Expansion and market concentration of Brazil's beef industry, 1966-2017

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March 10, 2019

[word count: 10,450 excluding figures and references]

Acknowledgements

The authors are thankful to the TRASE (Transparency supply chains for sustainable economies) team for providing data on cattle transactions for three states, to Juliana Assunção for compiling data on state-inspected slaughterhouses, to Renato Marcondes and Lélio de Oliveira for providing historical references, to Ticiana Amaral for providing data on actions by the Federal Public Prosecutors Office, to Rodrigo Moita, Fanny Moffette, Jens Engelman, Eduardo Florence, Eliezer Martins, Kemel Kalif, George Allez and Nathalie Walker for comments, and to Isabel Vale and Wladimir Drumond for support in designing maps. Funding provided by the Gordon and Betty Moore Foundation and the Norwegian Agency for Development Cooperation's Department for Civil Society under the Norwegian Forest and Climate Initiative. Funders had no involvement in the study execution or in the decision to submit it. All errors are our own.

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Abstract

Brazil's largest meatpacking companies lead the world in beef production. Prior to international expansion starting in 2005, the cattle slaughter industry spread from the country's coastal areas to the interior, where cattle herds were also expanding. Slaughterhouses play a central role in coordinating supply chains, yet current knowledge of the industry is limited by the absence of plant level data. Here, we map the beef industry's evolution into the Cerrado, Pantanal and Amazon biomes over the last six decades and quantify changes in market concentration between 2006 and 2016. To accomplish this, we triangulated across fiscal and animal sanitation data sources to produce the first longitudinal dataset with information on the opening and closing dates, locations, and production volumes of 2,602 inspected and uninspected slaughterhouses. We show the linear movement of slaughterhouses and cattle herds to the Amazon by tracking their geographic centers of gravity. The distance between the industry's midpoint and the coastline increased by 650 km between 1966 and 2017. We also show the clustering pattern of slaughterhouses with kernel densities. Until the 1960s, all the geographic clusters were located south of the capital, Brasília; but by the early 2000s, clusters north of Brasília were almost as extensive as those to the south. Finally, we used the Herfindahl-Hirschman concentration index to assess the degree of market power that the largest beef processing companies possess. Our results indicate that the industry is moderately concentrated and that this had increased in the states where slaughterhouses were spatially clustered. In small beef-producing states (Acre, Amazonas, Bahia, Tocantins) and states with a consolidated industry (Minas Gerais, São Paulo), concentration remained relatively stable. Where settlement was recent and cattle herds expanded rapidly, however, (Goiás, Mato Grosso, Mato Grosso do Sul, and Rondônia), market concentration increased. Our results shed light on the relationship between geographic expansion and economic concentration.

Keywords: cattle, beef, meatpacking, slaughterhouse, Brazil, market concentration, land use.

1. Introduction

The livestock sector is the largest land-use system on earth and a source of income for an estimated 1.3 billion people (Herrero et al., 2013, 2009). The industry is highly heterogeneous; production practices range from pastoralism and subsistence agriculture to large scale commercial production and industrial farming. Short supply chains, where full-cycle producers use service slaughter facilities to retail directly to consumers, do exist but long supply chains, where animals change hands several times before reaching slaughterhouses, are much more prevalent for both beef and dairy across the world.

The meatpacking industry, which comprises manufacturing and part of the wholesale components of the supply chain, plays a central role in coordinating beef production, as it is well placed to transmit consumer requirements to cattle producers (MacDonald, 2003; Peterson, 2002). Over the last decade, deforestation and labor related standards, have been imposed, though imperfectly, on cattle producers in Brazil through the procurement practices of some slaughterhouses (Alix-Garcia and Gibbs, 2017; Gibbs et al., 2015; Lambin et al., 2018). Starting in 2009, Greenpeace International successfully campaigned to motivate large food retailers to take an active role in anti-deforestation efforts. The result was a private supply chain initiative known as the "G4 cattle agreement," involving the largest four meatpackers at that time (JBS, Bertin, Marfrig and Minerva). The signatory companies are expected to monitor their direct suppliers and to block sales with properties with any deforestation in the Amazon biome that took place after October 2009. The companies took various steps to comply, but the impacts on deforestation have been limited(Alix-Garcia and Gibbs, 2017; Lambin et al., 2018).

The G4 meatpacking companies responded to boycott threats from advocacy groups and non-government organizations in part because of the intense competition they face to market boxed beef and related products. On the purchasing side, however, meatpacking companies are in a more powerful position due weak competition in the cattle procurement markets — farmers often have little choice among competing slaughterhouses when marketing animals (Koontz, 2003; McLaren, 2015). This combination of sensitivity to demand-side constraints and the power to shape input markets likely plays a significant role in organizing production practices, exerting influence on the size, type, and location of ranches (Sporleder and Boland, 2011).

Despite the importance of meatpacking companies in Brazil to shape business practices, only a handful of studies have focused on this specific part of the supply chain (Table S3). Pigatto and Souza Filho (2001) and Boechat and Parré (2018) used cross-sectional data on federally inspected plants (SIF) from the Ministry of Agriculture (MAPA), while Boechat and Alves (2014) obtained panel records, but these lack information about the many smaller plants that are not federally inspected. Others used time-series for periods of a decade or more, but with the data aggregated at the state or country level (Caleman and Cunha, 2011; Moita and Golon, 2014). Carvalho (2016) used archival research to construct a meatpacking company level panel dataset, but it was restricted to the "big four" group (JBS, Marfrig, Minerva and BRF). Barreto et al. (2017) were the first to include a wider coverage of SIF and state (SIE) inspected plants for the entire Legal Amazon, but their analysis was a snapshot for 2016 and did not include a temporal component or the full Cerrado. The only studies that accessed plant level historical data were limited to the states of Rio Grande do Sul (Leães, 2015) and Mato Grosso (Vale et al., 2019).

Here, we create the first map and historical dataset to track the evolution of inspected and uninspected slaughterhouse locations and production volumes across the Amazon, Cerrado and Pantanal biomes of Brazil. We use these data to answer two questions. First, what was the historical pattern of localization of slaughterhouses? We show the movements of the industry over time and identify patterns of densification and geographic clustering. Second, how has competition evolved within the industry? We use an economic index of market concentration to establish whether cattle slaughter is concentrated in specific firms, and how this concentration has evolved over time. Our plant level dataset considers each physical unit of a cattle slaughtering operation to be a plant. This dataset provides a significant improvement over previous analyses that relied on aggregated, cross-sectional, or data that were restricted to SIF plants.

Brazil is the largest beef exporting country and has the second largest production volume (FNP, 2017, pp. 62–64); its meatpacking complex is the worldwide leader in beef production (Sharma, 2018). The top global meatpacker, JBS, was founded in 1953 in the Brazilian Midwest, a region that includes the states of Goiás, Mato Grosso and Mato Grosso do Sul, and recently expanded to incorporate such historical players as Swift, which once dominated the U.S. meatpacking sector. Other Brazilian companies, Marfrig and BRF, have also reached top-five positions in global meat production (Al-Muslim, 2018; Sharma, 2018), and Minerva is a leader in South America.

Currently, the big three beef production companies in Brazil (JBS, Marfrig and Minerva) account for 50% of the country's market (Carvalho, 2016). Given the enormous growth that characterized the emergence of these multinationals, concerns over increased market power in the hands of a limited number of companies have emerged (Boechat and Parré, 2018).

We approach the dynamics of the beef industry by exploring the interrelation between cost-saving agglomeration forces and competition-avoiding dispersion forces. The spatial distribution of economic activities is the outcome of a friction between scale economies and transportation costs (Fujita and Thisse, 2013). Generalized historical data show that prior to refrigeration, which first became available in Brazil in 1914, it was nearly impossible to transport fresh meat to distant consumer markets, so slaughterhouses had to be located near urban centers (Bosi, 2014). Animals were thus trailed to coastal cities where the bulk of the population was — at huge health risks for the animals and economic costs to the producers — to be slaughtered in butcheries or in public abattoirs just outside the urban perimeters (Herbeth, 2015; Lopes, 2015). As an indirect consequence of being located close to cities, slaughterhouses could enjoy the external scale economies typical of densely populated areas, such as a high supply of labor and easy access to machinery.

With the coming of refrigerated transportation, the beef industry witnessed a substantial spatial shift away from coastal areas and into the Cerrado biome and later into the Amazon (Valverde, 1967). This dynamic continued for many decades. The Cerrado initially attracted cattle production due to the combination of a favorable ecosystem with historical contingencies such as the collapse of the mining industry (Silva et al., 2017). The slaughter industry soon followed, which meant that it progressively sacrificed the external scale economies of big cities. The interiorization of meatpackers started in the 1920s and became more pronounced after 1955 (Mamigonian, 1976). From the late 1960s, cattle production began to move into the Amazon; slaughterhouses followed in the 1980s. As plants moved westward into the interior, the weight loss, animal deaths, and feed costs from droving cattle to distant slaughterhouses were drastically reduced (Valverde, 1967). It made sense to trade economies of scale against transportation costs. At the same time, the continued expansion of the beef industry to the Cerrado, Pantanal and Amazon biomes was the main driver of the deforestation of an area equivalent to 8.75% of those biomes between 1985-2017 (MapBiomas, 2018).

The study of the industry after the 1960s is facilitated by the availability of detailed plant level data. However, the information is not readily accessible, as it is scattered across various sources and formats. This paper is thus the first to triangulate across these sources and thereby create a panel dataset of slaughterhouses and cattle herds spanning six decades. It includes all plant types (federally- and state-inspected, and others, including uninspected) for the 16 states in the Amazon, Cerrado, and Pantanal biomes of Brazil, an area that represents 87% of the country. This data production effort is a generalized version of the method deployed by Vale et al.(2019). By combining various sources of public information, including cattle transactions, fiscal data, and sanitation inspection data, we were able to infer the opening and closing dates, locations, and production volumes of 2,602 slaughterhouses.

Our empirical analyses show how the geographic configuration of slaughterhouses evolved over time. We estimated the center of gravity of cattle herds and slaughterhouses for our study area, confirming the northward movement of the industry as it crossed the Cerrado biome at an average rate of 36 km/year; it is now located very near the border with the Amazon biome. Subsequently, we used kernel density estimation to generate a density surface of cattle slaughter volumes across space and time. For each year, we could see how the geographic clusters of the slaughter industry consistently moved northward, which provides further detail for the pattern of expansion out of coastal areas. Finally, we calculated a Herfindahl-Hirschman Index (HHI) of market concentration to evaluate the degree to which inspected slaughterhouses have market power over ranchers. While the HHI is widely used by competition authorities worldwide, it has never been used by the Brazilian competition defense agency (CADE) due to lack of data on slaughter volumes (Boechat and Alves, 2014, p. 120). Scholars studying this topic also have had to rely on aggregated data (Moita and Golon, 2014; Neves et al., 2001). We found evidence of moderate overall concentration at present, and an increased level over time especially in the Midwest and Rondônia.

Below, we begin by introducing the study area. We then present the details of our dataset construction and analysis in the sections that follow. Specifically, we describe the information and method used to generate the historical slaughterhouse dataset, and our approach to calculate the geographic center of gravity, kernel density estimates, and market concentration index. We then use the results to describe how the beef industry evolved geographically, the distribution of slaughter units across space and time, and the assessment of market concentration. In the final section, we discuss causes and implications of the industry's movements, factors that are likely to influence market concentration, and finally, how these results can affect the analysis of supply chains and environmental governance.

2. Materials and methods

2.1. Study area

The analysis of the human-environmental interactions pertaining to livestock systems is increasingly performed at the biome level (e.g.: Bustamante et al., 2012; Lapola et al., 2014). Some important policies that affect livestock production in Brazil — such as the Brazilian Forest Code that regulates in-property land conservation, and supply chain interventions such as the cattle agreements — are also implemented at jurisdictional levels that largely overlap with biome lines. While the Amazon biome has been the focus of attention since the late 1980s, the Cerrado tropical savannas and the Pantanal wetlands are increasingly seen as very important targets for conservation efforts (Klink and Machado, 2005; Nolte et al., 2017; Ratter et al., 1997).The biomes closer to the coast — Caatinga, Atlantic Forest, and Pampa — are where most economic activities, including livestock raising, first developed. To capture the beginning of the geographic expansion toward the northwest, we define *coastal areas* as all locations within 100 km of the coast. The *interior* of the country — the Cerrado, Pantanal and Amazon biomes — was not subject to large scale occupation until late in the 19th century. But these *hinterland* spaces, which occupy almost exactly three-fourths of the country, became very dynamic as sites of agricultural activity during the 20th century. Our study area includes the 16 of 27 states that substantially overlap the Cerrado, Pantanal or Amazon biomes. Together, these states account for 87.4% of Brazil's territory and 79.7% of the 2016 cattle slaughter (FNP, 2017). Our study area also includes some of the most significant coastal areas, notably in the states of Bahia, Minas Gerais and São Paulo, which allows us to map coast-to-interior dynamics.

[Figure 1]

2.2. Data

In this section, we present the historical slaughterhouse, slaughter volume, and cattle herd data used in the analyses.

<u>Historical slaughterhouse dataset</u>

Our dataset contains all plants, both in operation or closed, that were registered in the federal or state taxation systems as of 2017 for any of the 16 states in our study area (Table 1). These plants are grouped into holding companies where applicable. In addition, the data include plants that were not in the tax registries but that appeared to have received cattle for slaughter under the sanitation inspection system, as inferred from GTA[1] data (Portuguese acronym for "animal transportation forms"). The complete slaughterhouse dataset contains the following: plant name, geolocation, company name, sanitation inspection status (a robust indicator of plant size), legal opening/closing dates, inferred ownership change date, and estimated slaughter volume. These data are the first to include historical information and to include plants outside of the federal or state inspection systems.

Table 1. Summary of historical slaughterhouse dataset

Feature	Total	Amazon	Cerrado	Pantanal	Other biomes
Unique plants (all years)	2,602	793	963	13	833
Active plants (2017)	1,626	475	637	8	506
Unique companies (all years)	1,714	396	640	11	667
Active companies (2017)	1,094	249	432	6	407
Oldest company registration (year)	1931	1931	1948	1977	1946
Federally inspected plants (SIF, all years)	214	70	83	4	57
State inspected plants (SIE, all years)	209	46	99	1	63
Other inspection or uninspected plants	2,179	677	781	8	713
Active SIF companies (2017)	116	22	50	4	40
Active SIE companies (2017)	201	43	96	0	62
Newest company registration (year)	2017	2017	2017	2017	2017
Active plants with supply chain commitments	121	75	33	2	11

[1] These data contain information on the transportation of cattle between any two locations. The data are collected by the state sanitation agencies and are used to prevent animal disease outbreaks, especially foot-and-mouth disease.

Documented plant ownership change	366	108	156	3	99

One significant limitation of our dataset is that it represents "surviving" slaughterhouses — those that still appeared in the 2017 digital CNPJ tax registries. While these official records include many instances of plants that have long been closed, it is possible that some of the inactive or closed companies were previously excluded from the records. Moreover, the paper records of companies that were closed in the predigital era may never have been digitized. Especially prior to the 1990s, business informality was very common, although this changed drastically in the mid-90s (Mendes et al., 2017). Therefore, our data become less accurate the further back into the past we go. For this reason, although in our data the first plant dates from 1931, we restricted our quantitative analyses to 1966 and after, the years for which our dataset contained at least 35 active companies.

A related limitation is that changes in plant ownership could not be reconstituted historically. Given the size of the dataset and the patchiness of the historical information, such reconstitution was not feasible. Therefore, we estimated the date of the most recent ownership change but could not identify previous ownership changes. In the methods section we show how this limitation affected the market concentration analysis.

Slaughter volumes

The absence of data on plant level slaughter volumes is a crucial impediment to the study of the meatpacking industry. In general, to protect commercial interests, companies do not make these data publicly available. Slaughter volumes are currently available from the Brazilian statistical agency (IBGE, 2017a) at an aggregated scale (by states) starting in 1996, or in recent years in a less aggregated format (by municipalities or transactions) in the GTA for some states. The IBGE data do not have variation at the state level among plants (Figure S11), and the GTA data are incomplete and have a restricted temporal coverage (Table S2).

However, we were able to generate synthetic plant level data on slaughtered cattle for SIF and SIE plants by combining different sources into a panel framework and using predictive regression models, as explained in the methods section and in the SI. The resulting data are production volumes measured as animals slaughtered per year for the years 2006-16 (Figure S12). Prior to that period, data needed for the estimation were unavailable. We could not produce estimates for other inspection types and uninspected plants because their slaughter volumes were very small and predictions are unreliable at the tail ends of the distribution (i.e., very small or very high values). A detailed account of the data and methods used to make these predictions is presented in the SI.

Cattle herds and geographic boundaries

Annual data on cattle herds at the municipality level were obtained from IBGE (2017a) for the years 1974-2016. These data are found in the 'Municipal Cattle Survey' (Portuguese acronym PPM), collected from informants at each municipality using a consistent methodology. Maps in shapefile format were used to process the geographic computations. We used a map of biomes, a state map, and maps for the different municipality grids between 1970-2015. All shapefiles were from IBGE's repository (IBGE, 2018).

2.3. Methods

In this section we provide details of the methods used to assess the historical pattern of localization of the slaughter industry and how has competition among slaughterhouses evolved over time. We initially present a summary of the sources used and the data generation methods for both the historical slaughterhouse dataset and for the slaughterhouse production volumes dataset; for a complete exposition of the data sources, raw data, and methods, readers are referred to supplementary information. We next describe the quantitative tools employed to analyze the data. These include our visualization of the spatial evolution of the slaughterhouse industry by computing the center of gravity of beef production; the kernel density estimation method used to visualize patterns of spatial densification over time; and, as we move from spatial to economic concerns, the Herfindahl-Hirschman index of market concentration used to assess market power.

Data generation

Generating data on slaughterhouses

The data collection and triangulation efforts that generated our slaughterhouse dataset were based on a method previously developed for the state of Mato Grosso. A synthetic description of the sources used and the method is provided as supplementary information (SI-A), while a detailed account can be found in Vale et al. (2019). To generate the data, we employed a sequential process in which information was added both vertically (new observations) and horizontally (new variables) to the dataset at each step. A data validation routine was then implemented.

First, we filtered lists of registered companies from the Federal Revenue Agency containing unique company codes (CNPJ, Portuguese acronym for “national registry of companies”) and other identifiers (Empresômetro, 2017) to extract slaughterhouse companies. We also added information on SIF and SIE plants using Barreto et al. (2017) and LAPIG (2016). Next, we retrieved information from the state revenue agencies (Sintegra, 2017), from the Ministry of Agriculture (MAPA, 2017a), and from the state sanitation agencies (SISBI-POA, 2016), including opening/closing dates and sanitation inspection codes. Third, we collected CNPJs into physical plants and geocoded the addresses into spatial coordinates. Fourth, we retrieved information on adherence to supply chain commitments (Gibbs et al., 2015; MPF, 2017).

Fifth, we allocated opening/closing dates and geographic coordinates to the physical plants. Sixth and finally, we added GTA records to the dataset, which allowed us to document slaughter activity for each year and state for which the data were available. To validate the data, we used high-resolution imagery by Bing Maps and Google Maps to verify whether the geocoded locations of SIE and SIF plants had the typical infrastructure of a slaughterhouse. We also compared our total counts of plants with official data from IBGE (2017a) and reran the six steps when the difference was > 15%. Finally, we downloaded lists of SIF plants from MAPA (2017b) to validate our SIF codes and addresses, making corrections where necessary.

Estimating slaughter volumes

Plant level production volumes are essential to measure the market concentration of the meatpacking industry. A detailed account of the data sources and methods used to generate our slaughter volume dataset is provided as supplementary information (SI-B, Table S1). To obtain plant level estimates, we disaggregated the state level slaughter volumes published by IBGE (2017a) among the plants in each state. To do that, we first predicted slaughter volumes at the municipality level. We used GTA municipality data on slaughter volumes in six states as the dependent variable in a regression framework to predict slaughter volumes in all states for 2006-16. The independent variables were cattle herds (IBGE, 2017b), GDP (IBGE, 2017c), population (IBGE, 2017d), number of employees in the meatpacking industry (MTE, 2017), counts of plants and animals slaughtered by inspection type (state level; IBGE (2017a)), municipality areas, and numbers slaughtered by originating municipality (Ipeadata, 2018). The predicted slaughtered head were disaggregated from municipalities to plants using shares derived from IBGE (2017a). We then adjusted the plant level estimates so that the sum for each state equaled the IBGE state level total. Finally, the 2006-16 series was extrapolated backward for the period 1966-2005 using the Stata ® 15 mipolate package for inverse distance weighting (Lu and Wong, 2008).

