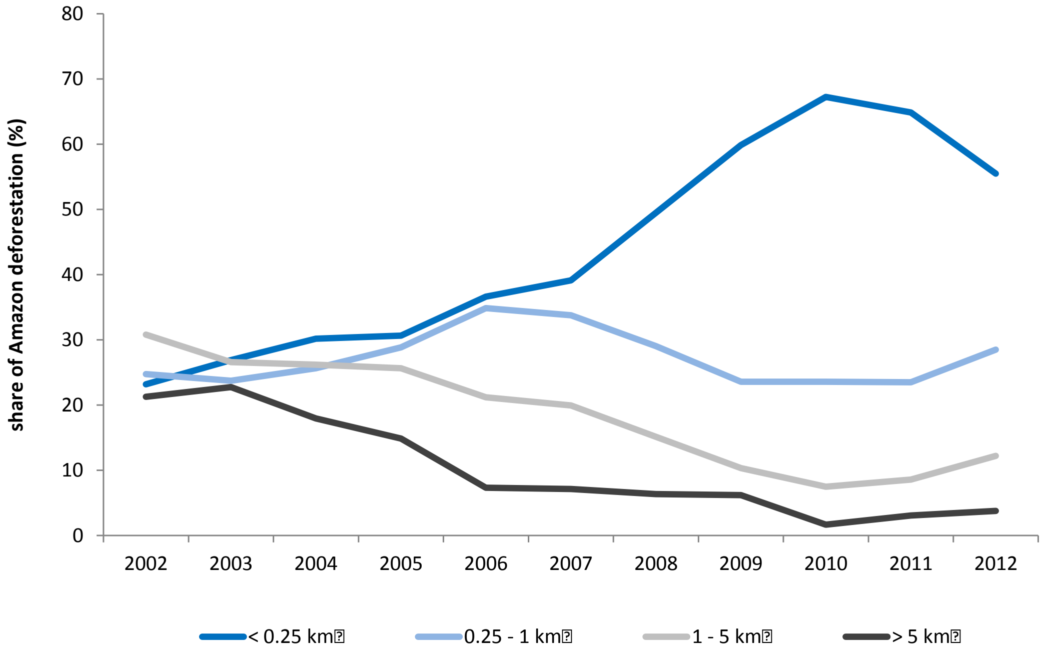
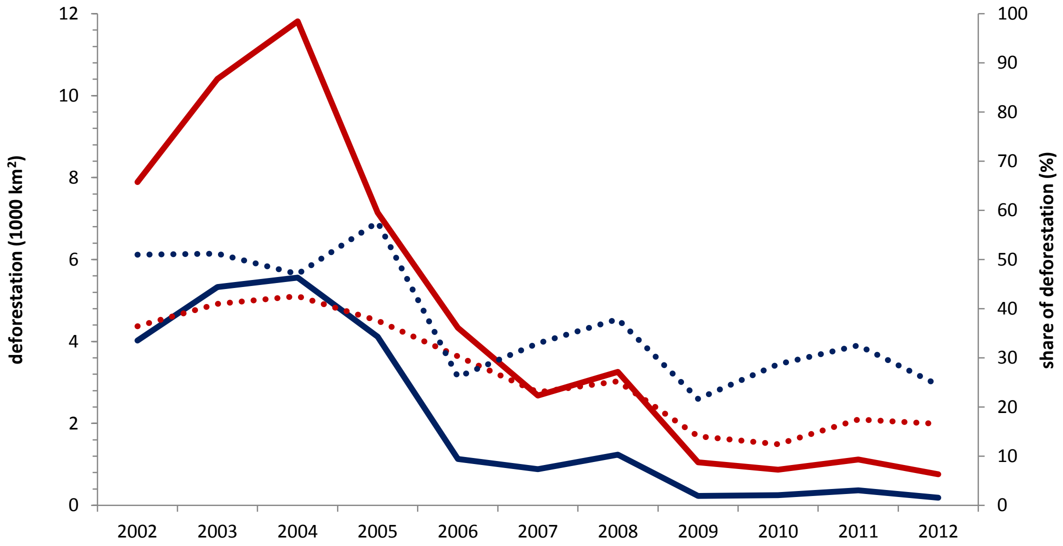
Figure 1: Amazon Deforestation by Polygon Size, 2002–2012



