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Industrial Activity, State Capacity, and Deforestation: Evidence from Brazil

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Abstract

Does industrial activity drive deforestation and land degradation, and can limited state capacity be overcome to decouple economic growth from environmental harm? We examine these questions in the context of slaughterhouse plant openings in Brazil from 1994 to 2019. Guided by a simple conceptual framework and using a staggered difference-in-differences approach, we show that plant openings increase livestock production while reducing forest cover and degrading pastureland. However, following the introduction of legally enforceable, incentive-compatible agreements between slaughterhouses and federal prosecutors—which penalize purchases of livestock from illegally deforested areas but act as a green certification mechanism—plant openings increase productivity without driving deforestation. Our findings suggest that tying firm performance to environmental goals through market-aligned legal mechanisms can generate economic and environmental gains at low cost to the government.

JEL classification

O13, Q01, Q15, Q56, K32, P18

Keywords

industrial activity, slaughterhouses, deforestation, land degradation, state capacity, green certification

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1 Introduction

Most developing countries struggle with limited state capacity, which hinders their ability to enforce laws effectively and provide public goods. This limitation affects many aspects of governance, including environmental regulation, and can lead to issues such as increased deforestation and land degradation. Policies that outsource state functions to market players under incentive compatibility constraints may partially address these limitations by leveraging the efficiency and reach of the private sector.

In this paper, we explore the relationship between limited state capacity and environmental outcomes in the context of cattle ranching and slaughterhouse operations in Brazil. The opening of new slaughterhouses—a type of industrial activity—can stimulate cattle ranching, which may lead to deforestation and other land-use changes. We leverage data on the opening of about 170 beef cattle slaughterhouses around the country since the mid 1990s. Similar to the United States, Brazil has become a major player in global beef markets, accounting for roughly 20% of all world beef exports (OECD/FAO, 2022). Extensive cattle ranching has been the dominant production system in Brazil, with more than 155 million hectares converted to pastureland in the last few decades—an area larger than the combined territories of France, Germany, and Spain.

To examine the impacts of industrial activity on cattle production and environmental outcomes, we exploit the staggered timing of slaughterhouse openings using comprehensive municipality level data for Brazil. Slaughterhouses usually purchase cattle from areas around them, often up to about 200 kilometers (Franco, 2013). Hence, the opening of a slaughterhouse affects ranchers across multiple localities by raising local demand for cattle. Ranchers' responses can vary—they may expand production intensively or extensively, with extensive expansion potentially driving deforestation. Because these responses differ, the overall impact of slaughterhouse openings on environmental outcomes is conceptually ambiguous and, ultimately, an empirical question.

Next, we assess how an intervention aimed at overcoming limited state capacity by outsourcing state functions to market actors may influence environmental outcomes. Similar to other countries (Greenstone and Jack, 2015; Jayachandran, 2022), Brazil has historically faced significant challenges with state-building and law enforcement, particularly in its frontier regions (Knudsen, 2023). In this context, we examine the effects of legally enforceable, incentive-compatible commitments between slaughterhouses and federal prosecutors—known as *Termos de Ajustamento de Conduta* ("*TAC* agreements")—which penalize plants for purchasing livestock from illegally deforested areas. *TAC* agreements serve as a form of mediation between the public sector and firms, allowing firms to adjust their behavior without undergoing a full judicial process. Importantly, once signed, these agreements carry the potential to act as a green certification mechanism. In 2009, following a deforestation-awareness campaign by Greenpeace, federal prosecutors in the Amazon region indicted existing plants for buying cattle from illegally deforested farms, effectively outsourcing monitoring and enforcement to key supply chain nodes, with third-party auditing (MPF, 2023).[1] The distinctive features of these agreements—including the state's focus on monitoring slaughterhouses rather than directly targeting ranchers, and their potential as a green certification—create a unique setting to study the impacts of government-and-market-led efforts to mitigate the environmental externalities of economic activity.[2]

Brazil holds some of the most important biomes still preserved in the world: the Amazon rainforest and the Cerrado (a savanna-type biome in central Brazil). Both have been considerably impacted by the expansion of agricultural and cattle production over the past three decades (Vale et al., 2022). Given the increasing demand for animal protein around the world, especially in Asia, the opening of new slaughterhouses followed by increasing beef production may be causing land-use changes and other forms of land degradation in surrounding areas. We assess whether *TAC* agreements can decouple increases in production from deforestation and pastureland degradation.

We develop a simple conceptual framework to illustrate how the entry of new slaughterhouses and environmental enforcement interact to shape cattle productivity, land use, and deforestation. In the model, producers choose between extensive and intensive ranching or forest conservation, with payoffs determined by cattle prices, production costs, yields, and the enforcement of environmental regulations. The framework emphasizes a key insight: stronger enforcement can either increase or decrease average cattle productivity, depending on the trade-offs between the relative yields of intensive versus extensive ranching, relative production costs, and the opportunity cost of forest conservation. The opening of a new slaughterhouse raises cattle demand and prices, incentivizing shifts toward production and deforestation. However, when the relative yields of intensive production exceed the relative costs and the opportunity cost of forest conservation, stronger environ-

[1]Amazon slaughterhouses that were signatories to the *TAC*s—and therefore subject to independent audits—exhibited irregularities in only about 4% of cattle purchases, compared to approximately 52% among non-signatories (MPF, 2025).

[2]In the Public Civil Action initiated by federal prosecutors, numerous instances highlight the precarious and limited state capacity in Brazil's Northern states, where the *TAC*s were initially signed (MPF, 2008). Examples include statements such as "due to precarious governmental oversight, there is a significant amount of illegal logging" and "insufficient action by the Brazilian state to ensure effective deforestation monitoring in the Amazon." These excerpts underscore the challenges of enforcing environmental regulations and the need for stronger institutional capacity in these regions.

mental enforcement can increase overall productivity without driving deforestation. This framework guides our empirical analysis, providing a lens to interpret how enforcement and market incentives jointly influence land-use decisions, pasture quality, forest cover, and cattle productivity.

To estimate the impact of slaughterhouse openings on cattle production and environmental outcomes, we use the staggered difference-in-differences approach of Callaway and Sant'Anna (2021). Municipalities that experience a slaughterhouse opening form the treatment group, while not-yet-treated municipalities serve as controls. Brazil's municipalities are autonomous administrative units roughly equivalent to U.S. counties. Between 1994 and 2019, our period of analysis, over 70% of the 5,570 municipalities are affected by slaughterhouse openings. We find little evidence of pre-trends, suggesting that treated and untreated municipalities followed broadly similar trajectories in key outcomes prior to the openings, which helps alleviate concerns about endogenous placement. We further address the concern of reverse causality by showing that openings are not correlated with pre-treatment levels or trends in our main outcome variables.

We highlight three main findings. First, slaughterhouse openings lead to more beef cattle grazing in nearby areas, increasing demand for pastureland. After a new opening, pasture areas increase their land share of a given municipality by approximately 1.47 percentage points. Given that the average municipality in Brazil is about 1,528 square kilometers in size, this represents an increase of about 2,250 hectares of pastureland per municipality over our analysis period—an area equivalent to about 3,200 FIFA-size soccer fields or approximately 4,250 American football fields. Notice that this is not a mechanical effect: cattle supply could respond intensively if ranchers increased productivity at existing pasture areas. Yet, our results suggest that was not the case. Bovine productivity did not respond to a new slaughterhouse, whereas the increase in cattle counts was pronounced.

Second, our results show a significant reduction in natural forest areas after a new slaughterhouse opening. The expansion of cattle grazing could take place over existing cleared areas—such as cropland or natural pasture areas—or over native forests. Our estimates imply that ranchers satisfy their demand for additional pastureland at least in part through deforestation. Consistent with increases in cattle grazing primarily at the extensive margin, we also find that pasture degradation increased as a response to new slaughterhouse openings. Severely and total degraded pasture areas increased their land share of a given municipality by as much as 1.04 and 1.6 percentage points, respectively, which is equivalent to approximately 1,600 and 2,450 hectares.

Third, *TAC* agreements increase cattle productivity without increasing deforestation.

After committing to not purchasing beef cattle from illegally deforested areas, slaughterhouses may have increased monitoring over ranchers to avoid violations. Such monitoring may have influenced ranchers decisions on land-use changes (e.g., GTFI, 2023). In fact, we find that after an existing slaughterhouse signs a *TAC* agreement, new slaughterhouse openings in the nearby areas lead to higher cattle productivity, and no further forest loss or severe pasture degradation. On the other hand, areas not impacted by *TAC*s experienced exactly the opposite. Importantly, areas under *TAC* influence seem to receive a price premium for their production. Hence, *TAC* appears to act like a "green certification."

This paper makes three main contributions. First, it advances the literature on limited state capacity and on strategies to overcome such constraints, particularly in the pursuit of environmental goals. Prior work has revealed how weak institutions may undermine environmental quality in the developing world (Vincent, 2010; Greenstone and Jack, 2015; Jayachandran, 2022; Shapiro, 2025), while also highlighting the potential of technology, citizen engagement, third-party certification, green trade policy, career concerns, targeting, information provision, property rights, and market-based instruments to mitigate institutional limitations and environmental externalities (Jack et al., 2008; Duflo et al., 2013; Greenstone and Hanna, 2014; Alix-Garcia et al., 2015; Jayachandran et al., 2017; Alix-Garcia et al., 2018; Souza-Rodrigues, 2019; He et al., 2020; Greenstone et al., 2022; Jha and La Nauze, 2022; Assunção et al., 2023a,b; Barwick et al., 2024; Buntaine et al., 2024; Balboni et al., 2025; Greenstone et al., 2025; Hsiao, 2025; Jack et al., 2025). We contribute to this literature by demonstrating that outsourcing state functions to market actors in an incentive-compatible manner can also reduce environmental degradation.

Second, it contributes to the extensive literature on the environmental impacts of economic activity. Prior studies have established the effects of industrial and agricultural production, as well as transportation, utility, and cooking services, on pollution and public health (Chay and Greenstone, 2003; Currie and Walker, 2011; Currie et al., 2015; Knittel et al., 2016; Cesur et al., 2017; Beach and Hanlon, 2018; Rangel and Vogl, 2019; He et al., 2018; Heblich et al., 2021; Alexander and Schwandt, 2022; Dias et al., 2023; Clay et al., 2024; Berkouwer and Dean, 2025; Gechter and Kala, 2025; Hansen-Lewis and Marcus, 2025; Parfitt, 2025). We show that the opening of new industrial plants induces land-use changes and land degradation—an externality that has been largely overlooked in the economics literature—and that government-led but market-aligned approaches can decouple economic growth from environmental harms.

Third, it contributes to the broad literature on the determinants of deforestation. Prior research has documented the roles of agricultural productivity, credit access, illegal activities, infrastructure expansion, local politics, poverty-alleviation programs, supply-chain initiatives, and trade in driving forest loss (Ferraro et al., 2011; Burgess et al., 2012; Alix-Garcia et al., 2013; Chimeli and Soares, 2017; Lambin et al., 2018; Asher et al., 2020; Assunção et al., 2020; Carreira et al., 2024; Garg et al., 2024; Girard et al., 2025; Katovich and Moffette, 2025). We contribute to this literature by providing causal evidence that industrial activity linked to beef markets—an increasingly important sector due to rising global demand for animal protein and a major source of carbon emissions—can lead to the expansion of extensive livestock production and accelerate deforestation.

This paper proceeds as follows. Section 2 provides background on Brazil's slaughterhouses and the certification-like, legally enforceable agreements. Section 3 presents a conceptual framework to guide our empirical analysis, illustrating how land allocation decisions and environmental enforcement interact to affect cattle productivity, pastureland use, and deforestation. Section 4 outlines the empirical strategy, while Section 5 describes the data. Section 6 reports and discusses the main results, while Section 7 offers concluding remarks, including policy implications.

2 Background

2.1 Slaughterhouse Openings in Brazil

Federally-inspected slaughterhouses are authorized to commercialize their meat products across the entire national territory, with some also holding export licenses.[3] These federally-inspected slaughterhouses play a central role in Brazil's meatpacking industry, as they process the majority of commercially slaughtered cattle in the country. The Brazilian National Inspection Service (*Serviço de Inspeção Federal*), part of the Ministry of Agriculture and Livestock (*Ministério da Agricultura e Pecuária*), oversees animal-product facilities and grants operational licenses. Opening a new slaughterhouse can be a lengthy bureaucratic process, often taking over a year from construction to full operation (e.g., Reuters, 2022; TO, 2007; MG, 2008). The requirements for licensing include detailed facility blueprints, waste treatment infrastructure, and an on-site office for Inspection Service's inspectors to use during their plant inspections (SIF, 2023).

Once a facility is fully built and equipped, Brazil's National Inspection Service has the final say on its authorization to begin operations. These facilities can then start purchasing

[3] There are other types of inspections at the state and local levels, but these only permit sales within their respective boundaries, resulting in significantly smaller operations compared to federally-inspected plants.

cattle from surrounding areas and selling meat to urban centers. The processing capacity of federally-inspected plants varies widely, from 500 to 2,000 heads of cattle per day. Panel (a) of Figure 1 shows the distribution of slaughterhouses across Brazil according to opening years (in groups)—summary statistics for the slaughterhouses, including the number of companies, their opening years, and company names, are presented in Appendix Table A.1.

Vertical integration is limited in Brazil's cattle market: with few exceptions, slaughterhouses do not own cattle ranches. Instead, they typically purchase "ready-to-slaughter" cattle from top-tier suppliers, who themselves buy from other ranchers down the supply chain (Cammelli et al., 2022). Only a few large ranches manage all stages—breeding, raising, and fattening. The sector is also highly fragmented. According to EMBRAPA (2021), 25% of production occurs on farms up to 100 hectares, and 37% on farms between 100 and 1,000 hectares.[4] Of the 2.55 million cattle-raising establishments, 1.95 million have fewer than 50 head of cattle, while 605,700 manage more than 50.

Given Brazil's average cattle productivity of around 0.85 animals per hectare in recent decades, slaughterhouse plants likely influence up to 116 million hectares of pastureland—roughly 74% of the country's total. This is consistent with data showing that over 75% of commercially slaughtered cattle are processed in federally inspected plants (IBGE, 2023), while the remaining 25% are handled by smaller, local facilities for local consumption.

Historically, slaughterhouse locations have shifted northward—from western *São Paulo* and southern *Goiás* and *Mato Grosso do Sul* to the southern Amazon, including *Pará*, *Rondônia*, and northern *Mato Grosso* (Vale et al., 2022). Cattle production in these states has risen, with the three accounting for 80% of deforestation and cattle production in the Amazon since 2000 (Skidmore et al., 2021). Appendix Table A.2 summarizes key statistics on new slaughterhouse openings, including the number of municipalities affected within a 200-kilometer radius, as well as forest cover, pastureland (including degraded pasture areas), and bovine counts, comparing periods before and after plant openings.

Panel (b) of Figure 1 shows the geographic cover of federally-inspected slaughterhouses in our sample considering the 200-kilometer radius. Slaughterhouses typically buy cattle from surrounding areas, often within a radius of approximately 200 kilometers (Franco, 2013). Importantly, aside from some municipalities in the Amazon and in Brazil's semiarid region—the country's driest area (see Da Mata and Resende, 2020)—more than 70% of municipalities in the country (3,944 municipalities out of 5,570) have a slaughterhouse within 200 kilometers.

[4] Ranches over 1,000 hectares comprise 2% of farms but hold 33% of the national herd.

2.2 The *TACs*: Certification-Like, Legally-Enforceable Commitments

Governments around the world have sought to implement policies to reduce the costs of economic externalities, such as deforestation (UNEP, 2021). In Brazil, during the 2000s and early 2010s, a series of government interventions and agreements were introduced to curb forest loss, particularly in the Amazon. These measures included policies like black-listing municipalities with high deforestation rates and restricting rural credit for farmers who were not compliant with environmental regulations (Assunção et al., 2015; Assunção et al., 2020). Additionally, private sector initiatives, such as the Soy Moratorium, led major commodity trading firms to pledge a halt on soybean purchases from deforested areas after 2006 (ABIOVE, 2014).

In May 2009, Greenpeace launched a campaign to raise consumer awareness about the links between Brazilian beef production and deforestation in the Amazon (Reuters, 2009). Using satellite imagery, the campaign highlighted how beef companies were sourcing cattle from farms involved in illegal deforestation. Following the campaign, Brazilian federal prosecutors initiated legal action against slaughterhouses for purchasing products linked to environmental violations, exposing them to potentially severe legal consequences (Barreto et al., 2017). These prosecutors are members of the *Ministério Público*, a constitutionally autonomous government institution. In contrast to their counterparts in countries such as the United States, they operate independently of the Executive, Legislative, and Judicial branches.

To avoid legal penalties, slaughterhouses in the Amazon entered into agreements with federal prosecutors, committing to stop sourcing cattle from farms that (i) deforested after October 2009, (ii) were partially embargoed by IBAMA (the Brazilian federal agency for the environment and natural resources) due to illegal deforestation, or (iii) were not registered in the Environmental Rural Registry (*Cadastro Ambiental Rural – CAR*) (Barreto and Araújo, 2012).[5] These agreements are known as *Termo de Ajustamento de Conduta* ("*TAC* agreements")—freely translated as Conduct Adjustment Agreements.

TAC agreements allow prosecutors to impose penalties on signatory slaughterhouses without court proceedings—such as fines and administrative sanctions, including license suspensions and exclusion from public contracts—or to take companies directly to court without filing a new lawsuit to establish wrongdoing. Although slaughterhouses are not required to sign a *TAC*, many do so voluntarily to avoid litigation. *TAC* agreements can be viewed as a form of mediation, as public prosecutors and slaughterhouses jointly negotiate

[5]The CAR is an environmental registration system requiring farmland owners to provide detailed, geo-referenced information about forests, reserves, and protected areas on their properties.

the terms and commitments, resembling standard mediation processes.

Figure 2 provides a map of municipalities and states hosting at least one *TAC*-signatory slaughterhouse. States with at least one signatory plant—hereafter referred to as *TAC* states—represent the broader influence area of the *TAC* agreements, reflecting the structure of Brazil's federal prosecutorial system, which operates at the state level (MPF, 2020). As a result, the presence of a signatory plant in a state signals the potential for additional plants within that state to also become signatories. It is important to note that the 2009 Greenpeace campaign primarily targeted the Amazon region; therefore, the municipalities directly affected by the campaign are located exclusively within that part of the country.

Appendix Table A.3 provides descriptive evidence on land use and livestock outcomes around slaughterhouse openings in *TAC* and non-*TAC* municipalities. *TAC* municipalities differ systematically at baseline, exhibiting substantially higher forest cover and lower pasture shares prior to openings. This pattern is consistent with the focus of the Greenpeace campaign on curbing Amazon deforestation. Following openings, both *TAC* and non-*TAC* areas experience increases in bovine counts, but the expansion is markedly larger in *TAC* municipalities. Importantly, in *TAC* areas this growth in cattle production is not accompanied by a proportional increase in degraded pasture or a sharp shift in pasture quality, whereas non-*TAC* municipalities display more heterogeneous changes and, on average, continued pressure on land use. Despite larger increases in cattle stocks, *TAC* municipalities do not show correspondingly worse pasture degradation in the post-opening period. Taken together, these patterns suggest that slaughterhouse openings in *TAC*-influenced areas are associated with greater cattle intensification rather than extensive expansion.

