Cows and Trees*

Paul T. Scott, Eduardo Souza-Rodrigues,
Ted Rosenbaum, Skand Goel†

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Abstract

The Brazilian Amazon plays a crucial role in regulating global climate and preserving biodiversity, yet it faces mounting pressures from deforestation, driven primarily by cattle ranching. The expansion of pastureland is shaped by cattle's dual role as both output and capital stock, leading to nontrivial dynamic patterns. We develop a structural empirical model of ranchers' cattle management and land use decisions that accounts for deforestation costs, herd dynamics, and forward-looking behavior. Model estimates reveal that deforestation is inelastic to temporary shocks to beef prices but highly elastic to persistent price changes, rationalizing existing estimates in the literature. We embed the estimated model in a dynamic equilibrium framework to evaluate Pigouvian deforestation and beef taxes. The simulations imply that a deforestation tax eliminates deforestation in equilibrium, while a beef tax substantially reduces it but does not eliminate it. By constraining pasture expansion, the deforestation tax also raises beef prices, benefiting farmers who do not engage in deforestation.

Keywords: Cattle, Dynamics, Deforestation, Amazon, Carbon Emissions
JEL Codes: C13, Q12, Q15, Q18, R14

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†Affiliations: Paul T. Scott, Massachusetts Institute of Technology (email: ptscott@mit.edu); and Eduardo Souza-Rodrigues, University of Toronto and CEPR (email: e.souzarodrigues@utoronto.ca); Ted Rosenbaum, Federal Trade Commission (email: trosenbaum@ftc.gov); and Skand Goel, Amazon (email: skandgoel50@gmail.com).

1 Introduction

How does deforestation respond to commodity prices? This is a central question for conservation policy. Deforestation is responsible for over 10% of global greenhouse gas emissions (Sims, Gibbs and Harris, 2025), and numerous policies have been proposed to curb forest loss, including deforestation taxes, taxes on commodities linked to deforestation, and payments for forest protection. Their effectiveness depends on how deforestation responds to prices: for example, highly elastic deforestation would lead to high rates of indirect land use change (Searchinger et al., 2008; Roberts and Schlenker, 2013) and undermine the effectiveness of payments for forest protection (Gan and McCarl, 2007). The question is especially important in the Brazilian Amazon. The Amazon is the world's most extensive rainforest. It is of enormous importance for carbon storage, biodiversity, and climate regulation, and continued forest loss raises concerns about large emissions releases and broader ecological tipping points.

In the Brazilian Amazon, cattle ranching is at the core of the deforestation process. Pasture accounts for two thirds of deforested land, and for nearly 90% of deforested areas with an identified human use (Almeida et al., 2016). Because cattle production in the region is predominantly extensive grazing (IBGE, 2006), increases in production are closely tied to pasture expansion and, therefore, to forest conversion. Brazil is also one of the world's leading beef producers and exporters, with 30% of its cattle herd located in the Amazon (IBGE, 2017). In this context, rising demand for beef can place enormous pressure on forest conversion (OECD and FAO, 2024).

Recovering deforestation elasticities in this setting is difficult, however, because the dynamic forces linking commodity prices, herd management, and land conversion are non-trivial. There are two main sources of dynamics. The first is that land conversion is forward-looking: clearing is costly, and deforestation today expands the land available for future production. The second is that cattle are both an output and a capital good (Jarvis, 1974; Rosen, 1987). Decisions about slaughter and herd accumulation therefore affect not only current revenues, but also future herd size and future returns to pasture expansion. These intertemporal margins are further shaped by the fact that cattle take time to mature.

The resulting dynamics imply that temporary and permanent price changes can have very different effects on deforestation. To fix ideas, consider a stylized example. When beef prices rise temporarily, ranchers have an incentive to sell more cattle while prices are high, which reduces future herd size and lowers the incentive to expand pasture. When price increases are permanent, the response is different: ranchers are more willing to retain cattle and expand the herd, because keeping animals becomes more valuable when future returns are expected to remain high. In that case, higher prices can increase the incentive to clear more land for pasture, leading to more deforestation.

These forces make it difficult to infer the relevant elasticities from price-deforestation correlations in panel data alone. Depending on the source of price variation, higher current prices can be associated with either more or less deforestation. Correlations with current prices may therefore look small, or even have the wrong sign, relative to the long-run responses that matter for policy.

For this reason, this paper develops a structural dynamic model of cattle ranching and deforestation

in the Brazilian Amazon. Ranchers face three state variables—pasture area, herd size, and local beef prices—and make two choices: how much forest to clear and how many cattle to slaughter. Deforestation is costly, but it expands future pasture. Managing cattle is also costly, and those costs rise with stocking density through congestion effects. The model also incorporates time to build, since cattle take several years to mature and reproduce. These cost functions, combined with time to build, govern how ranchers adjust land and cattle over time, and are therefore central to recovering the elasticities of interest.

We estimate the model using a municipality-year panel from the Brazilian Amazon covering 2002–2020. The data combine information on deforestation, cattle herds, pasture, beef prices, transportation costs, and land prices, together with other determinants of land use and cattle management, such as topography and weather. The estimation uses the model's implied Euler equations together with a land-price equation to identify the cost parameters. Intuitively, the Euler conditions relate the timing of slaughter and deforestation to the dynamic tradeoffs faced by ranchers over herd accumulation, congestion, and pasture expansion, while land prices help identify fixed costs and pin down pasture profitability.

Our estimates indicate that deforestation is highly elastic with respect to permanent changes in the long-run mean of beef prices. This result follows from the estimated parameters, which are economically reasonable, and from solving the model under alternative long-run price environments. For example, the model implies that the rancher's deforestation choice has an elasticity with respect to the mean beef price of around 3. By contrast, the response of deforestation to contemporaneous price changes is much smaller, and can even have the opposite sign. Simulated data from the estimated model generate correlations between current prices and deforestation that are typically small and concentrated near zero, even when the underlying long-run elasticity is large.

The estimated model also provides a framework for studying counterfactual policy interventions. We focus on two policies in particular: deforestation taxes and beef taxes. To analyze these policies, we embed the estimated rancher's problem in a broader dynamic competitive equilibrium environment. In this environment, ranchers are price takers at the local level, while aggregate Brazilian supply affects equilibrium prices through its interaction with global beef demand, global crop demand and supply, and an international beef supply that uses crops as animal feed in more intensive beef production systems, with key elasticities and other parameters drawn from the literature (Roberts and Schlenker, 2013; Bouyssou, Jensen and Yu, 2024). This framework makes it possible to trace how policy-induced changes in ranching behavior feed back into prices and, through those prices, into deforestation dynamics.

The counterfactuals imply that both deforestation taxes and beef taxes can substantially reduce deforestation and emissions. The deforestation tax is set equal to the social cost of carbon released by deforestation, while the beef tax is set equal to the social cost of the emissions embodied in beef. The key difference is that the deforestation tax directly targets land conversion, whereas the beef tax affects deforestation only indirectly through output prices. In the equilibrium simulations, the deforestation tax is strong enough to halt deforestation entirely, while the beef tax also delivers a large reduction in deforestation, but does not eliminate it. Under our estimates, this reflects the fact that the social value of

carbon preserved in a hectare of Amazon forest is much larger than the private value of converting that hectare into pasture. The difference in emissions reductions across the two policies is also substantial, with the deforestation tax generating much larger emissions savings.

Relative to the no-policy baseline, the deforestation tax raises the producer price of beef by sharply constraining pasture expansion. This benefits farmers who do not engage in deforestation, though it harms those who would have expanded through forest clearing in the absence of the tax. This distributional contrast matters for policy support, since ranchers who benefit from higher beef prices may favor the tax, while those whose profits depend on further deforestation are likely to oppose it. Aggregating these gains and losses across the Brazilian cattle sector, we estimate a net income loss of about $1.3 billion per year. This magnitude provides a benchmark for the compensation the international community would need to offer Brazilian ranchers to support a deforestation tax.

Beyond these tax counterfactuals, our results also have broader implications for policy design. Policies such as biofuel mandates can raise agricultural commodity prices and thereby induce agricultural expansion in other locations. Likewise, policies that protect forests by paying landowners for conservation can be undermined by equilibrium effects: reducing the amount of land available for agricultural production can raise commodity prices and induce other land to be converted into agriculture. These leakage effects are stronger when land use is highly elastic. Back-of-the-envelope calculations using our estimates suggest that a policy that reduces deforestation locally may generate only about 20% of that impact globally once leakage is taken into account.

Related Literature. A growing literature studies how deforestation depends on commodity prices using static models. Souza-Rodrigues (2019) uses cross-sectional variation to examine the demand for deforestation in private properties and the long-run implications of permanent conservation policies. Static models that incorporate general equilibrium effects include Pellegrina (2022), Dominguez-Iino (2024), and Barrozo (2024).[1] These models emphasize the spatial distribution of land use and the associated equilibrium effects in a tractable way but abstract from forward-looking behavior, which is the central focus of our paper. A common feature of the literature on Amazonian deforestation, including Hargrave and Kis-Katos (2013), Assunção and Rocha (2019), and Assunção et al. (2022), is that deforestation regressions often yield coefficients on beef prices that are small (inelastic), statistically insignificant, and sometimes negative. Ultimately, we will argue that such regressions do not capture the long-run price responsiveness of deforestation.

Meanwhile, several studies have emphasized the importance of dynamic considerations in understanding land use change. Scott (2014) demonstrates the importance of dynamic modeling for accurately estimating land-use elasticities, with dynamics stemming from the costs of switching land use. Sant'Anna (2024) and Hsiao (2024) also estimate dynamic models of costly land use change, studying, respectively,

[1] Dominguez-Iino (2024) and Barrozo (2024) examine the market power of agricultural supply chains and its impact on deforestation. Farrokhi et al. (2024) extends trade general equilibrium models to include dynamic land use change and deforestation, albeit with myopic agents.

the expansion of sugarcane cultivation in Brazil and the palm oil industry in Indonesia and Malaysia. Building on the dynamic frameworks of Scott (2014) and Kalouptsidi, Scott and Souza-Rodrigues (2021), Araujo, Costa and Sant'Anna (2024) models dynamic land use change in the Brazilian Amazon, using a model that includes crops, pasture, and forest. The results of Araujo, Costa and Sant'Anna (2024) and Peter and Arima (2025) point to a strong association between crop prices and deforestation rates, in stark contrast to the lack of association between beef prices and deforestation rates. This contrast is especially puzzling given that pastureland occupies a much larger share of deforested land in Amazonia than cropland. Our study resolves this puzzle by introducing dynamics resulting from cattle management, which leads to dynamic behavioral patterns not found in models where costly land use change is the only source of dynamics.

Early studies of cattle dynamics, such as Jarvis (1974) and Rosen (1987), examined the dual role of cattle as both consumption and capital goods, highlighting their influence on supply responses and production dynamics. Subsequent work by Favaro (1990), Rosen, Murphy and Scheinkman (1994), Mundlak and Huang (1996), and Aadland (2004) analyzed the time-series properties of cattle production across countries with varying technologies, including Argentina, the United States, and Uruguay, to explore the role of cattle management in shaping industry dynamics. This literature demonstrates that temporary spikes in beef prices can lead to reductions in cattle herds as ranchers seek to profit from the high prices, but persistent price shocks tend to have the opposite effect, with increased prices spurring herd growth. Assunção, Gandour and Rocha (2015) discuss the possibility that cattle dynamics may complicate the relationship between beef prices and deforestation in Brazil. Goel (2022) confirms this idea quantitatively, showing that temporary price shocks can decrease deforestation while permanent price shocks can increase deforestation. Our study builds on Goel's approach. We estimate a structural model and find that, while deforestation is highly elastic in the long run–and while policies that affect beef prices or deforestation costs can drastically change deforestation rates–deforestation can appear highly inelastic in the data.

2 Institutional Background

The Amazon Rainforest is an immense region nearly ten times the size of California, two-thirds of which is in the Brazilian territory. Before the 1960s, the Brazilian Amazon was sparsely populated, characterized by open access and subsistence-based local economies centered on rubber and Brazil nut extraction (see, e.g., Souza-Rodrigues (2019) for further details). Cattle ranching in the area began only after Brazil's military dictatorship launched policies in the 1960s and 1970s to encourage settlement in the region, with the dual objectives of securing national borders and promoting regional development. It was not until the late 1980s that environmental concerns began to influence policy.

Land Use, Tenure and Regulation. Approximately 20 percent of the Brazilian Amazon has been deforested, totaling over 700,000 square kilometers—an area larger than Texas. The majority of cleared land is used for agriculture, with more than 70% designated as pasture and roughly 8 percent allocated

to crop cultivation (Almeida et al., 2016).

About half of the Amazon is protected through various legal designations, including indigenous territories and conservation units such as national parks, extractive reserves, and areas of ecological interest. Deforestation in these areas is either strictly regulated or entirely prohibited. The remainder of the Amazon consists of undesignated public lands, where deforestation is forbidden, and private lands, which make up approximately 20 percent of the region's total area, according to the 2006 Agricultural Census (IBGE, 2006). Although deforestation on private land can be legal if authorized and in accordance with the Forest Code, empirical evidence suggests limited compliance with these regulations, with much of the deforestation in the Amazon occurring illegally (Borner et al., 2014; Rajão et al., 2020).

Over the past 25 years, two key policy initiatives have significantly influenced deforestation control in the region: the introduction of satellite monitoring and the Priority List, both integral to the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm) launched in 2004. The DETER satellite system, developed by the Brazilian Institute for Space Research (INPE), employs high-frequency remote sensing to monitor forest loss, enabling the almost-real-time regular processing of land-use images and generating deforestation alerts for law enforcement. This innovation has been instrumental in curbing deforestation rates (Assunção, Gandour and Rocha, 2023). Introduced in 2008, the Priority List targets municipalities with high deforestation levels, focusing regulatory efforts on these "blacklisted" areas. Within its first two years, this policy reduced deforestation by approximately 40% (Assunção et al., 2022) in treated municipalities. These changes fundamentally reshaped conservation policies in the region: Prior to the mid-2000s, the Brazilian Environmental Protection Agency's (IBAMA) monitoring operations in the Amazon relied primarily on data collected by its headquarters and regional offices, with land and air patrols being limited in effectiveness due to the vast size of the region and the risks faced by law enforcement.

While the mid-2000s saw a shift toward some regulation of deforestation in the Brazilian Amazon, and the policy changes are widely perceived to have been effective, it remains the case that enforcement of restrictions on deforestation is low, with a very small proportion of fines being collected (Sampaio and McCann, 2022).

Cattle Industry Structure. Cattle ranching in the Amazon is characterized by extensive grazing, with feedlots comprising only 1.5% of the cattle stock in the region (IBGE, 2006). Cattle reach adulthood at around three years old, which is the slaughter age for males and the breeding age for females. The production process consists of two main stages: breeding, where calves are raised, and fattening, where cattle are prepared for slaughter.[2] While some farms specialize in one stage, others—referred to as complete-cycle farms—manage both. Trade between breeding and fattening farms is common but limited by the costs and risks of transporting live animals, particularly younger ones, who are more susceptible to stress and injury during transit.

[2]Cattle used for milk production account for only about 4% of the total Amazonian herd (IBGE, 2006, 2017).

