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LETTER

Land speculation and conservation policy leakage in Brazil

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Abstract

The Brazilian Amazon and Cerrado biomes have been subject to strong pressure from agricultural expansion over the past two decades. A common claim is that the associated tree cover loss was partly driven by speculative land acquisition. In this paper, we analyze the effects of information on planned road infrastructure improvements and changes in conservation policy implementation on expectations of forest conversion. We use a unique land price dataset covering the period from 2001–2012. Based on land rent and hedonic valuation theory, we argue that forestland prices convey information on expected future land use. We decompose forestland prices into a conventional forestland rent and a speculative part related to forestland conversion and alternative land use rents. Using a fixed-effect panel, we then assess whether, where, and to what extent changes in conservation policy affect forestland prices over time. Our results confirm that forestland prices contain expectations about converting forestland to agricultural or pasture land. We also find indications that the Brazilian land market conveys information about potential conservation policy leakage and explore this conjecture descriptively using dynamic deforestation hotspot maps.

1. Introduction

Land resources are under pressure to satisfy global demand for agricultural products (Tilman *et al* 2011, Leblois *et al* 2017). Countries with large amounts of fertile land like Brazil are thus expected to produce additional food, feed, and energy crops (OECD 2015, FAO 2018). However, the production of globally traded commodities such as soy and beef is often associated with the expansion of agricultural frontiers in ecologically sensitive biomes, such as the Amazon and the Cerrado Savannah, at considerable environmental and social costs (McAlpine *et al* 2009, Karstensen *et al* 2013, Nepstad *et al* 2013).

Conversion of natural vegetation at agricultural frontiers is often both a result of productive input allocation decisions and a strategy to secure land claims either for subsistence or to benefit from appreciating land markets (Hecht 1985, Caldas *et al* 2007, Fearnside 2008). Converting forest areas to pasture has long been an effective strategy to secure land ownership. The market price of forestland therefore consists not only of the value related to the *current* land uses (e.g. forest-products) but also of *expected revenues* from future land uses, such as pasture (Barreto *et al* 2008, Carrero and Fearnside 2011, Strassburg *et al* 2014). The latter is uncertain and thus an inherently speculative component of the forestland price. Changes in land prices can thus reveal information on the incentives of deforestation and related expectations on future land use change (Margulis 2003, Merry *et al* 2008, Sills and Caviglia-Harris 2009).

In the context of agricultural frontier expansion, the speculative component of the price of forestland constantly changes with new investments into infrastructure making pastures or cropland more profitable (Hecht and Mann 2008, Sauer and Pereira Leite 2012). Similarly, priority shifts in the enforcement of

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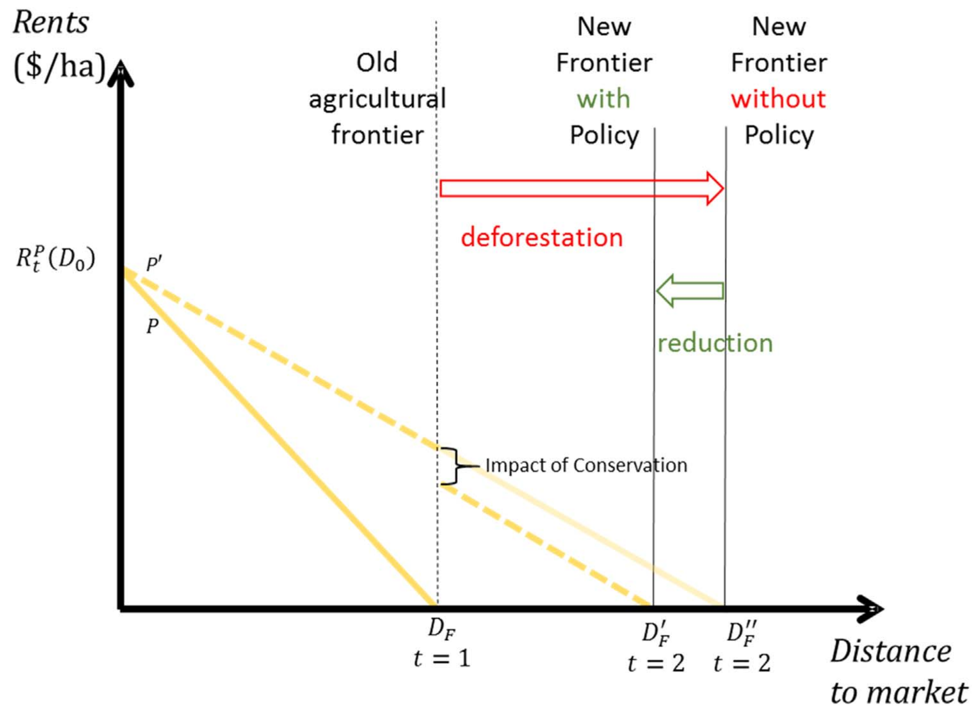

