Deforestation Slowdown in the Brazilian Amazon: Prices or Policies?

Online Appendix

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A. Conceptual Framework

The model presented in this section describes a situation in which a farmer seeking to increase his agricultural production may do so by expanding farmland beyond the limits of his original landholding. It therefore focuses on the extensive margin of agricultural production. In particular, the model shows how conservation policies may influence the farmer's choice of optimal farmland size, as well as his response to changes in agricultural output prices. Implications derived from this conceptual framework guide our empirical investigation of the relationship between agricultural commodity prices, conservation policies, and deforestation.

A.1. The Model

Consider a farmer having an endowment of $\overline{T}$ hectares of cleared homogeneous land that may be used for agricultural activities. There is no rental market for land and all area outside the farmer's property is public forest. The expansion of the farmer's agricultural activities

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beyond his landholding of $\overline{T}$ can therefore only be done at the expense of areas of public forest.

For each hectare of land used beyond $\overline{T}$, in addition to bearing the cost of clearing the new area, the farmer also faces the risk of paying a penalty for having broken the law and illegally cleared forest areas. The stringency of conservation policies determines the magnitude of this penalty. We express the shadow cost of expanding farmland beyond $\overline{T}$ as $\Gamma > 0$, which represents the combination of clearing costs and expected monetary infringement costs associated with the illegal use of areas of public forest. Hence, Γ is the model's policy stringency parameter.

Agricultural output is determined by the production function $Y = AT^{\beta}$, where T is farmland A is a productivity parameter. Returns to scale are decreasing ($\beta < 1$). We assume there are non-scalable inputs such as managerial resources. Given the expected price of agricultural output, p, the farmer chooses farmland size to maximize his end-of-season profit, which is defined by:

$$\pi(p, \overline{T}, \Gamma) = \begin{cases} pAT^{\beta} - T & \text{if } T^* \leq \overline{T} \\ pAT^{\beta} - T - \Gamma(T - \overline{T}) & \text{if } T^* > \overline{T} \end{cases}$$

subject to $T \geq 0$. The price of a hectare of farmland is normalized to 1 for $T^* \leq \overline{T}$, and is interpreted as the per hectare cost of capital and labor-related inputs that are assumed to be employed at fixed proportions. For $T^* > \overline{T}$, the price of a hectare of farmland increases to $(1 + \Gamma)$ due to clearing and infringement costs.

Considering only internal solutions ($T^* > 0$), the farmer's optimal choice of farmland is given by:

$$T^* = \begin{cases} (\beta pA)^{\frac{1}{1-\beta}} < \overline{T} & \text{if } p < \overline{P_1} \\ \overline{T} & \text{if } \overline{P_1} \leq p \leq \overline{P_2} \\ \left(\dfrac{\beta pA}{1+\Gamma}\right)^{\frac{1}{1-\beta}} > \overline{T} & \text{if } p > \overline{P_2} \end{cases} \tag{1}$$

where $\overline{P_1} \equiv \dfrac{\overline{T}^{1-\beta}}{\beta A}$ and $\overline{P_2} \equiv \dfrac{\overline{T}^{1-\beta}(1+\Gamma)}{\beta A} = \overline{P_1}(1+\Gamma)$. Equation (1) determines optimal farmland size for different agricultural output price levels. When output prices are relatively low, $p < \overline{P_1}$, part of the farmer's land is left idle, with $T^* < \overline{T}$. For all output price levels between $\overline{P_1}$ and $\overline{P_2}$, optimal farmland size is fixed at $\overline{T}$. The choice of T^* at this concentration point results from the fact that, at $\overline{T}$, the marginal per hectare cost of land discontinuously jumps from 1 to $(1+\Gamma)$ and remains greater than the marginal revenue up to the point at which output price equals $\overline{P_2}$. Note that the size of the $\overline{P_1}$ to $\overline{P_2}$ price range is proportional to $1+\Gamma$. Finally, for output price levels above the $\overline{P_2}$ threshold, the farmer chooses to operate beyond $\overline{T}$, which implies clearing $(T^* - \overline{T})$ hectares of public forest. In this case, agricultural output prices are sufficiently high to sustain optimal production at levels of $T^* > \overline{T}$, despite higher production costs.

In the following sections, we examine the model's main policy implications from both theoretical and empirical perspectives.

A.2. Policy Effects on Land Use: Theoretical Implications

In our model's simplified setting, deforestation is defined as the act of clearing areas of public forest to use cleared land for agricultural production. All land beyond the farmer's property (beyond $\overline{T}$) is public forest. Thus, as long as output prices are high enough to induce the clearing of previously unused land, comparative statics for optimal farmland size are analogous to those for deforestation. Policy therefore affects deforestation via its impact on farmland size.