The Amazonian cattle industry is composed of nearly half a million farms (IBGE, 2006, 2017), most of which are price takers selling cattle on the spot market. These cattle are typically sold to local slaughterhouses, which are owned by meatpackers, part of a concentrated meatpacking industry. Once processed, the beef is either exported—approximately 22% of the total production—or sold to domestic markets, accounting for about 78% of the supply. Domestic sales are primarily directed to supermarkets outside the Amazon region. The price of beef is largely determined by international market conditions, adjusted for transportation costs to the port.

3 Data and Descriptive Evidence

3.1 Data Sources

This study combines data from various sources. Land use and deforestation data are obtained from Mapbiomas, an annual panel data at a 30-meter resolution from 1985 to 2023, including classifications for primary forest, pasture (good vs. degraded), cropland, secondary forest, and other land types. Our primary variable of interest from Mapbiomas is the deforestation rate by municipality and year, which we calculate as the area of gross forest loss in a given year divided by the total municipality area.

Our second primary dataset comes from IBGE's Municipal Livestock Survey (PPM-IBGE), which provides cattle counts by municipality and year.[3]

Beef prices, exchange rates, and price index are taken from the CME Group, B3, Brazilian Central Bank, and IBGE. Local prices are obtained by subtracting transportation cost from the international prices. To calculate transport costs, we follow a strategy similar to Souza-Rodrigues (2019) in using data on transportation networks from the Brazilian Ministry of Transportation, information on ports used for exporting beef from the Ministry of Industry, Foreign Trade, and Services, and freight values and gas prices from SIFRECA and the Brazilian National Agency for Petroleum, Gas, and Biofuels.

In addition to these primary data sources, several other datasets are used. Municipality-level land price data for various types of agricultural land (2000–2012) comes from ANUALPEC. Agricultural yield data comes from FAO-GAEZ. Zootechnical indices are provided by Amigos da Terra (2020). Geographic boundaries are provided by IBGE. Consumer price indices for the US and Brazil are obtained from the World Bank.

3.2 Descriptive Statistics

Our final dataset includes 585 municipalities in the Legal Amazon. All variables are available for 2002–2020. Table 1 presents descriptive statistics for the sample used for estimation; the coverage of this sample is 2002-2018 because our estimating equations use two-year leads of some variables. On average (unweighted averages across municipalities), the annual deforestation rate across municipality-years is

[3]Cattle data was downloaded from `https://sidra.ibge.gov.br/tabela/3939`.

about 0.91% of the total municipality area. Pasture accounts for an average of 35.79% of municipal land area, while crops cover approximately 5.06%.

The average spot price of beef during the sample period is \$2.77/kg (live weight), with transportation costs accounting for about 5.78% of the beef price. Appendix B.5 explains the calculation of transportation costs in detail. Pastureland is priced at an average of \$1065.3 per hectare. For most estimates of the social cost of carbon, the pasture land values we observe are far lower than the value of carbon released by deforestation, which is typically estimated as having a value of over \$10,000 per hectare.[4] The largest pasture land values in the data are just over \$3,500 per hectare.

Table 1: Summary Statistics

	count	mean	sd	min	max
Deforestation rate (prop of total area)	8901	0.009	0.007	0.0000	0.074
Share of area in pasture	8901	0.358	0.233	0.0020	0.932
Share of area in crops	8901	0.051	0.093	0.0000	0.649
Stocking density (head/ha)	8901	1.014	0.547	0.0046	3.117
Grass yield	8901	4.043	0.373	3.1239	5.092
Spot price at port (USD/kg live weight)	8901	2.767	0.770	1.8242	4.669
Transportation cost to port (USD/kg live wt)	8901	0.149	0.079	0.0345	0.434
Price of pasture land (USD/ha)	813	1065.327	642.450	80.4655	3557.449
Year	8901	2010.746	4.586	2002.0000	2018.000
Municipality ID	8901	296.272	167.894	1.0000	585.000

Notes: Means are unweighted across municipalities and years. Dollar values are based on deflating BRL to 2012 levels and then converting to USD using the 2012 exchange rate of .5473 USD per BRL. The units for grass yields are 3826.61kg/ha/year, which is roughly the production needed to sustain one adult animal.

Figure 1 illustrates the evolution of Amazonian deforestation and international beef prices over time. It also highlights the range of net prices, which are calculated by subtracting transportation costs from the international prices. The figure clearly shows that the time variation in international prices far outweighs the cross-sectional variation caused by transportation costs.

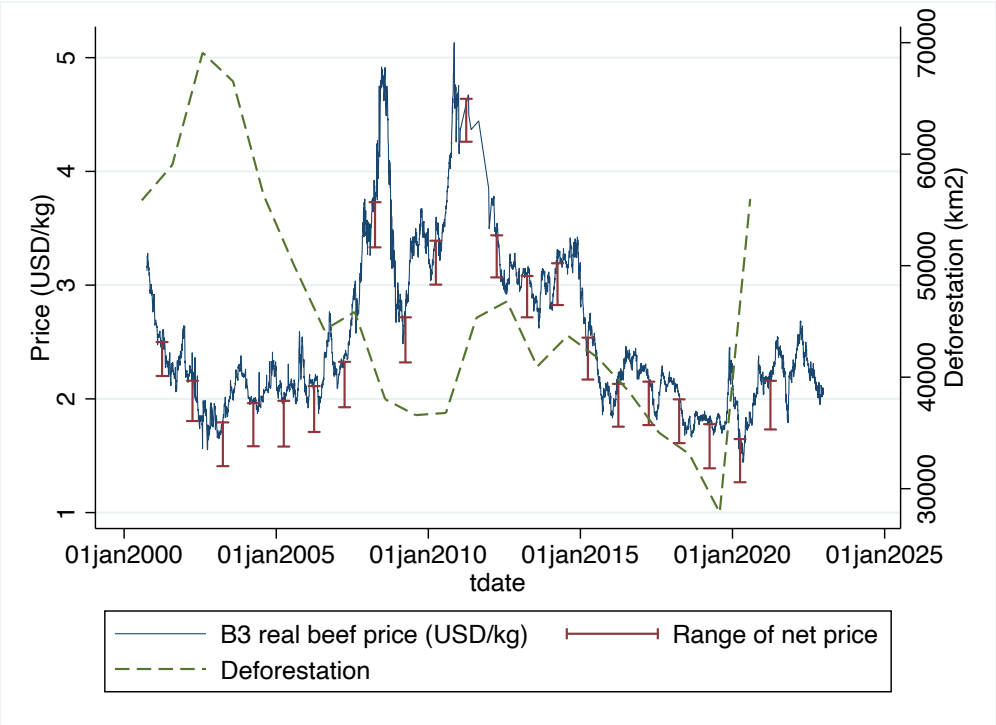
Broadly, deforestation rates and beef prices have opposite time trends during the sample period, despite the fact that we would expect increasing prices to be associated with increasing deforestation in the long run. The sharp decline in deforestation in the late 2000s is typically thought to be due to the policy changes in Brazil, rather than being driven by prices (Assunção, Gandour and Rocha, 2015).

[4]For example, Ometto et al. (2023) estimate that the average above-ground biomass in the Brazilian Amazon is 174 Mg C per hectare. At .434 tonnes of carbon per Mg biomass, we end up with over 270 tonnes of CO2 released per hectare:

$$\frac{174 \text{ tonnes biomass}}{\text{ha}} \frac{.434 \text{ tonnes C}}{\text{tonne biomass}} \frac{44 \text{ tonnes CO2}}{12 \text{ tonnes C}} = \frac{276.9 \text{ tonnes CO2}}{\text{ha}}.$$

Given Rennert et al.'s 2022 range of \$44-413/tonne, the value of 270 tonnes/ha has a range of \$11,880-111,510/ha. This does not include below-ground carbon released by deforestation.

Figure 1: Deforestation and Beef Prices



Notes: The solid blue line represents the price of B3's soonest expiring live cattle futures contract, adjusted to 2012 BRL using the Brazilian CPI, and then using the 2012 exchange rate of .5473 USD per BRL. The intervals show the range of net prices after subtracting transportation costs. The dashed line represents gross forest loss in the Brazilian Amazon calculated using Mapbiomas data.

3.2.1 Reduced-Form Regressions

We now present some descriptive regressions. We begin by regressing the log of deforestation rates on the log of beef prices, along with control variables and municipality fixed effects. The results are shown in Table 2. In the first column, the estimated relationship is negative but statistically insignificant, suggesting that prices may have little to no effect on reducing deforestation. This is a counterintuitive finding, particularly the negative sign, that is yet common in the literature; see e.g., Hargrave and Kis-Katos (2013), Assunção and Rocha (2019), Harding et al. (2021), and Assunção et al. (2022).

Table 2: Descriptive Deforestation Regressions

	(1) ln(DF)	(2) ln(DF)	(3) ln(DF)	(4) ln(DF)
Log(net spot price)	-0.27	0.12	-1.40	24.2***
	(0.29)	(0.31)	(0.84)	(1.05)
Log(futures price)			1.80	
			(1.08)	
Priority list	-0.29**	-0.20*	-0.094	0.37***
	(0.11)	(0.099)	(0.12)	(0.060)
Post-2005		-0.36***	-0.26***	
		(0.081)	(0.087)	
Rainfall Jan-Jun	-0.16	-0.15*	-0.12	-0.48***
	(0.11)	(0.081)	(0.086)	(0.090)
Dry season length	0.00094	-0.0046	-0.0053	-0.0062
	(0.0047)	(0.0052)	(0.0045)	(0.0065)
Cattle density	-0.16***	-0.14***	-0.15***	0.0087
	(0.037)	(0.033)	(0.036)	(0.013)
Grass yield				1.27***
				(0.18)
Observations	15,382	15,382	13,074	15,382
R-squared	0.783	0.798	0.800	0.354
Municipality FEs	✓	✓	✓	-
Year FEs	-	-	-	✓
Annual Clusters	✓	✓	✓	✓

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

In column 2, we add a dummy that is equal to one for all years after 2005, indicating the period where Brazil engaged in at least some enforcement of restrictions on deforestation. This changes the sign of the price coefficient, but it remains inelastic and insignificantly different from zero.

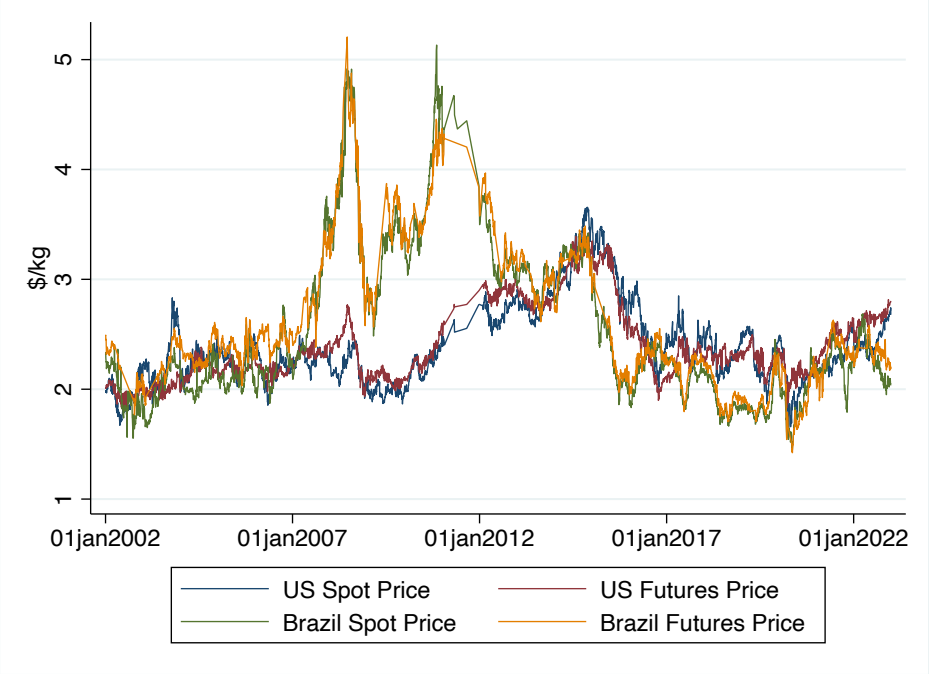
In column 3, we add one-year-ahead beef futures prices to the regression, which increases the magnitude of the coefficient on spot prices substantially. The coefficient on future prices has the opposite sign of the coefficient on spot prices, with a similar magnitude. This seemingly suggests that while current prices may reduce deforestation, expected price increases may lead to more deforestation. However, futures prices and spot prices are strongly positively correlated, as seen in Figure 2, and consequently, the covariance between the two price coefficients is very strong. In other words, while we do not have a precise estimate of the coefficient on either the spot price or futures price, the data indicates that if the coefficient on the

spot price is highly positive, then the coefficient on the futures price must be highly negative (and vice versa), with mostly canceling effects.

In the last column, we see what happens when we rely on cross-sectional price variation (coming from transportation costs) for identification. This column drops the municipality-level fixed effects and adds time fixed effects. We now see a highly positive and significant coefficient on the spot price, qualitatively consistent with Souza-Rodrigues (2019), whose model implies an elasticity of about 7.

In principle, a straightforward approach to disentangle short- and long-run price elasticities would be to explore distinct short- and long-run price variation in the data. However, as illustrated in Figure 2, there are no clear instances where spot and futures prices move in opposing directions. Even if we had more independent variation in spot and futures prices, our interest in long-run elasticities comes from wanting to understand the impacts of effectively permanent changes in the economic environment, and one-year ahead futures prices may not capture the sort of variation that a new policy change would produce.

Figure 2: Futures and spot prices



Notes: US prices come from the CME; Brazil prices from B3. Spot prices are defined as the soonest expiring live cattle futures contract. Futures prices are defined as the soonest expiring live cattle futures contract with a delivery date at least nine months in the future. All prices are converted to 2012 levels using their country's respective CPI.

4 Model of Agriculture in Amazonia

We develop our model at the municipality level, assuming the presence of a representative rancher-deforester in each municipality (henceforth referred to simply as a 'rancher'). We could equivalently

assume that there is a representative continuum of ranchers in each municipality (see Appendix A.2). The rancher engages in both pasture preparation and the complete cattle production cycle, encompassing breeding, fattening, and preparing cattle for slaughter. We follow Araujo, Costa and Sant'Anna (2024) in assuming that the decision maker may either formally own, lease, or hold informal property rights to the land. In essence, the requirement is that they are residual claimants to the net discounted cash flow generated by their farming operations.

4.1 Ranching

We let K_{mt} denote the adult-equivalent cattle herd size in municipality m and year t. B_{mt} is the amount of beef produced in municipality m and year t. Ultimately, the cost of holding cattle will depend on the stocking rate—cattle per hectare—which is given by

$$k_{mt} \equiv \frac{K_{mt} - B_{mt}}{A_{rmt}},$$

where A_{rmt} is the area of land used for pasture—we will explain below how this is endogenously determined.

Ranching flow payoffs are given by

$$\pi_{rmt}\left(B_{mt}, k_{mt}, A_{rmt}\right) = P_{mt}^{B} Y \cdot B_{mt} - k_{mt} A_{rmt} \cdot C_{mt}^{r}\left(k_{mt}\right), \tag{1}$$

where P_{mt}^{B} is the local price of beef (\$/kg live weight), i.e., the international price net of transportation costs to ports, Y is the live weight per animal (403.226 kg), and $C_{mt}^{r}\left(k_{mt}\right)$ is the per-head cost of raising cattle.

