The value of property rights and environmental policy in Brazil: evidence from a new database on land prices

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Abstract

Lack of property rights is associated with lower investment, development, and welfare. In the Brazilian Amazon, insecure property rights have historically led to civil conflicts and deforestation, which would be expected to provide incentives for landowners to seek formal title. In this paper, we construct a novel database of land prices in Brazil to measure the market value of formal title to land and compliance with environmental regulation. Using online advertisements of land sale offers scraped from a widely used seller's platform, we first estimate a hedonic model that regresses the last offer price on property attributes such as farm-level agricultural production, land characteristics, structure amenities, and capital equipment included in the offer, as well as spatial and temporal fixed effects. We use this hedonic model to examine how property rights and environmental compliance capitalize into land prices across the Amazon and Cerrado biomes. Our main results imply low net benefits from property rights and low net benefits from compliance with the central Brazilian regulation that aims to maintain forest cover, the Forest Code. Finally, we estimate a duration model that follows the sequence of weekly offers for a specific property until it sells. Our findings show that parcels compliant with the Forest Code sell 46% faster in the Amazon, while entitled properties in the Cerrado sell 9% faster, unless they are compliant with the Forest Code, which requires a substantial portion of the property to be under native vegetation cover.

Keywords: land prices, property rights, natural language processing, hedonic model, environmental policy, Brazilian Amazon.

1. Introduction

Developing regions' lack of property rights is associated with lower investment, development, and welfare (Acemoglu, Johnson and Robinson, 2001). In the Brazilian Amazon, the absence of property rights has led to land conflicts and deforestation. Brazil's constitution partly explains intrinsic incentives for land grabbing since individuals that deforest and make productive use of the land can be granted formal title by the government (Alston, Libecap and Mueller, 2000). As such, a large proportion of deforestation occurs on land owned by the state (Azevedo-Ramos and Moutinho, 2018; Reydon, Fernandes and Telles, 2020). Further, the pathway from claiming land to securing tenure is long and winding, with most properties remaining in an intermediate status of not having fully recognized legal tenure for years before it is ultimately granted. This situation of widespread insecure property rights have also led to civil conflicts (Alston, Libecap and Mueller, 2000; Fetzer and Marden, 2017) and incentivized additional speculative clearing. The economic and personal safety risks associated with this tenure insecurity is likely a strong incentive for landowners to seek formal property rights, but little is known about how the value of securing a title translates into increased value on the property asset. In this paper, we construct a new database on land values in Brazil to measure the market value of formal title to land and compliance with environmental regulation. Using advertisements of sale offers for specific properties, we estimate the marginal implicit price of formal property rights using hedonic regressions and investigate market dynamics (e.g., do farms with property rights sell faster?). We then examine how property rights are associated with outcomes both on average and conditional on environmental policy contexts. To the best of our knowledge, these important questions for conservation and economic development have never been analyzed.

In the Brazilian Amazon and Cerrado biomes, institutional features suggest that formal titling, which we refer to as property rights, may generate net costs for landowners. Formal titling is associated with properties being certified through the Terra Legal program or the National Institute of Colonization and Agrarian Reform (INCRA). Restrictions and possible penalties from increased exposure to environmental policies can decrease the demand for titled forested land, particularly for owners who plan to expand their agricultural land by deforesting (Lipscomb and Prabakaran, 2020). Further, titling facilitates the collection of land taxes (Reydon, Fernandes and Telles, 2020), and obtaining or transferring titles generates transaction costs (Libecap and Lueck, 2011). Lastly, the benefits of property rights may have been diminished by Resolution No. 3545/2008 of Brazil's Central Bank, which modified the requirements to obtain a subsidized public loan. This policy change removed the requirement to present the formal property title and replaced it with a requirement for environmental property registration, CAR (Azevedo *et al.*, 2017; Jung *et al.*, 2017). These institutional details may reduce the benefits of securing property rights via titling overall. Measuring the marginal benefit of formal title is therefore an empirical question that heretofore has been difficult to address due to a lack of suitable data.

While the availability of detailed data on property values across wide regions of Brazil has been limited or nonexistent, a handful of studies have estimated hedonic price functions in specific regions of the Amazon using small samples and self-reported land values from interviews (Chomitz *et al.*, 2005; Lourival *et al.*, 2008; Merry, Amacher and Lima, 2008; Sills and Caviglia-Harris, 2008). These studies focus on understanding the value of land with different uses, often to infer the opportunity cost of conserving native vegetation. Here, we construct our database by scraping weekly advertisements for land sales from OLX, the most popular selling and buying Brazilian online platform. We compile information on over 12,000 individual properties offered for sale between 2019 and 2020. Each observation is a single advertisement to sell a farm at a point in time. We use supervised machine learning and text mining to extract information from the ads, including offer price (i.e., list price), location, parcel size, and several other property characteristics. A unique property identifier allows us to track the same parcel over time, including changes in the offer price, and we proxy transactions by recording the last record before a property falls off the platform. We focus on the Amazon and the Cerrado biomes, where property rights are generally less established. Although there is no explicit market for formal titling, we hypothesize that the demand for this attribute correlates with the duration a property stays on the market and capitalizes into the sale prices.

Our analysis is based on two models. First, focusing on information provided in the most recent record for the property, we estimate a hedonic model that regresses the offer price on a vector of property attributes. Then, using weekly variation, we estimate a duration model that follows the sequence of offers (willingness to accepts) for a specific property that leads to a transaction. This model provides information about which farms' characteristics are associated with properties selling faster in the market context of our study region. In our preferred specification, we include municipality and year-month fixed effects, and control for the following attributes: types of production at the farm (e.g. soy, cattle, fruit trees), land characteristics (e.g. flat land), structure amenities (e.g. electricity, water), and capital equipment included in the offer (e.g. tractors, irrigation, confinements). Since owners self-select property rights for their land, our results are presented as informative and rich descriptors and a key example of the vast possibilities of studies provided by our database. Lastly, we analyze how prices vary based on compliance with the Forest Code, the central piece of legislation for land use and management on private properties, and according to whether those farms also hold property rights.

2. Background

2.1 Land tenure

Coordinated efforts to incorporate the Cerrado biome into Brazil's economy began in the 1960s (Klink and Machado, 2005). Approximately a decade later, the main focus of a slew of official and non-official development and colonization projects became the Amazon biome (Barona *et al.*, 2010), which was previously under traditional indigenous land governance. This recent history was accompanied by large scale clearing of natural vegetation often concentrated in undesignated/untitled public areas with poorly defined property rights (Pacheco and Meyer, 2022). Reform movements sparked by inequalities in land distribution led to modifications of the Brazilian constitution, which now stipulates that land should be used productively to fulfill its "social function" (Araujo *et al.*, 2009). The definition of productive use was not clearly defined but was generally interpreted to require a portion of the land to be cleared. As such, the reform resulted in incentives for settlers to deforest and in land disputes arising from the fact that settlers can occupy incumbent owners' properties to claim property rights (Alston, Libecap and Mueller, 2000; Fetzer and Marden, 2017).

The main institution that confers property rights in Brazil is INCRA. Established in 1988, INCRA has provided over a million households with more than 75 million hectares of land (Fetzer and Marden, 2017). Two other programs, which have had important implications for the enforcement of environmental regulations, are the property rights program Terra Legal and the environmental property registration program CAR. With the additional objective of responding to land conflict, Terra Legal was created in 2009 to provide landholders with a pathway to acquire formal property rights. It stated that households making productive use of the land for more than five years could request a legal title. The land titling was free for smallholders, subsidized for medium-size parcels and full cost for large parcels. Claimants of larger parcels also benefited because the program made the overall land titling process substantially easier (Lipscomb and Prabakaran, 2020). Different rules were included to favor compliance with environmental regulations. For example, final titling for smallholders is dependent upon a verification of compliance with the Forest Code, while failure to maintain compliance can result in property appropriation by the government for other landowners. Unlike formal titling, CAR is a way to georeference land that is self-declared and verified by environmental agencies at a second stage (Alix-Garcia *et al.*, 2018). CAR registration does not confer property rights and the datasets of CAR registrations presents the following challenges : (i) property boundaries sometimes have invalid GIS geometry and frequently overlap (e.g., when studying the whole country, Luiz et al. (2018) found that 47% of CAR area overlaps, compared to 6% for Terra Legal and 0% for properties certified through INCRA); (ii) CARs can be split into multiple properties which is sometimes done to avoid consequences for violating the Forest Code, and (iii) documentation is not consistently updated (Sparovek et al. 2019; L'Roe et al. 2016; Gibbs et al. 2020). Further, it is a common practice for landowners to put some of their land under a relative's name to avoid the negative consequence of violating environmental policies (Moffette and Gibbs, 2021). Because of the challenges of CAR, property rights certified through INCRA and Terra Legal are the ones recognized by legal and judicial institutions when evaluating historical and legal precedents in land conflicts.

Including the portion of rural land (encompassing all areas excluding water bodies and urban regions) that possesses private land tenure through INCRA or Terra Legal, or that is encompassed by conservation units, indigenous areas, military zones, or Quilombola land, we find that 31.7% of the Amazon and 33.5% of the Cerrado lack official and documented land tenure (see Appendix D for detailed methodology). The Amazon has a considerably higher percentage of its land designated as protected areas than the Cerrado, while the Cerrado has approximately four times more of its area categorized under private land tenure than the Amazon. Of the area without documented tenure in the Amazon, 17.5% is found within CAR boundaries, and within the Cerrado, 23.5% of the area without documented tenure is found in the CAR.

Previous work has generally found limited evidence that deforestation was reduced by Terra Legal (Lipscomb and Mobarak, 2017; Probst *et al.*, 2020) or CAR (Azevedo *et al.*, 2014; L'Roe *et al.*, 2016) although there is some evidence of such an effect in two of Brazil's Amazon states (Alix-Garcia *et al.*, 2018). The limited nature of the effects from these programs is potentially due to leakage or other types of policy avoidance such as deforesting smaller patches (which are less likely to lead to interventions from the Brazilian environmental police, IBAMA), or intentionally choosing the timing of deforestation before legal titling. No studies have investigated the effect of titles conferred by Brazil's land titling institution, INCRA.

The marginal benefit of formal titles in the Brazilian Amazon is generally considered low (Merry, Amacher and Lima, 2008). Compared to pastoral or agricultural parcels, forested parcels are characterized by lower prices with potentially large speculative gains, as the expected rent from land increases with deforestation (Margulis, 2003). This notwithstanding, the environmental policies and increased enforcement since 2004 (see for example Nepstad et al. 2014; Assunção, Gandour, and Rocha 2015; Hargrave and Kis-Katos 2013; Assunção, Gandour, and Rocha 2023) are also likely to have affected rents. Indeed, descriptive evidence suggests that changes in environmental policy can switch speculation to areas that are under less stringent policy (Miranda *et al.*, 2019). In sum, prices of forested land are likely to integrate the future benefits of agriculture and Forest Code compliance.

2.2 The Forest Code

Since 2001, the Forest Code has required landowners to preserve 80% of most private properties in the Amazon biome as natural vegetation, 20%-35% in the Cerrado biome, and 20% in all other biomes of the country, with these preserved set-asides designated as Legal Reserves. Brazilian environmental agencies tasked with enforcing the Forest Code have the ability to monitor illegal deforestation through satellite imagery and landowner identification using property boundary maps with personal information identifiers. IBAMA, under Decree no 6686, holds the specific mandate to enforce the Forest Code on private properties, while state enforcement agencies also play a role. IBAMA is authorized to impose fines for illegal deforestation, destroy machinery used in illegal deforestation, and seize exploited timber.