For farmers operating beyond $\overline{T}$, an increase in policy stringency ($d\Gamma > 0$) raises the per hectare cost of farmland and thereby makes production more expensive. Direct effects of an increase in policy stringency on optimal farmland size are formally given by:

$$\frac{dT^*}{d\Gamma} = \begin{cases} 0 & \text{if } p \leq \overline{P_2} \\ -\dfrac{1}{1-\beta}\dfrac{(\beta p A)^{\frac{1}{1-\beta}}}{(1+\Gamma)^{\frac{2-\beta}{1-\beta}}} < 0 & \text{if } p > \overline{P_2} \end{cases} \tag{2}$$

Equation (2) states that when output prices are low ($p \leq \overline{P_2}$), variations in policy stringency do not affect optimal farmland size. This is because relatively low output prices do not encourage the farmer to extend production beyond his landholding ($T^* \leq \overline{T}$). In this case, there is no incentive to clear areas of public forest and therefore no deforestation. However, when output prices are sufficiently high ($p > \overline{P_2}$) and the farmer's optimal choice implies in forest clearings ($T^* > \overline{T}$), stricter policies reduce optimal farmland size. As a result, increased policy stringency alleviates the pressure on public forests and restrains deforestation. Figure A illustrates this point graphically.

In addition to its direct effect on optimal farmland size, policy stringency also indirectly impacts deforestation by affecting the relationship between agricultural output prices and optimal land use choices. Indirect effects of an increase in policy stringency on optimal farmland size are formally given by:

$$\frac{d^2T^*}{d\Gamma dp} = \begin{cases} 0 & \text{if } p \leq \overline{P_2} \\ -\frac{1}{(1-\beta)^2}\frac{(\beta A)^{\frac{1}{1-\beta}}}{(1+\Gamma)^{\frac{2-\beta}{1-\beta}}}p^{\frac{\beta}{1-\beta}} < 0 & \text{if } p > \overline{P_2} \end{cases} \tag{3}$$

Equation (3) states that while policy stringency has no effect on the relationship between output prices and optimal farmland size when output prices are low ($p \leq \overline{P_2}$), stricter policies weaken this relationship for sufficiently high output prices ($p > \overline{P_2}$). Figure A again illustrates this effect — an increase in policy stringency flattens the curve relating output prices and optimal farmland size for all $p > \overline{P_2}$. Greater policy stringency therefore decreases the elasticity of optimal land use choice with respect to agricultural output prices.

Finally, although policy stringency has no effect on land use when the farmer operates within his landholding ($T^* \leq \overline{T}$), it does affect marginal costs at $\overline{T}$, since $\overline{P_2} = (1+\Gamma)\overline{P_1}$. Indeed, as policy becomes more stringent, the distance between $\overline{P_1}$ and $\overline{P_2}$ widens. From an economic perspective, this means that greater policy stringency enlarges the discontinuity in per hectare cost of land at the concentration point $\overline{T}$. Thus, by sufficiently driving up the value of the relevant threshold $\overline{P_2}$, stricter policies curb deforestation in a context of high agricultural output prices. These results are summarized in the following proposition:

Proposition 1. *The impact of conservation policies on optimal land use choices and deforestation depends on agricultural output price levels. If output prices are low ($p \leq \overline{P_2}$), there is no deforestation and policies do not affect optimal farmland size. If output prices are high ($p > \overline{P_2}$), farmers clear areas of public forest to expand production beyond their landholding — in this case, policies exert both a direct and an indirect effect on optimal farmland size and, thus, on deforestation. Increased stringency of conservation policies will therefore:*

1. *Reduce optimal farmland size,*
$$\frac{dT^*}{d\Gamma} < 0 \text{ if } p > \overline{P_2} \text{ (or } T^* > \overline{T}\text{), and } \frac{dT^*}{d\Gamma} = 0 \text{ otherwise;}$$
and
2. *Weaken the relationship between agricultural output prices and forest clearings,*
$$\frac{d^2T^*}{d\Gamma dp} < 0 \text{ if } p > \overline{P_2} \text{ (or } T^* > \overline{T}\text{), and } \frac{d^2T^*}{d\Gamma dp} = 0 \text{ otherwise.}$$

A.3. Policy Effects on Land Use: Empirical Implications

How can our conceptual framework be used to structure the empirical evaluation of conservation policies? What are the main empirical challenges and possible solutions implied by our model? The theoretical implications discussed in the previous section can be mapped onto empirical implications that help answer these questions. Two of these implications are particularly relevant for our empirical strategy.

First, the model states that agricultural output prices must be included in the analysis of the effects of conservation policies on deforestation. Because variations in output prices affect incentives to clear forest areas, the observed effectiveness of policy will also vary with agricultural prices. In particular, if a new set of policy measures is implemented in a period of decreasing agricultural prices, it may not be possible to capture its effects until prices recover. This is one of the empirical challenges we face when estimating the relative contribution of prices and policies to the recent deforestation slowdown. We must therefore control for agricultural output prices to better identify the policy impact.

This implication also has relevant consequences for the design of public policies. Maintaining a constant (e.g. zero) deforestation rate, for instance, requires command and control efforts to vary in the same direction as agricultural prices.[1] PES policies serve as another example. As the shadow price of preserving the forest varies with agricultural prices, compensation schemes should also vary accordingly.

Second, the model predicts that the effect of conservation policies is influenced not only by agricultural output prices, but also by the relative tightness of land constraints. The smaller the land area that is legally available for use in agriculture within a municipality, the tighter the land constraint faced by farmers, and, thus, the larger the price range within which we observe deforestation in that municipality. In this sense, $\overline{T}$ is a relative measure of land constraint, as it depends on the relationship between legally and illegally available land. Hence, we should explore the tightness of land constraints within our empirical setup as a means of introducing cross-sectional variation in response to policy.