TAC agreements require third-party auditing. Recent evidence indicates that compliance with socio-environmental standards in the Amazon cattle supply chain is substantially higher among slaughterhouses that are signatories to the *TAC* and therefore subject to independent audits. Data released by Brazil's Federal Public Prosecutor's Office (MPF) in May 2025 show that audited *TAC* signatories exhibited irregularities in only about 4% of cattle purchases made in 2022, whereas firms that did not undergo independent audits—whose transactions were assessed using automated verification systems—showed non-compliance rates of approximately 52%, a gap of roughly thirteen to one (MPF, 2025). These findings are based on the second unified audit cycle, which covered 89 slaughterhouse units across six Amazon states (Acre, Amazonas, Mato Grosso, Pará, Rondônia, and Tocantins) and evaluated compliance with origin-control and deforestation-related criteria established in the agreements.

Because these agreements emerged partly from market pressure (e.g., Greenpeace's campaign) and partly from governmental enforcement, we classify them as certification-like, legally enforceable commitments—they are essentially "extrajudicial" agreements.[6] Since 2009, they have affected major beef companies in the Amazon, with around 70% of all cattle in the region being processed in *TAC*-signatory slaughterhouses by 2016 (Barreto et al., 2017). As a result, ranchers in the surrounding areas of *TAC*-signatory slaughterhouses may have altered their land-use decisions in response to the new requirements, potentially diverging from practices in other parts of the country, especially because there is evidence of enforcement (Unearthed, 2022; Independent, 2024; CanalPecuarista, 2024).

If the certification-like hypothesis of these legally enforceable commitments is correct, areas influenced by *TAC*s would likely see higher cattle prices, similar to the premiums observed for environmentally certified products (e.g., Ferraro et al., 2005; Casadesus-Masanell et al., 2009). We perform a simple difference-in-differences analysis comparing municipalities affected by *TAC* and those outside its influence, before and after *TAC*, which supports that hypothesis. Appendix Table A.4 reports price premiums ranging from 5% to 10%, depending on how the treatment is defined.[7]

3 Conceptual Framework

In this section, we develop a conceptual framework to guide our empirical analysis, showing how the entry of a new slaughterhouse and the enforcement of environmental regulation interact to influence cattle productivity, land use, and deforestation. The framework highlights that the effect of enforcement on productivity may be *ambiguous*, depending on relative yields, production costs, and conservation priorities.

We build a simple land-use choice model, inspired by Roy's framework, in which property owners in a municipality allocate land among three uses: extensive ranching (E), intensive ranching (I), and forest conservation (F). Cattle productivity per acre of land depends on the allocation to extensive and intensive uses, as well as the enforcement of environ-

[6]Henceforth, we use certification-like, legally enforceable commitments, extrajudicial agreements, and *TAC*s interchangeably throughout the text.

[7]Appendix Table A.4 presents a simple 2-by-2 difference-in-differences estimation using bovine prices, cattle counts, and bovine production value as dependent variables. The treatment is defined by *TAC* area status, including *TAC* municipalities, the 200 km radius around *TAC* plants, and *TAC* states. Agricultural census data are available only for 2006 and 2017, making a comparison between these years particularly informative, as they capture the periods before and after *TAC*s began to be signed in 2009. Results show not only higher prices but also increased production in treated areas.

mental regulation. The profit per acre for each activity can be expressed as

$$\pi_E = (p_C\, y_E - \theta c_E)\,\varepsilon_E, \quad \pi_I = (p_C\, y_I - \gamma c_I)\,\varepsilon_I, \quad \pi_F = p_F \varepsilon_F,$$

where p_C is the market price of cattle, y_E and y_I are cattle output per acre of land under extensive and intensive production, respectively, and p_F represents the revenue from forest conservation (e.g., payments for ecosystem services or carbon credits).[8] The terms c_E and c_I capture, respectively, the land that is illegally deforested for extensive ranching and the inputs required for intensive ranching (e.g., levelized costs of feedlots, fertilizer, and other inputs to maintain pastureland quality).[9] Here, θ represents the penalties associated with violating environmental laws (e.g., deforestation), γ is the price of inputs required to operate intensive cattle production, and ε_E, ε_I, and ε_F are idiosyncratic productivity shocks.

Within a municipality, property owners allocate land to the use with the highest payoff:

$$\max\{\pi_E, \pi_I, \pi_F\}.$$

Assuming idiosyncratic productivity shocks follow a Frechet distribution, the expected shares of land allocated to each use in a municipality are

$$s_j = \frac{r_j}{r_E + r_I + r_F}, \quad j \in \{E, I, F\}, \quad \text{where the expected payoffs are} \quad r_j = \frac{\pi_j}{\varepsilon_j}. \tag{1}$$

Slaughterhouse Entry. This framework naturally allows us to analyze the effect of market-driven shocks, such as the entry of a new slaughterhouse, which increases demand for cattle and raises p_C. Higher cattle prices increase the expected payoffs to both extensive and intensive production. Consequently, municipalities are likely to allocate more land to cattle production at the expense of forests, particularly when enforcement (θ) is weak.

Enforcement and Productivity. Besides market-driven incentives from slaughterhouse entry, the enforcement of environmental legislation shapes how land-use changes affect cattle productivity and deforestation. Expected livestock productivity (P) across the mu-

[8]See discussions of these forest services in Bousfield et al. (2022) and Montero-de-Oliveira et al. (2023).

[9]Cattle ranching and crop farming differ sharply in how forestland is cleared, making ranching a clearer focus for modeling deforestation. Ranching typically relies on extensive, low-input clearing—often slash-and-burn—with minimal soil preparation, while crop farming involves intensive preparation, higher inputs, and greater variability across crops. Because ranching dominates early deforestation, has more uniform land-use dynamics, and covers far larger areas, focusing on it captures the main driver of forest loss. Indeed, MapBiomas data show that 72.7% of land converted to agriculture in Brazil from 1992 to 2022 came from areas already modified by humans, mainly pastureland (MapBiomas, 2023).

nicipality is

$$P = s_E y_E + s_I y_I,$$

where, again, s_E and s_I denote the shares of municipal land allocated to extensive and intensive cattle production, respectively, and y_E and y_I denote per-acre cattle output in extensive and intensive ranching.

The effect of enforcement (θ) on expected cattle productivity in a municipality is

$$\frac{\partial P}{\partial \theta} = y_E \frac{\partial s_E}{\partial \theta} + y_I \frac{\partial s_I}{\partial \theta},$$

which implies that

$$\frac{\partial P}{\partial \theta} \propto \left[p_C y_I (y_I - y_E) - \gamma c_I (y_I - y_E) - y_E p_F \right].$$

The effect of enforcement on average livestock productivity is therefore *ambiguous* and depends on the relative sizes of intensive and extensive yields, production costs, and the opportunity cost of forest land. The term $p_C y_I (y_I - y_E)$ illustrates how higher cattle prices amplify the productivity effect: when intensive yields are substantially larger than extensive yields, stronger enforcement shifts land from extensive to intensive production, raising average productivity. Conversely, if intensive yields are only moderately larger than extensive yields, or if extensive yields themselves are significant, this effect may be small or even negative. The second term, $-\gamma c_I (y_I - y_E)$, captures the role of intensive production costs, which reduce the relative benefit of intensification. The third term, $-y_E p_F$, reflects the opportunity cost of forest conservation: enforcing environmental regulation reallocates land toward forest, reducing productivity to the extent that extensive yields are substantial. Note that if p_F is low or zero, there is no reallocation toward forest.

Taken together, the net effect of enforcement is positive if the weighted difference between intensive and extensive yields, amplified by cattle prices, outweighs the combined effects of intensive production costs and the forgone output from forest conservation. Formally, productivity increases with stronger enforcement if and only if $p_C y_I (y_I - y_E) - \gamma c_I (y_I - y_E) - y_E p_F > 0$. Intuitively, when intensive yields are high relative to extensive yields and cattle prices are elevated, stronger enforcement tends to *increase* productivity. In contrast, if extensive yields are relatively high, intensive production is costly, or the value of forested land is substantial, increasing enforcement may *reduce* average productivity. In this way, the conceptual framework captures the nuanced trade-offs between environmental enforcement, production efficiency, and conservation goals.

Enforcement and Deforestation. Deforestation in this framework is directly tied to the share of land allocated to extensive ranching, since this activity may require clearing of forest area for pasture. Let deforestation D be proportional to the share of land allocated to extensive land use:

$$D = \delta\, s_E,$$

where δ represents the amount of forest cleared per acre allocated to extensive ranching.

The effect of enforcement (θ) on expected deforestation is therefore

$$\frac{\partial D}{\partial \theta} = \delta \frac{\partial s_E}{\partial \theta}.$$

Because stronger enforcement reduces the relative payoff of extensive ranching (r_E), it follows that $\frac{\partial s_E}{\partial \theta} < 0$, implying

$$\frac{\partial D}{\partial \theta} < 0.$$

Thus, while the effect of enforcement on productivity is *ambiguous*, its effect on deforestation is *unambiguous*: stronger enforcement lowers deforestation by shifting land away from extensive ranching and toward intensive or forest uses. In this framework, deforestation is directly linked to the share of land allocated to extensive ranching, while intensive ranching expands output without necessitating additional forest clearing (and forest conservation maintains standing forest). This distinction yields a clear implication: when growth in cattle production comes from extensive expansion, it necessarily increases deforestation.

However, when enforcement shifts land use away from extensive toward intensive ranching, it is possible to raise cattle output without additional forest loss. In this sense, stronger environmental enforcement not only affects average productivity but also creates the possibility of "decoupling" production growth from deforestation. Conversely, slaughterhouse entry increases the risk that growth occurs through extensive expansion, unless enforcement is strong enough to redirect land use toward intensification.

We will use the predictions from this conceptual framework to guide our empirical analysis, examining how market incentives (proxied by slaughterhouse entry) and enforcement (measured by *TAC* implementation) shape land use and production. In particular, we focus on a set of key outcomes, including total cattle production, the area of pastureland, the degree of pastureland degradation, forest coverage, and cattle productivity. We will analyze these outcomes both in aggregate and across enforcement intensity, allowing us to assess how stronger or weaker enforcement influences land allocation and the efficiency of cattle production.

4 Empirical Strategy

In our setting, the unit of observation is the municipality–year. Slaughterhouse plants are introduced at different points in time across municipalities and, once introduced, remain in operation for the remainder of the sample period; the treatment is therefore staggered and absorbing. Given this treatment structure, we use the estimator proposed by Callaway and Sant'Anna (2021) to identify the effects of new plant openings on our outcomes of interest. Recall our treatment consists of a slaughterhouse opening *within* a 200-kilometer radius of a given municipality, so the treatment goes beyond a municipality's borders.

The estimator is a staggered difference-in-differences (DiD) design that allows for treatment effect heterogeneity across cohorts and over time. Following Callaway and Sant'Anna (2021), we define the group-time average treatment effect as:

$$ATT(g,t) = \mathbb{E}[Y_t(g) - Y_t(0) | G = g]. \tag{2}$$

Each municipality has a vector of potential outcomes (e.g., cattle counts, pasture area, forest cover). The term $Y_t(0)$ denotes the untreated potential outcome in year t, while $Y_t(g)$ denotes the potential outcome in year t if the municipality first receives a slaughterhouse in year g. Municipalities are assigned to groups indexed by G, where $G = g$ indicates that the municipality is first exposed to a slaughterhouse within a 200-kilometer radius in year g, which defines our treatment.

Equation (2) captures the average treatment effect for municipalities first treated in year g evaluated at calendar year t. To estimate the effects of slaughterhouse openings on our outcomes of interest, we aggregate the group-time average treatment effects into two target parameters proposed by Callaway and Sant'Anna (2021).

First, we estimate a general-purpose summary measure: the group-aggregated treatment effect of slaughterhouse openings. This parameter is analogous to the traditional DiD estimand in staggered adoption settings and summarizes treatment effects over the entire sample period. Specifically, we compute the average treatment effect across municipalities treated in different periods as:

$$\theta^O_{sel} = \sum_{g \in \{2,\ldots,T\}} \frac{1}{T-g+1} \sum_{t=g}^{T} ATT(g,t) \times \mathbb{P}[G = g | G \leq T]. \tag{3}$$

Second, we estimate event-study coefficients that compare outcomes before and after treatment. To do so, Callaway and Sant'Anna (2021) propose a target parameter that explicitly accounts for heterogeneity by length of exposure to treatment:

$$\theta_{es}(e) := \sum_{g \in \{2,\dots,T\}} 1\{g + e \leq T\} \times \mathbb{P}\left[G = g \mid G + e \leq T\right] \times ATT(g, g + e), \tag{4}$$

where $e = t - g$ denotes the number of years since a municipality first received a slaughterhouse within a 200-kilometer radius. This parameter measures the average effect of a plant opening e years after treatment, aggregated across all municipalities that are observed for at least e post-treatment periods.

To estimate the target parameters in Equations (3) and (4), we use the doubly-robust estimator proposed by Callaway and Sant'Anna (2021), which combines outcome regression and inverse probability weighting and is consistent provided that at least one of the two components is correctly specified. For outcomes observed over the full sample period (1994–2019), we restrict the sample to municipalities exposed to treatment for at least eight post-treatment periods.[10] For outcomes available over shorter time spans, we require at least five or four post-treatment periods, corresponding to the 2000–2019 and 2009–2019 subsamples, respectively.

These restrictions affect both the number of periods and the number of observations used in estimation. The full sample and the 2000–2019 subsample include 144,846 and 111,420 municipality-year observations, respectively, while the 2009–2019 subsample contains 61,281 observations, including both treated and untreated municipalities. For inference, we follow Callaway and Sant'Anna (2021) and compute bootstrap standard errors clustered at the municipality level.

Our identifying assumption is that, absent slaughterhouse openings, municipalities that eventually receive a slaughterhouse and those that have not yet received one would exhibit similar trends in the outcome variables. In our main specification, the control group consists of "not-yet-treated" municipalities. That is, at each point in time, treated municipalities—those with a slaughterhouse opening within a 200-kilometer radius—are compared to municipalities that have not yet been exposed to such an opening but will be exposed in subsequent periods.

Restricting the control group to municipalities that are eventually treated improves comparability between treated and control units. While the placement of slaughterhouse plants is clearly non-random, the timing of plant openings is plausibly more exogenous. In

[10]Results are robust to alternative restrictions on the minimum exposure length.

particular, the start date of plant operations depends on factors such as land acquisition, permitting, contractor selection, and legal processes, all of which may delay construction in ways that are unlikely to be systematically related to short-run changes in local economic or environmental outcomes. For these reasons, not-yet-treated municipalities provide a more credible counterfactual for treated units.

A potential concern in any DiD framework is the validity of the parallel trends assumption. In our staggered design, we impose a conditional parallel trends assumption by controlling for pre-determined covariates that may influence the evolution of our outcomes of interest. Livestock production and environmental outcomes, for instance, may vary systematically with population characteristics and geographic location. Conditioning on such covariates therefore strengthens the plausibility of parallel trends relative to an unconditional assumption. Moreover, as emphasized by Callaway and Sant'Anna (2021), failure to account for covariate-specific trends can lead to biased estimates in staggered adoption settings. In all specifications, we include the following pre-treatment covariates: rural population in 1991, average temperature over the 1960–1990 period, and illiteracy rates among adults aged 25 and older in 1991. We also control for geographic characteristics by including latitude and longitude.

Our empirical specification additionally allows for limited treatment anticipation. As discussed in Section 2, the construction of a new slaughterhouse typically takes at least one year. Ranchers may respond to credible signals of a forthcoming plant—such as the initiation of construction—by adjusting production decisions in advance of the plant's opening. We therefore allow for one period of anticipation, interpreting the beginning of construction (following the pre-construction phase) as the relevant event that triggers ranchers' responses. In practice, this implies that production adjustments may occur approximately one year before the plant becomes operational.

A central feature of our research design is that slaughterhouse openings affect the outcomes of interest primarily through ranchers' responses to increased local demand for cattle (see the conceptual framework in Section 3). Ranchers may respond by expanding production extensively or by intensifying production, with potentially different environmental externalities associated with each margin of adjustment. Importantly, ranchers do not systematically influence the spatial placement or timing of slaughterhouse openings, nor do they affect slaughterhouses' commercial decisions beyond the farm gate. Under these conditions, variation in the timing of slaughterhouse openings across municipalities generates plausibly exogenous shocks to local cattle demand, allowing us to interpret our estimates as causal.

A remaining concern is the possibility of reverse causality—namely, that slaughterhouse locations are chosen in response to pre-existing trends in cattle inventories or land use. We address this concern in Section 6.5, where we show that slaughterhouse openings are not correlated with pre-treatment levels or trends in our main outcome variables.

Finally, we conduct a series of robustness checks to assess the sensitivity of our results. These include alternative transformations of the dependent variables, different definitions of the treatment radius, and the use of alternative estimators such as those proposed by Sun and Abraham (2021) and Roth and Sant'Anna (2021), which rely on different identifying assumptions. We also explore the use of an alternative control group consisting of "never-treated" municipalities. As discussed in detail in Section 6.5, our main findings remain largely robust across these alternative specifications.

5 Data

Our main analysis spans a 25-year period from 1994 to 2019, but, as noted above, we also examine two shorter sub-periods—2000–2019 and 2009–2019—to account for differences in data availability across outcomes and to ensure sufficient statistical power when comparing pre- and post-opening periods. We compile a publicly available municipality-year dataset that integrates multiple sources of information. The data are organized into three categories: (i) outcome variables, (ii) treatment variables capturing the timing and location of slaughterhouse openings, and (iii) additional covariates used to control for potential confounders. Summary statistics for all variables are reported in Appendix Table A.5.

5.1 Outcome Variables

Cattle Heads. We collect data on the number of bovines from the *Pesquisa Pecuária Municipal* (PPM), produced by IBGE (*Instituto Brasileiro de Geografia e Estatística*—the Brazilian Bureau of Statistics), for the period 1994–2019. The PPM is an annual municipality-level survey that reports counts of commercially raised animals across multiple species. Because the PPM does not distinguish animals by age or sex, we supplement these data with information from the Brazilian Agricultural Censuses of 2006 and 2017 to construct a weighted average of animal units hosted by each municipality in a given year.[11]

[11] An animal unit is a standardized measure of animal size and weight. For cattle, one animal unit corresponds to 450 kilograms of live weight.