As the density of cattle increases, the capacity of the land to nourish the cattle through grass becomes strained, and it may be necessary to purchase supplementary feed. High stocking rates also pose other costs—for example, screwworm parasites become a larger threat and must be monitored more carefully at higher stocking rates. In addition to the stocking rate, holding costs depend on the productivity of the land. Specifically, we assume that the relevant factor is the ratio of the stocking rate to a measure of the productivity of the land, which we denote by Y_{gm}. Y_{gm} represents the annual grass yield (in kilograms per hectare) obtained from FAO-GAEZ data.[5] We model per-head holding costs as follows:

$$C_{mt}^{r}\left(k_{mt}\right) = \theta_{r0} + \theta_{r1} \frac{k_{mt}}{Y_{gm}}.$$

θ_{r0} represents a fixed cost component, θ_{r1} controls the sensitivity of holding costs to congestion.

The parameter θ_{r0} can also absorb per-unit processing costs and slaughterhouse markups. That is, the rancher receives $P_{mt}^{B} Y - \theta_{r0}$ per animal slaughtered (not counting congestion costs), and so θ_{r0} can also capture the gap between the net price of an animal $P_{mt}^{B} Y$ and the wholesale price ranchers actually

[5] We take municipality-level averages of FAO-GAEZ's high-input, rain-fed grass yield.

receive, in addition to any actual fixed costs that ranchers incur.

4.1.1 Herd Composition and Dynamics

Underlying the aggregate stock variable K_{mt} are cattle stocks of different ages: K_{1mt} represents calves, K_{2mt} represents yearlings, and K_{3mt} represents adults. The aggregate herd size is given by $K_{mt} = \gamma_1 K_{1mt} + \gamma_2 K_{2mt} + K_{3mt}$, where γ_1 and γ_2 are weights that convert calves and yearlings into adult-equivalent units. We assume $\gamma_1 = .33$ and $\gamma_2 = .67$.

Following RMS, we employ a three-period maturation model, based on the idea that cattle take roughly two years to mature. Formally, the cattle stock evolves according to the following equations:

$$K_{1,m,t+1} = g\left(K_{3mt} - B_{mt}\right) \tag{2}$$

$$K_{2,m,t+1} = K_{1mt} \tag{3}$$

$$K_{3,m,t+1} = (1-\delta)\left(K_{3mt} - B_{mt}\right) + K_{2mt} \tag{4}$$

Equation 2 indicate that cows successfully give births to calves at rate g. It can be understood that maturing steers are always slaughtered, so $(K_{3mt} - B_{mt})$ corresponds to the number of adult cows that are not culled. Equation 3 indicates that calves mature into yearlings. Equation 4 indicates that yearlings mature into adults, and adult cows are subject to natural mortality at rate δ.

We calibrate $g = .6256$ and $\delta = .02$ based on zootechnical studies from the Brazilian Amazon (Amigos da Terra, 2010).[6]

We let $\mathbf{K}_{mt} = (K_{1mt}, K_{2mt}, K_{3mt})$ denote the vector of cattle stocks. Note that we previously defined rancher's payoffs as a function of the stocking rate and area of pasture land: $\pi_{rmt}\left(B_{mt}, k_{mt}, A_{rmt}\right)$. We will alternatively express these payoffs as a function of the full cattle stock vector and area of pasture land, which of course implies the stocking rate: $\pi_{rmt}\left(B_{mt}, \mathbf{K}_{mt}, A_{rmt}\right)$.

4.2 Deforestation

Let $\bar{A}_m$ denote the area of available land in municipality m. Available land can either be in forest or pasture. Other land uses, such as urban development and mining, are excluded from $\bar{A}_m$ by assumption. In year t, available land is either in agricultural land, denoted by A_{mt}, or in forested land. The amount of forested land is therefore given by $\bar{A}_m - A_{mt}$.

We assume that all deforestation during year t converts forested land directly to agricultural land, which becomes available for use in the following year. The deforestation rate in year t and municipality m is given by

$$D_{mt} = A_{m,t+1} - A_{mt}.$$

[6] We assume beef quality is invariant to age and breeding history, so mature cows are treated the same as adult males. This simplification allows us to model all adults as neoclassical capital with an exponential death rate. These assumptions are necessary because the stock data consist of total head counts, without classification by age or sex, thus eliminating the need to track the adult age distribution.

The deforestation cost per hectare deforested is given by:

$$C_{mt}^{d}(D) = \theta_D \frac{D}{\bar{A}_m} + \theta_X X_{mt}.$$

This function implies that per-hectare deforestation costs are increasing with respect to the share of the municipality being deforested. This reflects the scarcity of local inputs, particularly labor. Deforestation typically occurs during the dry season (July-September), and clearing a large portion of a municipality in a single year would require a substantial amount of short-term labor. Increasing average costs may also arise because the deforestation process likely begins in less costly areas and progresses to more costly ones over time. Furthermore, these rising costs can serve to rationalize the likely presence of credit constraints, which can lead to incremental deforestation over the years.

The term $\theta_X X_{mt}$ captures other factors that may influence deforestation costs. In particular, we include a dummy variable indicating years from 2006 and onward: the enforcement era. Additionally, we include a dummy variable that indicates whether a municipality was included on Brazil's Priority List ("blacklist"), which began in 2008. See Assunção et al. (2023) for a study of the impact of this policy.

For a continuum of agents to aggregate to a representative agent in this context, each agent's per-hectare deforestation cost must depend on the total amount of deforestation in their municipality (not only their own deforestation).

4.3 Rancher's Problem

Every year, the representative rancher for municipality m chooses two variables the maximize expected discounted payoffs: the slaughter rate B_{mt}, and the deforestation rates D_{mt}.

The representative rancher's expected discounted payoffs at time t can be expressed as follows:

$$E_t \left[\sum_{s=t}^{\infty} \beta^s \left(\pi_{r,m,t+s}\left(B_{mt}, s_{cms}, \mathbf{K}_{mt}, A_{ms}\right) - C_{mt}^{d}(D_{mt}) \right) \right]. \tag{5}$$

The corresponding Bellman equation is

$$\begin{aligned} V_{mt}\left(\mathbf{K}_{mt}, A_{mt}\right) = \max_{B_{mt}, D_{mt}, s_{cmt}} & \pi_{rmt}\left(B_{mt}, s_{cmt}, \mathbf{K}_{mt}, A_{mt}\right) - C_{mt}^{d}(D_{mt}) \\ & + \beta E_t \left[V_{m,t+1}\left(\mathbf{K}_{m,t+1}, A_{m,t+1}\right) \right], \end{aligned} \tag{6}$$

with $A_{m,t+1} = A_{mt} + D_{mt}$, and $\mathbf{K}_{mt}$ and B determining $\mathbf{K}_{m,t+1}$ through equations 2-4.

4.4 First-Order Conditions

In this section, we lay out the first-order conditions to the rancher's problem that we will use for estimation below. Each of these first-order conditions will be used for estimation in Section 5.

4.4.1 Cattle Euler Equation

In Appendix A.1.1, we show that the first-order condition with respect to the slaughter rate B_{mt} can be expressed as follows:

$$\begin{aligned}\underbrace{Y \times P^B_{mt}}_{\text{Revenue from selling cow today}} &= \underbrace{\frac{d}{dB_{mt}}\left[\left(K_{mt}-B_{mt}\right)C^r_{mt}\left(\frac{K_{mt}-B_{mt}}{A_{rmt}}\right)\right]}_{\text{Cost of holding cow one more period}} \\ &+ \underbrace{\beta(1-\delta)E_t\left[Y \times P^B_{m,t+1}\right] + g\beta^3 E_t\left[Y \times P^B_{m,t+3}\right]}_{\text{Revenue from selling cow and offspring in the future}} \\ &+ \underbrace{g\beta E_t\left[\gamma_1 \frac{d}{dB_{m,t+1}}\left[\left(K_{m,t+1}-B_{m,t+1}\right)C^r_{m,t+1}\left(\frac{K_{m,t+1}-B_{m,t+1}}{A_{r,m,t+1}}\right)\right]\right]}_{\text{Cost of holding offspring as calf}} \\ &+ \underbrace{g\beta^2 E_t\left[\gamma_2 \frac{d}{dB_{m,t+2}}\left[\left(K_{m,t+2}-B_{m,t+2}\right)C^r_{m,t+2}\left(\frac{K_{m,t+2}-B_{m,t+2}}{A_{r,m,t+2}}\right)\right]\right]}_{\text{Cost of holding offspring as yearling}}\end{aligned} \tag{7}$$

This equation captures the trade-off between slaughtering and holding a cow to slaughter it next period. If slaughtered in time t, the cow will generate revenues $Y \times P^B_{mt}$. If held for one period, it will generate expected discounted revenues of $\beta\left(1-\delta\right)E_t\left[P^B_{m,t+1}\right]$, and its progeny will generate discounted revenues $g\beta^3 E_t\left[P^B_{m,t+3}\right]$. Holding the cow a year longer also implies extra holdings costs, both from the cow itself and its offspring.

4.4.2 Deforestation Euler Equation

In Appendix A.1.2, we show that the first-order condition with respect to the deforestation rate D_{mt} can be expressed as follows:

$$\underbrace{\frac{d}{dD_{mt}}C^d_{mt}\left(D_{mt}\right)}_{\text{Current DF costs}} = \beta E_t\left[\underbrace{\frac{d}{dA_{r,m,t+1}}\left(\left(K_{m,t+1}-B_{m,t+1}\right)C^r_{m,t+1}\left(\frac{K_{m,t+1}-B_{m,t+1}}{A_{r,m,t+1}}\right)\right)}_{\text{Future holding costs}} + \underbrace{\frac{d}{dD_{m,t+1}}C^d_{m,t+1}\left(D_{m,t+1}\right)}_{\text{Future DF costs}}\right]. \tag{8}$$

This Euler equation expresses the idea that there should be indifference (in expectation) between incurring deforestation costs now and delaying them one period, accounting for the extra holding costs next period associated with delayed pasture expansion.

4.5 Land Values

To complete the model, we note that land prices can provide important information about the model parameters. Specifically, suppose pasture is competitively supplied to the rancher. In this case, the value of the marginal land determines the land price. This implies that the derivative $\frac{d}{dA_{mt}}V_{mt}$ equals the price of pasture land, denoted as P^L_{mt}. It is important to emphasize that the rancher's full value function, $V_{mt}(\mathbf{K}_{mt}, A_{mt})$, should not simply be equated with land values in municipality m in year t. The full value function reflects not only the value of land but also the value of the cattle stock. Instead, it is more appropriate to equate the rancher's marginal value of land with observed land prices, which will hold as an equilibrium condition if land markets are competitive. Under this assumption, we obtain the following equation:

$$\begin{aligned} P^L_{mt} = \frac{dV_{mt}}{dA_{mt}} = &- \frac{d}{dA_{mt}}\left[(A_{mt+1} - A_{mt}) \cdot C^d_{mt}\left(A_{mt+1} - A_{mt}\right)\right] \\ &- \frac{d}{dA_{rmt}}\left[(K_{mt} - B_{mt}) \cdot C^r_{mt}\left(\frac{K_{mt} - B_{mt}}{A_{rmt}}\right)\right], \end{aligned} \tag{9}$$

where we rely on the envelope theorem to take the derivative of the value function with respect to the state variable A_{mt}.

Intuitively, land prices help identify the fixed cost parameter θ_{r1}. The fixed cost influences the profitability of pasture land, and the price of pasture land provides information about its profitability.

5 Estimation

At a high level, our estimation strategy is based on the first-order conditions described above (equations (7), and (8)) and the land value equation (9). We use the generalized method of moments (GMM) to estimate the cost parameters θ_D, θ_{r0}, and θ_{r1}. We let $\theta = (\theta_D, \theta_{r0}, \theta_{r1})$ denote the vector of parameters to be estimated. With three equations and three unknown parameters the model is exactly identified, so we do not need to choose a weighting matrix for the GMM objective function. Following standard practice, we impute $\beta = .9$ for the discount factor.

For the Euler equations, equations (7), and (8), we replace the expectation terms by the realized future values of the variables and forecast errors, e_{dmt} and e_{rmt}. That is, the deforestation equation becomes

$$\begin{aligned} e_{dmt}(\theta) = &\frac{d}{dD_{mt}} C^d_{mt}(D_{mt}; \theta) \\ &- \beta\left(\frac{d}{dA_{r,m,t+1}}\left((K_{m,t+1} - B_{m,t+1}) C^r_{m,t+1}\left(\frac{K_{m,t+1}}{A_{r,m,t+1}}; \theta\right)\right) + \frac{d}{dD_{m,t+1}} C^d_{m,t+1}(D_{m,t+1}; \theta)\right), \end{aligned} \tag{10}$$

where we have now made the cost functions' dependence on the parameters explicit. Formally, the forecast

error $e_{dmt}(\theta)$ is defined as the expectation term on the right-hand side of equation (8) minus its realization:

$$\begin{aligned} e_{dmt}(\theta) =& \beta E_t \left[\frac{d}{dA_{r,m,t+1}} \left((K_{m,t+1} - B_{m,t+1}) C^r_{m,t+1} \left(\frac{K_{m,t+1} - B_{m,t+1}}{A_{r,m,t+1}}; \theta \right) \right) + \frac{d}{dD_{m,t+1}} C^d_{m,t+1} \left(D_{m,t+1}; \theta \right) \right] \\ & - \beta \left[\frac{d}{dA_{r,m,t+1}} \left((K_{m,t+1} - B_{m,t+1}) C^r_{m,t+1} \left(\frac{K_{m,t+1} - B_{m,t+1}}{A_{r,m,t+1}}; \theta \right) \right) + \frac{d}{dD_{m,t+1}} C^d_{m,t+1} \left(D_{m,t+1}; \theta \right) \right]. \end{aligned} \tag{11}$$

Equation (10) is then equation (8) with equation (11) substituted in.

Similarly, the cattle Euler equation becomes

$$\begin{aligned} e_{rmt}(\theta) \quad &= Y \times P^B_{mt} - \tfrac{d}{dB_{mt}} \left[(K_{mt} - B_{mt}) C^r_{mt} \left(\tfrac{K_{mt} - B_{mt}}{A_{rmt}}; \theta \right) \right] \\ &\quad -\beta(1-\delta) Y \times P^B_{m,t+1} - g\beta^3 Y \times P^B_{m,t+3} \\ &\quad -g\beta\gamma_1 \tfrac{d}{dB_{m,t+1}} \left[(K_{m,t+1} - B_{m,t+1}) C^r_{m,t+1} \left(\tfrac{K_{m,t+1} - B_{m,t+1}}{A_{r,m,t+1}}; \theta \right) \right] \\ &\quad -g\beta^2\gamma_2 \tfrac{d}{dB_{m,t+2}} \left[(K_{m,t+2} - B_{m,t+2}) C^r_{m,t+2} \left(\tfrac{K_{m,t+2} - B_{m,t+2}}{A_{r,m,t+2}}; \theta \right) \right], \end{aligned} \tag{12}$$

where the forecast error $e_{rmt}(\theta)$ is defined as the right-hand side of equation (7) (which contains expectations) minus its realization.