If there is no available data that fully characterizes the extent to which the land constraint is binding at the municipality level, the model suggests two ways in which we can proxy for this tightness. First, we can calculate the ratio between land area that is not legally available for use in agricultural production within a municipality and total municipal land area. This variable depends on the municipality land endowment, a relatively fixed or slow-moving municipality feature. This proxy is valid because, for a given municipality, the greater the calculated ratio, the smaller the relative land area that is legally available for use in agricultural production, and the tighter the relative municipal constraint. Section 5.3 discusses this variable in more detail. Second, we can use observed deforestation during periods of peak prices. This variable depends on conjunctural price fluctuations. Although potentially noisy, this proxy is valid to the extent that, for a given municipality and period, the tighter the land constraint, the higher the incentive to clear new areas as agricultural

[1] This conceptual framework only considers the simplified case in which the relationship between output prices and agricultural production is contemporaneous. In a richer setting with leads and lags, this implication should be adapted.

prices increase.

B. Data

B.1. Policies: Alternative Proxy Variable

We use the normalized annual deforestation increment for municipality i in $t = 2004$, $D_{i,2004}$, as an alternative proxy for the tightness of municipal land constraints. This proxy is also suggested by our conceptual framework. Recall that our model implies that farmers will respond to rising agricultural output prices by expanding farmland, and that sufficiently high prices ($p > \overline{P_2}$) will push optimal farmland beyond private landholdings ($\overline{T}$), driving deforestation. Observed deforestation behavior can therefore reflect underlying tightness of land constraints. As the 2004 deforestation increment refers to the 2003 peak in agricultural commodity prices, $D_{i,2004}$ captures how binding municipal land constraints were in 2004, or how close farmers were to $\overline{T}$ at the time. Because this alternative proxy variable depends on conjunctural price fluctuations, which are potentially noisy and can introduce measurement error, we restrict its use to robustness checks.

C. Results

This section expands discussions on empirical results.

C.1. The Effect of Cattle Prices on Deforestation

This pattern of behavior for cattle prices and deforestation agrees with models of cattle cycles under fairly general conditions. Beef cattle stocks have been placed among the most periodic time series in economics. The explanation for this is that cattle are both capital and consumption goods. Some analysts suggest the existence of a negative supply response in animal industries (Jarvis, 1974; Rosen et al., 1994). For instance, if the price increase is sufficiently permanent, producers may optimally retain a larger number of females to add to the breeding stock so as to take advantage of higher prices in the future. On the other hand, a temporary demand shock leading to an increase in beef cattle prices should drive a positive short run supply response by cattle producers. The response in terms of increasing slaughter would therefore lower the pressure on land use and new forest clearings. In fact, a positive supply response can be derived even under permanent price shocks once the beef cattle industry is modeled in a more general framework. Aadland and Bailey (2001), for instance, allow producers to make decisions in different margins. The authors show that producers will respond positively to relatively higher prices along the consumption margin (increasing heifer cull rates) and will build up stocks along the investment margin (retaining females). These dynamics are therefore much in line with the relationship we find between cattle prices and deforestation. While a positive shock to lagged annual cattle prices could lead to increases in both heifer and cow inventories (and more pressure towards forest clearings), positive shocks to current prices could raise heifer cull rates and lower the pressure on land use.

D. Robustness Checks

Our empirical strategy relies on two important identification cornerstones. First, that our strategy adequately controls for direct price effects and municipality-specific time trends. This crucially depends on our understanding of the relationship between price variation, choice of farmland size, and deforestation. Thus far, our analysis has been based on the assumption that farmers take spot prices before the sowing period to choose the season's farmland size and the associated extent of forest clearings. However, whether this timing adequately represents farmers' real behavior in the Amazon region is still subject to further empirical investigation. In Section D.1, we use placebo tests to check whether we are indeed capturing the relevant relationship between price variations and deforestation.

Second, that we adequately capture the cross-sectional variation in land constraints at the municipality level. Although not directly observed, the tightness of land constraints was proxied in our analysis by the ratio between the land area that is not legally available to farmers for production and total municipal area. This proxy should be valid because, for a given municipality, the greater the calculated ratio, the smaller the relative land area legally available for use in agricultural production, and the tighter the relative municipal land constraints. However, detailed information on land use and landholding sizes is available only from 2006 Brazilian Agricultural Census data, which was collected after the 2004 policy turning point had occurred. Although this proxy depends on the municipality land endowment, a relatively fixed or slow-moving municipality feature, it is not totally free from endogenous variation due to policy effects. We can address this potential source of concern by using the alternative proxy for the tightness of municipal land constraints suggested by our conceptual framework. As discussed in Section A.3, an increase in agricultural prices will push for larger optimal farmland size, thereby tightening the relative land constraint. In Section D.2, we explore this by using observed deforestation increments associated with a period of peak prices as an alternative proxy variable for tightness. This proxy is valid under the hypothesis that, for a given municipality and period, the tighter the land constraint, the greater the incentive to clear new areas as agricultural prices increase.