Figure 1. Land rents in a two period model with infrastructure investments and conservation policy enforcement. Note: This graph shows bid-rents for an alternative land use (e.g. pasture). In a first period, at the agricultural frontier, D_F, rents of an alternative land uses are zero and land remains forest. In a second period (half-dashed, half-straight yellow line), a driver of deforestation, e.g. road infrastructure improvement, shifts bid-rents outwards and induces frontier expansion up to D''_F. If conservation policies are implemented effectively, they will reduce the impact of this effect on deforestation by incrementing the cost of converting forestland beyond the old frontier (dashed yellow line).

property rights and conservation policies may affect speculative behavior on land markets (Araujo *et al* 2009, Brown *et al* 2016, Azevedo *et al* 2017, Koch *et al* 2017). When governments devise conservation policies to counteract frontier expansion, conservation priorities and enforcement effectiveness tend to vary in space leading to leakage effects (Fearnside 2009, Barona *et al* 2010, Lapola *et al* 2010, Soares-Filho *et al* 2010, Arima *et al* 2011, Gibbs *et al* 2015). Leakage refers to the displacement of land use activities from a region subject to conservation policy enforcement to another region without or with lower levels of enforcement (Lambin and Meyfroidt 2011, Meyfroidt *et al* 2018). If the leakage effect is large, it should be reflected in land markets, with increasing land prices indicating growing demand for land in regions subject to lower levels of conservation policy enforcement.

This paper seeks to shed light on how spatially heterogeneous infrastructure investments and conservation policy enforcement affect the Brazilian land market. We focus on the speculative component of the land price, which contains expectations on the appreciation of low-value forestland after converting it to high-value pasture or cropland. The potential role of speculation as a driver or timely indicator of deforestation has so far rarely been considered explicitly in predictive models of deforestation (Kaimowitz and Angelsen 1998, Busch and Ferretti-Gallon 2017). Uncovering the economic mechanisms driving speculative behavior may thus help policy makers to anticipate future deforestation hotspots.

The reminder of the paper is structured as follows. In section 2 we develop a theoretical framework that decomposes market prices of forestland into rents, conversion costs, and a speculative component. Section 3 provides a background on the study area and documents our empirical strategy. Results are presented in section 4. We find that a reduction in expected travel time from a location in the landscape to the nearest market contributes to an increase in forestland prices, an effect reinforced in our area of study by policy-induced leakage. In section 5 we discuss our findings and policy implications.

2. Land prices and speculation

Land rent theory explains how access to markets affects land rents and associated land use patterns (Holland *et al* 2016). According to this theory, land rents are a function of (a) distance to sources of trade or relevant markets (Thünian notion), and (b) land productivity (Ricardian notion) determined by biogeophysical factors, such as topography, soil fertility, climate conditions, and agricultural technology (Munroe *et al* 2002).

Figure 1 depicts a land rent theory framework for an alternative use of forestland over two time periods *t*. Yellow lines represent rents of an alternative land use (e.g. pasture), R^{P}[6]. Straight bold line indicates the first period land rent that depends on distance to market and transport nodes. The agricultural frontier (D_F) is located where land rent becomes zero. The dashed line illustrates the effect of infrastructure improvement in the second period, implying lower transportation costs and therefore a flatter rent curve. The agricultural frontier expands to D_F''. This expansion happens if conversion of forestland to pasture involves negligible costs. If infrastructure investments are accompanied by improved conservation policy enforcement, conversion costs increase (e.g. due to the risk of paying fines) implying a downward shift of the rent curve (Börner *et al* 2014). This leads to a leftward shift of the agricultural frontier ($D_F' < D_F''$ in figure 1). Figure 1 also shows that infrastructure improvements lead to higher rents from pastures at any location due to travel time savings. Furthermore, land rents beyond the agricultural frontier D_F, but within the frontier D_F', are zero in the first period and become positive in the second period. Here the conversion of forests to alternative land uses increases land rents.

Standard land rent theory, as summarized in figure 1 can only explain deforestation as a result of changing production incentives (Jepson 2006). To capture speculative behavior we need to expand our perspective to account for land market transactions and expectations.