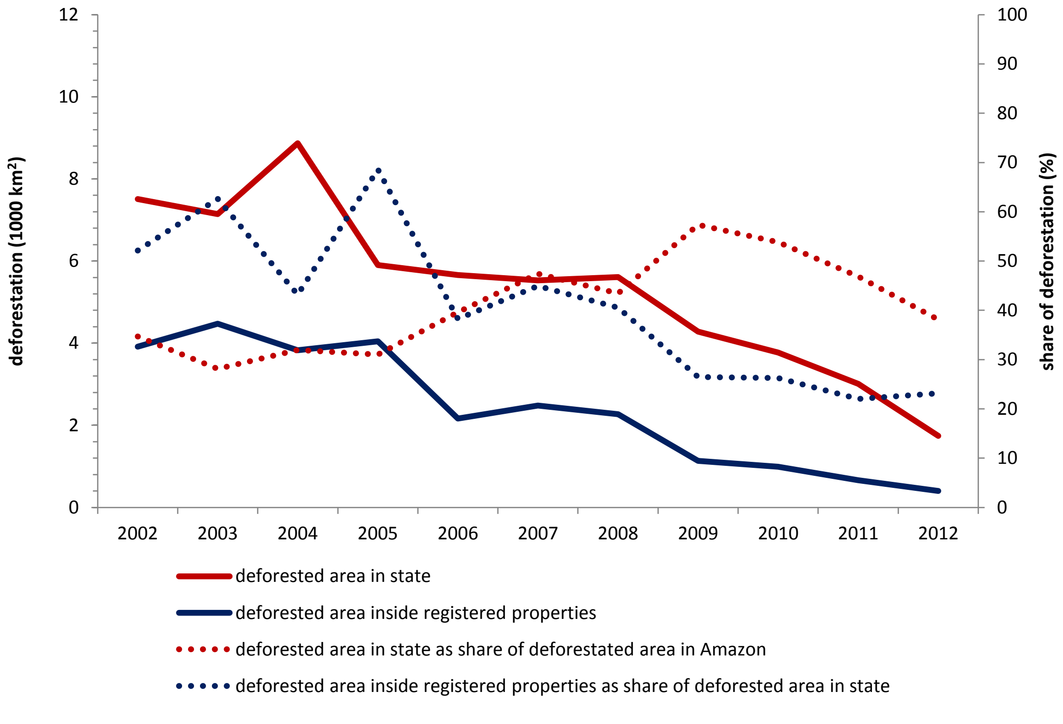
Notes: the figure illustrates annual Amazon deforestation decomposed by deforestation polygon size. Data from PRODES/INPE.

