Market Power and Carbon Emissions in the Amazon

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Abstract

The beef cattle sector is the leading driver of deforestation worldwide. This creates high sectoral emissions, which are geographically concentrated in expanding agricultural frontiers. I focus on the Brazilian Amazon and study how market power in the cattle supply chain shapes production and emissions. Intermediaries exert buyer (monopsony) power over ranchers, but market structure also varies geographically. Ranchers in core regions face the most market power, while the deforestation frontier is relatively competitive. Using rich transaction-level data and a quantitative spatial model, I show that intermediary monopsony reduces prices paid to ranchers, but primarily in regions away from the frontier. While this burdens ranchers and lowers beef production, its effect on emissions is muted because the deforestation frontier is competitive. In counterfactual analysis, I show that many proposed policies fail to target the deforestation frontier and would instead further reduce production in the places already distorted by market power. However, a combination of targeted production subsidies and a carbon tax can reallocate production away from the frontier and reduce emissions by one third while keeping beef production constant.

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1 Introduction:

Agriculture is a key driver of climate change, generating as much as one-fifth of global greenhouse gas emissions (IPCC, 2022). A large fraction of those emissions occurs through deforestation to expand farming and ranching. With deforestation, carbon stocks stored in plant biomass are lost to fire and decomposition (Soto-Navarro et al., 2020). Clearing forests for cattle ranching has been responsible for 36% of global deforestation (WRI, 2022). In the Brazilian Amazon, the cattle sector drives 90% of deforestation, causing 1.7% of *global* (2017) greenhouse gas emissions. Amazonian cattle contributes to greenhouse gas emissions primarily through land use change CO2, but also through animal enteric fermentation CH4. The relative contribution of each varies geographically, with higher land use CO2 emissions on the deforestation frontier. As a result, regions in the frontier that account for 10% of cattle production are the source of 40% of emissions.

The geography of cattle ranching influences not only the pollution externality, but also market power. Ranchers sell to nearby slaughterhouses, the intermediaries that process cattle into beef products sold in Brazil and abroad. In various agricultural contexts, intermediary firms play a prominent role and often exert buyer market power over farmers (Chatterjee, 2023; Zavala, 2020; Krishna and Sheveleva, 2017; Osborne, 2005; Bergquist and Dinerstein, 2020; Méndez and Van Patten, 2022; Rubens, 2023). Slaughterhouses vary greatly in size across the Amazon, with a fringe of many small firms and a few very large ones. The largest 2% of slaughterhouses concentrate 75% of slaughtered cattle. But these firms are not homogeneously distributed across space, and high transportation costs make it such that ranchers only sell to nearby slaughterhouses. As a result, slaughterhouses exert buyer (monopsony) power over ranchers in their surrounding regions, and the geographic nature of this setting creates variation in market structure across space.

Using rich transaction data and a structural model of the cattle supply chain, I find that market power also has a clear geographic pattern. Regions in the agricultural "core" face monopsony power, while the agricultural frontier is relatively competitive. This is driven by differences in the size and number of slaughterhouse operations – frontier ranchers sell to many small scale, lower-productivity buyers: a competitive fringe.

As a result, market power and carbon emissions follow opposite spatial patterns. Market power affects core regions, but emissions come from the frontier. The interactions between market power and environmental externalities have long been a topic of theoretical discussion in economics (Buchanan, 1969), and recent work examines them empirically (Fowlie, Reguant, and Ryan, 2016; Kellogg and Reguant, 2021; Borenstein and Bushnell, 2022; Preonas, 2023). The two market failures have countervailing effects; whereas market power is an *underproduction* problem, negative externalities create *overproduction*. This paper empirically shows that the scale and distribution of this interaction depends on *where* each market failure operates. In my setting, slaughterhouse market power distorts rancher production decisions and leads to lower output, but its beneficial effect on emissions is limited because it does not affect the emissions-intensive frontier.

The spatial pattern of market power is driven by sorting of the smallest and least productive slaughterhouses with the least productive and least tenure-secure landowners. Ranchers along the frontier face naturally less productive land, use less intensive production practices and often occupy land without proper title, creating conflict with indigenous reservations and other subsistence communities. These factors impede the type of cattle production that is preferred by the largest buyers and exporters. But the lack of access to large buyers is compensated by more competition - the geographic "fringe" of ranchers sells to a competitive fringe of small slaughterhouses. Core regions, on the other hand, have better access to major markets but face distortions resulting from the strategic sourcing behavior of the largest slaughterhouses.

I quantify the extent and distribution of market power, as well as its environmental impacts, using a structural model. Market power depends on the endogenous decisions of slaughterhouses, which strategically respond to each other and the supply decisions of ranchers. In addition, supply changes in one region can affect others through equilibrium demand spillovers. To account for these different interactions in equilibrium, I develop a quantitative spatial model of the cattle supply chain in the Amazon. The model allows me to estimate the extent of market power in each region and also study the effect of counterfactual policies.

The quantitative spatial model has three parts: cattle sourcing under slaughterhouse market power, land use change, and beef demand. In the first, I build on existing models of oligopsony (Zavala, 2020; Berger, Herkenhoff, and Mongey, 2019; Dominguez-Iino, 2020) to describe how cattle sourcing varies across space. Slaughterhouses strategically choose cattle quantities in each municipality (county), internalizing rancher supply elasticities and the behavior of other slaughterhouses. This results in markdowns on the prices paid to cattle ranchers. Markdowns are larger (prices lower) in municipalities where cattle supply is inelastic and where a slaughterhouse possesses a high market share.

I contribute to existing oligopsony frameworks by explicitly modeling the geography of sourcing on both the intensive and extensive margins. On the intensive margin, I use variation in quantities sourced across space to estimate slaughterhouse productivities and transportation costs. I also add an extensive margin to the model - slaughterhouses choose *where* they source cattle considering transportation costs and the competition they would face in a particular region. This part of the model bears similarity to models of entry under different firm types (Mazzeo, 2002; Toivanen and Waterson, 2005; Reiss, 1996), but I apply it to sourcing decisions in a spatial economy. It provides a microfoundation for the variation in market structure I observe across space. To estimate this rich array of sourcing relationships, I rely on a dataset of over 10 million cattle movement records. These records exist due to strict health regulations that track animal vaccinations and seek to prevent the spread of food-borne diseases. With these rich data, I observe the purchasing behavior of slaughterhouses large and small, and also how it varies geographically.

Oligopsony markdowns depend on the supply elasticities of ranchers, which I estimate using a land use change model. The model draws from recent work on the dynamics of land use change and deforestation (Hsiao, 2020; Araujo, Costa, and Sant'Anna, 2020; Scott, 2012). Atomistic landowners observe prices for cattle and other commodities and make per-period land conversion decisions (e.g. from forest to pasture, or pasture to forest, and so on). In my main specification, I focus on dynamics from a medium-run perspective, predicting land transitions between 2015 and 2019. I estimate the model using high-resolution land use change data. Because land property rights matter for decisions along the frontier, I use every record in Brazil's land property registry (more than 1 million) as well as all public land parcels to build a novel dataset tracking land tenure across space. By joining the land use change data with the property records, I estimate the model separately for four different land tenure categories. This leads to different supply elasticity estimates across space and land tenure. To deal with endogeneity concerns, I use a shift-share instrument (Borusyak et al., 2018) for producer prices that interacts demand shocks from importing countries with the spatial production networks for beef and soy.

With model estimates, I then use counterfactual exercises to compare different policy interventions. First I quantify how the distribution of market power across space is biased towards burdening low-emitting regions far from the frontier. To do so, I solve a counterfactual scenario where each municipality is controlled by a monopsonist that can only extract a regulated markdown. I set the markdown to be homogeneous across space (with no environmental targeting), and such that aggregate beef supply equals that of the original equilibrium. This exercise in homogenizing markdowns induces a reallocation of production across space, from the competitive frontier towards the more concentrated core. In this scenario without spatial inequality in market power, emissions would be 7.5% lower. For scale, this figure is approximately the level of US emissions in the cement sector (EPA, 2021).

In the environmental policy sphere, most policy proposals to regulate the cattle supply chain have centered on the largest slaughterhouses and exporters. These include tariffs or standards imposed by import partners (EU, 2023) and pressures placed on large slaughterhouses to monitor their supply chains (Alix-Garcia and Gibbs, 2017; Moffette, Skidmore, and Gibbs, 2021; Heilmayr, Rausch, Munger, and Gibbs, 2020). My work shows that these policies are ineffective for several reasons. First, Brazil only exports 20% of its beef output. Second, what it does export comes from the largest and most productive slaughterhouses, which are located in the lower-emitting core. Even if domestic consumption is also regulated, any policy that targets only large slaughterhouses will fail to affect the deforestation frontier, the key source of emissions. By affecting the core, it will lower production in regions already distorted by market power.

To illustrate this, I solve a series of counterfactual scenarios, each taxing a different set of slaughterhouses. Instead of attempting to emulate particular policy designs, I use cattle taxes in the counterfactual exercises to exemplify the trade-offs that arise when regulating slaughterhouses in different regions. Emissions reductions come at the cost of reductions in beef production, but these trade-offs vary geographically. A tax only on slaughterhouses with export permits would need to reduce beef production by 1% in order to reduce emissions by 1%. If this tax were levied on all slaughterhouses, it would only need to reduce beef output by 0.5% to achieve the same emissions reduction. If it were to target the high-emitting frontier, it would need to reduce production by only 0.1%.

This policy exercise speaks to a recent literature on the interactions between trade and the environment (Shapiro, 2016, 2021; Copeland and Taylor, 1994; Antweiler, Copeland, and Taylor, 2001; Kortum and Weisbach, 2021; Nordhaus, 2015; Böhringer, Carbone, and Rutherford, 2016; Farrokhi and Lashkaripour, 2020), and more specifically in the context of commodity-driven deforestation (Harstad, 2022; Dominguez-Iino, 2020; Hsiao, 2020; Farrokhi and Pellegrina, 2020). Hsiao (2020) and Dominguez-Iino (2020) find that foreign-led, demand-side efforts (e.g. tariffs) to reduce deforestation are only effective when there is coordination and commitment across the international community. In Brazil's case, taxing exporters is ineffective even under full coordination. Exports are a small fraction of output, even less in the high-emitting frontier. More broadly, my work shows that the geography of supply chains matters for the effectiveness of policies to reduce deforestation. Deforestation is a frontier phenomenon, and the economic actors in a frontier differ from those of other regions. Frontier firms tend to be smaller and less connected to export supply chains. Despite their smaller volumes, they are key actors in expanding the deforestation frontier and drive a disproportionate share of emissions.

Finally, I turn to a policy that uses both taxes and subsidies to address the two market failures in this setting. This exercise is inspired by Brazil's recently approved value-added tax (Brazil, 2023; Ayres et al., 2023), which has provisions for lower rates in food production but higher rates for environmentally damaging goods. I first introduce a production subsidy with different rates across regions to drive prices to what they would be under perfect competition. Then I introduce a tax on the carbon embedded in the production of cattle in each region. I set the rate (60 cents per ton of CO_2e) such that aggregate beef output equals that of the original equilibrium. Under this counterfactual scenario, emissions would be 34% lower.

Such a low carbon tax can achieve emissions reductions of this magnitude for two reasons. First, returns to cattle ranching are low and, in the frontier, emissions are extremely high.

The tax on embedded carbon emissions leads is equivalent to a 35.5% (average) cattle tax on the frontier. In addition, the subsidies induce a reallocation of production towards regions that produce more with less land. Despite keeping beef output constant, the policy leads to a 5% reduction in pasture area.

This exercise suggests that, by shifting incentives across space, it is possible to reduce emissions by a sizable margin without compromising food production. It relates to a literature examining policies to curb deforestation (Assunção et al., 2015; Moffette et al., 2021; Burgess et al., 2012, 2019; Nepstad et al., 2009; Pfaff, 1999; Assunção et al., 2013, 2020; Skidmore et al., 2021a; Balboni et al., 2021; Bragança and Dahis, 2022), and in particular work that uses structural models (Souza-Rodrigues, 2019; Araujo, Costa, and Sant'Anna, 2020; Araujo, 2023; Farrokhi and Pellegrina, 2020). My work adds the supply chain dimension, identifying another market failure - monopsony power - and examining its geographic distribution. By moving output out of the frontier where it threatens the forest, towards core regions distorted by market power, policy can reduce emissions and still preserve current beef production. I show how taxes and subsidies can create this reallocation, but command-and-control policies can achieve similar effects. For example, strengthening the land rights of indigenous people or subsistence communities can prevent encroachment on vulnerable regions (Baragwanath, Bayi, and Shinde, 2023) and reduce deforestation on the frontier. Improving cattle traceability (Prizibisczki, 2023) can also aid enforcement against deforestation and other illegal activities.

In the next section, I describe the setting at greater detail with some stylized facts. Those motivate a structural model, which I introduce in section 3. I discuss data and estimation in sections 4 and 5, then present results and policy counterfactuals in sections 6 and 7.

2 Context and descriptive evidence

Key data - Cattle Movement Records: To understand the role of the cattle supply chain in shaping the spatial distribution of carbon emissions in the Amazon, one needs data on where the cattle are raised and how they are processed. Data on the sub-national origin of food products are difficult to come across, especially in developing countries. This setting, however, provides a unique opportunity to observe how supply chains are organized in space. Sanitary concerns over food-borne illnesses have led to strict regulations in the beef sector. To curb the spread of diseases, ranchers are required to issue a record of every cattle movement, whether it be between different farms or from farms to slaughterhouses.

Those cattle movement records constitute the key data source for this study. Known in Portuguese as "*Guias de Transito Animal*" (GTA, roughly translated to "Records of animal transit"), GTAs must be issued every time a rancher moves a herd outside their property. Each record includes information on the number of heads in the herd, the sex and age of the animals, and whether they are properly vaccinated. And most importantly for the purposes of this paper, it contains information on the origin and destination properties, whether they be a farm or a slaughterhouse.

The GTA data have been used in various studies in geography and environmental studies (Klingler et al., 2018; West et al., 2022; Skidmore et al., 2021b), but only recently have they begun to appear in economics (Skidmore, 2023). To my knowledge, this is the first paper to use such detailed data for a study of market structure in the cattle supply chain. Dominguez-Iino (2020), which looks at a variety of commodities in South America, observes the supply chain for cattle exports. Those comprise only 20% of production in Brazil and only include large slaughterhouses. Comprehensive supply chain data are essential for uncovering the role of small slaughterhouses, which are especially important in the frontier. Since I use these data in relation to environmental outcomes, it is also important to emphasize that there are no environmental policies tied to the making of these records. While compliance with health regulations is subject to thorough checks by health authorities, ranchers issue GTAs regardless of compliance with the forest code [1]

GTA records are publicly available from a variety of local agencies in Brazil. I gained access to the records through a data use agreement with a partner organization. This paper focuses on Brazil's Legal Amazon, a subset of Brazilian states which faces a special regime of environmental and social policies tied to the rainforest. Among those, I have supply chain transaction data for the subset highlighted on Figure 1. Those states contain 92% of the

[1] This was confirmed in a series of field interviews I conducted in February 2023. There are heavy fines for failing to issue GTAs or failing to prove proper animal vaccination, but environmental compliance is completely separate from any process related to GTAs.

Amazon's total pasture area.

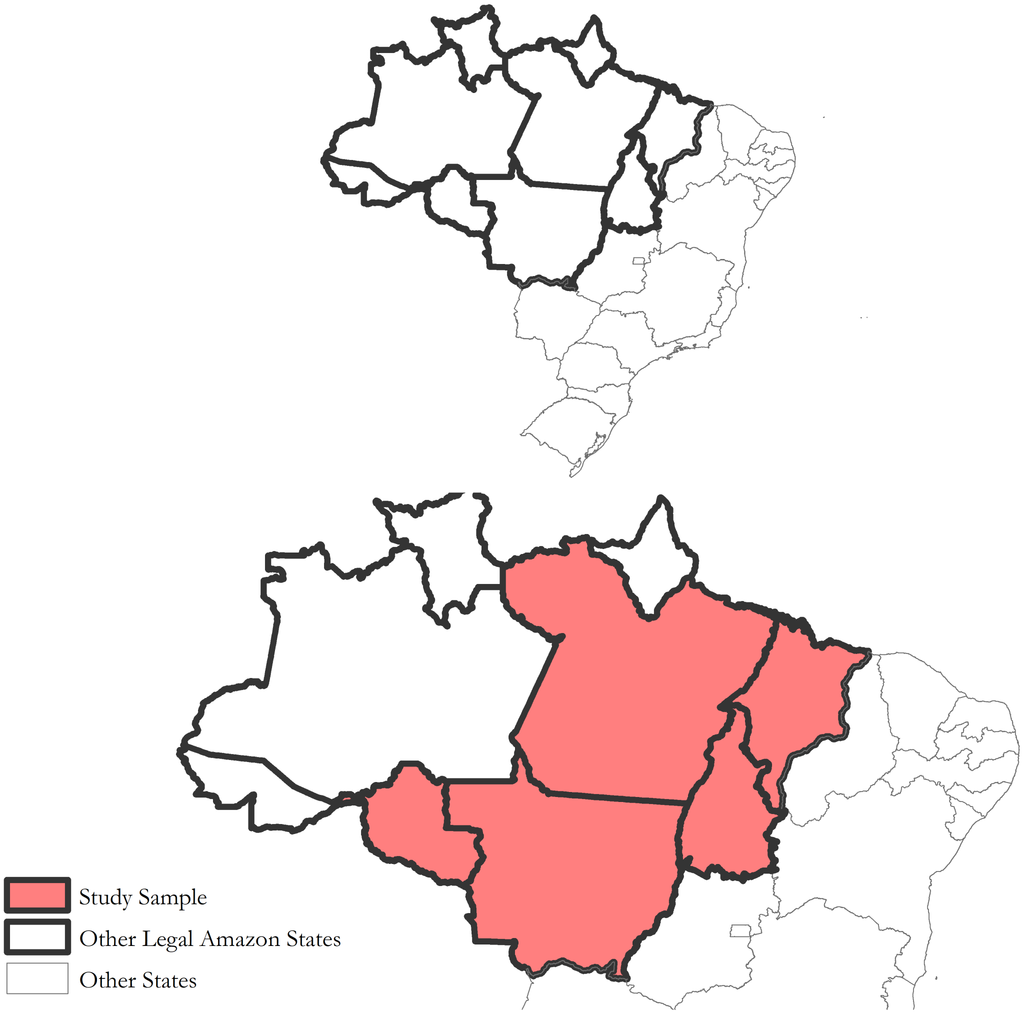


Figure 1: Sample of Study and the Legal Amazon

1) Carbon emissions in the Amazon's cattle sector come primarily from the deforestation frontier:

The cattle sector in the Brazilian Amazon is responsible for 1.7% of global greenhouse gas emissions (2017). This one sector in a single region within a country creates emissions in the same order of magnitude as global industries - such as aviation (2.1%) and cement (4%).

Deforestation is the primary driver of emissions in the sector, roughly 90% of the total in a given year[2]. As figure 2 illustrates[3], clearing for pasture releases large amounts of carbon that were once stocked in old-growth forest. In addition, forest sequesters carbon every year through its natural processes - deforestation creates the loss of these negative flows of carbon. Whereas there are high rates of deforestation between 2015 and 2019, I also observe reforestation (Table 1). This occurs when a rancher abandons a land plot, either because of pasture degradation or because they faced eviction through a property rights dispute or environmental enforcement. The land regrows into secondary forest, which slowly replenishes carbon stocks over many years.

Those aggregate figures conceal important spatial heterogeneity. Deforestation rates vary across space and are clustered on the agricultural frontier. Closer to major markets, agricultural land is more consolidated. Figure 3 illustrates this spatially and by plotting deforestation rates against remoteness, which here I define as distance from São Paulo, Brazil's largest city. Currently, roughly 20% of land in the Amazon is agricultural. Deforestation is a long process, and the frontier is likely to expand slowly over many decades or centuries.

Not only are deforestation rates higher on the frontier, but also those regions emit more per hectare (or acre) deforested. Figure 4 illustrates this. This variation is due to natural factors - carbon stocks are higher further north in the Amazon - and because of the history of agricultural expansion. Deforestation along the frontier is more likely to affect previously untouched old-growth forest.

To further sharpen the differences in environmental impact, yields also vary greatly across space. Frontier regions are naturally less suitable for any agriculture. As rich as the forests may look, Amazon soils are poor in nutrients. This, compounded by less efficient cattle-rearing practices, results in lower cattle output per hectare in frontier regions.

Frontier regions, to summarize, emit more carbon to produce less cattle. Figure 6 joins all the different sources of emissions to map the carbon emissions intensity of cattle production; that is, the amount of carbon embedded in producing one head of cattle in a given region over the 2015-19 time period. The three aforementioned factors contribute to much higher per-head emissions in the frontier. Regions in the top decile of emissions intensity emit on

[2]The remainder consists primarily of enteric fermentation from the animals and soil management. The data Appendix discusses those in more detail.

[3]These are example numbers, actual carbon rates vary spatially.

average 251.52 tCO2e per head, whereas the bottom decile emits 9.52. In addition to carbon emissions, the expansion of agriculture along the frontier poses other risks, such as a decline in biodiversity and conflicts with indigenous populations and other traditional communities. In the data appendix, I show that what is now the commodity frontier has hosted subsistence communities for generations. Deforestation for cattle threatens the resources that those communities rely on.