Noncompliance with the Forest Code carries significant costs, including the direct expense of reforestation in cases of illegal deforestation and the indirect cost of forfeiting rents from agricultural production (Azevedo *et al.*, 2017). Fines, when unpaid, can lead to imprisonment for illegal deforesters, burning of materials used for illegal deforestation, seizure of timber, and the need to engage legal representation in court (e.g., Justiça Federal 2013; Ibama 2016). In essence, legal compliance with the Forest Code offers substantial benefits by avoiding penalties, restoration costs, and the legal challenges associated with environmental fines. It is worth noting, however, that a significant number of fines have gone unpaid (Escobar, 2006; Imazon, 2013) and the situation has worsened with the relaxation of environmental policies under President Jair Bolsonaro's administration (Human Rights Watch, 2020; Coelho-Junior *et al.*, 2022). Studies suggest that most recent deforestation is occurring in public and untitled lands (Escobar, 2020). More details on the Forest Code are available in Appendix B.

3. Original dataset and summary statistics

We collected data between August 2019 to April 2020 for all lands offered for sale on the OLX online platform. Each observation represents one advertisement offering to sell a farm at a specific point in time and provides the following information: unique ID, ad title, description, price, parcel size, municipality name, state, date the advertisement was initially published, and date of scraping. We limit our sample to advertisements posted in municipalities (roughly the equivalent of a county in the United States) located in the Amazon or Cerrado biomes.

3.1 Data description

Our process begins by standardizing several text elements. We first remove diacritics (i.e., special characters such as accents and cedilla) and transform all text into uppercase letters. We then regularize spelling, which includes removing double spaces, replacing abbreviations with the full word (e.g. replacing "ha" with "hectare"), correcting common spelling mistakes (e.g. replacing "hetare" with "hectare"), and simplifying keywords with *stemming*. Stemming involves removing the ends of words to reduce the total number of unique words in the dataset (Grimmer and Stewart, 2013). Although parcel size and price are contained in dedicated post fields, their units are inconsistent across users and not clearly specified. For example, parcel size could be in hectares or square meters, while prices could be per area unit or total. Given these inconsistencies, we first extract parcel size and price from the advertisement title and description. We prioritize information extracted from the title because we consider this information to be more precise and succinct. This means that if there is a price in the title, we use this value and omit any price from the description. For those parcels from which we cannot recover the parcel price from the title or the description, we use the dedicated post field combined with penalized regression (described below) to determine whether a per-area unit or a total price was provided.

Parcel size data are constructed from numbers that precede an area measure. We do not use the dedicated area post field because the unit measure is not clearly specified. Area measures include square meters, hectares, *alqueires*, and *tarefas*, all of which can also be expressed in thousands. Once extracted, we convert all numbers into hectares. Dimensions of *tarefas* and *alqueires* vary by state. *Tarefa* is a unit that was originally used for sugarcane land; it is equivalent to 0.363 ha in Ceará, 0.3052 ha in Alagoas and Sergipe, and 0.4356 ha in Bahia (Stolze Gagliano and Pamplona Filho, 2018). *Alqueires* are a legacy of Portuguese colonization and are similar by geographic zones (e.g. regions near São Paulo use the *alqueire paulista*, which is 2.42 ha/*alqueire*, while regions near Minas Gerais, commonly use the *alqueire mineiro*, which is 4.84 ha/*alqueire*). To define the conversion factors of *alqueire* to hectare, we use the most common conversion factor in the state (IBGE, 1948). When users register multiple values, we use the following priority order for assigning size: hectares, *alqueires*, *tarefas*, and square meters.

We create indicator variables describing property characteristics by looking for keywords in the text description. To reduce the total number of variables for which we construct categories; for example, corn, rice, sugar cane, wheat and beans are grouped under the "non-soy agriculture" category. Soy is its own category, given its importance in our study region (Jung and Polasky, 2018; Rausch *et al.*, 2019). Similarly, property rights are defined by the combination of multiple keywords. Using the advice of two Brazilian experts (a lawyer and an environmental engineer specializing in land change science), we combine common expressions for property rights and formal titling program names such as Terra Legal, SIGEF (*Sistema de Gestão fundiária*) and CCIR (*Certificado de Cadastro de Imóvel Rural*). The Forest Code compliance designation requires keywords specifically related to compliance with the Forest Code (i.e. Legal Reserve, Areas of Permanent Preservation, Forest Code compliance). This definition is thus indicative of Forest Code compliance, does not imply full compliance, and possibly in certain cases shorthand for "no illegal clearing." Other keywords refer to whether the land is sold through a realtor, types of production on the farm (e.g. soy, cattle, fruit trees), structure characteristics (e.g. electricity, water), and capital equipment included in the offer (e.g. tractors, irrigation, confinements). Table A1 presents the exact Portuguese words and stemming that created our key formal characteristic variables and their English translation.

To assign sale prices to properties, we use an algorithm that (a) distinguishes offers that are expressed per area unit from those that are given as total price; (b) converts to consistent currency units; and (c) uses a machine learning protocol to fill in the missing information. Figure 1 illustrates the steps in our algorithm. We first look for explicit mention of price in the advertisement title, resorting to the description only if it is absent from the title. We then determine the price format, first checking to see if the price is total or per area unit. For example, we identify numbers that follow the currency character (e.g., "$") and that precede "per hectare". We convert all per-unit prices to total prices based on the previously determined parcel size. Next, we determine the currency units by identifying prices that need to be multiplied by scale factors. For example, we identify numbers followed by "thousands" or "millions" and convert them accordingly.

For posts we cannot recover the price from the advertisement title or description, we consider the dedicated price field, which can be a per-unit price or a total price. We first assign all prices greater than 500,000 reais (a threshold corresponding to a value greater than the 99th percentile of the price per hectare distribution) as total price and then use machine learning to differentiate values lower than 500,000 reais. Specifically, we implement lasso with log total price as the dependent variable and the following right-hand side variables: fourth-order polynomial of log size, whether the land is sold through a realtor, types of production at the farm, structure characteristics, and capital equipment included in the offer, as well as state fixed effects. We do not use property rights and Forest Code compliance indicators since these are our variables of interest. The sample is composed of the properties for which we can identify prices from the title or description and we keep only the last record before a property falls off the platform to maintain equal weights for all properties.[1] Figure 2 compares predictions for total

[1] An advantage of machine learning methods that rely on both regularized estimation and data-driven choices of the regularization parameter is that, due to the bias-variance trade-off, it avoids over-fitting (Ahrens, Hansen and Schaffer, 2019). The regularization parameter is chosen through 10-fold cross-validation, since the performance of cross-validation rarely increases for values greater than 10 (Hastie, Tibshirani and Friedman, 2009; Arlot and Celisse, 2010). Cross-validation implies that the sample is divided in the training and the test sample. The training sample is in itself divided into a number of cross-validation samples. For each subsample, the cross-validation sample is set

price with their real values to illustrate the predictive power. The R^2 is equal to 0.51 and we observe a good fit with high density of points around the fitted line (which has a slope close to one).
To ascertain whether the price field represents a per-unit price or a total price, we evaluate the (i) difference between the predicted total price and the designated field against the (ii) difference between the total price and the price per unit multiplied by the number of units (both transformed logarithmically). If the minimum of these two differences corresponds to (i), we classify the price field as a total price; conversely, if the minimum corresponds to (ii), we classify it as a per-unit price. Whether we employ lasso, ridge, or elastic net as machine learning models yields nearly indistinguishable outcomes.

3.2 Summary statistics and maps

To arrive at our analysis sample, we sorted our scraped and processed data as follows. First, due to the renewal policy, OLX advertisements expire automatically after 60 days unless the seller pays an amount that varies between 22.99 reais and 114.99 reais (4.51 2020 USD and 22.54 2020 USD). For this reason, we drop ads when a property falls off the platform after 56 to 60 days, where the 56-day threshold is the minimum number of days that we could observe if no payment occurs since our scraping algorithm runs every 7 days. Next, we drop potential entry errors: properties with per hectare price less than the 5th percentile or greater than the 95th percentile of the empirical distribution, since these values could be associated with post errors in the price or the size (e.g., a dot instead of a comma before the thousands place). Finally, we drop advertisements for land rentals and those offering parcels that are less than 2 hectares. The latter are unlikely to represent sales of productive agricultural land and are therefore not comparable to the rest of the sample. To minimize prediction error, these steps are executed before implementing lasso.

Figure 3 presents the geographical distribution of the median prices in the Amazon and Cerrado biomes. We observe that smaller-area municipalities are correlated with higher median prices, which is expected since smaller municipalities are more densely populated, and more densely populated areas are generally more expensive because the demand is comparatively higher than the supply. We also note spatial clustering, in that neighboring municipalities tend to have similar prices. The full distribution of log prices and log parcel sizes in our sample is presented in Figure A1. The median per hectare price is 8,000 reais, and the 10th and 90th percentiles are 1,458 reais and 33,057 reais, respectively. The mean price per hectare is 15,857 reais. The median parcel size is 376 ha, the 10th

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aside, and the remainder is used to predict outcomes for the excluded subsample. The model is fit to the training data for a given value of the regularization parameter (λ). The regularization parameter is chosen based on the one that minimizes the mean squared prediction error for each subsample (Athey and Imbens, 2016). Because lasso, unlike ordinary least square, is not invariant to linear transformations, data are standardized for each subsample in order to ensure that the training data does not contain information from the cross-validation sample (Ahrens, Hansen and Schaffer, 2019). In other words, in each step where the model is used to fit the training data for a certain value of λ, the training data are re-centered and re-standardized *on-the-fly*. This regularization method is guaranteed to work well in high-dimensional estimation and prediction settings (Abadie and Kasy 2019).

percentile is 43 ha, the 90th percentile is 2,555 ha, and the mean equals 3,971 ha. In Figure A2, we compare the correlation between municipal prices from our dataset and prices from the best alternative of land prices data in Brazil, FNP. We observe an excellent fit between the two datasets for the three categories of productive uses of land: agricultural, livestock, and timber. Estimated correlations vary between 0.942 and 1.092, with all R^2 values at least 0.98 (i.e., an estimated coefficient equal to 1 and an R^2 equal to 1 would mean a perfect fit).

Figure 4 summarizes the indicator variables constructed from advertisement keywords, including property rights, Forest Code compliance, and types of production (Figure 4a) and land characteristics, structure amenities, and capital equipment included in the offer (Figure 4b). Among all land for sale, 31.5% have property rights, 3.4% are compliant with Forest Code, and the most common type of production is livestock. Most of the land (67%) includes a house and less than 7.6% are advertised by a realtor.

To illustrate the market's competitiveness, we map the total number of farms on the market (Figure 5a). To understand the spatial distribution of variables of interest, we map the percent of the farms on the market that have property rights (Figure 5b) and compliance with the Forest Code (Figure 5c). In both cases, we see spatial variation. Compliance with the Forest Code is more frequent in the Cerrado biome than in the Amazon, most likely because of the lower requirement of 20%-35% instead of 80% of the property in natural vegetation.

Finally, Table 1 provides means, standard deviations, and normalized differences of means for our chosen descriptors for parcels with and without property rights. The comparisons show that many parcels with and without property rights are comparable in their attributes. On average, parcels with property rights have about the same price, are slightly larger, and are more frequently in compliance with the Forest Code. In terms of production at the farm, parcels with and without property rights are relatively similar. In terms of capital included, the parcels with property rights tend to include tanks (most of them of water) and corrals (pens for livestock) more frequently. We further note that 8% of parcels with property rights are sold by realtors, compared to 7% for parcels without property rights. This suggests there is no systemic bias regarding whether realtors prefer to sell properties with property rights. The most considerable difference between parcels with and without property rights is the likelihood to have a CAR (40% for those with property rights vs 15% for those without). This is expected because documentation linked with property rights would facilitate registering a CAR. Finally, summary statistics show that parcels with property rights are generally flatter, more likely to be fenced, and more likely to have electricity and water.