Figure 2: Annual Deforestation by Region, 2002–2012

(a) Mato Grosso

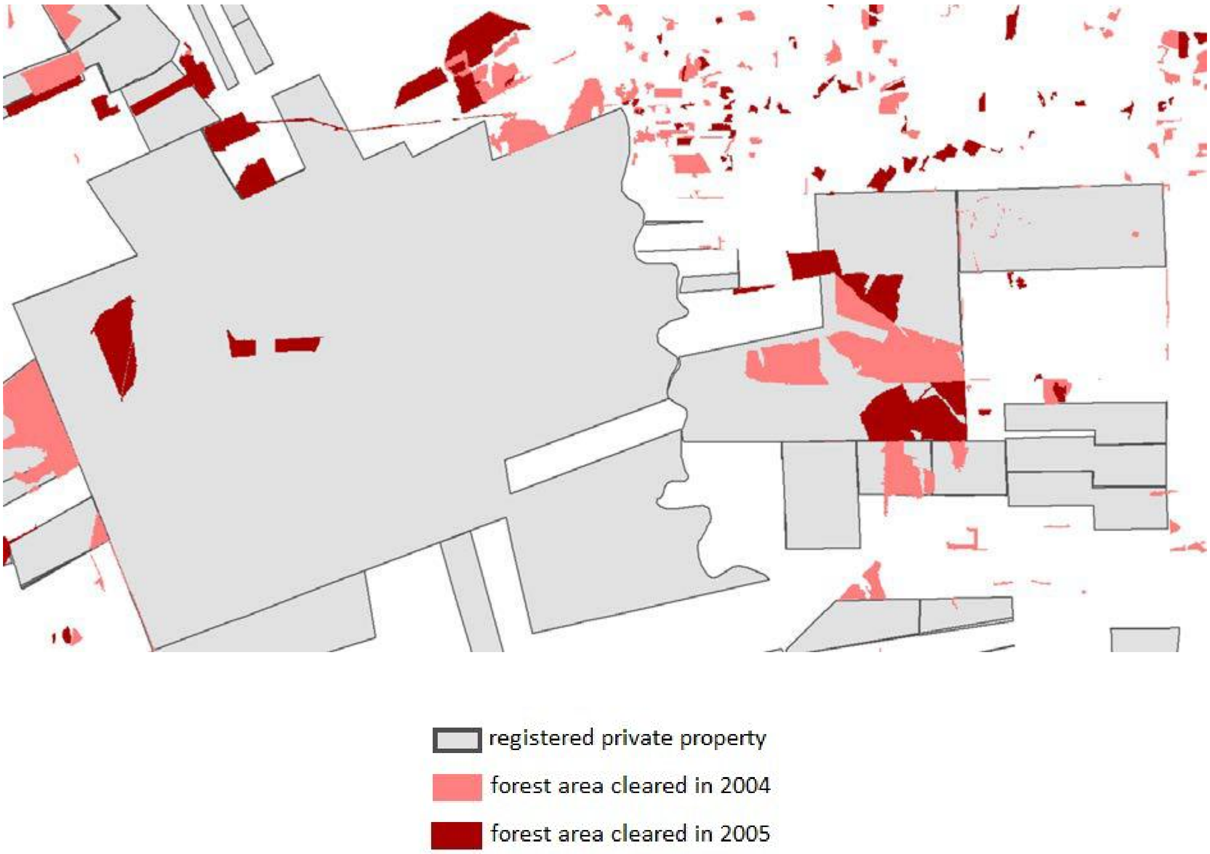


(b) Pará



Notes: the figures present total state deforestation and total forest area cleared within registered properties in both absolute and relative terms. Data from PRODES/INPE (deforestation) and State Secretariats for the Environment (private property registries).

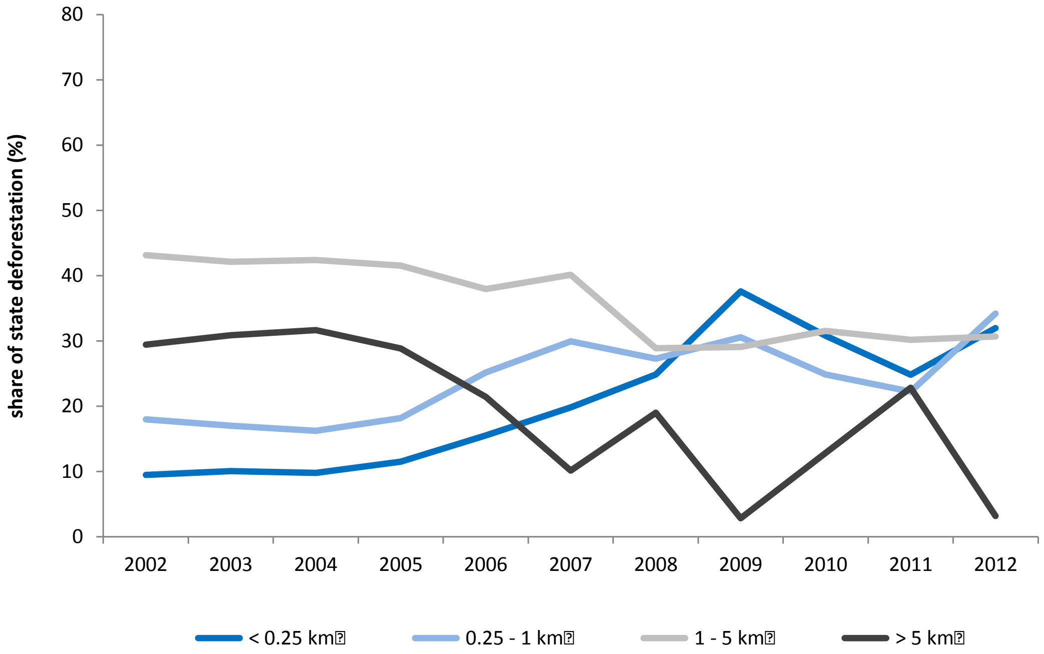
Figure 3: Combining Property and Deforestation Georeferenced Data