For the dependent variable, the unbalanced panel had 551 municipalities with years ranging between 2008-16. To avoid underestimating the slaughter volumes, we restricted the sample to those years for which the total GTA slaughter volume at the state level was equal to or higher than 60% of the total by IBGE (2017a). We also dropped municipalities with slaughter volumes lower than 504 cattle/year from the estimation — assuming a minimum operation size for a single slaughterhouse of two animals/day for a total 252 days/year[2]. Finally, we dropped municipalities without any SIF or SIE plant. The municipality panel dataset was then split into an estimation sample, with 60% of the municipality-year pairs for which slaughter volumes were not missing, and a training sample with the remaining 40% of the municipality-year pairs. The samples were randomly selected. A total of 10 different training sets were sampled.

All specifications were implemented using the estimation sample and two alternative estimators: random effects Poisson and Poisson for pooled panel data. A total of 103 specifications were tested with different combinations of the independent variables, including year effects, state fixed effects, interactions, and exponentials. The predicted values were then compared to the observed values from the training sample, and the 10 models with the lowest total absolute prediction errors were selected. The 2006-16 estimates were then obtained by taking the average prediction from among the 10 models. Once the slaughter volumes had been predicted for all municipalities and years, we proceeded to disaggregate from municipalities to plants. Where only one plant existed, that plant was allocated the total slaughter volume estimated for the inspection type and municipality. This was true for most municipalities. In the remaining cases, shares within municipalities were estimated from IBGE (2017a).

For all states, the estimated slaughter volumes reflect the plant-to-plant variation in the GTA data, which include some level of temporal inconsistency, along with the municipality-to-municipality

[2] The slaughter volume of a small abattoir operating at full capacity. We are thus assuming that a municipality must have at least the slaughter volume of a single small abattoir that operates at full capacity.

variation in the other data sources, all of which have a higher temporal consistency than the GTA. The estimated values are therefore more accurate than the original GTA data as well as consistent through time.

Data analysis

Calculating the center of gravity of slaughterhouses and cattle

Grether and Mathys (2008) propose a definition for the world's economic center of gravity directly based on the physics concept of center of mass (gravity), "which is the point in space that typifies a system as a whole when it is treated as a particle". This notion is very useful and serves as an indicator that summarizes the temporal movements of a geographically determined phenomenon. For example, Quah (2011) calculated the earth's economic center of gravity by summing the GDPs of all countries in a spatially weighted framework. He showed that the world economic center had been moving eastward due to the growth of China and East Asia. Similarly, we wish to depict trajectories of the beef industry in our study area by mapping the centers of gravity of its main output, meat production, and its main input, cattle herds.

Holler et al. (2013) and McManus et al. (2016) calculated the midpoint of cattle herds for Brazil, and found that the industry was moving northward. Our method differs in two important aspects. First, they calculated spatially weighted averages over a flat surface with a two coordinate system, while we use three dimensions. The advantage of the three-dimensional approach is akin to what is gained by working with volumes in a spherical surface rather than simply with areas. Aboufadel and Austin (2006) showed the advantages of using a three-dimensional perspective to compute population centers of gravity. In this approach, and assuming an idealized spherical representation of the earth, no map projection choice needs to be made. Only after calculating the weighted average are the three-dimensional points projected onto the surface. The other difference is that we considered the input and output dimensions of the beef industry by calculating the center of gravity for slaughterhouses and cattle herds, while the previous authors used only the herds.

To compute the center of gravity, the earth is assumed to be a perfect sphere with a radius (R) = 6,371 km. Our geocoded units of observation are points (P) on the three-dimensional earth's surface, where x, y and z are the Cartesian coordinates:

$$\mathrm{P} = \left(\mathrm{P}_x, \mathrm{P}_y, \mathrm{P}_z\right) \text{ with } |\mathrm{P}| = \left(\mathrm{P}_x^2 + \mathrm{P}_y^2 + \mathrm{P}_z^2\right)^{\frac{1}{2}} = R = 6{,}371\ km$$

As our original points were defined on the two-dimensional globe surface, we converted their latitude and longitude to Cartesian coordinates. Let α be longitude and β be latitude measured in radians:

$$\mathrm{P}_x = R\cos\beta\ \cos\alpha$$

$$\mathrm{P}_y = R\cos\beta\ \sin\alpha$$

$$\mathrm{P}_z = R\sin\beta$$

Our points came from separate collections, the slaughterhouse production volume dataset, where each plant (n = 2,602) is an observation, and the municipality cattle herd dataset, where the centroid of each municipality is an observation (n = 3,800 (min)/ 5,592). A collection of points is represented as:

$$\{\mathrm{P}^{(i)} : i = 1,2,\dots,N\}$$

For weights ω given by the slaughter volumes or the cattle herds, the weighted spatial average yields a three-dimensional center of gravity $\overline{\mathrm{P}}$:

$$\overline{\mathrm{P}} = \frac{\sum_{i=1}^{N} \omega^{(\mathrm{i})}\mathrm{P}^{(i)}}{\sum_{i=1}^{N} \omega^{(i)}}$$

Since $\overline{\mathrm{P}}$ can be situated within the sphere's volume, it needs to be projected onto the surface for the temporal trajectories to be visualized:

$$\alpha = \tan^{-1}\left(\mathrm{P}_y \backslash \mathrm{P}_x\right) \text{ and } \beta = \sin^{-1}(\mathrm{P}_z/|\mathrm{P}|).$$

Identifying density hotspots and geographic clusters

The geographic densification of industries is known in the social sciences as "clustering." While the concept is derived from the work of Alfred Marshall (1919) on the textile industrial districts in England, over time it has acquired different connotations in various branches of the literature (Vorley, 2008). We refer to the idea of "geographic cluster" to avoid confusion with an economic geographic assessment (such as in Porter (1998)) where nonrandom geographic distribution is only one important factor, others being the presence of suppliers, service providers, related government organizations, and synergies. Here, we are interested only in making a simple assessment of whether the meatpacking industry has increased in density and how this has changed over time and across space.

We used Kernel Density Estimation to identify patterns of geographic clustering (implemented with the Qgis 2.14.20 Heatmap plugin). This method is widely used in applications that range from identifying traffic accident hotspots (Anderson, 2009), to studying crime time-space patterns (Nakaya and Yano, 2010), to assessing geographic customer density (Donthu and Rust, 1989). The method produces a smooth density surface having spatial points as inputs (Xie and Yan, 2008). To do this, a kernel bandwidth (or search radius, *d*) is selected for circles to be drawn around each point. The entire area of each circle is attributed to the value of the corresponding point (animals slaughtered, for example) according to a kernel decay function (KDF), and the density is calculated from the overlapping among the circles — no circle implies no density, many overlapping circles imply high density (DeBoer, 2015). If the kernel function is uniform, then the full extent of the circles have the same value; if triangular, the value decays linearly from the point to the edges; the most widely used functions are Epanechnikov and Quartic. We used the Quartic function:

$$KDF(P) = w\frac{15}{16}(1 - d^2)^2$$

Based on this function, we made two spatial density analyses. First, we used all the data to plot density maps for the years 1966-2017 with a 200 km search radius. This assumes that all slaughterhouses buy cattle from a maximum distance of 200 km and that they are more likely to buy from closer properties. The threshold that configures a high density circle in the map varies according to each year’s density: for example, in 1966 it corresponded to 67.7 thousand head while in 2017 it corresponded to 1.16 million head.

Next, to identify the specific patterns of different sized slaughterhouses, we separated the data into SIF and non-SIF plants and replotted the density estimates using specific density thresholds for each group, which are fixed across the years. The analysis was then limited to 2010 and 2017. To select the threshold, we divided the 2015 distribution into nine categories and designated the top three as high density. For the SIFs, areas with densities greater than 810,000 head were classified as clusters, while for non-SIFs the threshold was 240,000 head.

Measuring market concentration

Market concentration processes change the economic efficiency of markets, but also alters the welfare of market participants. On the one hand, market concentration can enable firms to gain substantial economies of scale which in turn can lead to higher profitability, lower output prices, and technological innovation. On the other hand, high levels of concentration can give some companies the power to set prices at monopsonistic levels and impose barriers to the entry through predatory pricing, thus distorting the market system. The assessment of what level of concentration is acceptable is a complex task that often involves specialized competition protection agencies. In the Brazilian case, CADE recognizes the HHI as an important tool in assessing market concentration, but it has never been able to use it for the meatpacking industry (Boechat and Alves, 2014, p. 120). Neves (2001) and Moita and Golon (2014) studied the domestic market shares of the beef export market and assumed market concentration but could not quantify it.

The HHI is a widely used statistical metric of market concentration originally derived from measures of income inequality (Roberts, 2014). It became popular through its use by U.S. regulators in assessing the competitive effects of mergers (Rhoades, 1993). The HHI is calculated by summing the squares of the firms' market shares. Thus, in a market with *N* slaughterhouses, each slaughterhouse *i* having a μ_i market share:

$$HHI = \sum_{i=1}^{N} (\mu_i)^2$$

Our goal is to calculate the HHI over time. However, given the lack of historical information on plant ownership, we make some assumptions to assess past concentration. We know the present level of agglomeration of plants into holding companies but do not know the former ownership structure. Thus, we restricted the analysis to the period for which we have better information (2006-16) and produced minimum and maximum curves for the years prior to 2016. The minimum values assume zero company agglomeration in 2006 (i.e., all plants were individually owned) and a linear trend toward the 2016 value; the maximum values are a projection of the 2016 level into the past (assuming that the plants were held by the same ownership as in 2016).

The HHI is useful to identify situations where some leaders control the greatest share of the markets. Imagine that a market consists of two firms. If the shares are evenly distributed, the HHI is 0.5. If the market has three players and the shares are still equally distributed, the HHI is 0.333, while if one of the firms has 50% of the market and the others share the rest the HHI rises to 0.375. This value remains noticeably lower than that for the duopolistic market with even shares. This makes sense because two of the three firms are now sharing what in the equal share duopoly is captured by one, but higher than the three-firm even share index, which suggests some degree of concentration. Based on this, we calculate an HHI_{even} based on the equal shares assumption to reflect the benchmark, that is, the even distribution situation. The equal share HHI was derived by Zhou (2003) as:

$$HHI_{even} = N \times \frac{1}{N^2} = \frac{1}{N}$$

A critical aspect of calculating the HHI is the definition of the relevant market. In our case, the meatpacking industry plays a significant role in two segments, the input market (where they acquire cattle) and the output market (where they sell boxed beef and other products). We are interested in measuring power in procurement markets, where a large number of ranchers sells to a restricted number of slaughterhouses (Moita and Golon, 2014). For this, we assume that the input markets are delimited by state borders. Leães (2015) used a jurisdictional approach for Rio Grande do Sul, a state with very high population density, based on substate jurisdictions. Our approach is credible because slaughterhouses very infrequently buy cattle from other states. This is due to fiscal and sanitary barriers to interstate cattle trade. Our approach has one potential limitation: slaughterhouses that are located near state borders might be more likely to buy from another state. However, because of the barriers to interstate trade, we believe that border effects are negligible.

3. Results

3.1. Northward convergence of the beef industry: economic centers of gravity

The historical literature suggests that the beef industry has moved west and north from the densely populated coastal areas (Silva et al., 2017; Valverde, 1967; Wilcox, 2017), but it provides few hints as to the speed of the expansion. To quantify the movement for our study area, we computed the centers of gravity of cattle herds and slaughter production volumes beginning in 1974, the initial year of IBGE's current cattle herd survey. The results confirm the northward displacement; they present an almost linear movement that crossed the Cerrado biome at 22 kilometers each year for the cattle herd and 37 kilometers for slaughterhouses, a displacement that has almost reached the Amazon (Figure 2). It is interesting to note that the midpoints of cattle herds and slaughter production are converging, attesting to the increased interconnectedness between the two industries.

The midpoints in 1974 were in the region known as the "Minas Gerais Triangle," one of Brazil's richest areas. This region emerged in the 19th century as a trading post between the coastal consumer centers and the growing production areas in the Midwest. The cattle herd midpoint was roughly north of the slaughterhouse midpoint; this last was near the city of Barretos, where since 1913 the first refrigerated slaughterhouse operated for many years. The Barretos plant would trail cattle from Goiás, where the 1974 cattle herd midpoint was located, and from across the Minas Gerais Triangle for stocking on its own properties (Costa, 2011). It is possible, therefore, that the region was a center of gravity — a spatial equilibrium between two or more areas of similar weight — as early as the 19th century. By the 20th century, it had become one of the most important cattle raising regions in Brazil (Martins, 1998). The fact that the midpoint was north of the state of São Paulo suggests that the Midwest was exerting an important counterweight to the coastal beef-producing areas.

[Figure 2]

This synthetic account of the dynamics of the cattle and slaughterhouse industries illuminates two characteristics of cattle production. First, those areas that specialize in dairy production do not fully overlap with the beef production sites; therefore, it is to be expected that the midpoint of animal slaughter is not the same as that of cattle herds as a whole. Second, the production of beef cattle itself is divided into breeding, stocking and fattening, and these processes have historically been spatially dissociated. In particular, cattle breeding can be located at a greater distance from consumption centers because calves can be trailed at a lower cost (in terms of weight loss and feed consumption) than adult animals. This pattern of locating breeding systems closer to the forest margins is a typical pattern of the beef industry in Brazil.

Overall, the center of gravity provides a useful aggregated view of historical trends. But as any summary statistic, it does not depict the distribution of economic activities.

3.2. Geographic densification of the meatpacking industry: hotspot analysis

To visualize industrial agglomerations for a specific region over the years, we produced a hotspot analysis of slaughterhouse production volumes. The darker red colors in Figure 3 represent higher slaughter volumes, with the absolute values of the densities being year-specific; for example, while in 1966 the highest density corresponded to 677 thousand head slaughtered, in 2016 it corresponded to 1.1 million head. More detailed maps, including an animation, are provided in Figures S13-S19.

[Figure 3]

The maps show that slaughterhouses were initially concentrated around the most densely populated coastal zones. At the same time, some of the expansion areas known to have emerged after 1955 appeared as high density in 1966: the Minas Gerais Triangle; western São Paulo around Andradina; and Campo Grande in today's Mato Grosso do Sul. However, the high-density areas were systematically located south of Brasília; this changed with the subsequent process of moving northwest. Over time, new clusters appeared around Goiânia, in the middle of the Cerrado biome, and in southern Mato Grosso. But it was not until the mid-1990s that the first high density areas appeared in the Amazon biome, stimulated by a supply of cattle that was growing very rapidly. By 1998, new slaughterhouse clusters had formed in Rondônia, northern Mato Grosso, and southern Pará. In the two decades that followed, a substantial reorganization of the meatpacking industry occurred as the clusters near the coast almost disappeared while those in the central and northern Cerrado and in the Amazon became increasingly important. The Pantanal biome remained largely beyond the slaughterhouse clustering areas throughout the study period. After 2010, Rondônia, Mato Grosso and Pará had clusters that rivaled those elsewhere in the study area.

By looking at the white crosses on the map we can readily visualize the rising number of plants. While in 1966 there were only a handful, by 2016 slaughterhouses were present even in the most remote parts of the Amazon (the Pantanal biome remained the exception; it had only eight plants in 2016). Yet despite this expansion, the kernel density estimates revealed no clustering pattern for many areas with many slaughterhouses. This is true for the whole Northeast region, most of the state of Tocantins, and northern Minas Gerais. These regions are all characterized by small scale slaughtering as shown in Figure 3. While numerous small plants operate in many states — such as in Maranhão — their slaughter volumes are very low in comparison to the SIF plants.

In Figure 4, we can see the clusters broken down by SIF and non-SIF slaughterhouses. Maps for other years are provided in Figures S20-S23. The results suggest a geographic separation between clusters of SIF plants to the west and non-SIFs to the east, with one major overlap in the state of Goiás.

[Figure 4]

This east-west division may be a consequence of higher human-to-cattle population ratios in the coastal areas, so that a larger share of the cattle production there is consumed in-state. In the newer areas of the Midwest and Amazon, where the ratio is much lower, SIF plants that produce large volumes sell across the country and internationally. The only exception to this pattern is the state of São Paulo, where the human-to-cattle ratio is very high yet SIFs are still clustered. In this case, the explanation is in part path dependency — refrigerated slaughterhouses first appeared there — but also because São Paulo hosts the largest national consumer market and is close to the main exporting ports.

As slaughterhouses consolidated their expansion into the Cerrado and Amazon in the second half of the 20^{th} century, large meatpacking groups emerged and built or acquired many SIF plants. These groups grew concurrently with industry expansion into our study region, starting in the 1960s, accelerating in the late 1990s and peaking around 2014. As the process unfolded, the question of whether their market power was rising to unreasonable levels naturally emerged, as high market concentration facilitates cartelization or can otherwise allow companies to extract monopoly benefits at the expense of society’s overall welfare.

3.3. Increased market concentration in the areas of recent settlement

With the objective of verifying if market concentration has increased in cattle procurement markets, we calculated HHI using the estimated production volumes in SIF and SIE plants for 2006-16 and considering states as the relevant markets. In Figure 5, we plot the results for the average state in our study region, where the average is weighted by the states' yearly slaughter volumes. The gray range indicates the evolution of the HHI for the minimum and maximum company agglomeration scenarios, while the black line is the hypothetical index for the case where market shares are equally distributed across all slaughterhouses. We expect the actual curve to sit halfway between the minimum and the maximum, as the maximum assumes the 2016 level of consolidation and there was largescale market consolidation before 2016. Indeed, using data from Carvalho (2016, Tables 4-5), we estimate that the number of SIF plants controlled by the largest four companies grew by 123% in 2006-2014. Since the total number of SIF plants decreased by 18% (IBGE, 2017a), the consolidation of big four group took place mostly through the acquisition of existing plants.

The HHI varies from zero to one, where values closer to unity indicate a higher concentration. To assess the degree to which a value is high or low, we use the U.S. official grading were values below 0.15 indicate unconcentrated markets, values in the 0.15-0.25 range indicate moderate concentration, and values above 0.25 suggest high (Justice and FTC, 2010).

The result shows that the equal shares level of concentration dropped by 4.5% between the 2006-08 and 2014-16 triennia. This indicates that, in the hypothetical world of zero inequality among companies, the market power of each individual company would have diminished. However, the gray curves show that, in the real world, the absolute level of concentration is very likely to have risen from 0.09/0.18 in 2006-08 to 0.15/0.16 in 2014-16. Assuming that the 2006-08 value was midway between the minimum and maximum, the change would be from a level close to 0.13, classified as unconcentrated, to a level close to 0.16, where markets start to be moderately concentrated.

The above conclusion becomes stronger when the change in the absolute HHI level is compared to the change in the baseline. We do this by plotting the ratio between the HHI and the even-distribution HHI in the green range. The result shows an unequivocal upward trend until 2013, followed by a more ambiguous pattern.

[Figure 5]

Next, we show how the average trend is distributed across our study area. We identify three distinct groups. The first group, depicted in Figure 6, includes the densely populated states of São Paulo and Minas Gerais, where relative concentration either remained stable or grew by a relatively small margin. In these states, the absolute level of concentration remained below the national average and well within the unconcentrated category. With very high resident demand, these states have a mix of large and medium slaughterhouses, and their industry was established long before that of other states.

[Figure 6]

In states with more recent settlement, with the possible exception of Pará, our results instead reveal a strong concentration pattern. The second group, shown in Figure 7, includes the Midwest, where concentration growth was noticeable: Goiás, Mato Grosso, and Mato Grosso do Sul. These states are newcomers to the slaughter industry, so their lack of consolidated companies may have facilitated the establishment of dominant players because the barriers to entry were lower. Rondônia is also part of this group although it experienced a lower concentration growth. Absolute concentration remained moderate for all these states. Finally, in the northernmost states of our study area (Figure 8), with the possible exception of Pará, the trend was a falling level of relative concentration.

[Figure 7]

[Figure 8]

Overall, what emerges is a picture of markets that do not have high concentration levels, but where the trend in the last decade has likely been one of increased concentration. While in smaller states or in those closer to the coast the industry may not have concentrated, in the Midwest and in Rondônia the leading companies were clearly gaining market power.