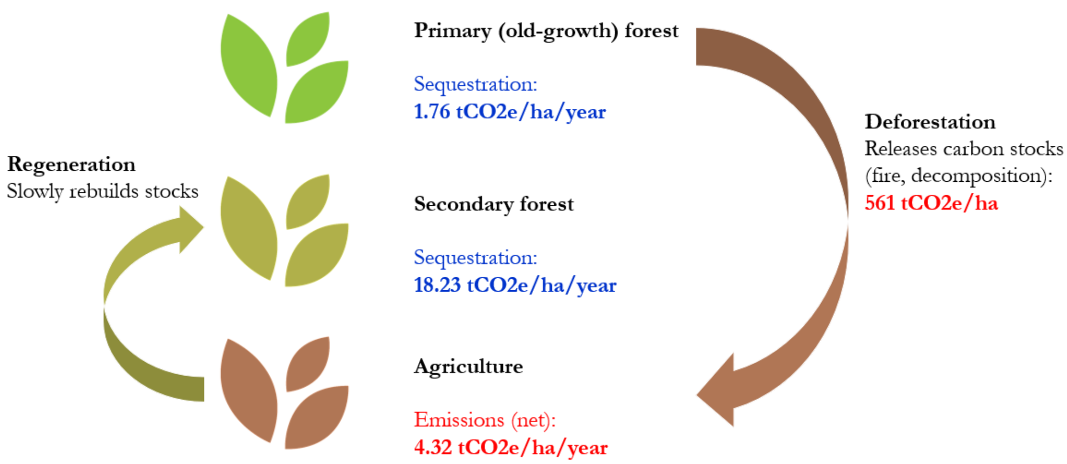
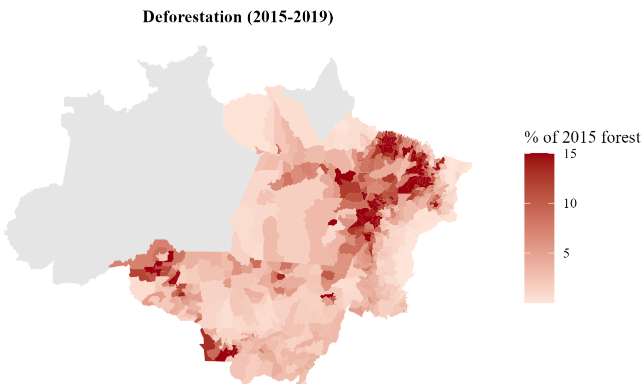


Figure 2: Illustrating land use emissions

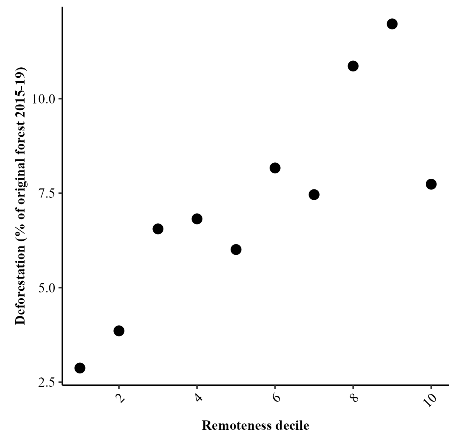
Row: 2015, Column: 2019

	Forest	Pasture	Crops
Forest	.962	**.035**	.003
Pasture	**.03**	.943	.027
Crops	.006	.019	.975

Table 1: Land Use Transitions 2015-2019

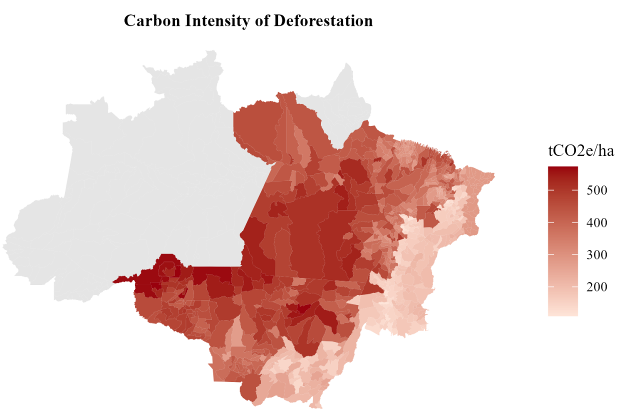


(a) Deforestation 2015-2019 (% of 2015 forest)

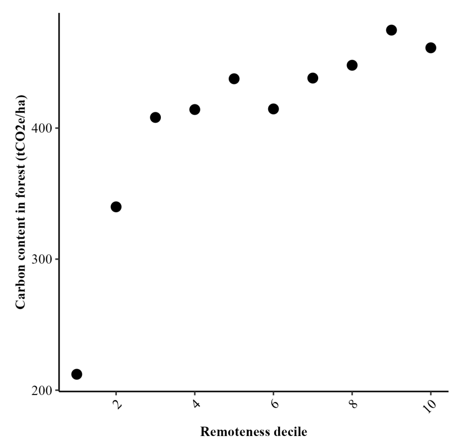


(b) Deforestation by deciles of distance to São Paulo

Figure 3: Deforestation is higher in more remote regions

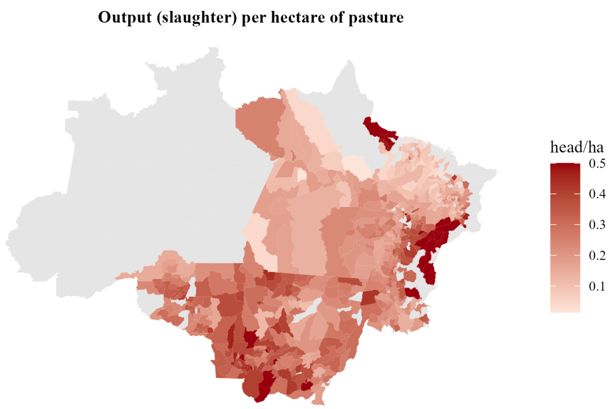


(a) Carbon content of forest lost (tCO2e/ha)

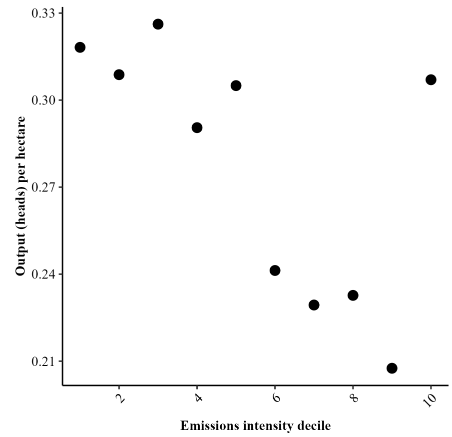


(b) Forest carbon by deciles of distance to São Paulo

Figure 4: Deforestation emits more in more remote regions



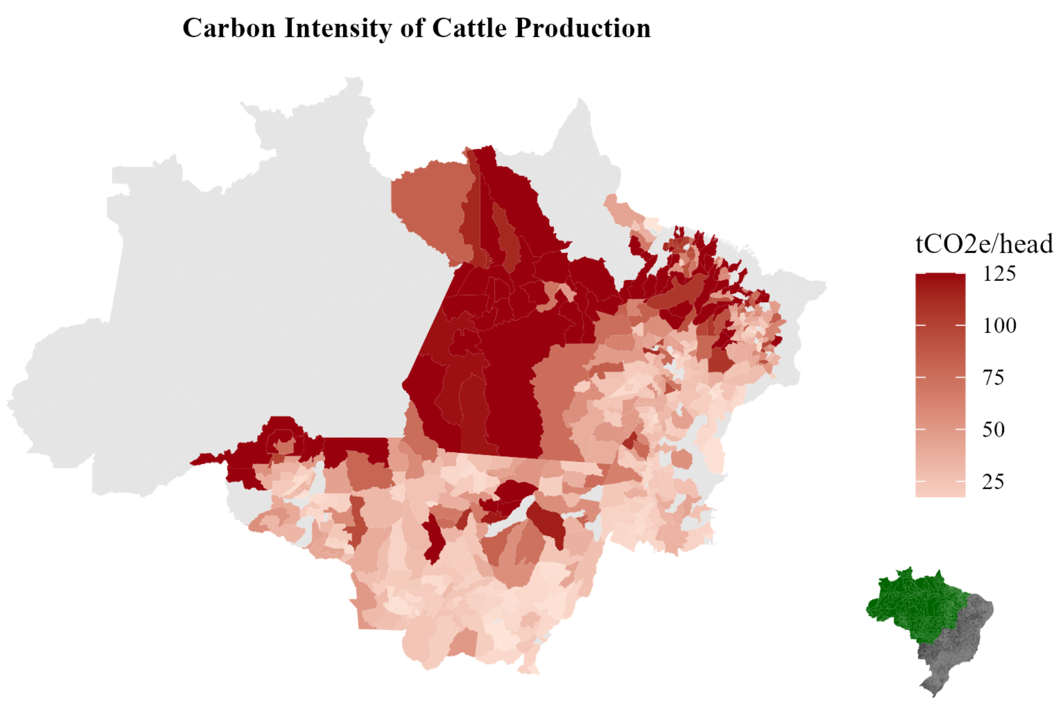
(a) Output (heads) per hectare/year



(b) Output per hectare/year by deciles of distance to São Paulo

Figure 5: Lower output per hectare in more remote regions

Figure 6: The carbon emissions intensity of cattle production (tCO2e/head)



Note: Values go above 125 but are capped to aid visualization.

2) Slaughterhouse monopsony power distorts cattle production, but frontier regions are the most competitive:

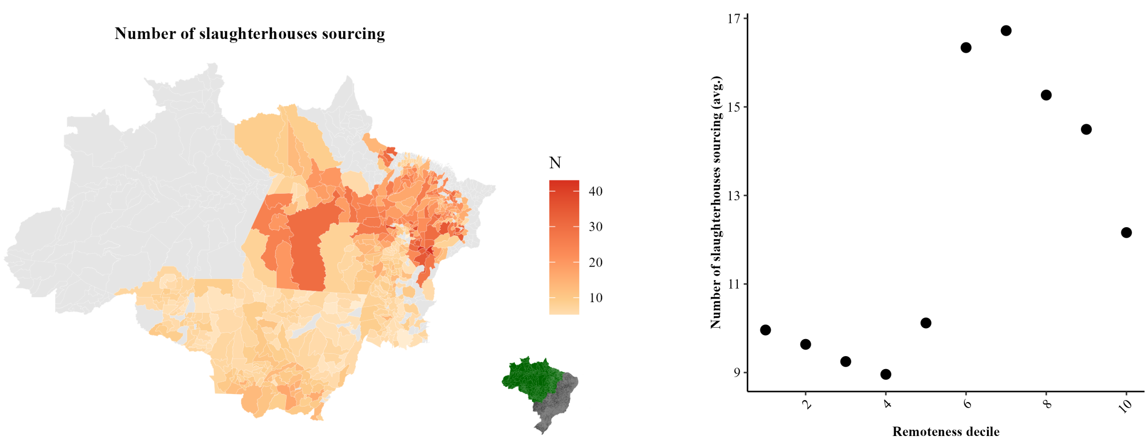
The cattle supply chain, like many agricultural supply chains in developing countries, relies on intermediaries to process output and ship it to consumer markets. In this setting, cattle ranchers sell their output to nearby slaughterhouses, which process the animals into beef products and sell them in Brazil and abroad. 80% of beef output in Brazil is consumed domestically.

Slaughterhouses vary greatly in size. There are many very small players, and a few large operations that concentrate a large share of cattle sourcing. My data for the Amazon show 3817 different points of slaughter, but the largest 3% of them control 85% of the market. Due to phytosanitary restrictions, in order to export slaughterhouses must apply for destination-specific permits. As a result, only the largest firms sell to the export market.

Because of the costs and risks involved in transporting cattle, rancher-to-slaughterhouse transactions occur over short distances. 75% of cattle sourcing takes place within 250 kilometers of the destination slaughterhouse. High transportation costs result in market concentration at the slaughterhouse step of the supply chain. Ranchers have few options of buyers, and as a result are prone to strategic behavior from those intermediaries. Slaughterhouse concentration varies across space according to regional market access and the scale of slaughter operations. The average municipality sells to 12 slaughterhouses, with an average Herfindahl-Hirschman index (HHI) of 0.3. For reference, a market with 3 players with equal shares would have an HHI of 0.33. In the empirical appendix, I show more direct evidence of market power through the incomplete pass-through of demand shocks, and also that market concentration is associated with lower prices paid to ranchers.

The geographic nature of cattle sourcing creates spatial variation in market concentration. Regions in the frontier are the most competitive while ranchers closer to major consumer markets sell to a few very large slaughterhouses. Figure 7 shows essentially a division into two types of regions (municipalities): a core that is characterized by slaughterhouse market concentration, and a frontier that sells to many small buyers.

The fringe of ranching sorts with a fringe of competitive buyers, and the most efficient ranchers sort with the largest, most productive slaughterhouses. This is driven, in part, by geography: large slaughterhouses tend to be located in large urban settlements where they can source labor. Cattle ranching is not labor-intensive but cattle slaughter is. In addition, large slaughterhouses demand certain types of animals that are more easily supplied by the core. For example, major importers like China buy meat of animals slaughtered younger, because those carry a lower risk of food-borne diseases. Frontier regions are less likely to employ the intensive practices required to shorten an animal's lifecycle. Poor pasture quality affects animal health and slows down development in what is known as the "accordion effect" (Skidmore, 2023). Investments in more intensive practices also require credit access, which is more difficult to achieve without having a proper land title that can serve as collateral.



(a) Number of slaughterhouses sourcing in a municipality

(b) Number of slaughterhouses by decile of distance to São Paulo

Figure 7: Remote regions are more competitive

A corollary of the two stylized facts is that there is a spatial correlation between the key hotspots for emissions and the places where cattle sourcing is the most competitive. While market power affects core regions and reduces their output, the effect on emissions is muted because those markets have lower emissions. In addition, some of these output reductions in the core may be offset by more production in the frontier through equilibrium spillovers. Quantifying these different forces across space requires a model that describes the decisions of ranchers and slaughterhouses in equilibrium. The next section develops this model.

3 Structural Model

The stylized facts above motivate a quantitative spatial model of the beef supply chain. At its core lies the relationship between geography and market concentration. As slaughterhouses decide how much to source from each region, they internalize rancher supply curves and choose quantities strategically to maximize profits. In equilibrium, this results in markdowns on cattle prices. More concentrated regions face higher markdowns and lower prices. Landowners are atomistic and make land use change decisions based on local commodity prices. The model also includes a beef demand side - slaughterhouses take beef prices as given and sell their output to markets in Brazil and abroad.

This model focuses on the evolution of the Amazon pasture frontier over the 2015-19 time period. By focusing on this "medium-run", I provide a tractable framework to quantify how market power distorts production incentives differently across space. The model also has a clear interpretation of counterfactual scenarios - given a policy change, it predicts production, market power and emissions levels across regions for the 2015-19 period. This "medium-run perspective" has limitations, some of which will be addressed in the appendix. On the slaughterhouse side, for example, I take the identity and locations of slaughterhouses as exogenous. This is largely due to a data limitation - I only have cattle records for 3 years. That said, I model both the extensive (which municipalities they source from) and intensive (how much they source) margins of sourcing, which allows me to explain the observed market concentration in different regions. Similarly, the land use model focuses on explaining observed land transitions for 2015-19 only. There are three possible uses to land: forest, pasture, and crops. With this framework, I estimate the spatial variation in agricultural supply elasticities, which is an input in quantifying the monopsony markdowns faced by ranchers. These medium-run dynamics are not meant to explain the long-term depletion of resources in the Amazon, but the model appendix provides a framework and estimation for more long-run dynamics. While I model crops as a land use option, the rest of the model remains simple for those. Crops comprise only 5% of agricultural area in the Amazon, so to keep things tractable I rely on an assumption of a perfectly competitive intermediary and perfectly elastic demand.

3.1 Slaughterhouse Problem

Landowners that choose to use their land for pasture grow cattle and sell to slaughterhouses[4]. Slaughterhouses internalize rancher supply curves and choose quantities strategically to maximize profits. This results in markdowns on cattle prices which depend on rancher supply elasticities and the intermediary market structure in each municipality m.

I model this as competition in quantities (Cournot) within each municipality m. Each slaughterhouse is located in one municipality, but they can source from surrounding regions subject to transportation costs. The two key fundamentals of this part of the model are z_i, a slaughterhouse-specific productivity term, and "iceberg" transportation costs τ_{im} for moving cattle from municipality m to where slaughterhouse i is located. This cost term shifts a slaughterhouse's efficiency in different municipalities and microfounds variation in market shares (and market structure) vary across space.

Formally, slaughterhouses maximize profits, which are separable in each sourcing origin:

$$\pi_i = \sum_m \pi_{im} = \sum_m \left(P z_i \tau_{im}^{-1} - c_m(Q_m) \right) * q_{im}$$

where P denotes the price of Brazilian beef. Slaughterhouses are price takers in the downstream market for Brazilian beef. $c_m(Q_m)$ denotes the price of cattle paid to ranchers in municipality m, and Q_m denotes the total amount of cattle sourced from m. Slaughterhouse sourcing decisions thus depend on rancher inverse supply. I model rancher supply in the next part of the model, which deals with land use.

The extensive margin of sourcing: The timing of the model is such that first slaughterhouses decide *where* they are sourcing, and then they decide *how much* they source from each location. In the first stage, slaughterhouses decide on their extensive margin, that is, they choose which markets m to source from.

Because of high transportation costs, not every slaughterhouse sources from every market. Indeed, a slaughterhouse makes negative profits if the cattle price in equilibrium (c_m) is greater than its unit earnings ($P z_i \tau_{im}^{-1}$). In equilibrium, all slaughterhouses sourcing in a

[4]Henceforth the model deals only with the beef cattle sector, so j = pasture is implied.

market m make positive profits; and if others were to add m to their sourcing mix, they would make negative profits. Formally, let I_m denote the set of slaughterhouses sourcing in m:

$$\begin{aligned} \pi_{im}(c_m(I_m)) &\geq 0 \qquad \forall i \in I_m \\ \pi_{i'm}(c_m(I_m \cup \{i'\})) &< 0 \qquad \forall i' \notin I_m \end{aligned}$$

Quantity setting: In the second stage, slaughterhouses simultaneously choose quantities in each market q_{im} in their sourcing footprint a la Cournot to maximize:

$$\max_{q_{im}} \{ \left(P z_i \tau_{im}^{-1} - c_m(Q_m) \right) * q_{im} \}$$

Solving the model: Beginning with the second stage - taking first-order conditions and solving for the equilibrium cattle price $c_m(Q_m)$:

$$c_m(Q_m) = P z_i \tau_{im}^{-1} \left(\underbrace{\frac{\partial c_m}{\partial Q_m} \frac{Q_m}{c_m} s_{im} + 1}_{\mu_{im}} \right)^{-1} \tag{1}$$

where $s_{im} = \frac{q_{im}}{Q_m}$ is slaughterhouse i's market share in m. In words, the equilibrium price of cattle in m is a markdown μ_{im} over the slaughterhouse marginal revenue product. Markdowns are increasing (price decreasing) in the inverse elasticity of municipal cattle supply, which depends on rancher land decisions.

Moving back to the extensive margin decisions, I make an assumption of sequential moves to ensure a unique equilibrium. The player with the highest transportation-adjusted productivity $P z_i \tau_{im}^{-1}$ for a given location m moves first and decides whether to source from that location, then the second-highest $P z_i \tau_{im}^{-1}$, and so on. Formally, the order is given by vector $E_m = (e_{tm}, ..., e_{Tm})$, where:

$$P z_{e_{tm}} \tau_{e_{tm}}^{-1} \geq P z_{e_{t'm}} \tau_{e_{t'm},m}^{-1} \quad \forall t \leq t'$$

This sequential assumption is common in the literature that examines entry decisions under different firm types (Reiss, 1996; Mazzeo, 2002; Toivanen and Waterson, 2005). In my application, it ensures a unique equilibrium for the extensive margin; that is, which slaughterhouses i are sourcing in a given market m. The highest $Pz_i\tau_{im}^{-1}$ moves first (e_{1m}) and considers whether it would make positive profits in m as a monopsonist[5]. If so, it adds to m to its set of origins. The second highest $Pz_i\tau_{im}^{-1}$ player e_{2m} moves next and considers whether it would make positive profits in a duopsony ($I_m = \{e_{1m}, e_{2m}\}$), and so on. In general, t adds market m to its set of sources if it can be profitable alongside all players which moved before it:

$$\pi_{im}(Pz_i\tau_{im}^{-1}, c_m(I_m = \{i' : Pz_{i'}\tau_{i'm}^{-1} \geq Pz_i\tau_{im}^{-1}\})) \geq 0$$

This continues until there is a cutoff player which would make negative profits from adding that location. At this point, the game is solved because all subsequent players would also make negative profits.

The theory appendix provides further detail and discusses a version of the model with fixed costs of sourcing.

3.2 Landowner Problem

I model landowner from a "medium-term" perspective: landowners observe prices and make land use change decisions for a given time period. In the empirics, I focus on the 2015-2019 time frame. There are three possible uses to the land: forest, pasture, and crops.