We introduce an error term, $e_{lv,mt}(\theta)$, into the land value equation, (9), which becomes

$$\begin{aligned} e_{lv,mt}(\theta) \equiv & P^L_{mt} - \frac{d}{dA_{mt}} \left[(A_{mt+1} - A_{mt}) \cdot C^d_{mt} (A_{mt+1} - A_{mt}; \theta) \right] \\ & + \frac{d}{dA_{rmt}} \left[(K_{mt} - B_{mt}) \cdot C^c_{mt} \left(\frac{K_{mt} - B_{mt}}{A_{rmt}}; \theta \right) \right]. \end{aligned} \tag{13}$$

In this case, the error term should be interpreted as measurement error in observed land prices.

We can estimate the model imposing that the error terms be mean zero—that is, that the first-order conditions and land value equation hold on average. In other words, the moments we use for estimation are

$$E \begin{pmatrix} e_{dmt}(\theta) \\ e_{rmt}(\theta) \\ e_{lv,mt}(\theta) \end{pmatrix} = 0. \tag{14}$$

For specifications with covariates X_{mt} in the deforestation cost function, we also include the moments $E\left[e_{dmt}(\theta) X_{mt}\right] = 0$.

Each of these moments has an economic interpretation. Equation (10) relates the marginal cost of deforestation to holding costs. In a static model, deforestation should proceed until its marginal cost corresponds to the marginal benefit of reducing holding costs. Equation (10) is the dynamic version of such a condition, and deforestation moment, $E\left[e_{dmt}(\theta)\right] = 0$, requires the parameter to make this optimality condition hold on average. Equation (12) relates the revenue from culling cattle to the value

of holding cattle for future sale. The moment condition $E\left[e_{rmt}\left(\theta\right)\right] = 0$ requires that this optimality condition hold on average. The land value moment, $E\left[e_{lv,mt}\left(\theta\right)\right] = 0$, requires that, on average, the observed land values correspond to the marginal value of pasture land in the model.

Our moments are appealing in that they do not rely on any particular exclusion restrictions or other assumptions regarding the correlations of variables. We assume only that agents' forecast errors average out to zero. The specification of the model in itself arguably represents a strong assumption; however, conditional on the model being correct, the assumption that forecast errors average out to zero represents a mild assumption about agents' expectations. If agents have rational expectations, then the agents' expectations correspond to the actual expectations given the equilibrium data generating process, and because forecast errors are mean zero by construction, our moments would be valid. While the assumption of rational expectations is sufficient for the validity of our moments, it is not necessary. All we need is that agent's expectations of the realized variables in the above equations are correct on average, whether or not they have fully rational expectations.

That said, care should be taken when constructing moments from Euler equations. Consider equation (12), and observe that the equation includes observed realizations of variables dated after time t. It would not be appropriate to use, for example, a moment like $E\left[e_{rmt}\left(\theta\right)P^B_{m,t+1}\right] = 0$. The forecast error $e_{rmt}\left(\theta\right)$ captures the difference between a time-t expectation (right-hand side of equation (7)) and its realization. One of the things that that influences this forecast error is the realization of $P^B_{m,t+1}$, so $P^B_{m,t+1}$ is naturally correlated with the forecast error.

5.1 Identification

We do not estimate a supply curve or supply elasticities directly. Instead, we recover the cost function parameters that underlie supply decisions. We can then compute supply responses based on this cost function. That is, we can solve and simulate the rancher's problem within various economic environments. Thus, supply responses are not primitives, but a function of the cost parameters and the economic environment.

We now provide some intuition for how the cost function is identified. It is simplest to begin with the Euler equation for cattle management, and consider the simplified version of the model where cattle mature in one period (what we say here applies equally well to the full model, but the notation is far more cumbersome):

$$P^B_{m,t}Y = \beta\left(1-\delta+g\right)E_t\left[P^B_{m,t+1}Y\right] + \frac{d}{dB_{m,t}}\left[\left(K_{m,t}-B_{m,t}\right)C^r_m\left(\frac{K_{m,t}-B_{m,t}}{A_{m,t}};\theta\right)\right]. \tag{15}$$

This equation states that a rancher should be indifferent between selling a cow today or holding it for one more period, incurring extra holding costs and selling it and its offspring next period. After substituting in the expectational error term and rearranging, we have The right hand side of the equation corresponds to the net present value of holding a cow for one more period. In general, as long as the discount rate

isn't too large, holding the cow will lead to more discounted revenues. That is, it is natural to expect that

$$\beta\left(1-\delta+g\right)E_t\left[P^B_{m,t+1}Y\right] > P^B_{m,t}Y.$$

The extra holding costs must then be sufficiently large to cancel out the extra revenue associated with holding the cow, keeping the rancher indifferent between selling now or later along the optimal path.

Recall that we introduce a forecast error term capturing the difference between expected and realized values in the Euler equation, which in the context of this simplified model becomes

$$e_{rmt} = \beta\left(1-\delta+g\right)Y\left(E_t\left[P^B_{m,t+1}\right] - P^B_{m,t+1}\right),$$

and equation (15) becomes

$$e_{rmt}\left(\theta\right) = P^B_{m,t}Y - \beta\left(1-\delta+g\right)P^B_{m,t+1}Y - \frac{d}{dB_{m,t}}\left[(K_{m,t}-B_{m,t})C^r_m\left(\frac{K_{m,t}-B_{m,t}}{A_{m,t}};\theta\right)\right]. \tag{16}$$

Therefore, the moment $e_{rmt}\left(\theta\right) = 0$ calls for finding holding cost parameters that make the marginal holding costs equal to the extra revenue associated with holding the for one more period. We can think of this as identifying the congestion cost parameter, θ_{r1}, although strictly speaking it provides information about both holding cost parameters.

We can then turn to the deforestation Euler equation, equation (10). If deforestation rates aren't increasing quickly, then the terms

$$\frac{d}{dD_{mt}}C^d_{mt}\left(D_{mt};\theta\right) - \beta\frac{d}{dD_{m,t+1}}C^d_{m,t+1}\left(D_{m,t+1};\theta\right)$$

reflect a temptation to defer deforestation to the next period. Along the optimal path, this must be balanced with the extra holding costs associated with delaying pasture expansion, captured by the term

$$\beta\frac{d}{dA_{r,m,t+1}}\left(K_{m,t+1}C^r_{m,t+1}\left(\frac{K_{m,t+1}}{A_{r,m,t+1}};\theta\right)\right),$$

which is intuitively related to the holding costs identified by the cattle Euler equation above. Having already identified the holding cost parameters, imposing the moment condition $E\left[e_{dmt}\left(\theta\right)\right] = 0$ requires that the level of deforestation costs be such the savings associated with delayed deforestation balance with holdings costs.

Finally, the land value equation tells us about the expected discounted stream of payoffs to the rancher. This provides information about the fixed cost parameter, θ_{r0}, which controls the average cost of holding cattle, and therefore the average profitability of pasture land.

Table 3: Cost Estimates: Simplified Cattle Dynamics

	(1)	(2)	(3)	(4)
θ_{r0}	15.0259	93.4089	46.5268	103.149
	(−199.04,278.03)	(−243.96,307.37)	(−162.63,295.92)	(−232.15,312.17)
θ_{r1}	1398.37	1150.91	1298.92	1120.16
	(945.87,1871.5)	(890.14,1612.5)	(925.36,1652.5)	(868.5,1811.8)
θ_d	62857.7	33633.3	57261.7	32734.7
	(43571.,89806.)	(24634.,97666.)	(40021.,93095.)	(24498.,1.34869×10^5)
Post-2006		578.568		547.12
		(−99.048,827.02)		(−570.82,776.18)
Blacklist			775.846	344.825
			(−173.52,1438.6)	(−185.4,1068.4)
Mean holding cost	236.489	275.68	252.239	280.55
	(66.537,446.12)	(107.47,469.34)	(80.164,456.27)	(47.738,473.49)
Mean DF cost	568.97	792.267	548.651	771.099
	(394.39,812.9)	(564.95,962.85)	(395.35,840.2)	(526.88,925.78)
Mean marginal DF cost	1137.94	1096.71	1066.97	1067.4
	(788.78,1625.8)	(889.58,1684.6)	(765.71,1695.5)	(900.24,1994.1)
Observations	8901	8901	8901	8901

Notes: The table presents cost parameter estimates and derived statistics for specifications with simplified cattle dynamics (i.e., no calf or yearling stocks). Mean cost statistics average over municipalities and years in our sample. The Post-2006 and Blacklist dummy variables are included in the deforestation cost function. Standard errors, shown in parentheses, are clustered by year and calculated using the block bootstrap procedure. Observations are by municipality-year.

5.2 Parameter Estimates

Tables 3 and 4 present the estimated cost parameters for specifications with simplified and full cattle dynamics, respectively. Standard errors, shown in parentheses in the table, are clustered by year to capture spatial dependence in the data, and calculated using the block bootstrap procedure.

The implied average cost of deforestation is on the order of $600 per hectare in most specifications (although the cost of the marginal hectare is somewhat larger). For comparison, Almeida and Uhl (1995) report slash and burn clearing costs of $291 per hectare in 1993; which is a comparable cost to the average deforestation cost estimated in our model after adjusting for inflation.

Table 4: Cost Estimates: Full Model

	(1)	(2)	(3)	(4)
θ_{r0}	-268.42	-179.668	-233.162	-169.027
	(−466.66,−64.5)	(−464.78,−16.444)	(−425.54,−61.047)	(−500.94,−41.004)
θ_{r1}	1680.37	1376.42	1559.62	1339.98
	(1135.8,2248.)	(1066.4,1916.5)	(1112.6,1980.6)	(1043.,2137.6)
θ_d	62806.5	32944.8	57156.1	32072.5
	(43484.,89747.)	(24352.,95144.)	(39963.,92859.)	(23992.,1.30116×10^5)
Post-2006		591.369		559.866
		(−68.025,840.71)		(−509.54,789.94)
Blacklist			783.909	341.712
			(−164.85,1448.7)	(−173.53,1051.3)
Mean holding cost	-52.1744	40.4941	-15.3599	51.6053
	(−360.9,234.2)	(−387.96,345.73)	(−318.13,263.76)	(−348.78,290.81)
Mean DF cost	568.507	796.828	548.009	775.73
	(393.61,812.36)	(574.32,969.49)	(395.24,838.71)	(535.92,933.41)
Mean marginal DF cost	1137.01	1095.04	1065.37	1066.04
	(787.22,1624.7)	(889.11,1665.1)	(764.32,1692.)	(901.1,1959.)
Observations	8901	8901	8901	8901

Notes: The table presents cost parameter estimates and derived statistics for specifications with the full cattle dynamic model (i.e., with time to build). Mean cost statistics average over municipalities and years in our sample. The Post-2006 and Blacklist dummy variables are included in the deforestation cost function. Standard errors, shown in parentheses, are clustered by year and calculated using the block bootstrap procedure. Observations are by municipality-year.

6 Short- and Long-Run Price Responses

In this section, we solve and simulate the rancher's problem to show that simulated data from the model can replicate empirical patterns in the data. In the simulated model, despite the fact that the long-run elasticity of deforestation is large, the correlation between contemporaneous deforestation and beef prices can be effectively zero, or even negative.

We solve the rancher's problem given an exogenous process for beef prices. When we compute policy simulations in section 7, prices will be endogenous, but here, we are only interested in how a rancher responds to price shocks in the short and long run.

For these simulations, we assume that beef prices follow a simple AR(1) process that matches the degree of persistence observed in the data:

$$P_t^B = (1 - 0.72)\,\mu_p + 0.72 P_{t-1}^B + \varepsilon_{B,t},$$

where $\varepsilon_{B,t}$ is i.i.d. normal with variance 0.50. The degree of autocorrelation and variance imputed here match those observed in Brazilian spot prices during our sample years.

We impute different values for the mean price μ_p, and solve and simulate the model separately for each value of μ_p. Given a mean price, we can think about responses to P_t^B (conditional on μ_p) as short-run price responsiveness. We will interpret differences in behavior for different values of μ_p as long-run price responsiveness.

We solve the model using a form of backward induction. Since deforestation is irreversible, we start by solving the model assuming full deforestation, i.e., $A_{mt} = \bar{A}_m$. With full deforestation, the A_{mt} state variable can no longer change, and the agent's problem simplifies to a cattle management problem.

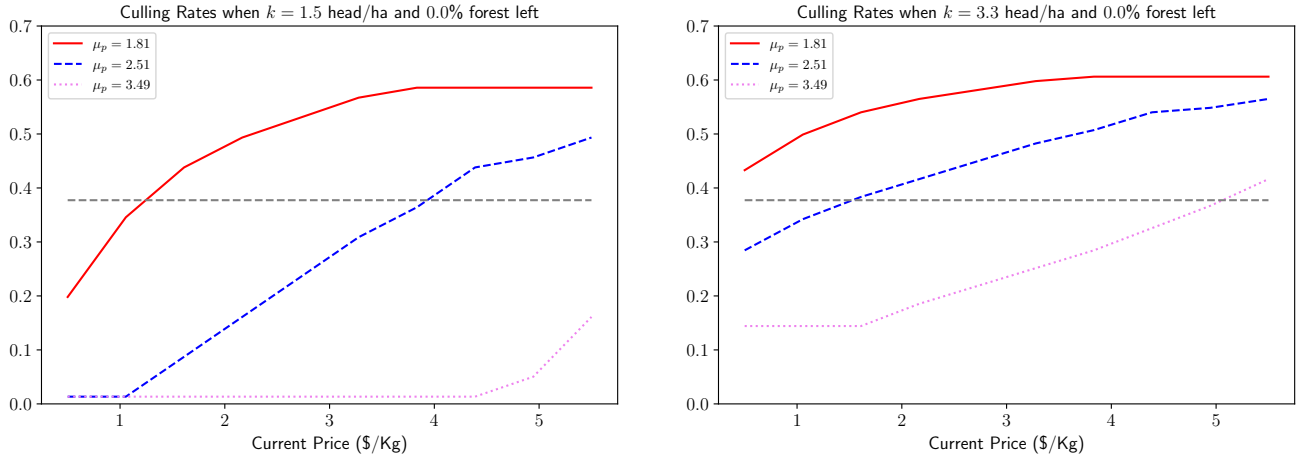
We discretize the state space for A_{mt}, and having solved the model for $A_{mt} = \bar{A}_m$, we then consider the next lower value of A_{mt}—say, $A_{mt} = \bar{A}_m - \epsilon$, where the rancher can either remain at this level of deforested land or deforest the last ϵ hectares of forest to arrive at the fully deforested state. Having solved the value function for the $\bar{A}_m$ and $\bar{A}_m - \epsilon$ states, we can then consider the $A_{mt} = \bar{A}_m - 2\epsilon$ state, where the rancher can remain at the current level of deforested land, deforest ϵ more, or deforest 2ϵ to reach the fully deforested state. We can proceed like this, backward inducting through the forest cover variable (rather than backward inducting through time). In our implementation, ϵ corresponds to .05% of the municipality's land area.

In what follows, we illustrate the model solution for a post-2006 municipality that has grass productivity equal to the sample mean and is not on the blacklist.