4. Discussion

4.1. Why did the beef processing industry expand to the interior?

The geographic dispersion of cattle production is an important driver in the growth of the slaughter industry. Cattle raising in Brazil is traditionally practiced in open pastures. As the areas around older settlements close to coastal areas became more developed and densely populated, land prices rose and cattle herds were pushed to the interior, initially from western São Paulo, then moving to Goiás and Mato Grosso do Sul, and finally reaching the Amazon through Mato Grosso, Rondônia and Pará. The dispersion of cattle herds, along with construction of roads that linked the new settlements to the main cities and export corridors, were among the major drivers of slaughterhouse expansion.

We identified nine clusters in 2017 with a 200 km influence radius around slaughterhouses. We also found that plants tend to locate close to roads and towns. At smaller scales, it is often the case that large plants face little or no competition in local markets. The limited number of slaughterhouses within any given region results from the friction between gains of scale and transportation costs. The gains of scale have to do with the substantial capital inputs needed to acquire the technologies used in slaughterhouses, and with the gains in efficiency that they yield, both of which promote domination of the market by the larger plants. On the other hand, transportation costs are significant across the supply chain. For procurement markets, it is generally uneconomical for ranchers to sell animals a long distance away (where *long* in this context is over 500 km) since the cost per kilometer of transporting live animals increases with distance because the animals get injured, lose weight, and require feeding and care (Boechat and Alves, 2014; Pigatto, 2001). Given the technology-related propensity of larger plants to dominate markets, and the fact that ranchers avoid selling to distant plants, slaughterhouses tend to move close to suppliers.

At the other end of the industrial process, where boxed beef is sold to retailers, transportation costs display the opposite pattern: as the distance between slaughterhouses and retailers increases, the per kilometer transportation cost drops. The meatpacker thus faces transportation costs that are marginally increasing in input markets and marginally decreasing in output markets. The consequence is that when roads or transportation technology improve, in order to maximize profits, slaughterhouses enter new markets. When they are expanding to less populated states, it is likely that it has become profitable to exchange lower output revenues for lower input costs, which make them move ever closer to cattle suppliers. Thus, at a broad spatial scale, the combination of technological advance and road improvement can contribute to the dispersal of the beef processing industry. This phenomenon became clear in Brazil when railroads with refrigeration technology connected the main cities to the interior, and when the major road connections were built after 1950 while the technological standard of slaughterhouses had evolved to become specialized in slaughtering bovines (Mamigonian, 1976; Valverde, 1967).

At smaller spatial scales, however, roads create densification as plants look for easy access to paved arteries. Indeed, by looking at the locational pattern of SIF and SIE plants in Figure S24 we can easily identify the delineation of federal roads in Rondônia, Tocantins and Pará. In similar fashion, cities and towns also create some clustering at the local scale. Towns not only concentrate the labor force, they supply such services as machinery maintenance, administration and transportation. Large cities are another source of industrial densification. For example, our results show that São Paulo was and continues to be a cluster of cattle slaughter activity, especially with regard to non-SIF plants that supply the city itself. Other cities that emerged with sizeable clusters are Goiânia, Campo Grande and Cuiabá, all of which have a combination of large and small plants. Therefore, roads and urban areas create local patterns of clustering.

The interiorization of beef production was also driven by government policy. The building of roads was part of a largescale development project to connect the different parts of the country. The government incentivized the displacement of people and companies to the interior by offering free lands through its land reform agency. It also created specific federal offices whose aim was to promote the settlement of the Midwest and the Amazon (Andersen et al., 2002; Law 1,806, 1953; SUDAM, 2018), but also of the Northeast, and these offices provided subsidies to cattle ranching and agricultural development (Law 5,173, 1966; Law 5,374, 1967; SUDAM, 2018). At present, three regions remain the object of such development policies in Brazil, which have funding provided by the 1989 Constitution: the Midwest, the Amazon, and the Northeast (Law 7,827, 1989; MIN, 2018).

One caveat to our findings is that our data represent formal and surviving companies, so the number of plants may have been underestimated, especially for earlier periods. In the late 2000s, the formalization of small companies increased in Brazil due to policy incentives (Law 123, 2006), tax exemptions (Law 12,058, 2009), and the spread of electronic fiscal receipts (Mendes et al., 2017), so slaughterhouses that operated clandestinely were incentivized to obtain a business registration. Tax exemptions for exports, enacted in 1996, may have further stimulated larger plants to formalize their status (Law 87, 1996). However, for this group, our data compare favorably with the historical record. Carvalho (2016, Table 2) provides counts of beef processing industries between 1970 and 1978 for 26 states, while the figures in our data for 16 states exceed those data by at least 22%. While Carvalho's data are also unlikely to have captured the informal market, they still validate our reconstitution. Note that for companies that operated informally, our data are certainly weaker than for formal companies.

Since our spatial analyses were performed as a set of cross-sectional computations, this factor would cause concern if informal and nonsurviving companies were overrepresented in some locations in a given year. This is indeed potentially the case, since informal companies were likely to be more frequent north of Mato Grosso until the mid-1990s. However, absent this problem, our results would have shown an industry that was displaced even farther north, one whose density was even higher in the north pre-1990. Our dynamic results would therefore not be compromised if the data limitation did not exist, rather they would become stronger.

4.2. Market concentration in the slaughter industry

In large and mature markets such as Brazil and the United States, the meatpacking industry is expected to display some level of concentration. However, the U.S. experience shows that there is no linear process leading to ever-increasing concentration. Indeed, the U.S. meatpacking industry has gone through three clear phases since 1865 (Hogeland, 2004). The first was widespread dominance by the big four — Swift, Armour, Cudahy and Wilson. They had gained enormous market power by the end of the 19th century by controlling the rail transportation of meat, which when combined with refrigeration technology generated massive gains of scale. Between 1920 and 1970, the industrial agglomerations in Chicago, New York and other major stockyards dispersed toward rural areas. A new technological combination — road transportation and feedlots — along with other policy- and market-related factors, caused the interiorization (Arnould, 1971). Meanwhile a wave of newcomers also caused the industry to deconcentrate (Anthony and Egertson, 1966). But by the 1980s, yet another technological change caused the trend to reverse: the production of boxed beef at the slaughter site (Azzam, 1998). Food processing companies engaged in vertical integration and supply chain coordination gained new leadership, leading to today's highly concentrated industry (MacDonald et al., 2000).

In Brazil, the history was similar in many ways. The first concentration process started in the early 20th century with the largest plants owned by some of the same companies as in the U.S. The organization around stockyards, however, never existed in Brazil. Instead, dispersion started early, and was already underway in the 1920s, gaining force in 1955. By then, the average size of plants was decreasing and the number of plants was increasing as they expanded north. The inland expansion was very strong and led to more competition, especially from a set of national companies that gained ground after 1960. By the mid-1990s, some of the national newcomers started to agglomerate plants across the country through mergers and acquisitions. JBS acquired Swift in 2007 and Bertin in 2009; Marfrig acquired large plants from Margen and Mercosul in 2009 (Moita and Golon, 2014). This growth was especially noticeable in the states where high cattle supply and low demand enabled access to export markets through SIF plants — essentially in the Midwest and later, Rondônia.

Besides growing in the domestic market, the big four conglomerates were supported by the Brazilian Development Bank (Portuguese acronym BNDES) to expand internationally. As these companies started to target foreign markets, some of their operations were financed with public capital, such as in JBS' acquisition of Swift's Argentinian branch in 2005 and of the American Smithfield Beef in 2008 (Mendes et al., 2017). One critique of these financing operations is that public funds were allocated to provide subsidized credit and capitalize companies that were already big, resulting in large holdings that have a significant participation of Brazilian government in their shares (Carvalho, 2016). However, it remains unclear whether BNDES' funds may have contributed to the observed concentration process in the domestic market.

Indeed, the big four group had an estimated 26.4% of the total SIF slaughter in 2006, which rose to 54.8% in 2014 (Carvalho, 2016, Table 4). Thus, following this rapid market restructuring, CADE vetoed the acquisition of more plants from Mercosul by Marfrig in 2009 on the grounds that regional competition would be undermined. Further investigations by CADE of cartel practices also led to fines and legal agreements in 2007 (CADE, 2017; Caleman and Cunha, 2011; JBS S.A., 2017). CADE's judgement was based on evidence of cartel practices raised by documental proofs, not by an empirical assessment of market concentration. In addition, two special investigations were conducted in 2016 by the legislative bodies in Rondônia and Mato Grosso, but conclusions were mixed, in part due to the difficulty in assembling data for a robust quantitative assessment (DOE-ALE/MT, 2016; DO-e-ALE/RO, 2016). The academic literature about this topic in Brazil generally suggests that the beef processing industry is becoming concentrated (Boechat and Alves, 2014; Carvalho, 2016, p. 28; Neves et al., 2001, p. 4), although the quantitative evidence used is typically limited.

Our market concentration analysis covers the most recent period from 2006-16. The results suggest an increasing level of absolute and relative concentration, in agreement with most of the literature. But the increased concentration was not always the rule. In small states where slaughterhouses are independently owned, and in the older states where markets are consolidated, the picture is one of stability. The bulk of the concentration happened in four states that hold 44.5% of Brazil's 2016 cattle herd (FNP, 2017). These states share many similarities. First, their agricultural economies grew very rapidly to become national leaders of livestock-raising technologies, including genetics, sanitation control, and integration with the grain complex for animal feed. If by the 1960s the slaughter industry was largely marginal in these states, it caught up very rapidly. By 1990, the geographic clusters of animal slaughter north of Brasília were almost as dense as those south of the capital. Our analysis shows that the spatial densification coincided with market concentration.

The main concern with market concentration is that it can lead to anticompetitive behavior and impose losses on the weaker parts of the supply chain — the ranchers and consumers. However, a market that is structurally concentrated does not necessarily operate in an anticompetitive way; the exercise of market power is a matter of company conduct (Azzam, 1998). While concentration favors harming monopolistic behavior, concentration may also yield benefits in the form of gains of scale. Indeed, in the U.S. case the evidence is mixed on whether the meatpacking industry displays monopolistic behavior in input or output markets, in spite of clear evidence suggesting concentration (Azzam and Pagoulatos, 1990; Koontz, 2003; Wohlgenant, 2013).

For Brazil, the evidence of noncompetitive behavior is also mixed (Boechat and Alves, 2014; Boechat and Parré, 2018; Carvalho, 2016; Moita and Golon, 2014), although it is severely limited by lack of data. Our results shed new light on industrial concentration by quantifying it with plant level estimates, and the data could be further employed to provide a much better understanding of market power in Brazil. Our analysis can therefore serve as a first step for the development of studies using the Empirical Industrial Organization framework (Azzam and Pagoulatos, 1990) to study market power.

4.3. Conclusion: What implications for supply chain conservation efforts?

The results in this paper are important for supply chain initiatives in the beef sector because slaughterhouses are well placed to influence cattle producers. Our plant level data confirm that not only did the cattle herd move into the Amazon, but the meatpacking industry followed very closely. Along with a noticeable densification of the beef processing industry along the southern and eastern borders of the Amazon biome came a process of market concentration. Indeed, the states of recent settlement where cattle advanced the most are also where the largest firms gained substantial market power. With more power, firms are better able to establish strong buyer-supplier relationships (Benton and Maloni, 2005; Touboulic et al., 2014) and thus to achieve successful coordination for environmental mandates. Therefore, to the extent that it creates bargaining power in supply chain management, market concentration is a desirable outcome for environmentally oriented interventions.

Very high levels of concentration, however, can cause advocacy groups to lose the power to bargain through boycott threats. In the extreme situation of a total monopoly, boycott threats are less effective because not all consumers are able to substitute beef for other products. A company that dominates the market may therefore be less responsive than if it had competitors. This suggests that increases in market concentration will facilitate conservation-related supply chain coordination only up to a point. Yet in our study area, the average level of concentration is only moderate, and certainly far from a total monopoly situation. Therefore, while the observed concentration could be harmful for ranchers and consumers through the setting of noncompetitive input and output prices, it may nonetheless play in favor of demands for changes in the environmental, sanitary, and other attributes of beef products.

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Figures of

Expansion and market concentration of Brazil’s beef industry, 1966-2017

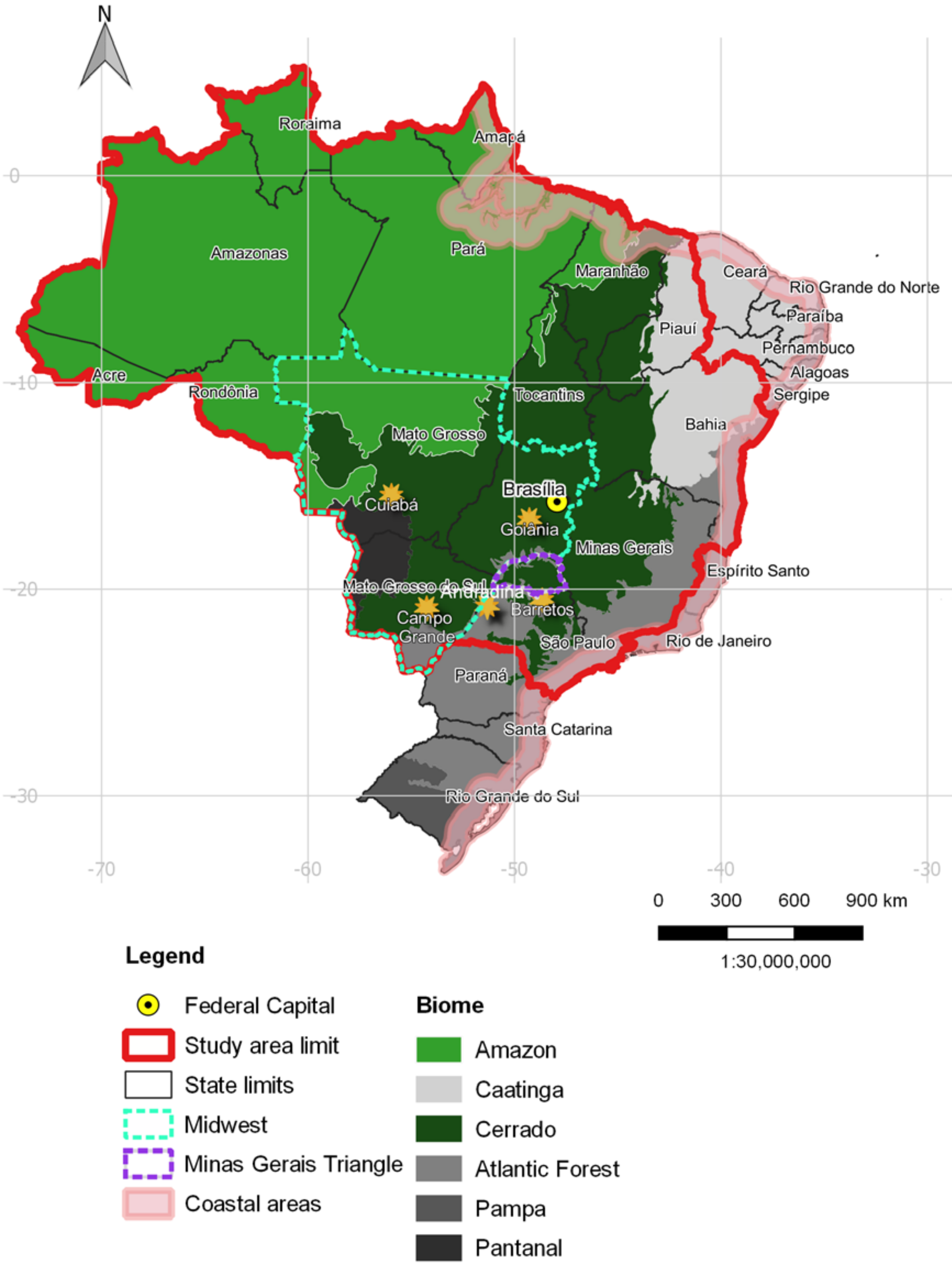

Figure 1. Study area, Brazilian biomes, states and relevant geographies. The study area includes the full extent of each state that overlaps with the Amazon, Cerrado, or Pantanal biomes, with the exception of Paraná.

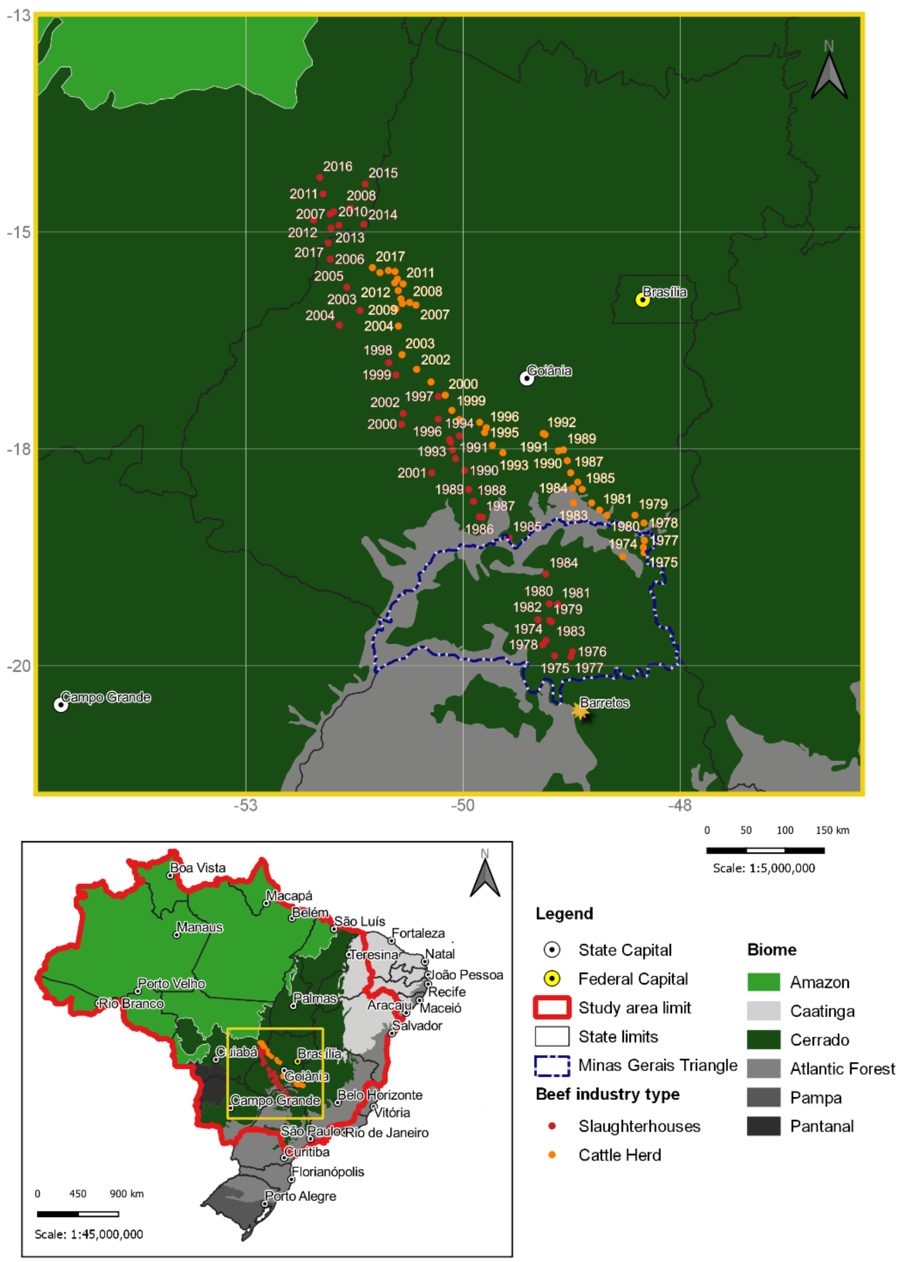

Figure 2. Centers of gravity of the beef industry. The map shows the temporal and spatial displacement of cattle herds and slaughterhouses. The beef industry's midpoint displays a converging pattern or northward movement. By 2017, the center of gravity was very close to the border between the Cerrado and Amazon biomes. The slaughter volumes data are backward extrapolated from IBGE (2017a) and the cattle herd data are from IBGE (2017b).