Pasture Quality. We collect satellite-derived data on pasture quality for all Brazilian municipalities from the *Atlas das Pastagens*—an initiative of LAPIG-UFG.[12] The data are available annually from 2000 to 2019 and classify pastureland into three levels of degradation: (i) severely degraded areas, (ii) intermediately degraded areas, and (iii) non-degraded areas. Pasture degradation is measured using the Enhanced Vegetation Index (EVI), derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Earth Observing System-Terra platform (Huete et al., 2002; LAPIG, 2022). The EVI ranges from 0 to 1. Values above 0.6 correspond to non-degraded areas; values between 0.4 and 0.6 correspond to intermediately degraded areas; and values below 0.4 correspond to severely degraded areas. Conceptually, the EVI captures pasture degradation based on several biophysical characteristics of the land, including (i) vegetation height, (ii) the number of termite nests, (iii) the degree of vegetation homogeneity, (iv) the number of weed invaders, and (v) the amount of exposed bare soil. Lower vegetation height, greater termite activity, lower homogeneity, a higher prevalence of weed invaders, and more exposed bare soil are all associated with higher levels of pasture degradation. By aggregating severely and intermediately degraded pasture areas, we construct a measure of total degraded pastureland, which we use as a dependent variable alongside severely degraded pasture areas.

Land Cover and Land Use. We utilize annual data on land cover and land use from MapBiomas for the period 1994–2019. MapBiomas processes 30-meter-by-30-meter Landsat-8 satellite images to document and classify land-use change and land cover in Brazil (MapBiomas, 2022).[13] In particular, we construct municipality-year-level measures of natural forest area, pastureland, and agricultural area. Natural forest area corresponds to land covered by forests and native vegetation and excludes planted forests used for commercial purposes. Pastureland and agricultural area refer to land covered by pastures and crops, respectively (with pastures being either planted or natural). MapBiomas data are measured in hectares and correspond to the period from January through December of each year.

[12] LAPIG-UFG stands for *Laboratório de Processamento de Imagens e Geoprocessamento* at the *Universidade Federal de Goiás* (Laboratory for Image Processing and Geoprocessing at the Federal University of Goiás).

[13] MapBiomas is a Brazilian collaborative network composed of NGOs, universities, and startup companies that maps land-use and land-cover change in Brazil using satellite data from 1985 to 2021 (MapBiomas, 2022). By applying machine-learning techniques at the pixel level, the MapBiomas platform classifies land into multiple uses and tracks changes over time (e.g., it provides information on areas used for (i) pasture, (ii) agriculture, (iii) urbanization, and (iv) forests, among others).

5.2 Treatment Variables

Slaughterhouse Openings. We collect annual data from the Ministry of Agriculture and Livestock (*Ministério da Agricultura e Pecuária*) on federally inspected bovine slaughterhouses for the period 1994–2019. The data include information on plant location, opening dates, and slaughter capacity for all regions of Brazil, covering a total of 174 slaughterhouses nationwide. Since our unit of analysis is at the municipality level—and a few municipalities host more than one plant—we define treatment timing based on the opening date of the first slaughterhouse in each municipality. In the aggregated data, we identify 167 municipalities that host at least one slaughterhouse. Based on evidence provided by Franco (2013), as discussed in the background section, we further assume that each slaughterhouse sources cattle within a 200-kilometer radius of its location. Given our municipality-level unit of analysis, we identify affected municipalities by computing whether they fall within a 200-kilometer radius of the slaughterhouse's geolocation (based on latitude and longitude).[14] Accounting for this sourcing radius, the initial 167 municipalities hosting slaughterhouses translate into 3,944 municipalities (out of 5,570 Brazilian municipalities) that are eventually impacted (treated) by plant openings.

Certification-like, legally enforceable commitments. Data on slaughterhouses that signed *Termos de Ajustamento de Conduta* (*TAC*s)—certification-like, legally enforceable commitments—starting in 2009 are drawn from Barreto et al. (2017). That study combines field and satellite data to identify individual plants that became *TAC* signatories. Building on their methodology, we adopt a similar approach to define the *TAC* influence zone, i.e., the set of municipalities influenced by *TAC*s. Specifically, we define the *TAC* influence zone as comprising all municipalities within a Brazilian state that hosts at least one federally inspected slaughterhouse that is a *TAC* signatory. This classification is motivated by the structure of Brazil's federal prosecution system, which operates at the state level, with federal prosecutors exercising jurisdiction within their respective states (MPF, 2020). Consequently, the presence of a *TAC*-signatory plant in a given state implies a higher likelihood that additional plants in that state may also become signatories. Ranchers located in these areas are therefore more likely to sell cattle to existing or potential *TAC*-signatory slaughterhouses, which may affect their land-use decisions. Based on this definition, we partition Brazilian municipalities into two groups: (i) those under the influence of *TAC*s (i.e., municipalities located in *TAC* states); and (ii) those located in other parts of the country. In Section 6, we use this partition to analyze how slaughterhouse openings after 2009 affect

[14] Only four slaughterhouses could not be geolocated. In those cases, we use the centroid of the municipality hosting the slaughterhouse as the reference point for computing the 200-kilometer radius.

our outcomes of interest across these regions.

5.3 Additional Data

Socio-economic covariates. We collect data on rural population and illiteracy (for individuals over 25 years old) for 1991 from the *Atlas dos Municípios* database, published by the United Nations. Note that these data are pre-period, as our main specification relies on the conditional parallel trends assumption, discussed in Section 4.

Geoclimatic covariates. Data on latitude, longitude, and temperature at the municipality level are sourced from Da Mata and Resende (2020). Consistent with the approach described above, we calculate average temperatures over the period 1960–1991 to obtain pre-period temperature means, which we include as covariates.

6 Results

We organize our results into four parts. First, we examine the effects of slaughterhouse openings on production outcomes, including cattle counts, pasture area, and bovine productivity. Second, we assess the effects on environmental outcomes—specifically, changes in natural forest areas and land degradation, including both total and severely degraded pastureland. Finally, we compare the effects of slaughterhouse openings between areas subject to and not subject to certification-like, legally enforceable commitments (*TAC*s), focusing on bovine productivity, pasture degradation, and deforestation. After presenting these results, we describe the robustness checks used to evaluate the strength of our empirical strategy and findings.

Our main results are presented in Tables 1 through 3 and Figures 3 and 4. We report results in a consistent format throughout. As discussed in Section 4, we first present group-aggregated average treatment effects in tables and then report event-study estimates in figures. This approach allows us to assess the consistency of the findings and alleviates concerns regarding our research design. All variables measured in area—such as pasture area and natural forest area—are normalized by municipal area. This normalization facilitates comparisons across municipalities of different sizes and allows coefficients to be interpreted as land shares.

6.1 Effects on Cattle Production and Productivity

We begin by examining the effects of slaughterhouse openings on production outcomes, focusing on cattle counts, the land share of pasture area, and bovine productivity. Table 1 reports group-aggregated average treatment effects for the period 1994–2019 across 3,944 Brazilian municipalities. Following a slaughterhouse opening, the average treated municipality experiences a sizable increase of approximately 15 thousand cattle heads, while the land share devoted to pasture rises by about 1.47 percentage points, as shown in columns (i) and (ii) of Table 1. For a municipality of average size in Brazil (1,528 square kilometers), this corresponds to an expansion of roughly 2,250 hectares converted into pastureland—an area comparable in size to roughly 3,200 FIFA-standard soccer fields, or about 4,250 American football fields—underscoring the substantial land-use implications of slaughterhouse entry.

Despite this concurrent expansion in cattle inventories and pastureland, we find no evidence of changes in bovine productivity, defined as the number of cattle heads per hectare of pastureland. Column (iii) of Table 1 shows a slightly negative and statistically insignificant effect on productivity. This result is consistent with Brazil's long-standing pattern of relatively low bovine productivity over the past three decades, reflecting the predominance of extensive livestock production systems.

The group-aggregated estimates are complemented by event-study results that trace the dynamic responses to slaughterhouse entry over time. Figure 3 shows that slaughterhouse openings lead to persistent increases in both cattle numbers and the land share allocated to pasture. For instance, as shown in panel (a), eight years after the start of construction of a new plant, ranchers located within a 200-kilometer radius of a municipality hosting a plant increase their cattle herds by approximately 33 thousand heads relative to the year prior to construction. Panel (b) documents similarly pronounced cumulative effects on pasture expansion. In contrast, panel (c) reveals no detectable effect on bovine productivity. Taken together, these patterns indicate that ranchers respond to increased demand from new slaughterhouses primarily by expanding production along the extensive margin rather than by intensifying production through productivity gains.

These findings align closely with the mechanisms outlined in the conceptual framework. Slaughterhouse entry raises cattle prices (p_C), increasing the profitability of both extensive and intensive ranching. In the absence of sufficiently strong enforcement, the framework predicts that land reallocates mainly toward extensive production, leading to higher cattle inventories and pasture expansion without improvements in average productivity. The empirical results support this prediction, suggesting that intensive yields are not sufficiently high relative to extensive yields, or that intensive production costs remain binding, thereby limiting incentives for intensification in response to market-driven demand shocks.

6.2 Effects on Deforestation

Our results thus far indicate that ranchers expand cattle production primarily through increases in pasture area. Such expansion may occur either by reallocating land from other agricultural uses or by clearing native vegetation. The latter channel entails substantial social costs through deforestation. Colunm (i) in Table 2 reports the group-aggregated average treatment effects of slaughterhouse openings on the land share of natural forest areas, our measure of remaining native vegetation at the municipality level.

We find that the share of natural forest area declines by approximately 2.3 percentage points following the opening of a new slaughterhouse. Again, for a municipality of average size in Brazil (1,528 square kilometers), a 2.3 percentage point reduction in native vegetation corresponds to roughly 3,500 hectares—an area equivalent to about 5,000 FIFA-size soccer fields or approximately 6,600 American football fields. This result indicates that deforestation increases significantly in response to slaughterhouse entry across municipalities.[15] The reduction in forest cover is consistent with ranchers' choice to expand production by converting land into pasture and aligns with the high rates of forest loss observed in Brazil over the period of analysis.

Panel (a) in Figure 4 presents the corresponding event-study estimates for the land share of natural forest areas. The figure shows a clear and persistent negative response following the entry of a slaughterhouse within a 200-kilometer radius, corroborating the group-aggregated effects reported in Table 2.

These findings closely mirror the predictions of the conceptual framework. In response to slaughterhouse entry, higher cattle prices (p_C) increase the profitability of extensive ranching, which relies on the conversion of forest into pasture. In the absence of sufficiently strong enforcement, the framework predicts increased deforestation. The observed decline in natural forest areas therefore reflects the expansion of extensive ranching as the primary adjustment margin, reinforcing the link between market-driven demand shocks, land-use change, and forest loss highlighted in the model.

[15]Although the increase in pastureland discussed above is slightly smaller than the corresponding deforestation response—with the difference not statistically significant—this pattern suggests that complementary activities may reinforce deforestation. Such activities could include expanding crop cultivation, building roads, or other land-use changes that improve access to newly cleared areas.

6.3 Effects on Land Degradation

We next examine how slaughterhouse openings affect land quality within existing pasture areas. Consistent with the expansion of cattle production primarily along the extensive margin, slaughterhouse entry also leads to increased pastureland degradation. Our analysis focuses on pasture conditions between 2000 and 2019, reflecting data availability only for this subperiod. Columns (ii) and (iii) in Table 2 report group-aggregated average treatment effects for the shares of degraded and severely degraded pastureland, measured as proportions of municipal area.

The results show substantial increases in the share of degraded pastureland following the opening of a new slaughterhouse (1.6 percentage points), driven in part by an expansion of severely degraded pasture areas (1.04 percentage points). For a municipality of average size in Brazil (1,528 square kilometers), this corresponds to roughly 2,450 hectares of pasture experiencing some level of degradation—equivalent to about 3,500 FIFA-size soccer fields or approximately 4,600 American football fields—including around 1,600 hectares classified as severely degraded.

These patterns indicate that, beyond expanding pasture area, ranchers increase grazing pressure on existing pastures. As discussed in previous subsections, ranchers raise both cattle inventories and the land share of pasture without improving bovine productivity. Combined with the degradation results in Table 2, this evidence suggests that ranchers also adjust by reducing inputs required to maintain pasture quality, leading to overgrazing and accelerated degradation. Because degraded pastures support fewer cattle per hectare, the expansion of degraded land is both a consequence of these production choices and a reinforcing factor behind stagnant bovine productivity.

Figure 4 presents the corresponding event-study estimates. Panel (b) shows a sustained increase in the share of total degraded pastureland following slaughterhouse entry. Evidence from panel (c) suggests that this increase is indeed partially accounted for by the expansion of severely degraded pasture areas. These dynamic patterns closely mirror the group-aggregated results and confirm that pasture degradation intensifies over time following slaughterhouse entry.

These findings are closely related to the conceptual framework. Slaughterhouse entry increases cattle prices (p_C), strengthening incentives to expand production. In the absence sufficiently high returns to intensive ranching, the framework predicts that producers rely on extensive expansion while reducing costly inputs (γc_I) needed to maintain pasture quality and support intensive production. Lower investment in pasture management leads to overgrazing and land degradation, shifting land away from productive intensive use toward lower-quality extensive use. In this sense, pasture degradation emerges as a key margin through which market-driven demand shocks translate into stagnant productivity and heightened environmental costs, reinforcing the framework's prediction that weak incentives for intensification can undermine both efficiency and land quality.

6.4 Certification-Like, Legally Enforceable *TAC* Commitments

Our findings thus far show that slaughterhouse openings increase demand for cattle, leading ranchers to expand both cattle inventories and pasture areas. This expansion occurs primarily along the extensive margin. In the absence of productivity gains, increased grazing pressure deteriorates pasture quality, as reflected in higher levels of land degradation, and induces land-use change through the conversion of natural forest areas into pastureland.

These patterns point to a fundamental trade-off between cattle production and environmental preservation in Brazil. However, the severity of this trade-off depends on the institutional environment, particularly the ability to enforce environmental regulations that restrict land-use conversion. If ranchers are legally constrained from expanding into native vegetation, they must rely on alternative margins of adjustment to meet rising demand from slaughterhouses. Under limited state capacity, weak enforcement may fail to deter illegal expansion, allowing deforestation and degradation to persist. Against this backdrop, we examine whether agreeable enforcement—through the outsourcing of monitoring and enforcement functions to private actors—can decouple land-intensive cattle production from deforestation and degradation. Specifically, we study the certification-like, legally enforceable commitments (*TAC*s) described in Section 2.

To conduct this analysis, we restrict the sample to the post-2009 period, as *TAC* agreements began being signed in 2009, and separate municipalities into two groups: (i) those within the influence of *TAC* commitments and (ii) those outside *TAC* influence. As described in Section 2, *TAC* influence depends on whether there is at least one signatory slaughterhouse in the municipality's state, reflecting the jurisdiction of federal prosecutors in Brazil. Once a plant in a given state signs a *TAC*, other plants in the same state may be more likely to sign similar agreements, shaping producers' expectations and land-use decisions statewide. The group of *TAC* municipalities includes all municipalities in the states of *Rondônia*, *Acre*, *Amazonas*, *Pará*, *Tocantins*, *Maranhão*, *Mato Grosso do Sul*, *Mato Grosso*, and *Goiás*, which substantially overlap with the Amazon and surrounding regions. All other municipalities are classified as non-*TAC*.

For each group, we implement the same empirical strategy described in Section 4, restricting the sample to 2009–2019 and defining treated units as municipalities located within a 200-kilometer radius of a slaughterhouse opening. Table 3 reports the estimated effects separately for *TAC* and non-*TAC* municipalities, allowing us to compare treatment effects across institutional contexts.

The results reveal sharp contrasts across enforcement regimes. In *TAC* municipalities, the share of natural forest area does not change following slaughterhouse openings (column (i) of Table 3), whereas it declines substantially in non-*TAC* municipalities (column (ii)), indicating increased deforestation in the absence of *TAC* enforcement. At the same time, the share of severely degraded pastureland decreases in *TAC* areas (column (iii), while no significant changes are observed in non-*TAC* municipalities (column (iv)). Consistent with these land-use patterns, *TAC* municipalities experience an increase in bovine productivity of nearly one additional head per hectare (column (v)), whereas productivity appears unchanged in non-*TAC* areas (column (vi)), although the point estimate is larger but not statistically significant.[16]

Appendix Figure A.1 presents the corresponding event-study estimates, with panels (a) through (f) showing outcomes separately for *TAC* and non-*TAC* municipalities. While some estimates are imprecise—due to splitting the main sample in two parts—the dynamic responses are, by and large, consistent with the group-level estimates and suggest that the divergence between *TAC* and non-*TAC* areas emerges following the entry of a slaughterhouse.

These findings are consistent with the predictions of the conceptual framework. In the model, stronger enforcement raises the effective cost of extensive ranching by increasing the penalties associated with deforestation (θ), reducing the relative payoff of land expansion into forested areas. Consequently, land reallocates away from extensive production and toward intensive ranching or improved pasture management. While the framework highlights that the effect of enforcement on productivity is theoretically ambiguous—depending on the relative sizes of intensive and extensive yields, production costs, and opportunity costs of forest—our results suggest a positive effect: *TAC* enforcement increases productivity by constraining forest conversion and incentivizing better pasture management. In this way, certification-like enforcement allows cattle production to respond to market-driven demand shocks without relying on environmentally costly extensive expan-

[16] In Appendix Table A.6, we formally test whether the estimated average treatment effects differ across *TAC* and non-*TAC* municipalities. Specifically, we compute pairwise differences between the group-aggregated ATT estimates obtained for each outcome under the two enforcement regimes and evaluate their statistical significance using a Wald-type test that accounts for the sampling uncertainty of the Callaway and Sant'Anna (2021) estimator. The results confirm statistically significant differences across regimes for natural forest area and severely degraded pastureland, while differences in bovine productivity are imprecisely estimated.

sion, effectively improving both land-use efficiency and environmental outcomes.

6.5 Robustness Checks

We conduct a series of robustness checks to assess the sensitivity of our results to alternative specifications and sample definitions. In these exercises, we follow a format similar to the main analysis, examining outcomes for cattle counts, pasture areas, degraded pastureland, and natural forest areas. In the Online Appendix, we first present the group-aggregated coefficients in Appendix Tables A.7 to A.14, followed by the corresponding event-study estimates in Appendix Figures A.2 to A.8.

No Outcome Variable Transformations. In our baseline analysis, several variables—particularly those measured in terms of area—are expressed relative to municipality size to account for the substantial heterogeneity in the size of Brazilian municipalities. In Appendix Table A.7, we present the main results without applying these variable transformations, focusing on pasture areas, degraded pastureland, and natural forest areas. Appendix Figure A.2 shows the corresponding event-study estimates for the same outcomes. Overall, the results remain qualitatively similar—however, some pre-trends are more pronounced, likely reflecting the variation in municipality sizes.