Figure 3 illustrates some culling policy functions conditional on $A_{mt} = \bar{A}_m$–that is, behavior for the cattle management problem when there is no deforestation left to be done. The left panel shows the culling rate on the vertical axis and the current beef price on the horizontal axis when the cattle stock density is 1.5 heads per hectare, while the right panel shows the same for a stock density of 3.3 heads per hectare. The red line represents the culling rate when the long-run mean price is \$1.85/kg; the blue

dotted line corresponds to a mean price of \$2.52/kg (similar to the mean in the data); and the purple dotted line, a mean price of \$3.48/kg.

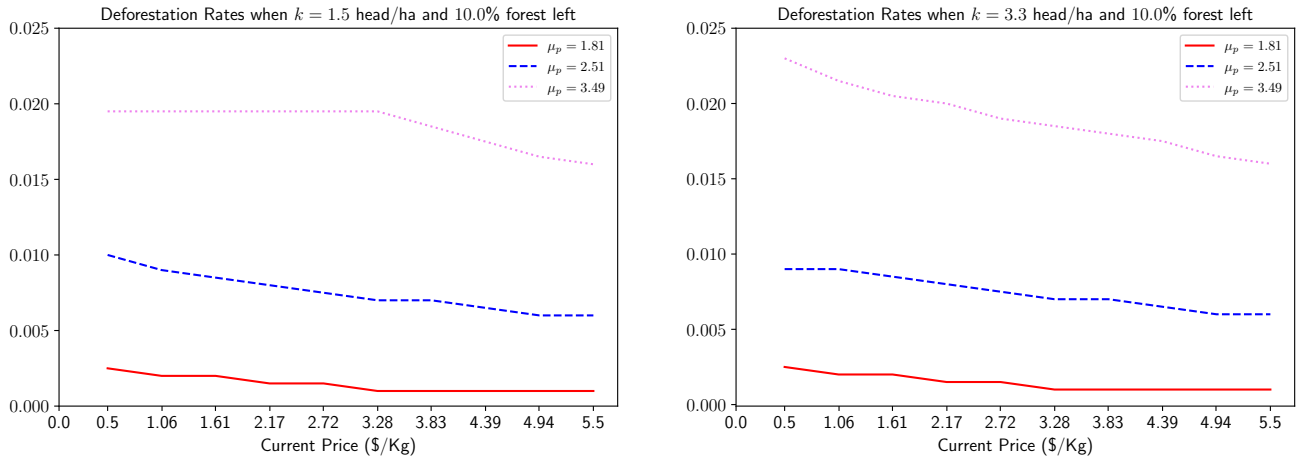
Figure 3: Cattle Management Policy Functions



Notes: The different lines correspond to policy functions for different mean prices. The horizontal axis maps out the current price of beef. The culling rate is measured as the fraction of the adult cattle stock slaughtered in a given year. The dashed gray line indicates the culling rate that would keep the herd size constant in the long run.

In both panels, the policy function is weakly increasing in P^B. This means that when the rancher observes a higher current price, she responds by slaughtering more cows to take advantage of the favorable price shock. However, when the long-run price increases, from say \$1.85/kg to \$2.52/kg, the rancher's culling rate is lower. These dynamic patterns are also reflected in deforestation policy functions.

Figure 4: Deforestation Policy Functions



Notes: The different lines correspond to policy functions for different mean prices. The horizontal axis maps out the current price of beef. The deforestation rate is measured as the fraction of the municipality's total area.

Figure 4 illustrates deforestation policy functions, conditional on two different stocking densities as in Figure 3, but now we are considering the state where deforested land A_{mt} is equal to 90% of the municipality's available land.

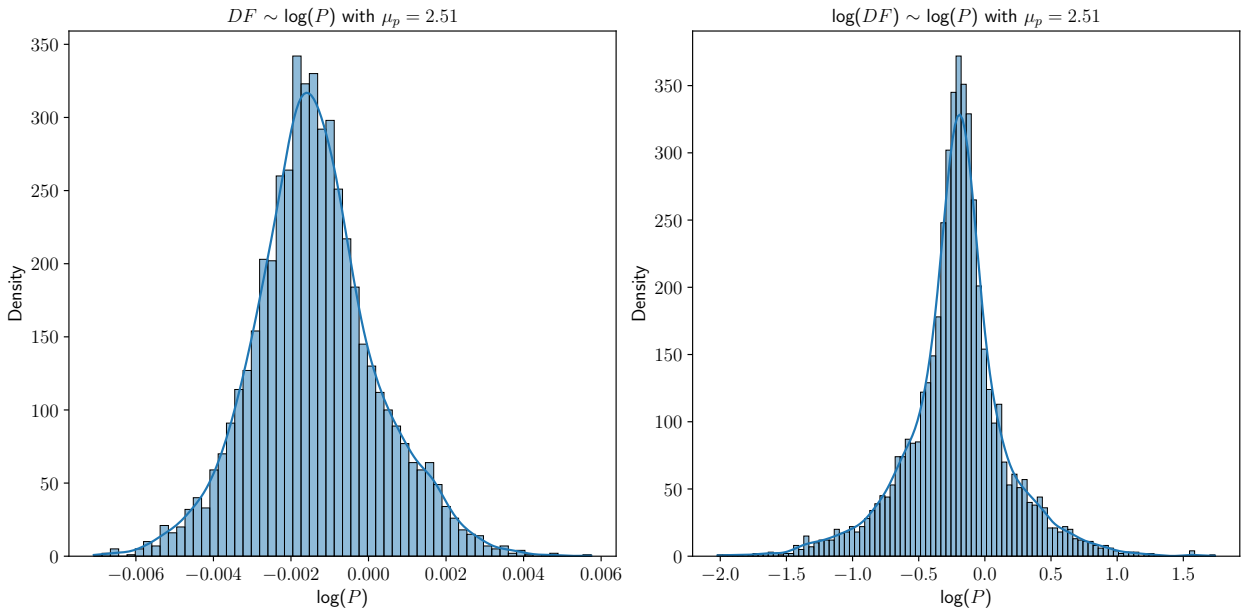
Conditional on the mean price, deforestation rates are decreasing with respect to the current price of beef. This reflects the fact that culling rates are higher and herd growth is lower when current prices are high. Thus, deforestation pressure is low when the current price is high.

However, comparing deforestation rates across mean prices, we have deforestation rates increasing with respect to (mean) price. This reflects the fact that ranching is more profitable in the long run when the mean price of beef is high, making the private returns to deforesting land higher.

These results point to a potential tension between the correlation we should expect to see within a given data generating process and the comparative statics we derive by changing the mean of the data generative process. Next, we confirm using simulations that the correlation we should expect to arise between deforestation and beef prices is likely to be close to zero, and can even be negative.

We simulate data using the solution to the rancher's problem described in this section. We simulate the model 5000 times, generating a sample of 30 years of data each time (after a 20-year burn-in period). For each sample, we regress deforestation rates on the log of the beef price. Figure 5 shows the histogram of the estimated coefficients.

Figure 5: Simulated Regressions



Notes: The figure presents the histogram of estimated coefficients on log price from simulated regressions of deforestation rates.

Figure 5 shows that the estimated elasticities are very small (inelastic) in magnitude, and more likely to be negative than positive. This is consistent with what we saw in our descriptive regressions.

The lesson from this exercise is that even though deforestation appears to be highly inelastic in the data, its long-run elasticity can be large. Comparing deforestation rates in Figure 5 for $\mu_p = 3.48$ and $\mu_p = 2.52$, we see that an approximately 33% increase in mean price is associated with an approximate doubling of the deforestation rate–we could call this a long-run elasticity of about 3.

Typically, when we are concerned about long-run elasticities, we are interested in understanding what will happen in a different policy environment. To that end, the next section performs policy simulations.

7 Policy Simulations

We embed the rancher's problem within a broader equilibrium model to perform policy simulations. We consider two kinds of policy interventions: beef taxes, and deforestation fines.

The model has five components: (1) the model of Brazilian ranchers introduced and estimated above, (2) a global beef demand function, (3) a global crops demand function, (4) a global crops supply function, and (5) a feedlot sector that converts crops into beef.

Our model of ranching consists of a municipality with average parameters that has been scaled up to match aggregate Brazilian production in recent data. This representative municipality has 178M hectares of available land. It is initially 33.5% deforested with a stocking density of .94 head/ha—values corresponding to our sample means.

Global beef demand has the following form:

$$Q_B^D\left(P^B\right) = 173.8 - 31.104P^B,$$

where the parameters were set to match recent consumption levels (when quantities are in millions of metric tons and prices in 2012 USD per kilogram live weight) and have an elasticity of $-.81$. This corresponds to a moderate estimate of the elasticity of demand for beef—see Bouyssou, Jensen and Yu (2024) for a review.

Global crop demand has the following form:

$$Q_C^D\left(P^C\right) = 795.6 - 383.3P^C,$$

where the parameters were set to match recent consumption levels of maize (for food, not counting feed and fuel) and have an elasticity of $-.06$, which corresponds to Roberts and Schlenker's (2013) estimate of the global demand elasticity for grain commodities.

Global crop supply has the following form:

$$Q_C^S\left(P^C\right) = 1365.1(P^C)^{.1},$$

where the parameters were set to match recent production levels of maize and have an elasticity of .1, which corresponds to Roberts and Schlenker's (2013) estimate of the global supply elasticity for grain

commodities.

The feedlot consists of a static, linear, and competitively available technology for converting crops into beef. We assume that each kilogram of feedlot beef (live animal weight) requires 5.4 kilograms of crop inputs and 1.53 units of numeraire good. In equilibrium, non-zero feedlot beef production requires a zero profit condition with respect to the prices of crops and beef:

$$P^B = 5.4P^C + 1.53. \tag{17}$$

We denote the amount of feedlot beef produced with Q_B^F. The amount of crops used for feedlot production is $5.4Q_B^F$.

Market clearing in beef requires

$$Q_B^D\left(P_t^B\right) = B_t + Q_{B,t}^F, \tag{18}$$

where B_t is pasture beef production.

Market clearing in crops requires

$$Q_C^D\left(P_t^C\right) + 5.4Q_{B,t}^F = Q_C^S\left(P_t^C\right) \tag{19}$$

Equations (17), (18), and (19) define a static equilibrium conditional on the pasture beef production level B_t. In each period, the aggregate state variables are the area of pasture land and the associated cattle herd, (A, K). Aggregate behavior will entail a culling rate $B_t^*(A, K)$ and associated level of beef production. We can then write $P_t^*(A, K)$ to denote the equilibrium beef price, which is given by the solution to equations 17-19 given $B_t = B_t^*(A, K)$.

The planner decides on pasture beef production rates B_t and deforestation rates D_t to maximize expected discounted private surplus. That is, the objective function for the planner's problem is consumer surplus (from both beef and crops) plus rancher profits. The social cost of emissions are not included at this stage, for we are solving the planner's problem only for the purpose of solving for competitive equilibrium.

We assume that time T^* is the last period in which deforestation is permitted, with $T^* = 10$ in our baseline specification. The model continues thereafter, but with a fixed pasture area; ranchers only make cattle management decisions from period $T^* + 1$ onward.

Let $W_{mt}(A, K)$ represent the planner's time specific value function. The post-T^* equilibrium will be stationary and we can drop the time subscripts and simply write $W_{m*}(A, K) = W_{mt}(A, K)$ for all $t \geq T^* + 1$. We solve for $W_{m*}(A, K)$ as the fixed point of the Bellman equation

$$W_{m*}(A, K) = \max_B \pi_m(B, 0, K, A, P) + \beta W_{m*}\left(A, K'(B, K), P'\right).$$

Having solved the value function for the post-deforestation world, we can use backward induction to define

and solve the value function in previous periods. That is,

$$W_{mT^*}(A,K,P) = \max_{B,D} \pi_m(B,D,K,A,P) + \beta W_{m*}\left(A+D, K'(B,K), P'\right),$$

and

$$W_{mt}(A,K,P) = \max_{B,D} \pi_m(B,D,K,A,P) + \beta W_{m,t+1}\left(A+D, K'(B,K), P'\right)$$

for $t < T^*$.

We can appeal to the Second Fundamental Welfare Theorem to establish that the solution to the planner's problem corresponds to a competitive equilibrium, supposing that each rancher owns an infinitesimally small amount of land. We can also verify this directly. The solution to the planner's problem implies an equilibrium path of prices that are exogenous from an individual rancher's perspective. We can then solve the rancher's optimal problem given this path of prices, and confirm that the individual rancher's cattle management and deforestation decisions correspond to the planner's aggregate decisions.

Figure 6 shows that Pigouvian deforestation taxes equal to the social cost of released carbon would completely halt deforestation, since that tax would far exceed the NPV that ranching generates per hectare. As noted above, the social value of carbon released by a hectare of deforestation in Amazonia is much higher than the values of pasture land observed in the data.

While deforestation taxes have been viewed by many as politically infeasible due to the costs on voters, Figure 6 suggests that ranchers may actually benefit from these policies: restricting supply leads to higher beef prices, which leads to higher profits per hectare. This means incumbent ranchers (particularly those who are not actively deforesting) stand to gain from increased enforcement of anti-deforestation measures. We note that policies restricting agricultural production to increase prices for farmers are common around the world.