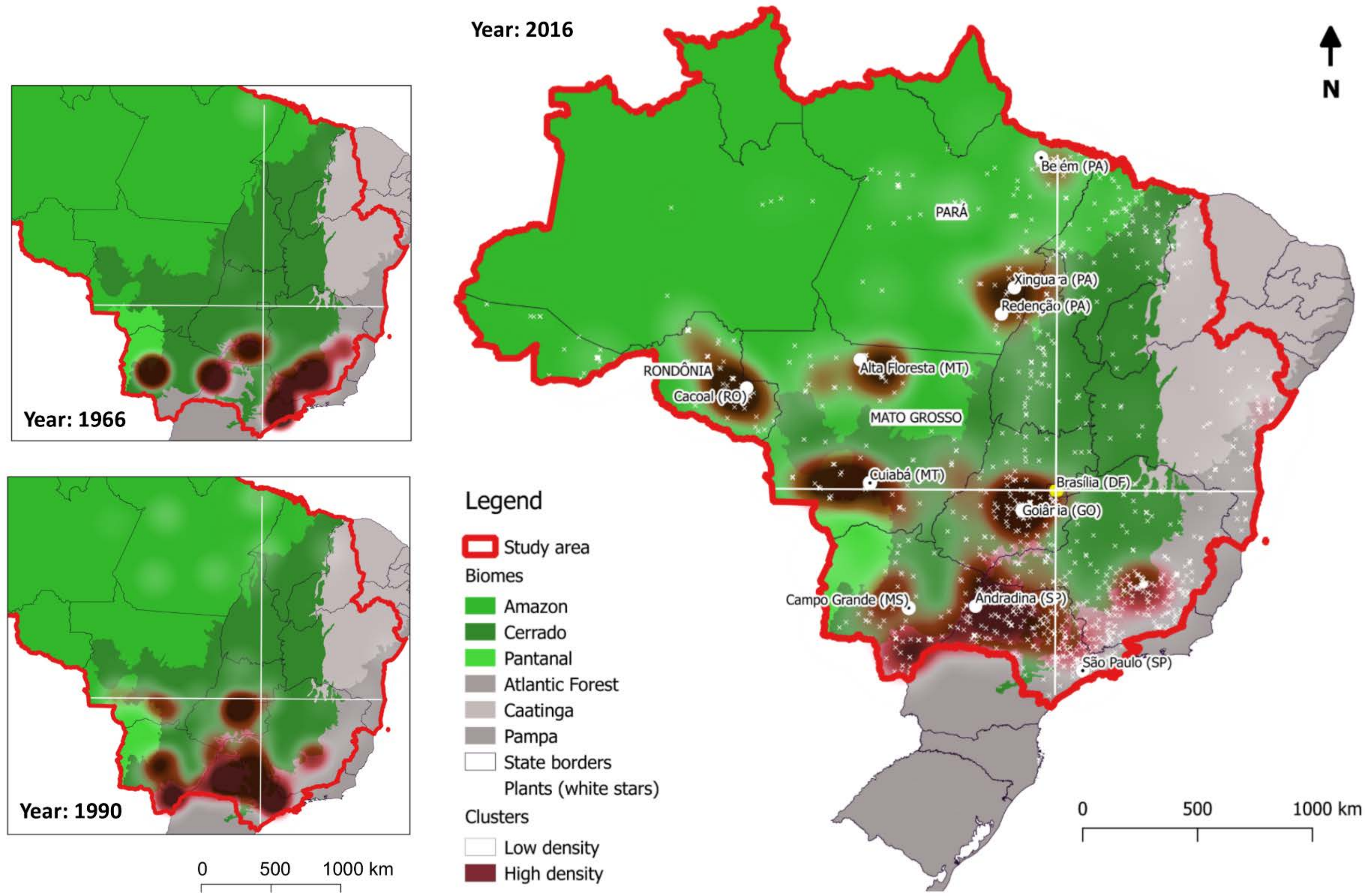

Figure 3. Geographic clustering of slaughterhouses. In 1966, the industry was concentrated south of the horizontal line crossing Brasília. The cluster to the west near Campo Grande, a Cerrado region in the state of Mato Grosso do Sul, shows that the expansion to the interior had already begun. In 1990, the clusters west of the vertical line crossing Brasília were larger than those east (nearer the coast). By 2016, the slaughter industry's zgeographic density northwest of Brasília was very high. Data sources: see Figure 2.

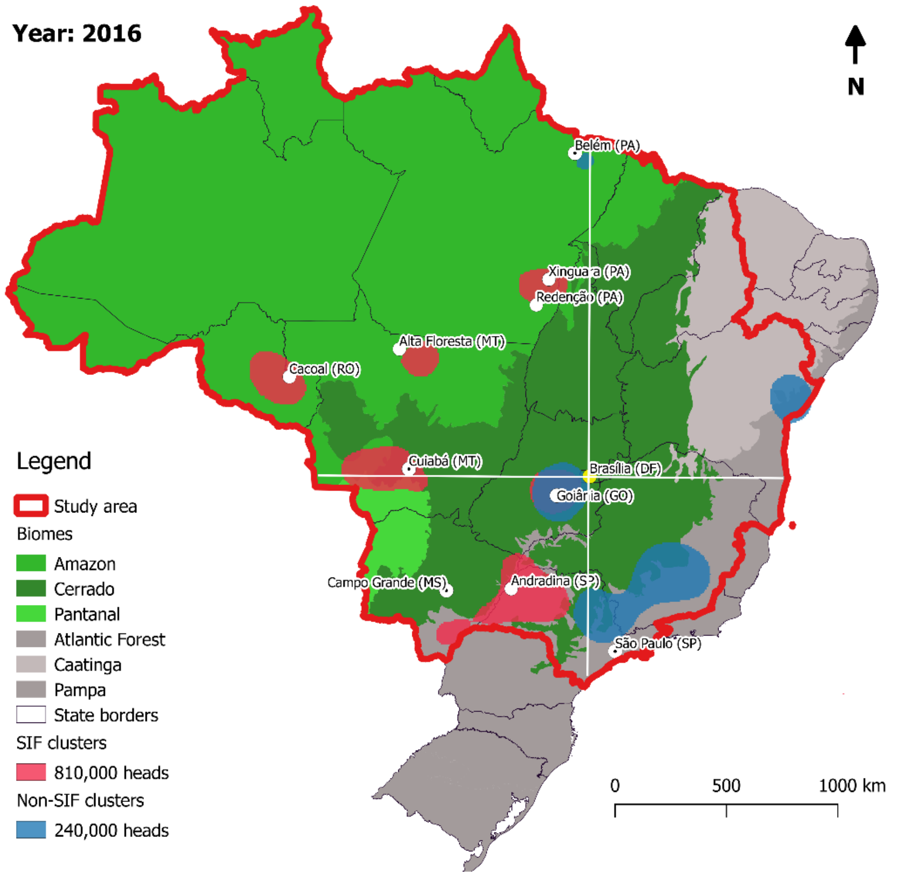

Figure 4. Geographic clustering of federal (SIF) and non-federal inspected slaughterhouses. SIF plants can sell across Brazil and internationally. This part of the industry is located in the interior, west of Brasília. The other plants, with more restricted markets, are instead located nearer the coast. This pattern is in part due to the very high cattle supply associated with a relatively small market size, in terms of demand, in the interior. Conversely, the coastal areas have large markets so they buy from SIFs in the interior and non-SIFs in nearby areas. Data sources: see Figure 2.

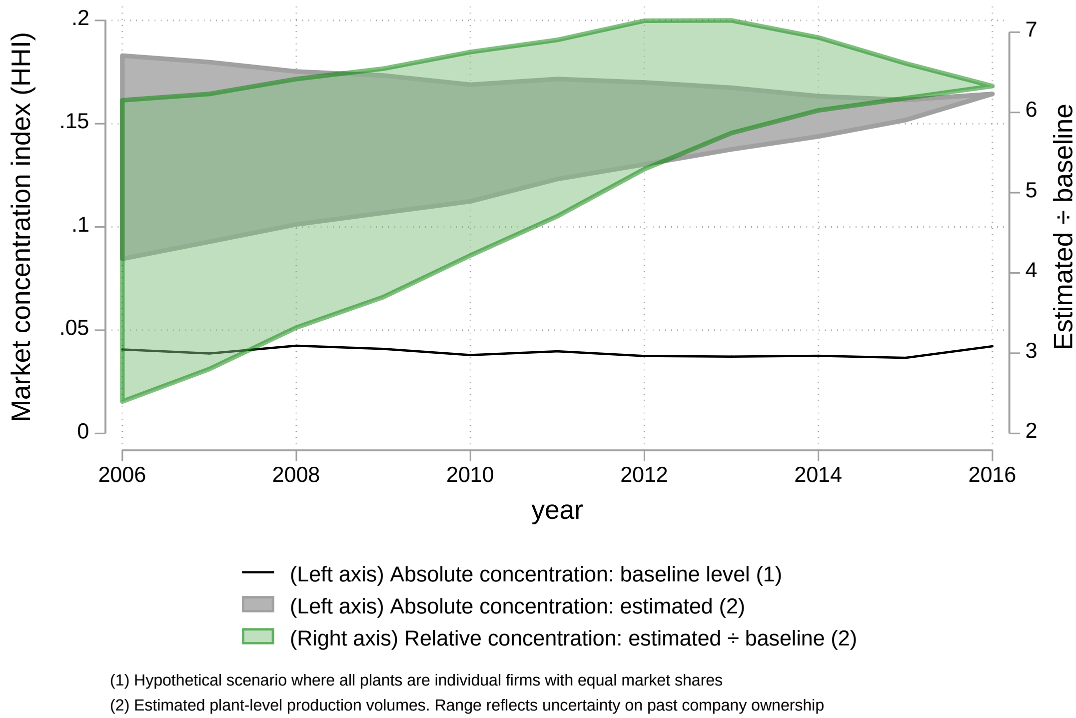

Figure 5. Market concentration in the slaughterhouse industry (average across states). Market concentration has been rising in the beef industry. The plotted Herfindahl-Hirschman Indexes (HHI) are calculated for each state and averaged across the country using cattle herds as weights. Based on the U.S. official rating (Justice and FTC, 2010), the absolute concentration level shifted from unconcentrated to moderately concentrated in 2006-16 (the threshold is at HHI=0.15). The relatively stable baseline concentration shows that the entry of new players in the 10-year period did not have a substantial effect on concentration. Indeed, the relative concentration estimate, which is free from the effect of the number of players, shows an even steeper rise until 2013.

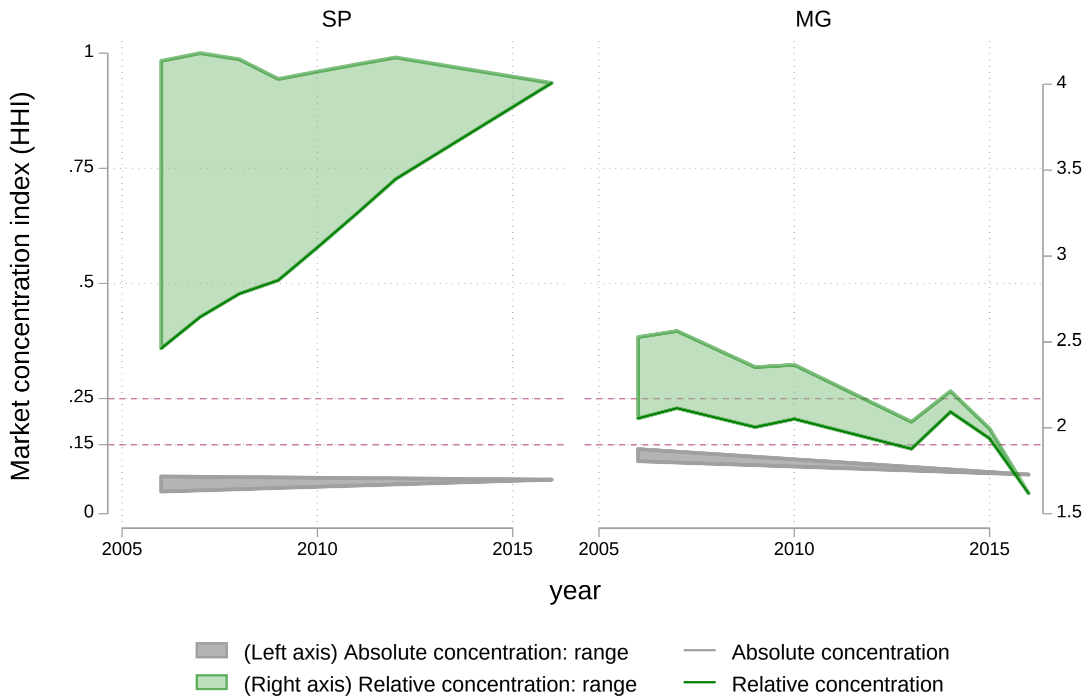

Figure 6. Market concentration in the slaughterhouse industry (São Paulo and Minas Gerais). São Paulo and Minas Gerais are consolidated cattle ranching states and their absolute concentration levels are very low. In São Paulo, the trend seems to show a small increase in relative concentration, while in Minas Gerais there was a decrease. These large cattle ranching states are of old settlement. The horizontal lines indicate the threshold levels for the unconcentrated category (HHI<0.15), moderately concentrated (HHI>=0.15, HHI<0.25), and highly concentrated (HHI>0.25) categories. States with five or less plants were omitted.

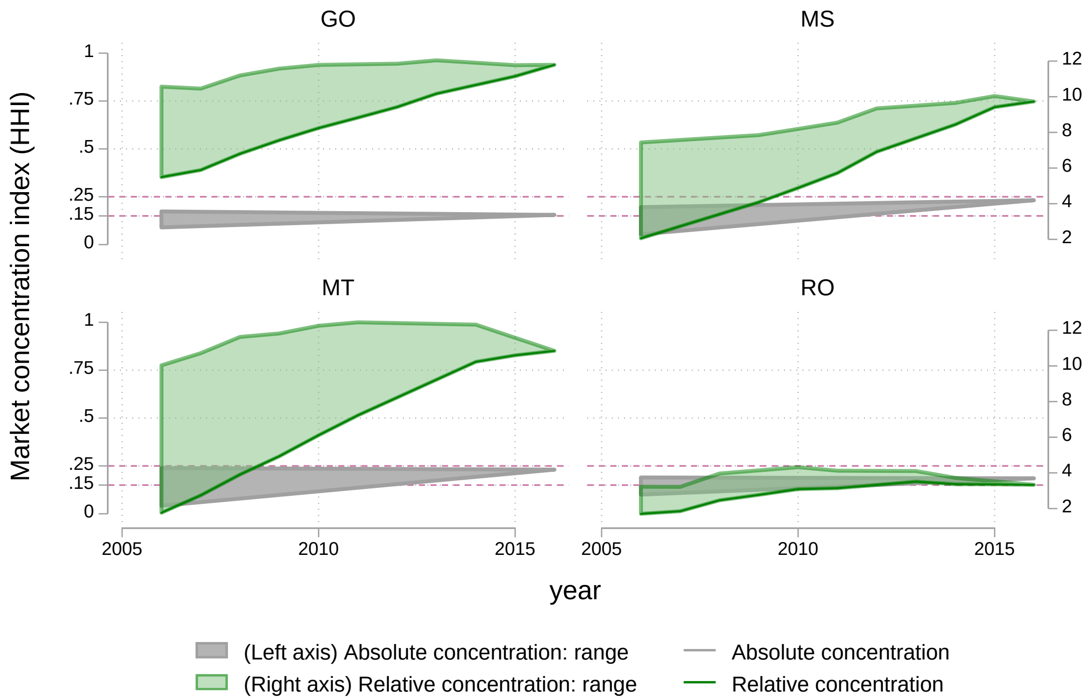

Figure 7. Market concentration in the slaughterhouse industry (Goiás, Mato Grosso do Sul, Mato Grosso and Rondônia). The states of Goiás, Mato Grosso do Sul, Mato Grosso and Rondônia experienced an upward trend in concentration relative to the baseline along with a moderate absolute level of concentration. The horizontal lines indicate the threshold levels for the unconcentrated category (HHI<0.15), moderately concentrated (HHI>=0.15, HHI<0.25), and highly concentrated (HHI>0.25) categories. States with five or less plants were omitted.

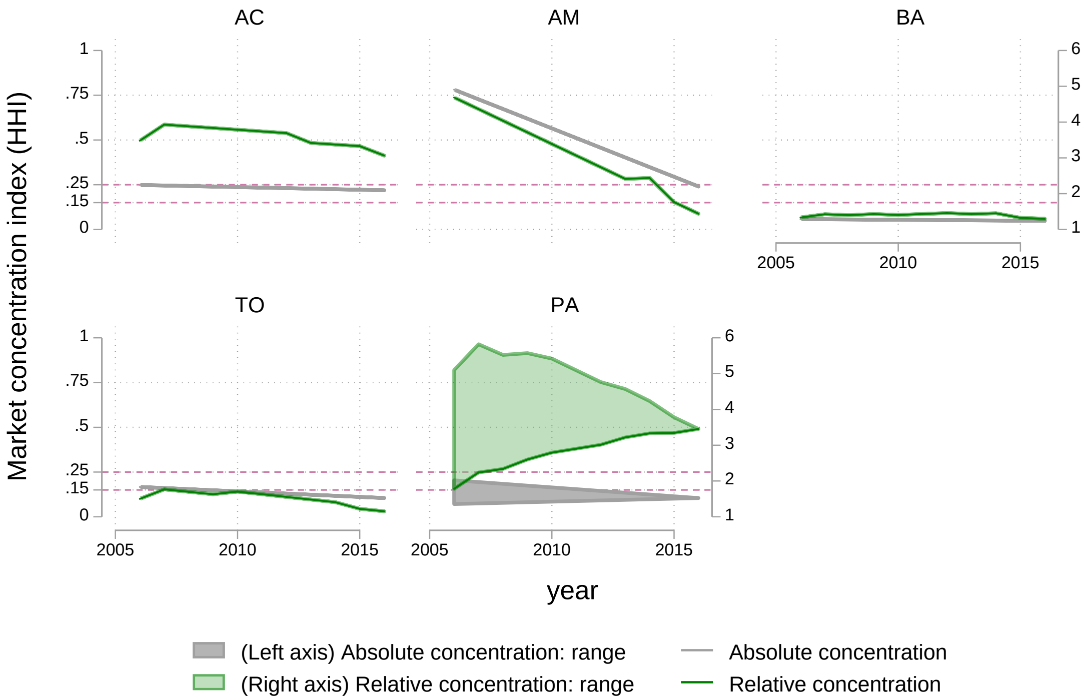

Figure 8. Market concentration in the slaughterhouse industry (Acre, Amazonas, Bahia, Tocantins and Pará). With the possible exception of Pará, this group of states experienced a fall in concentration relative to the baseline. Acre, Amazonas and Bahia are relatively small cattle ranching states. States for which there was no company agglomeration do not show ranges. The horizontal lines indicate the threshold levels for the unconcentrated category (HHI<0.15), moderately concentrated (HHI>=0.15, HHI<0.25), and highly concentrated (HHI>0.25) categories. States with five or less plants were omitted.

Supplementary Information for

Expansion and market concentration of Brazil’s beef industry, 1966-2017

This PDF file includes:

Supplementary text
Figs. S1 to S24
Tables S1 to S3
References for SI reference citations

Contents (hyperlinks)

Methodological appendix

A. Historical slaughterhouse dataset

In this section we provide a summary of the data and methods used to build the slaughterhouse dataset. A full account can be found in Vale et al. (2019).

Data. The following eight sources of raw data were used:

1) Lists of registered companies from the Federal Revenue Agency containing unique company codes (CNPJ, Portuguese acronym for “national registry of companies”), names, opening dates, addresses, geocodes, and closing dates (Empresômetro, 2017).
2) Cross sectional data on SIF and SIE plants compiled by Barreto et al. (2017) and Lapig (2016).
3) Company registries from the state revenue agencies aggregated in the federal system Sintegra (2017).
4) Data from the Ministry of Agriculture on SIF plants (MAPA, 2017a).
5) Data from the state sanitation agencies on SIE plants (SISBI-POA, 2016).
6) Data from the Federal Prosecutors Office on supply chain commitments (MPF, 2017).
7) Cattle transaction data from the state sanitation agencies (GTA), which were available for six states (Maranhão, Mato Grosso, Mato Grosso do Sul, Minas Gerais, Pará, Rondônia) and were obtained by the Gibbs Land Use and the Environment Lab and Trase (Transparency supply chains for sustainable economies).
8) Lists of SIF plants compiled each year by the Ministry of Agriculture (MAPA, 2017b).

These data were assembled following a sequential process in which information from new sources was added both vertically (new observations) and horizontally (new variables) at each step.