3.3 Data limitations

To our knowledge, we are the first to create a large sample dataset based on scraped land advertisements that brings high-frequency land market information. Here, we focus on its three main limitations and possible consequences. First, we acknowledge that some errors are likely present in the price and size data. Since most errors emerge from people posting advertisements, measurement errors are likely random and, as such, unlikely to bias our results given our large sample (although they increase standard errors). Second, the identification of property attributes depends on the thoroughness of the ad description, meaning that our understanding of property attributes is likely incomplete. Statistical bias could be introduced if owners with property rights are more precise in their property descriptions than their counterparts without property rights. Still, our dataset allows us to control for property characteristics well beyond what other data sources have been able to do in the Brazilian context, and in the context of most other developing countries. Finally, ideal data would also include the spatial location of properties as we would then be able to measure their land use change over time. However, we only know the municipality where the land is located and thus, cannot control for the parcel's specific cleared area. In our regressions, we use this second-best information to control for characteristics that do not vary over time and can confound land prices.

4. Empirical approach

We interpret the sequence of weekly ads that we observe for a given seller prior to a property leaving the online platform as a series of offers for that seller. As explained in our theoretical model, the functions P^2 and P^3 in Figure A3 are not market transactions, but these offers do tell us about the seller's willingness to accept payment and likely reflect sellers' evolving understanding of market dynamics. When a property falls off the platform, we interpret this as a sale. This is represented in Figure A3 by a tangency between offer and bid functions (as shown in the figure for the functions U^1 and P^1). From these assumptions, we use the last observed offer price as the market sale price for the specific land parcel. As presented in Appendix C, our theoretical model illustrates how these two features are relevant for our empirical analysis.

We consider two empirical models, a hedonic price analysis and a duration until sale analysis. First, using the observed transactions for our main analysis, we estimate a first-stage hedonic price function to characterize the market equilibrium. We use specifications given by

$$ln\, P_i = \beta Prop.Right_i + \eta\, ln(S_i) + \varphi_{m(i)} + \tau_t + \gamma X_i + \theta Z_i + \varepsilon_i, \quad (1)$$

where lnP_i is the natural logarithm of the price per hectare for property *i*, S_i is the size in hectares, and $Prop.Right_i$ is a binary variable that takes the value of 1 if the land has property rights, and 0 otherwise. A municipal fixed effect $\varphi_{m(i)}$ accounts for location-specific determinants of land prices, such as tax levels, population, and other factors that may be correlated with the presence of property rights and environmental regulations on the property. To control for the seasonality of sales (which can be impacted by macroeconomic factors affecting the different regions in Brazil similarly), we use month-of-year fixed effects for the date of sale τ_t. We also use a broad set of attributes at the property level: X_i is a vector indicating commodities produced at the farm (agriculture, livestock, timber, fruits, fish) and an indicator for deforested; and Z_i is a vector of other property attributes, which includes land characteristics, structure amenities, capital equipment included in the offer, whether the land has a CAR and whether the ad was posted by a realtor. Finally, ε_i includes all unobserved determinants of property prices.

Our coefficient of primary interest is β, which determines the marginal implicit price of the property rights attribute. While the specification in (1) recovers the homogenous correlation of property rights on land prices, the implicit price of property rights may vary with other observable land characteristics, including environmental policy. To analyze this heterogeneity, we first consider two distinct samples and test whether the implicit price of property rights vary across biomes. We then estimate equation (1) with our indicator for compliance with the Forest Code alone as well as its interactions with the property right indicator.

In a secondary analysis we examine the time that individual properties stay on the market. We use the random variable T_i to denote the number of days that property *i* is listed on the platform before it sells, or until our observation period ends. We interpret each weekly record prior to a transaction as points on a seller's offer functions, like the functions Π^3 and Π^2 show in Figure A3, and the last record as a transaction marking the observed value of T_i. We are interested in a descriptive analysis of how property attributes affect time until sale – particularly regarding property rights and environmental compliance characteristics. For this we use a duration model to characterize the conditional distribution of *T*. That is, we estimate the parameters in

$$F(t\,|\,x) = \Pr\left[T \leq t\right], \tag{2}$$

where *F*() is based on a Weibull survival distribution. Covariates include property rights, the Forest Code compliance indicator, and the same controls as for the hedonic model.

5. Results

We first estimate the correlation between property rights and parcel prices on the full sample composed of all parcels in the Amazon and the Cerrado biomes. Table 2 shows the results where we gradually integrate our set of controls; column (1) presents our naïve estimates and only includes property rights and log(size), column (2) adds municipal fixed effects, column (3) adds the month-year fixed effects, column (4) adds the production at the farm (X_i), and column (5) adds the amenity controls (Z_i). Our estimates show that property rights are associated with low benefits to parcel owners. The change in coefficient magnitude and statistical significance when we add the municipal fixed effects supports our assumption that characteristics of municipalities may confound the implicit price of property rights and support the importance of controlling for these. The gradual integration of the controls in columns (3), (4), and (5) does not modify the qualitative interpretation of our results, which is that the marginal net benefits of property rights are low. The estimated coefficients linked to the controls provide validation for the quality of our database, as they align intuitively with recognized characteristics of the region. As an initial example, while keeping all other attributes constant, parcels engaged in soy production exhibit the highest marginal price, followed by fruit trees, non-soy agriculture, livestock, fish, and timber. This ordering of marginal values corresponds to the observation that deforested land holds a higher value compared to forested land utilized for timber production, and is consistent with the FNP data where the price of forested properties are, on average, 78% lower than properties used for agriculture and 58% lower than properties used for livestock in the Amazon and Cerrado biomes. As a second example, the price per hectare decreases as the size of the property increases—a common characteristic in land markets, and particularly pronounced in our study region due to the tendency of larger parcels to have more vegetation cover, resulting in a lower price per hectare. Results remain consistent if we remove the variable controlling for CAR registration.

To test whether the implicit price of property rights varies with the institutional context, we then estimate the same model separately for the Amazon and the Cerrado biomes. Since the sample corresponding to the Cerrado parcels is about five times larger than the one for the Amazon, these biome-specific results provide a clearer understanding of the differences between biomes. Results are presented in Table 3, where columns (1) and (3) integrate municipal and month-year fixed effects and columns (2) and (4) add the land-use and the amenities controls. We find that property rights in the Cerrado biome are associated with low net benefits while in the Amazon, they increase the price by 11%, although this is not statistically significant. This may be associated with the fact that the risk of civil conflicts and violence are higher in the Brazilian Amazon.

In Table 4, we show how indication of Forest Code compliance by itself capitalizes into land prices (columns (1), (2), (5), and (6)) and how it capitalizes differentially according to property rights (columns (3), (4), (7), and (8)). Since the stringency of the environmental policy is fundamentally different between the two biomes, we run separate analyses. In Brazil, and particularly in the Amazon biome, forested properties sell for less than properties with agricultural activities. We observe this in the results of our hedonic model where the marginal price for parcels that produce timber, while holding other attributes constant, is 47% lower in the Amazon and 15% lower in the Cerrado biome, than the average property that does not produce timber (Table 4). Controlling for timber production and for other variables plausibly removes confounding variation, as suggested by the decrease in the point estimate associated with Forest Code compliance in the Amazon biome (columns (2) and (4)). For this reason, we focus on interpreting our results presented in the columns with even numbers.

As presented in columns (2) and (6) of Table 4, the indication of Forest Code compliance does not translate into price changes for either of the two biomes. However, this overall result might conceal some heterogeneity based on the property rights attribute. In column (4), we explore the interactions between Forest Code compliance and the property rights attribute for the Amazon biome. Results, statistically significant at the 10% level, reveal that: (i) the indication of Forest Code compliance for properties without property rights increases the parcel price by 54%; (ii) in the absence of Forest Code compliance, the property rights attribute raises parcel prices by 12%; and (iii) these individual effects offset each other for parcels with both property rights and indications of Forest Code compliance. For the Cerrado biome, we show that indication of Forest Code compliance does not increase the parcel price, whether the parcel has property rights or not. This is unsurprising since this biome presents lower requirements and receives less enforcement pressure from the Forest Code. Results are extremely robust to the inclusion of municipal-level total embargoes (see Table A2), an embargo-free property indicator variable (see Table A3), as well as municipal percent vegetation cover (see Table A4).

The interpretation of our results depends on two main assumptions of the equilibrium price function. The first assumption is that the posted offer before the ad falls off the listing is the transaction price, and the second assumption is that markets are competitive and thick. If these assumptions are correct, then we are recovering the hedonic price function. However, if markets are thin, individual negotiating skills and market power could directly affect price outcomes. Here, we argue that the website we are scraping approximates market competitiveness to a reasonable degree (the total number of ads per municipality is illustrated in Figure 5a) and that our rich set of controls takes care of potential confounding variables such as land-use and municipal specific characteristics that influence both prices and property rights.

The duration model is first analyzed for the sample composed of all parcels in the Amazon and the Cerrado. Table 5 shows the results where we gradually integrate our different controls. In all specifications, the coefficient on property rights is negative and statistically significant indicating that parcels with property rights tend to sell faster. Results from column (5), our preferred specification that includes all controls, suggest that parcels with property rights tend to sell 6% faster compared to the baseline hazard. Table A5 demonstrates that this effect is exclusively observed in the Cerrado biome. We also note that properties for which the main production is livestock take more time to sell; which is consistent with anecdotal evidence for the region.

Then, we investigate market dynamics for those parcels compliant with the Forest Code as well as the potential differentiation in terms of property rights. Table 6 presents the results. In the Amazon biome, parcels with Forest Code compliance tend to sell 46% faster compared to the baseline hazard. In the Cerrado biome, we observe that land with property rights is sold 9% faster while unregistered land compliant with the Forest Code is sold 43% faster. However, if the parcel had both property rights and compliance with the environmental regulations, it follows the baseline hazard. Findings in the Cerrado biome suggest that parcels with either property rights or compliance with the Forest Code attract greater demand compared to those possessing both characteristics—a trend mirroring what we observed in the hedonic model for the Amazon biome.

6. Discussion and conclusion

In this paper, we measure the market value of formal title to land using online advertisements of sale offers scraped from a widely used seller's platform. Our results suggest low net benefits from property rights on average, although benefits in the Amazon are higher than in the Cerrado, most likely due to the violent conflicts and possibility of land seizure in the region. We also examine how environmental compliance capitalizes into land prices by itself as well as conditional on property rights. We observe that indications of Forest Code compliance alone do not alter parcel prices, either in the Amazon or in the Cerrado. This finding suggests that there is no inherent value in Forest Code compliance, potentially reflecting the low enforcement during our study period and the higher prices of deforested land.