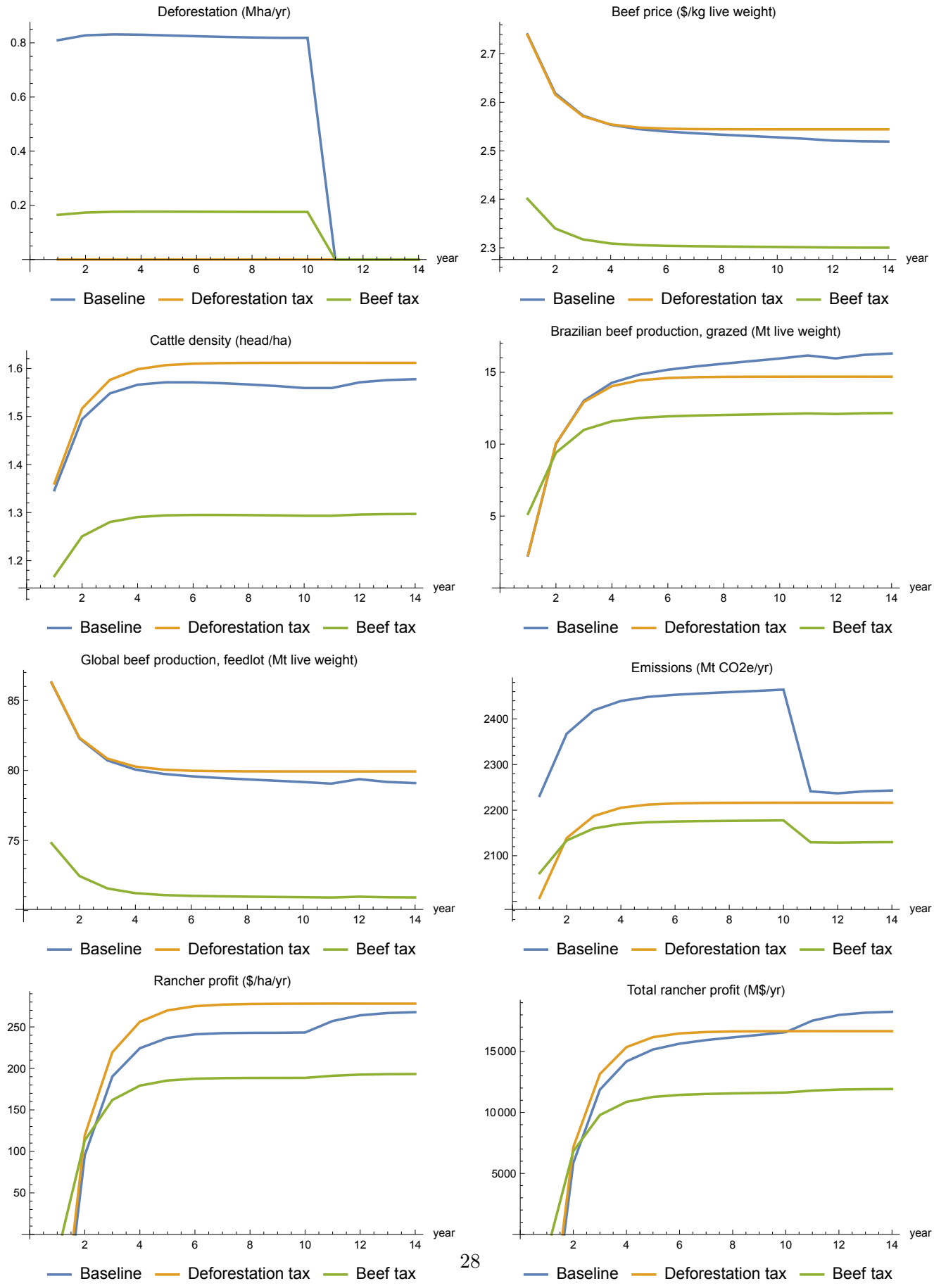
While deforestation taxes would increase profits per acre, pasture land would decrease, and Figure 6 shows that total profits for Brazilian ranchers would decrease slightly with deforestation taxes. The estimated loss of ranching income to Brazil would be \$1331.6 M/yr. Given that forest preservation programs such as REDD+ already receive hundreds of millions of dollars in funding per year, it may be feasible for other countries to compensate Brazil for this loss of income.

7.1 Implications for Indirect Land Use Change and Leakage

Going beyond the explicit policy simulations above, we comment here on the broader conceptual implications of high elasticities for indirect land use change and leakage.

While our dynamic model does not have a single long-run elasticity of deforestation—long-run elasticities can be defined in many different ways—our results clearly indicate that deforestation is highly elastic in the long run. We can see this both in the policy functions and simulations results. As discussed above, we can see a long-run elasticity of approximately 3 in the policy functions displayed in Figure 5. Turning to Figure 6, we can see that the beef tax lowers the price received by ranchers by about 18%

Figure 6: Counterfactual Simulations



in the steady state; meanwhile, during the period when deforestation is allowed, deforestation rates are about 77% lower than in the baseline. This implies a long-run elasticity of about 4.3. Either way, we have a large long-run elasticity of deforestation, and this has important implications for policy concerns like indirect land use change and leakage.

Indirect land use change refers to the phenomenon that, when a policy causes the prices of agricultural commodities to rise, it can induce new agricultural production around the world, potentially far away from the places where the policy is implemented. For a given price change, the amount of indirect land use change in a given location is proportional to the price elasticity of land use in that location. Therefore, our result that deforestation is highly elastic in the long run indicates that policies that increase agricultural commodity prices (and particularly the price of beef) are likely to have large indirect land use change impacts in the Brazilian Amazon.

Highly price elastic deforestation also has important implications for leakage in the context of forest protection programs, such as the UN's REDD+ program. Consider a market clearing equation,

$$Q_D(P) = \lambda Q_S(P),$$

where $Q_D(P)$ is demand for some commodity, $Q_S(P)$ is supply, with $1-\lambda$ being the fraction of land protected. To keep this illustration simple, we ignore yield heterogeneity and targeted land protection, so $1-\lambda$ can represent both the reduction in production and the proportion of land protected. The implicit function theorem implies

$$\frac{dP^*}{d\lambda} = \frac{-Q_S(P)}{\frac{dQ_S(P)}{dP} - \frac{dQ_D(P)}{dP}}.$$

By the chain rule,

$$\frac{dQ_S(P^*)}{d\Delta} = \frac{dQ_S(P^*)}{dP}\frac{dP^*}{d\Delta} = Q_S(P)\frac{\frac{dQ_S(P)}{dP}}{\frac{dQ_S(P)}{dP} - \frac{dQ_D(P)}{dP}}.$$

Putting these expressions together,

$$\frac{d(\lambda Q_S(P^*))}{d\lambda} = Q_S(P^*)\left(1 - \frac{\frac{dQ_S(P)}{dP}}{\frac{dQ_S(P)}{dP} - \frac{dQ_D(P)}{dP}}\right) = Q_S(P^*)\left(1 - \frac{\mathcal{E}_{\mathcal{S}}}{\mathcal{E}_{\mathcal{S}} - \mathcal{E}_{\mathcal{D}}}\right),$$

where $\frac{\mathcal{E}_{\mathcal{S}}}{\mathcal{E}_{\mathcal{S}} - \mathcal{E}_{\mathcal{D}}}$ is the rate of leakage.

With supply highly elastic (relative to demand), leakage can be close to 100%. While elasticities are not quite so extreme in the context of deforestation, it does seem to be the case that supply elasticities are substantially above demand elasticities. We had back-of-the-envelope estimates of the elasticity of deforestation of 3 and 4.3 above. Meanwhile, our borrowed elasticity of beef demand from the literature was $-.81$. Using these numbers, we have a back-of-the-envelope leakage estimates of 79% and 84%, implying that a large majority of forest protection is undermined by equilibrium effects.

8 Conclusion

This paper models dynamic deforestation and cattle management jointly. In the short run, deforestation may appear highly inelastic or even negatively correlated with prices, which helps explain previous empirical findings in reduced-form regressions. However, our model shows that, in the long run, deforestation becomes highly elastic—a result not captured in existing reduced-form analyses.

These findings have profound policy implications. A simplistic analysis, extrapolating from the reduced-form estimates, might suggest that deforestation is largely unresponsive to economic incentives, leading to the conclusion that policies affecting beef prices would have minimal impact on deforestation, and that forest protection policies would suffer from minimal leakage. Our results indicate otherwise.

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Online Appendix

A Model Details

A.1 Deriving the Euler Equations

A.1.1 Cattle Euler Equation

The first-order condition for the choice of culling B is

$$P_{mt}^{B}Y - \frac{d}{dB_{mt}}\left[\left(K_{mt}-B_{mt}\right)C_{mt}^{c}\left(\frac{K_{mt}-B_{mt}}{A_{rmt}}\right)\right] + \beta E_t\left[\frac{d}{dB_{mt}}V\left(\mathbf{K}m,t+1,A_{m,t+1}\right)\right] = 0,$$

which implies

$$\begin{aligned}
&Y \times P_{mt}^{B} - \frac{d}{dB_{mt}}\left[\left(K_{mt}-B_{mt}\right)C_{mt}^{c}\left(\frac{K_{mt}-B_{mt}}{A_{rmt}}\right)\right] \\
&+\beta E_t\left[-(1-\delta)\frac{d}{dK_{3,m,t+1}}V\left(K_{1,m,t+1},K_{2,m,t+1},K_{3,m,t+1},A_{m,t+1}\right)\right. \\
&\left.- g\frac{d}{dK_{1,m,t+1}}V\left(K_{1,m,t+1},K_{2,m,t+1},K_{3,m,t+1},A_{r,m,t+1}\right)\right] \\
&= 0,
\end{aligned} \tag{A1}$$

as each cow culled decreases next period's breeding stock by $(1-\delta)$ units and decreases the number of calves next period by g units.

Next, we consider the derivatives of the value function with respect to the cattle stock state variables, using the Envelope Theorem. Recall that $K_{mt} = \gamma_1 K_{1mt} + \gamma_2 K_{2mt} + K_{3mt}$. First, consider the derivative with respect to K_{3mt}. To reduce clutter, we write V_{mt} without its arguments:

$$\begin{aligned}
\tfrac{d}{dK_{3mt}}V_{mt} &= \tfrac{d}{dK_{3mt}}\left[-\left(K_{mt}-B_{mt}\right)C_{mt}^{c}\left(\tfrac{K_{mt}-B_{mt}}{A_{rmt}}\right)\right] + \beta E_t\left[\tfrac{d}{dK_{3mt}}V_{m,t+1}\right] \\
&= \tfrac{d}{dB_{mt}}\left[\left(K_{mt}-B_{mt}\right)C_{mt}^{c}\left(\tfrac{K_{mt}-B_{mt}}{A_{rmt}}\right)\right] \\
&\quad +\beta E_t\left[(1-\delta)\,\tfrac{d}{dK_{3,m,t+1}}V_{m,t+1} + g\,\tfrac{d}{dK_{1,m,t+1}}V_{m,t+1}\right] \\
&= Y \times P_{mt}^{B},
\end{aligned} \tag{A2}$$

where the second equality uses the fact that

$$\frac{d}{dK_{mt}}\left[-\left(K_{mt}-B\right)C_{mt}^{c}\left(\frac{K_{mt}-B}{A_{rmt}}\right)\right] = \frac{d}{dB}\left[\left(K_{mt}-B\right)C_{mt}^{c}\left(\frac{K_{mt}-B}{A_{rmt}}\right)\right];$$

and the last line follows from (A1).

Next, we consider the value function's derivative with respect to the yearling stock K_{2mt}:

$$\begin{aligned}\tfrac{d}{dK_{2mt}}V_{mt} &= \gamma_2 \tfrac{d}{dK_{mt}}\left[-\left(K_{mt}-B_{mt}\right)C^c_{mt}\left(\tfrac{K_{mt}-B_{mt}}{A_{rmt}}\right)\right]+\beta E_t\left[\tfrac{d}{dK_{2mt}}V_{m,t+1}\right]\\ &= \gamma_2 \tfrac{d}{dB_{mt}}\left[\left(K_{mt}-B_{mt}\right)C^c_{mt}\left(\tfrac{K_{mt}-B_{mt}}{A_{rmt}}\right)\right]+\beta E_t\left[\tfrac{d}{dK_{3,m,t+1}}V_{m,t+1}\right]\\ &= \gamma_2 \tfrac{d}{dB_{mt}}\left[\left(K_{mt}-B_{mt}\right)C^c_{mt}\left(\tfrac{K_{mt}-B_{mt}}{A_{rmt}}\right)\right]+\beta E_t\left[Y\times P^B_{m,t+1}\right].\end{aligned} \tag{A3}$$

Now, we take the value function's derivative with respect to the calf stock K_{1mt}:

$$\begin{aligned}\tfrac{d}{dK_{1mt}}V_{mt} &= \gamma_1 \tfrac{d}{dK_{mt}}\left[-\left(K_{mt}-B\right)C^c_{mt}\left(\tfrac{K_{mt}-B}{A_{rmt}}\right)\right]+\beta E_t\left[\tfrac{d}{dK_{1mt}}V_{m,t+1}\right]\\ &= \gamma_1 \tfrac{d}{dB_{mt}}\left[\left(K_{mt}-B_{mt}\right)C^c_{mt}\left(\tfrac{K_{mt}-B_{mt}}{A_{rmt}}\right)\right]+\beta E_t\left[\tfrac{d}{dK_{2,m,t+1}}V_{m,t+1}\right],\\ &= \gamma_1 \tfrac{d}{dB_{mt}}\left[\left(K_{mt}-B_{mt}\right)C^c_{mt}\left(\tfrac{K_{mt}-B_{mt}}{A_{rmt}}\right)\right]\\ &\quad +\beta E_t\left[\gamma_2 \tfrac{d}{dB_{m,t+1}}\left[\left(K_{m,t+1}-B_{m,t+1}\right)C^c_{m,t+1}\left(\tfrac{K_{m,t+1}-B_{m,t+1}}{A_{r,m,t+1}}\right)\right]+\beta E_{t+1}\left[Y\times P^B_{m,t+2}\right]\right]\end{aligned} \tag{A4}$$

where we have substituted for $\frac{d}{dK_{2,m,t+1}}V_{t+1}$.

We then substitute for the value functions in A1 and get

$$\begin{aligned}Y\times P^B_{mt} &= \tfrac{d}{dB_{mt}}\left[\left(K_{mt}-B_{mt}\right)C^c_{mt}\left(\tfrac{K_{mt}-B_{mt}}{A_{rmt}}\right)\right]\\ &\quad +\beta E_t\left[\left(1-\delta\right)\tfrac{d}{dK_{3,m,t+1}}V_{m,t+1}\right]+\beta E_t\left[g\tfrac{d}{dK_{1,m,t+1}}V_{m,t+1}\right]\\ &= \tfrac{d}{dB_{mt}}\left[\left(K_{mt}-B_{mt}\right)C^c_{mt}\left(\tfrac{K_{mt}-B_{mt}}{A_{rmt}}\right)\right]\\ &\quad +\beta(1-\delta)E_t\left[Y\times P^B_{m,t+1}\right]\\ &\quad +\beta g E_t\left[\gamma_1 \tfrac{d}{dB_{m,t+1}}\left[\left(K_{m,t+1}-B_{m,t+1}\right)C^c_{m,t+1}\left(\tfrac{K_{m,t+1}-B_{m,t+1}}{A_{r,m,t+1}}\right)\right]\right]\\ &\quad +\beta g E_t\left[\beta E_{t+1}\left[\gamma_2 \tfrac{d}{dB_{m,t+2}}\left[\left(K_{m,t+2}-B_{m,t+2}\right)C^c_{m,t+2}\left(\tfrac{K_{m,t+2}-B_{m,t+2}}{A_{r,m,t+2}}\right)\right]\right]\right]\\ &\quad +\beta g E_t\left[\beta E_{t+1}\left[\beta E_{t+2}\left[Y\times P^B_{m,t+3}\right]\right]\right]\end{aligned} \tag{A5}$$

Rearranging:

$$\begin{aligned}Y\times P^B_{mt} &= \tfrac{d}{dB_{mt}}\left[\left(K_{mt}-B_{mt}\right)C^c_{mt}\left(\tfrac{K_{mt}-B_{mt}}{A_{rmt}}\right)\right]\\ &\quad +\beta(1-\delta)E_t\left[Y\times P^B_{m,t+1}\right]+g\beta^3 E_t\left[Y\times P^B_{m,t+3}\right]\\ &\quad +g\beta E_t\left[\gamma_1 \tfrac{d}{dB_{m,t+1}}\left[\left(K_{m,t+1}-B_{m,t+1}\right)C^c_{m,t+1}\left(\tfrac{K_{m,t+1}-B_{m,t+1}}{A_{r,m,t+1}}\right)\right]\right]\\ &\quad +g\beta^2 E_t\left[\gamma_2 \tfrac{d}{dB_{m,t+2}}\left[\left(K_{m,t+2}-B_{m,t+2}\right)C^c_{m,t+2}\left(\tfrac{K_{m,t+2}-B_{m,t+2}}{A_{r,m,t+2}}\right)\right]\right]\end{aligned} \tag{A6}$$

where nested expectations have been suppressed following the law of iterated expectations.