Step 1. The first source was the federal CNPJ registry (Empresômetro, 2017). In step 1.1, we filtered these data to extract the entries that seemed related to slaughterhouses. These were later validated against other sources, and entries found to not refer to slaughterhouses were dropped. In step 1.2, we added data on SIF and SIE plants by Barreto et al. (2017) and Lapig (2016). This allowed us to retrieve SIF and SIE codes, key identifiers for inspected slaughterhouses.

Step 2. We used the CNPJ codes to retrieve information from other sources. First, we accessed information from the State Revenue Agencies through Sintegra (2017). This data source tends to have more accurate opening and closing dates. Next, we used data from MAPA (2017a) to obtain the dates in which the federal inspection stamps were first granted. Finally, we used data from the state sanitation agencies to identify plants that were under state inspection and retrieve their SIE codes.

Step 3. A physical plant may have zero, one, or multiple CNPJ registries. Where an active plant does not have a CNPJ, it is operating in a clandestine way. If it has more than one CNPJ, this could be due to managerial reasons (e.g.: different markets managed through different CNPJs), fiscal motivations (splitting revenue into different companies to benefit from low tax brackets), or otherwise to explore regulatory loopholes (e.g.: environmental regulations). Given this, we used common names and addresses to aggregate CNPJs into physical plants. We also geocoded the addresses into spatial coordinates for all CNPJs.

Step 4. We retrieved information on adherence to supply chain commitments that mandate better labor and environmental practices. These include the G4 cattle agreement, where the big three meatpackers voluntarily committed to monitor their supply chains and exclude noncompliant suppliers (Gibbs et al., 2016), and the TAC (Portuguese acronym for ‘conduct adjustment term’) legally binding contracts where the Federal Prosecutors’ Office required that slaughterhouses monitor and exclude noncompliant properties from their supply chains (MPF, 2017).

Step 5. Once the CNPJs were collected into plants, the dataset contained duplicate observations for plants with multiple CNPJs, so we had to single out a single opening/closing date and location for those plants. For example, if two CNPJs had different opening dates, the earliest one was attributed to the plant. We further inferred that the date of the last ownership change was the date in which the most recent CNPJ was opened, if this CNPJ had a different name than the earlier CNPJ (except where the names were known to belong to the same holding company).

Step 6. The last data source used were the GTA records. We used the GTA for two purposes. First, we added plants to our dataset that had not been identified through other sources; this included plants without sanitation inspection. Second, we checked whether the plants were operating during each year by documenting whether they had at least one slaughter transaction. For 10 states where GTA records were not available, we inferred activity and inactivity from the opening and closing dates.

Finally, we validated the data. First, we used high-resolution imagery by Bing Maps and Google Maps to verify whether the geocoded locations of SIE and SIF plants had the physical infrastructure typical of a slaughterhouse. Where the geocoded location could not be visually matched to a plant, we geocoded the plant with the city's or town's centroid. Next, we compared our total counts of plants at the state level with official data from IBGE (2017a). If our count was >15% lower than the official count, we carefully re-ran steps 1-6. Finally, we downloaded lists of SIF plants from MAPA (2017b) to validate our SIF codes and addresses, making corrections where necessary.

B. Estimating slaughterhouse production volumes

Here we present the definitions, data and methods used to estimate slaughter volumes for slaughterhouses in Brazil, and the results. Slaughter volumes are currently available at an aggregated scale (states) for the entire country starting in 1997, or in a less aggregated format (municipality, transaction) for some states in recent years. Our challenge was to disaggregate state level slaughter volumes among individual plants without knowing the slaughter volumes of most municipalities and plants in most years. Municipality level data on slaughter volumes in Mato Grosso, Pará and Rondônia were used as the dependent variable in a regression framework to predict slaughter volumes for 2006-16. The independent variables included cattle herds, GDP, population, number of employees in the meatpacking industry, and others highly correlated with slaughter volumes. The predicted number of cattle slaughtered were disaggregated from municipalities to plants using shares derived from official data.

Definitions

Plant: individual physical unit of a cattle slaughter facility. We produce estimates only for federally-inspected plants (SIF) and state-inspected plants (SIE); municipality-inspected (SIM) and uninspected are omitted due to lack of data. All plants considered here are assumed to have operated for the entire year.

Holding / company: controller of one or more plants.

Slaughter volume: number of head slaughtered in one year (Jan. 1st - Dec. 31st).

GTA: Portuguese acronym for 'Animal Transit Form,' a registry of cattle transactions between properties. All transactions involving the movement of cattle are recorded, including for slaughter, auction, regular between-property sales, and others.

Data used

All data sources are described in Table S1. Except for the GTA and for the slaughterhouse locations from GLUE, all data are from official government sources and, to the best of our knowledge, were collected with consistent methodologies over the years. For the GTA, methodological inconsistencies across time and space led to varied degrees of inaccuracy (see Table S2 for accuracy estimates). To avoid using highly inaccurate information, we restricted the sample to the years for which the total GTA slaughter volume at the state level was equal to or higher than 60% of the total according to credible sources (we took the average between the official IBGE 1 and the Anualpec estimates). We also dropped municipalities with slaughter volumes lower than 504 head/year for the estimate — assuming a minimum operation size for a single slaughterhouse of two head/day for a total of 252 days/year[1]. The state with the highest accuracy problems is Pará, where our version of the GTA has consistently underreported slaughter volumes. Therefore, for Pará the estimated volumes are expected to be higher than those in the GTA. The same is valid for Rondônia, although the underreporting is less pronounced. For Mato Grosso, the GTA data are highly accurate, so our estimates are expected to mimic the observed GTA values.

Methods

We produced a set of estimates of slaughter volumes for all municipalities in the studied area. The 2006-16 estimates were obtained through the backward extrapolation of an unbalanced panel of 551 municipalities with years ranging between 2008-16. We used Poisson regressions for count data. Once

[1] The slaughter volume of a small abattoir operating at full capacity. We are thus assuming that a municipality must have at least the slaughter volume of a single small abattoir that operates at full capacity.

the slaughter volumes were estimated for all municipalities and years, we proceeded to disaggregate from municipalities to plants. Where only one plant existed, the plant was allocated the total slaughter volume estimated for the inspection type and municipality. This was true for most municipalities. In the remaining cases, shares within municipalities were estimated from IBGE 1 data. For all states, the estimated slaughter volumes capture the variation in the GTA data, which include some level of inconsistency, and the variation in the other data sources, with greater consistency. Therefore, the estimated values are deemed to be more accurate than the original GTA data.

Detailed procedures

Estimation and training samples. For the estimation, the sample was restricted to municipalities with at least one inspected plant. The dataset was then split into an estimate sample, with 60% of the municipality/year pairs for which slaughter volumes were not missing, and a training sample with the remaining 40% of the municipality/year pairs. The samples were randomly selected. A total of ten estimate/training sets were sampled from the panel dataset.

Model selection. All specifications were implemented using the estimate sample and two alternative estimators: random effects Poisson and Poisson for pooled panel data. A total of 103 specifications were tested with various combinations of the independent variables in Table S1, including year effects, state fixed effects, interactions, and exponentials.

Predicted values and corrections. For each specification, predicted values were generated for the slaughter volume at each municipality and year (ptotalslmt) for the training sample. These were then adjusted so that:

Eq. 1. $\sum_{m=1,t}^{n_s,t} ptotalsl_{mt} = head\_slaughtered_{st}$,

where m represents municipalities, n_s is the number of municipalities in state s, t is the year, and head_slaughtered is the yearly slaughter volume reported to IBGE.

To adjust, all predicted values were multiplied by a correction factor:

Eq. 2. $Correction\ factor\ A = head\_slaughtered_{st} / \sum_{m=1,t}^{n_s,t} ptotalsl_{mt}$

The predicted values were further adjusted so that the maximum value was limited to the overall sample maximum (586,024 head). This was done by multiplying all predicted values by the following correction factor:

Eq. 3. $Correction\ factor\ B = ptotalsl\ [maximum]/586{,}024$

Plant share in municipality. For each municipality and year, the share of plants of inspection type j in the total slaughter volume of the municipality was calculated as:

Eq. 4. $share_{jm} = \frac{head\_slaughtered_{js}/count\_plants_{js}}{\sum_{j=1}^{3}\left(\frac{head\ \ slaughtered_{js}}{count_{plants_{js}}} * count_{plants_{jm}}\right)}$, where j is inspection type (1=SIF, 2=SIE, 3=uninspected). All state level data are from IBGE 1 and all municipality level data are from GLUE (see Table S1).

Plant level slaughter volume. The predicted slaughter volume for each plant p was calculated as:

Eq. 5. $volume_{pjmt} = share_{jmt} * ptotalsl_{mt}$

Calculate error size and correlation. The plant level volumes were then compared to the training data slaughter volumes (tsl) to calculate a total absolute prediction error for model m1:

Eq. 6. $error_{pmt} = |volume_{pt} - tsl_{pt}|$

Eq. 7. $\text{total\_}error_{m1} = \sum_{p=1}^{k} error_{pmt}$

Eq. 8. $corr_{m1} = corr(volume_{pt}, tsl_{pt})$

Select best models based on 10 replications of estimate/training samples. Steps 1-7 where replicated ten times, one for each pair of estimate/training samples. For each replication, the 20 models with the lowest error were selected. Next the 10 most frequent models were selected, all of which had similar correlations (Eq. 8). The estimated slaughter volume was calculated as an average among the selected models.

Final correction. The estimated slaughter volume was then adjusted so that:

Eq. 9. $\sum_{p=1,jt}^{k_s,jt} volume_{pjst} = head\_slaughtered_{jst}$,

where ks is the number of plants in state s. Also recall that j is inspection type, t is the year, and head_slaughtered is the yearly slaughter volume reported to IBGE.

To adjust, all predicted values were multiplied by a correction factor:

Eq. 10. $Correction\ factor\ C = head\_slaughtered_{jst} / \sum_{p=1,jst}^{k_s,jst} volume_{pjst}$

Results

Part 1 – municipality estimates

The results of all 103 specifications for the municipality slaughter volumes are plotted in Figs. 1-3. These results were obtained by implementing steps 1-3 above. The green lines show the models that were selected through the validation in steps 4-7. For the goodness-of-fit R^2 measure, the selected models were among those with the highest values, with an average .92 [.90,.93]. For the total absolute prediction error, which was the sum of the modules of all absolute prediction errors, the selected models had values that were also among the lowest. The correlation between the estimated and the observed municipality slaughter volumes ranged from .825 to .844.

Part 2 – plant level estimates

The results are plotted in Figs. 4-10. The predicted values are first averaged by inspection type, state and year, and plotted along with the original GTA values and with IBGE 1 values. In Figure S4, the predicted values for SIF plants are shown to vary relatively smoothly over the years for most states. For the state of Mato Grosso, for which the most accurate GTA data are available (Table S2), the predictions are very close to the GTA values. In all other states for which GTA data are available, the predictions are above the observed values, which is also expected because the observed GTA values were consistently underestimated. Both the predictions and the GTA values are systematically below the IBGE 1 values, which suggests that the average estimated volume may still be underestimated. Despite that, the temporal trend of the predicted values seems to mimic that of IBGE 1.

For SIE plants (Figure S5), the estimated values also vary smoothly over the years in most cases, and they also remain above the observed values for all states. The SIE estimates are also slightly higher than the IBGE 1 data, although the difference is small. This could suggest underreporting in SIE plants (especially in the GTA), although it is inconclusive. Figures S6-S7 show minimum and maximum plant slaughter volumes for each state and year. While in many cases the predictions capture the data range well, in some cases, particularly SIFs in Pará and SIEs in Rondônia, the predicted values have a larger range.

Finally, Figures S8-S10 plot the predicted against the observed values in a scatter plot, with an added quadratic fitted line.

Table S1. Data used to estimate plant-level slaughter volumes

Variable type	Name	Source(s)	Scale	Description	Years	Coverage
Dependent	GTA Head slaughtered[1]	Indea Adepará Idaron MAPA	Municipality	Yearly slaughter volume	MT: 2013-2016 PA: 2014, 2016 RO: 2008, 2010, 2012, 2016 MA: 2016 MG: 2015, 2016 MS: 2016[1]	MT, PA, RO, MA, MG, MS
Training set	GTA Head slaughtered	Indea Adepará Idaron MAPA	Plant	Yearly slaughter volume	MT: 2013-2016 PA: 2014, 2016 RO: 2008, 2010, 2012, 2016 MA: 2016 MG: 2015, 2016 MS: 2016[1]	MT, PA, RO, MA, MG, MS
Independent	Formal employment	MTE	Municipality	Yearly count of workers employed in the slaughter industry	2006-2016	Brazil
Independent	Slaughterhouses[2]	IBGE 1	State	Quarterly count of SIF, SIE and SIM plants	1997-2017	Brazil
Independent	GDP[3]	IBGE 2	Municipality	Yearly GDP	2002-2015	Brazil
Independent	GDP deflator[3]	Ipeadata	Brazil	Yearly index used to deflate GDP	2002-2015	Brazil
Independent	Head slaughtered[4]	IBGE 1	State	Quarterly slaughter volume in SIF, SIE and SIM	1997-2017	Brazil
Independent	Municipality areas	IBGE 3	Municipality	Area (km^2)	_	Brazil
Independent	Head slaughtered origin[5]	MAPA	Municipality	Yearly head slaughtered in SIFs by municipality of origin of cattle	2002-2017	Brazil
Independent	Population[6]	IBGE 4	Municipality	Yearly human population estimates	2000-2017	Brazil
Independent	Herd	IBGE 5	Municipality	Yearly cattle herd	2000-2016	Brazil
Unit of observation	Slaughterhouses	Glue	Plant	Geocoded with various attributes	1930-2017	Amazon, Cerrado
Boundaries	Biomes	IBGE 6	Biome	Amazon and Cerrado boundaries	–	Brazil
Accuracy check	Head slaughtered	Anualpec	State	Yearly slaughter volume	2008-2016	Brazil

Notes: Indea, Adepará and Idaron are cattle sanitation inspection agencies; MTE is Brazil's labor Ministry; IBGE is Brazil's statistical agency; MAPA is Brazil's Agriculture Ministry; GLUE is the Gibbs Land Use and the Environment Lab at the University of Wisconsin-Madison; Anualpec is the cattle statistics yearbook published by Informa Economics.

[1]GTA = "Animal Transit Form" is the public dataset on cattle transactions from which the data were downloaded. The slaughter volumes were aggregated by year and municipality. Only years for which the total slaughter volume for the state was equal to or higher than 60% of the official IBGE slaughter volume were kept. [2]The slaughterhouse counts from IBGE were averaged out between quarters to generate yearly counts. [3]Nominal GDPs were converted to R$ 2016 using the official GDP deflator. The 2002-15 series was then forecast to 2016 using linear regression. [4]Where there are three or less plants of a single inspection type in one state, the data are censored by IBGE. For example, no data are provided for the state of Roraima in the year 2015 as there were only three inspected plants in total. In these cases, the time series was used to interpolate the censored values. [5]Three variables were generated based on these data: SIF-slaughtered head originated in municipalities within a 100 km radius (as measured by municipality centroids), 200 km radius, and 500 km radius.

Table S2. Accuracy assessment of GTA slaughter volumes

Year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017*
State = Mato Grosso										
GTA head	_	_	_	_	0	6,011,894	5,525,708	4,684,569	4,627,177	3,193,537
IBGE head	_	_	_	_	_	5,837,857	5,332,226	4,540,805	4,577,459	3,514,045
Anualpec head	_	_	_	_	_	4,559,991	5,032,319	5,098,444	5,097,124	_
Accuracy[1]	_	_	_	_	_	116%	107%	97%	96%	91%
State = Pará										
GTA head	_	_	_	_	106,214	99,587	1,608,387	394,379	2,176,758	357
IBGE head	_	_	_	_	2,177,806	2,447,439	2,624,231	2,647,762	2,724,137	2,003,628
Anualpec head	_	_	_	_	2,803,181	2,791,436	2,711,075	3,023,648	2,967,362	_
Accuracy[1]	_	_	_	_	4%	4%	60%	14%	76%	0%
State = Rondônia										
GTA head	1,307,381	292,671	1,692,858	479,274	1,885,368	1,227,114	724,376	1,079,461	1,838,332	527,290
IBGE head	1,729,348	1,804,866	1,902,369	1,893,136	2,046,868	2,289,653	2,004,591	1,904,823	2,191,620	1,664,215
Anualpec head	1,780,956	1,884,505	2,057,029	2,001,263	2,204,520	2,277,270	2,300,158	1,865,717	1,999,000	_
Accuracy[1]	74%	16%	86%	25%	89%	54%	34%	57%	88%	32%
State = Maranhão										
GTA head	_	_	_	_	_	_	_	58,674	591,644	445,191
IBGE head	_	_	_	_	_	_	_	839,121	776,772	738,542
Anualpec head	_	_	_	_	_	_	_	979,517	934,994	950,751
Accuracy[1]	_	_	_	_	_	_	_	6%	69%	53%
State = Minas Gerais										
GTA head	_	_	_	_	_	_	151,896	2,153,467	1,924,794	1,769,151
IBGE head	_	_	_	_	_	_	3,240,379	2,840,812	2,469,873	2,766,901
Anualpec head	_	_	_	_	_	_	5,093,776	3,965,019	3,666,609	3,554,025
Accuracy[1]	_	_	_	_	_	_	4%	63%	63%	56%
State = Mato Grosso do Sul										
GTA head	_	_	_	_	_	_	18,859	412,122	2,452,077	1,373,986
IBGE head	_	_	_	_	_	_	3,931,653	3,408,741	3,292,279	3,436,886
Anualpec head	_	_	_	_	_	_	3,731,598	4,390,671	4,714,941	4,695,677
Accuracy[1]	_	_	_	_	_	_	0%	11%	61%	34%

*GTA data cover the period Jan 1st - Sept. 13 for Mato Grosso and Jan. 1st - Sept. 10 for Rondônia; accordingly, the IBGE counts are for Jan. 1st - Sept. 30 [1]Accuracy is calculated as GTA head ÷ (IBGE head + Anualpec head)/2. Values in red are where accuracy <60%

Sources: GTA head are from Indea, Adepará, Idaron, the state cattle sanitation inspection agencies, and MAPA, the Ministry of Agriculture; IBGE is Brazil's statistical agency; Anualpec is the cattle statistics yearbook published by Informa Economics.