We use a present value formulation of land prices similar to previous studies to decompose forestland prices in its different components (Shiller 1981, Burt 1986, Tegene and Kuchler 1991, Engsted 1998). Forestland prices can be expressed as follows:

$$P_{it}^F = \mathrm{EDR}_{it}^F + \mathrm{EDR}_{it}^P - \mathrm{EDCC}_{it}. \quad (1)$$

In equation (1), the price of forestland at location i at time t, P_{it}^F, is the sum of the expected discounted stream of forestland rent, EDR_{it}^F, and the discounted stream of rents of the most profitable alternative land use option (e.g. pasture), EDR_{it}^P, net of the expected discounted conversion costs, EDCC_{it}[7].

At a given location in the landscape, the market price of forestland thus depends on whether and when conversion occurs. To reflect this probabilistic notion we define the discounted stream of rents from forestland as a function of key components at a given time t: the pure forestland rents (R_{it}^F), a probability of conversion from forest to pasture at the beginning of time t (ρ_t), and a discounted rate (r_t), so that:

[6] In the remaining we exemplify alternative uses with pasture. This has been pointed as a major source of deforestation in Brazil and often as the land conversion resulting from speculation (Bowman 2016).

[7] For expositional reasons we use pasture as the only alternative land use in our model.

$$\mathrm{EDR}_{it}^F = (1-\rho_0)\mathrm{R}_{i0}^F + \frac{(1-\rho_0)(1-\rho_1)\mathrm{R}_{i1}^F}{1+r_1} + \frac{(1-\rho_0)(1-\rho_1)(1-\rho_2)\mathrm{R}_{i2}^F}{(1+r_1)(1+r_2)} + \ldots \quad (2)$$

Pasture rents accrue only after the forestland has been converted to pasture. Under the same assumptions as above, the discounted stream of pasture rents becomes a function of pasture rents (R_{it}^P), and the same probability of conversion and a discounted rate as for EDR_{it}^F apply, so that:

$$\mathrm{EDR}_{it}^P = \rho_0\left[\mathrm{R}_{i0}^P + \frac{1}{1+r_1}\mathrm{R}_{i1}^P + \frac{1}{(1+r_1)(1+r_2)} \times \mathrm{R}_{i2}^P + \ldots\right] + (1-\rho_0)\rho_1\left[\frac{1}{1+r_1}\mathrm{R}_{i1}^P + \frac{1}{(1+r_1)(1+r_2)}\mathrm{R}_{i2}^P + \ldots\right] + (1-\rho_0)(1-\rho_1)\rho_2\left[\frac{1}{(1+r_1)(1+r_2)}\mathrm{R}_{i2}^P + \frac{1}{(1+r_1)(1+r_2)(1+r_3)}\mathrm{R}_{i3}^P \ldots\right] + \ldots \quad (3)$$

To reduce complexity, we assume R_{it}^F, R_{it}^P, ρ_t, and r_t are constant over time. In addition, expected discounted conversion costs (EDCC_{it}) depend also on the probability of conversion and the discount rate but additionally in a cost, τ, which we assumed to be constant in time and space and only accrue at the point of conversion from forest to pasture land, then:

$$\mathrm{EDCC}_{it} = \rho\tau + \frac{(1-\rho)\rho\tau}{1+r} + \frac{(1-\rho)^2\rho\tau}{(1+r)^2} + \ldots \quad (4)$$

Substituting equations (2)–(4) in (1) and all our assumptions combined allow us to construct the current price of forestland as follows (see also SM is available online at stacks.iop.org/ERL/14/045006/mmedia):

$$P_{it}^F = \frac{(1+r)(-r\rho\tau + (r - r\rho)R_i^F + (1+r)\rho R_i^P)}{r(r+\rho)}. \quad (5)$$

When conversion probability ρ equals zero, the forestland price is absent of any speculative behavior related to future land conversion, i.e. forestland price depends purely on discounted forestland rents. Further, equation (5) emphasizes that even when forestland rents remain unchanged, forestland prices change if the conversion probability, conversion costs or pasture rents change.

Comparative static analysis of the expression in equation (5) (see SM) leads us to the following hypotheses:

(H.1). Expected improvements and investments in infrastructure will affect expected net rents from alternative uses and will, thus, increase the forestland price by increasing the probability of conversion.

(H.2). Increases in expected conversion cost, for example, due to improved conservation policy enforcement:

a. Decrease the forestland price regionally (i.e. land market region), because expected rents from forest conversion are reduced through a lower conversion probability and/or increased conversion costs.

b. Can increase the forestland price globally (i.e. our study area) if policies focus on sub-regions (i.e. areas inside the Brazilian Legal Amazon in a land market) and actors in the land market anticipate future policy-induced land scarcity through increased (global) pasture rents (speculation-induced policy leakage).