We also test a second alternative proxy for the tightness of municipal land constraints, a dummy variable that flags whether a given municipality is above or below the median value in the distribution of $Tight$. This is a simple binary way of comparing municipalities where land constraints are more or less binding.

We also complement the analysis by replacing the normalized deforestation increment with the deforestation increment in square kilometers in the main specifications. Although noisy due to outliers, the regressions based on this alternative dependent variable yield coefficients that can be directly interpreted in terms of deforested area.

Overall, together with our main results, placebo regressions from Section D.1 indicate that price effects are being consistently estimated. These results are important since agricultural prices (and, therefore, demand for land) should be seen as the most relevant determinant of land use that varies in high frequency at the local level, over time. Together with municipality and time fixed-effects, local specific-time trends and price effects should determine deforestation trends. The remaining variation in deforestation should therefore be due to policy effects. This interpretation is valid since there is no evidence in support of any other determinants of deforestation in the Brazilian Amazon in such high frequency. The remaining variation in deforestation could be therefore associated with policy efforts. Moreover, Section D.2 shows that robustness checks based on our alternative proxy variable for tightness provides qualitatively similar results in comparison to our main proxy variable.

D.1. The Timing of Price Variations and Deforestation

In Table C, we perform placebo tests to further investigate the relationship between the timing of price variations and deforestation rates. The baseline specification is the same as the one used in Table 1, columns 1 through 4. In column 1 of Table C, we add future $(t+1)$ and past $(t-2)$ crop prices as regressors. As in Table 1, we confirm that deforestation is associated positive and significantly with crop price variations in $t-1$. We find no significant association between deforestation and future or past price variations.

In columns 2 through 4, we repeat the analysis for specific periods. As in Table 1, we find that deforestation is positively and significantly associated with variation in crop prices before the sowing season of $t-1$ (columns 2 and 3), while no significant impact is found for crop price variations before the sowing seasons of $t+1$ or $t-2$. In the last column we confirm that price variations during the sowing season are not associated with forest clearings. This set of results is consistent with farmers making decisions on land use and forest clearings just before the sowing season of $t-1$. This indicates that our specifications control for the relevant source of crop price variation.

D.2. Alternative Proxy Variables for Tightness

Column 1 of Table D repeats the baseline specification found in column 2 of Table 2. In columns 2 and 3, we replace our baseline proxy variable for tightness with alternative variables.

In column 2, our baseline proxy is replaced with a dummy variable indicating municipalities that have tightness measures greater than the median of the baseline proxy variable distribution. In column 3, we replace it with $D_{i,2004}$, the normalized annual deforestation increment for each municipality i in $t = 2004$, as defined in Section 5.3. In columns 4 and 5 we add to specifications in columns 2 and 3, respectively, interactions between policies and prices to control for potential heterogeneities in policy and price effects. We find that the effects associated with the policy variables remain significant in all regressions. Finally, in columns 6 through 8 we use the deforestation increment in square kilometers as the dependent variable to ensure that our results are not driven by the normalization of our dependent variable. Although noisy due to outliers and large municipalities, the results remain robust.

References

Aadland, D. and Bailey, D. (2001). Short-Run Supply Responses in the U.S. Beef-Cattle Industry. *American Journal of Agricultural Economics*, 84(4):826–839.

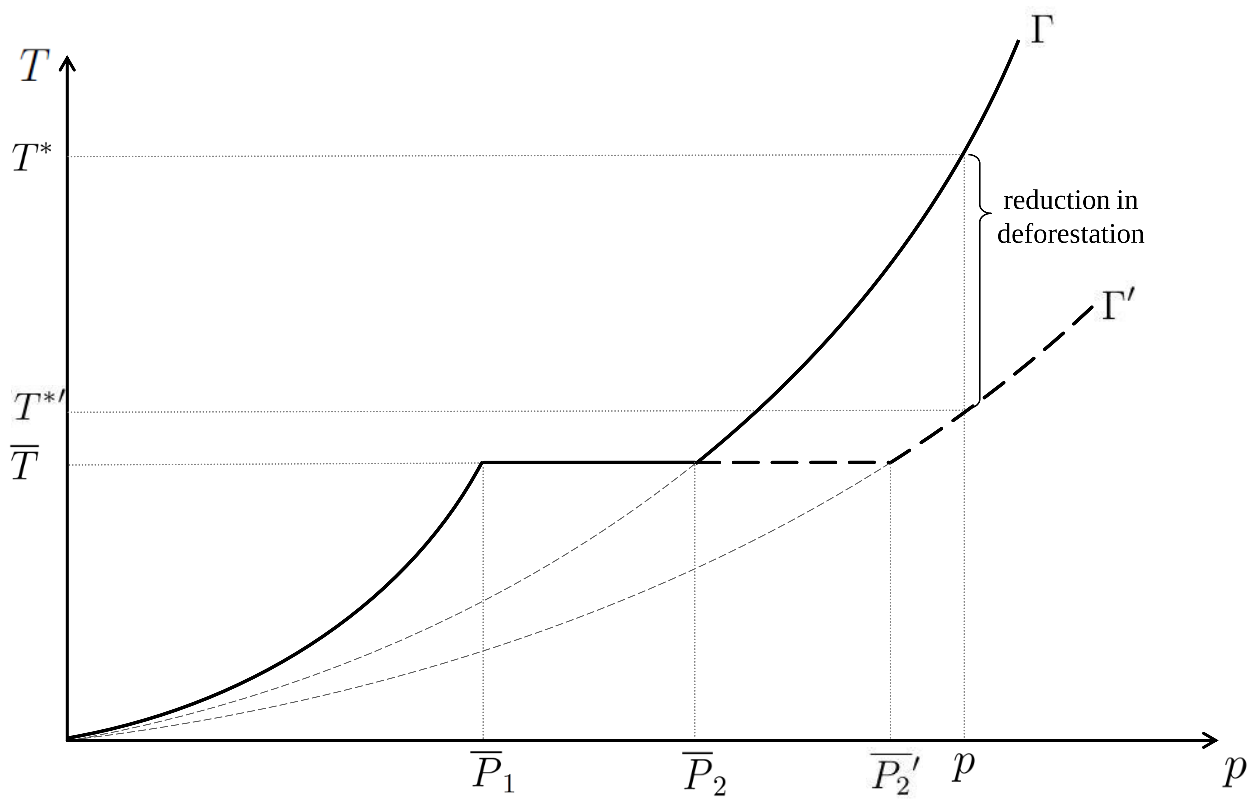
Jarvis, L. S. (1974). Cattle as Capital Goods and Ranchers as Portfolio Managers: An Application to the Argentine Cattle Sector. *Journal of Political Economy*, 82:489–520.