In the Amazon biome, only untitled parcels with indications of Forest Code compliance demonstrate a positive association with regard to prices, potentially because titled properties are less appealing to buyers seeking environmentally compliant properties. This interesting correlation suggests that some characteristics of compliance with the Forest Code in the Amazon become less desirable when the property is titled. One possible explanation is that owners of multiple productive properties look for indicators of Forest Code compliance but prefer to avoid the transaction costs of going through the involved and expensive process of changing the name on a title: for this type of buyer, a property less advanced in terms of titling might be a better asset. An alternative explanation is that, given the current and anticipated future lack of enforcement of the Forest Code, certain buyers may be considering speculative use of untitled land. Here, by speculative use of untitled land, we mean acquiring highly forested land, a proxy indicated by the compliance with the Forest Code, with the intention of deforesting and subsequently selling the property in hopes of obtaining commensurate gain. If landowners with deforestation intentions anticipate stricter enforcement of the Forest Code in the future, opting for a property without a title might be perceived as less risky. This is because titled properties are explicitly linked to their owner and landowners are aware that satellite imagery can track deforestation over time on their properties. However, it is worth noting that a more extensive investigation spanning a longer timeframe and encompassing a larger parcel population would be necessary to formulate clearer interpretations and conclusions regarding this specific result.

The findings of the duration model complete our understanding of market dynamics and show that properties compliant with the Forest Code in the Cerrado biome sell faster if they do not have property rights. The hedonic and the duration models provide different insights into our research questions. While the hedonic model directly connects the attributes with their implicit price, the duration model conveys information about the speed at which parcels with certain characteristics tend to sell. In the Amazon biome, the hedonic model suggests capitalization of the property rights and Forest Code compliance in the prices. In the Cerrado biome, the duration model suggests that parcels with property rights or Forest Code compliance sell faster, but there is no indication that these attributes capitalize into the prices. One possible explanation to reconcile those results resides in the fundamental differences between the two regions, both in terms of property rights and Forest Code requirements. Indeed, the greatest advantage of formal title to land in the Amazon is to protect against land seizure and conflicts. Since this risk is somewhat smaller in the Cerrado biome, it is reasonable to expect that property rights do not capitalize as much into land prices on average. Since requirements for the Forest Code are much greater in the Amazon, the capitalization should be expected to differ.

One limitation of our empirical design is that the decision to buy or sell a parcel with formal title is endogenous to the landowner characteristics. In studies specific to developed countries, economists deal with the endogeneity of property rights with techniques (e.g., regression discontinuity) that leverage large dataset both spatially explicit and rich in covariates (e.g. Turner, Haughwout, and van der Klaauw 2014; Ayres et al. 2020). While these represent the best analyses, implementation in developing countries is difficult since obtaining transaction prices and spatially explicit characteristics for a large sample is often impossible.

Absence of property rights in Brazil has led to land conflicts and deforestation. In this paper, we contribute to the empirical literature on the costs and benefits of property rights and environmental compliance. To our knowledge, we are the first to use land advertisements obtained from an internet marketplace to create a large dataset of high-frequency land market information to study these questions. Further research will help determine how the recent surge in prices amid the post-pandemic context, characterized by global supply chain disruptions and input inflation, influenced how property rights and environmental policies capitalize into land prices in the region. That said, quantifying the implicit value of property rights and environmental policy compliance is an essential step toward understanding the motivating and discouraging factors for entitling properties and how environmental policies influence property rights incentives, both questions being essential for the sustainable development of tropical forests and human livelihoods.

Main figures and tables

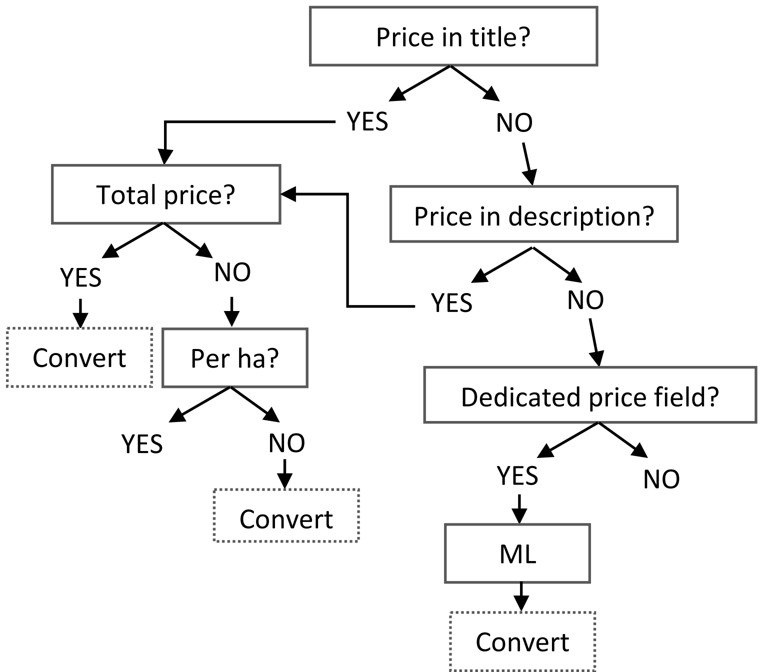

Figure 1 Algorithm to extract the price per hectare. The count of parcels from which the price is extracted from the title is 102, from the description is 10,076, and from which the machine learning algorithm aided in determining whether the price was per hectare or total is 1,822.

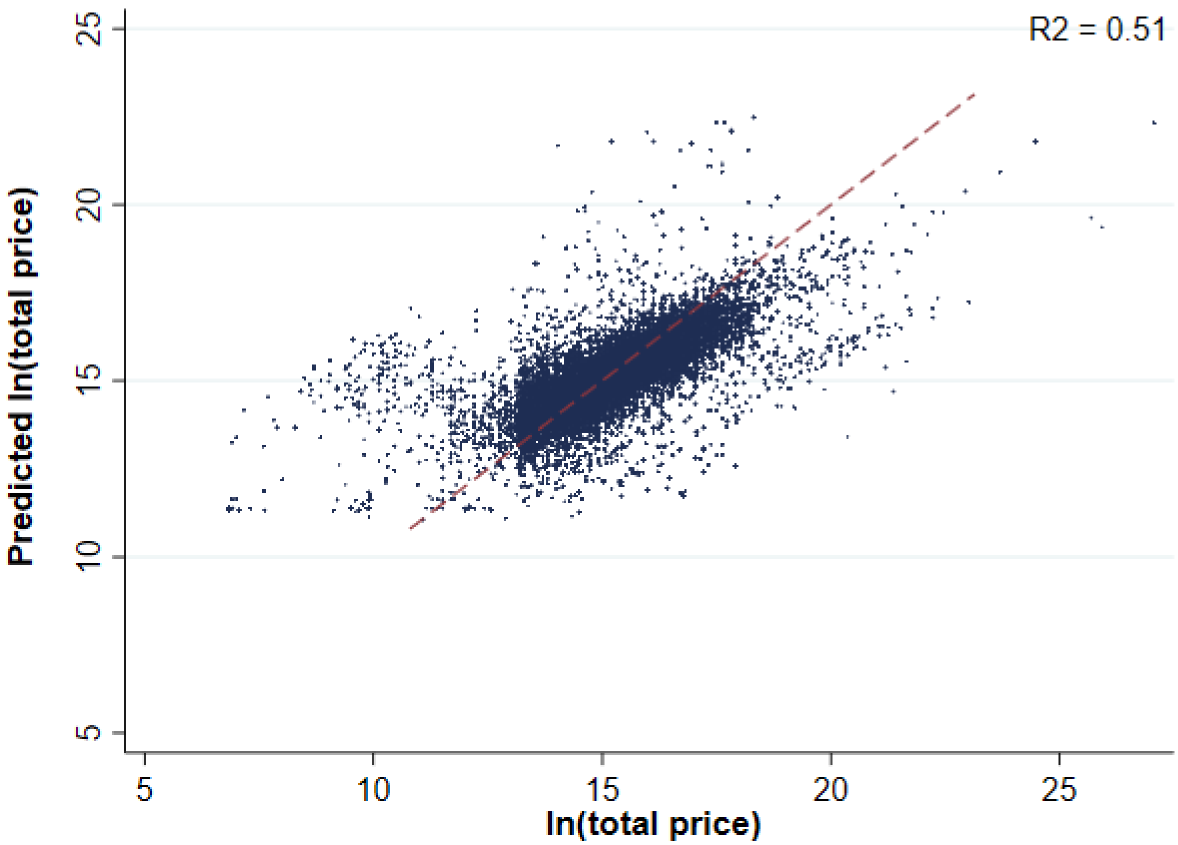

Figure 2 Scatter plot of the total price and its predicted value. R^2 is equal to 0.51. Extracted from lasso with a cross-validation minimum lambda equal to 0.002.

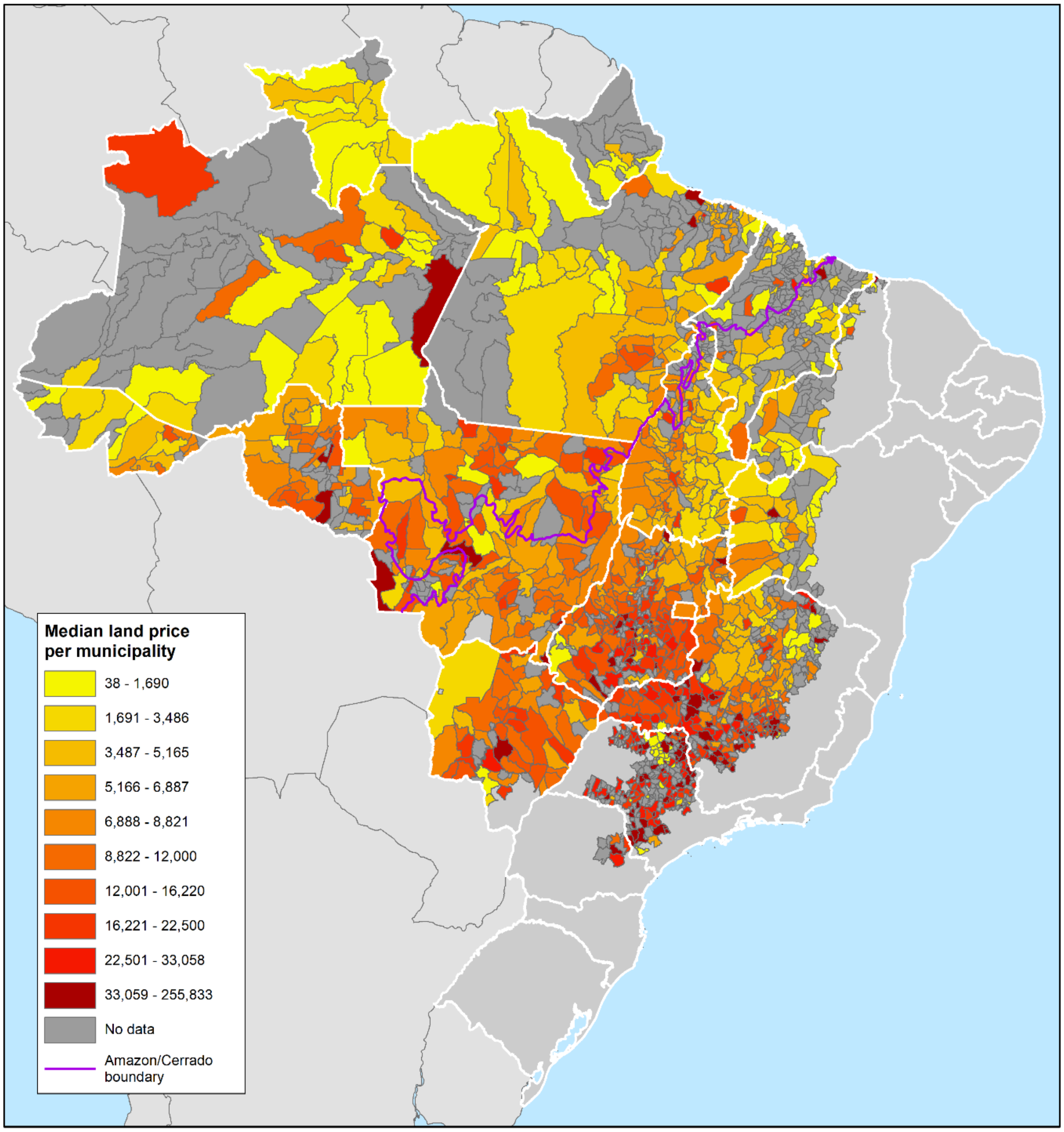

Figure 3 Geographical distribution of median land prices per hectare for each municipality in the Amazon and Cerrado biomes. High values in the North-Western states are often associated with a single or a few properties. Values come from the last weekly records.