Each municipality m consists of a set of atomistic landowners f, which begin the period in a land state $j_{t-1} \in \{\text{Pasture, Crops, Forest}\}$. They then choose a land use j for the period, which can be different from j_{t-1}, to maximize:

$$\pi_{fm}(j, j_{t-1}, \nu_{fj}) = \alpha_0(j, j_{t-1}) + \alpha_R R_{jm} + \xi_{jj_{t-1}m} + \nu_{fjm} \tag{2}$$

where R_j is an observable measure of returns for land use j, $\xi_{jj_{t-1}m}$ is a market-level un-

[5] In the absence of fixed costs the top $Pz_i\tau_{im}^{-1}$ always makes positive profits.

observable return, ν_{fjm} an idiosyncratic preference shifter. State-dependence comes from $\alpha_0(j, j_{t-1})$, which depends on j_{t-1} and can capture, for example, the costs of transitioning from forest to pasture.

Agriculture returns are a function of output prices c_{jm} (for cattle or crops) and observable yields a_{jm}

$$R_{jm} = \begin{cases} 0 & \text{if } j = \text{ forest} \\ a_{jm}\, c_{jm} & \text{otherwise} \end{cases} \tag{3}$$

since I do not observe prices for goods resulting from forest activities, I set those to 0.

I assume that idiosyncratic shock ν_{fj} follows a Type-1 (Gumbel) extreme value distribution, which yields a closed-form solution for conditional choice probabilities:

$$\rho_m(j, j_{t-1}) = \frac{\exp\left(\alpha_0(j, j_{t-1}) + \alpha_R R_{jm} + \xi_{jj_{t-1}m}\right)}{\sum_{j' \in J} \exp\left(\alpha_0(j', j_{t-1}) + \alpha_R R_{j'm} + \xi_{j'j_{t-1}m}\right)} \tag{4}$$

Another useful property of this model is the elasticity of supply with respect to prices:

$$\frac{\partial Q_{jm}}{\partial p_{jm}} \frac{p_{jm}}{Q_{jm}} = \alpha_R \sum_{j_{t-1}} \rho_m(j, j_{t-1})\, \rho_{j_{t-1}m}(1 - \rho_m(j, j_{t-1})) \frac{c_m}{\rho_{jm}} \tag{5}$$

where $\rho_{j_{t-1}m}$ denotes the land share of use j in the beginning of the period, and ρ_{jm} at the end. This expression will be useful in estimating the parameters related to slaughterhouse sourcing behavior.

3.3 Demand for Beef:

Consumers in Brazil and abroad make quantity choices of beef purchased according to beef prices in each origin country. Consider a world economy comprised of countries $d \in \mathcal{D}$. In each country, a representative agent has quasilinear preferences across beef products and a freely-traded outside good:

$$U_d = C_d^0 + \beta_d \ln C_d$$

The beef consumption aggregate depends on beef consumption from each origin country o.

$$C_d = \left[\sum_{o \in \mathcal{O}} \left(\beta_{od}\right)^{1/\sigma} \left(C_{od}\right)^{(\sigma-1)/\sigma} \right]^{\sigma/(\sigma-1)}$$

In equilibrium, utility maximization delivers d's demand for beef from origin o:

$$C_{od} = \beta_d \frac{\beta_{od} \left(P_o T_{od}\right)^{1-\sigma}}{\sum_{o' \in \mathcal{D}} \beta_{o'd} \left(P_{o'} T_{o'd}\right)^{1-\sigma}} \tag{6}$$

where T_{od} is the (iceberg) trade cost of delivering beef from origin o to d.

Crop sector is perfectly competitive and demand is perfectly elastic: Crops (e.g. soy) comprise less than 5% of land cover in my study region[6]. While I do model crops as a choice option in the land use part of the model, I simplify the sourcing and demand side for crops. For crop land uses, I assume there is a single perfectly competitive intermediary which pays $\bar{c}_m^{\text{crop}} = P^{\text{crop}}(\frac{z_m^{\text{crop}}}{\tau_m^{\text{crop}}}))$. That is, it pays an international price for crops net of transportation costs. Any regional differences in crop prices are due to differences in transportation costs only. Assuming perfectly elastic demand (constant P^{crop}) is equivalent to assuming the Amazon is a "small open economy" with respect to crop production. This is consistent with the fact that crop production takes a small share of land and is generally oriented for export.

Market Clearing: Aggregate beef supply in Brazil totals demand for Brazilian beef. Since there are iceberg costs in sourcing and trade, market clearing requires:

$$\sum_{i,m} s_{im} Q_m z_i \tau_{im}^{-1} = \sum_d C_d^{BRA} T_{od} \tag{7}$$

where C_d^{BRA} denotes demand for Brazilian beef from country d.

[6] And even less considering the Amazon as a whole

Equilibrium Given a set of land use parameters $\{\alpha\}$, slaughterhouse productivities and iceberg costs, and beef demand parameter σ, an equilibrium is a vector of municipal cattle prices $\{c_m\}_m$ and origin-country beef prices $\{P_o\}_o$ consistent with equations (1),(4),(6) and (7).

4 Data

In addition to the cattle movement records, I use a variety of other data sources, the most important of which are summarized here. The data appendix provides supplemental information.

Land Use: I draw land use data from Mapbiomas[7]. It is the result of a collaboration between different researchers to classify land uses in Brazil using Landsat imagery between 1985-2019. The resulting data comprise a set of raster layers at a 30x30m resolution. Each pixel reports land use categories, such as native forest, pasture, crops, and many others. The Mapbiomas platform also offers a set of rasters documenting transitions between land use states for each pixel[8]. I use the transition rasters between 2015-2019 to create municipal land transition matrices for private land plots. Land tenure data are drawn from the Imaflora Atlas[9].

Predicted Yields: Farm yields can vary across space, which affects land use decisions. I draw predicted yield data from the FAO-GAEZ[10] dataset. FAO researchers use land suitability, humidity, altitude and solar exposure information to model predicted yields (in tons/hectare) for a variety of crops. This dataset has been widely used in economics (Costinot et al., 2016; Nunn and Qian, 2011). I average potential yields at the municipality level to match the remaining municipality-level data.

[7] https://mapbiomas.org/en?cama_set_language=en

[8] Methodology is described in detail here: https://mapbiomas.org/en/download-dos-atbds?cama_set_language=en

[9] http://atlasagropecuario.imaflora.org/publicacoes

[10] https://iiasa.ac.at/web/home/research/researchPrograms/water/GAEZ_v.4_Data_Portal.html

Agricultural Census: Through the Agricultural census of 2017, I observe average sales prices of cattle at the municipality level, as well as average prices for different crops. To obtain one aggregate "crop price", I weigh yield-adjusted prices by the land shares of each crop.

Trade Flows: I draw international trade flows from the United Nations Food and Agriculture Organization's FAOSTAT dataset.[11] In addition, I draw firm-level data on beef exports from Zu Ermgassen et al. (2020), in addition to production and export data for soy from TRASE [12].

Carbon: Emissions in agriculture come from a variety of sources and vary in intensity across space. To account for this, I rely on SEEG [13], a civil society project in Brazil building an inventory of the country's carbon emissions. It draws from a variety of sources to estimate the emissions intensity of various activities, including deforestation (and how it varies regionally), enteric fermentation, soil correction, fertilizer, among others. All emissions figures in this paper draw from intensity estimates from SEEG's methodological notes - all figures and assumptions are available on their website. Using their methodology for each activity allows me to estimate emissions under counterfactual scenarios, including environmental policies.

5 Estimation

In order to connect theory and data, one needs to estimate parameters governing the spatial patterns of slaughterhouse sourcing, that is, slaughterhouse productivity and the impacts of distance on costs. In addition, in order to derive the ranching supply elasticity, one needs to estimate the parameters governing land use decisions in the model.

Remotely-sensed data from Mapbiomas provides land use transitions $\rho_m(j, j_{t-1})$. Cattle movement records deliver slaughterhouse market shares s_{im} in each source municipality m. Regional prices c_{jm} for both commodities (cattle and crops) come from the 2017 agricultural

[11] http://www.fao.org/faostat/en/#data
[12] https://www.trase.earth/
[13] https://seeg.eco.br/#

census. Potential yields for commodities a_{jm} come from the FAO-GAEZ dataset.

First I estimate land use parameters $\{\alpha\}$ using land transition matrices and prices instrumented with import shocks. Then, drawing on land use elasticities implied by the land model, I estimate parameters for slaughterhouse productivity and transportation costs. Finally, I estimate σ beef export-import data and beef prices instrumented with weather shocks.

Step 1 - Land use parameters:

Taking log odds-ratios between any j-pairs from equation (3), we have the following regression:

$$\log\left(\frac{\rho_m(j, j_{t-1})}{\rho_m(j', j_{t-1})}\right) = \Delta\alpha_{0,j,j',j_{t-1}} + \alpha_R \Delta R_{j,j',m} + \Delta\xi_{j,j',j_{t-1},m} \tag{8}$$

where Δ implies a difference, e.g. $\Delta R_{j,j',m} = R_{jm} - R_{j'm}$. $\Delta\xi_{j,j',j_{t-1},m} = \xi_{j,j_{t-1},m} - \xi_{j',j_{t-1},m}$ is an error term. As is common in logit models, I do not separately identify each $\alpha_0(j, j_{t-1})$, so I work with their relative values.

Identification Regression (9) is essentially a supply curve, which raises endogeneity concerns. That is, unobservable shocks might be correlated with observable returns, so that $E[\Delta\xi_{j,j',j_{t-1},m}|\Delta R_{j,j',m}] \neq 0$. One possible example for such a correlation is a situation in which a region faces a positive and unobserved (to the econometrician) shock to pasture yields. This would induce an increase in pasture area and, as a result of higher supply, might lead to lower cattle prices that clear the supply chain/demand side. In this example, α_R estimates would be biased downward.

To address this issue, I use a demand shifter to serve as an instrument for agricultural prices. I rely on exogenous changes in export demand g_{dt} from partner countries to build two shift-share instrumental variables (SSIV), one for beef and another for soy. This interacts changes in export demand with regional exposure shares to those countries. Using the cattle supply chain as an example, ranchers in different regions are exposed to different slaughterhouses (s_{im}), which in turn export to different countries (s_{id}). Changes in demand in country d affect different regions m differentially. Each shift-share instrument is defined as follows:

$$SSIV_m = \sum_d g_{dt}\, s_{id}\, s_{im}$$

where s_{id} is the share of intermediary i's output which goes to d, s_{im} is i's market share sourcing from m. s_{id} is constructed from customs data, and s_{im} is constructed from data on the production networks of beef and soy.

From the lens of the model, the instruments can be interpreted as shocks to the efficiency z_i of intermediaries. Slaughterhouses, for example, have different exposures to different countries because each facility needs to face inspection from each of the countries it exports to. These country-specific export authorizations vary widely across slaughterhouses, and the model rationalizes changes in demand conditions at destination countries effectively as changes in firm productivity.

The key identifying assumption is that the country-level shocks are as good as randomly assigned. That is, $E\left[g_d \mid \bar{\xi}_d, s_d\right] = \mu$, demand shocks in destination countries have the same expected value (μ) regardless of the average exposure shares they face (s_d) or the average supply shocks in the regions most exposed to it ($\bar{\xi}_d$) (Borusyak et al., 2018). Not all beef is exported, which leads to an "incomplete shares" problem. I address this by controlling for the share of each region's output that goes to exports (separately for soy and beef).

Step 2 - Slaughterhouse parameters:

I estimate slaughterhouse productivities and how they are shifted by local conditions, like distance. To estimate the slaughterhouse-specific element of productivity (z_i), I separate slaughterhouses into groups ranked by size, each corresponding to roughly 10% of sourcing. To estimate iceberg trade costs in sourcing (τ_{im}), I let costs vary flexibly as a function of distance. This can account for non-linearities that arise from procuring trucks for transportation and the risks from transporting animals over long distances. I use a flexible specification that includes the log of distance (and its square) between the slaughterhouse and a municipality m. I also let slopes vary between large and small slaughterhouses, separating the largest 65 plants that carry 75% of sourcing from all others. To account for regional variation in transportation, I let iceberg costs vary by state. I also include municipality shifters which capture local conditions - the share of land in m that is public and the share of large landowners (>500ha) in m.

Estimation algorithm: I take a set of parameters, solve the model (extensive and intensive margins), and evaluate how closely it predicts observed moments. More formally, for a given guess of parameters $\tilde{\Theta}$:

1. Derive the $\log(\varphi_{im}(\tilde{\Theta})) = X'\tilde{\Theta}$ implied by the parameters.
2. Solve the model for each m, finding equilibrium c_m:
    (a) Solve the Cournot game first including only the highest z_i/τ_{im} slaughterhouse within a 400km radius.
    (b) Add the next highest z_i/τ_{im} slaughterhouse to the set. Solve Cournot again. If it is profitable, keep it.
    (c) Repeat 2.b until no slaughterhouse can profitably join a market.
3. Given equilibrium c_m, solve for implied quantities q_{im} and the vector I_{im} denoting the sourcing footprint of each slaughterhouse i. Define model-implied moments (more on this below).
4. Define objective function: $\hat{\Theta} = \arg\min_{\tilde{\Theta}} \left(m - \hat{m}(\tilde{\Theta})\right)' W \left(m - \hat{m}(\tilde{\Theta})\right)$
5. Iterate over guesses $\tilde{\Theta}$ to find the $\hat{\Theta}$ which minimizes the objective function in step (4.)

I use three blocks of moments. First I use slaughterhouse quantities ($\mathrm{E}[\sum_i \ln q_{im}]$) and interactions of quantities with covariates. Those include: dummies for percentiles of the slaughterhouse size distribution, distance between the slaughterhouse and m (and other functions of distance), the distance from m to the nearest federal highway and the average age of cattle sold in m. The second block of moments is similar, but uses the vector of extensive margin decisions (0 or 1, whether it adds m to its footprint) also interacted with covariates. Finally, the third block of moments targets equilibrium cattle prices (p_m) and their interaction with distance to the port of Santos (a major export hub), distance to the nearest federal highway and the age of cattle sold in m.

My preferred estimation procedure includes 56 moments and 29 parameters. I implement it with *nloptr* in R using a Nelder-Mead algorithm.

Step 3 - Demand:

The goal of this section is to estimate σ, which governs the demand elasticity for beef from different country origins. Note again that for crops I assume perfectly-elastic demand. Taking the log of (6) yields the following gravity equation:

$$\ln C_{od} = \ln \beta_d - \ln \sum_{o' \in \mathcal{D}} \beta_{o'd} \left(P_{o'} T_{o'd}\right)^{1-\sigma} + (1-\sigma) \ln P_o T_{od} + \ln \beta_{od}$$

Collecting the first two terms into origin-destination fixed effects leads to the following regression:

$$\ln C_{od} = \alpha_d + \alpha_o + (1-\sigma) \ln P_o T_{od} + \epsilon_{od} \tag{9}$$

For C_{od} I use trade flows in beef products from FAOSTAT. Prices are implied from quantities in dollars over weight. A common concern in demand estimation is simultaneity bias. Changes in demand conditions can influence quantities in ways that confound the estimation of $(1-\sigma)$. I address this using supply shifters, namely rainfall and temperature deviations from the (1960-2000) mean during the pasture growing season in origin countries.

6 Results

Table 2 shows some key coefficients. On the land use side, α_R is the parameter that governs responses to yield-adjusted commodity prices. I run estimation separately for different land tenure categories to account for differences in property rights regimes. The data appendix discusses how I track land tenure at greater detail. To aid interpretation, I also computed the average elasticity of cattle supply implied by the estimates. They hover around 1, which

Table 2: Key estimation coefficients

	Parameter	Estimate	SE	Elasticity	F Stat
Land Use	$\alpha_{R(PublicDesignated)}$	0.62	(0.19)	1.29	10.87
	$\alpha_{R(PublicUndesignated)}$	0.32	(0.11)	0.46	20.55
	$\alpha_{R(PrivateUndisputed)}$	0.39	(0.14)	0.52	13.62
	$\alpha_{R(PrivateDisputed)}$	0.59	(0.16)	0.90	13.49
Slaughterhouses	Log-dist.	0.135	(0.007)	-	-
	Log-dist.^{2}	-0.048	(0.001)	-	-
	Log-dist (small)	-0.436	(0.081)	-	-
	Public land share x Large	-0.336	(0.086)		
Demand	(1-σ)	-2.84	(0.68)	-	4.41

Note: Land use estimation includes state FE and policy covariates. Elasticities are computed by simulating the model with a small increase in cattle prices, then solving for the increase in pasture area. For the slaughterhouse estimates, the first two distance coefficients apply to the 65 largest slaughterhouses, which control 75% of sourcing. "Log-dist (small)" applies to the rest. Standard errors for the slaughterhouse estimates come from 500 bootstrap runs. Other GMM estimates for the slaughterhouse model are included in the appendix.

places them in the middle range compared to previous structural models of deforestation in the Amazon. Static models (e.g. Souza-Rodrigues (2019)) find values well below 1, whereas long-run dynamic models (Araujo et al., 2020) tend to estimate elasticities above 1. From the slaughterhouse side of estimation, the distance coefficients reveal highly convex transportation costs. This is likely due to the stresses caused upon animals during transportation - over large distances, cattle can lose weight and risk injuries. For flexibility, I include separate distance coefficients for the 65 largest slaughterhouses (which control 75% of sourcing) and the many small plants which account for the remainder. Demand estimates imply a σ of 3.84.

Table 3: GMM Coefficient Estimates

	Description	Coefficient	SE
1	Constant	1.552	0.032
2	Group 1	1.114	0.041
3	Group 2	1.189	0.040
4	Group 3	1.020	0.043
5	Group 4	1.170	0.040
6	Group 5	1.142	0.043
7	Group 6	1.064	0.036
8	Group 7	0.927	0.038
9	Group 8	1.088	0.034
10	98th Percentile	2.351	0.267
11	90th-98th Percentile	0.298	0.018
12	50th-90th Percentile	0.227	0.013
13	RO x 98th Percentile and below	0.153	0.164
14	TO x 98th Percentile and below	0.245	0.070
15	MA x 98th Percentile and below	0.039	0.033
16	MT x 98th Percentile and below	-0.150	0.177
17	Log dist. above P98	0.135	0.007
18	Log-dist.^{2} above P98	-0.048	0.001
19	Log dist. P98	-0.436	0.081
20	Public land share x Large	-0.336	0.086
21	Share farms >500ha	0.263	0.070

Note: Top 2% of slaughterhouses divided into 8 groups of roughly equal size. Some coefficients refer to states: “MA” for Maranhão, “MT” for Mato Grosso, “PA” for Pará, “RO” for Rondônia, “TO” for Tocantins.

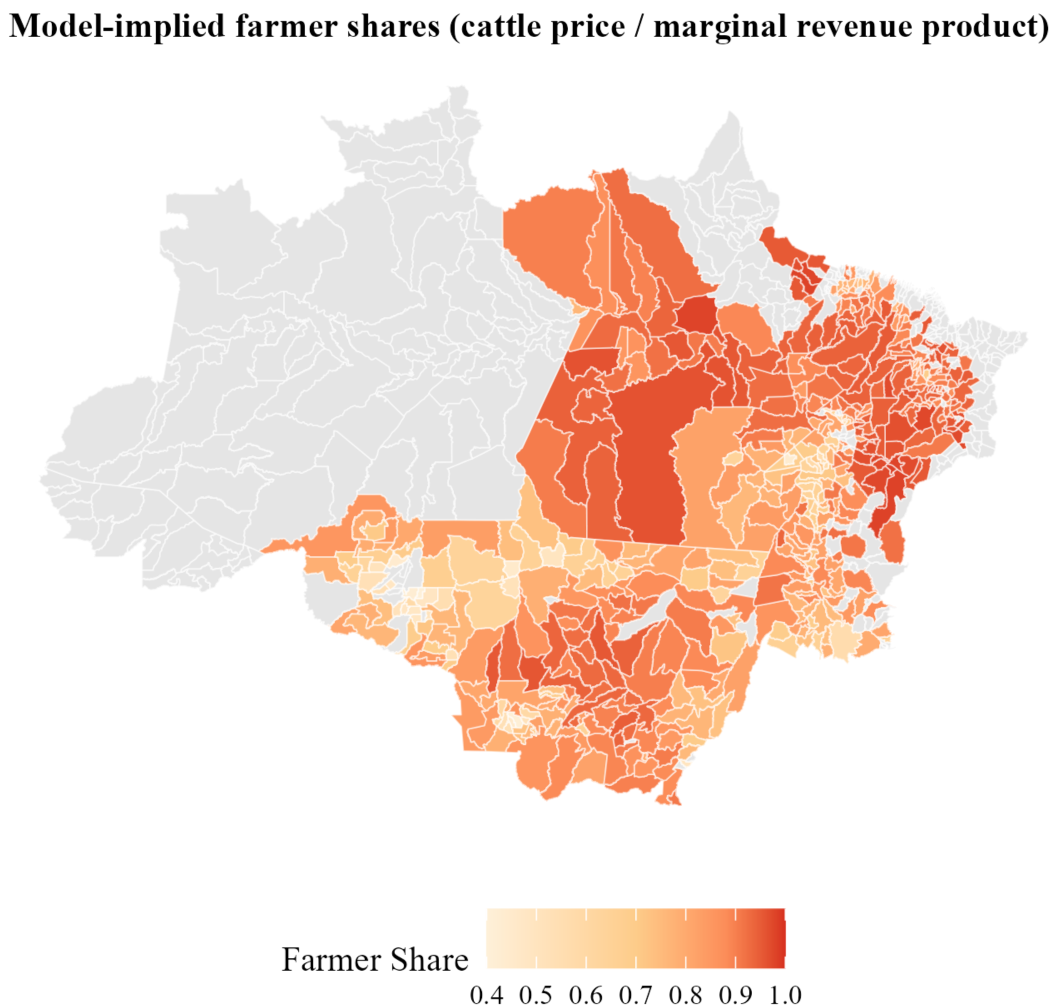
Oligopsony markdowns: The model also allows me to estimate the markdowns faced by cattle ranchers. Figure 8 maps the spatial distribution of rancher shares implied by the model; that is, how much cattle ranchers take home as a fraction of slaughterhouse marginal revenue product. The estimates confirm the patterns seen in the stylized facts. The top decile of emissions intensity has an average rancher share of 93%, whereas for the lowest decile ranchers take home 71%.