Addressing Reverse Causality Concerns. A potential concern in our empirical strategy is the direction of causality: we argue that slaughterhouse openings drive changes in production and environmental outcomes at the local level. However, it is possible that slaughterhouse openings occurred in municipalities that already had high cattle inventories, extensive pasture areas, or forest available for conversion, implying that pre-existing conditions may have influenced plant location. To address this possibility, we estimate a two-way fixed effects regression to test for correlations between lags and leads of outcome variables (e.g., cattle counts, pasture area, and natural forest area) and the timing of slaughterhouse openings. If no significant correlation exists, this strengthens the credibility of our identification strategy. Specifically, we estimate:

$$y_{it} = \gamma + \beta X_{i,t-j} + \eta W_{i,t+j} + \varepsilon_{it}, \tag{5}$$

where y_{it} is a dummy variable equal to 1 if municipality i receives a slaughterhouse in year t and 0 otherwise; $X_{i,t-j}$ and $W_{i,t+j}$ for $j \in [1,5]$ are vectors of lagged and lead values of the outcome variables—specifically, bovine counts and the shares of pasture area and natural forest areas. The parameters of interest, β and η, capture the correlation between slaughterhouse openings (the treatment variable in our main specification, but the dependent variable in this exercise) and past or future values of these outcomes.

Appendix Table A.8 reports the results for municipalities that eventually receive a slaughterhouse. Most coefficients on both lags and leads for bovine counts, pasture area shares, and natural forest shares are near zero and statistically insignificant. The F-test of the joint null hypothesis also provides no evidence of pre-existing correlations.

Finally, we perform the same analysis separately for *TAC* and non-*TAC* municipalities to assess whether the outcome variables are systematically correlated with outcome variables in *TAC*-signing areas. Appendix Tables A.9 and A.10 report the results. Consistent with the previous results, all coefficients on both lags and leads of bovine productivity, pasture area shares, and natural forest shares are statistically insignificant. Moreover, the F-test for the joint null hypothesis again indicates no pre-existing trends. These findings should alleviate concerns regarding potential reverse causality in our setting.

Placebo Test With *Swine* Slaughterhouses. Our baseline results, in which treated municipalities are defined as those within a 200-kilometer radius of a bovine-slaughterhouse opening, reveal a clear pattern: following a new plant opening, nearby localities experience increases in cattle inventories and pasture area, accompanied by reductions in both natural forest cover and pasture quality. To assess whether this pattern depends on our specific treatment, we conduct a placebo test using openings of *swine* slaughterhouses.[17]

Bovine production in Brazil is highly land-intensive, currently requiring over 155 million hectares to raise more than 200 million cattle. In contrast, swine production relies on intensive capital and labor inputs rather than land (EMBRAPA, 2023a; EMBRAPA, 2023b). Consequently, we expect that swine-slaughterhouse openings should have different effects from those observed for bovine plants, particularly regarding deforestation via pasture expansion.

Appendix Table A.11 reports the effects of swine-slaughterhouse openings on cattle inventories, pasture area, and natural forest cover. The results show no detectable effects on pasture or natural forest areas, as expected, and we find opposite effects on cattle counts relative to our baseline results, which may reflect substitution between cattle and swine activities in response to swine-slaughterhouse openings. Appendix Figure A.3 presents the corresponding event-study estimates.

As anticipated, replacing *bovine*-slaughterhouse openings with *swine*-slaughterhouse

[17] Data on federally-inspected swine slaughterhouses were collected using the same database and methodology described for bovine slaughterhouses in Section 5. We apply the same 200-kilometer radius procedure to define treated municipalities. While our baseline bovine-slaughterhouse openings affect 3,944 municipalities, swine-slaughterhouse openings impact 1,940 municipalities over the same period.

openings in our main analysis produces markedly different outcomes. This placebo exercise reinforces our main interpretation: land-intensive industries, such as beef cattle, drive the observed trade-off between environmental preservation and production.

Alternative Radiuses from Slaughterhouses. In our main specification, treated municipalities are defined as those located within a 200-kilometer radius of slaughterhouse openings, consistent with evidence on typical cattle procurement distances (Franco, 2013). To assess the sensitivity of our results to this choice, we redefine treated municipalities using alternative radiuses of 100 kilometers and 300 kilometers. Recall that in our main analysis, 3,944 municipalities were treated out of the 5,570 municipalities in Brazil. Using a 100-kilometer radius reduces the number of treated municipalities to 2,798, whereas a 300-kilometer radius increases it to 4,188. Appendix Table A.12 reports the group-aggregated effects, while Appendix Figure A.4 presents the corresponding event-study estimates.

Overall, our qualitative results remain broadly consistent: slaughterhouse openings continue to increase cattle inventories and pasture area, and reduce natural forest coverage. The magnitude of the estimated coefficients is larger in absolute terms for the 300-kilometer radius and smaller for the 100-kilometer radius, reflecting the expected dilution or concentration of treatment intensity as the radius changes. However, the effect on pasture degradation becomes statistically insignificant for both alternative radiuses, suggesting that this outcome may be sensitive to the definition of the treatment area.

These patterns are also consistent with considerations related to the Stable Unit Treatment Value Assumption (SUTVA). Expanding the radius increases the chance that municipalities classified as controls are indirectly affected by nearby treated units, potentially diluting estimated effects and inflating the magnitude of coefficients in treated units. Conversely, contracting the radius reduces potential spillovers but may exclude economically affected municipalities from the treated group, underestimating local impacts and attenuating the estimated effects. Taking all this evidence together, the 200-kilometer radius likely captures the relevant spatial extent of slaughterhouse impacts, providing a reasonable balance between treatment intensity, coverage, and the plausibility of SUTVA.

Alternative Control Group. Our baseline approach defines the control group as "not-yet-treated" municipalities, which are localities that eventually receive treatment in the panel—i.e., a new slaughterhouse opening within a 200-kilometer radius. For robustness, we re-estimate our results using an alternative control group consisting of "never-treated" municipalities. The corresponding estimates are reported in Appendix Table A.13, with event-study results shown in Appendix Figure A.5. Although never-treated municipalities may differ systematically from those that eventually receive a slaughterhouse, our findings remain qualitatively and quantitatively similar to the main results under this alternative control group; notably, there is no evidence of pre-trends prior to slaughterhouse openings.

Alternative Event-Study Estimators. Our baseline analysis follows the difference-in-differences framework of Callaway and Sant'Anna (2021). To assess the sensitivity of our findings, we also consider alternative approaches from the recent event-study literature. Specifically, we implement the estimator of Sun and Abraham (2021) and the inference framework of Roth and Sant'Anna (2021). The Sun-Abraham estimator constructs cohort- and relative-time-specific treatment effects using comparisons with never- or last-treated units, thereby avoiding contamination from already-treated cohorts. In contrast, Roth and Sant'Anna (2021) do not propose a new estimator but instead provide tools for inference that evaluate the sensitivity of event-study estimates to deviations from parallel trends based on observed pre-treatment dynamics.

For completeness, we also report estimates from our baseline specification following Callaway and Sant'Anna (2021) without covariates, as well as from a conventional two-way fixed effects (TWFE) event-study model.[18] Event-study estimates from these approaches are reported in Appendix Figure A.6. In this exercise, we do not impose a universal base period; instead, each estimator is normalized using its own pre-treatment estimates to facilitate comparability across methods.

Across specifications, the estimated responses are similar in sign and timing to our baseline results. Slaughterhouse openings are generally associated with increases in cattle counts, pasture area shares, and degraded pastureland shares, as well as declines in natural forest area shares. Some specifications exhibit pre-treatment dynamics, however, reflecting differences in identifying assumptions across approaches.

Slaughterhouse Size: *Above* and *Below* the Median. In our baseline analysis, we treat all slaughterhouse openings equally, without distinguishing by plant size. However, as shown in Appendix Table A.1, slaughterhouses in our sample vary substantially in processing capacity, measured in tons of bovines per hour. To assess whether plant size matters for our results, we conduct a robustness check that divides openings into two groups: above-median capacity (plants processing more than 80 heads/hour, with or without storage capacity of 20 tons/day) and below-median capacity (plants processing up to 80 heads/hour, including those as small as 20 heads/hour).

We then estimate the effects of above- and below-median openings—within a 200km

[18]Although TWFE estimators can be difficult to interpret in the presence of dynamic and heterogeneous treatment effects, we include them for comparison.

radius—on key municipal outcomes: cattle heads, pasture area share, degraded pastureland share, and natural forest area share. These results are reported in Appendix Table A.14 and Appendix Figures A.7-A.8.

Examining results by plant size helps identify whether larger slaughterhouses exert differential local impacts, potentially reflecting differences in supply chain integration, technology adoption, or management practices. We find that patterns for cattle heads, pasture area share, and natural forest area share are broadly similar across both size categories. Interestingly, the effects on degraded pastureland differ by plant size: openings of above-median capacity are associated with decreases in degraded land, whereas below-median capacity openings are associated with increases. This pattern suggests that larger plants may encourage more modernized or technologically advanced ranching practices.

Placebo Test with Timing Randomization. To further assess the validity of our identification strategy, we conduct placebo exercises based on timing randomization inference. Specifically, we randomly shuffle the opening dates of slaughterhouses across Brazil 100 times and re-estimate our staggered difference-in-differences specification following Callaway and Sant'Anna (2021) using these randomized dates. We then plot the median event-study coefficients with standard errors and construct density plots of the distribution of group-aggregate average treatment effects. Results are reported in Appendix Figures A.9 and A.10. These exercises help evaluate whether our baseline estimates could arise from chance timing of treatment: across all placebo draws, we observe no statistically significant effects on any of our outcomes, supporting the credibility of our main findings.

7 Concluding Remarks

This paper examines how land-intensive industrial activity affects local production and environmental outcomes in settings characterized by limited state capacity. Focusing on slaughterhouse openings in Brazil, we provide causal evidence that industrial expansion in the beef sector substantially reshapes land use. New plants increase local demand for cattle, inducing ranchers to expand production primarily along the extensive margin. As a result, pastureland expands, bovine productivity remains largely unchanged, pasture quality deteriorates, and natural forest cover declines. In the absence of effective enforcement, industrial activity thus generates economic gains that are tightly coupled with land degradation and deforestation.

These patterns underscore a central challenge faced by many developing countries: when land is abundant and regulatory capacity is weak, increases in industrial demand can translate into environmentally harmful production responses rather than productivity improvements. Ranchers respond to higher prices by expanding grazing areas instead of intensifying production, leading to forest conversion and degraded pastureland. In this sense, our findings highlight a channel through which industrial activity can indirectly accelerate deforestation, even when production occurs far from forest frontiers.

We then ask whether these environmental costs are inevitable, or whether institutional innovations can decouple economic growth from environmental harm. Our analysis of legally enforceable, incentive-compatible commitments between slaughterhouses and federal prosecutors—the *TAC* agreements—shows that such decoupling is possible. In municipalities exposed to *TAC*s, new slaughterhouse openings no longer lead to forest loss or severe pasture degradation. Instead, ranchers adjust along the intensive margin: cattle productivity increases while land use and forest cover remain stable. These results suggest that *TAC*s effectively alter incentives throughout the supply chain, encouraging more sustainable production practices without suppressing economic activity.

Importantly, *TAC* agreements achieve this outcome by outsourcing monitoring and enforcement to key market actors—slaughterhouses—rather than relying on direct state oversight of dispersed ranchers. By tying access to markets and price premia to environmental compliance, these agreements function as a form of green certification that is both incentive-compatible and relatively low-cost for the government. In contexts where traditional command-and-control regulation is difficult to enforce, such market-aligned legal mechanisms can therefore serve as powerful substitutes for direct state capacity.

Our findings carry broader implications for environmental policy in developing economies. They suggest that land-intensive industrial expansion does not inherently require environmental degradation, but that outcomes depend critically on the institutional environment governing production. When private incentives are aligned with public environmental goals through enforceable and credible mechanisms, economic growth can proceed without deforestation or land degradation. More generally, the logic of incentive-compatible outsourcing may extend beyond the cattle sector, offering a scalable framework for reconciling industrial and agricultural expansion with conservation objectives in other resource-intensive industries. Overall, this study shows that limited state capacity need not preclude effective environmental protection. By leveraging market forces and legal accountability together, governments can design policies that decouple production growth from environmental harm, generating both economic and environmental gains.

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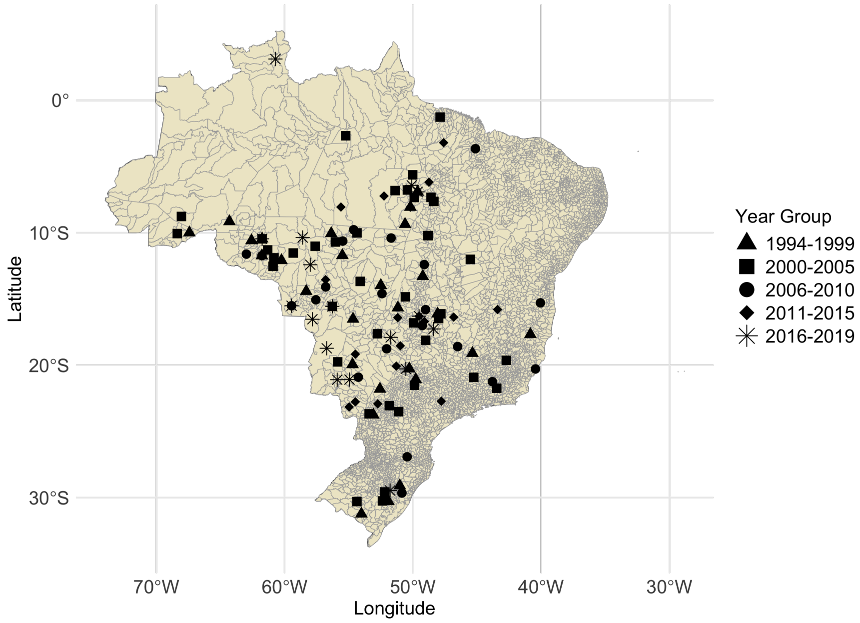
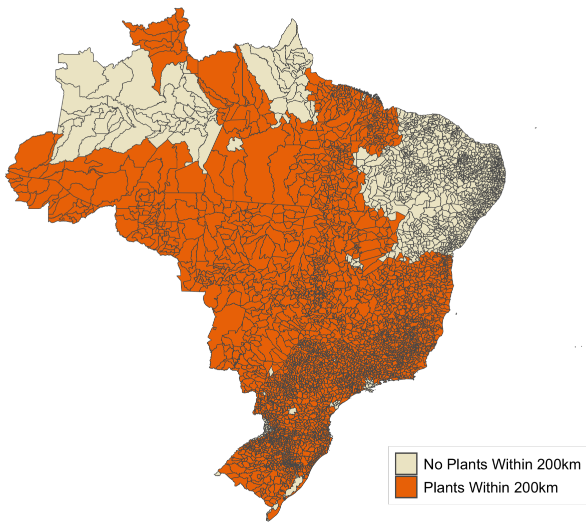
Figures and Tables

Figure 1: Slaughterhouse Openings and Affected Municipalities Across Brazil



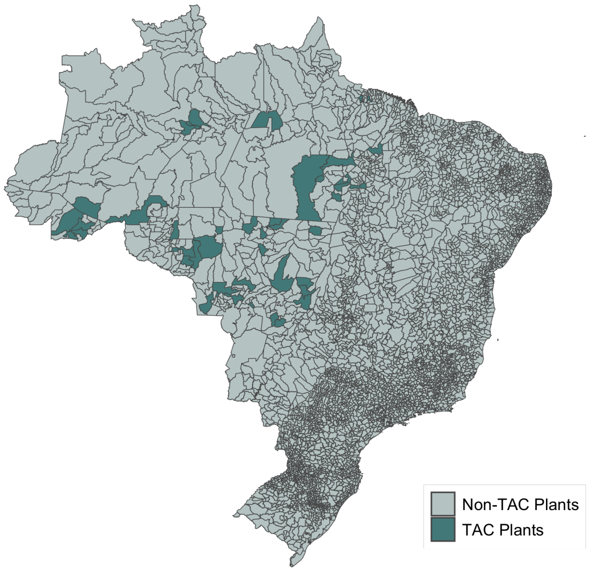
(a) Geographic Distribution and Opening Periods of Slaughterhouses



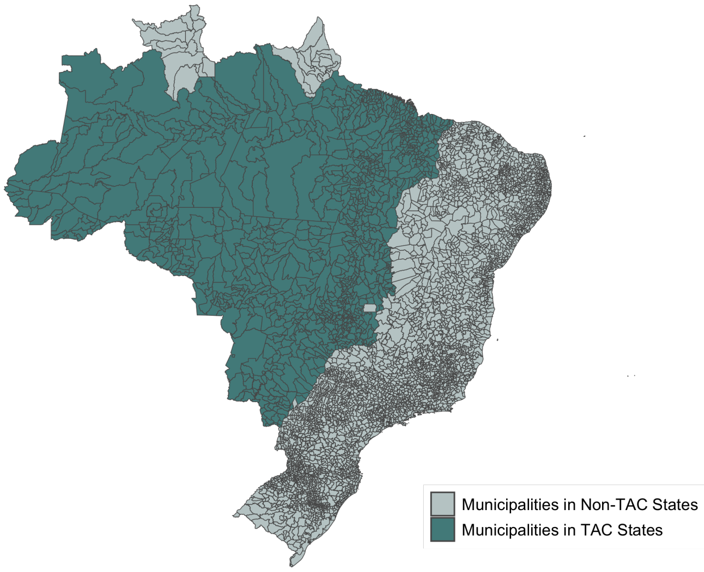
(b) Municipalities Located Within a 200-Kilometer Radius of a Slaughterhouse

Notes: Panel (a) shows the geographic distribution of federally inspected slaughterhouses across Brazil, categorized by opening year intervals: 1994–1999, 2000–2005, 2006–2010, 2011–2015, and 2016–2019. Panel (b) highlights municipalities that fall within a 200-kilometer radius of at least one slaughterhouse, representing the primary area of influence for cattle sourcing.