A.1.2 Deforestation Euler Equation

For the choice of deforestation D, we first recall that $D_{mt} = A_{m,t+1} - A_{mt}$. The rancher's first-order condition with respect to $A_{m,t+1}$ is:

$$\frac{d}{dA_{m,t+1}} C^d_{m,t}\left(A_{m,t+1} - A_{mt}\right) + \beta E_t\left[\frac{d}{dA_{m,t+1}} V_{m,t+1}\right] = 0, \tag{A7}$$

or equivalently,

$$\frac{d}{dD_{mt}} C^d_{mt}\left(D_{mt}\right) + \beta E_t\left[\frac{d}{dA_{m,t+1}} V_{m,t+1}\right] = 0, \tag{A8}$$

Next, let's consider the derivative of the value function with respect to state variable A_{mt}, using the Envelope Theorem:

$$\frac{d}{dA_{mt}} V_{mt} = \frac{d}{dA_{mt}} \pi_{m,t}\left(B_{mt}, \mathbf{K}_{mt}, A_{mt}\right) + \frac{d}{dA_{mt}} C^d_{mt}\left(A_{m,t+1} - A_{mt}\right). \tag{A9}$$

We can express the derivative of agricultural payoffs in terms of the marginal returns to land in either pasture or cropland:

$$\begin{aligned}
\tfrac{d}{dA_{mt}} \pi_{m,t}\left(B_{mt}, \mathbf{K}_{m,t}, A_{mt}\right) &= \tfrac{d}{dA_{mt}}\left(\pi_{rmt}\left(B_{mt}, \mathbf{K}_{mt}, A^*_{rmt}\right) + \pi_{cmt}\left(\tfrac{A^*_{cmt}}{A_{mt}}, A_{mt}\right)\right) \\
&= \tfrac{dA^*_{rmt}}{dA_{mt}} \tfrac{d}{dA^*_{rmt}} \pi_{rmt}\left(B_{mt}, \mathbf{K}_{mt}, A^*_{rmt}\right) \\
&\quad + \tfrac{dA^*_{cmt}}{dA_{mt}} \tfrac{d}{dA^*_{cmt}} \pi_{cmt}\left(\tfrac{A^*_{cmt}}{A_{mt}}, A_{mt}\right) \\
&= \tfrac{d}{dA_{cmt}} \pi_{cmt}\left(\tfrac{A_{cmt}}{A_{mt}}, A_{mt}\right). \\
&= \tfrac{d}{dA_{rmt}} \pi_{rmt}\left(B_{mt}, \mathbf{K}_{mt}, A_{rmt}\right)
\end{aligned} \tag{A10}$$

The second equality comes from the chain rule. The third and fourth equalities rely on the fact that agricultural land must be divided between pasture and cropland, so that $\frac{dA^*_{rmt}}{dA_{mt}} + \frac{dA^*_{cmt}}{dA_{mt}} = 1$, and from the fact that the marginal returns to land is equalized across crops and pasture (equation **??**).

Next, we can combine equations A8, A9, and (A10):

$$\frac{d}{dD_{mt}} C^d_{mt}\left(D_{mt}\right) = \beta E_t\left[-\frac{d}{dA_{r,m,t+1}} \pi_{rmt}\left(B_{m,t+1}, \mathbf{K}_{m,t+1}, A_{r,m,t+1}\right) + \frac{d}{dD_{m,t+1}} C^d_{m,t+1}\left(D_{m,t+1}\right)\right], \tag{A11}$$

and since pasture land affects payoffs through the holding costs:

$$\frac{d}{dD_{mt}} C^d_{mt}\left(D_{mt}\right) = \beta E_t\left[\frac{d}{dA_{r,m,t+1}}\left(K_{m,t+1} C^r_{m,t+1}\left(\frac{K_{m,t+1}}{A_{r,m,t+1}}\right)\right) + \frac{d}{dD_{m,t+1}} C^d_{m,t+1}\left(D_{m,t+1}\right)\right], \tag{A12}$$

Given the equivalence of the marginal returns to land across crops and pasture (equation **??**), we can

also express this deforestation Euler equation in terms of cropland:

$$\frac{d}{dD_{mt}}C_{mt}^{d}\left(D_{mt}\right)=\beta E_{t}\left[\frac{d}{dA_{c,m,t+1}}\pi_{c,m,t+1}\left(\frac{A_{c,m,t+1}}{A_{m,t+1}},A_{m,t+1}\right)+\frac{d}{dD_{m,t+1}}C_{m,t+1}^{d}\left(D_{m,t+1}\right)\right]. \quad \text{(A13)}$$

A.2 The Representative Rancher

Case 1: no deforestation

Suppose there are potentially many ranchers indexed by r, each of whom owns a pasture area a_r. Let $A \equiv \sum_r a_r$. We're going to compare the situation with many ranchers in a competitive equilibrium to the situation with a single rancher operating the full pasture area A. In either case, the path of beef prices P_t is exogenous

The representative rancher maximizes

$$\max_{\{B_t \geq 0\}} E\left[\sum_t \beta^t A\pi\left(B_t, K_t/A, P_t\right)\right].$$

subject to

$$K_{t+1} = (1+g-\delta)\left(K_t - B_t\right).$$

Rearranging,

$$B_t = K_t - \frac{K_{t+1}}{1+g-\delta}.$$

Then we can rewrite the problem

$$\max_{\{K_t\}} \sum_t \beta^t A\pi\left(K_t - \frac{K_{t+1}}{1+g-\delta}, K_t/A, P_t\right).$$

The constraint $B_t \geq 0$ in the original problem will translate to the constraint

$$K_t - \frac{K_{t+1}}{1+g-\delta} \geq 0$$

in the modified problem.

First-order condition, assuming interior solution for all t:

$$\partial K_t: \quad E\left[\frac{d\pi\left(K_{t-1}-\frac{K_t}{1+g-\delta}, K_{t-1}/A, P_{t-1}\right)}{dK_t} + \beta\frac{d\pi\left(K_t-\frac{K_{t+1}}{1+g-\delta}, K_t/A, P_t\right)}{dK_t}\right] = 0\ ,$$

which we can rewrite

$$\partial K_t: \quad E\left[\frac{d\pi\left(B_{t-1}, K_{t-1}/A, P_{t-1}\right)}{dB_{t-1}} + \beta\frac{d\pi\left(B_t, K_t/A, P_t\right)}{dK_t}\right] = 0.$$

Notice that these first order conditions depend only on K_t/A for various t—cattle densities. Therefore, if $\{k_t\}$, where $k_t = K_t/A_t$ satisfy the first order conditions for the representative rancher, then the same densities of $\{k_t\}$ solve the first order conditions for a rancher of any size. Thus, the representative rancher will choose the same cattle density that smaller ranchers would.

Case 2: with deforestation

Now we add the decision of how much to deforest, D_t. This cost function is thought to be convex, i.e., $C(D) = \gamma_D D^2$. Deforestation increases the pasture area: $A_{t+1} - A_t = D_t$ The representative rancher's problem is now

$$\max_{\{K_t, A_t\}} \sum_t \beta^t \left[A_t \pi \left(K_t - \frac{K_{t+1}}{1+g-\delta}, K_t/A_t, P_t \right) - C\left(A_{t+1} - A_t\right) \right].$$

With the representative rancher, we now have these first-order conditions:

$$\begin{aligned} \partial K_t: \quad & E\left[A_{t-1} \tfrac{d\pi\left(B_{t-1}, K_{t-1}/A_{t-1}, P_{t-1}\right)}{dB_{t-1}} + \beta A_t \tfrac{d\pi\left(B_t, K_t/A_t, P_t\right)}{dK_t} \right] &= 0 \\ \partial A_t: \quad & E\left[-C'\left(A_t - A_{t-1}\right) + \beta \left(A_t \tfrac{d\pi\left(B_t, K_t/A_t, P_t\right)}{dA_t} + \pi\left(B_t, K_t/A_t, P_t\right) + C'\left(A_{t+1} - A_t\right) \right) \right] &= 0. \end{aligned}$$

For the competitive market, we imagine that there is a continuum of forest landowner engaging in deforestation, each of whom owns some infinitesimal amount of land. Landowner i's decision variable is D_i. For each of them, the marginal cost of deforestation is given by $2\gamma_D D$, where $D = \int D_i di$. The idea here is that the convexity of deforestation cost does not come from convexity in a firm-specific deforestation cost function, but from some underlying scarcity—e.g., we can suppose that labor is the main input into deforestation, and the local labor supply curve is upward sloping. Then, the wages that clear the market are increasing with respect to the level of deforestation.

Landowners sell land to ranchers in a frictionless land market. Let P_t^A be the price of pasture land per hectare in time t.

A rancher's objective function is

$$\max_{\{K_t, a_t\}} \sum_t \beta^t a_t \pi \left(K_t - \frac{K_{t+1}}{1+g-\delta}, K_t/a_t, P_t \right) - P_t^A \left(a_t - a_{t-1}\right).$$

A rancher's first order conditions will be

$$\begin{aligned} \partial K_t: \quad & E\left[a_{t-1} \tfrac{d\pi\left(B_{t-1}, K_{t-1}/a_{t-1}, P_{t-1}\right)}{dB_{t-1}} + \beta a_t \tfrac{d\pi\left(B_t, K_t/a_t, P_t\right)}{dK_t} \right] &= 0 \\ \partial a_t: \quad & E\left[\left(a_t \tfrac{d\pi\left(B_t, K_t/a_t, P_t\right)}{da_t} + \pi\left(B_t, K_t/a_t, P_t\right) - P_t^A \right) + \beta P_{t+1}^A \right] &= 0. \end{aligned}$$

A forest landowner's objective function, assuming they always sell the land they deforest immediately

$$\max_{\left\{A_{it}^F\right\}} \sum_t \beta^t \left[P_t^A \left(A_{it-1}^F - A_{it}^F \right) - \left(A_{it-1}^F - A_{it}^F \right) C'\left(D_t\right) \right],$$

noting that the aggregate deforestation rate D_t is exogenous from the perspective of an infinitesimally small landowner.

$$\partial A_t^F : E\left[-P_t^A + C'\left(D_t\right) + \beta \left(P_{t+1}^A - C'\left(D_{t+1}\right) \right) \right] = 0.$$

Substituting the deforester's Euler equation into the rancher's a_t Euler equation,

$$\partial a_t : \quad E\left[\left(a_t \frac{d\pi\left(B_t, K_t/a_t, P_t\right)}{da_t} + \pi\left(B_t, K_t/a_t, P_t\right) - C'\left(D_t\right) \right) + \beta C'\left(D_{t+1}\right) \right] \;=\; 0.$$

Now, if we consider a solution to the represenative rancher's problem and let $k_t = K_t/A_t$, that same cattle density and $a_t/a_{t-1} = A_t/A_{t-1}$ will solve a small rancher's decision problem.

B Data Appendix

This appendix describes the construction of the dataset used in our analysis. We combine data from multiple sources covering land use, cattle herds, prices, transportation costs, and policy variables for municipalities in the Legal Amazon region of Brazil. The final estimation sample covers the period 2002–2020.

B.1 Geographic Sample

Our analysis focuses on municipalities within the Legal Amazon (*Amazônia Legal*), an administrative region established by Brazilian law that encompasses nine states: Acre, Amapá, Amazonas, Maranhão, Mato Grosso, Pará, Rondônia, Roraima, and Tocantins. We obtain the list of municipalities in the Legal Amazon from official Brazilian government sources (IBGE). For estimation, we restrict our sample to municipalities within the Amazon biome, which is a subset of the Legal Amazon defined by ecological rather than administrative boundaries.

B.2 Land Use Data

Land use and land cover data come from MapBiomas, a collaborative project that produces annual land cover maps for Brazil using Landsat satellite imagery. We use Collection 6.0, which provides consistent annual land cover classifications from 1985 to 2021 at 30-meter resolution.

We aggregate the MapBiomas classifications into forest, cropland, and pasture. Pixels that are ever classified in another type of land cover are dropped.

We measure gross deforestation as the transition from forest to non-forest land use between consecutive years. Note that because deforestation measured in year t reflects land use change between $t-1$ and t,

we treat this as a decision made in year $t-1$. The deforestation rate in year t is defined as the proportion of the municipality's pixels (after dropping excluded land cover types as described above) that transition from forest in t to non-forest in year $t+1$.

B.3 Cattle Herd Data

Cattle herd data come from the Pesquisa Pecuária Municipal (PPM), an annual survey conducted by IBGE that reports livestock counts at the municipality level. The PPM reports the cattle herd size as of December 31 of each year.

B.3.1 Data Cleaning

The raw PPM data contain several apparent errors and inconsistencies. We manually correct observations that appear to be clear data entry errors (e.g., missing or extra digits).

When herd growth exceeds biological limits, this may reflect cattle transfers between nearby municipalities that are not recorded in the data. To address this, we aggregate groups of municipalities within the same geographic subregion (*região geográfica imediata*) when individual municipalities have infeasible herd dynamics.

We drop municipality-years from the sample when:

- Herd size is very small (≤ 10 head at any point)
- Forest cover is trivially small (< 10 km^2)
- Maximum deforestation rate is trivially small ($< 0.1\%$)
- Agricultural area is trivially small (< 10 km^2)
- Stocking density exceeds estimated carrying capacity (likely feedlot operations)

B.3.2 Demographic Variables and Culling Rate Measurement

We construct age-structured herd variables to capture herd dynamics. Our cattle stock data include only total headcounts, not headcounts by age. This limitation makes it challenging to precisely measure culling rates, as we cannot directly observe the age distribution of the herd. We let $K_{mt}^{count} = K_{1mt} + K_{2mt} + K_{3mt}$ denote the observed cattle stock in year t. Note that this raw count is different from the model's aggregate K_{mt}, in which the calves and yearlings are weighted down to produce an adult-equivalent measure.

Given the herd dynamics in equations (2)-(4), we can express the time-$t+1$ cattle stock as follows:

$$K_{m,t+1}^{count} = (1 - \delta + g)\left(K_{3mt} - B_{mt}\right) + K_{1mt} + K_{2mt}.$$

Rearranging, we have

$$B_{mt} = K_{3mt} - \frac{K_{m,t+1}^{count} - K_{1mt} - K_{2mt}}{1 - \delta + g}. \tag{B14}$$

If the initial cattle stocks by age were observed, equation (B14) would allow us to measure the culling rate directly. In the absence of such data, we pursue two strategies to estimate the culling rate.

The first is that we assume the initial period is in a steady state. However, there is a continuum of steady states with different ratios of young and old cattle. Observe that if we impose a steady state with constant young and adult stocks—that is, $K_y = K_{1mt} = K_{2mt}$ and and $K_3 = K_{3mt}$, but not necessarily $K_3 = K_y$—then the cattle dynamic equations imply

$$K_3 = (1-\delta)(K_3 - B) + K_y \tag{B15}$$

$$K_y = g(K_3 - B). \tag{B16}$$

Here, we have two equations and three unknowns (K_3, K_y, and B), so we need to impose another condition to pin down a unique steady state. Aggregate statistics from IBGE show a ratio of adult cows to yearlings of about 2.8. We therefore impose $K_3/K_y = 2.8$ in the initial period. That is, in the initial period $t = 1$ we assume that $K_{3mt} = 2.8K_{1mt} = 2.8K_{2mt}$, which implies $K_{1mt} = K_{2mt} = K_{mt}^{count}/4.8$, and $K_{3mt} = 2.8K_{mt}^{count}/4.8$. We can then use (B14) to measure the culling rate in the initial period, and we can use the herd dynamic equations to infer the cattle stocks by age and culling rates for subsequent periods. In the text, we refer to this measure, which imposes a demographic assumption on the initial cattle stock, as our *primary measure* of the culling rate.