(H.3). Any increase in output prices or decrease in input prices will increase the forestland price through the rent component of forest or pasture.

3. Empirical strategy and data

Since we cannot directly observe the key components of our theoretical model, we empirically decompose forestland prices according to hedonic theory (first exposed by Rosen 1974) in order to test our hypotheses. In our context, hedonic modeling rest on the assumption that the price of a parcel of land is the sum of the unobserved prices of a bundle of attributes associated with that good (Snyder *et al* 2008). We thus account for heterogeneity in the quality of land and, using panel data, for changes in key attributes that we hypothesized to affect land prices (Chicoine 1981, Sills and Caviglia-Harris 2009), see details in the SM.

Following this notion we can specify a reduced-form model of forestland prices:

$$P_{it}^{F} = \sum_{n=1}^{N} \alpha_n R_{nit} + \sum_{j=1}^{J} \gamma_j S_{jit} + d_t + \mu_i + \epsilon_{it}. \quad (6)$$

Here P_{it}^{F} represents forestland prices in region i at time t as a function of attributes that are averaged at the location, e.g. land market region. R_{it} is a vector of N attributes related to forestland and pasture rents and conversion costs. S_{it} is a vector of J attributes with influence on the probability of conversion, i.e. our indicators of speculation and stringent conservation policy. In equation (3) α_n and γ_j are vectors of parameters to be estimated. All specifications are estimated as two-way models in log–log form including vectors of time (d_t) and individual (μ_i) fixed effects to capture unobserved year and region specific factors (Baltagi 2016). ε_{it} represents an idiosyncratic error term. In our first specification, we estimate forestland prices by considering attributes that affect land rents and disentangle the effect of speculation. That is, the term S_{it} in equation (6) only has our speculation related variable ($J = 1$). In a second specification, we estimate the same model as before but additionally including our proxy for conservation stringency which allow us to test potential leakage effects. In this second specification S_{it} includes two variables affecting the probability of conversion ($J = 2$). As robustness check, we use the first lag of all covariates instead of the contemporaneous values for both specifications (see SM). We point out that our contemporaneous model does not consider the year 2001, so that the results of the contemporaneous and lagged models can be comparable.

Our units of observation are land market regions in the Amazon and Cerrado biomes (61 out of 133 in the whole Brazil), for which average forestland prices were collected between 2001–2012 (see figure S1 in SM). Land market regions differ in size, number of sample points, and types of land considered, e.g. easy/difficult access Amazon forest or dense/open Cerrado (see also S2 in SM). During our period of study, major infrastructure investments and forest governance reforms were announced and partially implemented in our study area (Reid and Cabral de Souza 2005, Nepstad *et al* 2014). First, the federal government published two multiannual development plans between 2000–2007, and in 2007, the Ministries of Transport and Defense published a National Plan on Logistics and Transportation (MP 2004, Zioni and Freitas 2015). These plans provide information on expected improvements and constructions in the federal road network. Among these are investments that aim to connect isolated agricultural areas (pavement of highway BR-319 in Amazonas state) or to facilitate exports from well-developed agricultural areas (pavement of highway BR-163 in Mato Grosso and Para). Some studies suggest that these infrastructure projects fueled land speculation and associated forest loss (Fearnside and deAlencastro-Graça 2006, Fearnside 2007). Second, a structural forest governance reform was launched in 2004 with the publication of the plan to combat deforestation in the Amazon (PPCDAm in its Portuguese acronym). By 2016, deforestation in the Amazon biome was 71% lower than in 2004 (INPE 2017), which has been attributed largely to the PPCDAm and accompanying private sector governance measures, such as the soy moratorium (Arima *et al* 2014, Nepstad *et al* 2014, Cisneros *et al* 2015).

To test the hypotheses laid out above, we choose variables that influence the three components of our conceptual framework (equation (5)), i.e. land use rents

Table 1. Summary of variables and sources used.