Figure 2: Municipalities with *TAC*-signatory Slaughterhouse Plants and Municipalities in *TAC* States



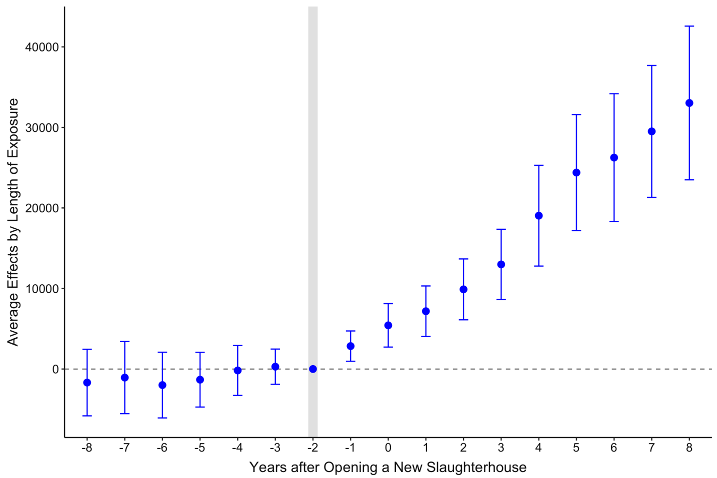
(a) Municipalities with at least one *TAC*-signatory Slaughterhouse Plant



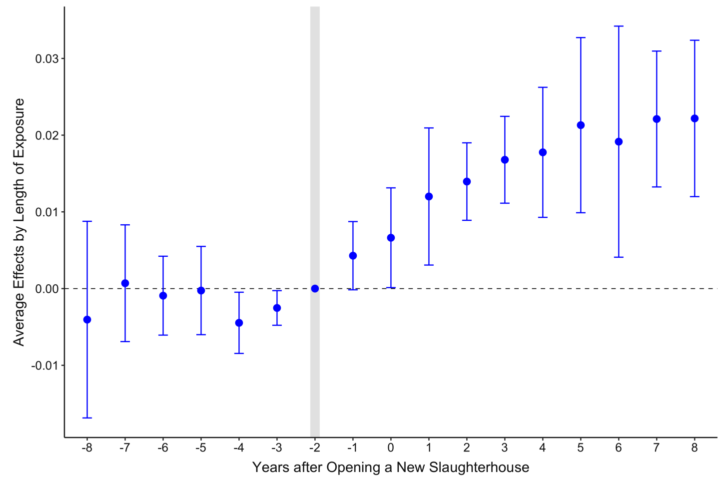
(b) Municipalities in States with at least one *TAC*-signatory Slaughterhouse Plant

Notes: The figure above displays the geographical locations of *TAC*-signatory slaughterhouses in Brazilian municipalities. Panel (a) shows municipalities which host at least one federally-inspected slaughterhouse plant which signed a *TAC*. Panel (b) presents municipalities which have a signatory slaughterhouse in their respective state.

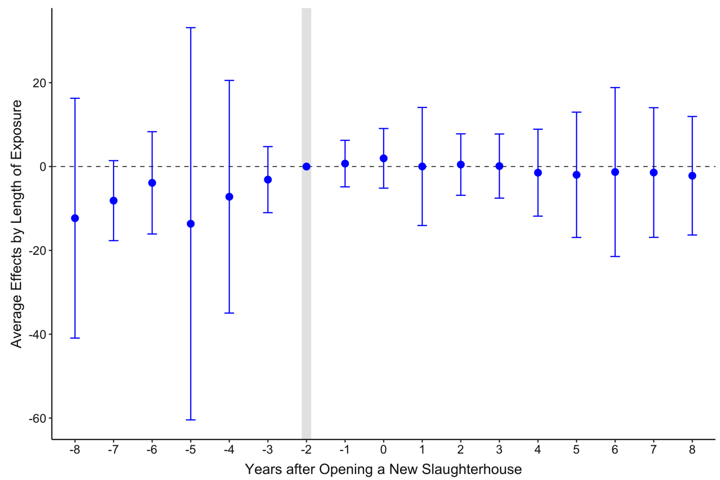
Figure 3: Production Responses to Slaughterhouse Openings: Cattle Counts, Pasture Areas and Bovine Productivity



(a) Cattle Counts



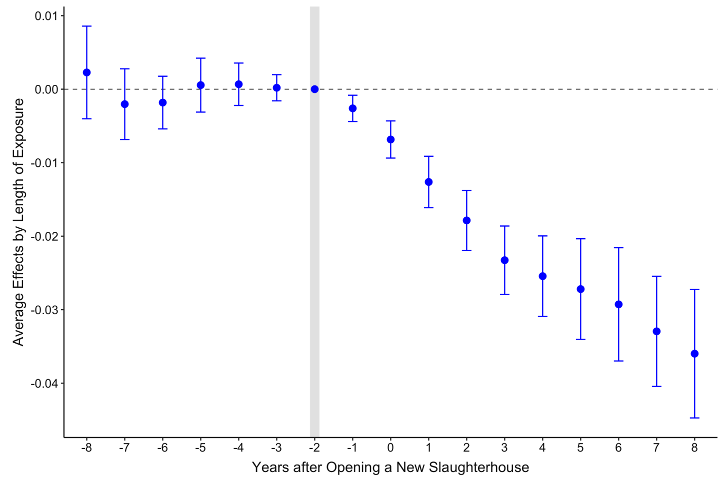
(b) Pasture Area



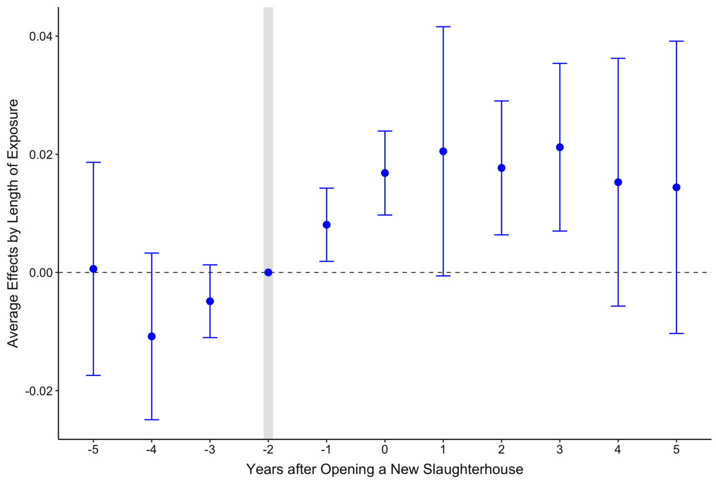
(c) Bovine Productivity

Notes: This figure presents the parameter estimates following Equation (4) for production variables. Panel (a) displays the effects on the number of “Cattle Counts". Panel (b) shows the impacts on “Pasture Area" as a share of municipal area. Finally, panel (c) presents the response of “Bovine Productivity", measured by number of heads per hectare. Period -1 is the first treatment period due to anticipation. We use data from 1994-2019.

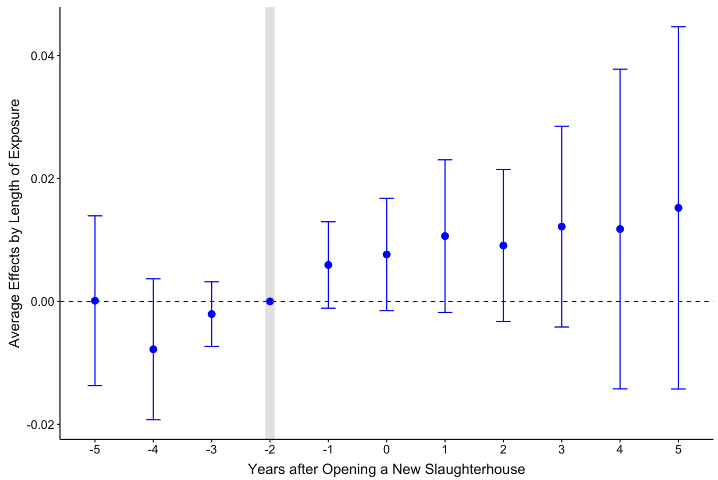
Figure 4: Environmental Responses to Slaughterhouse Openings: Natural Forest Area and Pasture Degradation



(a) Natural Forest Area



(b) Total Degraded Pastureland



(c) Severely Degraded Pastureland

Notes: This figure presents the parameter estimates following Equation (4) for environmental variables. Panel (a) displays the effects on “Natural Forest Area" as a share of municipal area. Panel (b) displays the effects on “Total Degraded Pastureland" as a share of municipal area. Panel (c) displays the effects on “Severely Degraded Pastureland" as a share of municipal area. Period -1 is the first treatment period due to anticipation. We use data from 2000 to 2019.

Table 1: Effects on Cattle Heads, Pasture Area, and Bovine Productivity

	Dependent Variable		
	Cattle Counts	Pasture Area	Bovine Productivity
	(i)	(ii)	(iii)
1{Slaughterhouse}	15,489.90***	0.0147***	-0.2503
	(1,952.73)	(0.0024)	(3.4900)
Year FE	Yes	Yes	Yes
Municipality FE	Yes	Yes	Yes
Weather Covariates	Yes	Yes	Yes
Socioeconomic Covariates	Yes	Yes	Yes

Notes. This table presents the overall summary of ATT's based on time/group/length of exposure aggregation (Equation (3)) according to Callaway and Sant'Anna (2021) for the following dependent variables: "Cattle Counts", "Pasture Area" as a share of municipal area, and "Bovine Productivity". Control group is "not-yet-treated" and anticipation period equals 1. Statistical significance is given by *p<0.1; **p<0.05; ***p<0.01. We use data from 1994-2019.

Table 2: Effects on Natural Forest Area and on Pasture Degradation

	Dependent Variable		
	Natural Forest Area	Total Degraded	Severely Degraded
	(i)	(ii)	(iii)
1 {Slaughterhouse}	-0.0230***	0.016***	0.0104***
	(0.0025)	(0.0053)	(0.0063)
Year FE	Yes	Yes	Yes
Municipality FE	Yes	Yes	Yes
Weather Covariates	Yes	Yes	Yes
Socioeconomic Covariates	Yes	Yes	Yes

Notes. This table presents the overall summary of ATT's based on time/group/length of exposure aggregation (Equation (3)) according to Callaway and Sant'Anna (2021) for the following dependent variables: "Natural Forest Area" as a share of municipal area, "Total Degraded Pastureland" as a share of municipal area, and "Severely Degraded Pastureland" as a share of municipal area. Control group is "not-yet-treated" and anticipation period equals 1. Statistical significance is given by *p<0.1; **p<0.05; ***p<0.01. We use data from 2000 to 2019.

Table 3: Effects on Natural Forest Areas, Pasture Degradation, and Bovine Productivity

	Dependent Variable					
	Natural Forest Area		Severely Degraded		Bovine Productivity	
	TAC	Non-*TAC*	*TAC*	Non-*TAC*	*TAC*	Non-*TAC*
	(i)	(ii)	(iii)	(iv)	(v)	(vi)
1 {Slaughterhouse}	0.0019	-0.0131***	-0.0161***	0.0144	0.8085***	4.3709
	(0.0074)	(0.0025)	(0.0053)	(0.0113)	(0.1996)	(6.7407)
Time FE	Yes	Yes	Yes	Yes	Yes	Yes
Municipality FE	Yes	Yes	Yes	Yes	Yes	Yes
Weather Covariates	Yes	Yes	Yes	Yes	Yes	Yes
Socioeconomic Covariates	Yes	Yes	Yes	Yes	Yes	Yes

Notes. This table presents the overall summary of ATT's based on time/group/length of exposure aggregation (Equation (3)) according to Callaway and Sant'Anna (2021) for the following dependent variables: "Natural Forest Area" as a share of municipal area, "Severely Degraded Pastureland" as a share of municipal area, and "Bovine Productivity" (cattle counts divided pasture area). All columns take covariates into account. Control group is "not-yet-treated" and anticipation period equals 1. Statistical significance is given by *p<0.1; **p<0.05; ***p<0.01. We use data from 2009 to 2019. The difference between coefficients across TAC and non-TAC municipalities is statistically significant for natural forest and degraded pastureland, but remains imprecisely estimated for bovine productivity. See Appendix Table A.6 for z-test estimates.

Industrial Activity, State Capacity, and Deforestation: Evidence from Brazil

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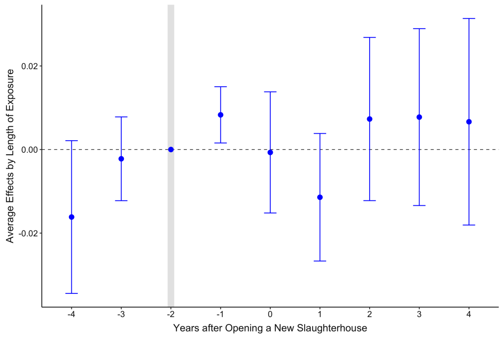
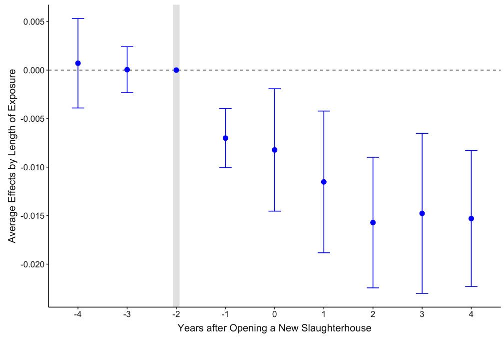
Appendix A Additional Figures and Tables

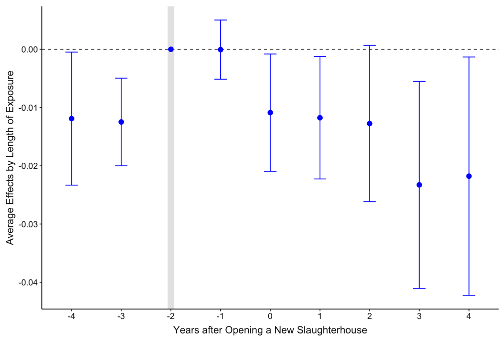
Figure A.1: Responses of *TAC* and non-*TAC* Areas to Slaughterhouse Openings



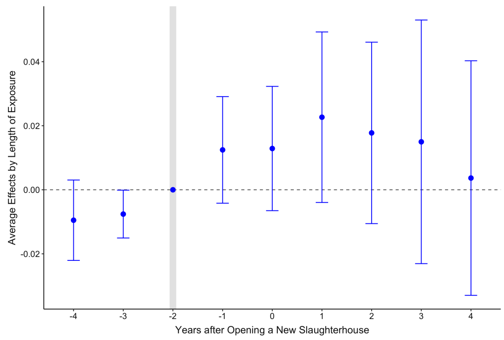
(a) *TAC*: Natural Forest Areas



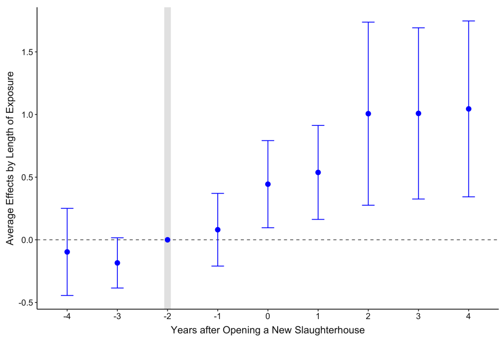
(b) Non-*TAC*: Natural Forest Areas



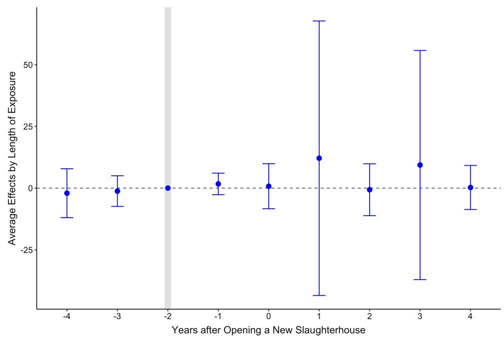
(c) *TAC*: Severely Degraded



(d) Non-*TAC*: Severely Degraded



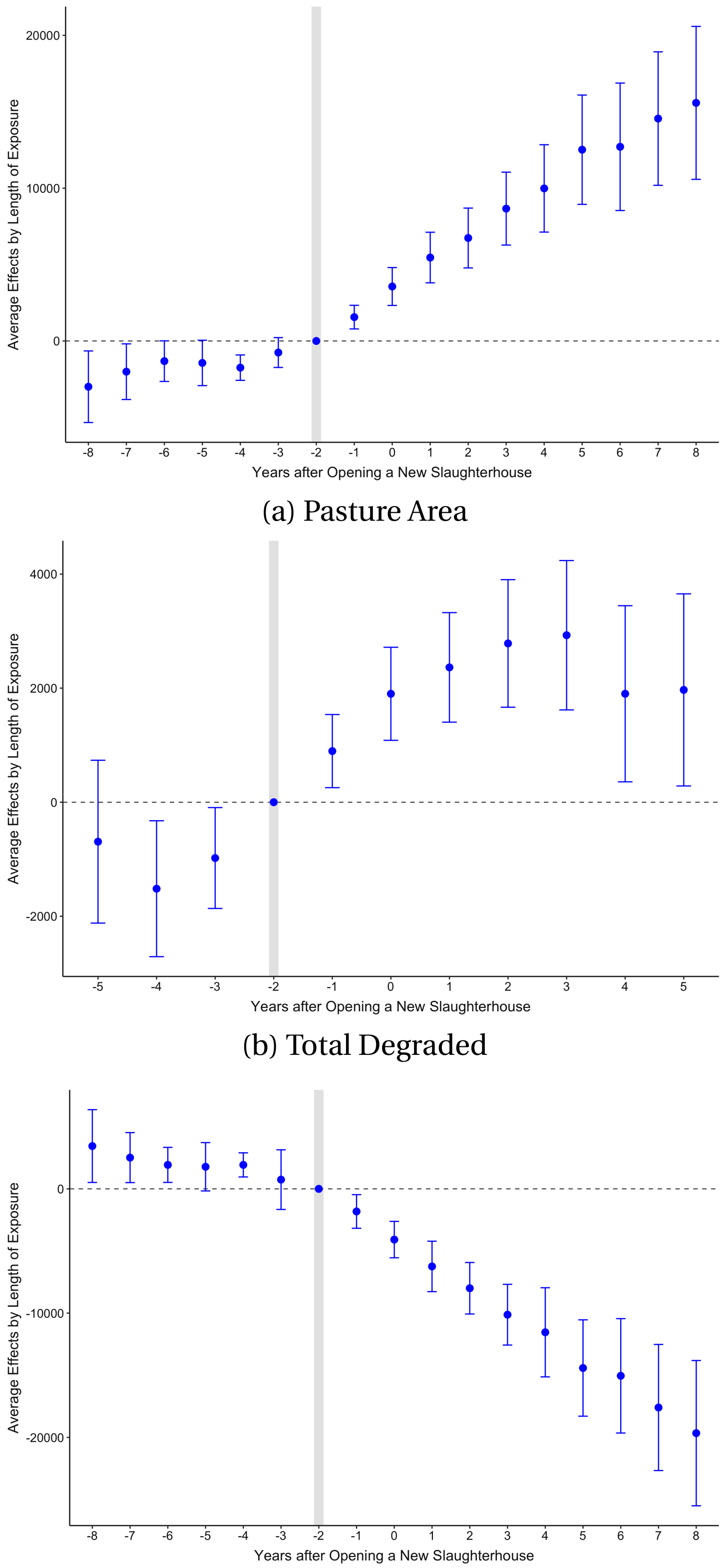
(e) *TAC*: Bovine Productivity



(f) Non-*TAC*: Bovine Productivity

Notes: This figure presents the parameter estimates following Equation (4) for areas under and outside the influence of *TAC* commitments. Panels (a) and (b) display the effects of slaughterhouse openings on "Natural Forest Area" as a share of municipal area, respectively. Panels (c) and (d) show the impacts on "Severely Degraded Pastureland" as a share of municipal area. Finally, panels (e) and (f) present the response of bovine productivity for *TAC* and non-*TAC* areas ("Bovine Productivity"), respectively. Period -1 is the first treatment period due to anticipation. We use data from 2009 to 2019.