An alternative measure imposes the herd demographic assumptions within each period. Specifically, we impose $K_{1mt} = K_{2mt} = K_{mt}^{count}/4.8$ and $K_{3mt} = 2.8K_{mt}^{count}/4.8$ within each time period, modifying equation (B14) to obtain

$$B_{mt} = 2.8K_{m,t}^{count}/4.8 - \frac{K_{m,t+1}^{count} - 2K_{m,t}^{count}/4.8}{1-\delta+g}. \tag{B17}$$

In other words, we do for every period what the primary measure does for the initial period. In the text, we refer to this measure, which imposes a demographic assumption on each period's cattle stock, as our *alternative measure* of the culling rate.

Simplified Model. Note that in the simplified version of the model without time-to-build, it is straightforward to infer the culling rate from observed changes in the cattle stock. In this version of the model, where there is only one measure of the cattle stock, the herd dynamics are characterized by

$$K_{t+1} = (1 + g - \delta)(K_t - B_t).$$

We can rearrange this equation to express the culling rate as

$$B_t = K_t - \frac{K_{t+1}}{1-\delta+g}.$$

B.4 Beef Prices

We obtain daily cattle futures prices from the B3 exchange (formerly BM&F Bovespa). The B3 live cattle futures contract specifies delivery of live cattle at an indicator price based on cash market prices in São Paulo state. Prices are quoted in Brazilian reais per arroba (approximately 15 kg of live weight).

We construct two price series from the futures data:

1. **Spot price**: The price of the nearest-to-expiration contract, which approximates the current cash market price

2. **Futures price**: The price of the contract expiring at least 9 months ahead, which reflects market expectations of future prices

We deflate nominal prices to 2012 levels using the Brazilian Consumer Price Index (IPCA). For the main analysis, we use prices observed in March–April of each year, as this corresponds to the beginning of the dry season when deforestation activity increases.

B.5 Transportation Costs

Transportation costs from each municipality to the nearest international port are a key determinant of the net price received by ranchers. Our strategy for measuring transportation costs to the port is similar to that in Souza-Rodrigues (2019).

We begin by defining the locations of thirteen ports, one location for each Brazilian state that has access to the ocean. Locations were selected by hand using the Brazilian government's shapefiles describing port locations.[7] The list of ports is: Santos (São Paulo), Paranaguá (Paraná), Rio Grande (Rio Grande do Sul), Vitória (Espírito Santo), São Francisco do Sul (Santa Catarina), São Luís (Maranhão), Salvador (Bahia), Recife (Pernambuco), Maceió (Alagoas), Pecém (Ceará), Rio de Janeiro (Rio de Janeiro), Barcarena (Pará), and Aracaju (Sergipe).

The next step is to construct a transportation network. Because beef is primarily transported by road, we ignore railways and rivers for this exercise, but we distinguish between paved and unpaved roads. Brazil's National Bureau of Infrastructure provides shapefiles of federal highways and waterways (`https://www.gov.br/dnit/pt-br/assuntos/atlas-e-mapas/pnv-e-snv`). Brazil's Ministry of Transport provides shapefiles for the federal road network, railway network, waterways, and ports (`https://www.gov.br/transportes/pt-br/assuntos/dados-de-transportes/bit/bit-mapas`). Finally, a shapefile of state highways was obtained from the World Bank (`https://datacatalog.worldbank.org/search/dataset/0038536`).

We use proprietary data from ESALQ for the per-kilometer cost of transporting beef by road. We directly use freight costs from this dataset as our measure of the cost of transportation by paved road. We then assume that unpaved roads have a 30% higher cost per kilometer than paved roads, following Souza-Rodrigues (2019).

[7] Obtained from `https://www.gov.br/transportes/pt-br/assuntos/dados-de-transportes/bit/bit-mapas`.

Then, for each municipality-port pair, we compute lowest possible cost of transporting beef from the centroid of the municipality to the port, taking into account the modes of transportation along each potential route. To do this, we use a shortest path algorithm, noting that we search for the path that minimizes transportation cost, not distance. Then, for each municipality, we choose the port with the lowest transportation cost. The cost-minimizing path does not vary across years because each potential route's cost is linearly proportional to the per-kilometer cost of transporting beef.

The ESALQ data only covers 1997–2012, so we use this procedure to construct transportation costs c_{mt} for each municipality m and year t through 2012. For subsequent years, we project transportation costs using diesel prices obtained from the Brazilian National Agency for Petroleum, Natural Gas and Biofuels. Specifically, we use OLS to estimate the equation

$$c_{mt} = \alpha_{0m} + \alpha_P P_{\text{diesel},t} \cdot \text{dist}_m + \epsilon_{mt},$$

where dist_m is the distance of the selected path for municipality m. For 2013 onward, we use fitted values from this regression to impute transportation costs.

The net price received by ranchers in municipality i in year t is:

$$p_{it}^{\text{net}} = p_t^{\text{spot}} - c_{it}$$

where p_t^{spot} is the spot price at the port and c_{it} is the transportation cost (converted to USD/kg).

B.6 Agricultural Yields

We obtain potential grass yields from the Global Agro-Ecological Zones (GAEZ) database, which provides estimates of potential crop and pasture productivity based on climate, soil, and terrain characteristics. Grass yields are measured in kg of dry matter per hectare per year.

B.7 Land Prices

Land price data come from FNP Informa surveys, which report pastureland prices by municipality and land type. We focus on prices for "formed pasture" and "native pasture with low support capacity," excluding difficult-to-access pastures that may have unusually low prices.

When multiple land types are reported for the same municipality, we use the lower price. Land prices are converted to USD and deflated to 2012 levels.

We run some descriptive regressions with our land price data to illustrate that it has sensible correlations with observable municipality-level characteristics. As anticipated, higher land productivity, proxied by grass yields, is associated with increased land prices, while higher transportation costs to the port lower land values. Moreover, larger cattle stocks and a greater share of cropland within a municipality indicate higher land demand, which pushes prices upward.

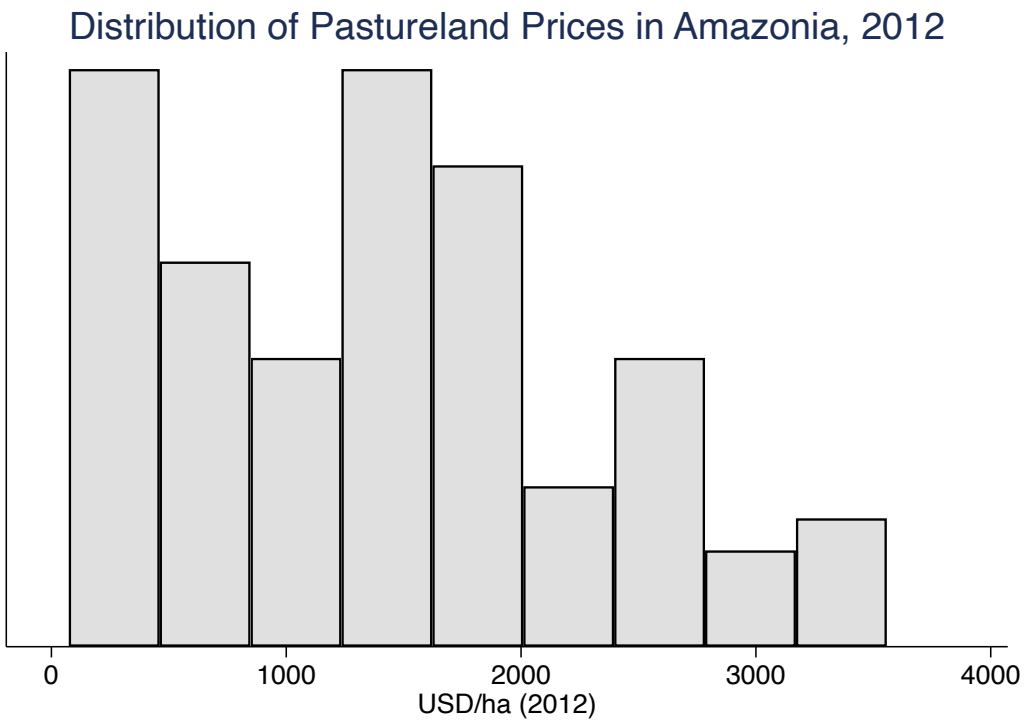
Table B1: Land prices and covariates

	(1) ln(Land price)	(2) ln(Land price)	(3) ln(Land price)	(4) ln(Land price)
ln(Grass yield)	5.19***	4.70***	4.20***	4.20***
	(0.54)	(0.55)	(0.52)	(1.56)
ln(Transportation cost)	-1.62***	-1.45***	-1.26***	-1.26***
	(0.13)	(0.13)	(0.14)	(0.43)
Herd density		0.33***	0.32***	0.32**
		(0.046)	(0.047)	(0.14)
Cropland share			1.12***	1.12**
			(0.16)	(0.49)
Observations	902	902	902	902
R-squared	0.614	0.632	0.645	0.645
Year FE	✓	✓	✓	✓
State FE	✓	✓	✓	✓
Clustered by municipality				✓

Observations are by municipality and year. Robust standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

Figure B1 displays a histogram of land prices. Note that even the highest land prices are well below $10,000 per hectare, which would be a conservative estimate of the value of carbon released by a hectare of slash and burn deforestation in the Amazon.

Figure B1: Histogram of log land prices (in $ per hectare)



B.8 Policy Variables

The Brazilian government maintains a "Priority List" of municipalities with high deforestation rates that face enhanced monitoring and restrictions. We construct a time-varying indicator for whether each municipality is on the priority list in each year, based on entry and exit dates.

We also construct an alternative version that assumes no enforcement during periods of lapsed federal attention to environmental policy (2013–2017 and 2019–2023).

We define a binary variable indicating the post-2006 period, when Brazil significantly increased deforestation enforcement efforts under the PPCDAm (Action Plan for Prevention and Control of Deforestation in the Legal Amazon).

B.9 Carbon Density

Forest carbon density data come from Walker et al. (2022). The data provide estimates of above-ground carbon stocks at 500-meter resolution, measured in tonnes of carbon per hectare. We compute the mean carbon density across forested pixels in each municipality.

C Robustness

C.1 Dropping low deforestation rates

While the data do not include zero deforestation rates, this is likely due to measurement error. Some municipalities have very low deforestation rates, and misclassification can produce spurious non-zero rates. See Torchiana et al. (2025) for a discussion of measurement error in the context of measuring land use change.

To assess robustness to potential zeros, we re-estimate the model after dropping very low deforestation rates. Table C2 demonstrates that our cost estimates are robust to dropping municipalities with very low deforestation rates.

C.2 Dropping sub-samples

One concern is that Amazonia is an expansive region with variation in agricultural practices across it. Table C3 presents cost estimates for two sub-samples, in contrast to our main sample. In column (2), we drop municipalities that always have forest cover above 95%. These tend to be very large municipalities in the Amazonas and Pará states. In column (3), we drop all municipalities within the states of Mato Grosso and Rondônia, which have relatively high stocking densities and are known to have a non-trivial presence of feedlots recently.

Results are relatively robust, with the only notable difference being that holding costs appear to be slightly higher when dropping Mato Grosso and Rondônia.

Table C2: Robustness to Zeros: Simplified Cattle Dynamics

	(1)	(2)	(3)
θ_{r0}	103.149	99.5005	89.616
	(−232.15,312.17)	(−236.5,309.48)	(−219.89,292.05)
θ_{r1}	1120.16	1112.83	1074.87
	(868.5,1811.8)	(863.18,1796.6)	(851.59,1639.6)
θ_d	32734.7	32234.	29951.
	(24498.,1.34869×10^5)	(24610.,1.32297×10^5)	(23325.,1.10376×10^5)
Post-2006	547.12	560.142	541.049
	(−570.82,776.18)	(−556.63,786.95)	(−478.31,787.23)
Blacklist	344.825	329.802	326.159
	(−185.4,1068.4)	(−194.75,1006.1)	(−201.48,965.13)
Mean holding cost	280.55	278.97	271.958
	(47.738,473.49)	(45.909,471.09)	(58.247,460.07)
Mean DF cost	771.099	785.392	782.22
	(526.88,925.78)	(553.74,940.18)	(507.92,946.59)
Mean marginal DF cost	1067.4	1083.7	1093.18
	(900.24,1994.1)	(912.29,2012.5)	(910.84,1925.7)
Observations	8901	8688	7561

Notes: The table presents cost parameter estimates and derived statistics for specifications with simplified cattle dynamics (i.e., no calf or yearling stocks). Column (1) uses the full sample. Column (2) drops observations involving deforestation rates below .05%. Column (3) drops observations involving deforestation rates below .2%. Mean cost statistics average over municipalities and years in our sample. The Post-2006 and Blacklist dummy variables are included in the deforestation cost function. Standard errors, shown in parentheses, are clustered by year and calculated using the block bootstrap procedure. Observations are by municipality-year.

Table C3: Robustness in Subsamples: Simplified Cattle Dynamics

	(1)	(2)	(3)
θ_{r0}	103.149	101.072	162.208
	(−232.15,312.17)	(−214.7,311.15)	(−218.91,1800.4)
θ_{r1}	1120.16	1122.27	1049.9
	(868.5,1811.8)	(869.5,1511.3)	(−4489.1,2499.2)
θ_d	32734.7	32291.2	34831.1
	(24498.,1.34869×10^5)	(23897.,1.01744×10^5)	(-2.24652×10^5,1.53622×10^5)
Post-2006	547.12	554.692	51.6238
	(−570.82,776.18)	(−94.927,789.2)	(−1187.8,3514.)
Blacklist	344.825	345.694	151.396
	(−185.4,1068.4)	(−180.9,978.1)	(−991.51,1247.1)
Mean holding cost	280.55	279.975	311.187
	(47.738,473.49)	(107.5,472.73)	(70.674,1163.4)
Mean DF cost	771.099	780.101	394.448
	(526.88,925.78)	(552.05,938.64)	(65.22,678.01)
Mean marginal DF cost	1067.4	1078.77	742.72
	(900.24,1994.1)	(911.11,1786.8)	(−1601.6,1536.8)
Observations	8901	8686	6141

Notes: The table presents cost parameter estimates and derived statistics for specifications with simplified cattle dynamics (i.e., no calf or yearling stocks). Column (1) uses the full sample. Column (2) drops observations from municipalities that always have forest cover above 95%. Column (3) drops all municipalities from Mato Grosso and Rondônia. Mean cost statistics average over municipalities and years in our sample. The Post-2006 and Blacklist dummy variables are included in the deforestation cost function. Standard errors, shown in parentheses, are clustered by year and calculated using the block bootstrap procedure. Observations are by municipality-year.