Variable (units)	Source	Obs	Mean	St. Dev.	Min	Max
Land market region size (km^2)	FNP (http://fnp.com.br/); own calculation	79	90 588.540	129 045.000	7147.439	795 965.700
Forestland price ($R ha^{-1})	FNP (http://fnp.com.br/)	756	467.594	434.631	8.702	2785.743
Expected accessibility improvements (h)	Own calculation; DNIT; Hansen *et al* (2013)	948	−0.497	1.255	−6.659	0.000
Agriculture price index	Own calculation; IBGE (http://sidra.ibge.gov.br/)	948	0.400	0.212	0.054	1.797
Soy aptitude within forest areas (share of region)	Own calculation; Soares-Filho *et al* (2016), Hansen *et al* (2013)	948	0.086	0.117	0.000	0.536
Protected areas (share of region)	Brazilian Ministry of Environment	948	0.077	0.111	0.000	0.509
Cattle density (heads km^{-2})	Own calculation; IBGE (http://sidra.ibge.gov.br/)	948	0.365	0.270	0.002	1.117
Accessibility (h)	Own calculation; DNIT; Hansen *et al* (2013)	874	4.263	5.320	0.000	24.489
Fines incidence ($\#/(10 \times km^2)$)	IBAMA (http://ibama.gov.br)	948	0.031	0.046	0.000	0.557
Districts outside the Brazilian Legal Amazon (share of region)	Own calculation; IBGE	948	0.417	0.487	0.000	1.000
Dummy PPCDAm (0/1)	Own calculation	948	0.750	0.433	0	1

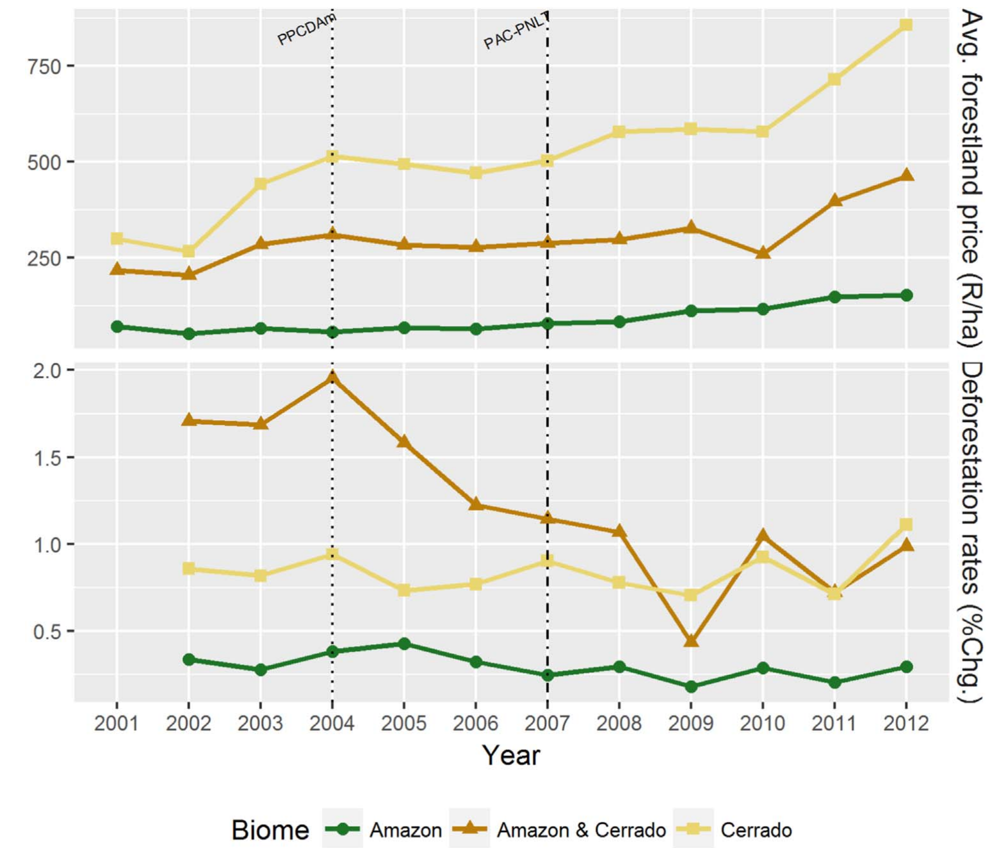

Figure 2. Forestland prices and deforestation during the study period. Note: We differentiate three types of regions: within Amazon, within Cerrado, and those overlapping with both biomes. All prices were deflated including the base year 2001. Vertical dotted line refers to the year in which the PPCDAm was implemented. Dotted-straight line represents the year in which a national plan on logistics and transportation was issued.

(e.g. crop prices), conversion costs (e.g. environmental fines), and probability of conversion (e.g. expected improvements in accessibility due to road infrastructure; stringent conservation policy). Summary statistics of our unit of analysis and all variables use in the empirical estimation are presented in table 1. Details on data processing steps are documented in the SM.