Figure A.2: Robustness Check: Using *No* Variable Transformations on the Effects on Pasture Area, Degraded Pastureland and Natural Forest Areas



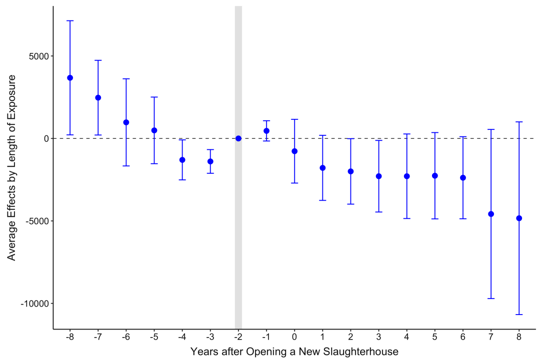
(a) Pasture Area

(b) Total Degraded

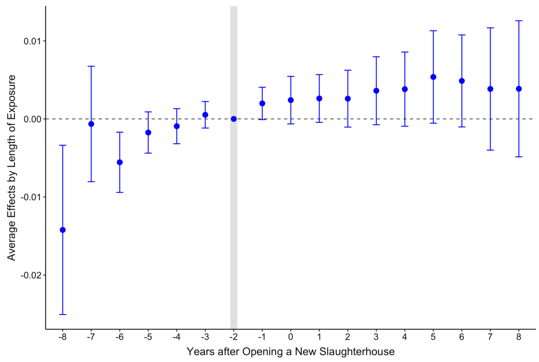
(c) Natural Forest Area

Notes: This figure presents the parameter estimates following Equation (4) for dependent variables with no transformations. Panel (a) displays results for "Pasture Area". Panelb (b) displays results for "Total Degraded Pastureland". Panels (c) shows results for "Natural Forest Area". Period -1 is the first treatment period due to anticipation.

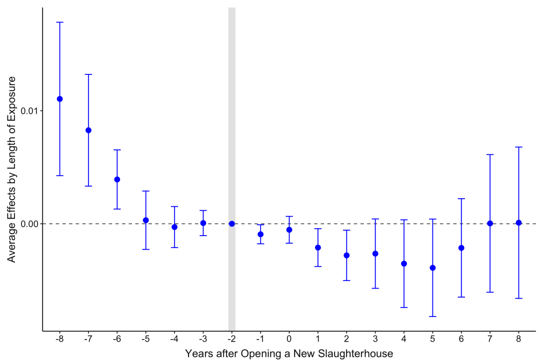
Figure A.3: Robustness Check: Placebo Test with *Swine* Slaughterhouses on the Effects on Cattle Counts, Pasture Area, and Natural Forest Areas



(a) Cattle Counts



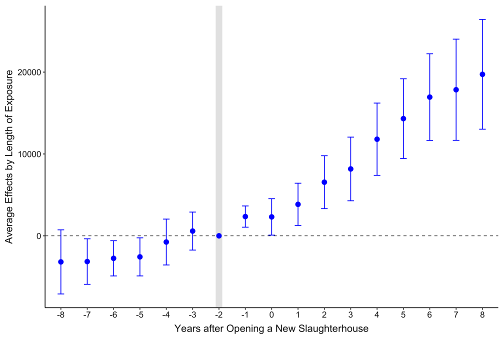
(b) Pasture Area



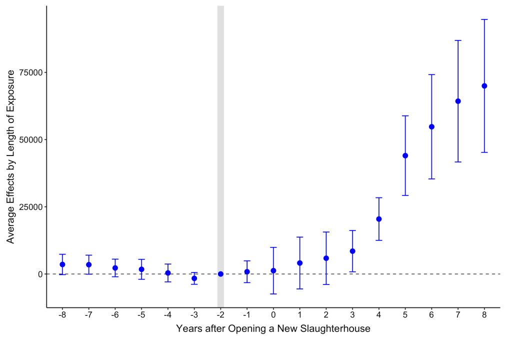
(d) Natural Forest Area

Notes: This figure presents the parameter estimates following Equation (4) for dependent variables "Cattle Counts", "Pasture area" as a share of municipal area, and "Natural Forest Area" as a share of municipal area. We use the opening of slaughterhouses for *swines* within 200 kilometers as treatment for municipalities. Panel (a) displays results for "Cattle Counts". Panel (b) displays results for "Pasture area" as a share of municipal area. Panels (c) shows results for "Natural Forest Area" as a share of municipal area. Period -1 is the first treatment period due to anticipation.

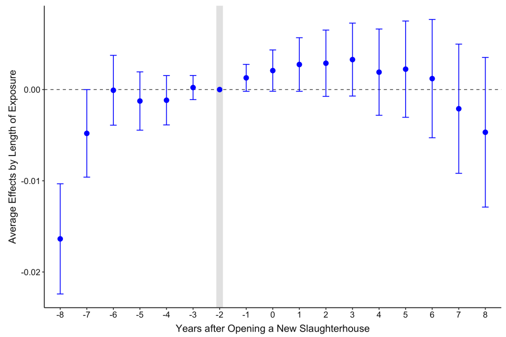
Figure A.4: Robustness Check: Using Different Radiuses to Estimate the Effects on Cattle Heads, Pasture Area, Degraded Pastureland, and Natural Forest Area



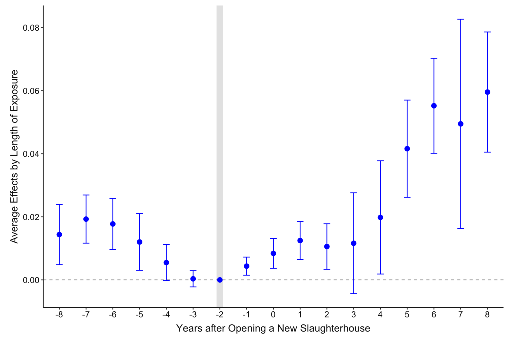
(a) Cattle Heads (100km)



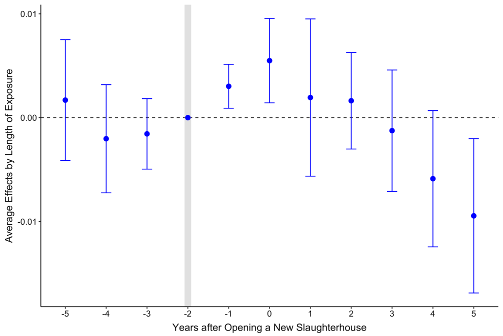
(b) Cattle Heads (300km)



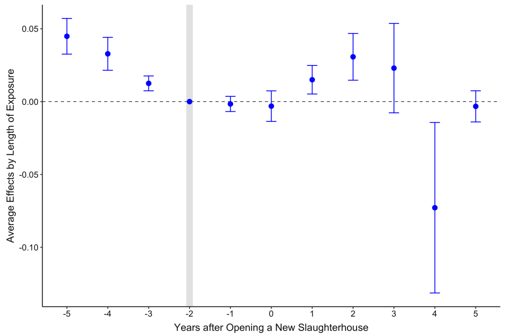
(c) Pasture Area (100km)



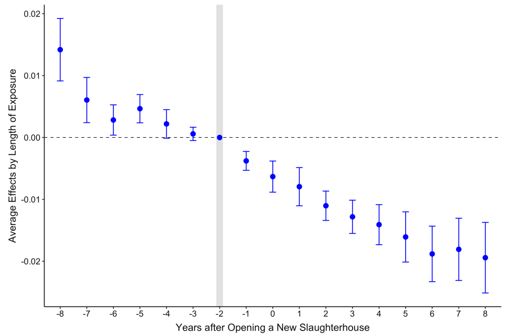
(d) Pasture Area (300km)



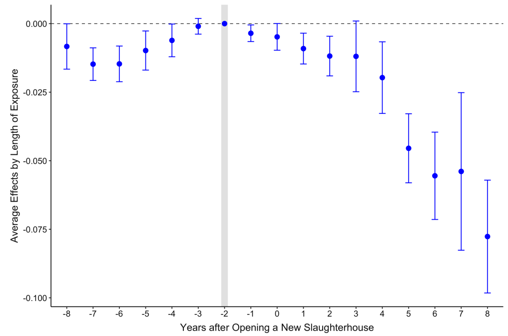
(e) Total Degraded (100km)



(f) Total Degraded (300km)



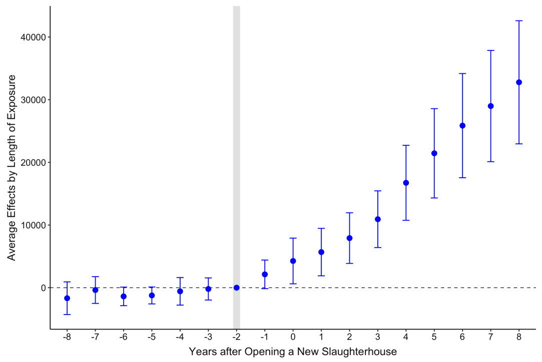
(g) Natural Forest Area (100km)



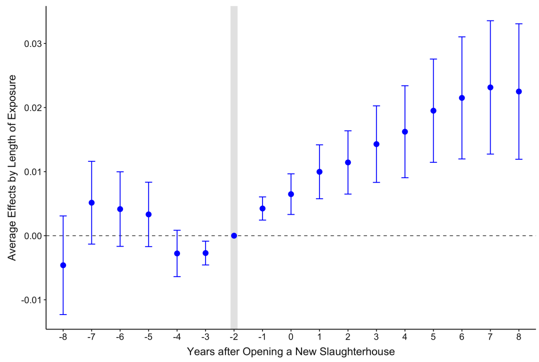
(h) Natural Forest Area (300km)

Notes: This figure presents the parameter estimates following Equation (4) for different radiuses of treatment. Panels (a) and (b) display results for “Cattle Heads" for 100km and 300km, respectively. Panels (c) and (d) show results for “Pasture Area" as a share of municipal area for 100km and 300km, respectively. Panels (e) and (f) display results for “Total Degraded Pastureland" as a share of municipal area for 100km and 300km, respectively. Panels (g) and (h) show results for “Natural Forest Area" as a share of municipal area for 100km and 300km, respectively. Period -1 is the first treatment period due to anticipation.

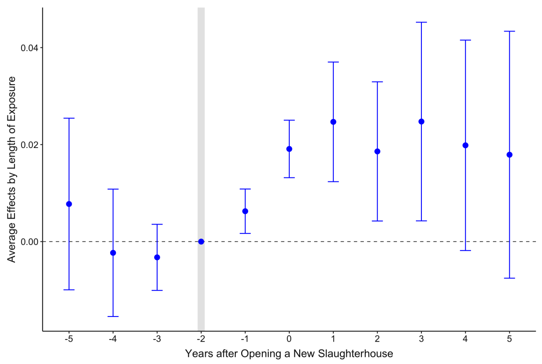
Figure A.5: Robustness Check: Using *Never-Treated* Municipalities as Control Group to Estimate the Effects on Cattle Heads, Pasture Area, Degraded Pastureland, and Natural Forest Area



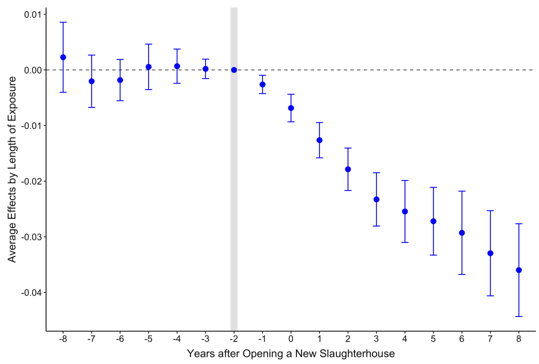
(a) Cattle Heads



(b) Pasture Area



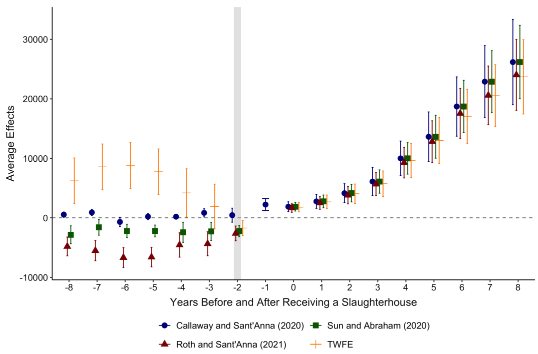
(e) Total Degraded



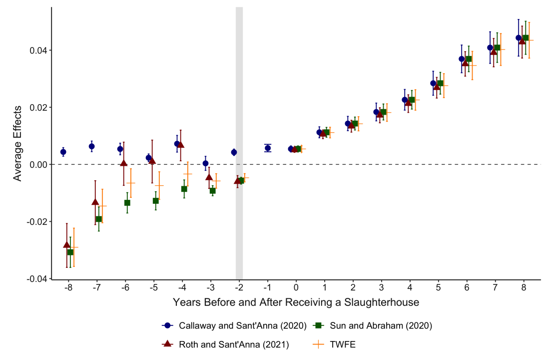
(f) Natural Forest Area

Notes: This figure presents the parameter estimates following Equation (4) for a different control group: never-treated municipalities. Panels (a) and (b) display results for “Cattle Heads" and “Pasture Area" as a share of municipal area, respectively. Panels (c) and (d) show results for “Total Degraded Pastureland" as a share of municipal area and “Natural Forest Area" as a share of municipal area, respectively. Period -1 is the first treatment period due to anticipation.

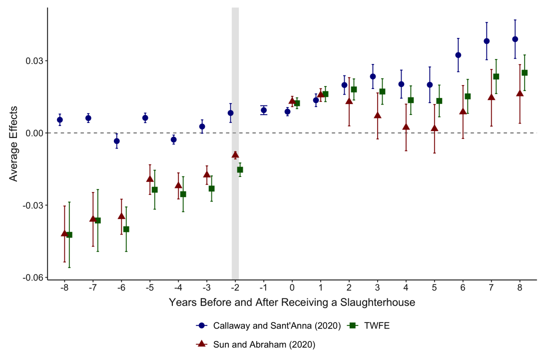
Figure A.6: Robustness Check: Using Alternative Estimators to Estimate the Effects on Cattle Heads, Pasture Area, Degraded Pastureland, and Natural Forest Area



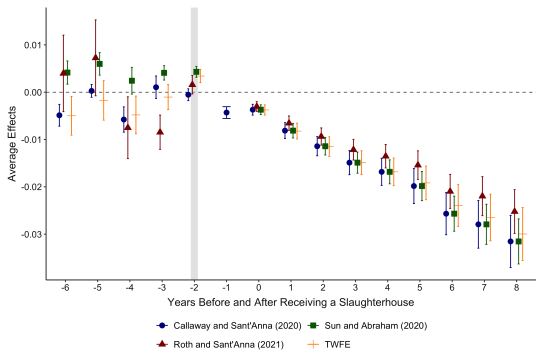
(a) Cattle Heads



(b) Pasture Area



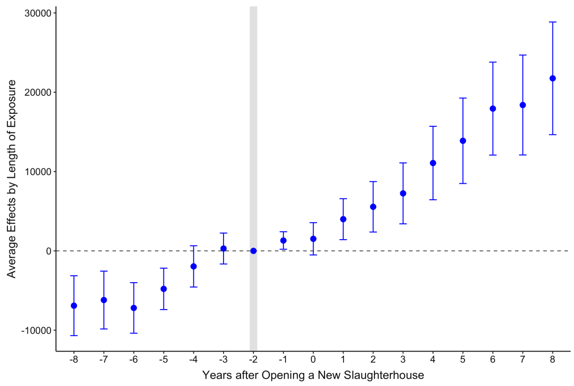
(c) Total Degraded



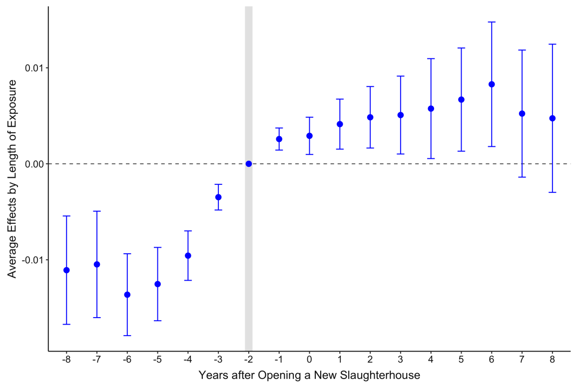
(d) Natural Forest Area

Notes: This figure presents the results of the alternative estimators described in Section 6.5 for dependent variable “Cattle Heads", “Pasture Area" as a share of municipal area, “Total Degraded Pastureland" as a share of municipal area and “Natural Forest Area" as a share of municipal area. Panel (a) displays the results for “Cattle Heads". Panel (b) shows the outcomes for “Pasture Area" as a share of municipal area. Panel (c) displays the results for “Total Degraded Pastureland" as a share of municipal area. Panel (d) presents the results for “Natural Forest Area" as a share of municipal area. We use the following estimators: Callaway and Sant’Anna (2021), Sun and Abraham (2021), Roth and Sant’Anna (2021), and the Two-Way Fixed Effects (TWFE). In estimating the event-studies, we do not make use of a universal base period like we do in the main results; we do not make use of covariates either, so all results present unconditional parallel trends—to ensure comparability among them. Period -1 is the first treatment period due to anticipation.