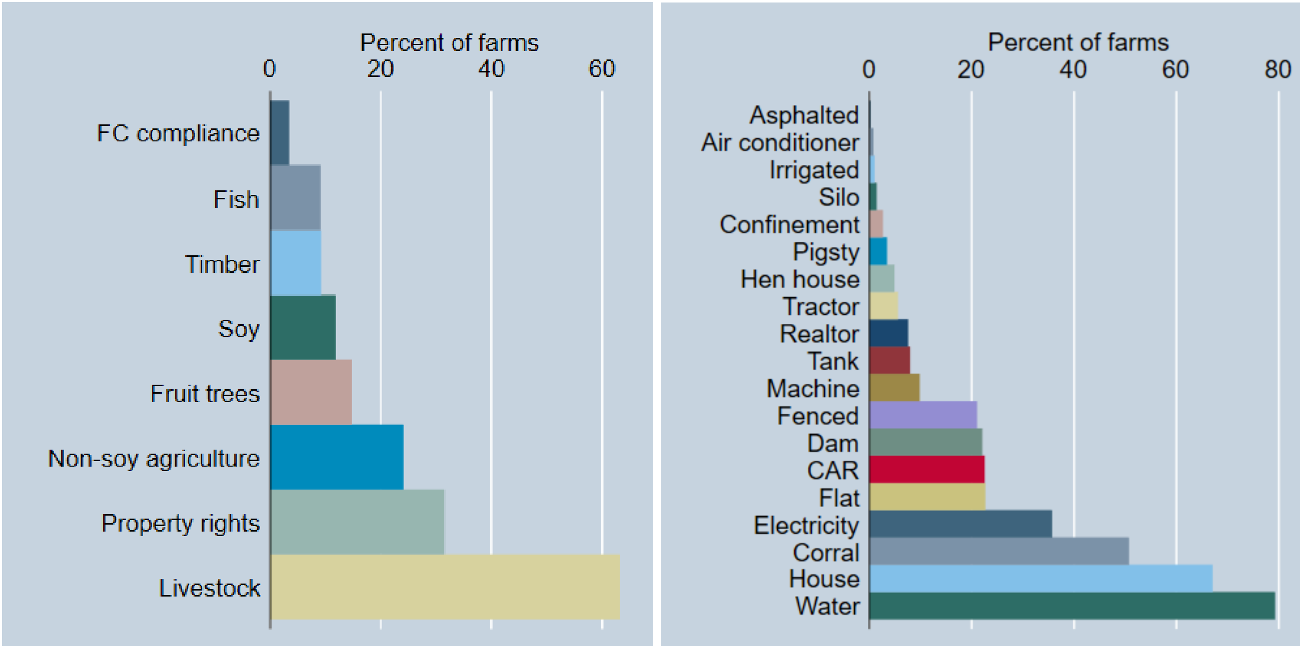

Figure 4 Percent of parcels with Forest Code compliance, property rights, and certain type of production (Fig. 4a) and percent of parcels with land characteristics, structure amenities, and capital equipment included in the offer (Fig. 4b). Data comes from the last weekly records.

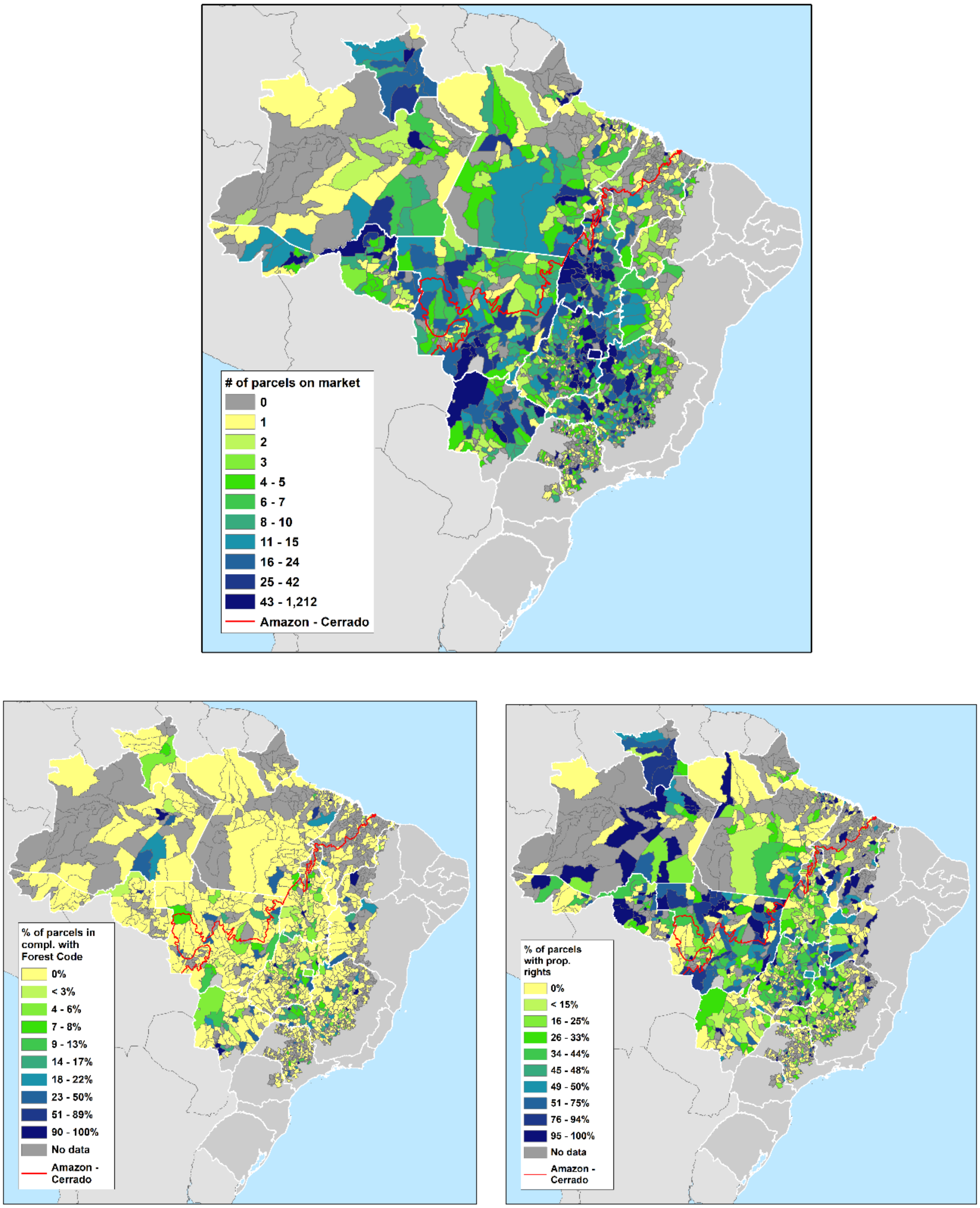

Figure 5 Number of parcels on the market (Fig. 5a), percent of parcels in compliance with the Forest Code (Fig. 5b), and percent of parcels with property rights (Fig. 5c) in the study-region. To represent competition on the market, the sample for Fig. 5a includes all parcels whether they have been sold or not. Sample for Fig. 5b and 5c composed of the parcels that have been sold.

Table 1 Summary Statistics and Normalized Differences

	Prop. rights		No prop. rights		
	mean	s.d.	mean	s.d.	norm. diff.
	(1)	(2)	(3)	(4)	(5)
Price and size					
Ln(price/ha)	8.78	(1.40)	8.92	(1.37)	-0.07
Ln(size)	6.01	(1.75)	5.77	(1.75)	0.10
Environmental policy					
FC compliance	0.07	(0.25)	0.02	(0.13)	0.18
Production on the farm					
Soy	0.13	(0.34)	0.11	(0.32)	0.04
Non-soy agriculture	0.30	(0.46)	0.21	(0.41)	0.14
Livestock	0.68	(0.47)	0.61	(0.49)	0.10
Timber	0.12	(0.33)	0.08	(0.27)	0.11
Fruit trees	0.16	(0.37)	0.14	(0.35)	0.03
Fish	0.11	(0.32)	0.08	(0.27)	0.08
Deforested	0.01	(0.11)	0.01	(0.10)	0.02
Capital included					
Tank	0.12	(0.32)	0.06	(0.24)	0.14
Irrigated	0.01	(0.11)	0.01	(0.10)	0.01
Dam	0.24	(0.43)	0.21	(0.41)	0.05
Pigsty	0.04	(0.19)	0.03	(0.18)	0.03
Hen house	0.07	(0.25)	0.04	(0.20)	0.08
Confinement	0.03	(0.16)	0.03	(0.16)	0.01
Corral	0.57	(0.49)	0.48	(0.50)	0.13
Silo	0.02	(0.13)	0.01	(0.11)	0.03
Machine	0.11	(0.31)	0.09	(0.29)	0.03
Tractor	0.06	(0.23)	0.05	(0.23)	0.01
Other covariates					
Realtor	0.08	(0.27)	0.07	(0.26)	0.02
CAR	0.40	(0.49)	0.15	(0.35)	0.42
House	0.71	(0.45)	0.65	(0.48)	0.09
Air conditioner	0.01	(0.09)	0.01	(0.09)	0.01
Fenced	0.28	(0.45)	0.18	(0.38)	0.17
Electricity	0.44	(0.50)	0.32	(0.47)	0.18
Water	0.86	(0.35)	0.76	(0.43)	0.17
Asphalted	0.00	(0.06)	0.00	(0.05)	0.02
Flat	0.30	(0.46)	0.19	(0.39)	0.18
Observations	3789		8211		12000

Note: Columns (1) and (3) present the mean values and columns (2) and (4) present the standard deviations. Normalized differences in column (5) are a scale-free measure of the difference in distributions between samples and has the advantage of being directly interpretable in terms of how much average standard deviation is the mean from one sample to the mean of the other sample (Imbens and Wooldridge, 2009).

Table 2 Hedonic Model: Low Net Benefits from Property Right

	(1)	(2)	(3)	(4)	(5)
Property rights	-0.07***	-0.01	-0.01	-0.03	0.01
	(0.02)	(0.03)	(0.03)	(0.03)	(0.03)
Ln(size)	-0.31***	-0.27***	-0.27***	-0.29***	-0.29***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Soy				0.39***	0.39***
				(0.04)	(0.04)
Non-soy agriculture				0.13***	0.13***
				(0.03)	(0.03)
Livestock				0.08***	0.01
				(0.03)	(0.03)
Timber				-0.25***	-0.24***
				(0.04)	(0.04)
Fruit trees				0.17***	0.11***
				(0.04)	(0.04)
Fish				0.01	-0.06
				(0.04)	(0.05)
Deforested				-0.10	0.04
				(0.17)	(0.17)
R^2	0.16	0.39	0.40	0.41	0.42
Observations	12,000	12,000	12,000	12,000	12,000
Municipal FE		X	X	X	X
Month-year FE			X	X	X
Amenities controls					X

Note: Dependent variable is the natural logarithm of the price per hectare. Unit of observation is the land at the last time the post was observed on the website. Estimation limited to the Amazon and the Cerrado biomes and to those farms that have been sold. * p< 0.10, ** p<0.05, *** p<0.01.