The two variables of interest in our analysis are those affecting the probability of forestland conversion component, ρ, as we assume they affect the expectation of land conversion among land market actors. First, we use information on existing and planned roads to calculate *expected accessibility improvements* to relevant markets (i.e. municipality capitals) as a source of speculative behavior. We expect land users to adjust their future land rent expectations based on expected road infrastructure improvements, which should be reflected in forestland prices. Second, we construct the variable *Post2004_Conservation* to capture the effect of time and biome-specific changes in conservation governance as follows: *Post2004_Conservation* = *Dummy PPCDAm* × *Area share of region outside the Brazilian Legal Amazon* × *Share of forest area suitable for soy production*; where, *Dummy PPCDAm* takes values of 0 for years before 2004 and 0 otherwise. This second variable of interest acts like a treatment effect indicator that identifies agriculturally suitable Cerrado regions as treated from 2004 onwards. Unless there were other significant structural changes affecting any region separately in this particular year, the indicator picks up changes in the behavior of land prices in the Cerrado that were induced by more rigorous conservation policy implementation in the Amazon region (i.e. leakage).

Based on our theoretical model, we expect (1) positive forestland price shifts in target areas of planned infrastructure investments (hypothesis H.1), (2) negative shifts in areas affected by forest governance measures (H.2a), and (3), positive shifts in the presence of conservation policy leakage in regions with comparatively little change in *de facto* governance effectiveness (H.2b).

4. Results

4.1. Descriptive analysis

Figure 2 below depicts the forestland price dynamics and deforestation rates for land market regions located

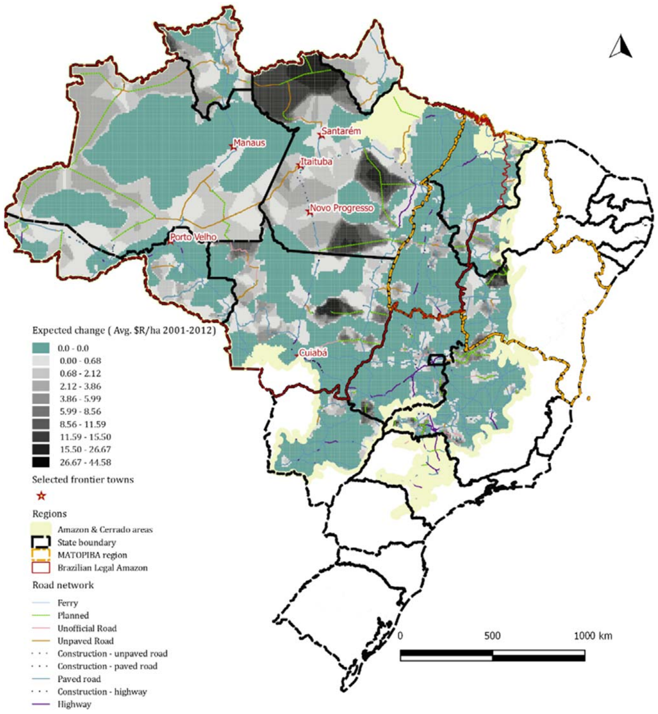

Figure 3. Effect of expected changes in accessibility on forestland prices. Note: We use the coefficients estimated in our second model together with a map of expected accessibility improvements at a 10 × 10 km raster resolution to obtain percentage changes holding all other factors constant. We then multiply this map with that of average prices in land market regions.

in different biomes: Amazon forest, Cerrado savannah, and regions with both biomes[8].

Average forestland prices (upper panel in figure 2) for the three groups were on the rise up to 2004. The implementation of the PPCDAm was accompanied by forestland price reductions across regions (see also figure S2 in the SM). Yet, forestland prices in the Cerrado clearly rose in subsequent years to levels seven times higher than in the Amazon region in 2012. Note also that land prices were relatively stable in regions with both biomes up until 2010, when they began to rise, and doubled by 2012. This increase coincides with the political debate that led to the reform of the Forest Code and associated amnesties for past forest law offenders (Soares-Filho *et al* 2014).

The lower panel in figure 3 illustrates deforestation rates measured as the percentage change of tree cover in the three types of regions (Hansen *et al* 2013). After 2004, deforestation rates dropped particularly in regions with historically high levels of forest loss (see figure 4 below and figure S3 in the SM). Another pronounced reduction in these region occurred between 2008–2009. In these years additional public and private sector initiatives reinforced conservation stringency leading to further reductions in deforestation rates (Arima *et al* 2014, Cisneros *et al* 2015). Meanwhile, deforestation rates remained relatively stable in Cerrado regions.

[8] This last group of regions is located within a highly dynamic area, the so-called 'Arc of Deforestation'.

4.2. The speculative component of forestland prices

According to our theoretical model, speculation, represented as an increase in the conversion probability due to market actors' anticipation of land appreciation, will increase forestland prices.