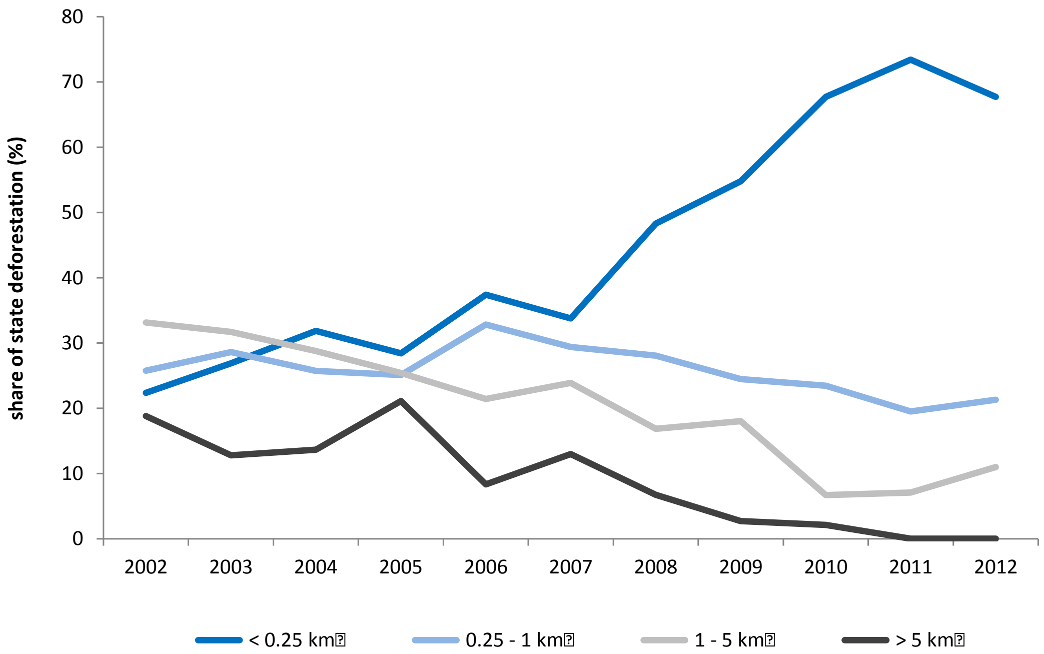
Notes: the figure illustrates how georeferenced property limits are combined with georeferenced deforestation polygons. Data from PRODES/INPE (deforestation) and State Secretariats for the Environment (private property registries).