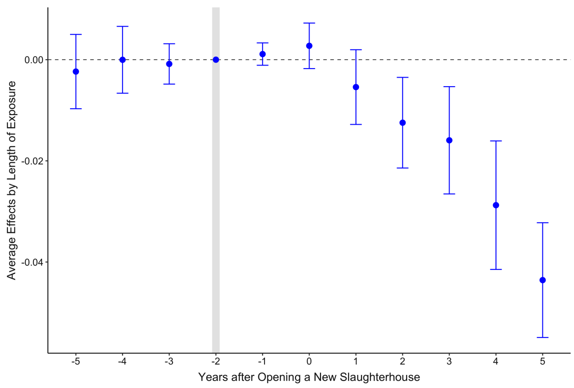
Figure A.7: Robustness Check: Using Only Plants *Above* Median Size to Estimate the Effects on Cattle Counts, Pasture Area, Degraded Pastureland, and Natural Forest Areas



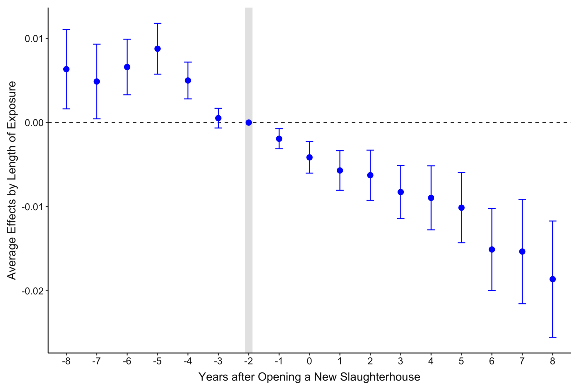
(a) Cattle Heads



(b) Pasture Area



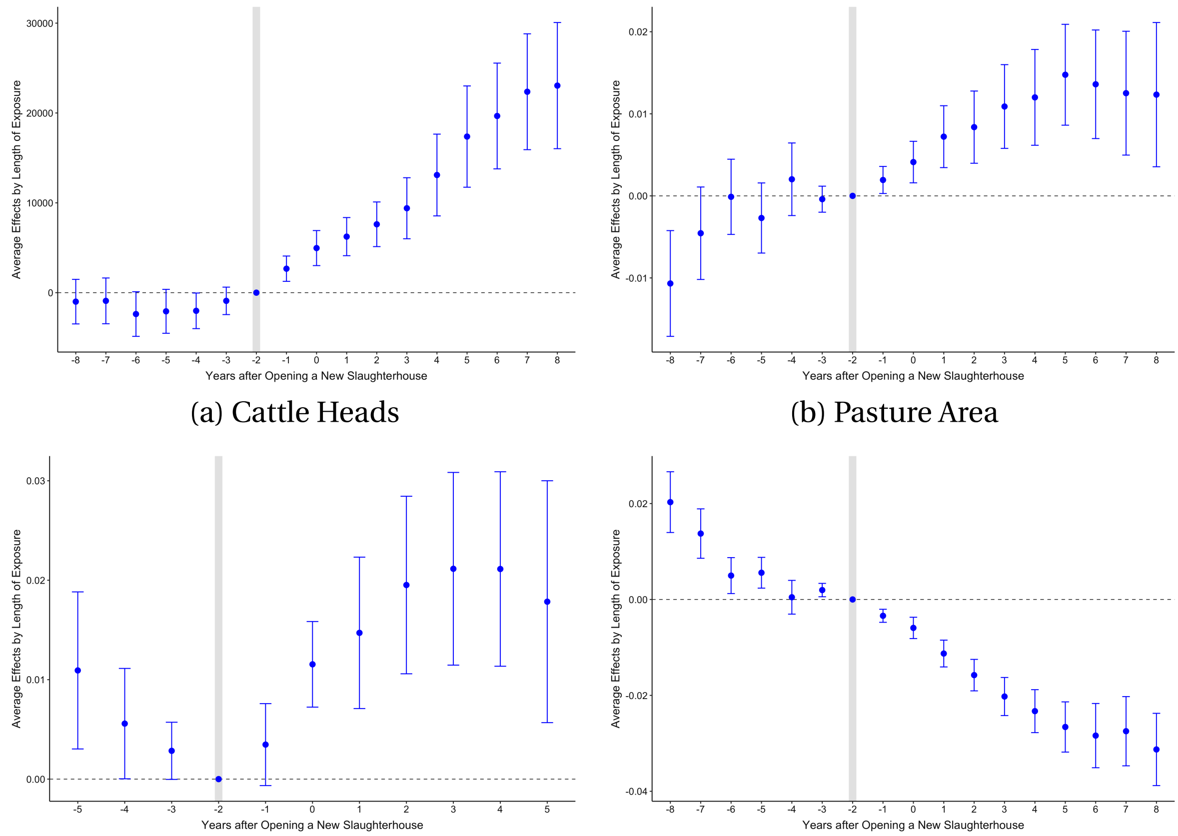
(c) Total Degraded



(d) Natural Forest Area

Notes: This figure presents the parameter estimates following Equation (4) for dependent variables “Cattle Heads", “Pasture Area" as a share of municipal area, and “Natural Forest Area" as a share of municipal area. We only use openings of slaughterhouse plants above the median size as treatment. Panel (a) displays results for “Cattle Heads". Panel (b) displays results for “Pasture Area" as a share of municipal area. Panels (c) shows results for “Natural Forest Area" as a share of municipal area. Period -1 is the first treatment period due to anticipation.

Figure A.8: Robustness Check: Using Only Plants *Below* Median Size to Estimate the Effects on Cattle Counts, Pasture Area, Degraded Pastureland, and Natural Forest Areas



(a) Cattle Heads

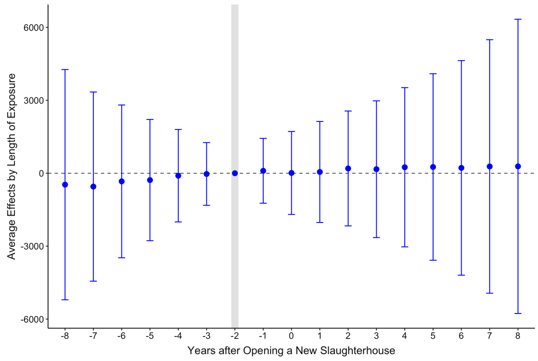
(b) Pasture Area

(c) Total Degraded

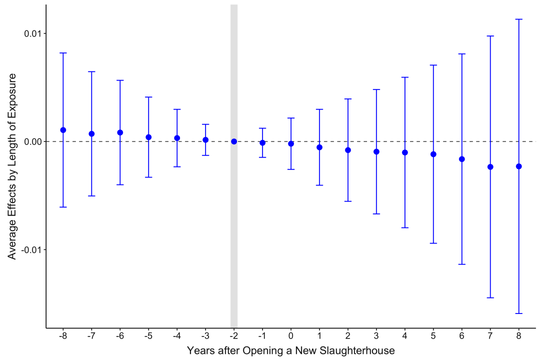
(d) Natural Forest Area

Notes: This figure presents the parameter estimates following Equation (4) for dependent variables "Cattle Heads", "Pasture Area" as a share of municipal area, and "Natural Forest Area" as a share of municipal area. We only use openings of slaughterhouse plants below the median size as treatment. Panel (a) displays results for "Cattle Heads". Panel (b) displays results for "Pasture Area" as a share of municipal area. Panels (c) shows results for "Natural Forest Area" as a share of municipal area. Period -1 is the first treatment period due to anticipation.

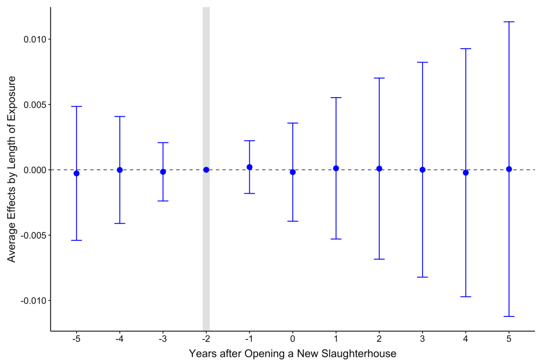
Figure A.9: Robustness Check: Event-Study Placebo With Time Randomization Shuffling Treatment-Time 100 Times



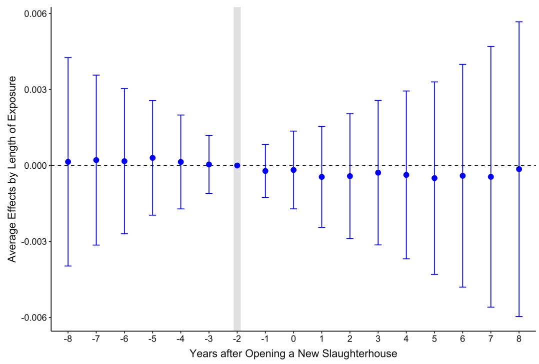
(b) Cattle Heads



(d) Pasture Area



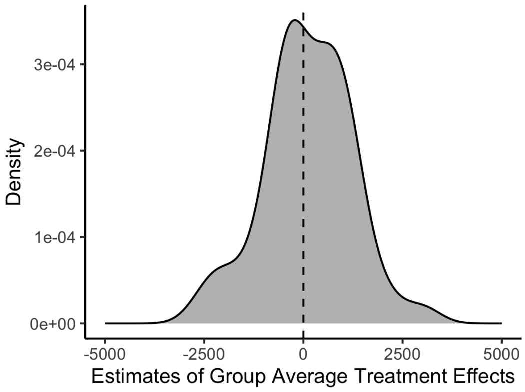
(f) Total Degraded



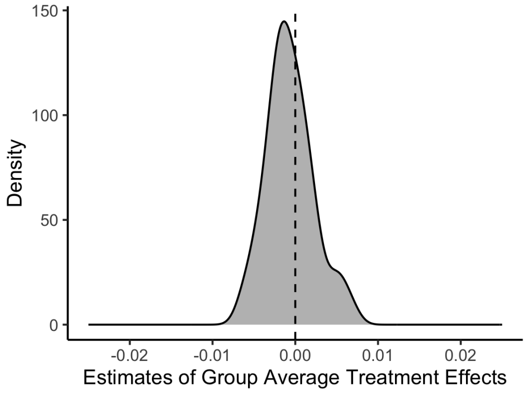
(h) Natural Forest Area

Notes: This figure presents the results with randomized treatment timing. We shuffle the treatment timing 100 times and re-run the regressions by Callaway and Sant'Anna (2021) using the same approach as in our baseline design (event-study). Above we plot the median coefficients and standard errors. Panel (a) displays results for "Cattle Heads", panel (b) shows results for "Pasture Area" as a share of municipal area, panel (c) displays results for "Total Degraded Pastureland" as a share of municipal area, and panel (d) shows results for "Natural Forest Area" as a share of municipal area. Period -1 is the first treatment period due to anticipation. We use data from 1994 to 2019.

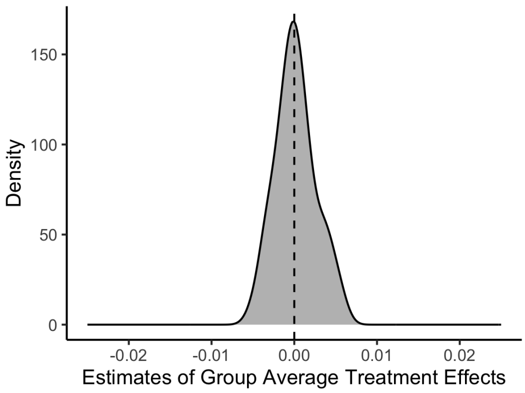
Figure A.10: Robustness Check: Group Average Treatment Effect Placebo With Time Randomization Shuffling Treatment-Time 100 Times



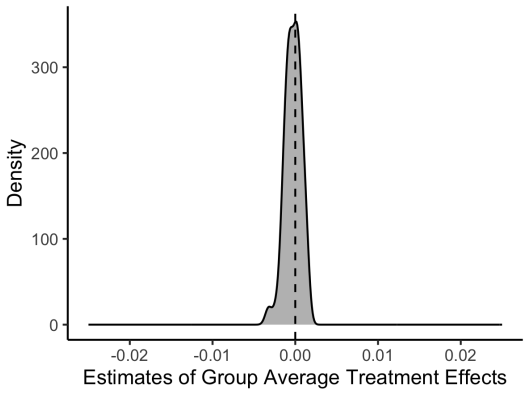
(b) Cattle Heads



(d) Pasture Area



(f) Total Degraded



(h) Natural Forest Area

Notes: This figure presents the distribution of coefficients using group average treatment effects with randomized treatment timing. We shuffle the treatment timing 100 times and re-run the regressions by Callaway and Sant'Anna (2021) using the same approach as in our baseline design (group average treatment effects). Above we plot the density distribution of the estimated coefficients. Panel (a) displays results for "Cattle Heads", panel (b) shows results for "Pasture Area" as a share of municipal area, panel (c) displays results for "Total Degraded Pastureland" as a share of municipal area, and panel (d) shows results for "Natural Forest Area" as a share of municipal area. Period -1 is the first treatment period due to anticipation. We use data from 1994 to 2019.

Table A.1: Summary Statistics on Federally Inspected Slaughterhouses

Slaughterhouse Capacity (i)	Number of Slaughterhouses (ii)	Number of Municipalities (iii)	Number of Companies (iv)	Median of Opening Years (v)	Most Frequent Company Name (vi)
More than 80/h (20 t/d store)	16	16	10	2008	JBS S/A
More than 80/h	44	40	26	2003	JBS S/A
Between 40 and 80/h	47	45	43	2002	JBS S/A
Between 20 and 40/h	45	44	38	2007	JBS S/A
Up to 20/h	22	22	21	1999	MARFRIG S/A
Total	174	167	138	2003	JBS S/A

Notes. This table presents a summary of slaughterhouses under federal inspection system in Brazil. Column (i) presents the slaughter capacity per day, in head counts. Notice that the first category also includes slaughterhouses with a storage capacity of at least 20 tons per day. Column (ii) gives the number of slaughterhouses for each category of slaughter capacity. Column (iii) shows the number of municipalities for each category. Column (iv) yields the number of companies per category. Column (v) gives the median opening year for slaughterhouses in each category. Finally, column (vi) provides the most frequent company name for slaughterhouse openings in each category.

Table A.2: Summary Statistics on Slaughterhouse Opening Years

Year of Slaughterhouse Opening	Impacted Municipalities Within 200km	Forest as % Mun. Area		Pasture as % Mun. Area		Number of Bovine Counts		Degraded Pasture as % Mun. Area	
		Before	After	Before	After	Before	After	Before	After
(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)	(ix)	(x)
1995	28	0.58	0.48	0.37	0.45	35,244	57,349		
1996	51	0.62	0.47	0.31	0.40	47,970	89,117		
1997	106	0.45	0.38	0.23	0.28	20,749	49,967		
1998	132	0.42	0.37	0.39	0.43	33,581	61,560		
1999	12	0.45	0.28	0.38	0.54	39,097	90,788		
2000	68	0.31	0.31	0.54	0.51	8,723	13,350	0.62	0.52
2001	82	0.32	0.33	0.50	0.44	6,947	8,511	0.67	0.55
2002	25	0.59	0.50	0.20	0.28	36,206	75,749	0.64	0.60
2003	49	0.71	0.66	0.16	0.20	17,752	26,565	0.44	0.45
2004	9	0.70	0.58	0.18	0.29	161,705	308,405	0.45	0.44
2005	111	0.30	0.31	0.49	0.47	8,353	10,450	0.61	0.52
2006	169	0.57	0.49	0.23	0.29	8,681	12,836	0.51	0.44
2007	1	0.46	0.42	0.33	0.35	19,160	34,039	0.94	0.92
2008	132	0.48	0.47	0.38	0.38	15,581	17,035	0.44	0.49
2009	4	0.80	0.69	0.09	0.14	39,212	65,099	0.66	0.67
2012	10	0.56	0.50	0.26	0.31	18,146	22,398	0.83	0.85
2013	79	0.43	0.43	0.15	0.11	4,121	6,932	0.58	0.42
2014	92	0.58	0.54	0.34	0.36	15,486	16,664	0.51	0.69
2015	28	0.50	0.39	0.48	0.57	42,217	47,146	0.51	0.47
2017	7	0.36	0.34	0.04	0.06	16,568	25,508	0.74	0.74
Mean	**77.8**	**0.50**	**0.44**	**0.32**	**0.35**	**28,777**	**45,065**	**0.63**	**0.61**

Notes. This table presents a summary of characteristics for opening years for slaughterhouses in all of Brazil. Columns (i) and (ii) display the year of opening and the number of impacted municipalities within 200km, respectively. Columns (iii) through (x) report forest area and pastureland as percentages of total municipality area, the number of bovine units, and degraded pastureland as a percentage of total municipality area.

Table A.3: Summary Statistics on Slaughterhouse Opening Years - *TAC* and Non-*TAC* Areas

Year of Slaughterhouse Opening	Impacted Municipalities Within 200km	Forest as % Mun. Area		Pasture as % Mun. Area		Number of Bovine Counts		Degraded Pasture as % Mun. Area	
		Before	After	Before	After	Before	After	Before	After
(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)	(ix)	(x)
Panel A — Non-TAC Municipalities									
2009	2	0.87	0.78	0.09	0.18	34,561	85,428	0.52	0.61
2012	10	0.56	0.50	0.26	0.31	18,146	22,398	0.83	0.85
2013	78	0.42	0.42	0.15	0.11	2,192	2,546	0.58	0.42
2014	92	0.58	0.54	0.34	0.36	15,486	16,664	0.51	0.69
2015	1	0.57	0.48	0.37	0.45	68,524	114,416	0.80	0.79
2017	7	0.36	0.34	0.04	0.06	16,568	25,508	0.74	0.74
Mean	**64**	**0.43**	**0.39**	**0.26**	**0.28**	**41,798**	**54,291**	**0.64**	**0.62**
Panel B — TAC Municipalities									
2009	2	0.72	0.61	0.09	0.09	43,863	44,769	0.80	0.72
2013	1	0.96	0.94	0.02	0.04	154,570	349,028	0.37	0.37
2015	27	0.49	0.39	0.49	0.58	41,242	44,655	0.50	0.45
Mean	**16**	**0.71**	**0.58**	**0.22**	**0.32**	**45,811**	**95,629**	**0.55**	**0.54**

Notes. This table presents a summary of characteristics for opening years for slaughterhouses in all of Brazil. Columns (i) and (ii) display the year of opening and the number of impacted municipalities within 200km, respectively. Columns (iii) through (x) report forest area and pastureland as percentages of total municipality area, the number of bovine units, and degraded pastureland as a percentage of total municipality area.

Table A.4: Simple DiD Regression on Bovine Prices, Number of Heads, and Values

	Municipalities with *TACs*			Municipalities (200km) *TACs*			Municipalities in *TAC* States		
	Prices	Heads	Values	Prices	Heads	Values	Prices	Heads	Values
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1{Signed *TAC*}	116*	48***	350***	145***	31***	174***	84***	18***	140***
	(66)	(7)	(25)	(26)	(3)	(10)	(21)	(2)	(8)
Average (control group)	1,445	79	116	1,465	60	91	1,490	40	61
Observations	3,324	3,324	3,324	3,324	3,324	3,324	3,324	3,324	3,324

Notes. This table displays the results for a simple differences-in-differences estimation following equation $y_{it} = \beta SignedTAC_{it} + \epsilon_{it}$ with dependent variables: (i) bovine prices sold to slaughterhouses, the number of heads of bovines, and total values (calculated as prices multiplied by heads) for each municipality i in year t (2006 and 2017). The treatment variable is $SignedTAC_{it}$, which equals 1 if municipality i has a signatory plant (for columns (1) to (3)), whether municipality i has a signatory plant within a 200-kilometer radius (for columns (4) to (6)), and whether municipality i is located in a Brazilian state which has signatory plants (for columns (7) to (9)). Prices are reported in Brazilian *reais* (BRL), with the number of heads in thousands and values in thousands of BRL (prices*heads)—-adjusted for 2017 values. Data originates from the 2006 and 2017 Agricultural Censuses. The analysis is limited to municipalities that have available census data. The averages provided for the control group are based on the data from the years 2006 and 2017.