The spatial patterns in markdowns are driven by both the market concentration one sees in the data and also the cattle supply elasticities implied by the model. Two types of region tend to have more elastic supply: (i) high-emitting regions, because they have a higher share of public land, which is estimated to be more elastic to prices;[14] (ii) regions suitable for soy

[14]The data appendix discusses property rights in the Amazon and potential causes for this higher elasticity.

agriculture, which serves as an outside option for ranchers. The latter are just above the bottom of the map, in the central part of the state of Mato Grosso.

Figure 8: Rancher shares implied by the model



Model fit: The model fits the targeted moments closely. Spatial patterns of market shares (Figure 10) and the extensive margin (whether a slaughterhouse sources from a municipality). In the aggregate, the cumulative distribution of sourcing against distance follows the data nearly exactly (Figure 9, dotted line shows model prediction). The estimation appendix shows that model fit is robust to different cuts of the data (by state and percentiles of the slaughterhouse size distribution).

Figure 11 plots the actual and predicted Herfindahl index (HHI) at the municipality-level. It is a measure of concentration among slaughterhouses sourcing in a given municipality[15], and I do not explicitly target it in estimation. The large yellow dots show binned averages, which follow the data especially in the values up to 0.4 (almost a duopsony). For the few very highly concentrated markets, the model tends to underpredict HHI. This is likely due to market-specific factors which create frictions that are not explained by geography.

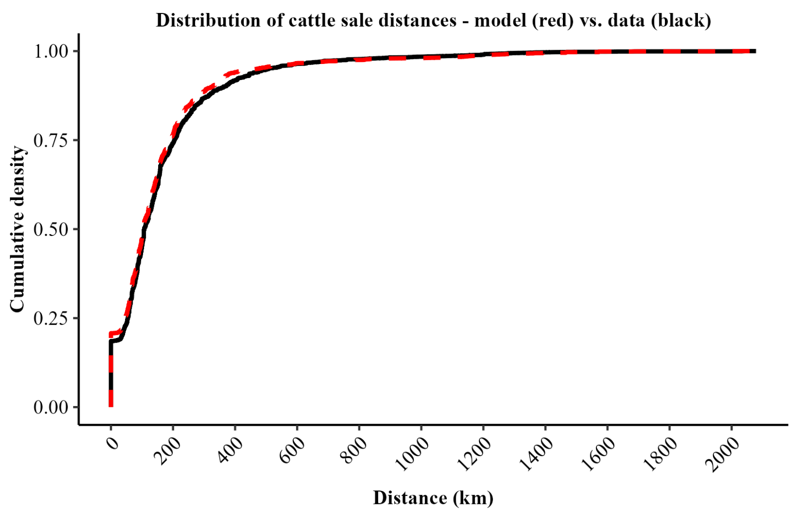
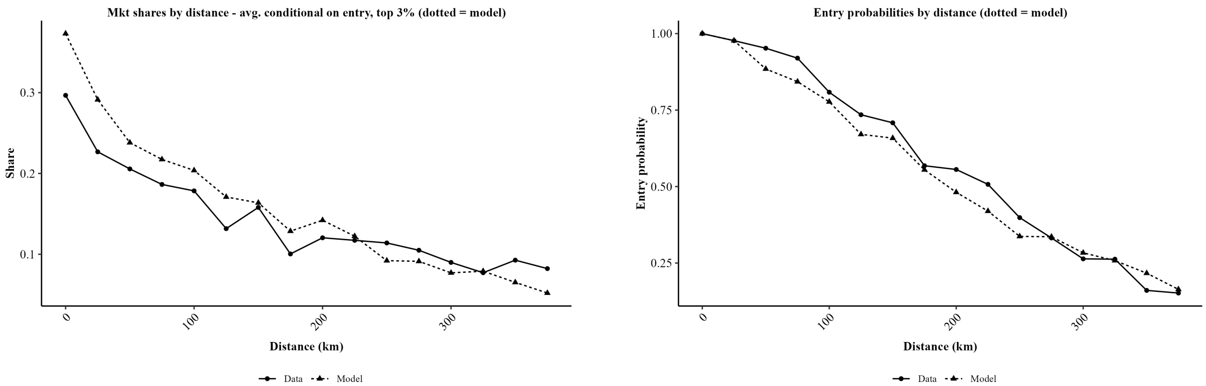


Figure 9: Cumulative cattle sales by distance

[15] $HHI_m = \sum_i s_{im}^2$, a value of 1 implies a complete monopsony.



(a) Market shares against distance

(b) Extensive margin against distance

Figure 10: Model fit - intensive and extensive margins

Note: The left panel shows the average market shares of all slaughterhouses sourcing at a given distance range (in 20km bins). The right panel shows the share of slaughterhouses that source (any quantity above 0) from municipalities in a given distance range.

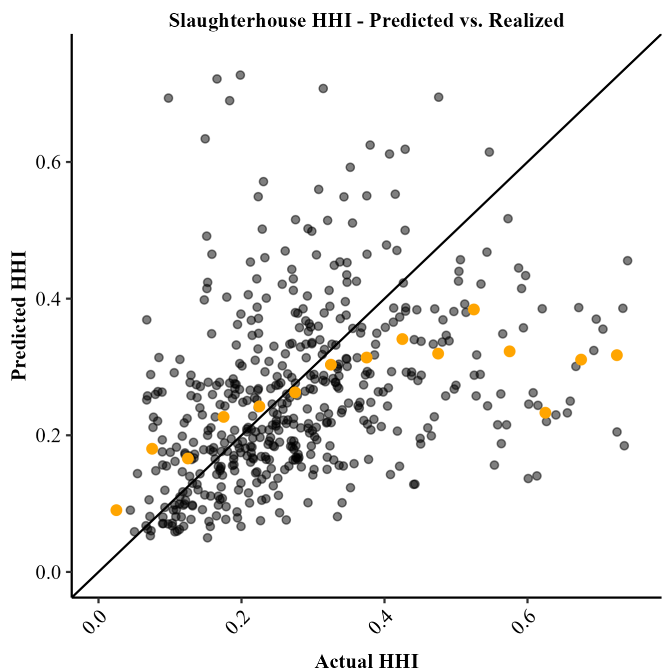
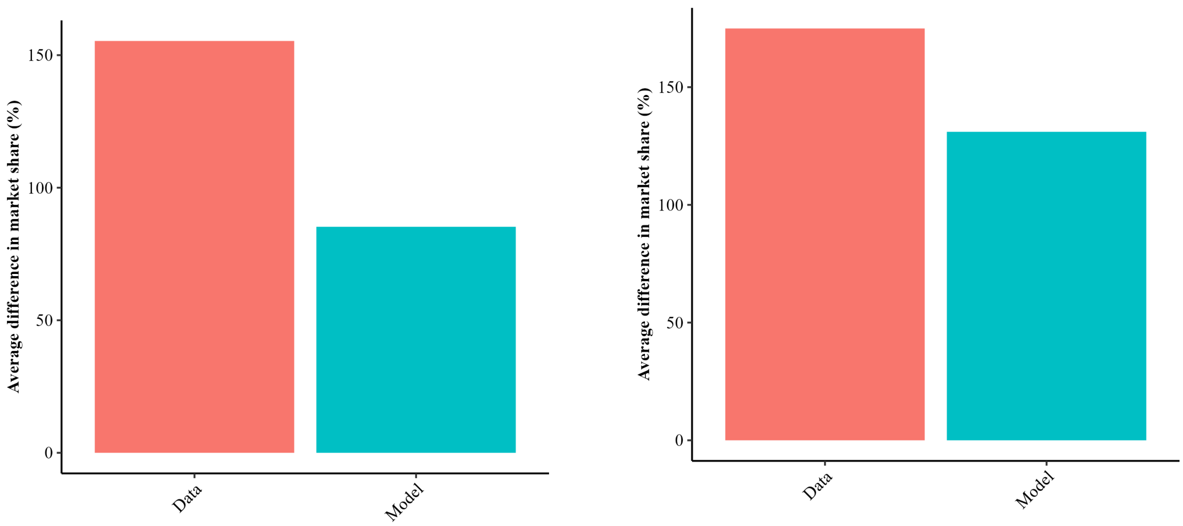


Figure 11: Model fit - HHI (non-targeted)

Note: Black dots show observations of slaughterhouse sourcing HHI at the origin municipality level. Yellow dots take bins of observed HHI and average the HHI predicted by the model for that range.

The most emissions-intensive ranchers tend to sell to small slaughterhouses, even when there are larger buyers nearby. In other words, there are factors beyond transportation costs that drive sorting of the highest emitters with the smallest slaughterhouses. And the model is able to account for these patterns. As figure 12 shows, smaller slaughterhouses tend to have higher market shares in places that emit more (per cattle head), even if I make this comparison only within a certain distance buffer (200km, robust to other definitions). The model predicts this pattern well even though I do not target it in estimation. Instead, it results from sorting of tenure-insecure ranchers with smaller, more informal slaughterhouses. As the right panel of figure 12 shows, smaller slaughterhouses have higher market shares in places with more public land. This highlights again the "frontier economy" nature of emissions in the Amazon. Regions where cattle ranching conflicts with public land (e.g. indigenous reservations) tend to cut down more pristine forests. Because of worse tenure security, they employ less efficient agricultural practices, generate lower output per land area, and their animals do not have the characteristics generally required by large slaughterhouses (young age at slaughter). While I do not explicitly model every aspect of the rancher production function, I can account for how differences in land tenure change slaughterhouse sourcing patterns. This matters for understanding the emissions content of different supply networks.

Figure 12: Small slaughterhouses source from dirtier, tenure-insecure regions



(a) Dirty regions sell to small slaughterhouses

(b) Regions with more public land sell to small slaughterhouses

Note: The left panel divides municipalities according to the average emissions per head in their output, separating the top quintile from the rest. Then, for each small (bottom 97%) slaughterhouse, I calculate its average market share in a radius of 200km (robust to other distances). The bars show the percent differences in average market shares between the "dirtiest" quintile versus all others. Small slaughterhouses source, on average, 150% more in the "dirtiest" quintile. The model predicts this difference to be 100%. The right panel does a similar exercise, but separating the top quintile by share of public land relative to municipal area.

7 Counterfactual Analysis

This counterfactual analysis has two goals. First, I use it to highlight the role of the spatial distribution of markdowns in relation to emissions intensity. Absent spatial inequality in markdowns, emissions would be lower. Second, I use the model to explore policy scenarios. I show that policies that target only the largest slaughterhouses or exporters fail to reach the key sources of emissions and distort markets that face the most market power. Finally, I combine production subsidies and a carbon tax to address both market failures. This scheme shows a path to reduce emissions by a third while keeping production constant.

7.1 The environmental bias of the markdown distribution:

The data show that the cleanest regions are also facing the most market concentration. With the structural model, I show that this is also true for the markdown distribution: monopsony affects high-emitting regions relatively little, while affecting cleaner places much more. Here, I quantify the size of this spatial bias in the markdown distribution with the following policy experiment. Suppose the government took over the slaughterhouse industry and assigned each municipality to a regulated monopsonist. This slaughterhouse would be allowed to extract only a fixed markdown, which would be set by policy to be the same across all regions. In this exercise, I set such a "regulated markdown" to be such that beef output equals the output in the original equilibrium.

Figure 13 shows how emissions would change in this scenario. More competitive places would see emissions go down, which would be partly offset by more production in concentrated areas (in the core). The net effect is a 7.5% reduction in aggregate carbon emissions. That amounts to 54 million tons of CO2-equivalent, just under what the entire US cement sector emitted in 2019 (EPA, 2021).

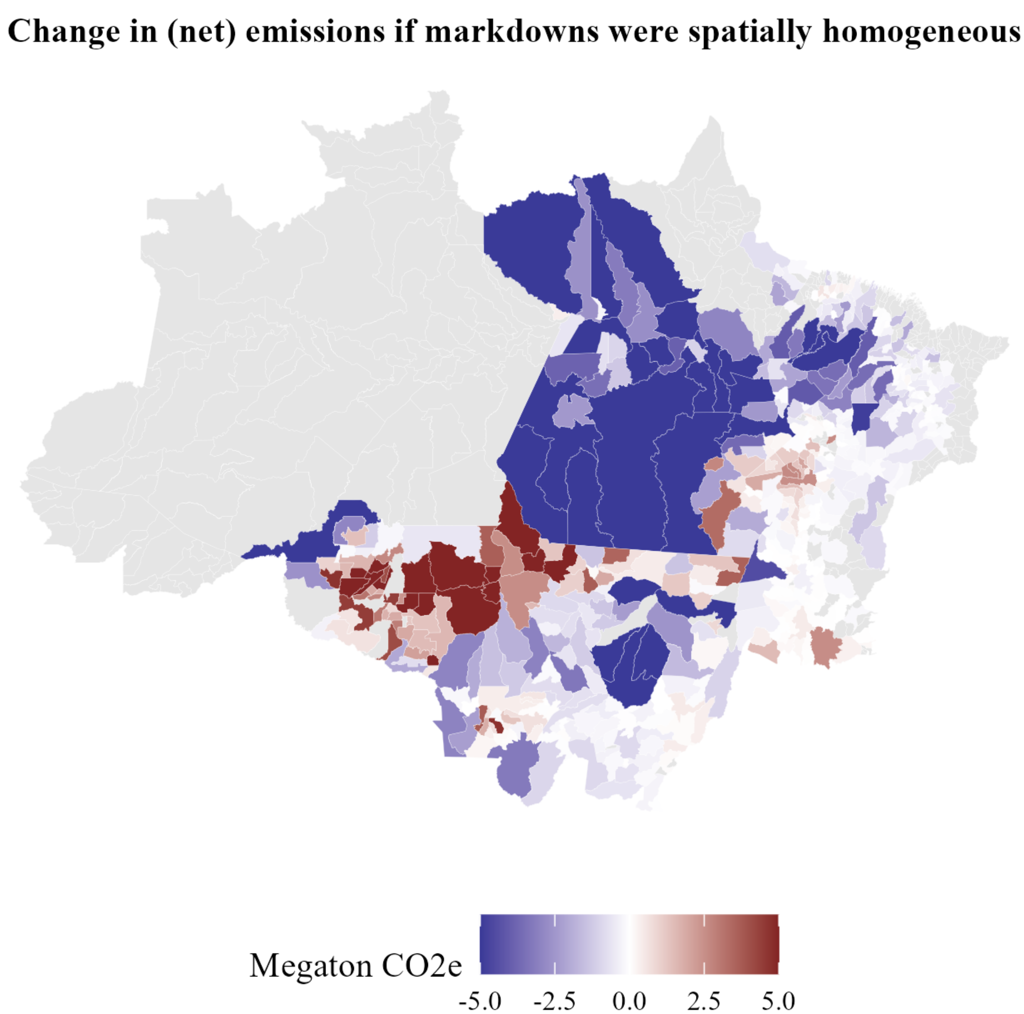


Figure 13: Emissions would be 7.5% lower under homogeneous markdowns

7.2 Policies that target only the largest slaughterhouses are less effective and burden already distorted markets:

Many policy proposals to reduce emissions in the Amazon's cattle supply chain have focused on the largest firms. The sector is concentrated, with the 3% largest slaughterhouses commanding 85% of sourcing. These large meatpackers naturally face more public scrutiny.

Exports also operate only through the largest firms, so pressures from international consumers have mostly targeted large players.

Examples of such policies include the EU's new regulation on deforestation-free products which entered into force in June 2023 (EU, 2023). This regulation seeks to "avoid that the listed products Europeans buy, use and consume contribute to deforestation and forest degradation in the EU and globally". Some civil society efforts have placed pressures on large slaughterhouses to monitor their sourcing for deforestation and other illegal activities. But the programs that have so far been implemented have been shown to have limited effectiveness due to design flaws and loopholes (Alix-Garcia and Gibbs, 2017). Beyond the cattle sector, the "soy moratorium" has been a notable example of deforestation reductions resulting from commitments by large companies (Heilmayr et al., 2020).

Instead of focusing on a particular policy design, for this counterfactual exercise I focus on displaying broadly how targeting the largest companies has limited effectiveness. I do this by implementing a per-head cattle tax levied exclusively on slaughterhouses that have export authorizations. Then I assess the implied economic trade-offs by examining how production falls in response the tax. To reduce emissions by 1%, the tax would need to reduce beef production by also 1%. If the tax were instead administered broadly to all slaughterhouses, it would need to sacrifice only 0.5% of output to achieve the same emissions reduction. If one targeted only regions in the top decile of carbon emissions intensity, a 0.1% reduction in output would be sufficient to reduce emissions by 1%.

These differences are driven primarily by the fact that exporting slaughterhouses are located far from the frontier and are thus not the key sources of emissions. A larger reduction in beef production would be necessary to reduce their emissions. In addition, there are production spillovers across regions. Lower output in the core regions drives an increase in the consumer price of beef, which then incentivizes production in the frontier, partly offsetting the beneficial environmental impacts. Finally, the tax burdens the regions that are already most impacted by market power.

Note that the tax on exporting slaughterhouses includes all their production, not just exports. Previous work has discussed tariffs from importing countries as a mechanism to address deforestation in the tropics (Hsiao, 2020; Dominguez-Iino, 2020). They find that tariffs are not effective unless there is coordination across multiple large countries and long-term commitment to maintaining the policy. In my setting, the cattle sourcing data suggest an even sharper result. Brazil as a whole only exports 20% of its beef, and an even lower fraction originates in the deforestation frontier. Even fully coordinated and committed policies will have modest effects if they do not contemplate domestic sourcing in remote regions.

7.3 Combining pigouvian taxes and production subsidies:

For this exercise, I explore how a carbon tax and production subsidies can come together to remediate the two market failures in this setting. I focus on policies set to keep output at the original level. This has the benefit of emphasizing spatial reallocations - the focus of this study, and also circumvents the discussion of how to value carbon emissions relative to food production, which is beyond the scope of this paper.

Here, I first introduce a production subsidy to bring output in each region to what it would be under perfect competition. Then I introduce a carbon tax levied on the average emissions embedded in the production of a head of cattle in each region. I adjust the tax rate such that beef output is at the same level as in the original equilibrium.

Figure 14 shows the "effective tax" implied by this exercise. There is a reallocation from the highest emitters towards concentrated regions which have relatively clean production. Output is the same as in business-as-usual, but emissions are 34% lower. For comparison, this would be equivalent to reducing US transportation emissions by 13% (EPA, 2022).

The carbon tax that sets the equilibrium output back to its original level is just over 60 cents per tCO2e. This small rate reflects both the extremely high emissions intensity - just over a ton of CO2e per kilogram of embedded emissions - and the extremely low agricultural returns in the frontier[16]. In the top decile of emissions intensity, a rancher earns roughly 2 dollars per kilogram of cattle (CWE) produced. The carbon tax applied to those regions is equivalent to an average of 71 cents per kg, so roughly a 35.5% tax. Supply in the frontier is more elastic, so it adjusts and leads to the stark emissions reductions I find. In addition, because of the subsidy ranching relocates to regions that produce more intensively; despite

[16] Araujo et al. (2020) and Souza-Rodrigues (2019) also find high reductions in emissions even with small carbon taxes in the Amazon.

keeping output constant, this policy induces a reduction of 5% in pasture area.