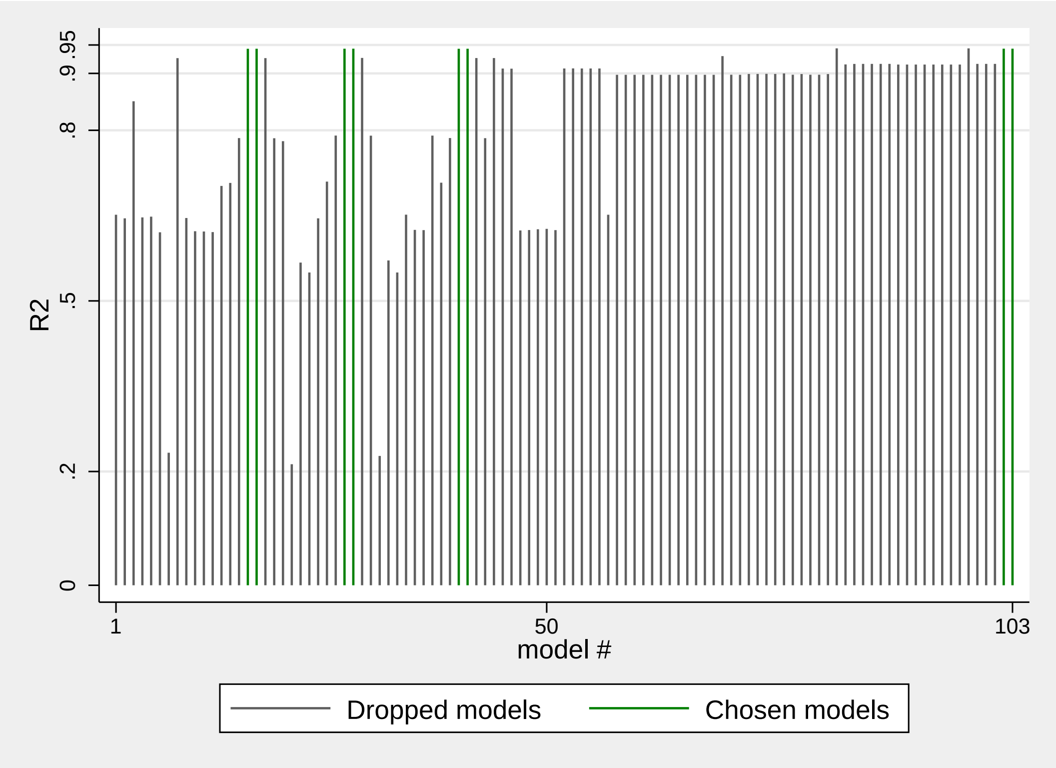

Figure S1. R-squared (R^2) of the tested Poisson models

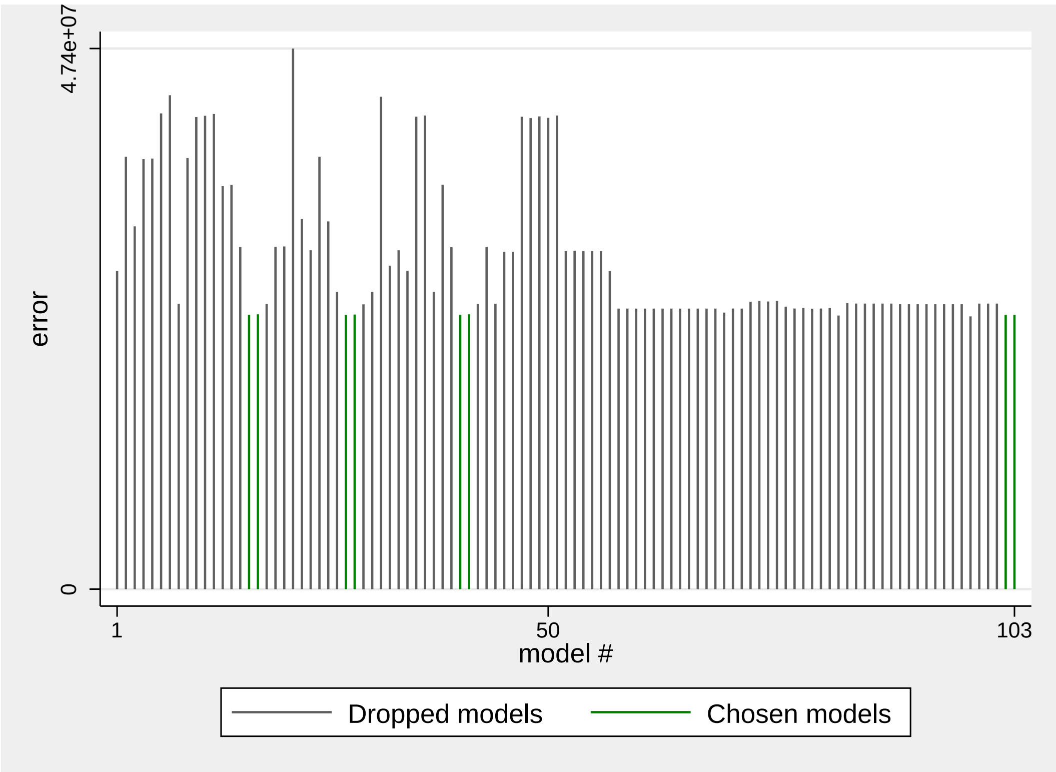

Figure S2. Total absolute prediction error of the tested Poisson models

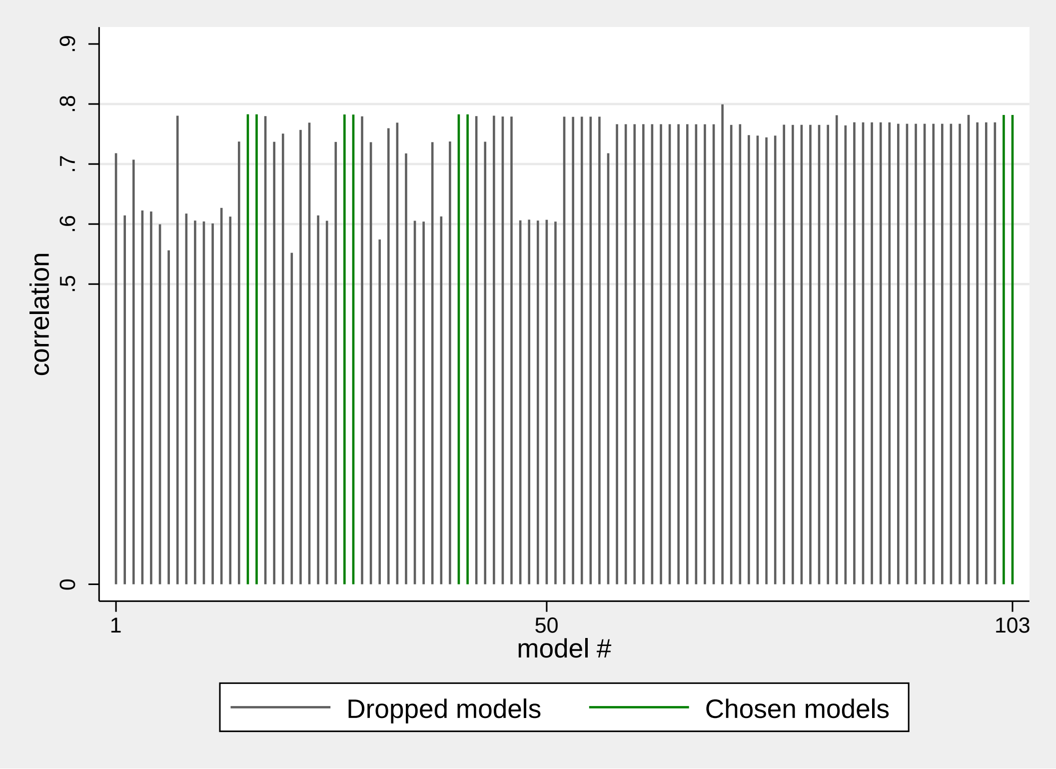

Figure S3. Correlation between predicted and observed slaughter volumes in the tested Poisson models

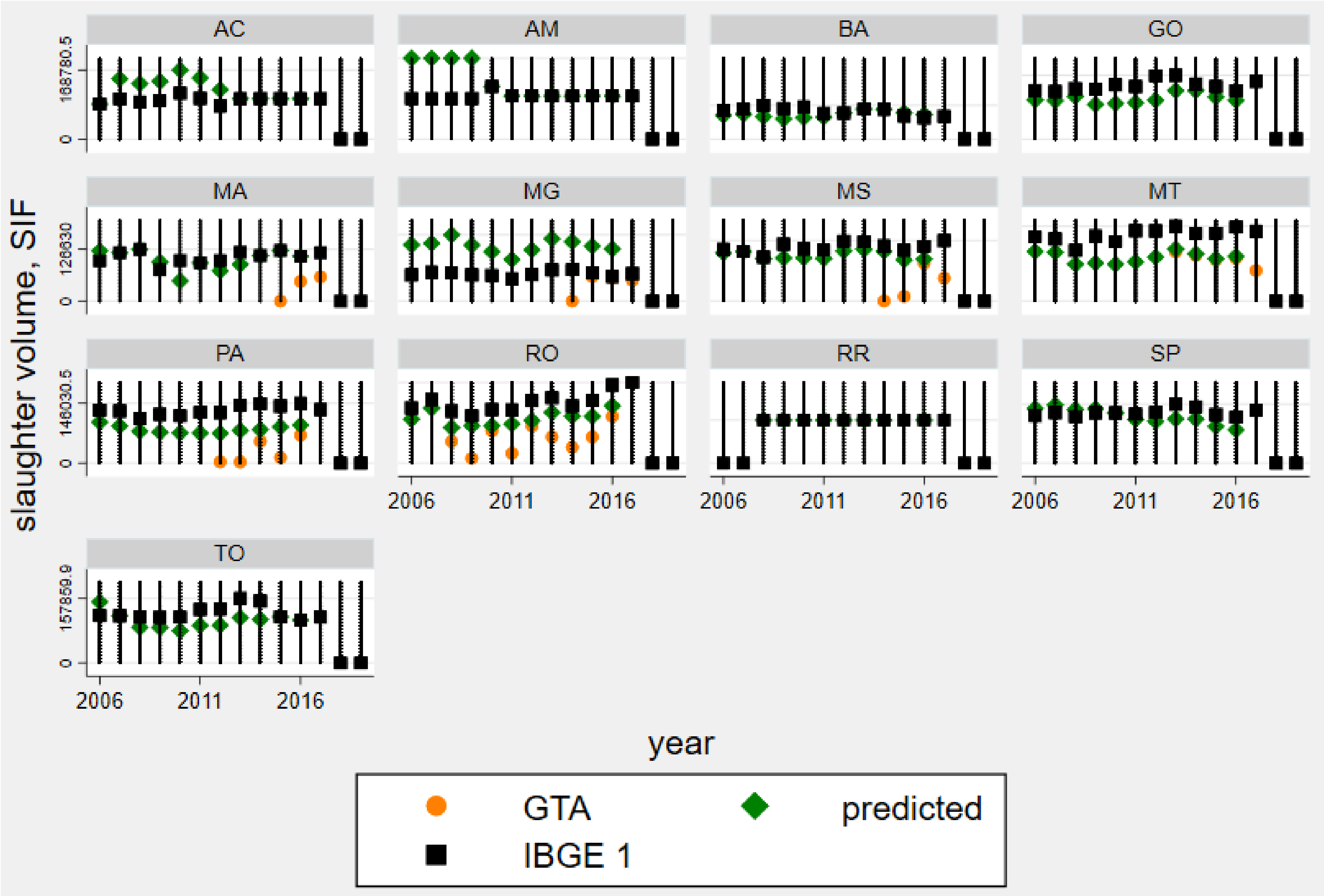

Figure S4. **Average observed plant-level (GTA), average plant-level (IBGE 1), and predicted plant-level slaughter volumes by state and year, SIF plants**

The IBGE 1 observations are not measured at the plant-level. Instead, they are calculated as total state slaughter volume divided by number of plants in the state.

By construction, the sum of the predicted values for each state is equal to the state-level IBGE 1 slaughter volume (Eq. 10).

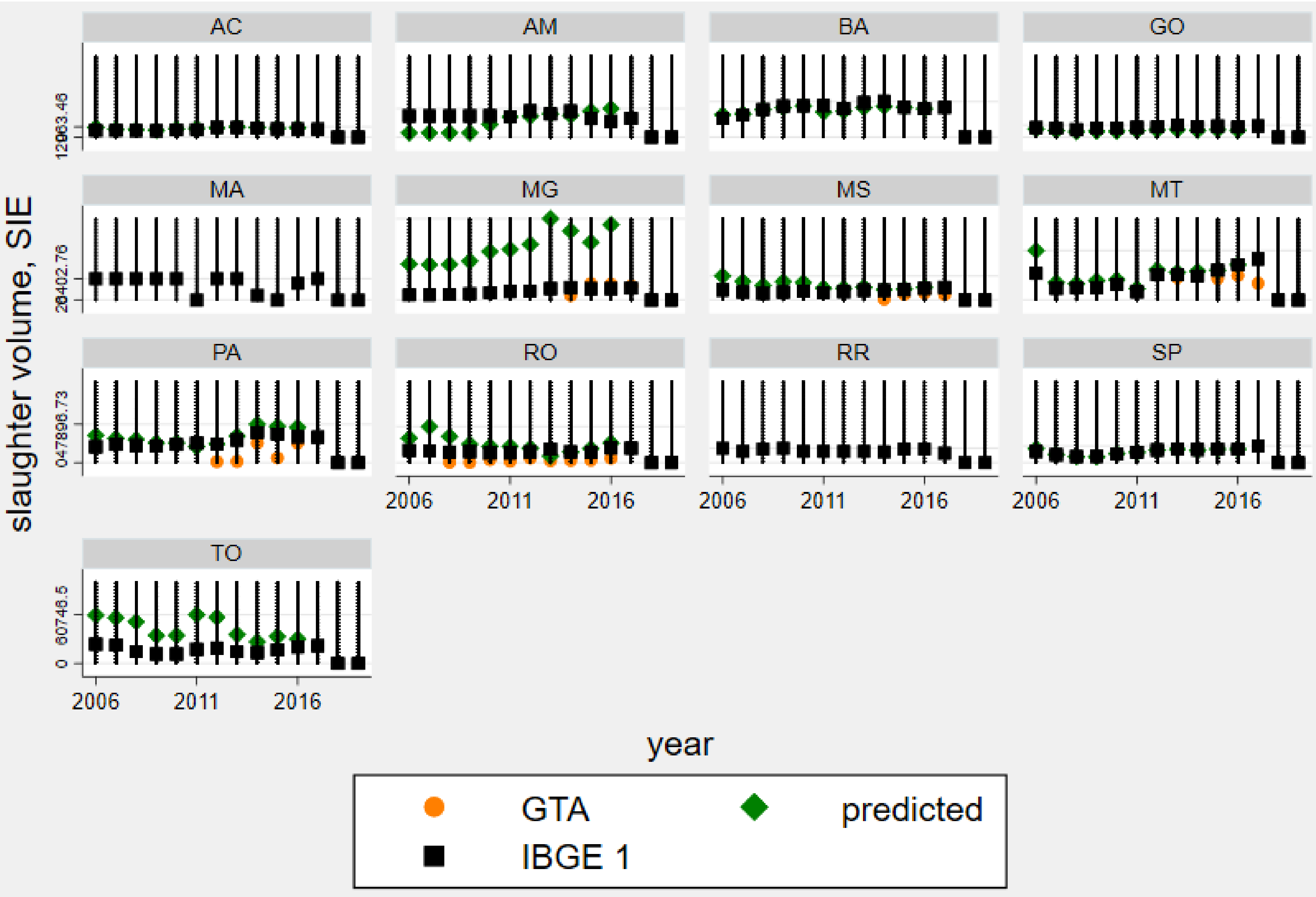

Figure S5. Average observed plant-level (GTA), average plant-level (IBGE 1), and predicted plant-level slaughter volumes by state and year, SIE plants

The IBGE 1 observations are not measured at the plant-level. Instead, they are calculated as total state slaughter volume divided by number of plants in the state.

By construction, the sum of the predicted values for each state is equal to the state-level IBGE 1 slaughter volume (Eq. 10).

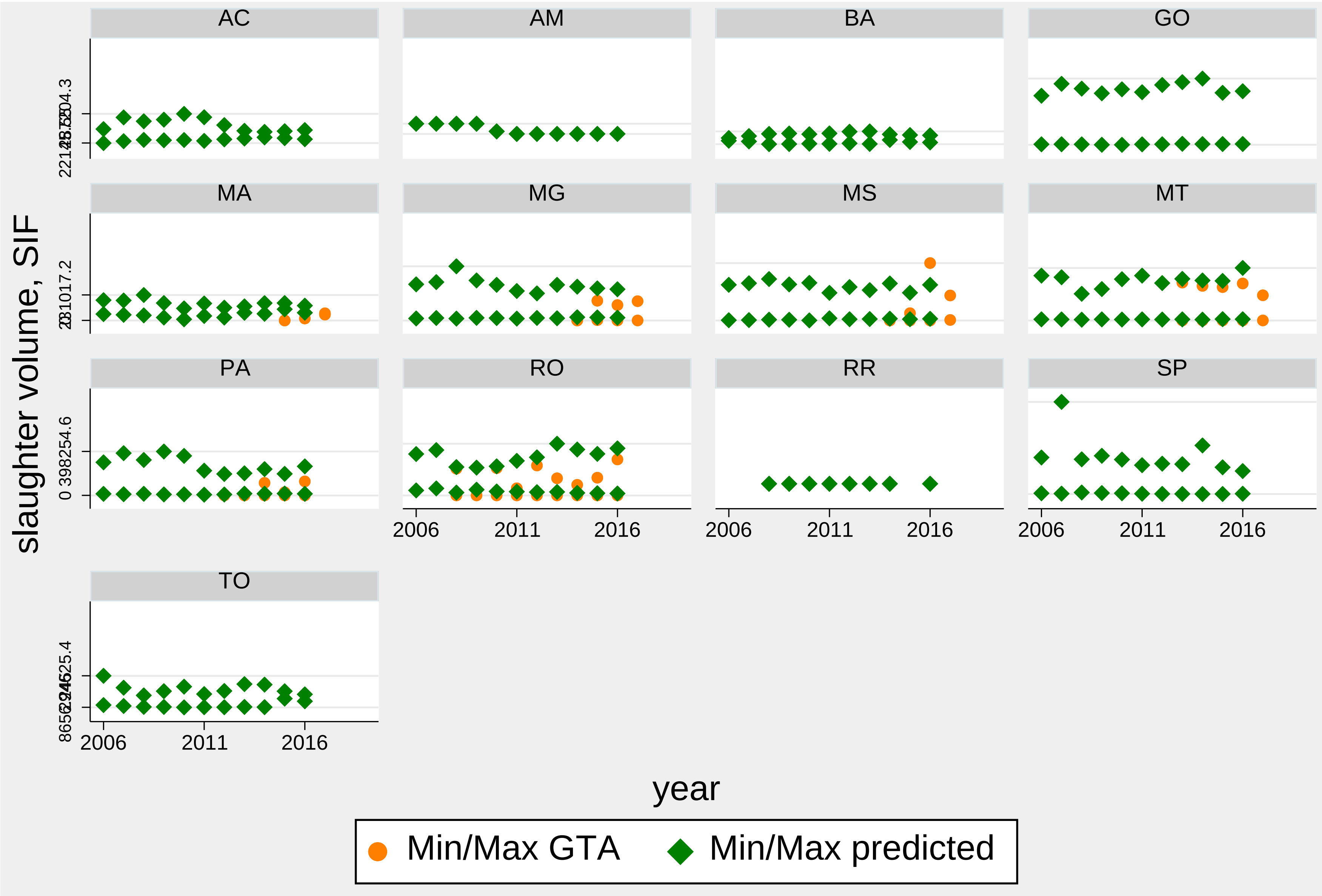

Figure S6. **<u>Ranges</u> of observed plant-level (GTA) and predicted plant-level slaughter volumes by state and year, SIF plants**

Min/Max are the minimum and maximum plant-level slaughter volumes. The graph shows that the dispersion of the predicted values is close to that of the original data, except for the state of Pará where the predicted dispersion is larger.

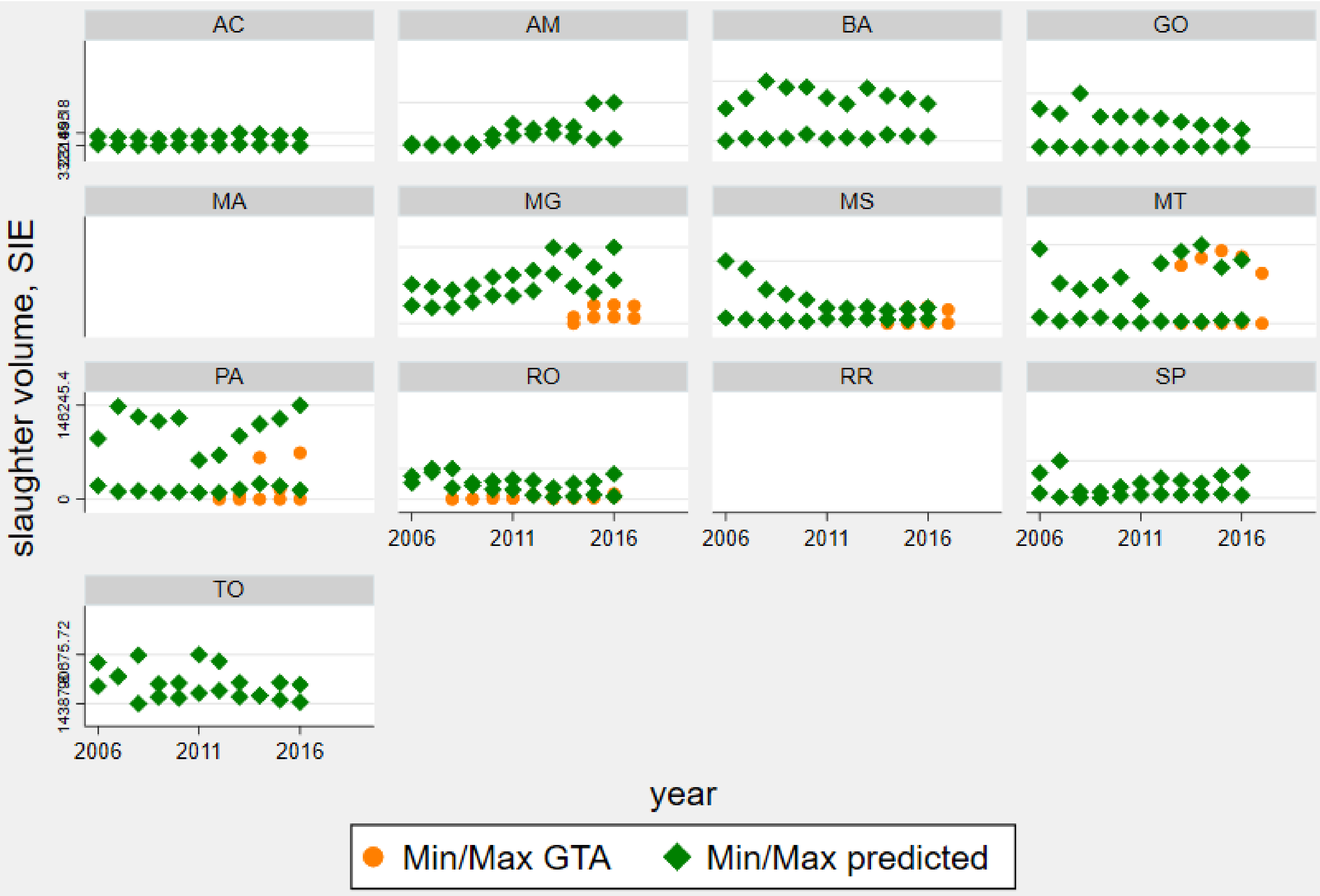

Figure S7. <u>Ranges</u> of observed (GTA) and predicted plant-level slaughter volumes by state and year, SIE plants

Min/Max are the minimum and maximum plant-level slaughter volumes. The graph shows that the dispersion of the predicted values is close to that of the original data, except for the state of Rondônia where the predicted dispersion is much larger. This may suggest that the GTA data for Rondônia are particularly inaccurate for SIE plants.