Figure 4: State Deforestation by Polygon Size, 2002–2012

(a) Mato Grosso



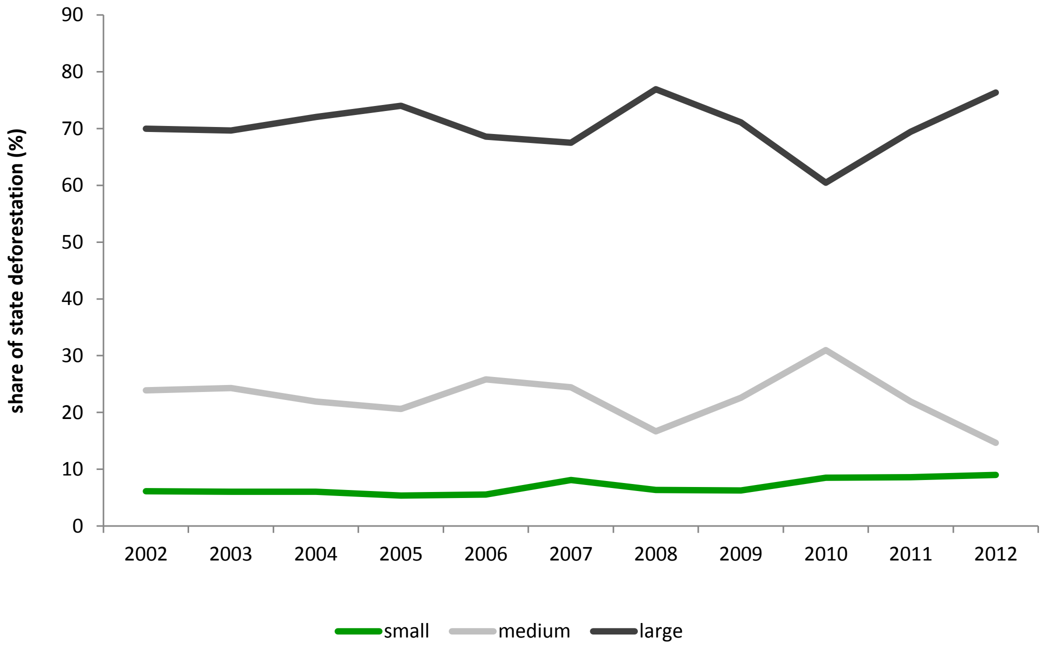
(b) Pará



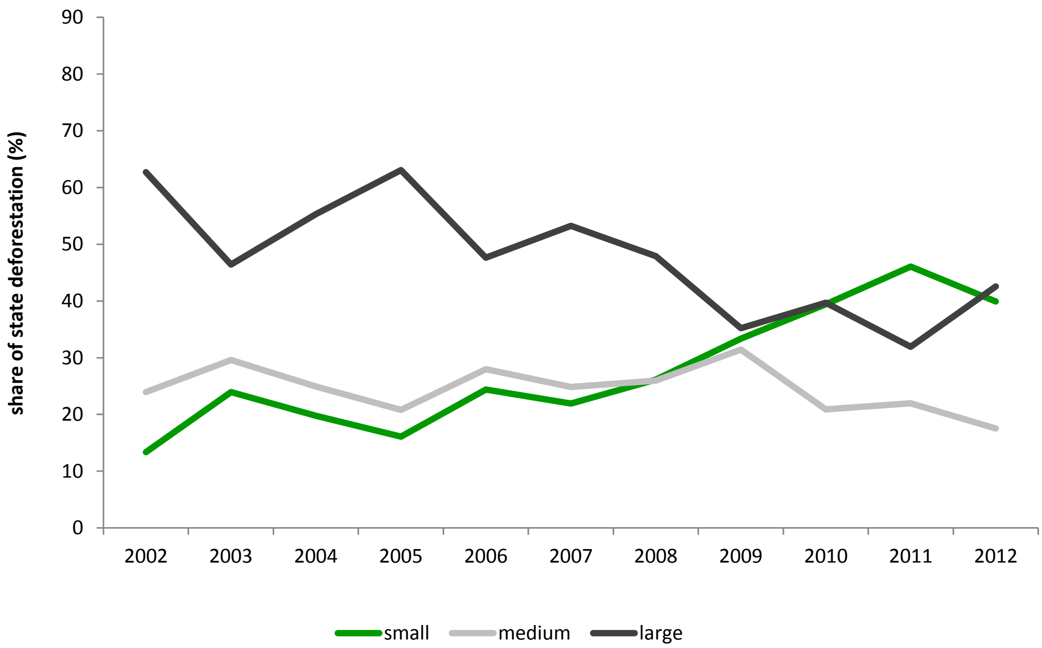
Notes: the figure illustrates annual state deforestation decomposed by deforestation polygon size. Data from PRODES/INPE (deforestation).

Figure 5: State Deforestation by Property Size, 2002–2012

(a) Mato Grosso



(b) Pará



Notes: the figure illustrates annual state deforestation decomposed by private rural property size. Data from PRODES/INPE (deforestation) and State Secretariats for the Environment (private property registries).