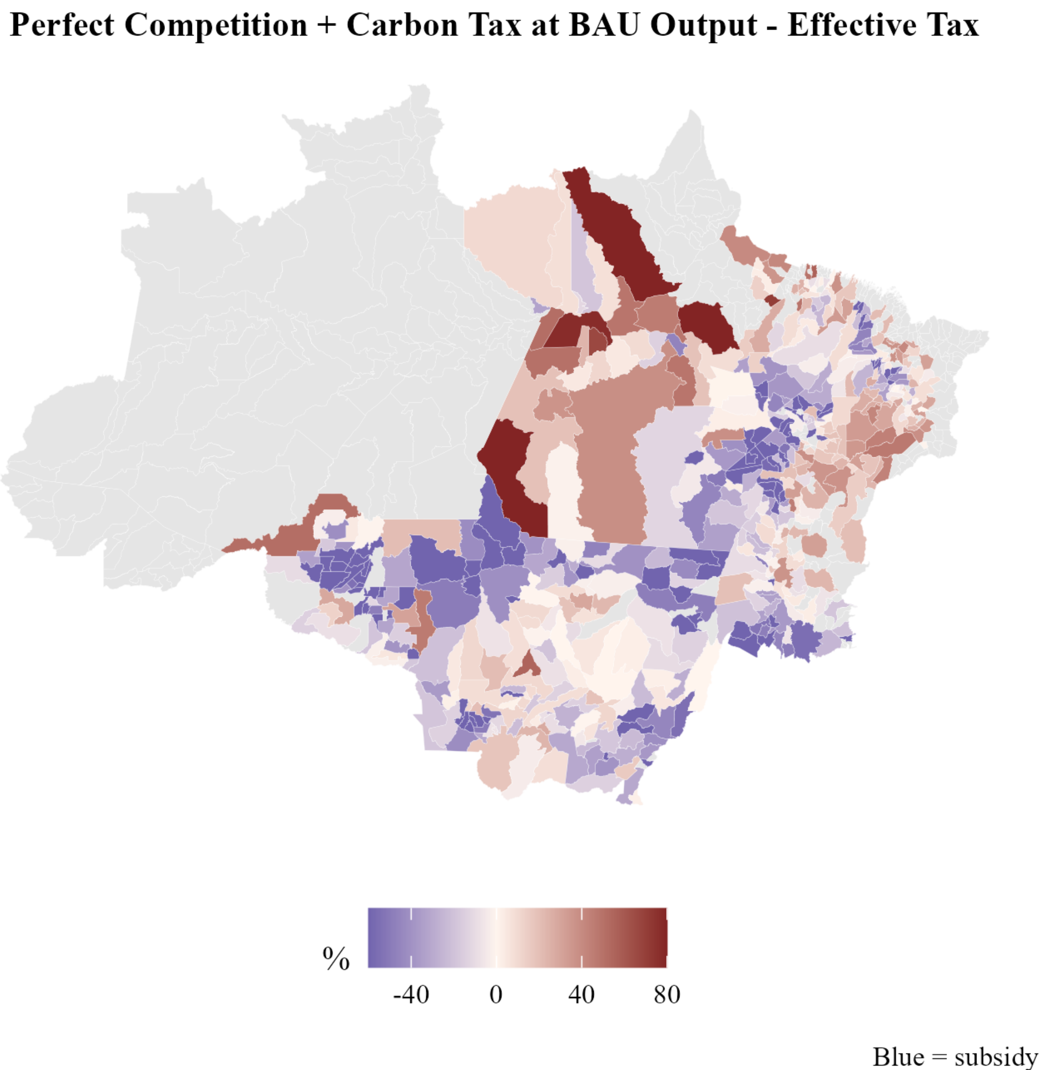


Figure 14: Combining a carbon tax and production subsidy - Effective tax

While this exercise is stylized and meant to show mechanisms in the structural model, it is not unreasonable to imagine a combination of taxes and subsidies in Brazil's cattle supply chain. Brazil's Congress recently approved a new value-added tax, which has yet to be implemented (Brazil, 2023). Under the new law, there are provisions for higher tax rates for environmentally damaging products, but lower rates for agricultural goods. How the sector is affected will ultimately depend on the details around implementation. This work shows that, if properly targeted, policy can shift incentives and reduce emissions without causing major reductions in food output.

8 Conclusion

Emissions from deforestation have global consequences, but their origins are geographically concentrated on agricultural frontiers. Understanding how frontier economies work, and especially how they differ from other regions, is paramount for the design of environmental policy.

In the Brazilian Amazon, frontier cattle ranching is intermediated by many small slaughterhouses, whereas core regions are controlled by few large ones. This has two implications. First, slaughterhouse market power distorts production decisions in the core, but not in the frontier. This diminishes the environmental benefits of market power and re-allocates output to less efficient, higher polluting regions. Second, policies that target the largest firms, such as trade tariffs or sustainability standards, are ineffective at reducing emissions where they are greatest (the frontier) and affect places already distorted by market power.

This work provides insights for environmental policy in the context of deforestation worldwide, and more broadly for imperfectly competitive industries. In deforestation, policy must consider the agents operating in the frontier. Targeting policy at the highest emitting, most competitive regions can reduce emissions without compromising food production. Beyond deforestation, market power can be a source of economic inefficiency, but it may lead to environmental benefits in polluting industries. Or, as Robert Solow put it, "the monopolist is the conservationist's best friend". This paper shows that for environmental impacts and welfare, it matters not only *how much* market power there is, but also *where* market power operates.

More specifically in the context of the Amazon, this work can inform debates around Brazil's recently-approved value added tax, which has provisions for higher rates in environmentally damaging industries, but lower rates for agricultural products. If spatial targeting is possible, lower taxes in cleaner regions could alleviate the deleterious effects of market power (effectively as a production subsidy), and higher taxes in dirty regions could address environmental externalities.

I use price mechanisms in my counterfactual exercises, but some command-and-control policies can have similar effects and may be more politically feasible. For example, increasing funding for federal organizations that enforce the land rights of indigenous people and other traditional communities can serve to both protect these vulnerable populations and also prevent high-emitting deforestation along the frontier. In addition, better animal traceability in the cattle supply chain could prevent deforestation and other illegal activities[17]. The state of Pará is set to pilot in late 2023 a system of animal-level[18] traceability, which could enable policymakers to effectively exclude cattle coming from non-compliant farms (land invasions, illegal deforestation, etc.) from reaching consumer markets. This may act as an important deterrent.

Future research can benefit greatly from new administrative datasets such as the one used in this paper. With more years of cattle movement data, future work can better trace the entry, exit, and growth of slaughterhouses and bring insight into industry dynamics. In addition, the cattle movement data reveal a dense network of vertical relationships between ranchers over the cattle lifecycle. Understanding how these relationships form and are sustained over time can help guide the design of policies aimed at the supply chain.

[17] The cattle sector is also notorious for its cases of modern slavery.

[18] The current system (from which the data I use are created) has herd-level traceability, so individual animals can "mix" across herds.

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Appendix A Model Extensions

A.1 Slaughterhouse sourcing under fixed costs:

The model I present in the main text is amenable to the addition of fixed costs in cattle sourcing. Suppose now that slaughterhouses, in addition to paying variable (iceberg) costs, must also pay a fixed cost f_{im} to include a location in their sourcing strategy.

The intensive margin remains unchanged because fixed costs are independent of quantity. But the equilibrium conditions for the extensive margin now depend on the fixed costs:

$$\pi_{im}(\varphi_{im}, c_m(I_m)) - f_{im} \geq 0 \qquad \forall i \in I_m$$
$$\pi_{i'm}(\varphi_{i'm}, c_m(I_m \cup \{i'\})) - f_{i'm} < 0 \qquad \forall i' \notin I_m$$

A slightly different sequential assumption can deliver tractability for estimation. For any given (φ_{im}, f_{im}) pair, there exists a critical cattle price c^*_{im}, above which the slaughterhouse makes negative profits and does not want to source in that location. Slaughterhouses with the same φ_{im} may differ in their profitability due to different fixed costs. I assume that slaughterhouses make extensive margin decisions in decreasing order of c^*_{im}. If $f_{im} = 0$ for all i, then this ordering is equivalent to the φ_{im} from the main text.

Like the model in the main text, this delivers a unique equilibrium. To solve it, one adds slaughterhouses to m until the prevailing price c_m is greater than the critical c^*_{im} for the next candidate.

A.2 Land use dynamics

Land use change is inherently a dynamic process. Actions such as deforestation carry sunk costs[19] and involve irreversibilities - forest takes decades to regrow once lost. In the paper, I rely on a "medium term" model of land use change - agents consider returns over a span of 5 years. This allows me to capture important aspects of land use emissions while keeping the model simple enough to focus on its supply chain aspects.

[19]Such as using tractors and metal chains to break large trees, burning vegetation, etc.

Here, I present an extension to the main land use model which incorporates dynamics. It is similar to Araujo et al. (2020) and Scott (2012), relying on rational expectations over the path of future returns to derive a discrete analog of an Euler equation which can be used for estimation. It delivers slightly higher pasture acreage elasticities. While it does incorporate some dynamic aspects, it may other important dynamic incentives faced by farmers in the Amazon - such as enforcement actions that vary over time, property rights issues, among others.

A dynamic model of land use change: A set of small fields i clustered in municipalities m make independent land use choices to maximize expected discounted profits. During each period, field owners make two decisions. First they decide on land use, whether it is pasture for cattle, crops or forest. Conditional on choosing pasture, they choose how much cattle to produce in their land.

Farmers choose land use to maximize their payoffs, which depend on the land choice, market conditions ω_t and the current state of the field. For simplicity, field state here depends only of the previous period's state j_{it-1}, such that payoffs are:

$$\pi(j, j_{t-1}, \omega_t, \nu_{it}) = \alpha_0(j, j_{t-1}) + \alpha_R R_j(\omega_t) + \xi_{jj_{t-1}}(\omega_t) + \nu_{jit} \tag{10}$$

where $\xi_{jk}(\omega_t)$ is a market level shock to returns and ν_{jit} is a field-level idiosyncratic shock. $R_j(\omega_t)$ is an observable component of returns.

Dynamic incentives come from term $\alpha_0(j, j_{t-1})$, which depends on field state j_{t-1}. This can rationalize, for example, switching costs between forest and agriculture.

The key assumption which will allow for estimation is one of *small fields*. That is such that a change in land use in one field will not affect market conditions or create externalities for other fields. Formally, I assume the market state evolves according to a Markov process which satisfies $G(\omega_{t+1}|\omega_t, j_{it} = j) = G(\omega_{t+1}|\omega_t)$.

Let β represent a common discount factor. A field owner i's value function is defined as follows:

$$V\left(k_{it},\omega_t,\nu_{it}\right)\equiv\max_{j^*}E\left(\sum_{s\geq t}^{\infty}\beta^{s-t}\pi\left(j^*\left(j_{is-1},\omega_s,\nu_{is}\right),j_{is-1},\omega_s,\nu_{is}\right)\mid k_{it},\omega_t,\nu_{it}\right) \tag{11}$$

I assume that shocks ν_{ijt} are distributed EV1 with variance normalized (WLOG) to $\frac{\pi^2}{6}$. This assumption will deliver closed-form solutions for conditional choice probabilities (CCP). To see that, I first need a few definitions. First the ex ante value function is defined as:

$$\bar{V}_t(j_{t-1})\equiv\int\ldots\int V_t\left(j_{t-1},\left(\nu_1,\ldots,\nu_J\right)\right)dF\left(\nu_1\right)\ldots dF\left(\nu_J\right) \tag{12}$$

which can be interpreted as the expectation of the value function before the realization of the idiosyncratic shocks. And the conditional value function, which represents expected returns *conditional* on an action, is defined as:

$$v_t(j,j_{t-1})\equiv\bar{\pi}_t(j,j_{t-1})+\beta E_t\left[\bar{V}_{t+1}\left(j\right)\right] \tag{13}$$

where $\bar{\pi}_t(j,k)$ represents period payoffs before the realization of idiosyncratic shocks. Using the definitions above, I can define the CCPs based on the EV1 assumption:

$$p_t(j,j_{t-1})=\frac{\exp\left(v_t(j,j_{t-1})\right)}{\sum_{j'\in J}\exp\left(v_t\left(j',j_{t-1}\right)\right)} \tag{14}$$

It also implies a convenient expression for the ex ante value function, which will soon be useful:

$$\bar{V}_t(j_{t-1})\equiv\ln\left(\sum_{j\in J}\exp\left(v_t(j,j_{t-1})\right)\right)+\gamma \tag{15}$$

From this theoretical basis I can derive a linear regression which can be used to estimate model parameters. This consists of deriving a discrete analog of an Euler equation: I set up short-term perturbations while holding long term decisions fixed such that continuation values difference out.

This derivation starts with the Hotz-Miller inversion, a rearrangement of the CCPs which provides information on differences in conditional value functions between two choices:

$$\ln\left(\frac{p_t(j, j_{t-1})}{p_t(j', j_{t-1})}\right) = v_t(j, j_{t-1}) - v_t(j', j_{t-1}). \tag{16}$$

Using the definition from (4), this becomes:

$$\bar{\pi}_t(j, j_{t-1}) - \bar{\pi}_t\left(j', j_{t-1}\right) - \ln\left(\frac{p_t(j, j_{t-1})}{p_t\left(j', j_{t-1}\right)}\right) = \beta E_t\left[\bar{V}_{t+1}\left(\left(j', j_{t-1}\right)\right)\right] - \beta E_t\left[\bar{V}_{t+1}\left(\left(j, j_{t-1}\right)\right)\right] \tag{17}$$

If j represents pasture and j' forest, then $\ln\left(\frac{p_t(j,j_{t-1})}{p_t(j',j_{t-1})}\right)$ can be interpreted as the cutoff value for the difference in idiosyncratic shocks $(\nu_{ijt}-\nu_{ij't})$ above which field i chooses pasture.

Now I replace the expected difference in continuation values with its realization and errors:

$$\begin{aligned}\bar{\pi}_t(j, j_{t-1}) - \bar{\pi}_t\left(j', j_{t-1}\right) - \ln\left(\frac{p_t(j, j_{t-1})}{p_t\left(j', j_{t-1}\right)}\right) &= \beta\left(\bar{V}_{t+1}\left(\left(j', j_{t-1}\right)\right) - \bar{V}_{t+1}\left(\left(j, j_{t-1}\right)\right)\right) \\ &+\varepsilon_t^V\left(j', j_{t-1}\right) - \varepsilon_t^V\left(j, j_{t-1}\right)\end{aligned} \tag{18}$$

where

$$\varepsilon_t^V\left(j, j_{t-1}\right) \equiv \beta\left(E_t\left[\bar{V}_{t+1}\left(\left(j, j_{t-1}\right)\right)\right] - \bar{V}_{t+1}\left(\left(j, j_{t-1}\right)\right)\right)$$

Finally, Lemma 1 in Arcidiacono and Miller (2011) provides a useful relationship between ex-ante $(\bar{V}_{t+1})$ and conditional $(v_t(j,k))$ value functions:

$$\forall j : \bar{V}(j_{t-1}) = v_t(j, j_{t-1}) - \ln\left(p_t(j, j_{t-1})\right) + \gamma \tag{19}$$

Note that this relationship applies for all j: take any given choice, its choice probability and conditional value function will inform the ex-ante value. Since this relationship holds for any choice, substituting the right-hand side above with the same choice allows me to cancel out terms:

$$\begin{aligned}\bar{\pi}_t(j, j_{t-1}) - \bar{\pi}_t\left(j', j_{t-1}\right) - \ln\left(\frac{p_t(j, j_{t-1})}{p_t\left(j', j_{t-1}\right)}\right) =& \beta\left(v_{t+1}\left(j', j\right) - v_{t+1}\left(j, j\right)\right) \\ & - \beta\left(\ln\left(\frac{p_{t+1}\left(j, j'\right)}{p_{t+1}\left(j, j\right)}\right)\right) \\ & + \varepsilon_t^V\left(j', j_{t-1}\right) - \varepsilon_t^V(j, j_{t-1}).\end{aligned} \tag{20}$$

Because the state variable only changes according to the previous period's decision, continuation values cancel out:

$$v_{t+1}\left(j, j'\right) - v_{t+1}\left(j, j\right) = \bar{\pi}_{t+1}\left(j, j'\right) - \bar{\pi}_{t+1}\left(j, j\right) \tag{21}$$

This is an example of *finite dependence*: because returns on a choice depend only on the previous period's state, once i makes the same choice in period $t+1$ the continuation values are the same in $t+2$ regardless of the decisions in t or before. This result also holds when longer lag periods also affect payoffs, as long as there is some "renewal action" after which payoffs don't differ (Scott, 2012). Thus I can cancel out the continuation values, which then imply the Euler equation below:

$$
\begin{aligned}
\bar{\pi}_t(j, j_{t-1}) - \bar{\pi}_t(j', j_{t-1}) - \ln\left(\frac{p_t(j, j_{t-1})}{p_t(j', j_{t-1})}\right) =& \beta\left(\bar{\pi}_{t+1}(j, j') - \bar{\pi}_{t+1}(j, j)\right) \\
& - \beta \ln\left(\frac{p_{t+1}(j, j')}{p_{t+1}(j, j))}\right) \\
& + \varepsilon_t^V(j', j_{t-1}) - \varepsilon_t^V(j, j_{t-1})
\end{aligned}
\tag{22}
$$

The left side of the equation can be interpreted as the minimum difference in period t profits necessary to justify a choice of j at t instead of j'. The right side denotes the loss in continuation values which result from choosing j and not j'. Because of equation (19), I can express that in terms of period $t+1$ profits and choice probabilities. Thus the right hand side of (22) can be interpreted as the (discounted) difference in profits in $t+1$ resulting from an action which compensates for the impact of period t land use plus a term which corrects for the fact that this action is not always optimal.

Using the definition of period profits and using combinations of the 3 land choices as j and j', I can derive the regression equation below:

$$
Y_{tj_{t-1}} = \tilde{\Delta}\alpha_{0j_{t-1}} + \alpha_R \Delta R_t + \tilde{\Delta}\xi_{tj_{t-1}} + \Delta\varepsilon^V_{tj_{t-1}} \tag{23}
$$

where:

$$
\begin{aligned}
Y_{tj_{t-1}} \equiv& \ln\left(\frac{p_t(\mathrm{j}, j_{t-1})}{p_t(j', j_{t-1})}\right) + \beta \ln\left(\frac{p_{t+1}(\mathrm{j}, j)}{p_{t+1}(\mathrm{j}, j'))}\right) \\
\tilde{\Delta}\alpha_{0j_{t-1}} \equiv& \alpha_0(\mathrm{j}, j_{t-1}) - \alpha_0(j', j_{t-1}) \\
& + \beta\left(\alpha_0(\mathrm{j}, j) - \alpha_0(\mathrm{j}, j'))\right) \\
\Delta R_t \equiv& R_{\mathrm{j},t} - R_{j',t} \\
\tilde{\Delta}\xi_{tj_{t-1}} \equiv& \xi_{\mathrm{j},j_{t-1},t} - \xi_{j',j_{t-1},t} + \beta\left(\xi_{\mathrm{j},0,t+1} - \xi_{\mathrm{j},1,t+1}\right) \\
\Delta\varepsilon^V_{tj_{t-1}} \equiv& \varepsilon^V_t(\mathrm{j}, j_{t-1}) - \varepsilon^V_t(j', j_{t-1})
\end{aligned}
$$

I run the following regression at the municipal level:

$$Y_{mtj_{t-1}} = \tilde{\Delta}\alpha_{0j_{t-1}} + \alpha_R R_{mt} + \tilde{\Delta}\xi_{mtj_{t-1}} + \Delta\varepsilon^V_{mtj_{t-1}} \tag{24}$$

where R_{mt} denotes yield-adjusted prices and returns to forest are set to 0. The outcome variable uses land use transition matrices for years 17-18 and 18-19. The usual identification concerns from estimating supply using prices apply. To address this, I use the same demand instrument as in the main model.

Results: Table 4 shows the key estimate on the ΔR_t coefficient. More importantly, I use the estimated model to compute the average elasticity of pasture acreage with respect to cattle prices. To provide a useful comparison with the main model, I forward-simulate simulate the model for 5 years given a perturbation to prices over the same period. In the main model, I estimate an elasticity of 0.52 for private undisputed land, whereas the dynamic model predicts an elasticity of 1.47. A single-year perturbation results in a 0.53 elasticity. These estimates would predict more competitive markets and stronger responses of land use to environmental policy. As mentioned earlier, the dynamics of deforestation in the Amazon have many interesting aspects which are not featured here and are worthy of their own analysis in future work.

Table 4: Dynamics estimates

	OLS	IV
ΔR_t	0.18^{***}	0.75^{***}
	(0.02)	(0.22)
R^2	0.93	0.91
Num. obs.	4268	4268

Regressions include fixed effects for state, j_{t-1}, and (j, j') pairs.$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$

Appendix B Data

B.1 Carbon Intensities:

This section presents a breakdown of the carbon intensity of cattle production across the Amazon. The key inputs shown here are: (i) the amount of deforestation happening in each region, (ii) the emissions resulting from a hectare of deforestation in a region, (iii) land occupation (how many cattle head are produced per hectare of pasture on average), and (iv) the emissions resulting from enteric fermentation per animal. Enteric emissions vary according to farming practices - more intensive techniques can speed up the cattle lifecycle and lead to lower emissions. Other (smaller) sources of emissions I account for include fertilizer use and soil correction.

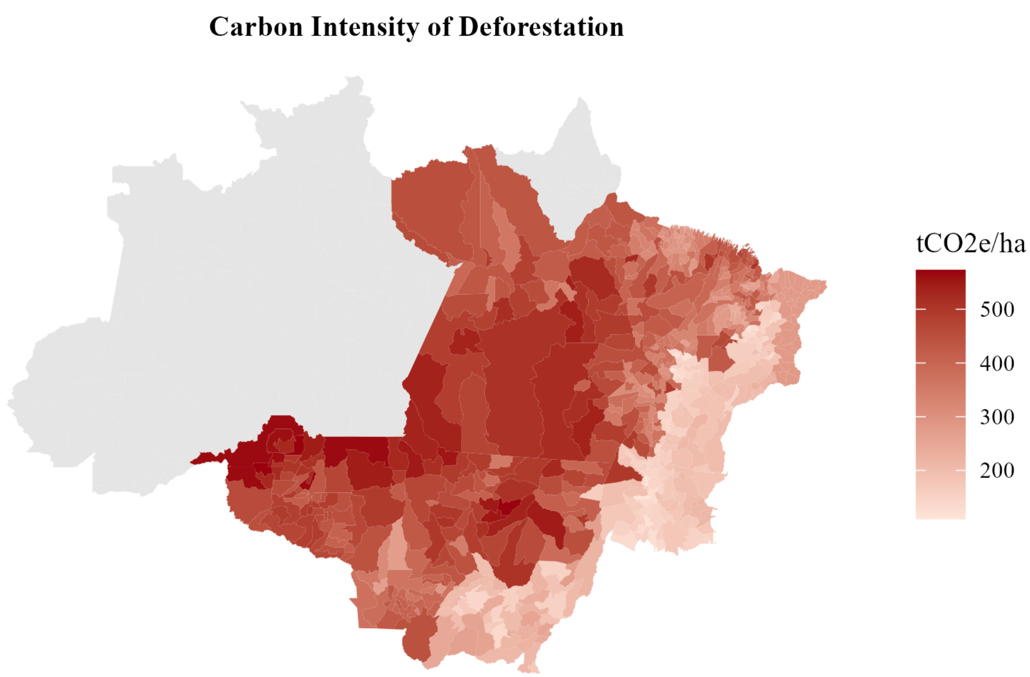

Figure 15: Carbon intensity of deforestation (tCO2e/ha)

The full breakdown by decile can be found on Table 5.