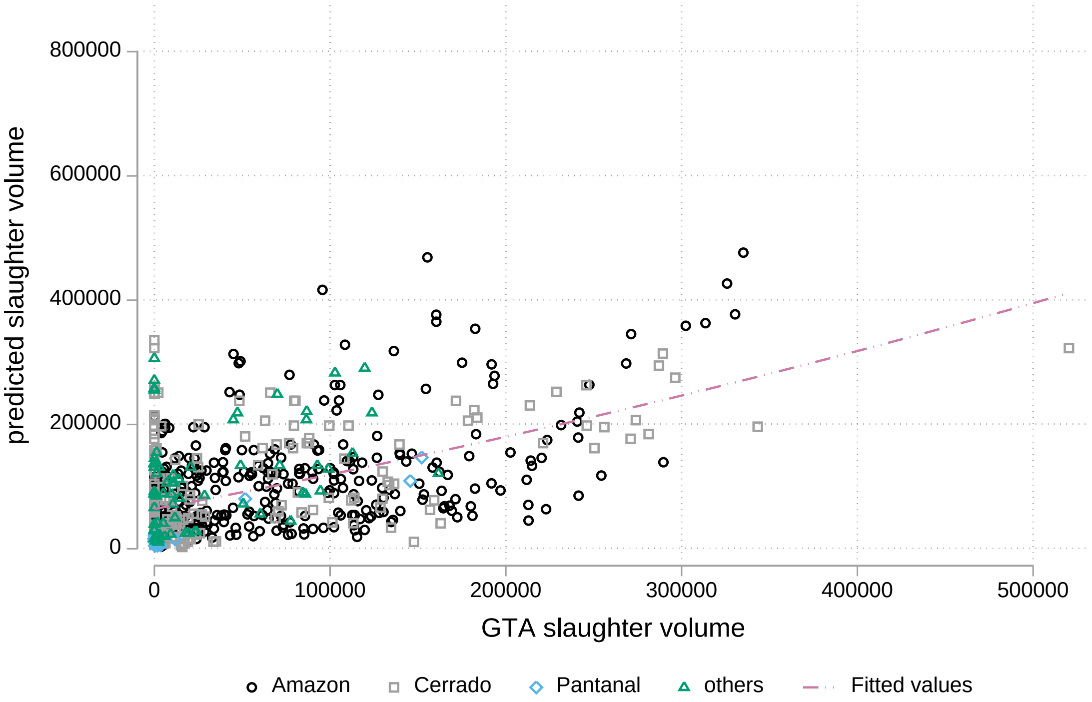

Figure S8. Plant-level observed (GTA) and predicted slaughter volumes by biome, all available years

The graph shows that the predicted values are higher than the observed GTA volumes for the vast majority of plants with very low GTA slaughter volumes (observations near the vertical axis). The models continue to predict higher values than observed for most plants with slaughter volumes under 100,000 heads/year. Then, between 100,000 and 3000,000, the models predict lower volumes than those observed. Finally, for a few plants with very high observed volumes, above 300,000, the models again predict higher values.

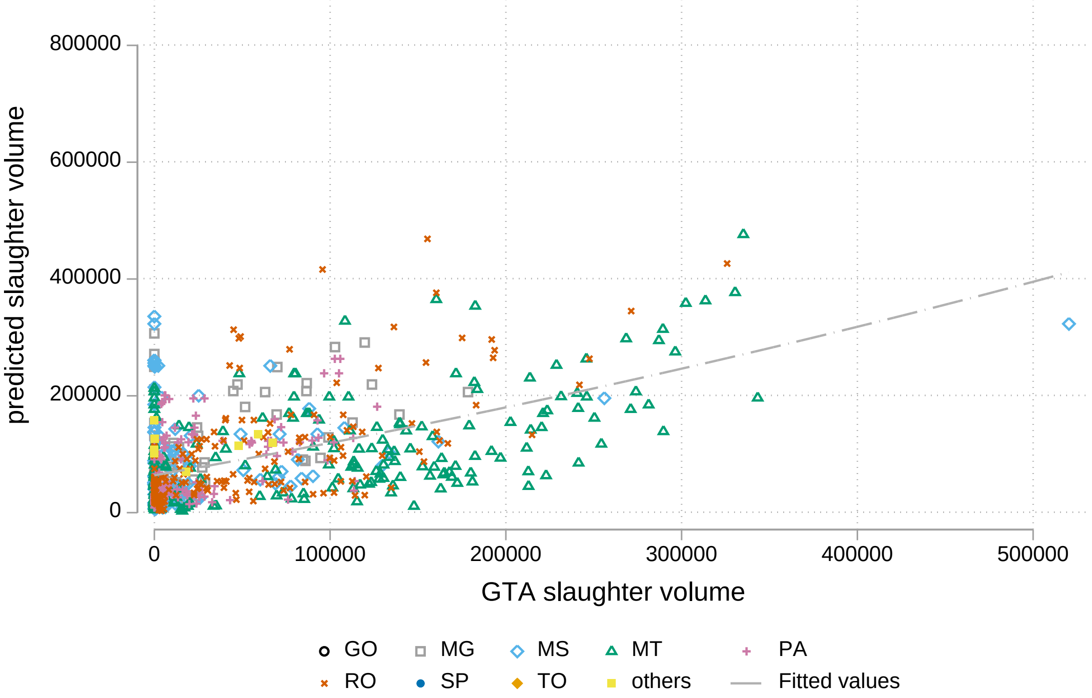

Figure S9. Plant-level observed (GTA) and predicted slaughter volumes by state, all available years

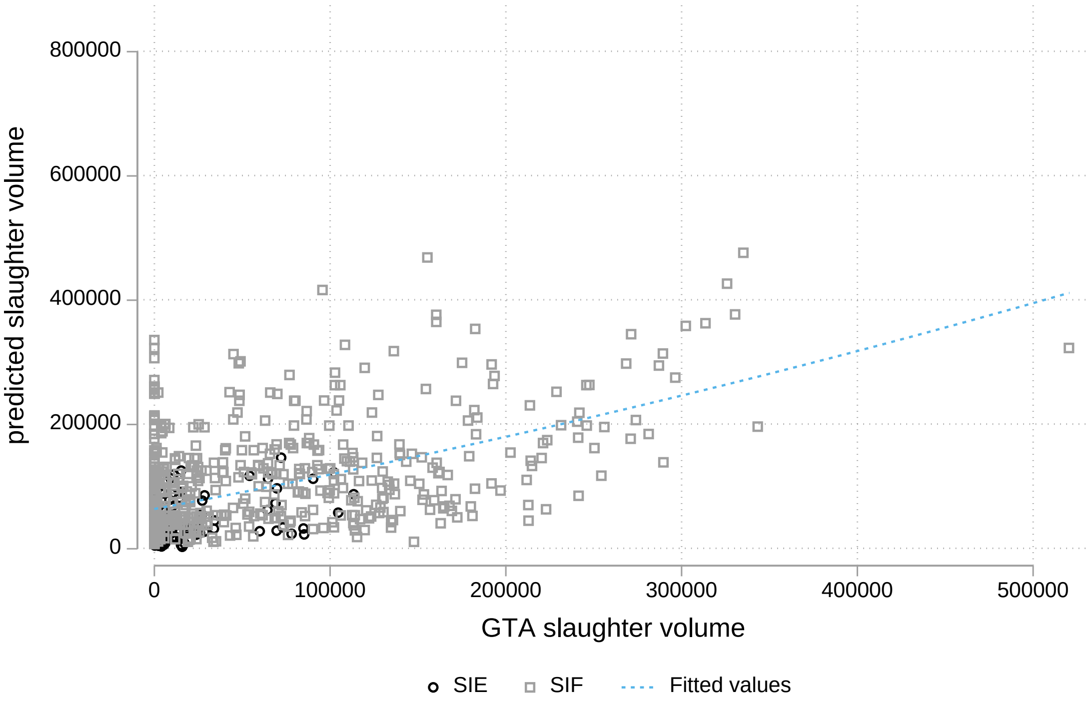

Figure S10. Plant-level observed (GTA) and predicted slaughter volumes by inspection type, all available years

Supplementary Information

C. Background data

Table S3. List of studies of the Brazilian meatpacking industry

	Unit of observation		Coverage	
Study	**Type**	**Scope**	**Geographic**	**Time**
Pigatto and Souza Filho (2001)	Plant	SIFs	Brazil	Cross-section
Caleman and Cunha (2011)	Country	Exporting plants	Brazil	Monthly time series
Boechat and Alves (2014)	Plant	SIFs	Brazil	Yearly panel
Moita and Golon (2014)	State	Inspected	São Paulo	Monthly time series
Leães (2015)	Plant	All	Rio Grande do Sul	Yearly panel
Carvalho (2016)	Company	Big four	Brazil	Quarterly panel
Barreto et al. (2017)	Plant	SIFs and SIEs	Legal Amazon	Cross-section
Boechat and Parré (2018)	Plant	SIFs	Brazil	Cross-section
Vale et al. (2019)	Plant	All	Mato Grosso	Yearly panel

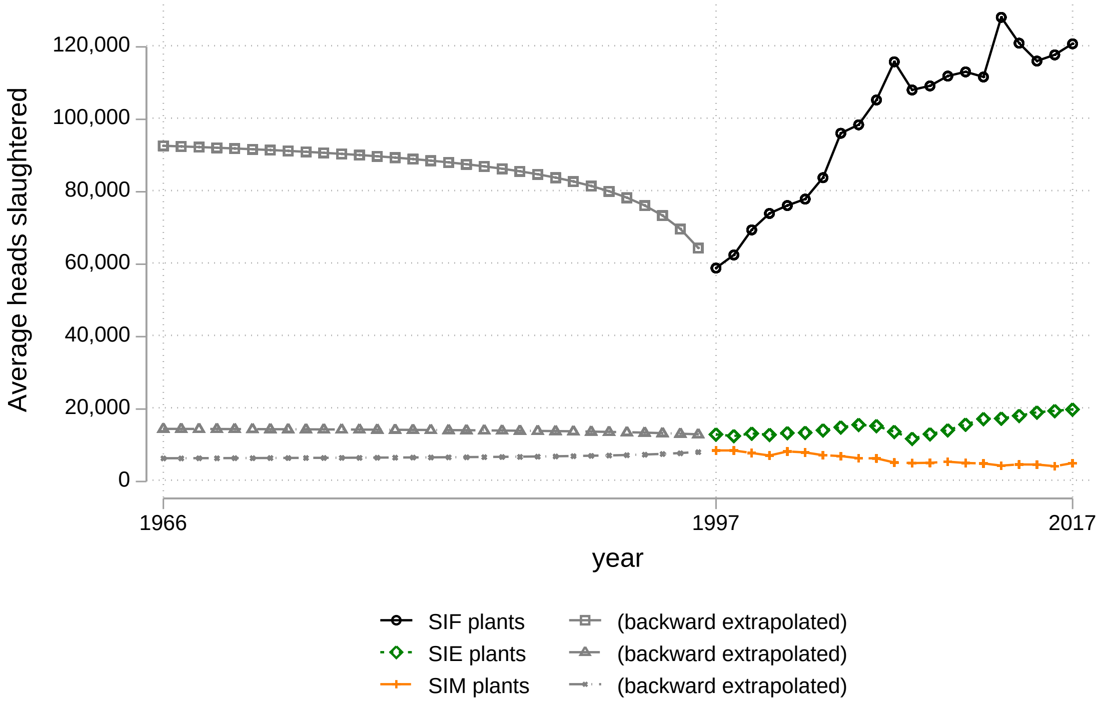

Figure S11. Yearly production volume of federal (SIF), state (SIE), and municipality (SIM) inspected plants, 1966-2017. The quarterly data from IBGE (2017a) for the years 1997-2017 were converted to yearly. The values for years 1966-1996 were obtained by backward extrapolation using the Stata® 15 mipolate package for inverse distance weighting (Lu and Wong, 2008). Values were then averaged among plants with the same inspection type for each year. The low levels of SIF production volumes between 1997 and 2005 are likely due to underreporting.

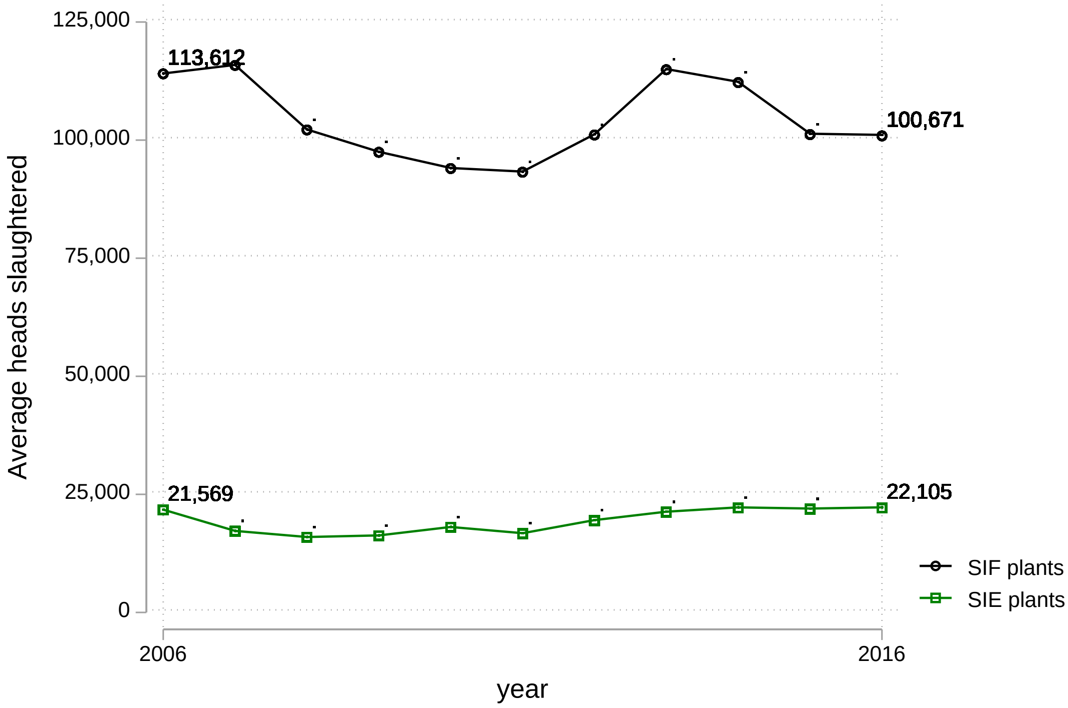

Figure S12. Yearly estimated production volumes of federal (SIF) and state (SIE) inspected plants, 2006-2016. The yearly slaughter volumes were allocated to each individual plant using a predictive model. The values are averaged among plants with the same inspection type for each year.

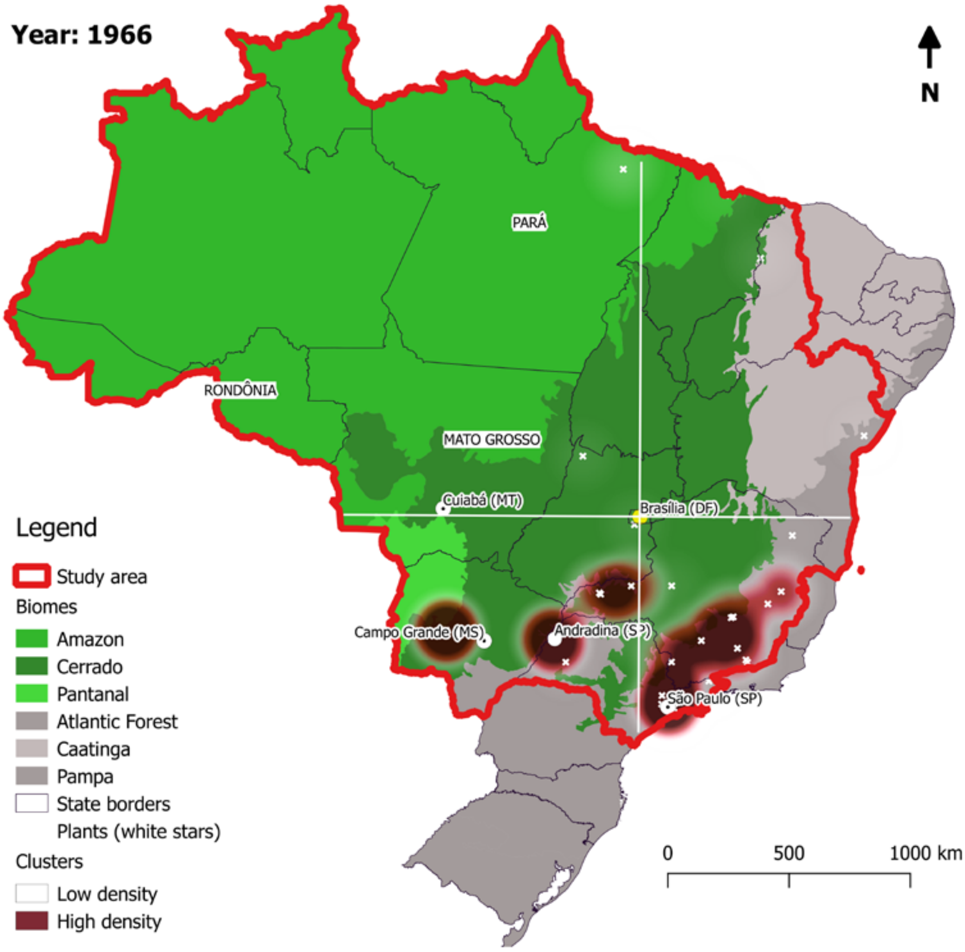

Figure S13. Geographic clustering of slaughterhouses, 1966.