Rosen, S., Murphy, K. M., and Scheinkman, J. A. (1994). Cattle Cycles. *Journal of Political Economy*, 102(3):468–492.

Figures and Tables

See figures and tables on pages that follow.

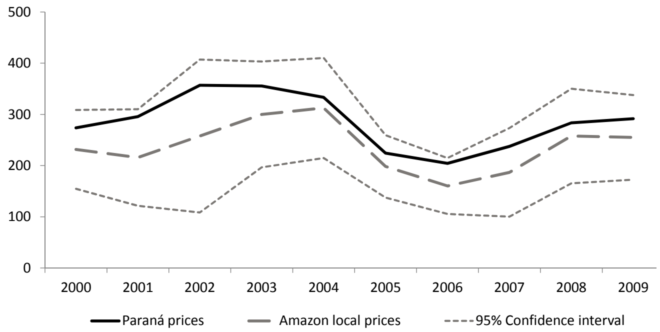
Figure A: Comparative Statics — Policy Effect on Optimal Farmland Size



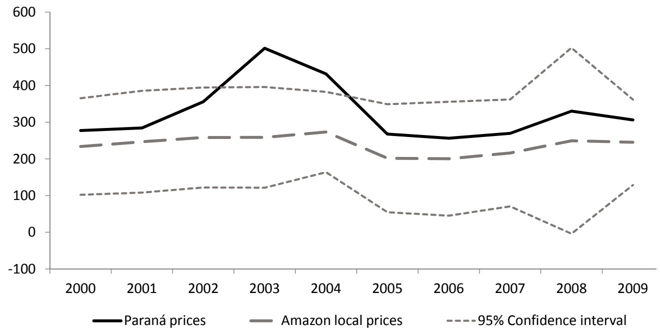
Notes: the graph illustrates a producer's optimal farmland choice (T^*) given agricultural output prices (p) under a shift from less stringent (Γ) to more stringent (Γ') conservation policy.