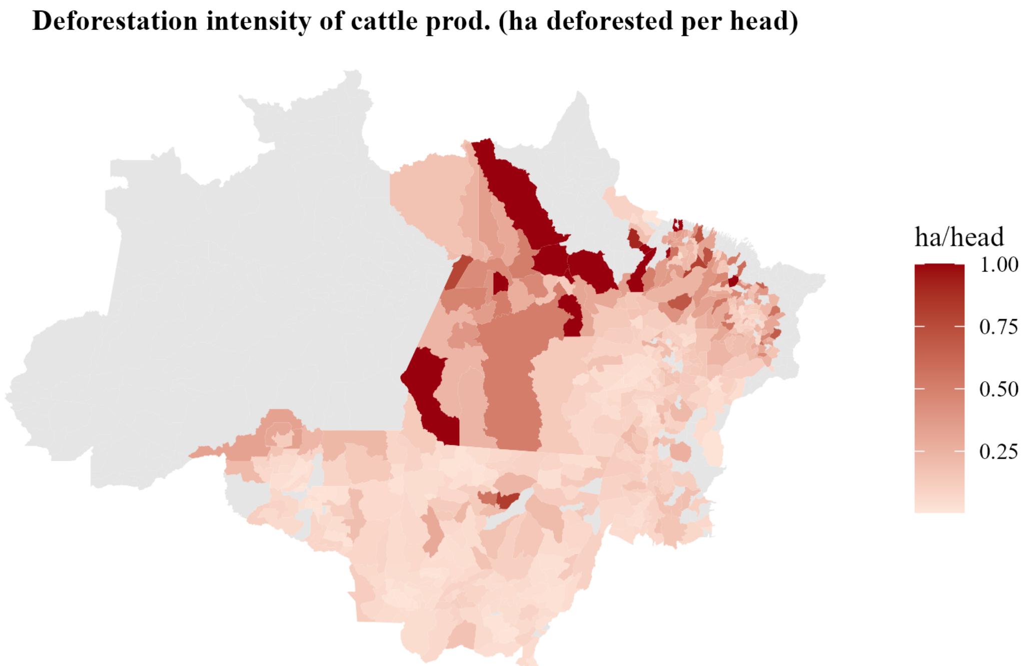

Figure 16: Deforestation (2015-19) her head (ha/head)

Decile	Emissions intensity	Enteric	Deforestation	Output	Defo. per head	N	HHI
	tCO2e/head		*tCO2e/ha*	*head/ha*	*ha/head*		
1	9.52	3.55	295.52	0.42	0.08	9.91	0.30
2	14.16	3.51	314.45	0.31	0.15	9.34	0.31
3	18.97	3.55	338.74	0.33	0.19	10.37	0.31
4	23.54	3.60	384.02	0.30	0.22	12.63	0.26
5	29.47	3.51	396.53	0.32	0.28	9.62	0.30
6	38.02	3.64	426.91	0.27	0.34	10.82	0.31
7	51.45	3.66	440.94	0.24	0.44	12.46	0.28
8	74.64	3.72	467.78	0.22	0.60	13.77	0.25
9	121.92	3.77	470.02	0.17	1.00	14.48	0.27
10	251.52	3.83	492.99	0.14	2.02	18.13	0.21

Table 5: Summary statistics by decile of emissions intensity

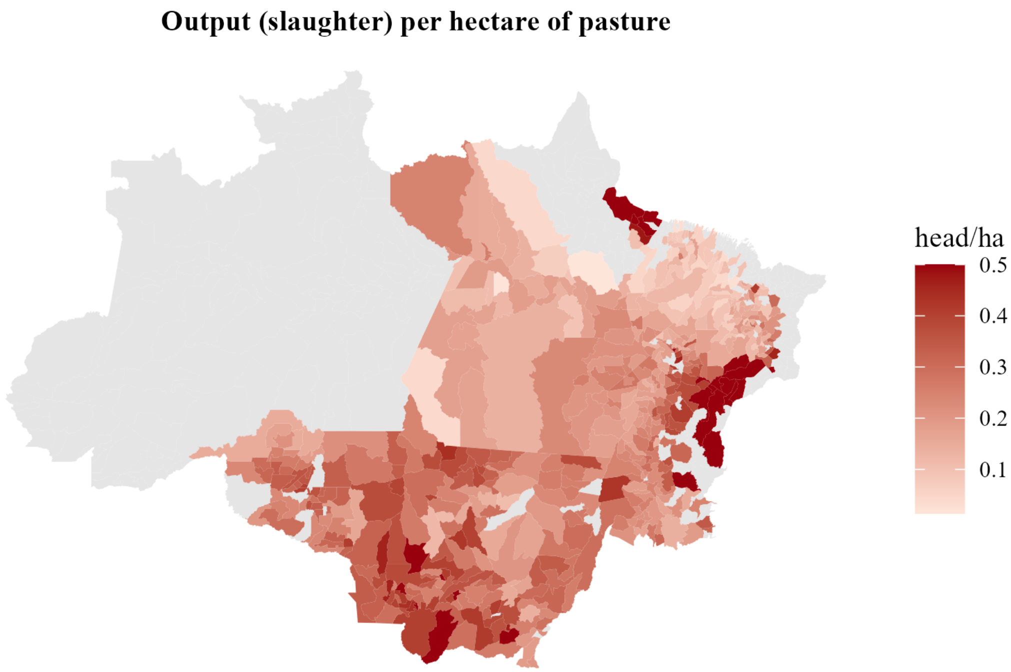

Figure 17: Land occupation (slaughtered head/ha,year)

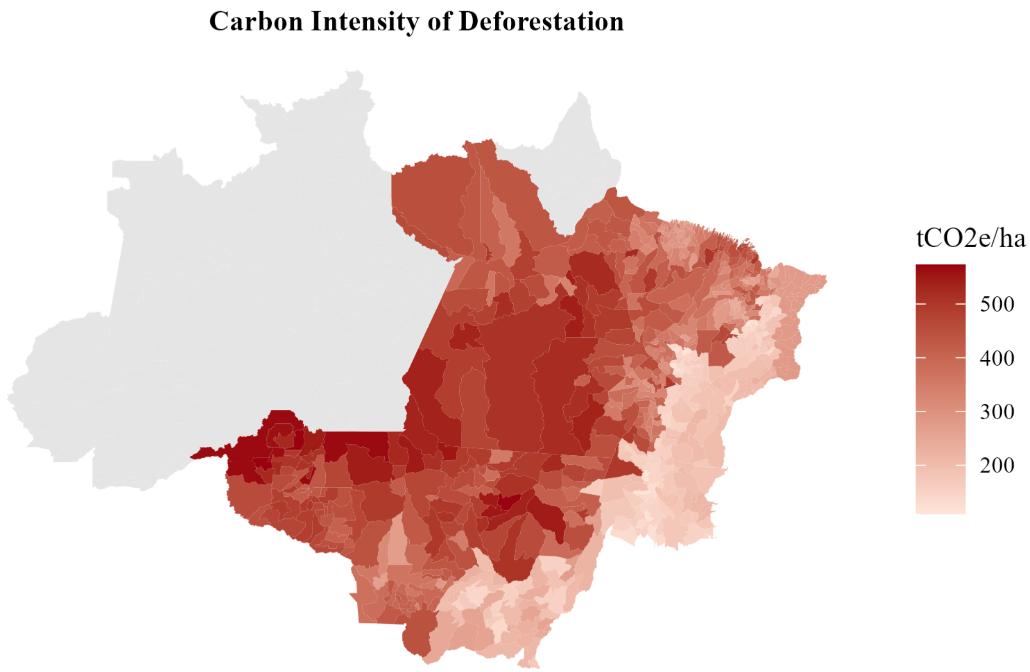

Figure 18: Enteric emissions per head (tCO2e/head)

B.2 Land tenure

Land property rights regimes vary across space in the Amazon. While that is not the focus of this work, I estimate the land use model for different land use categories in order to account for their different patterns of land use change.

To do this, I rely on various administrative data sources to create a novel land tenure dataset. It divides land in the Amazon into two categories, each with two subcategories. I used the Imaflora Atlas to separate public from private land, as Figure 19 shows. Within public land, there is designated public land (national and state parks, indigenous reservations, protected areas) and undesignated public land (not private but also not set for a particular purpose, a bit of a "wild west").

Within private land, I create two subcategories: disputed and undisputed. To do this, I pull land claims from Brazil's Cadastro Ambiental Rural (CAR). CAR is an effort from the Brazilian federal government to centralize information on land ownership. Land property rights have been the subject of disputes since the colonial period, and before the introduction of CAR in 2012 there was no centralized collection of claims. With CAR, each landholder submits a record (using mapping software) to the land which they claim. A CAR record is a requirement for access to subsidized farm loans. The problem is that there are vast areas where multiple people claim to own the same land. I extracted all CAR records and created a dataset which maps where there are intersecting claims. Even after removing anything resembling a duplicate, there were places with over 10 intersecting claims. 7% of all land (15% of private land) in my sample has more than one intersecting claim.

Regions with different property rights regimes display different patterns of deforestation and reforestation, as Table 6 shows. Here, deforestation is defined as the percent of forest

Table 6: Land tenure summary statistics

	Private		**Public**	
	Undisputed	**Disputed**	**Designated**	**Undesignated**
Land Share	42%	7%	42%	11%
Deforestation	4%	5%	2%	7%
Reforestation	5%	6%	8%	10%

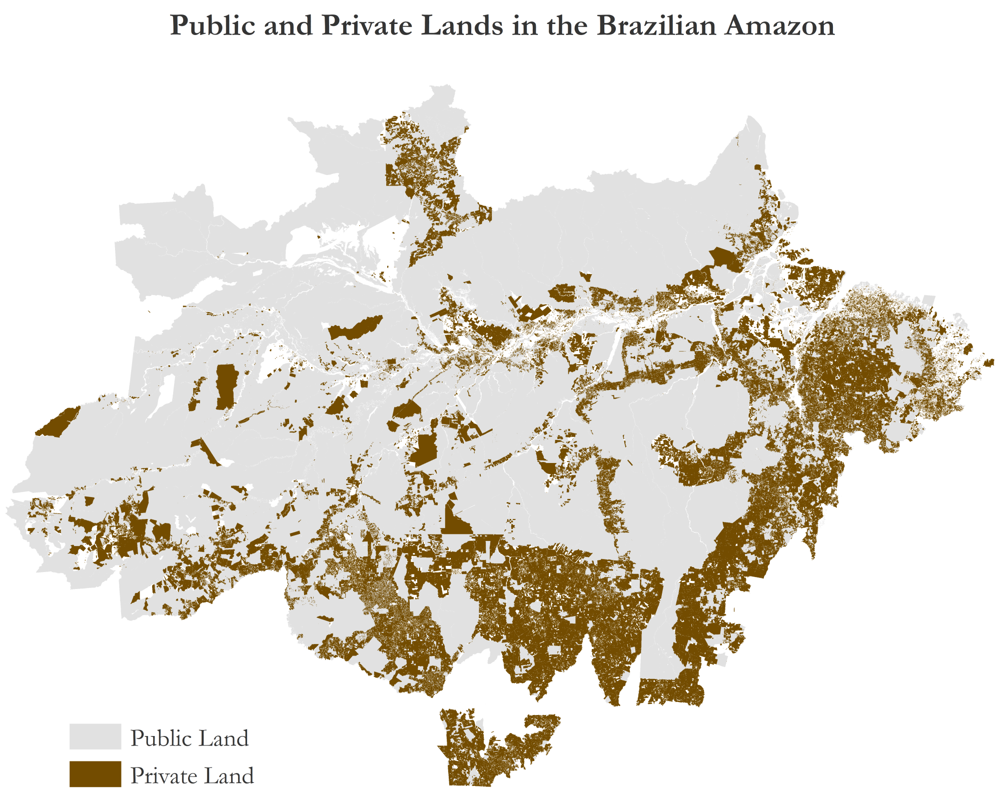

Figure 19: Public and private land in the Brazilian Amazon

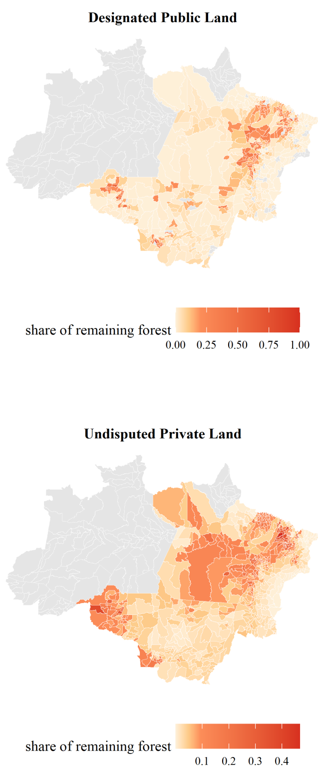

Figure 20: Deforestation patterns vary by land tenure

area in 2015 that became pasture in 2019; reforestation is the percent of pasture area in 2015 that became forest in 2019. Broadly, the data suggest that property rights uncertainty is associated with more land use change. Disputed private areas have more deforestation and reforestation than those undisputed. Undesignated public lands display more deforestation and reforestation than designated areas.

This suggests more volatile behavior in contested areas. It's consistent with a story where, given uncertain land tenure or the possibility of a land grab, agents are quicker to respond to shocks by clearing more forest or abandoning their agricultural land. In other work (in progress), I explore how property rights affect deforestation more explicitly.

B.3 Other data sources

Appendix C Empirics

C.1 Evidence of market power in cattle sourcing

Market concentration hints at the existence of market power in the cattle supply chain. But to establish that it is indeed present one needs to show that firms are behaving in a way consistent with oligopsony conduct. In this section I show that more concentrated regions display lower prices, and that pass-through of demand shocks to cattle prices is incomplete.

The first piece of evidence is more intuitive. Slaughterhouse monopsony power should lead to cattle prices that are lower than they would be under perfect competition. Table 7 shows exactly that - more concentrated regions (as measured by the Herfindahl index) face lower cattle prices.

Table 7: Concentration is associated with lower prices

HHI	-0.110^{**}	-0.092^{*}
	(0.041)	(0.040)
SIF share	0.254^{***}	0.182^{***}
	(0.026)	(0.046)
Distance to Highway	-0.003	-0.009
	(0.006)	(0.006)
Intercept	1.861^{***}	1.946^{***}
	(0.060)	(0.070)
State FE		X
R^2	0.134	0.208
Num. obs.	613	613

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$

The specification has log cattle prices as the outcome variable.

Pass-through is another useful tool for studying market power (Weyl and Fabinger, 2013; Pless and van Benthem, 2019). I show that, consistent with market power, demand shocks face incomplete pass-through to cattle prices. To establish a connection between the model and this empirical exercise, I first take equation 1 and sum it over all slaughterhouses:

$$c_m = \bar{\varphi}_m \left(\frac{1}{\varepsilon_m} \frac{1}{N_m} + 1 \right)^{-1}$$

where $\bar{\varphi}_m = \frac{\sum_i \varphi_{im}}{N_m}$ is the average marginal revenue product across all slaughterhouses sourcing in m, ϵ_m denotes the elasticity of cattle supply from farmers, and N_m is the number of slaughterhouses sourcing in m. Taking the total differential around the equilibrium[20] and substituting terms:

$$d \ln c_m = d \ln \bar{\varphi}_m \left(1 - \frac{1}{N \varepsilon_m + 1} \frac{\partial \ln \varepsilon_m}{\partial \ln c_m} \right)^{-1} \tag{25}$$

Equation 25 shows that whenever $\frac{\partial \ln \varepsilon_m}{\partial \ln c_m} < 0$ [21], pass-through is incomplete. Further, the pass-through rate is lower for lower values of N_m and ϵ_m. Using equation 5 from the land

[20] And assuming the extensive margin of slaughterhouse sourcing is held fixed

[21] That is, farmers are less elastic at higher levels of c_m

use model:

$$\frac{\partial \ln \epsilon_m}{\partial \ln c_m} = \left(\frac{\alpha_R\, \rho_{jm} - \alpha_R\, c_m\, \rho'_{jm}}{(\rho_{jm})^2}\, \rho'_{jm} + \frac{\alpha_R\, c_m}{\rho_{jm}}\, (\rho'_{jm}\, \rho_{j_{t-1}m} \; - 2\, \rho'_{jm}\, \rho_{j_{t-1}m}\, \rho_m(j, j_{t-1})) \right) \frac{c_m}{\epsilon_m} \tag{26}$$

where $\rho'_{jm} = \sum_{j_{t-1}} \rho_m(j, j_{t-1})\, \rho_{j_{t-1}m}(1 - \rho_m(j, j_{t-1}))$. The sign of the expression above depends on model parameter values - the estimated model delivers elasticities that decrease in prices (Figure 21).

Guided by equation 25, I estimate the following regression:

$$\Delta \ln c_{mt} = \alpha_0 + \alpha_1 Shock_{mt} + \alpha_2 Shock_{mt} \, * \, HHI_{mt} + \epsilon_{mt} \tag{27}$$

where $Shock_{mt}$ is a shift-share like the one used as an instrument in land-use estimation. I use demand shocks [22] at destination countries d over two-year intervals (2015-2017, 2017-2019). The shocks are interacted with each slaughterhouse i's exposure to that destination in the initial period, as well as the market share of that slaughterhouse in each m. HHI_{mt} is the Herfindahl index of market concentration among slaughterhouses sourcing in m at the beginning of each period.

I only have prices for all municipalities in the Amazon for one year (2017). However, for one of the states in my sample (Mato Grosso) I have yearly data from 2008. Those come from the Instituto Mato-grossense de Economia Agropecuaria (IMEA), an agricultural non-profit. Limitations in the supply chain data only allow me to run the regression over the 2015-17 and 2017-19 intervals for that subset of municipalities. The sample is thus small, but sufficient to show suggestive evidence of market power.

Table 8 shows the regression results. As predicted, the pass-through of export demand shocks to prices is lower in more concentrated regions. Municipality fixed effects absorb a lot of the variation in a limited time panel, so the interaction coefficient loses significance in the last specification - but it remains negative.

[22] This is defined as changes in country d demand from all countries excluding Brazil.