Column 1 in table 2 reports our main results of estimating the respective specification of equation (6) considering price attributes that affect rents, conversion costs and the speculation component of land prices. We find that regions with lower average crop prices and high concentration of environmental-related fines tend to exhibit lower forestland prices (as expected by our hypotheses H.3 and H.2a, respectively). Environmental fines are negatively associated with the forestland price, reflecting conversion costs. Due to the log–log specification, we interpret estimated coefficients as elasticities of forestland prices with respect to its corresponding variable (Wooldridge 2013, p 44). Looking at our indicator of speculation (i.e. expected accessibility improvements), the estimated coefficient is significant at the 5% level and positive, i.e. cutting expected travel time from a location to the nearest market by 1% (0.6 min) increases the regional forestland price by 1.5%. This finding indicates speculative behavior in land markets hinting toward the future location of agricultural frontiers and corroborates our hypothesis H.1.

Table 2. Regression results of speculation and stringent conservation analysis.

	Dependent variable: lnForestland price		
	Speculation (1)	Stringent conservation (2)	Model component
lnExpected accessibility improvements	1.541[a]	1.530[a]	Speculative (ρ)
	(0.760)	(0.740)	
lnCrop price index	0.398[a]	0.416[a]	Rents (R)
	(0.197)	(0.197)	
lnSoy apptitude	4.697	6.594	Rents (R)
	(4.768)	(4.896)	
lnProtected areas	1.108	1.127	Cost of conversion (τ)
	(0.858)	(0.847)	
lnCattle density	0.791	0.979	Rents (R)
	(0.693)	(0.694)	
lnAccessibility	0.516	0.268	Rents
	(0.963)	(0.960)	+ Cost of conversion ($R+\tau$)
lnFines incidence	−1.459[b]	−1.440[b]	Cost of conversion (τ)
	(0.397)	(0.391)	
lnAccessibility × nonBLA[c]	−0.587	−0.298	Rents
	(1.090)	(1.105)	+ Cost of conversion ($R+\tau$)
Post2004 Conservation		1.677[d]	Stringent conservation (ρ)
		(0.887)	
Time and regional fixed effects	Yes	Yes	
Observations	682	682	
R^2	0.091	0.100	
F Statistic	7.503[b] (df = 8; 602)	7.392[b] (df = 9; 601)	

[a] Significant at 0.05 level.
[b] Significant at 0.01 level.
[c] NonBLA refers to the share of area outside the Brazilian Legal Amazon in a land market region.
[d] Significant at 0.1 level. Robust standard errors are given in parentheses.

4.3. Land prices and conservation policies

To explore the effects of regionally focused conservation policy interventions we add the policy shock variable to the model (second column table 2).

Our previous results remain stable and our post-2004 policy indicator is significant at the 10% level and on average positively associated with forestland prices[9]. Our post-2004 conservation variable is associated with an increase in forestland prices by 1.6% on average. Assuming no bias from unobserved variables (see discussion below), this finding speaks to our hypothesis H.2b, i.e. speculation-induced conservation policy leakage to regions and areas that are less controlled or not protected by law. This would primarily affect regions with large reserves of agronomical suitable forestland (e.g. Cerrado areas).

Our results reflect the immanent tradeoff between conservation and agricultural development at the Brazilian agricultural frontier. Without increases in environmental law enforcement (here measured in terms of fine incidence), road infrastructure expansion tends to increase land demand, which is associated with deforestation.

4.4. Policy relevance and speculation

Figure 3 depicts the 2001–2012 average effect of expected improvements in road infrastructure on forestland prices, while keeping all other covariate effects constant. Our model thus serves to identify speculation zones that potentially require additional scrutiny by environmental law enforcement agencies. Some of these zones happen to lie outside the Legal Amazon region, where regulations are less stringent. Here the risk of developing into future deforestation hotspots can be comparatively high. Visual comparison with the dynamics of deforestation hotspots after implementation of the PPCDAm (figure 4), confirm this conjecture only for some speculation zones, such as along the BR-163 in the states of Mato Grosso and Pará and in the so-called 'MATOPIBA' region at the eastern border of our study area[10]. This observation shows that various factors have to come together for land market speculation to result in deforestation and deserves further research.

In sum, our findings suggest that land market prices in Brazil are not merely governed by expectations

[9] As mentioned in the Empirical strategy section, our contemporaneous model does not consider the year 2001. We run an alternative contemporaneous model that includes the year 2001 and found that our conservation policy variable became marginally insignificant (p-value of 0.1145) pointing to limited robustness of this finding. We present this version of the model in the SM table S4.