Figure B: Paraná Price Series and Average Amazon Prices, 2000-2009

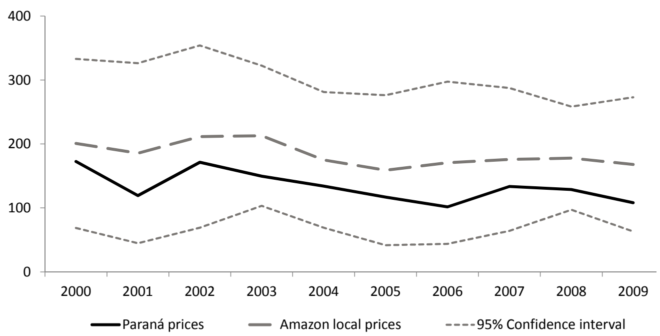
(a) Soybean



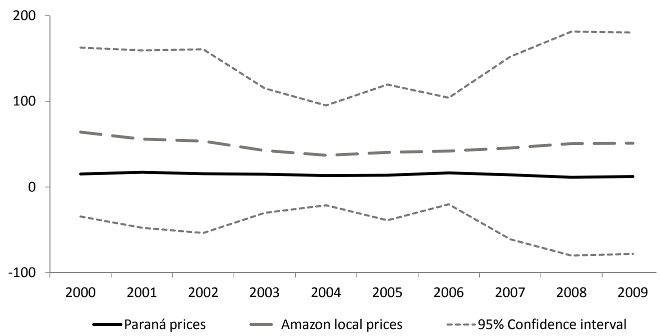
(b) Rice



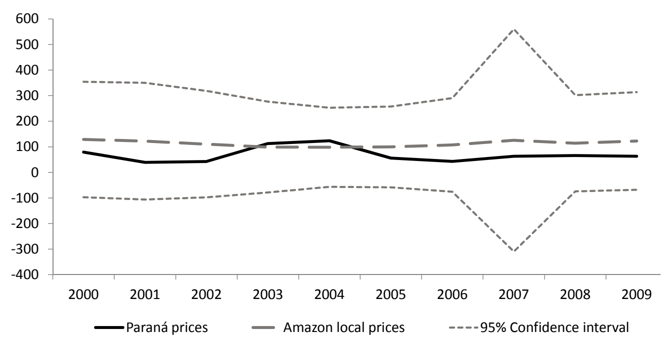
(c) Corn



(d) Sugarcane



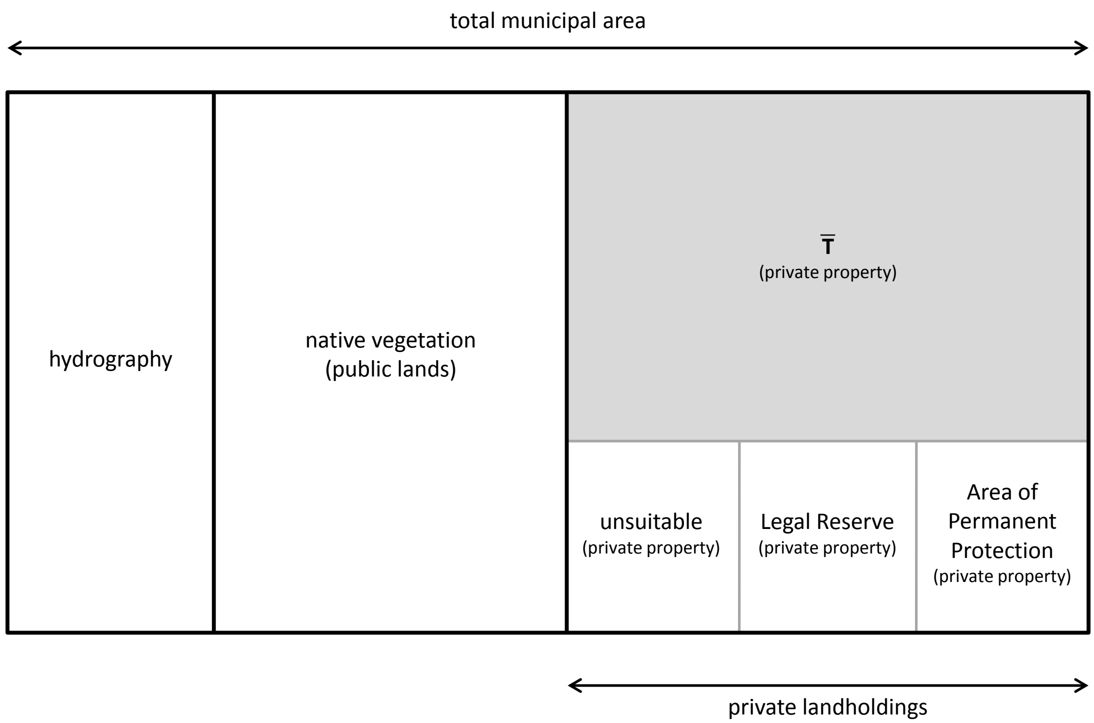
(e) Cassava



Notes: Paraná prices capture agricultural commodity prices from a non-Amazon Brazilian state. Amazon local prices are agricultural commodity prices calculated from municipality-level production data averaged across sample municipalities.

Source: data from SEAB-PR and PAM.

Figure C: Variable Construction — Proxy for Tightness of Land Constraint



Notes: the figure illustrates the construction of the proxy variable for tightness of municipal land constraints. Note that Legal Reserves, Areas of Permanent Protection and areas unsuitable for agricultural use are all inside private landholdings. We assume, as in our model, that all land beyond $\overline{T}$ is public forest.

Figure D: Counterfactual Simulation — What Would Have Happened in the Absence of the Policy Change?