Table 8: Incomplete Pass-through of export demand shocks to cattle prices

Shock	0.018^{***}	0.030^{***}	0.034^{**}
	(0.004)	(0.006)	(0.011)
Shock x HHI		-0.021^{*}	-0.014
		(0.010)	(0.018)
HHI		0.010^{**}	0.020^{*}
		(0.004)	(0.008)
Export Share	0.004^{*}	-0.003	-0.011
	(0.002)	(0.003)	(0.007)
Intercept	-0.045^{***}	-0.044^{***}	-0.051^{***}
	(0.001)	(0.001)	(0.006)
Year FE	X	X	X
Munic FE			X
R^2	0.993	0.993	0.997
Num. obs.	251	251	251

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$

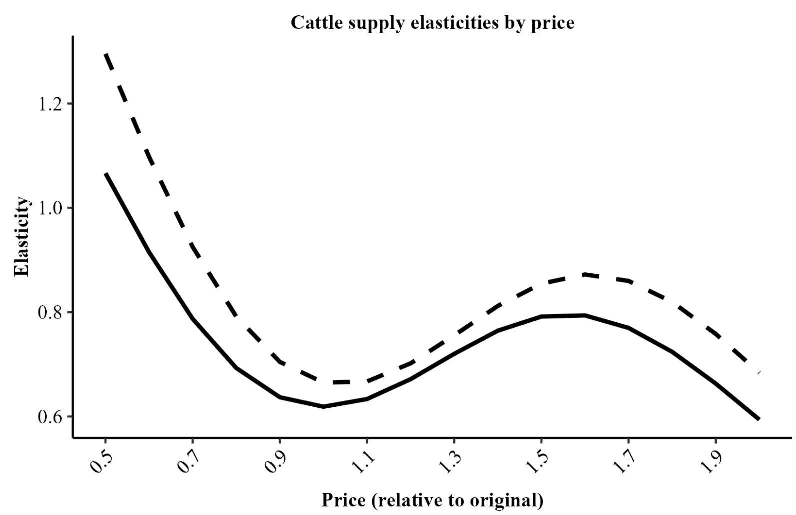

Figure 21: Cattle supply elasticity by price (proportional changes from observed, averaged across regions)