Table 3 Specifications by Biome Show Higher Net Benefits in the Amazon

	Amazon		*Cerrado*	
	(1)	(2)	(3)	(4)
Property rights	0.13*	0.11	-0.04	-0.01
	(0.06)	(0.07)	(0.03)	(0.03)
Ln(size)	-0.26***	-0.27***	-0.28***	-0.30***
	(0.02)	(0.02)	(0.01)	(0.01)
Soy		0.43***		0.39***
		(0.10)		(0.04)
Non-soy agriculture		0.07		0.13***
		(0.08)		(0.03)
Livestock		-0.09		0.03
		(0.06)		(0.03)
Timber		-0.46***		-0.15***
		(0.07)		(0.05)
Fruit trees		0.14		0.10**
		(0.09)		(0.04)
Fish		0.09		-0.09*
		(0.13)		(0.05)
Deforested		0.99		-0.03
		(0.84)		(0.17)
R^2	0.44	0.50	0.35	0.37
Observations	1,904	1,904	10,096	10,096
Municipal FE	X	X	X	X
Month-year FE	X	X	X	X
Land-use controls		X		X
Amenities controls		X		X

Note: Dependent variable is the natural logarithm of the price per hectare. Unit of observation is the land at the last time the post was observed on the website. Estimation limited to the Amazon and the Cerrado biomes and to those farms that have been sold. * p< 0.10, ** p<0.05, *** p<0.01.

Table 4 Interaction Effects in the Hedonic Model Shows Lower Net Benefit of Property Rights in the Amazon if the Land is Compliant with the Forest Code

	Amazon				*Cerrado*			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
FC compliance	0.28	0.08	0.85**	0.54*	0.01	-0.02	-0.04	-0.10
	(0.25)	(0.24)	(0.40)	(0.32)	(0.08)	(0.08)	(0.14)	(0.13)
Property rights			0.13**	0.12*			-0.04	-0.02
			(0.07)	(0.07)			(0.03)	(0.03)
Prop. rights x FC compliance			-0.82	-0.67			0.10	0.14
			(0.51)	(0.44)			(0.17)	(0.16)
Ln(size)	-0.26***	-0.27***	-0.27***	-0.27***	-0.28***	-0.30***	-0.28***	-0.30***
	(0.02)	(0.02)	(0.02)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)
Soy		0.43***		0.42***		0.39***		0.39***
		(0.10)		(0.10)		(0.04)		(0.04)
Non-soy agriculture		0.08		0.08		0.13***		0.13***
		(0.08)		(0.08)		(0.03)		(0.03)
Livestock		-0.09		-0.08		0.03		0.03
		(0.06)		(0.06)		(0.03)		(0.03)
Timber		-0.47***		-0.46***		-0.15***		-0.15***
		(0.07)		(0.07)		(0.05)		(0.05)
Fruit trees		0.14		0.15		0.10**		0.10**
		(0.09)		(0.09)		(0.04)		(0.04)
Fish		0.08		0.08		-0.09*		-0.09*
		(0.13)		(0.13)		(0.05)		(0.05)
Deforested		0.95		0.91		-0.03		-0.03
		(0.83)		(0.84)		(0.17)		(0.17)
R^2	0.44	0.50	0.44	0.50	0.35	0.37	0.35	0.37
Observations	1,904	1,904	1,904	1,904	10,096	10,096	10,096	10,096
Municipal FE	X	X	X	X	X	X	X	X
Month-year FE	X	X	X	X	X	X	X	X
Land-use controls		X		X		X		X
Amenities controls		X		X		X		X

Note: Dependent variable is the natural logarithm of the price per hectare. Unit of observation is the land at the last time the post was observed on the website. Estimation limited to the Amazon and the Cerrado biomes and to those farms that have been sold. * p< 0.10, ** p<0.05, *** p<0.01.

Table 5 Duration Model: Farms with Property Rights are Sold Faster

	(1)	(2)	(3)	(4)	(5)
Property rights	-0.13***	-0.10***	-0.09***	-0.08***	-0.06**
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
Ln(size)	-0.01*	-0.02***	-0.02**	-0.02***	-0.02**
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Soy				-0.06	-0.03
				(0.04)	(0.04)
Non-soy agriculture				-0.02	-0.00
				(0.03)	(0.03)
Livestock				0.05**	0.07***
				(0.02)	(0.02)
Timber				0.05	0.08**
				(0.04)	(0.04)
Fruit trees				-0.13***	-0.12***
				(0.03)	(0.03)
Fish				-0.06	-0.05
				(0.04)	(0.04)
Deforested				0.16	0.18
				(0.15)	(0.15)
Observations	75,205	75,205	75,205	75,205	75,205
Log(L)	-2.0e+04	-1.8e+04	-1.6e+04	-1.6e+04	-1.6e+04
Municipal FE		X	X	X	X
Month-year FE			X	X	X
Amenities controls					X

Note: Hazard Model Estimation (with Weibull distribution). Unit of observation is the land on sale. Estimation limited to the Amazon and the Cerrado biomes and to those farms that have been sold. * p< 0.10, ** p<0.05, *** p<0.01.

Table 6 Specifications of the Duration Model with Interaction Effects

	Amazon				*Cerrado*			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
FC compliance	-0.34	-0.46**	-0.38	-0.37	-0.16***	-0.13**	-0.43***	-0.43***
	(0.21)	(0.22)	(0.44)	(0.48)	(0.06)	(0.06)	(0.09)	(0.10)
Property rights			-0.05	-0.06			-0.11***	-0.09***
			(0.06)	(0.06)			(0.03)	(0.03)
Prop. rights x FC compliance			0.07	-0.10			0.53***	0.55***
			(0.51)	(0.54)			(0.12)	(0.12)
Ln(size)	-0.03*	-0.03	-0.03*	-0.03	-0.01*	-0.02*	-0.01	-0.02*
	(0.02)	(0.02)	(0.02)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)
Observations	12,321	12,321	12,321	12,321	62,884	62,884	62,884	62,884
Log(L)	-2283	-2246	-2282	-2245	-1.4e+04	-1.4e+04	-1.4e+04	-1.4e+04
Municipal FE	X	X	X	X	X	X	X	X
Month-year FE	X	X	X	X	X	X	X	X
Land-use controls		X		X		X		X
Amenities controls		X		X		X		X

Note: Hazard Model Estimation (with Weibull distribution). Unit of observation is the land on sale. Estimation limited to the Amazon and the Cerrado biomes and to those farms that have been sold. * p< 0.10, ** p<0.05, *** p<0.01.

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Appendix A

Additional tables and figures

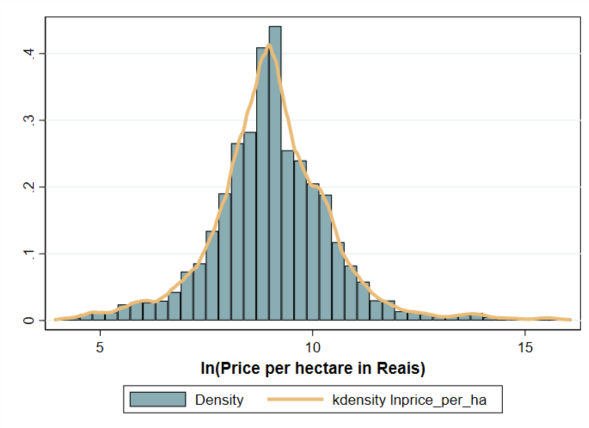
Table A1 Keywords use for creating the indicator variables.

Variables	Portuguese keywords	Translation
Property rights	AVERBADA, REGISTRAD, ESCRITURA (which includes ESCRITURADA), REGULARIZAD, DOCUMENTACAO, DOCUMENTACOES TODAS REGULARES, DIREITO DE PROPRIEDADE, TITULARIZADA, TEM TITULO, TERRA LEGAL, SIGEF, SNCI, CERTIFICADO DE CADASTRO DE IMOVEL RURAL, and CCIR.	Registered (averbada), registered (registrad), regularized, documented, property rights, entitled, has a title, and three specific names of property right documents in Brazil (Terra Legal, SIGEF, SNCI, and CCIR).
Compliant with the Forest Code	RESERVA LEGAL (and its plural form RESERVAS LEGA), AREA DE PRESERVACAO PERMANENTE (and its plural form AREAS DE PRESERVACAO PERMANENTE), and CODIGO FLORESTAL.	Legal Reserve, Areas of Permanent Preservation, and Forest Code. [2,3]
Soy	SOJA	Soy
Non-Soy Agriculture	ARROZ, CANA, TRIGO, MILHO, FEIJAO, and PLANTIO DIRETO.	Rice, cane (of sugarcane), wheat, bean, and no-till.
Livestock	PECUARIA (which includes AGROPECUARIA), PASTA (which includes PASTAGEM and its plural form PASTAGENS), PASTO, CABECA, BOI, and GADO.	Livestock, pasture, pastures, head, ox, and cattle.
Fruit trees	FRUTIFERA, BANAN, FRUTA, LARANJA, CAFE, POMAR, and ACAI.	Fructiferous (adjective associated with trees in "fruit trees"), banana, fruit, orange, coffee, orchard, and acai.
Timber	MADEIRA and EUCALIPTUS	Timber and eucalyptus

[2] We verified one by one each observation to make sure they corresponded to a statement of the type "the property is compliant with the Forest Code."

[3] We also investigated whether landowners advertised "COTA DE RESERVA AMBIENTAL", the transferable quotas for excess in Legal Reserve (presented in section 2.2), but none did.

Variables	Portuguese keywords	Translation
Fish	PEIXE and PESCA	Fish and fishery.
Deforested	DESMATADA	Deforested



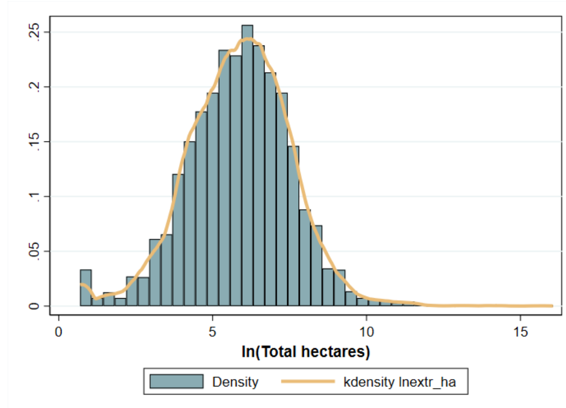


Figure A1 Distribution of the natural logarithm of land prices and sizes. Data come from the last posts.