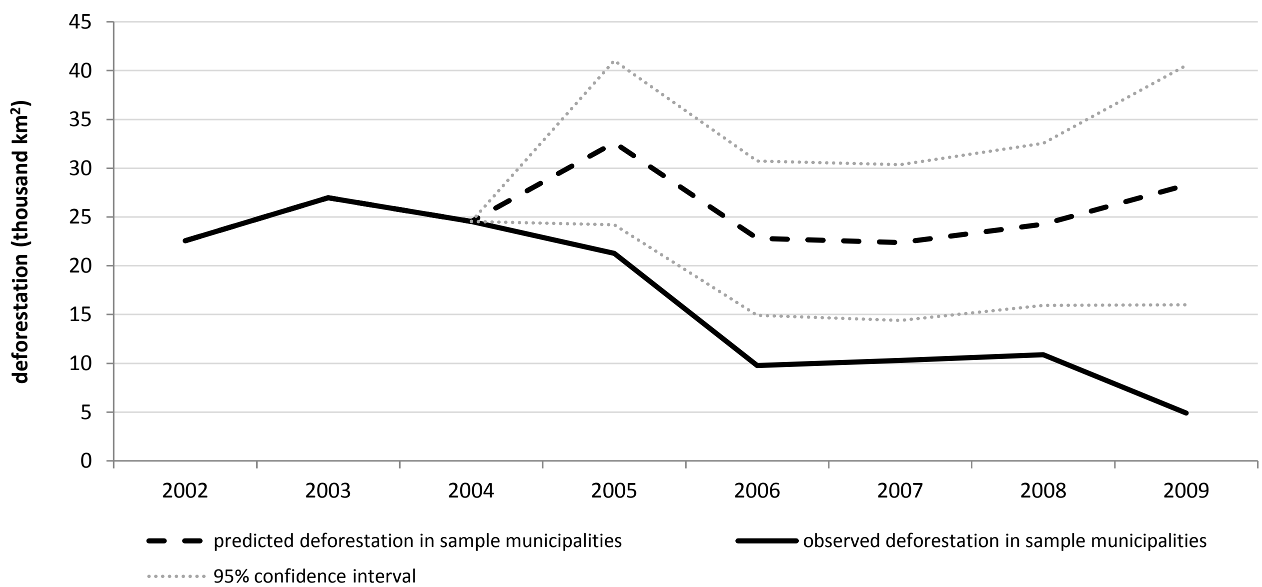


Table A: The Annual Index of Crop Prices and Descriptive Statistics

	Weights of 1^{st} Component of PCA	Sown Area as Share of: Total Municipality Area 2002	2009	Difference	Total Municipality Sown Area 2002	2009	Difference
Soybean	0.5940	0.0147	0.0226	0.0079	0.1076	0.1549	0.0474
Rice	0.4879	0.0041	0.0028	-0.0013	0.2278	0.1578	-0.0700
Corn	0.6362	0.0067	0.0101	0.0034	0.2867	0.2830	-0.0037
Sugarcane	0.0631	0.0022	0.0025	0.0003	0.0339	0.0363	0.0024
Cassava	0.0171	0.0041	0.0047	0.0006	0.3440	0.3680	0.0240

Notes: the table presents descriptive statistics for the constructed annual index of crop prices. Sample includes 380 municipalities located in the Legal Amazon states of Amazonas, Mato Grosso, Pará, and Rondônia. Data from SEAB-PR (agricultural prices) and PAM (agricultural production).

Table B: Impacts on Population, GDP, and Agricultural Production

	Ln(Population)	Ln(GDP per capita)	Sowed Area / Municipal Area	Production (crops, 1,000t)	Ln(Cattle)
	(1)	(2)	(3)	(4)	(5)
Tight * Post2004	-0.026	0.111	-0.021	-12.378	-0.046
	(0.025)	(0.054)**	(0.008)***	(15.906)	(0.073)
Tight * Post2008	-0.000	0.059	0.009	-11.757	0.196
	(0.014)	(0.045)	(0.007)	(10.156)	(0.096)**
Crop price index (t-1)	0.000	0.120	0.011	21.874	0.004
	(0.005)	(0.025)***	(0.006)*	(6.897)***	(0.022)
Cattle price index (Jan-Jun, t)	0.002	-0.005	0.000	0.147	-0.002
	(0.002)	(0.002)**	(0.000)	(0.379)	(0.003)
Cattle price index (Jan-Dec, t-1)	0.000	-0.000	0.000	-0.517	0.008
	(0.001)	(0.002)	(0.000)	(0.393)	(0.003)***
Mean of dependent variable	9.792	1.224	0.038	74.658	10.685
(2004 coefficient * mean of Tight) / mean of dependent variable	-0.2%	6.0%	-37.0%	-11.1%	-0.3%
(2008 coefficient * mean of Tight) / mean of dependent variable	0.0%	3.2%	15.8%	-10.5%	1.2%
Observations	3,040	3,040	3,040	3,040	3,040
Year and municipality fixed effects	yes	yes	yes	yes	yes
Controls	yes	yes	yes	yes	yes
Municipality-specific time trends	yes	yes	yes	yes	yes

Notes: analysis is based on a municipality-by-year panel data set covering the 2002 through 2009 period. Sample includes the 380 municipalities located in the Legal Amazon states of Amazonas, Mato Grosso, Pará, and Rondônia, which exhibited variation in forest cover during the sample period. Dependent variable is: the log of municipal population (column 1); the log of municipal GDP per capita in column 2; the ratio of sowed to municipal area (column 3); total crop production (column 4); the log of head of cattle (column 5). Data from IBGE (population, municipal GDP), PAM (sowed area, crop production), and the Municipal Livestock Survey (PPM) (head of cattle). All regressions include year and municipality fixed effects, municipality time trends and controls for unobservable areas and cloud cover. Robust standard errors are clustered at the municipality level to account for serial correlation in error terms. Significance: *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table C: Placebo Regressions — The Timing of Price Variation and Its Impact on Deforestation