C.2 Model fit plots

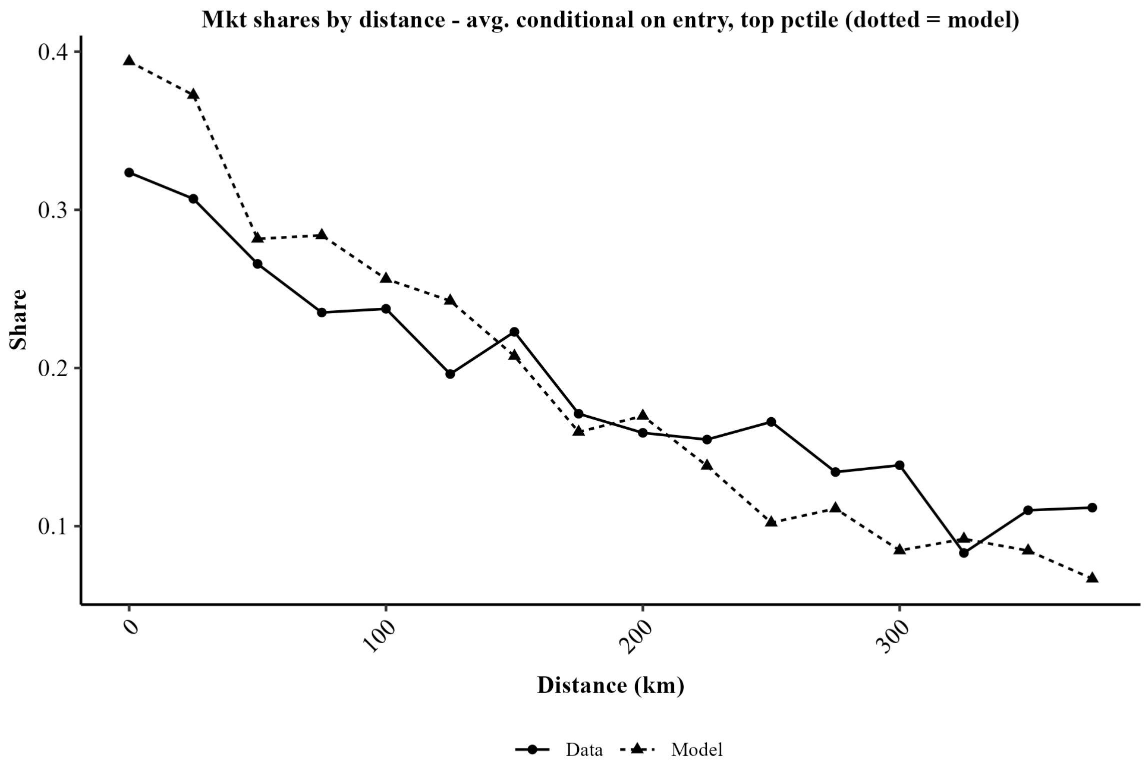

Figure 22: Shares by distance - top percentile

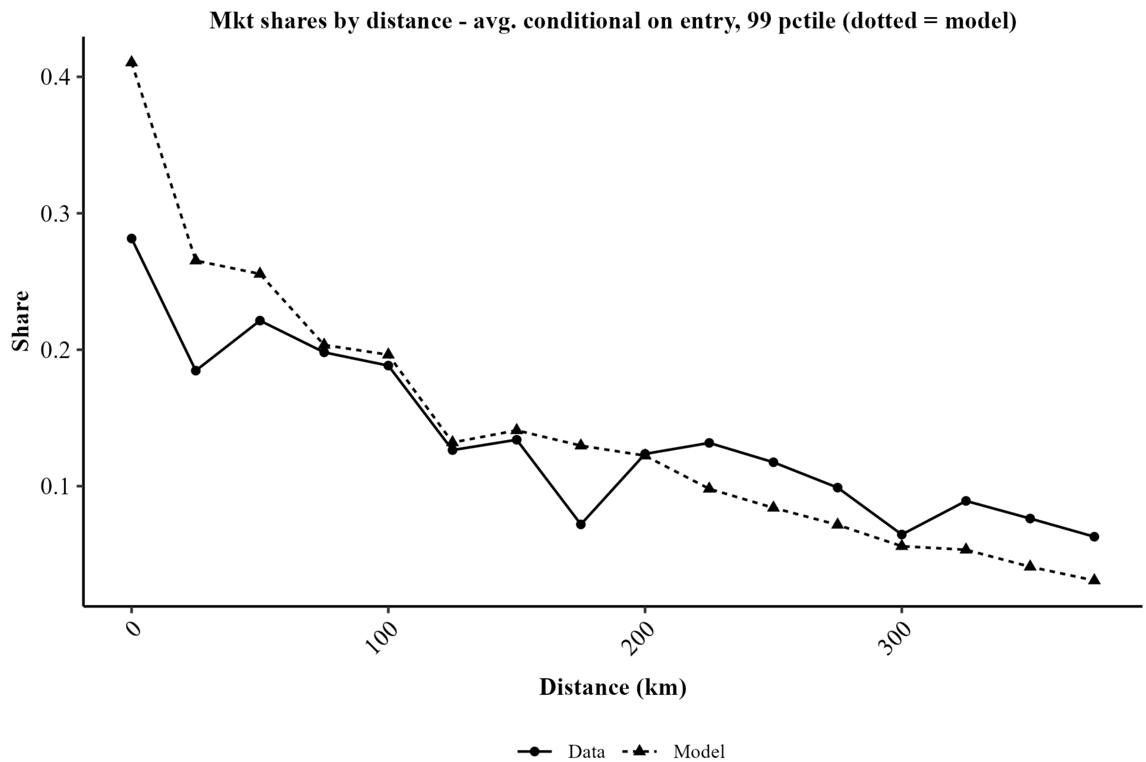

Figure 23: Shares by distance - 99th percentile

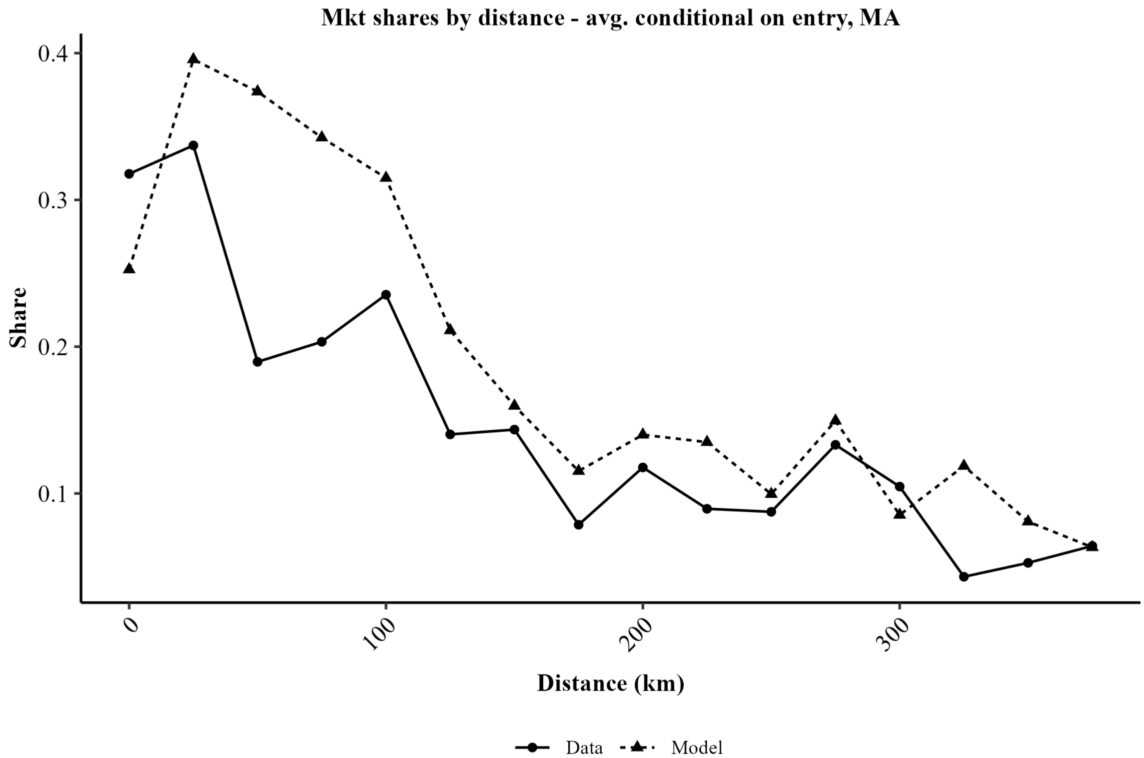

Figure 24: Shares by distance - Maranhao

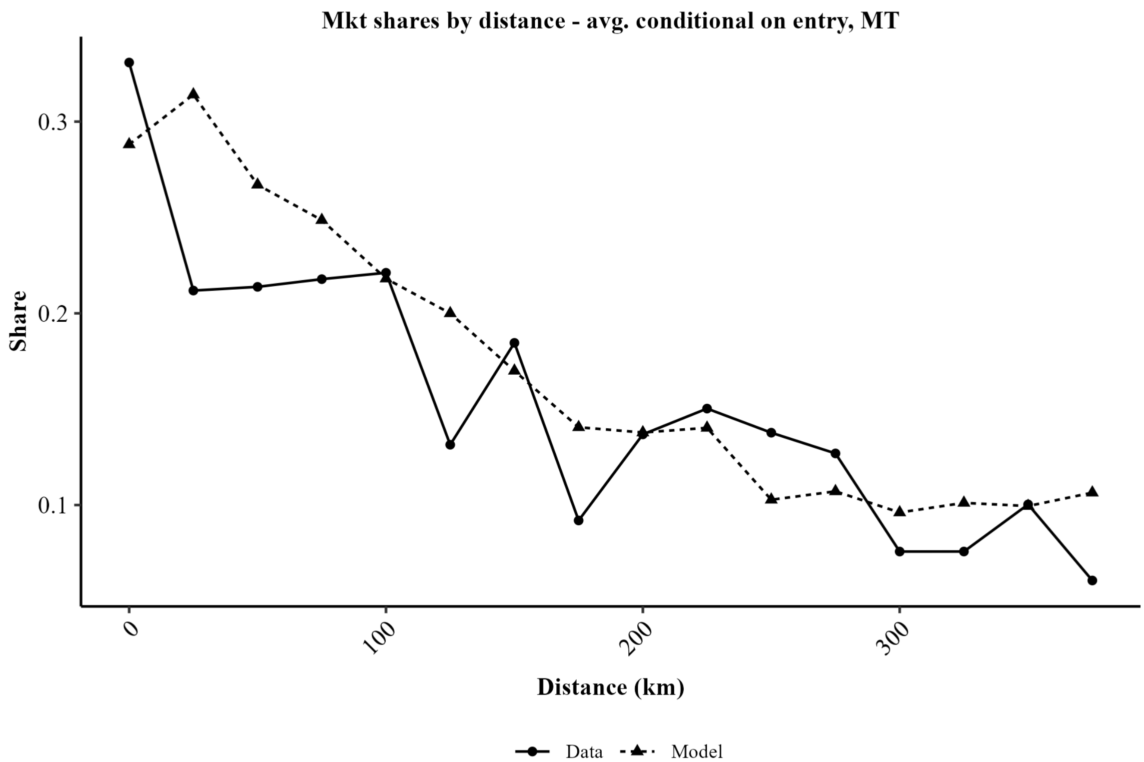

Figure 25: Shares by distance - Mato Grosso

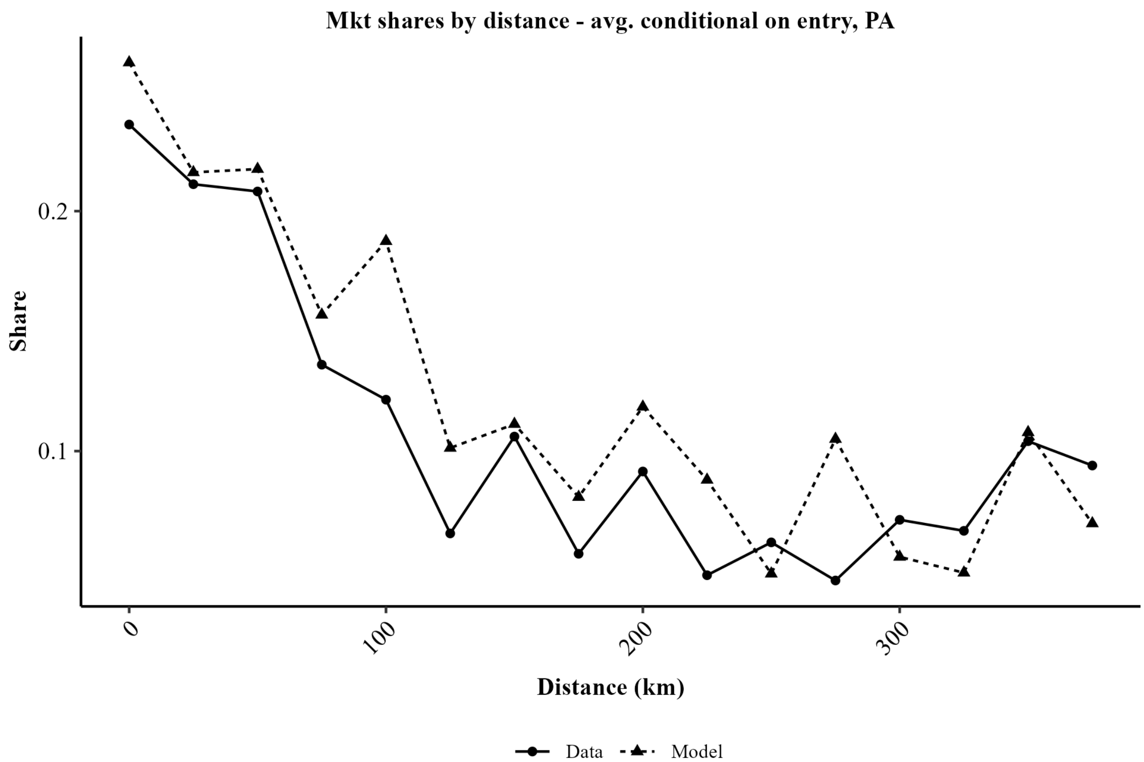

Figure 26: Shares by distance - Para

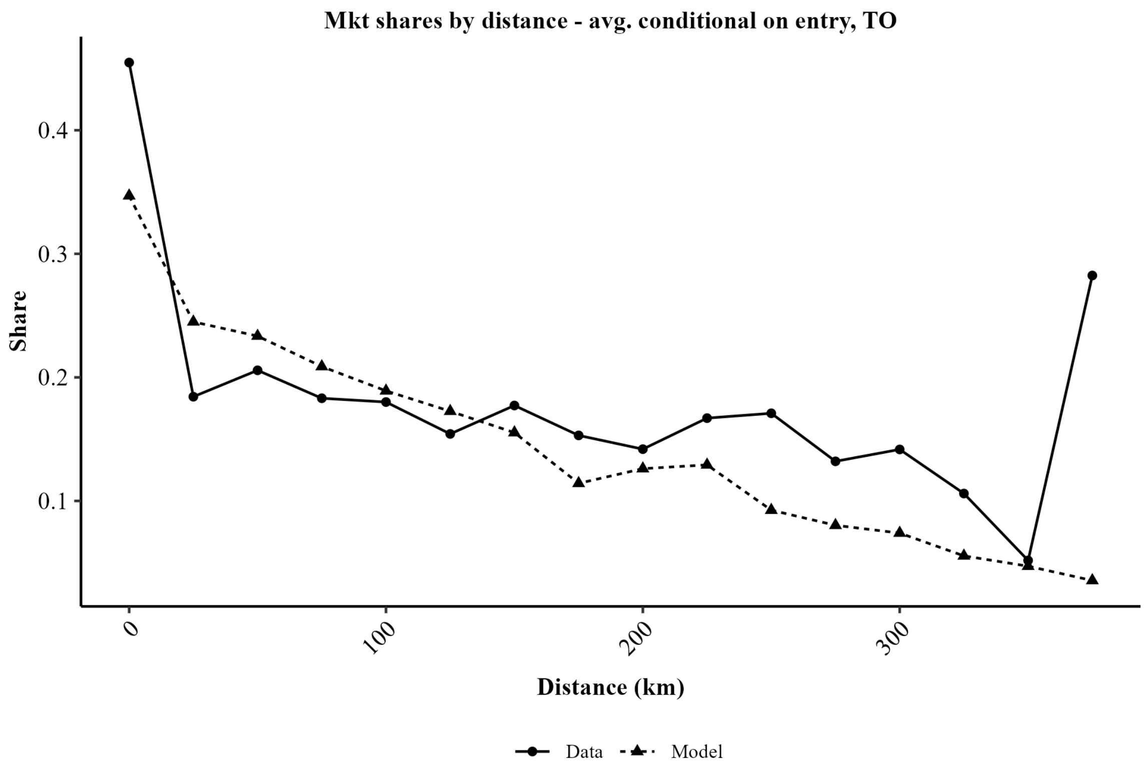

Figure 27: Shares by distance - Tocantins

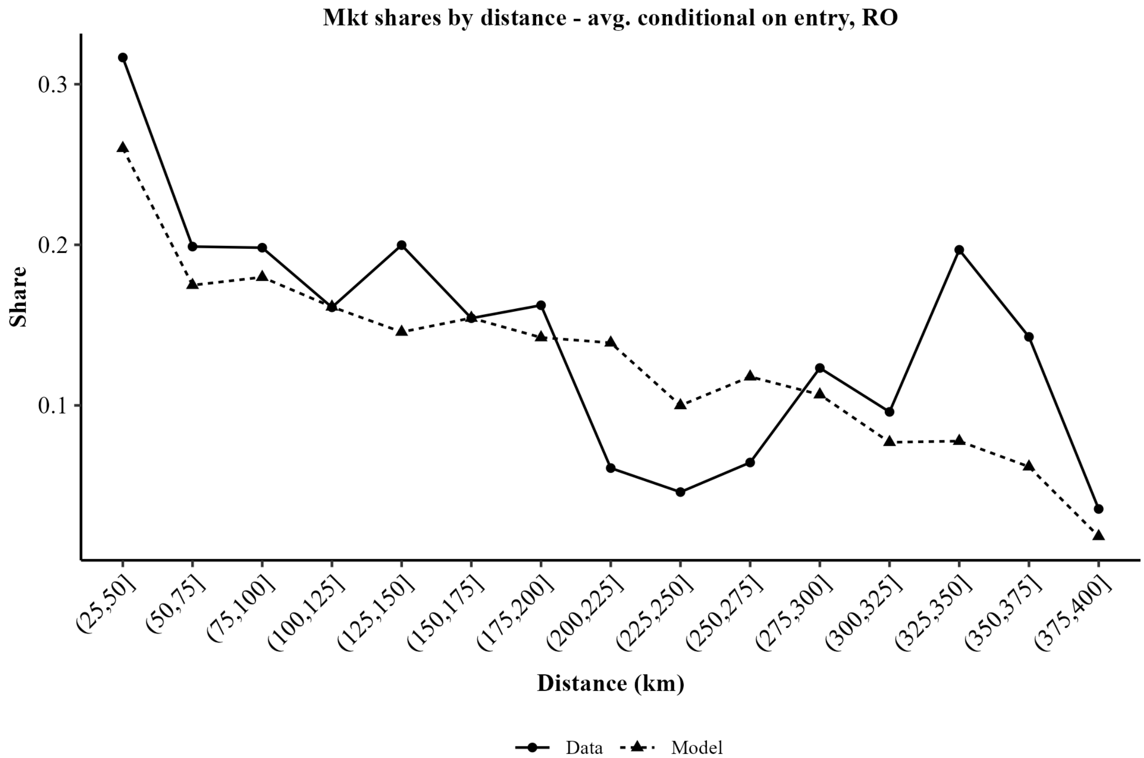

Figure 28: Shares by distance - Rondonia

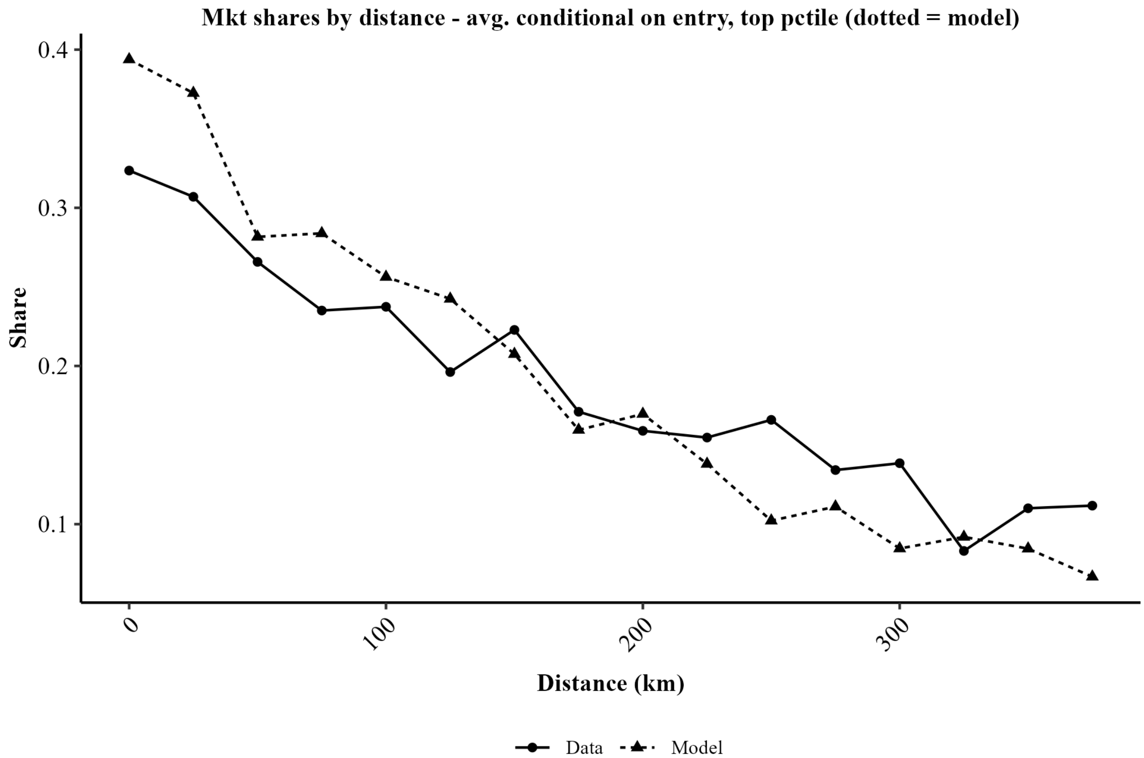

Figure 29: Shares by distance - top percentile

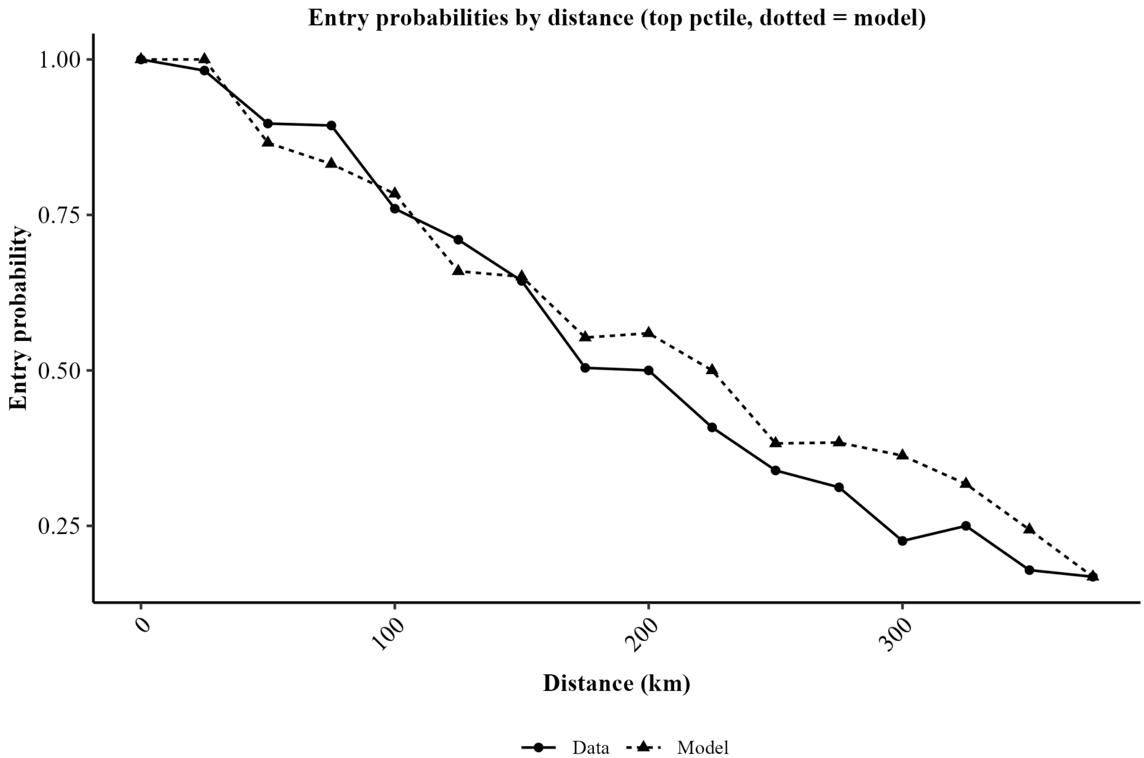

Figure 30: Extensive margin - top percentile

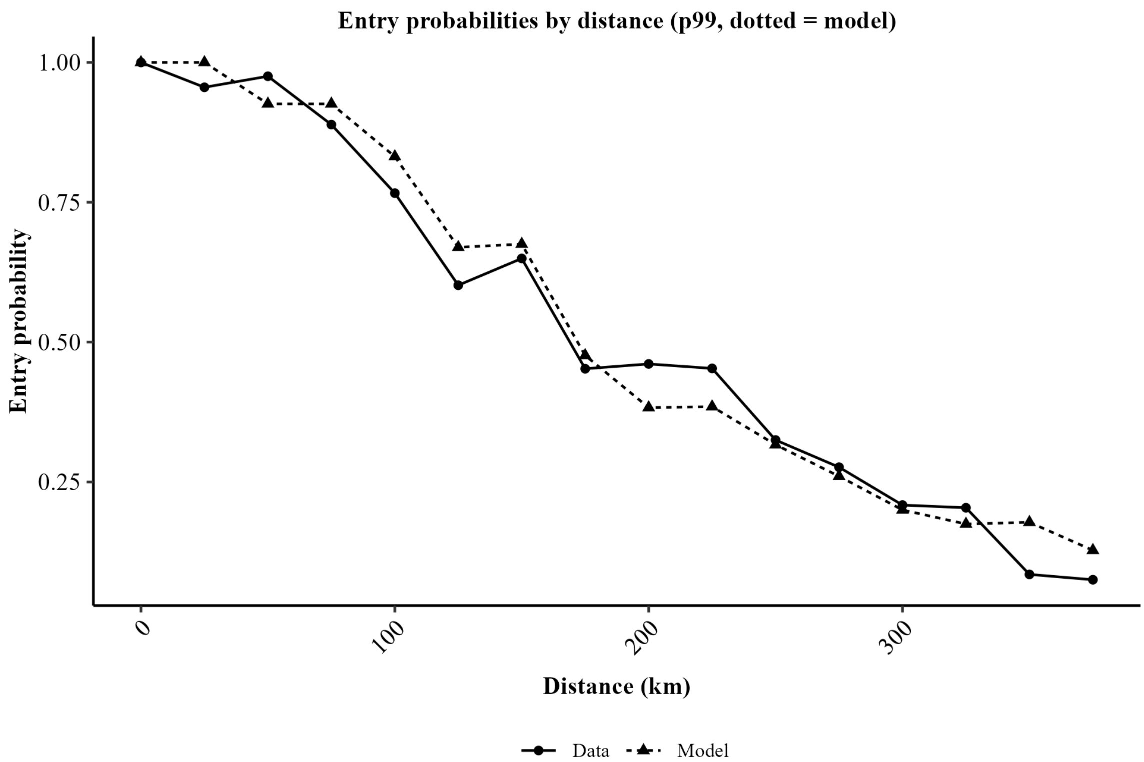

Figure 31: Extensive margin - 99th percentile

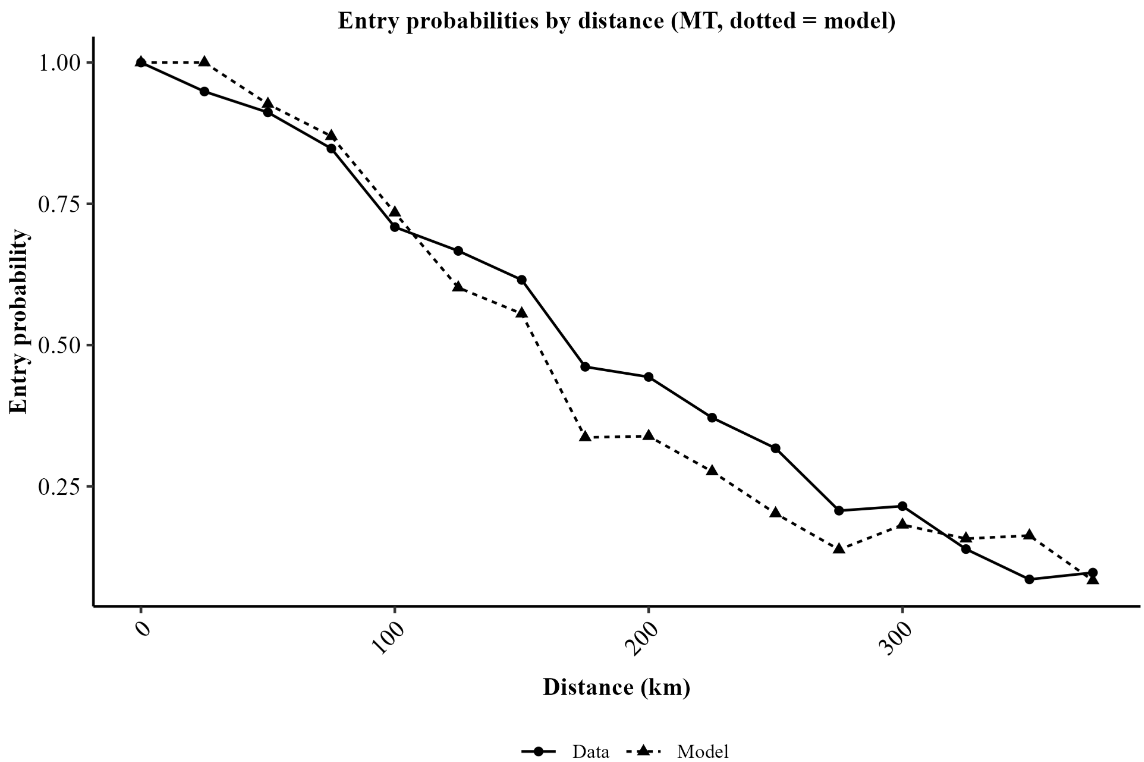

Figure 32: Extensive margin - Mato Grosso

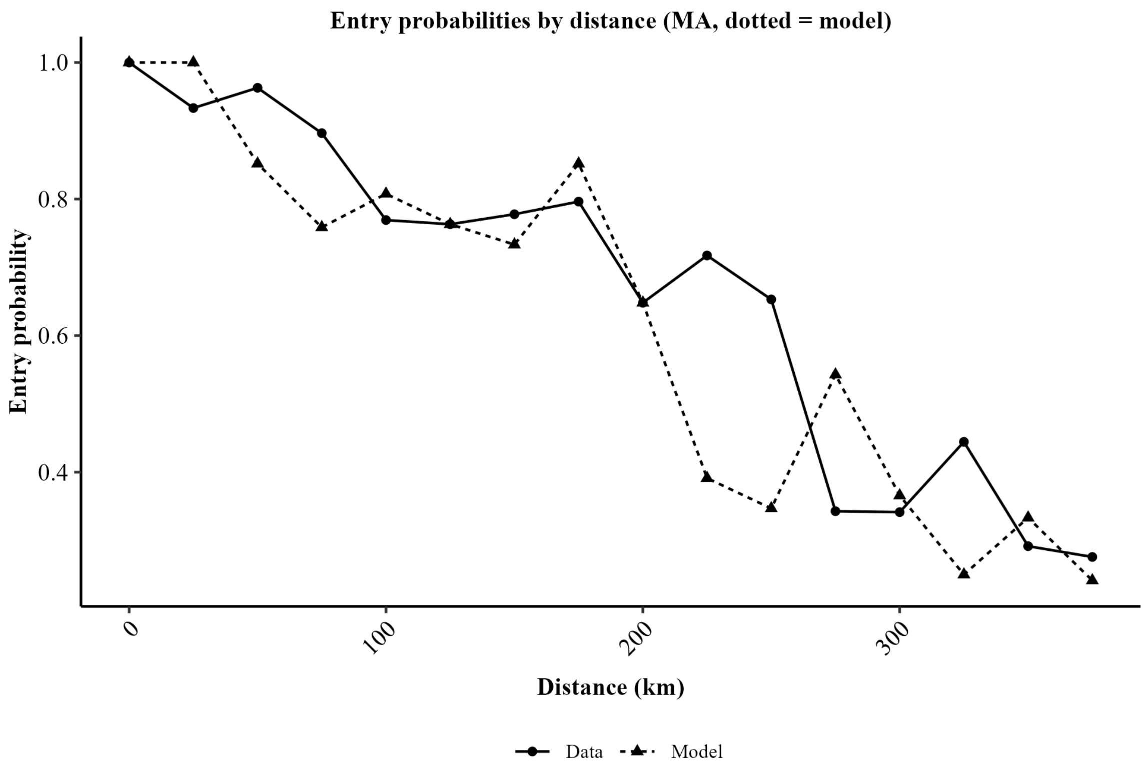

Figure 33: Extensive margin - Maranhao

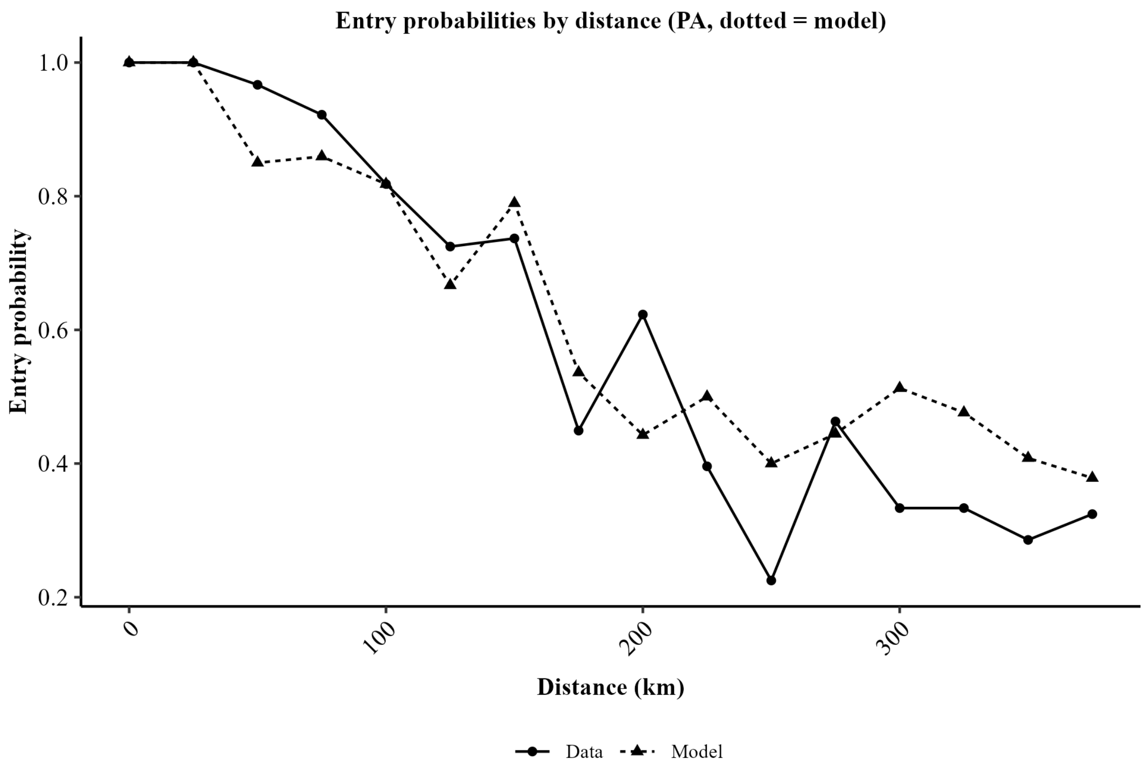

Figure 34: Extensive margin - Para

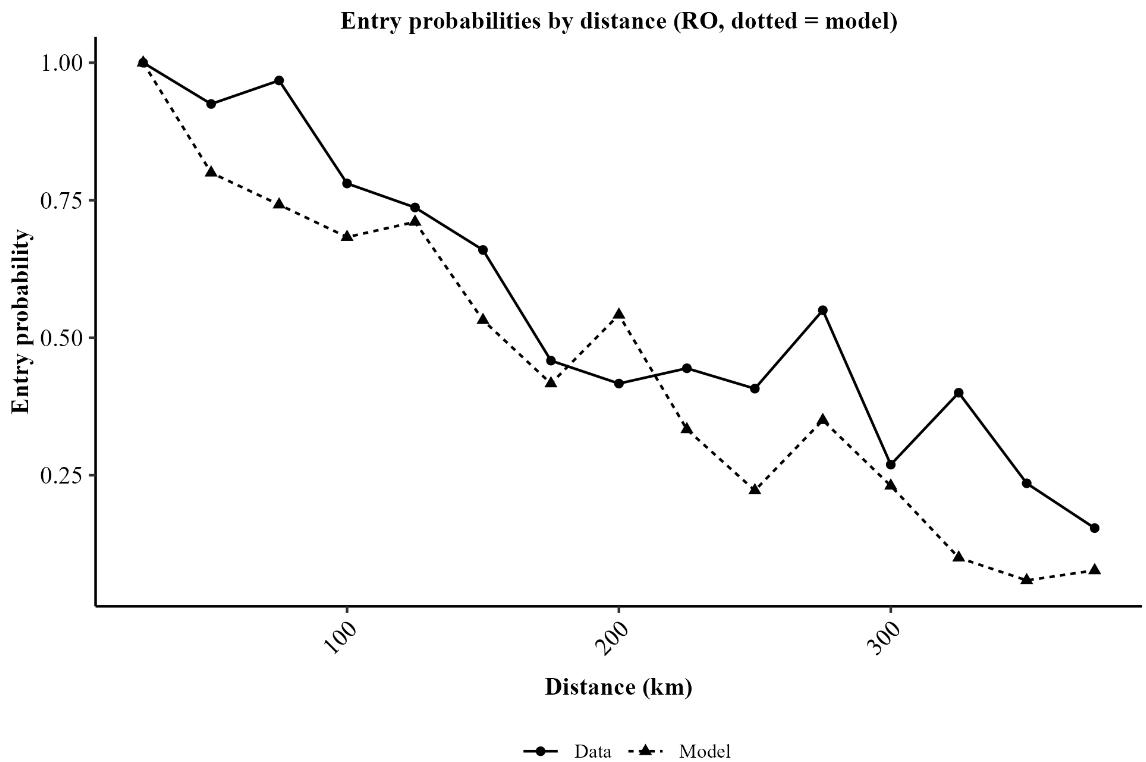

Figure 35: Extensive margin - Rondonia

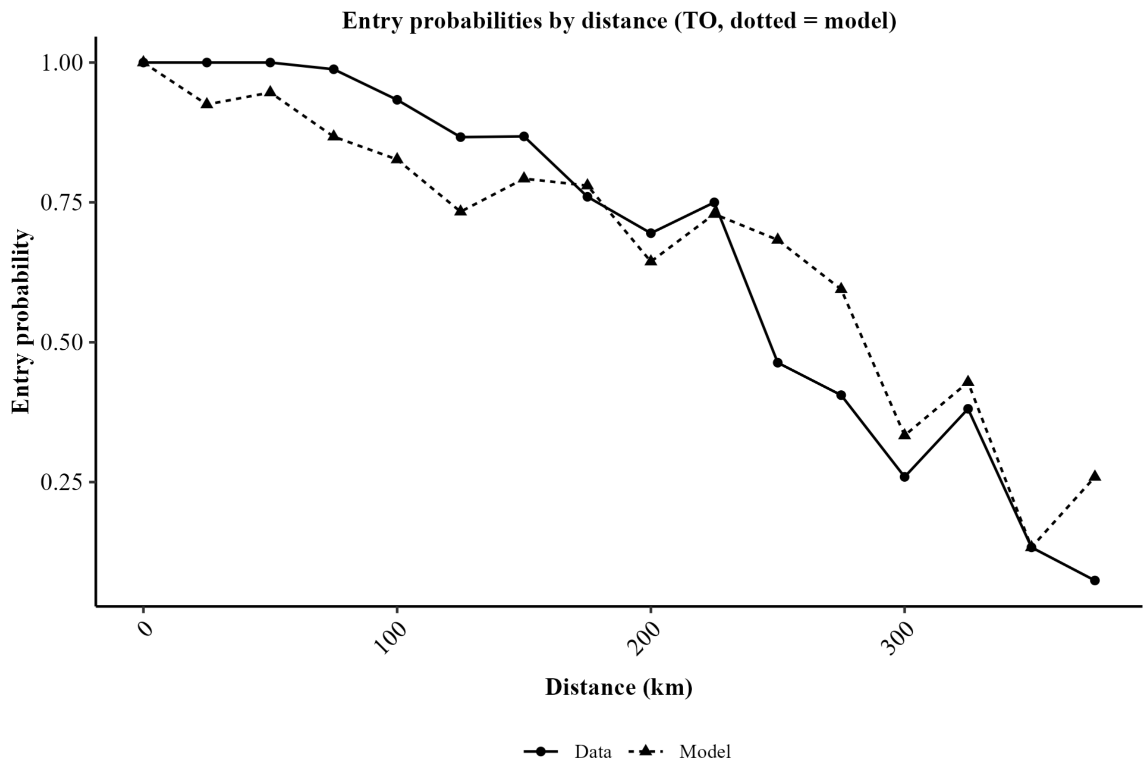

Figure 36: Extensive margin - Tocantins