[10] See S7 in SM for a description on how our deforestation hot spots map is generated.

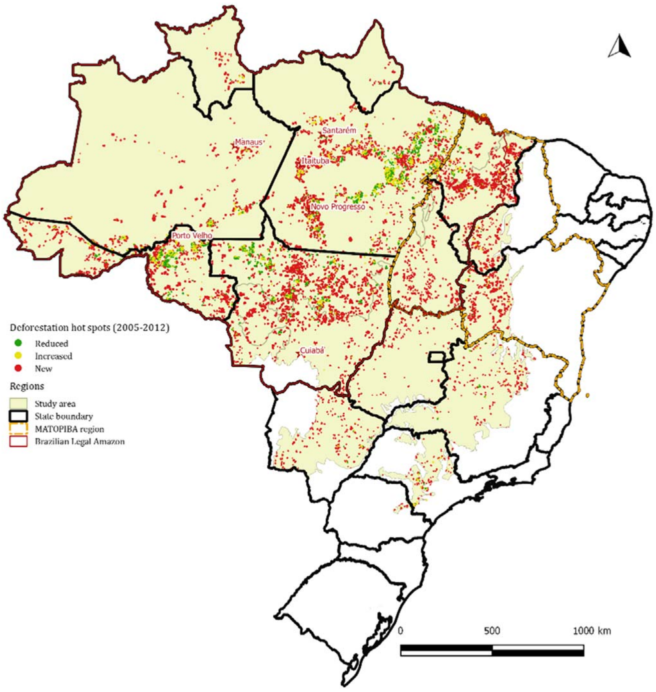

Figure 4. Hot spots of forest cover loss (2005–2012). Note: This figure depicts hot spots in Amazon and Cerrado biomes between 2005 and 2012. Three types of hot spots are identified: (a) reduced (green), (b) increased (yellow), and (c) new (red). High concentration of new hot spots are located in eastern parts of Cerrado in the MATOPIBA region, as well as in Mato Grosso and Pará along the BR-163.

on rents and forest conversion costs (hypotheses H.1 and H.2b). Expectations on future infrastructure improvements and conservation policy-induced land scarcity are likely to be priced into today's land market transactions.

5. Conclusion and discussion

We have developed a theory of land market price formation at agricultural frontiers that explains why forestland prices can contain information about future expectations of land market actors. The subsequent empirical analysis using a panel dataset of forestland prices and their determinants shows that land markets: (1) convey information about anticipated infrastructure improvements (hypothesis H.1), (2) may indicate conservation policy leakage between regions with heterogeneous levels of legal protection and policy enforcement effectiveness (hypothesis H.2b)—though this finding is less robust to alternative model specifications than the first. This paper contributes to the debate in indirect land use change (Hertel 2018) by scrutinizing the potential role of land markets both as mechanisms behind land use leakage and as an early warning system to anticipate future deforestation hotspots.

It is worth noting that land market speculation may or not require policy action depending on its social and environmental implications. For example, depending on asymmetries in bargaining power between buyers and sellers, speculative land market transaction may result in suboptimal outcomes for poor smallholder with insecure property rights (Baletti 2012). Moreover, in contexts where deforestation is a means to secure land claims, land market speculation may be associated with irrationally high levels of forest conversion. Speculation thus eventually becomes a mechanism that complements market-based leakage to the extent of neutralizing direct conservation policy effects, as our results seem to suggest for the behavior of forestland prices. Preemptive and spatially targeted policy action may thus sometimes be necessary to counteract potentially negative social and environmental outcomes of land market speculation.

A number of caveats applies, which can be addressed in future research, but should be taken into account when interpreting our findings. First, our indicator of expected infrastructure improvements only accounts for primary road expansion and ignores other important planned infrastructure investments, such as in the mining and energy sectors. It is well known from the literature that secondary roads contribute a great deal toward improving accessibility in agricultural frontier development (Arima *et al* 2008, Perz *et al* 2008, Walker *et al* 2011). While this may have led us to underestimate speculation, one should keep in mind that land market actors may not take infrastructure investment plans at face value, given that implementation often lags behind actual plans (Amann *et al* 2016). Second, our policy shock indicator (representing the implementation of PPCDAm) is imperfect in that it captures more than just policy shocks. We can only argue that this policy event has probably dominated land market dynamics in subsequent years, but our results are likely to be simultaneously driven by other unobserved macro-changes. Follow-up research requires land price data at higher spatial resolution (Coomes *et al* 2018) and should focus on directly linking land price dynamics to deforestation patterns.

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