	Annual Normalized Deforestation Increment			
	(1)	(2)	(3)	(4)
Crop price index (t-1)	0.390			
	(0.181)**			
Crop price index (t+1)	-0.027			
	(0.215)			
Crop price index (t-2)	0.066			
	(0.188)			
Crop price index (Jan-May, t-1)		0.228		
		(0.125)*		
Crop price index (Jan-May, t+1)		0.077		
		(0.164)		
Crop price index (Jan-May, t-2)		-0.006		
		(0.136)		
Crop price index (Jun-Sep, t-1)			0.434	
			(0.161)***	
Crop price index (Jun-Sep, t+1)			0.045	
			(0.156)	
Crop price index (Jun-Sep, t-2)			0.188	
			(0.158)	
Crop price index (Oct-Dec, t-1)				0.135
				(0.094)
Crop price index (Oct-Dec, t+1)				-0.139
				(0.159)
Crop price index (Oct-Dec, t-2)				0.101
				(0.117)
Cattle price index (Jan-Jun, t)	-0.112	-0.114	-0.109	-0.113
	(0.022)***	(0.022)***	(0.022)***	(0.022)***
Cattle price index (Jan-Dec, t-1)	0.180	0.185	0.175	0.183
	(0.040)***	(0.039)***	(0.039)***	(0.040)***
Observations	2,280	2,280	2,280	2,280
Year and municipality fixed effects	yes	yes	yes	yes
Controls	yes	yes	yes	yes
Municipality-specific time trends	yes	yes	yes	yes

Notes: analysis is based on a municipality-by-year panel data set covering the 2002 through 2009 period. Sample includes the 380 municipalities located in the Legal Amazon states of Amazonas, Mato Grosso, Pará, and Rondônia, which exhibited variation in forest cover during the sample period. Dependent variable is the annual normalized deforestation increment at the municipality level. All regressions include year and municipality fixed effects, municipality time trends and controls for unobservable areas and cloud cover. Robust standard errors are clustered at the municipality level to account for serial correlation in error terms. Significance: *** p<0.01, ** p<0.05, * p<0.1.

Table D: Robustness Checks — Alternative Dependent Variable and Proxy Variables for Tightness

	Annual Normalized Deforestation Increment					Annual Deforestation Increment (in km^2)		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Tight * Post2004	-1.633	-0.546	-0.748	-0.529	-0.740	-39.647	-18.744	-16.179
	(0.363)***	(0.151)***	(0.065)***	(0.163)***	(0.069)***	(14.123)***	(8.952)**	(3.745)***
Tight * Post2008	-0.978	-0.293	-0.516	-0.382	-0.533	-36.071	-17.315	-14.180
	(0.326)***	(0.130)**	(0.057)***	(0.139)***	(0.058)***	(10.978)***	(6.689)**	(2.364)***
Crop price index (t-1)	0.279	0.261	0.208	0.272	-0.073	-54.254	-2.685	-16.804
	(0.077)***	(0.074)***	(0.067)***	(0.085)***	(0.135)	(11.922)***	(2.919)	(4.679)***
Cattle price index (Jan-Jun, t)	0.005	-0.007	-0.019	-0.008	-0.017	0.288	0.234	-0.128
	(0.010)	(0.009)	(0.008)**	(0.009)	(0.008)**	(0.285)	(0.269)	(0.206)
Cattle price index (Jan-Dec, t-1)	-0.011	-0.000	0.008	0.001	0.009	-0.290	-0.361	-0.060
	(0.010)	(0.008)	(0.006)	(0.008)	(0.006)	(0.306)	(0.276)	(0.183)
Tight * Crop price index				0.324	0.277	118.275	52.893	
				(0.269)	(0.114)**	(27.388)***	(20.232)***	
Crop price index * Post2004				-0.009	0.177	-0.978	-2.997	-0.909
				(0.049)	(0.107)*	(7.322)	(0.997)***	(1.462)
Crop price index * Post2008				-0.054	0.029	8.217	1.607	5.877
				(0.030)*	(0.044)	(5.217)	(1.420)	(1.740)***
Tight * Crop price index * Post2004				0.024	-0.072	-4.670	-1.960	0.885
				(0.128)	(0.063)	(16.632)	(9.852)	(0.898)
Tight * Crop price index * Post2008				-0.080	-0.018	-15.236	-5.592	-2.042
				(0.114)	(0.026)	(10.714)	(6.128)	(1.055)*
Observations	3,040	3,040	3,040	3,040	3,040	3,040	3,040	3,040
Year and municipality fixed effects	yes	yes	yes	yes	yes	yes	yes	yes
Controls	yes	yes	yes	yes	yes	yes	yes	yes
Municipality-specific time trends	yes	yes	yes	yes	yes	yes	yes	yes
Robustness	Tight = baseline	Tight = dummy: baseline > median	Tight = 2004 deforestation increment	Tight = dummy: baseline > median	Tight = 2004 deforestation increment	Tight = baseline	Tight = dummy: baseline > median	Tight = 2004 deforestation increment

Notes: analysis is based on a municipality-by-year panel data set covering the 2002 through 2009 period. Sample includes the 380 municipalities located in the Legal Amazon states of Amazonas, Mato Grosso, Pará, and Rondônia, which exhibited variation in forest cover during the sample period. Dependent variable is the annual normalized deforestation increment at the municipality level. All regressions include year and municipality fixed effects, municipality time trends and controls for unobservable areas and cloud cover. Robust standard errors are clustered at the municipality level to account for serial correlation in error terms. Significance: *** p<0.01, ** p<0.05, * p<0.1.