Figure 6: State Deforestation by Property and Polygon Size, 2002–2012

(a) Mato Grosso, Large Properties

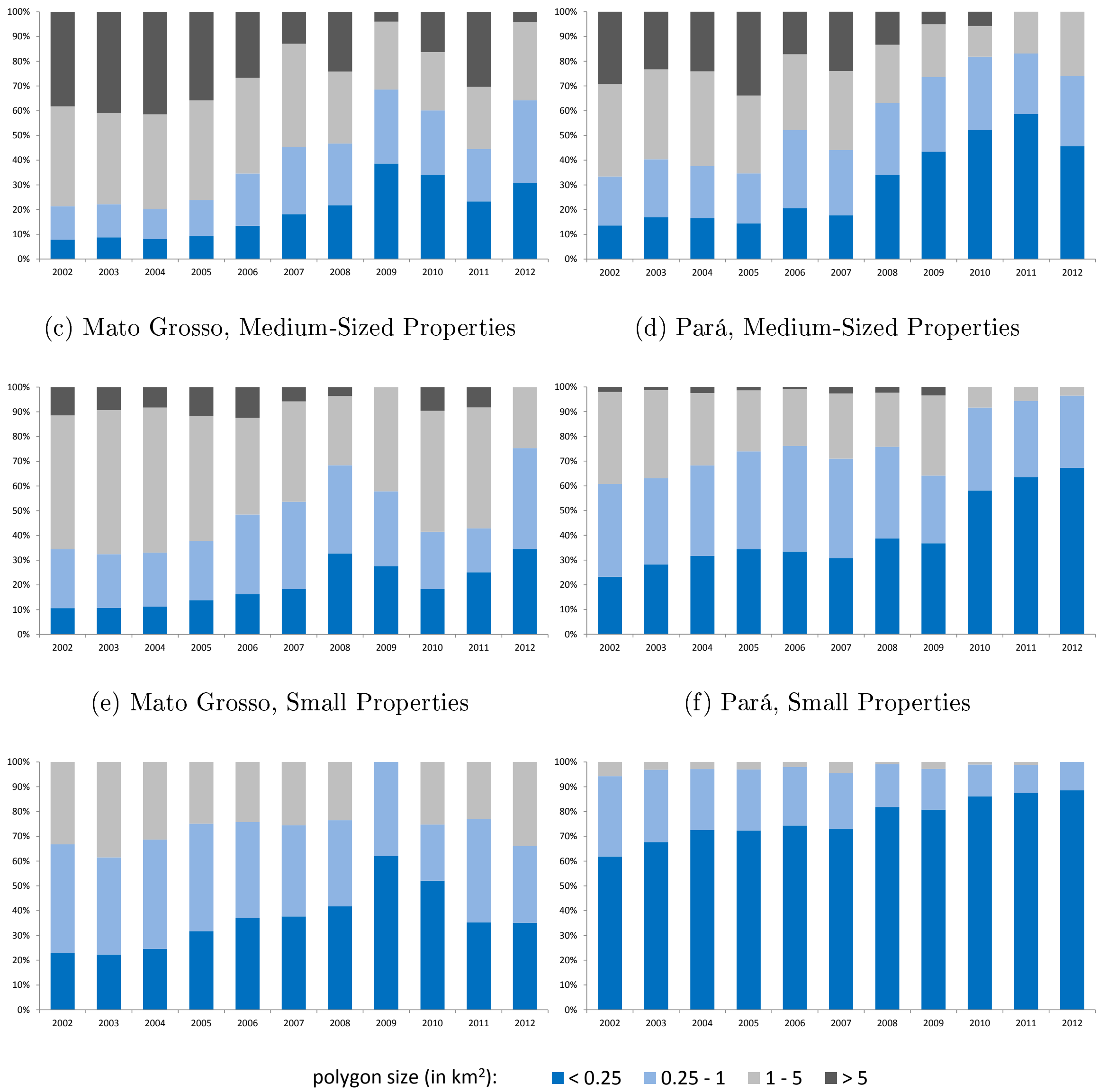
(b) Pará, Large Properties

(c) Mato Grosso, Medium-Sized Properties

(d) Pará, Medium-Sized Properties

(e) Mato Grosso, Small Properties

(f) Pará, Small Properties



Notes: the figure illustrates annual state deforestation decomposed by private rural property size and deforestation polygon size. Data from PRODES/INPE (deforestation) and State Secretariats of the Environment (private property registries).

Table 1: Descriptive Statistics — State Territory and Registered Properties

	Mato Grosso	**Pará**
State area	903,378	1,247,955
Protected area	160,983	679,208
Unprotected area	742,395	568,747
Registered area	356,865	229,024
Registered area as share of state area	40%	18%
Registered area as share of unprotected area	48%	40%
Registered area: small properties	12,086	32,021
Registered area: medium-sized properties	56,184	41,692
Registered area: large properties	288,595	155,311
Number of registered properties	23,731	47,412
Average size of registered property	15.04	4.83
Average size of fiscal module	0.88	0.70

Notes: The table presents descriptive statistics for each sample state. All areas are in km^2. Protected areas are composed of indigenous lands and conservation units (includes both integral protection and sustainable use units at federal, state, and municipal levels). Registered properties refer to all private rural landholding holding either a temporary or permanent CAR or LAU — see detailed description in Section 3.1. A fiscal module is defined as the minimum area needed to ensure the economic viability of exploring a rural establishment within a given Brazilian municipality. Property size is defined as follows: small properties are smaller than 4 fiscal modules; medium-sized properties are larger than 4 but smaller than 15 fiscal modules; and large properties are larger than 15 fiscal modules. Data from the Ministry of the Environment and the National Indian Foundation (protected areas) and State Secretariats for the Environment (private property registries).