Table A.5: Summary Statistics for Outcome, Treatment, and Control Variables

Variable	Unit	N	Mean	SD	Min	Max	Period	Source
Cattle Counts	Count	144,482	34,849.87	79,173.40	0.00	2,282,445.00	1994-2019	IBGE/PPM
Pastureland	Hectares	144,534	29,509.27	62,912.37	0.00	1,748,281.00	1994-2019	MapBiomas
Pastureland (%)	Percentage	144,534	0.31	0.26	0.00	1.00	1994-2019	MapBiomas
Bovine Productivity	Heads/Hectare	144,482	12.60	707.28	0.00	242,263.80	1994-2019	IBGE and MapBiomas
Natural Forest Area	Hectares	144,534	96,553.08	509,556.20	0.00	15,598,690.00	1994-2019	MapBiomas
Natural Forest Area (%)	Percentage	144,534	0.39	0.27	0.00	1.00	1994-2019	MapBiomas
Severely Degraded Pasture	Hectares	109,895	7,618.30	27,987.54	0.08	1,374,166.00	2000-2019	LAPIG
Total Degraded Pasture	Hectares	109,852	20,544.15	51,693.69	0.18	1,829,387.00	2000-2019	LAPIG
Severely Degraded Pasture (%)	Percentage	109,895	0.07	0.10	0.00	0.88	2000-2019	LAPIG
Total Degraded Pasture (%)	Percentage	109,852	0.20	0.20	0.00	0.98	2000-2019	LAPIG
Average Temp.	Celsius	144,456	21.96	3.59	0.00	29.38	1960-1991	Da Mata and Resende (2020)
Rural Population	Count	5,559	6,417.32	9,878.78	0.00	445,352.00	1991	Atlas dos Municípios
1 {Slaughterhouse}	Count	140	-	-	-	-	1994-2019	Estimated
1 {Slaughterhouse} $_{100km}$	Count	2,798	-	-	-	-	1994-2019	Estimated
1 {Slaughterhouse} $_{200km}$	Count	3,944	-	-	-	-	1994-2019	Estimated
1 {Slaughterhouse} $_{300km}$	Count	4,188	-	-	-	-	1994-2019	Estimated

Notes. This table presents the descriptive statistics of all relevant variables taken into account in the estimations. Observations range from 1994 to 2019. Variables in % are expressed in percentage relative to municipality area, thus representing the land share in a given municipality. The subscripts in the indicator variables relate to the radius which slaughterhouses may acquire cattle and its count is in municipalities affected by such radius.

Table A.6: Comparison of ATT Coefficients Between *TAC* and Non-*TAC* States

Outcome	ATT Difference	Std. Error	z-statistic	p-value
Natural Forest Area	0.0150	0.0074	2.02	0.0433**
Severely Degraded Pasture	-0.0305	0.0123	-2.48	0.0131**
Bovine Productivity	-3.5624	7.4288	-0.48	0.6316

Notes. This table compares treatment effects between *TAC* and non-*TAC* municipalities using z-tests for independent samples. ATT differences are computed as $\widehat{\theta}_{\text{TAC}} - \widehat{\theta}_{\text{non-TAC}}$. The test statistic is calculated as: $z = (\widehat{\theta}_{\text{TAC}} - \widehat{\theta}_{\text{non-TAC}}) / \sqrt{\widehat{\sigma}^2_{\text{TAC}} + \widehat{\sigma}^2_{\text{non-TAC}}}$, where $\widehat{\theta}$ denotes the ATT and $\widehat{\sigma}$ its standard error in each sample. "Natural Forest Area" and "Severely Degraded Pasture" are expressed as shares of municipal area, while "Bovine Productivity" is measured as bovine counts per hectare. We treat the two regional samples as independent, since they are constructed using mutually exclusive sets of Brazilian states. The difference in treatment effects is statistically significant for natural forest and degraded pasture, but remains imprecise for bovine productivity. Statistical significance is denoted by *p<0.1; **p<0.05; ***p<0.01.

Table A.7: Robustness Check: Using *No* Variable Transformations on the Effects on Pasture Area, Degraded Pastureland, and Natural Forest Area

	Dependent Variable		
	Pasture Area	Total Degraded	Natural Forest Area
	(i)	(ii)	(iii)
1{Slaughterhouse}	8,447.17***	2,018.24***	10,266.05***
	(970.1548)	(422.2490)	(1,024.6424)
Socioec. Covariates	Yes	Yes	Yes
Weather Covariates	Yes	Yes	Yes
Municipality FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes

Notes. This table presents the overall summary of ATT's based on time/group/length of exposure aggregation (Equation (3)) according to Callaway and Sant'Anna (2021) for the following dependent variables: "Pasture Area", "Degraded Pastureland", and "Natural Forest Area", with no transformations. All columns take into account covariates. The anticipation period equals 1. Statistical significance is given by *p<0.1; **p<0.05; ***p<0.01.

Table A.8: Reverse Causality Analysis: Correlation Between Slaughterhouse Openings and Main Outcome Variables

	Dependent Variable: 1{Opening of a Slaughterhouse}		
	Estimate	Std. Error	p-value
Bovine Counts (-1)	-0.0000000305	0.0000000631	0.6288
Bovine Counts (-2)	0.0000000901	0.0000000703	0.2005
Bovine Counts (-3)	-0.0000000471	0.0000000960	0.6235
Bovine Counts (-4)	0.0000001109	0.0000000936	0.2359
Bovine Counts (-5)	-0.0000000457	0.0000000822	0.5780
Bovine Counts (+1)	-0.0000000476	0.0000001393	0.7327
Bovine Counts (+2)	0.0000001936	0.0000001848	0.2948
Bovine Counts (+3)	-0.0000001130	0.0000001562	0.4693
Bovine Counts (+4)	0.0000000400	0.0000001300	0.7584
Bovine Counts (+5)	-0.0000001372	0.0000001288	0.2868
Pasture Area (-1)	-0.0095	0.0061	0.1205
Pasture Area (-2)	0.0150	0.0109	0.1670
Pasture Area (-3)	-0.0183	0.0129	0.1557
Pasture Area (-4)	0.0107	0.0087	0.2185
Pasture Area (-5)	-0.0011	0.0040	0.7767
Pasture Area (+1)	0.0087	0.0060	0.1443
Pasture Area (+2)	-0.0197**	0.0098	0.0450
Pasture Area (+3)	0.0043	0.0082	0.5980
Pasture Area (+4)	0.0095	0.0068	0.1621
Pasture Area (+5)	-0.0028	0.0046	0.5339
Natural Forest (-1)	0.0022	0.0050	0.6588
Natural Forest (-2)	-0.0035	0.0053	0.5062
Natural Forest (-4)	0.0014	0.0042	0.7290
Natural Forest (-5)	0.0085**	0.0042	0.0432
Natural Forest (+1)	-0.0037	0.0067	0.5783
Natural Forest (+2)	0.0021	0.0086	0.8065
Natural Forest (+3)	-0.0010	0.0075	0.8925
Natural Forest (+4)	-0.0007	0.0070	0.9160
Natural Forest (+5)	-0.0007	0.0038	0.8568
Year Fixed Effects	Yes		
Municipality Fixed Effects	Yes		
State Fixed Effects	Yes		
Wald F-test (p-value)	0.5658		
Observations	88,912		

Notes. This table presents the results for the regression with the dependent variable being a dummy which equals one for years which municipalities received a slaughterhouse and 0 otherwise. Explanatory variables include the lags (from -1 to -5) and leads (from +1 to +5) of "Bovine Counts", "Pasture Area" as a share of municipal area, and "Natural Forest" as a share of municipal area. The table shows estimates, standard errors, and p-values for each variable. Statistical significance is given by *p<0.1; **p<0.05; ***p<0.01.

Table A.9: Reverse Causality Analysis: Correlation Between Slaughterhouse Openings and Main Outcome Variables in *TAC* States

	Dependent Variable: 1{Opening of a Slaughterhouse}		
	Estimate	Std. Error	p-value
Bovine Productivity (-1)	-0.000001880	0.00000476	0.6928
Bovine Productivity (-2)	0.000007061	0.00000448	0.1151
Bovine Productivity (-3)	0.000000238	0.00000496	0.9618
Bovine Productivity (-4)	-0.000002249	0.00000370	0.5433
Bovine Productivity (-5)	-0.000005561	0.00000289	0.0547·
Bovine Productivity (+1)	0.000001357	0.00000408	0.7395
Bovine Productivity (+2)	0.000002246	0.00000698	0.7478
Bovine Productivity (+3)	-0.000002375	0.00000476	0.6182
Bovine Productivity (+4)	-0.000001585	0.00000564	0.7787
Bovine Productivity (+5)	-0.000008857	0.00000750	0.2379
Pasture Area (-1)	-0.01374836	0.03862777	0.7220
Pasture Area (-2)	0.00099396	0.04252847	0.9814
Pasture Area (-3)	-0.02805003	0.02836661	0.3230
Pasture Area (-4)	0.03445857	0.02595386	0.1846
Pasture Area (-5)	-0.00435417	0.02052909	0.8321
Pasture Area (+1)	-0.05102653	0.04906148	0.2985
Pasture Area (+2)	0.00089793	0.04510782	0.9841
Pasture Area (+3)	0.00801635	0.03378322	0.8125
Pasture Area (+4)	0.03830005	0.03335193	0.2511
Pasture Area (+5)	-0.01633409	0.03523208	0.6430
Natural Forest (-1)	0.00202682	0.04391964	0.9632
Natural Forest (-2)	-0.04206498	0.04665785	0.3675
Natural Forest (-4)	0.03599224	0.02840644	0.2054
Natural Forest (-5)	0.00449731	0.01977553	0.8201
Natural Forest (+1)	-0.06531568	0.05620942	0.2455
Natural Forest (+2)	0.03411944	0.05254599	0.5163
Natural Forest (+3)	0.00635545	0.03452054	0.8540
Natural Forest (+4)	-0.00051764	0.03663046	0.9887
Natural Forest (+5)	-0.01583820	0.02852678	0.5789
Municipality Fixed Effects	Yes		
Year Fixed Effects	Yes		
Wald Test (p-value)	0.5313		
Observations	17,584		

Notes. This table presents the results for the regression with the dependent variable being a dummy which equals one for years which municipalities received a slaughterhouse and 0 otherwise. The sample includes only municipalities in *TAC* states. Explanatory variables include lags (from −1 to −5) and leads (from +1 to +5) of "Bovine Productivity", "Pasture Area" as a share of municipal area, and "Natural Forest Area" as a share of municipal area. All regressions include municipality and year fixed effects, with standard errors clustered at the municipality level. Statistical significance is denoted by $^{\cdot}\, p < 0.10$, $^{*}\, p < 0.05$, and $^{**}\, p < 0.01$.

Table A.10: Reverse Causality Analysis: Correlation Between Slaughterhouse Openings and Main Outcome Variables in Non-*TAC* States

	Dependent Variable: *data_reser_dummy*		
	Estimate	Std. Error	p-value
Bovine Productivity (-1)	-3.49×10^{-7}	3.01×10^{-7}	0.2455
Bovine Productivity (-2)	1.19×10^{-7}	1.59×10^{-7}	0.4559
Bovine Productivity (-3)	1.63×10^{-7}	1.57×10^{-7}	0.2977
Bovine Productivity (-4)	8.78×10^{-9}	9.26×10^{-8}	0.9245
Bovine Productivity (-5)	-7.36×10^{-8}	5.84×10^{-8}	0.2076
Bovine Productivity (+1)	1.62×10^{-7}	1.53×10^{-7}	0.2902
Bovine Productivity (+2)	1.49×10^{-7}	1.34×10^{-7}	0.2644
Bovine Productivity (+3)	4.37×10^{-7}	5.96×10^{-7}	0.4635
Bovine Productivity (+4)	6.12×10^{-7}	8.58×10^{-7}	0.4759
Bovine Productivity (+5)	-3.73×10^{-7}	5.03×10^{-7}	0.4580
Pasture Area (-1)	−0.0032	0.0041	0.4391
Pasture Area (-2)	0.0015	0.0043	0.7329
Pasture Area (-3)	−0.0052	0.0045	0.2452
Pasture Area (-4)	0.0074^{**}	0.0031	0.0190
Pasture Area (-5)	0.0010	0.0027	0.7010
Pasture Area (+1)	0.0111	0.0067	0.1003
Pasture Area (+2)	−0.0136	0.0111	0.2201
Pasture Area (+3)	0.0017	0.0060	0.7720
Pasture Area (+4)	0.0007	0.0053	0.8980
Pasture Area (+5)	0.0002	0.0032	0.9388
Natural Forest (-1)	−0.0039	0.0025	0.1200
Natural Forest (-2)	0.0028	0.0023	0.2254
Natural Forest (-4)	−0.0022	0.0029	0.4486
Natural Forest (-5)	0.0019	0.0023	0.4129
Natural Forest (+1)	0.0027	0.0030	0.3698
Natural Forest (+2)	−0.0041	0.0037	0.2741
Natural Forest (+3)	−0.0031	0.0033	0.3512
Natural Forest (+4)	0.0017	0.0040	0.6743
Natural Forest (+5)	−0.0013	0.0030	0.6615
Municipality Fixed Effects	Yes		
Year Fixed Effects	Yes		
Wald F-test (p-value)	0.6429		
Observations	71,328		

Notes. This table presents the results for the regression with the dependent variable being a dummy which equals one for years which municipalities received a slaughterhouse and 0 otherwise. The sample includes only municipalities in non-*TAC* states. Explanatory variables include lags (from −1 to −5) and leads (from +1 to +5) of "Bovine Productivity", "Pasture Area" as a share of municipal area, and "Natural Forest Area" as a share of municipal area. All regressions include municipality and year fixed effects, with standard errors clustered at the municipality level. Statistical significance is denoted by $^{\cdot} p < 0.10$, $^{*} p < 0.05$, and $^{**} p < 0.01$.

Table A.11: Robustness Check: Using *Swine* Slaughterhouse Openings to Estimate the Effects on Cattle Heads, Pasture Area, and Natural Forest Area

	Dependent Variable		
	Cattle Heads	Pasture Area	Natural Forest Area
	(i)	(ii)	(iii)
1{Slaughterhouse}	-2,412.91**	0.0034	-0.0018
	(1,001.91)	(0.0018)	(0.0012)
Socioec. Covariates	Yes	Yes	Yes
Weather Covariates	Yes	Yes	Yes
Municipality FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes

Notes. This table presents the overall summary of ATT's based on time/group/length of exposure aggregation (Equation (3)) according to Callaway and Sant'Anna (2021) for the following dependent variables: "Cattle Heads", "Pasture Area" as a share of municipal area, and "Natural Forest Area" as a share of municipal area. In this robustness check, we utilize *swine* slaughterhouse openings as treatment for municipalities up to 200-kilometer from the centroid of municipalities which host swine plants. Results follow our baseline approach with control group "not-yet-treated" municipalities. The anticipation period equals 1. Statistical significance is given by *p<0.1; **p<0.05; ***p<0.01.

Table A.12: Robustness Check: Using 100-kilometer and 300-kilometer Radiuses to Estimate the Effects on Cattle Heads, Pasture Area, Degraded Pastureland, and Natural Forest Area

	Dependent Variable							
	Cattle Heads		Pasture Area		Total Degraded		Natural Forest Area	
	100km	300km	100km	300km	100km	300km	100km	300km
	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)
1{Slaughterhouse}	10,059.01***	23,374.24***	-0.0003	0.0245***	-0.0017	-0.0016	-0.0127***	-0.0258***
	(1,424.64)	(3,520.73)	(0.0016)	(0.0041)	(0.0020)	(0.0073)	(0.0013)	(0.0038)
Socioec. Covariates	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weather Covariates	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Municipality FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Notes. This table presents the overall summary of ATT's based on time/group/length of exposure aggregation (Equation (3)) according to Callaway and Sant'Anna (2021) for the following dependent variables: "Cattle Heads", "Pasture Area" as a share of municipal area, "Degraded Pastureland" as a share of municipal area, and "Natural Forest Area" as a share of municipal area. Columns (i), (iii), (v), and (vii) use 100-kilometer radii to define treated units, while columns (ii), (iv), (vi), and (viii) use 300-kilometer radii. Control group is "not-yet-treated" and anticipation period equals 1. Statistical significance is given by *p<0.1; **p<0.05; ***p<0.01.

Table A.13: Robustness Check: Using *Never-Treated* Municipalities as Control Group to Estimate the Effects on Cattle Heads, Pasture Area, Degraded Pastureland, and Natural Forest Area

	Dependent Variable			
	Cattle Heads	Pasture Area	Total Degraded	Natural Forest Area
	(i)	(ii)	(iii)	(iv)
1{Slaughterhouse}	14,119.27***	0.0141***	0.0193***	-0.0221***
	(1,957.53)	(0.0024)	(0.0058)	(0.0018)
Socioec. Covariates	Yes	Yes	Yes	Yes
Weather Covariates	Yes	Yes	Yes	Yes
Municipality FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes

Notes. This table presents the overall summary of ATT's based on time/group/length of exposure aggregation (Equation (3)) according to Callaway and Sant'Anna (2021) for the following dependent variables: "Cattle Heads", "Pasture Area" as a share of municipal area, "Total Degraded Pastureland" as a share of municipal area, and "Natural Forest Area" as a share of municipal area. Results follow our baseline approach with a different control group, given by "never-treated" municipalities. The anticipation period equals 1. Statistical significance is given by *p<0.1; **p<0.05; ***p<0.01.

Table A.14: Robustness Check: Using Slaughterhouses *Above* and *Below* the Median Size to Estimate the Effects on Cattle Heads, Pasture Area, Degraded Pastureland, and Natural Forest Area

	Dependent Variable							
	Cattle Heads		Pasture Area		Total Degraded		Natural Forest Area	
	Above	Below	Above	Below	Above	Below	Above	Below
	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)
1{Slaughterhouse}	9,768.57***	12,370.58***	0.0058***	0.0099***	-0.0165***	0.0153***	-0.0113***	-0.019***
	(1,480.57)	(1,413.12)	(0.0016)	(0.0018)	(0.0033)	(0.0029)	(0.0014)	(0.0015)
Socioec. Covariates	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weather Covariates	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Municipality FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Notes. This table presents the overall summary of ATT's based on time/group/length of exposure aggregation (Equation (3)) according to Callaway and Sant'Anna (2021) for the following dependent variables: "Cattle Heads", "Pasture Area" as a share of municipal area, "Total Degraded Pastureland" as a share of municipal area, and "Natural Forest Area" as a share of municipal area. Columns (i), (iii), (v), and (vii) present results using as treatment only slaughterhouses above the median size. Columns (ii), (iv), (vi), and (viii) present results using as treatment only slaughterhouses below the median size. Control group is "not-yet-treated" and anticipation period equals 1. Statistical significance is given by *p<0.1; **p<0.05; ***p<0.01.