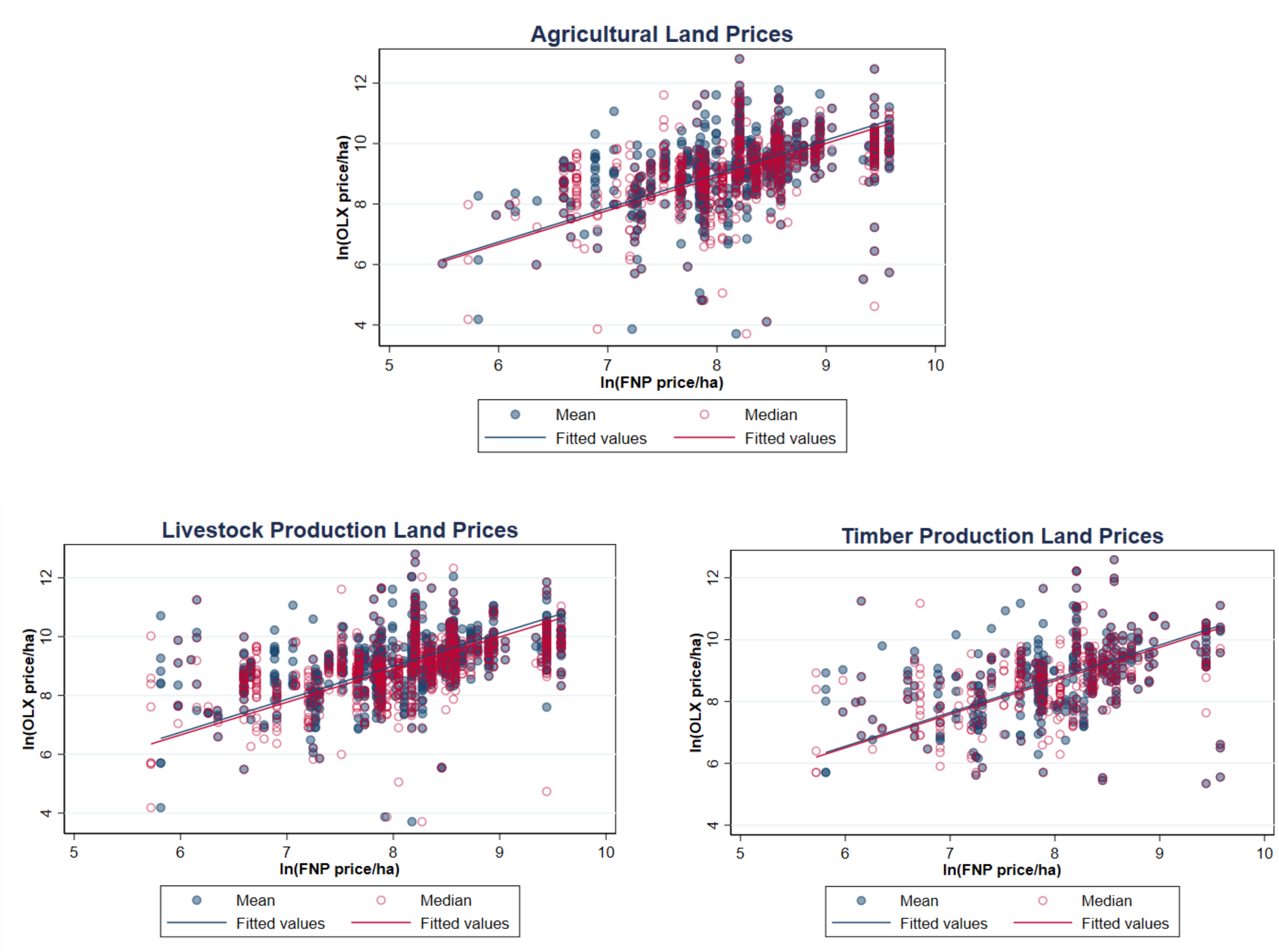


Figure A2 Comparisons between the mean and median price per hectare from our dataset (extracted from OLX) with the most popular alternative for land prices in Brazil (the FNP data). To accommodate the limitations of the FNP data, we aggregate for each municipality the mean and median price per hectare according to the same categories their data provide: agriculture, livestock, or timber (while our data accommodates that a given parcel can produce in more than one category). FNP are transformed in 2019 Reais using the World Bank GDP Deflator. Estimated coefficients for fitted lines are: Agricultural Land Prices mean 0.954 (R^2 = 0.98) and median 0.942 (R^2 = 0.984); Livestock Production Land Prices mean 1.018 (R^2 = 0.985) and median 1.001 (R^2 = 0.984), and Timber Production Land Prices mean 1.092 (R^2 = 0.983) and median 1.084 (R^2 = 0.983).

Table A2 Robustness: Interaction Effects in the Hedonic Model Shows Lower Net Benefit of Property Rights in the Amazon if the Land is Compliant with the Forest Code, while Controlling for Municipal-Level Embargoes

	Amazon				*Cerrado*			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
FC compliance	0.26	0.06	0.84**	0.54*	0.04	0.01	0.01	-0.05
	(0.25)	(0.24)	(0.40)	(0.32)	(0.08)	(0.08)	(0.13)	(0.13)
Property rights			0.13**	0.12*			-0.05*	-0.02
			(0.07)	(0.07)			(0.03)	(0.03)
Prop. rights x FC compliance			-0.83	-0.68			0.07	0.10
			(0.51)	(0.44)			(0.17)	(0.16)
Ln(size)	-0.26***	-0.27***	-0.27***	-0.27***	-0.28***	-0.30***	-0.28***	-0.30***
	(0.02)	(0.02)	(0.02)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)
Mun-level cumulative embargoes	-0.01	-0.00	-0.01	-0.00	0.02	0.01	0.02	0.01
	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)	(0.02)	(0.02)	(0.02)
Soy		0.39***		0.39***		0.33***		0.33***
		(0.10)		(0.10)		(0.04)		(0.04)
Non-soy agriculture		0.06		0.06		0.08**		0.08**
		(0.09)		(0.09)		(0.03)		(0.03)
Livestock		-0.08		-0.08		0.03		0.03
		(0.06)		(0.06)		(0.03)		(0.03)
Timber		-0.47***		-0.47***		-0.15***		-0.15***
		(0.07)		(0.07)		(0.05)		(0.05)
Fruit trees		0.14		0.15		0.11***		0.11***
		(0.09)		(0.09)		(0.04)		(0.04)
Fish		0.08		0.08		-0.09		-0.09
		(0.13)		(0.13)		(0.05)		(0.05)
Deforested		0.97		0.93		-0.03		-0.03
		(0.83)		(0.84)		(0.17)		(0.17)
R^2	0.44	0.50	0.44	0.50	0.35	0.37	0.35	0.37
Observations	1,904	1,904	1,904	1,904	9,827	9,827	9,827	9,827
Municipal FE	X	X	X	X	X	X	X	X
Month-year FE	X	X	X	X	X	X	X	X
Land-use controls		X		X		X		X
Amenities controls		X		X		X		X

Note: Dependent variable is the natural logarithm of the price per hectare. Unit of observation is the land at the last time the post was observed on the website. Estimation limited to the Amazon and the Cerrado biomes and to those farms that have been sold. Municipal-level embargoes represent the total embargoes recorded by the IBAMA embargo list from September 30 2019 and vary monthly. The baseline for August is calculated by excluding any embargos with dates on or after August 1 2019 from the list. * p< 0.10, ** p<0.05, *** p<0.01.

Table A3 Robustness: Interaction Effects in the Hedonic Model Shows Lower Net Benefit of Property Rights in the Amazon if the Land is Compliant with the Forest Code, while Controlling for an Embargo-Free Property Indicator Variable

	Amazon				*Cerrado*			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
FC compliance	0.28	0.08	0.85**	0.54*	0.01	-0.02	-0.04	-0.10
	(0.25)	(0.24)	(0.40)	(0.32)	(0.08)	(0.08)	(0.14)	(0.13)
Property rights			0.13**	0.12*			-0.04	-0.02
			(0.07)	(0.07)			(0.03)	(0.03)
Prop. rights x FC compliance			-0.82	-0.67			0.10	0.14
			(0.51)	(0.44)			(0.17)	(0.16)
Ln(size)	-0.26***	-0.27***	-0.27***	-0.27***	-0.28***	-0.30***	-0.28***	-0.30***
	(0.02)	(0.02)	(0.02)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)
Soy		0.43***		0.42***		0.39***		0.39***
		(0.10)		(0.10)		(0.04)		(0.04)
Non-soy agriculture		0.08		0.08		0.13***		0.13***
		(0.08)		(0.09)		(0.03)		(0.03)
Livestock		-0.09		-0.08		0.03		0.03
		(0.06)		(0.06)		(0.03)		(0.03)
Timber		-0.47***		-0.46***		-0.15***		-0.15***
		(0.07)		(0.07)		(0.05)		(0.05)
Fruit trees		0.14		0.15		0.10**		0.10**
		(0.09)		(0.09)		(0.04)		(0.04)
Fish		0.08		0.08		-0.09*		-0.09*
		(0.13)		(0.13)		(0.05)		(0.05)
Deforested		0.95		0.91		-0.03		-0.03
		(0.83)		(0.84)		(0.17)		(0.17)
R^2	0.44	0.50	0.44	0.50	0.35	0.37	0.35	0.37
Observations	1,904	1,904	1,904	1,904	10,096	10,096	10,096	10,096
Municipal FE	X	X	X	X	X	X	X	X
Month-year FE	X	X	X	X	X	X	X	X
W/o embargo control	X	X	X	X	X	X	X	X
Land-use controls		X		X		X		X
Amenities controls		X		X		X		X

Note: Dependent variable is the natural logarithm of the price per hectare. Unit of observation is the land at the last time the post was observed on the website. Estimation limited to the Amazon and the Cerrado biomes and to those farms that have been sold. Property-level indicator that there is no embargo is extracted from the ad description. * p< 0.10, ** p<0.05, *** p<0.01.

Table A4 Robustness: Interaction Effects in the Hedonic Model Shows Lower Net Benefit of Property Rights in the Amazon if the Land is Compliant with the Forest Code, while Controlling for Municipal-Level Percentage of Vegetation Cover

	Amazon				*Cerrado*			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
FC compliance	0.28	0.07	0.85**	0.54*	0.04	0.02	0.02	-0.04
	(0.25)	(0.24)	(0.40)	(0.32)	(0.08)	(0.08)	(0.13)	(0.13)
Property rights			0.13**	0.12*			-0.04	-0.02
			(0.07)	(0.07)			(0.03)	(0.03)
Prop. rights x FC compliance			-0.82	-0.67			0.06	0.10
			(0.51)	(0.44)			(0.17)	(0.16)
Ln(size)	-0.26***	-0.27***	-0.27***	-0.27***	-0.28***	-0.30***	-0.28***	-0.30***
	(0.02)	(0.02)	(0.02)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)
Mun. veg. cover (%)	-0.32	2.85	-0.38	2.99	23.54***	20.38**	23.20***	20.24**
	(8.20)	(8.06)	(8.18)	(8.05)	(8.11)	(8.07)	(8.11)	(8.08)
Soy		0.43***		0.42***		0.40***		0.40***
		(0.10)		(0.10)		(0.04)		(0.04)
Non-soy agriculture		0.07		0.07		0.13***		0.13***
		(0.08)		(0.08)		(0.03)		(0.03)
Livestock		-0.08		-0.08		0.04		0.04
		(0.06)		(0.06)		(0.03)		(0.03)
Timber		-0.47***		-0.47***		-0.15***		-0.15***
		(0.07)		(0.07)		(0.06)		(0.06)
Fruit trees		0.14		0.15		0.11**		0.11**
		(0.09)		(0.09)		(0.04)		(0.04)
Fish		0.08		0.08		-0.09*		-0.09*
		(0.13)		(0.13)		(0.05)		(0.05)
Deforested		0.95		0.90		-0.03		-0.03
		(0.83)		(0.84)		(0.17)		(0.17)
R^2	0.44	0.50	0.44	0.50	0.35	0.38	0.35	0.38
Observations	1,904	1,904	1,904	1,904	9,827	9,827	9,827	9,827
Municipal FE	X	X	X	X	X	X	X	X
Month-year FE	X	X	X	X	X	X	X	X
Land-use controls		X		X		X		X
Amenities controls		X		X		X		X

Note: Dependent variable is the natural logarithm of the price per hectare. Unit of observation is the land at the last time the post was observed on the website. Estimation limited to the Amazon and the Cerrado biomes and to those farms that have been sold. Municipal-level percentage vegetation is the yearly percent of municipal property area (from SICAR) in forest formation, savanna, mangrove, or floodable forest as indicated by MapBiomas version 8.0. * p< 0.10, ** p<0.05, *** p<0.01.