Table 2: State Deforestation by Property Size, 2002–2012

Year	**Mato Grosso**			**Pará**		
	small	**medium**	**large**	**small**	**medium**	**large**
2002	247	961	2,816	522	938	2,456
2003	322	1,294	3,710	1,072	1,324	2,077
2004	336	1,219	4,001	758	954	2,118
2005	221	849	3,047	651	842	2,551
2006	63	293	777	528	606	1,032
2007	71	215	595	544	617	1,322
2008	79	206	950	594	590	1,088
2009	14	51	162	378	356	399
2010	21	77	151	390	207	393
2011	31	80	253	305	146	211
2012	17	27	141	161	71	171
difference 2002–2012	-93%	-97%	-95%	-69%	-92%	-93%

Notes: the table presents total forest area cleared within each category of property size. All areas are in km^2. A fiscal module is defined as the minimum area needed to ensure the economic viability of exploring a rural establishment within a given Brazilian municipality. Property size is defined as follows: small properties are smaller than 4 fiscal modules; medium-sized properties are larger than 4 but smaller than 15 fiscal modules; and large properties are larger than 15 fiscal modules.

Table 3: OLS Regressions — Deforestation in Small *vs.* Medium and Large Properties

	(1) Probability of Clearing Forest	(2) Size of Largest Cleared Polygon	(3) Cleared Area as Share of Property Area	(4) Probability of Clearing Forest	(5) Size of Largest Cleared Polygon	(6) Cleared Area as Share of Property Area
*small * year2003*	-0.109	-0.393	0.023	-0.121	-0.214	0.018
	(0.017)***	(0.045)***	(0.007)***	(0.021)***	(0.035)***	(0.007)***
*small * year2004*	-0.100	-0.410	0.034	-0.158	-0.199	0.011
	(0.017)***	(0.038)***	(0.007)***	(0.014)***	(0.026)***	(0.002)***
*small * year2005*	-0.084	-0.295	0.027	-0.167	-0.215	0.007
	(0.013)***	(0.032)***	(0.006)***	(0.015)***	(0.043)***	(0.002)***
*small * year2006*	-0.038	-0.062	0.006	-0.102	-0.092	0.010
	(0.007)***	(0.019)***	(0.003)**	(0.011)***	(0.017)***	(0.002)***
*small * year2007*	-0.029	-0.028	0.009	-0.111	-0.116	0.010
	(0.006)***	(0.016)*	(0.003)***	(0.012)***	(0.024)***	(0.001)***
*small * year2008*	-0.050	-0.049	0.011	-0.085	-0.075	0.016
	(0.008)***	(0.019)**	(0.003)***	(0.012)***	(0.010)***	(0.002)***
*small * year2009*	-0.008	0.012	0.004	-0.039	-0.025	0.012
	(0.006)	(0.012)	(0.002)**	(0.008)***	(0.010)**	(0.002)***
*small * year2010*	-0.003	0.011	0.005	-0.017	-0.008	0.016
	(0.006)	(0.012)	(0.001)***	(0.011)	(0.007)	(0.002)***
*small * year2011*	-0.008	0.006	0.006	0.002	0.002	0.013
	(0.006)	(0.013)	(0.002)***	(0.010)	(0.005)	(0.002)***
*small * year2012*	-0.001	0.020	0.003	0.002	0.005	0.006
	(0.007)	(0.013)	(0.002)*	(0.008)	(0.006)	(0.001)***
Observations	261,041	115,192	115,192	521,532	361,053	361,053
R-squared	0.147	0.057	0.084	0.135	0.042	0.066
State	MT	MT	MT	PA	PA	PA
Municipality FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Coefficients shown are estimated using a property-by-year panel data set covering the 2002 through 2012 period. The sample includes all registered properties in Mato Grosso (columns 1–3) and Pará (columns 4–6). All specifications are estimated using OLS and model 1. The dependent variables are: a dummy variable flagging whether a property cleared any patches of forest (columns 1 and 4); the size of the largest deforestation polygon cleared in a property (columns 2 and 5); and total cleared area in a property as a share of total property area (columns 3 and 6). Only regressions using the first dependent variable include all registered properties; all other regressions use a restricted sample that excludes properties in which there was no deforestation from 2002 through 2012. All specifications include controls for cloud coverage and accumulated deforestation through 2001, as well as municipality and year fixed effects. Robust standard errors are clustered at the municipality level. Significance: *** $p<0.01$, ** $p<0.05$, * $p<0.1$.