Table A5 Duration Model: Farms with Property Rights are Sold Faster, but only in the Cerrado biome

	Amazon		*Cerrado*	
	(1)	(2)	(3)	(4)
Property rights	-0.05	-0.07	-0.10***	-0.07**
	(0.06)	(0.06)	(0.03)	(0.03)
Ln(size)	-0.03*	-0.03	-0.01*	-0.02**
	(0.02)	(0.02)	(0.01)	(0.01)
Soy		-0.28***		-0.00
		(0.10)		(0.04)
Non-soy agriculture		0.03		-0.01
		(0.08)		(0.03)
Livestock		-0.12*		0.10***
		(0.06)		(0.03)
Timber		0.10		0.08*
		(0.07)		(0.04)
Fruit trees		0.04		-0.13***
		(0.10)		(0.03)
Fish		0.13		-0.07
		(0.12)		(0.05)
Deforested		1.05*		0.15
		(0.62)		(0.15)
Observations	12,321	12,321	62,884	62,884
Log(L)	-2284	-2248	-1.4e+04	-1.4e+04
Municipal FE	X	X	X	X
Month-year FE	X	X	X	X
Land-use controls		X		X
Amenities controls		X		X

Note: Hazard Model Estimation (with Weibull distribution). Unit of observation is the land on sale. Estimation limited to the Amazon and the Cerrado biomes and to those farms that have been sold. * p< 0.10, ** p<0.05, *** p<0.01.

Appendix B

Additional background information on the Forest Code

Initially created in 1965, the Forest Code became law following multiple presidential decrees in the 1990s (Soares-Filho *et al.*, 2014). Since 2001, the Forest Code has required landowners to preserve 80% of most private properties in the Amazon biome as natural vegetation, 20%-35% in the Cerrado biome, and 20% in all other biomes of the country. These protected areas within private properties are called Legal Reserves. The Forest Code also defines Areas of Permanent Preservation, which were created to prevent soil erosion and protect water resources (Soares-Filho et al., 2014). Areas of Permanent Preservation include two subcategories: Riparian Preservation Areas, to conserve riverside forests, and Hilltop Preservation Areas, at high elevations, steep slopes, or hilltops. Amendments to the Forest Code were adopted in late 2012. A major reform was to allow amnesty related to illegal deforestation that occurred before 2008 for properties under a certain size threshold fixed at four fiscal modules, i.e., 200-300 hectares (Federal Forest Code (12,651/2012); Federal Decree on Land Environmental Reserve Quota Regularization (6,992/2009)). Another major change was the creation of the Environmental Reserve Quota. Specifically, this is a tradable legal title to be negotiated within the same biome between those that have a surplus of Legal Reserves (e.g., in the Amazon biome, having more than 80% of their property forested) and those that have insufficient Legal Reserves. Although the system remains marginally implemented, some organizations like BVRio and Biofilica have begun to create markets or play intermediary roles in the exchanges of quotas. In sum, there are benefits to having certain aspects of Forest Code compliance so landowners can sell their surplus in markets.

IBAMA is empowered to fine illegal deforestation. Fines for illegal deforestation in Legal Reserve or Areas of Permanent Preservation are the highest: $5,000 per hectare compared to $1,000 for other types of deforestation. When deforested, areas defined as Legal Reserves or Areas of Permanent Preservation need to be replanted. Specifically, landowners must provide a plan of restoration to return to legal compliance and promise to engage in the necessary actions to reforest. If the landowner passes the 120 days allocated to present a reforestation plan to comply with the Forest Code, an additional $50 to $500 reais per day per hectare can be charged. Finally, deforestation that occurs with fires can also be fined under the Art. 62 II of the same Decree and offenders can be liable for respiratory damage borne by populations.

Thus, noncompliance with the Forest Code could be quite expensive. Costs include both the direct cost of reforestation (if deforestation occurred illegally) and the indirect cost of losing rents from agricultural production (Azevedo *et al.*, 2017). The restoration costs range from US $536 to 1,327/ha (Soares-Filho *et al.*, 2014; Soterroni *et al.*, 2018) and the opportunity cost from not using embargoed areas is estimated to be US $673/ha (Stickler *et al.*, 2013). Costs can be high even when fines go unpaid: illegal deforesters can go to jail, material used for illegal deforestation can be burned and timber seized, and lawyers may need to be paid to represent illegal deforesters' interests in judiciary court. In essence, there can be substantial benefits of legal compliance with the Forest Code that stem from avoiding the penalties and restoration costs and the burden generated to evade environmental fines.

Appendix C

Theoretical Approach

We use the standard hedonic model of quality differentiated goods to interpret our data and motivate our approach to estimation (Phaneuf and Requate, 2017). In a version of this model specific to land markets we assume there are many price taking land sellers who maximize profits by selling land defined by a vector of property attributes *x*. In general, the list of attributes includes indicators for property rights and compliance with environmental policies, but for illustration we assume *x* is a scalar representing parcel size. Sellers earn profit by selecting the level of *x* to maximize

$$\Pi = P(x) - C(x), \tag{1}$$

where *P*(*x*) is the market price for a property with attributes *x* and *C*(*x*) is the cost function for selling the property. The seller's profit maximizing behavior is characterized by the first order condition *P'*(*x*)=*C'*(*x*). That is, marginal revenue from selling an incrementally larger parcel equals the marginal cost of doing so. Based on the seller's behavior we define iso-profit curves

$$\overline{\Pi} = o - C(x), \tag{2}$$

where *o* is the payment the seller would accept for a parcel of land with attributes *x*, in order to maintain profit level $\overline{\Pi}$. Equation (2) implicitly defines a seller's *offer function* $o\left(x, \overline{\Pi}\right)$, which summarizes the landowner's willingness to accept (WTA) payment for parcels with different values of *x*, conditional on reaching a reference profit level. Plugging the offer function into (2) and differentiating with respect to *x* we can derive the seller's marginal willingness to accept for *x* as

$$\frac{\partial o\left(x, \overline{\Pi}\right)}{\partial x} = C'(x) = P'(x), \tag{3}$$

where the second equality comes from the first order conditions for profit maximization.

Following standard hedonic price theory, we also define the *bid function* $b(x, \overline{U})$ that summarizes a buyer's willingness to pay (WTP) for a parcel with different levels of *x*, conditional on reaching a reference utility level $\overline{U}$. In this model the buyer's marginal willingness to pay for *x* is

$$\frac{\partial b\left(x, \overline{U}\right)}{\partial x} = P'(x). \tag{4}$$

Equilibrium in the land market is defined by outcomes that simultaneously satisfy a pair of buyer and seller first order conditions. This joint satisfaction constitutes a transaction. By combining (3) and (4) we see that equilibrium is characterized by

$$\frac{\partial o\left(x,\bar{\Pi}\right)}{\partial x} = P'(x) = \frac{\partial b\left(x,\bar{U}\right)}{\partial x}. \tag{5}$$

That is, the slopes of the bid and offer functions are equal to the marginal implicit price of the attribute.

Figure A3 illustrates how this concept of equilibrium is useful for our empirical analysis. It relates the price function *P*(*x*) to different levels of an attribute *x*. A series of offer functions illustrates different profit levels that a seller can obtain at different prices, where $P^1 < P^2 < P^3$. That is, for a given level of *x* the seller earns higher profit when the price is higher. A series of bid functions illustrates different utility levels that a buyer can obtain for different prices, where $U^1 < U^2 < U^3$. For a given level of *x* the buyer receives lower utility when the price is higher. There is a tangency between offer and bid functions at the point x_1 that corresponds to equation (5); this defines a price $P(x_1)$ that is mutually agreeable and hence represents a transaction. A second point of tangency by a different buyer and seller pair (and without the other bid and offer curves) occurs at point x_2, which defines another transaction at price $P(x_2)$. In market equilibrium, a continuum of buyers and sellers with heterogenous offer and bid functions traces out the equilibrium price function *P*(*x*), which is shown as the heavy line in the figure. The equilibrium price function provides important information on how buyers and sellers value attributes of land parcels. For example, equations (3) ad (4) show that buyers' marginal WTP and sellers' marginal WTA for a change in an attribute level is equal to the marginal implicit price *P'*(*x*).

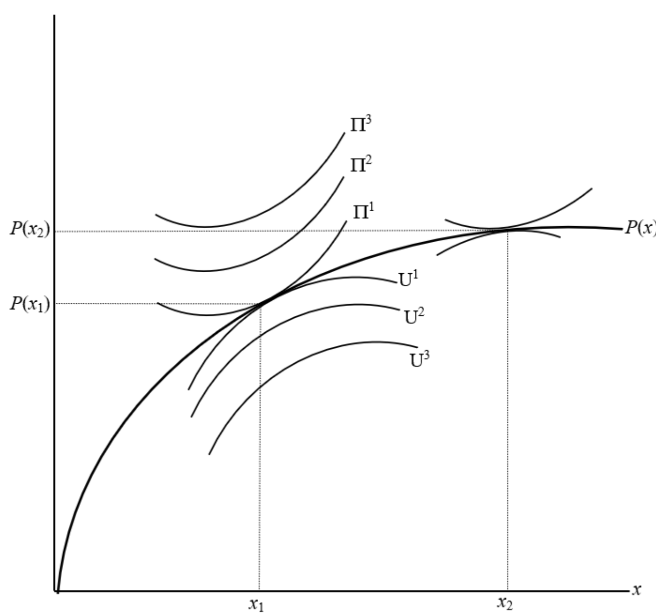


Figure A3 Hedonic equilibrium in land markets.

Appendix D

To create the land tenure map for the Amazon and Cerrado biomes, several land cover and property registry datasets were combined. To address spatial overlaps between maps, the input datasets were separated into four levels of priority, with areas of overlap assigned to the higher priority. For example, areas of overlap between Priority 1 and Priority 2 were assigned to Priority 1.

- Priority 1 (land not potentially available for agriculture): water and urban[1]
- Priority 2 (stable land tenure): Conservation Units[2], Indigenous areas[3], Quilombolas[4], military zones[5], Terra Legal[6], Assentamentos[7], Sigef-Privado[7], SNCI-Privado[7]
- Priority 3 (unstable land tenure): Sicar[8]
- Priority 4 (all other areas): all remaining areas of Amazon and Cerrado biomes[9]

All processing work for the land tenure map was completed using ArcGIS Pro software[10]. All input datasets were first reprojected to SRID 102033 (SAD 1969 South America Albers Equal Area Conic). All input datasets were then restricted to the extents of the Amazon and Cerrado biomes using the ArcGIS Pro clip tool[11]. All datasets within the same priority level were then combined using the ArcGIS Pro merge tool[12] and their boundaries were dissolved to create a single overlap-free map using the ArcGIS Pro dissolve tool[13]. The ArcGIS Pro update tool[14] was then used to remove overlaps between priority levels. First, the lowest/4th priority level (Amazon and Cerrado biome boundaries) was updated/overlaid with the 3rd priority level. The output was a map where areas of overlap between the 3rd and 4th priority levels were assigned to the 3rd priority level. This process was then repeated for the 2nd and 1st priority levels.

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