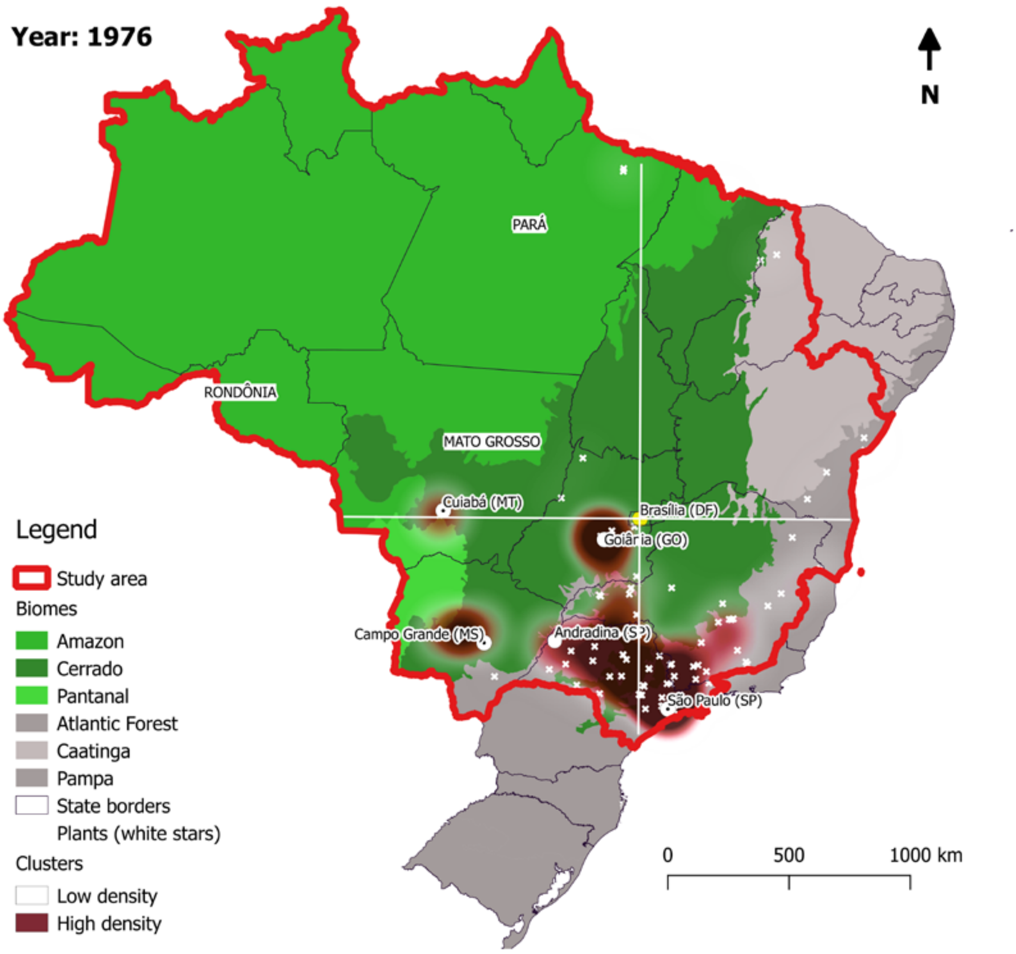

Figure S14. Geographic clustering of slaughterhouses, 1976.

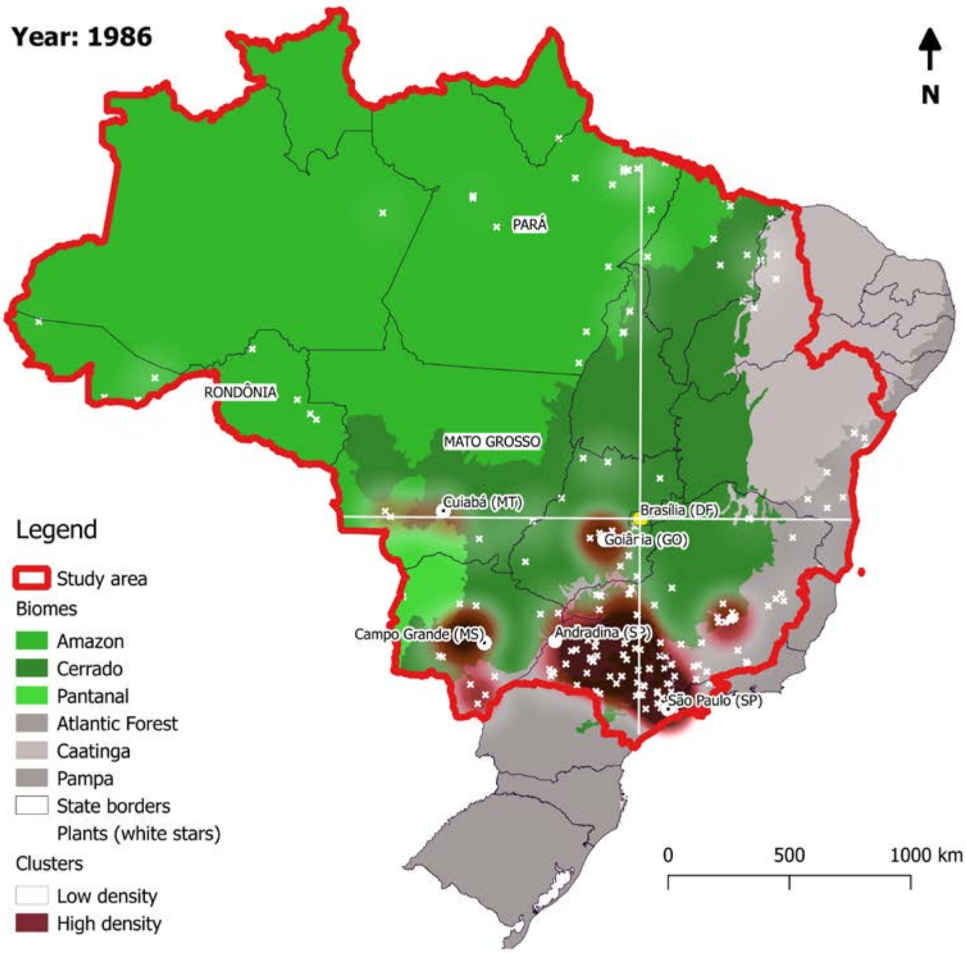

Figure S15. Geographic clustering of slaughterhouses, 1986.

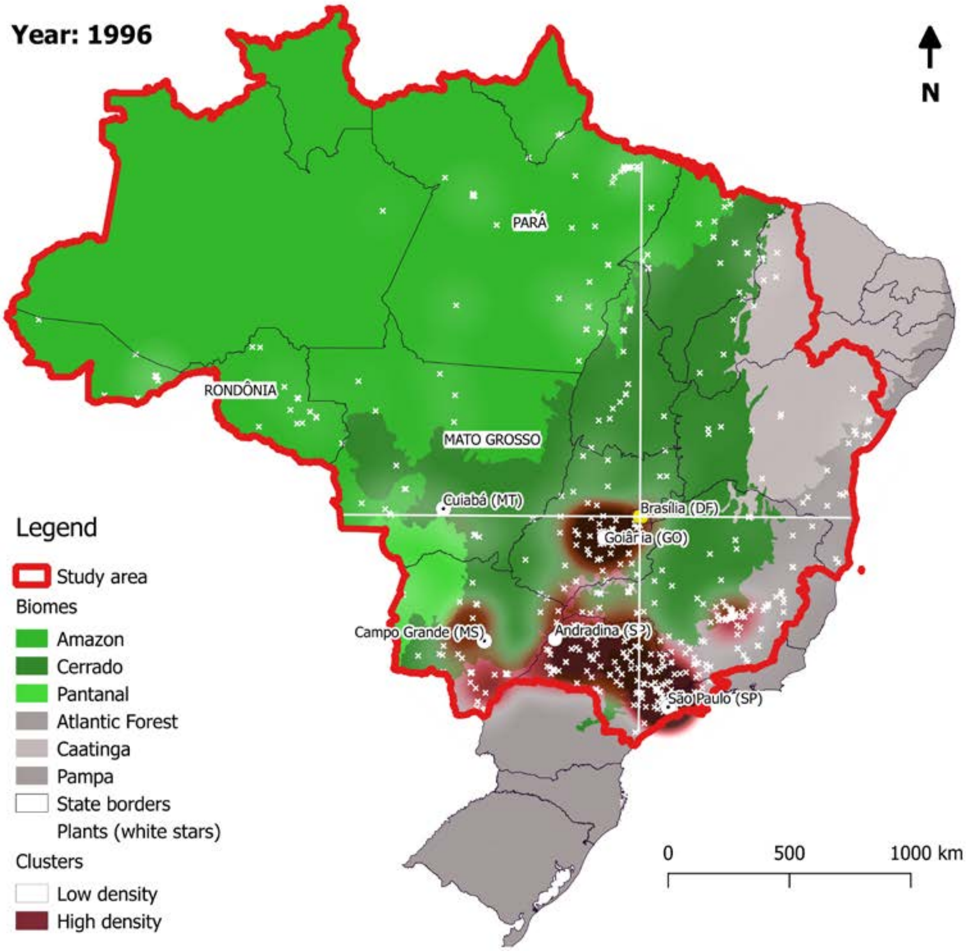

Figure S16. Geographic clustering of slaughterhouses, 1996.

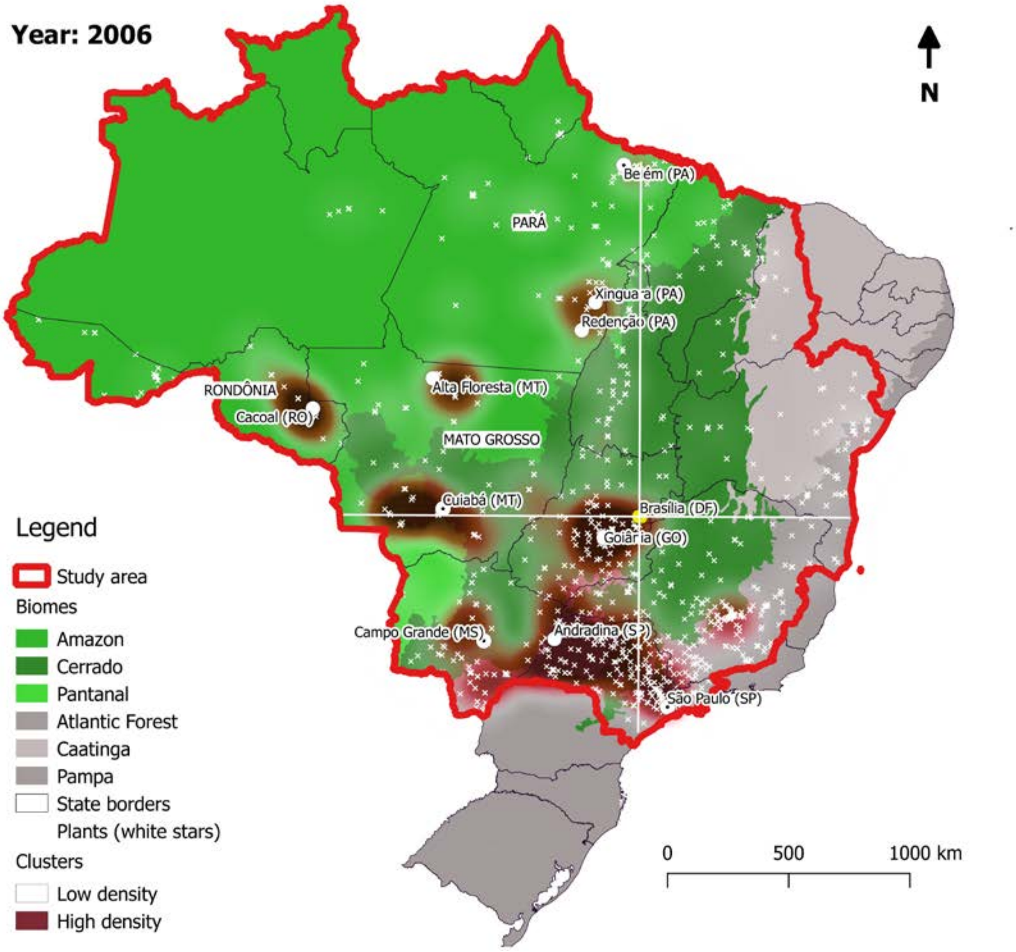

Figure S17. Geographic clustering of slaughterhouses, 2006.

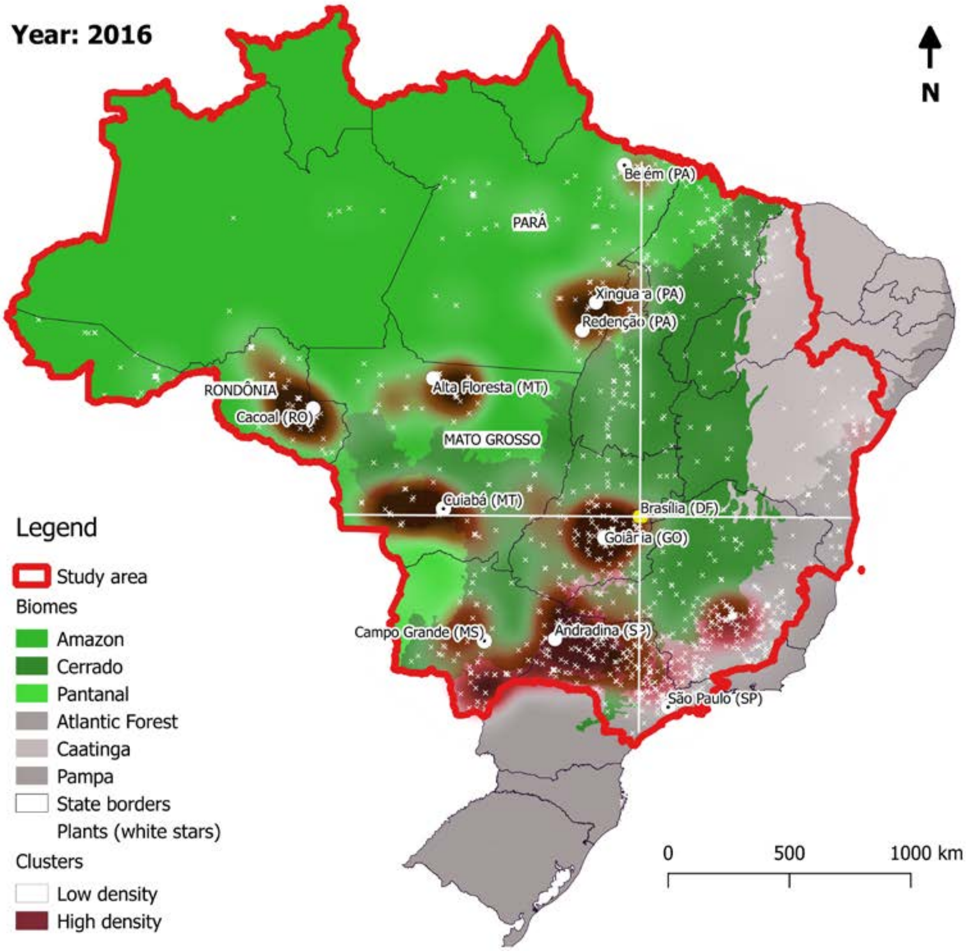

Figure S18. Geographic clustering of slaughterhouses, 2016.

CLICK HERE [ADD LINK] TO SEE ANIMATION.

Figure S19. Animation: Geographic clustering of slaughterhouses, 1966-2017.

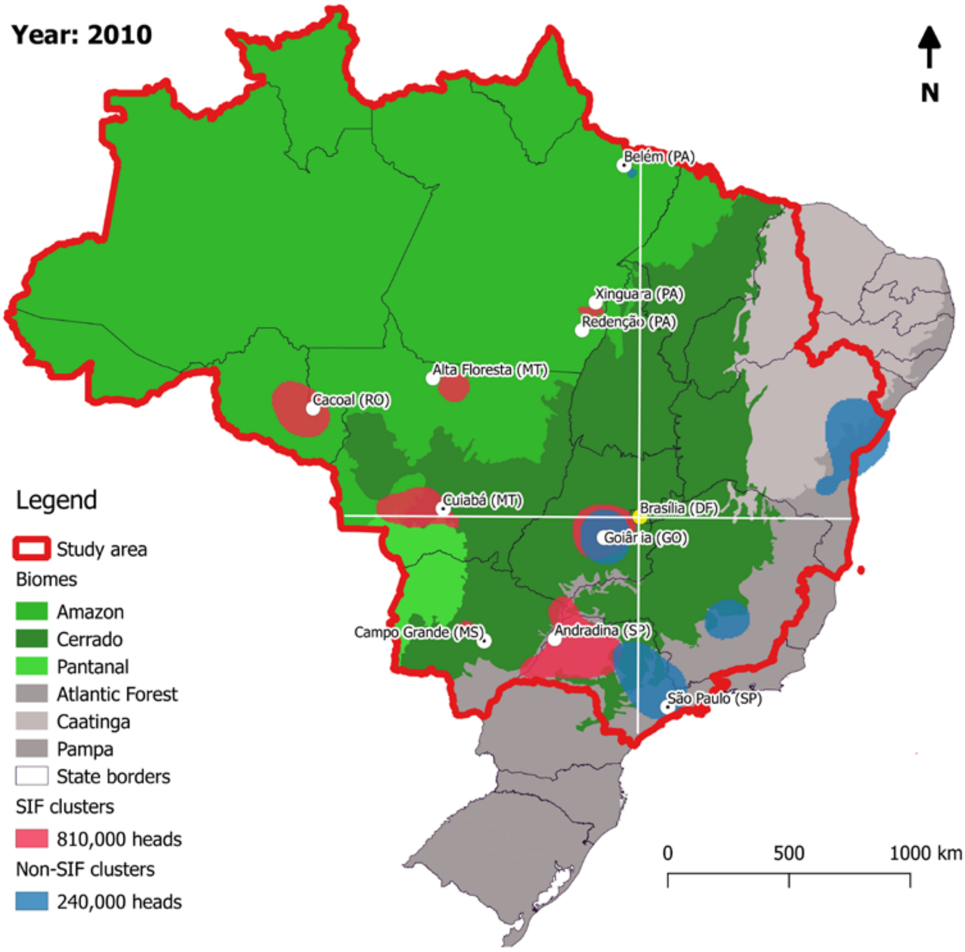

Figure S20. Geographic clustering of federal (SIF) and non-federal inspected slaughterhouses, 2010.

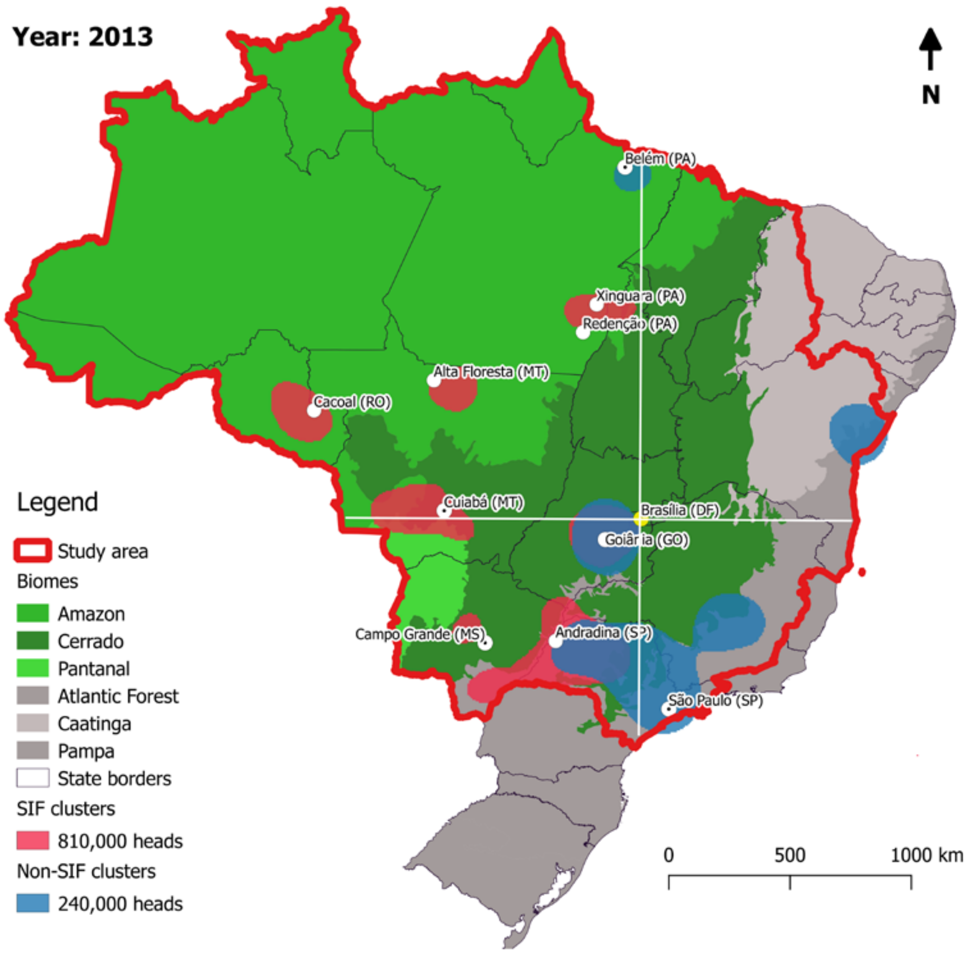

Figure S21. Geographic clustering of federal (SIF) and non-federal inspected slaughterhouses, 2013.

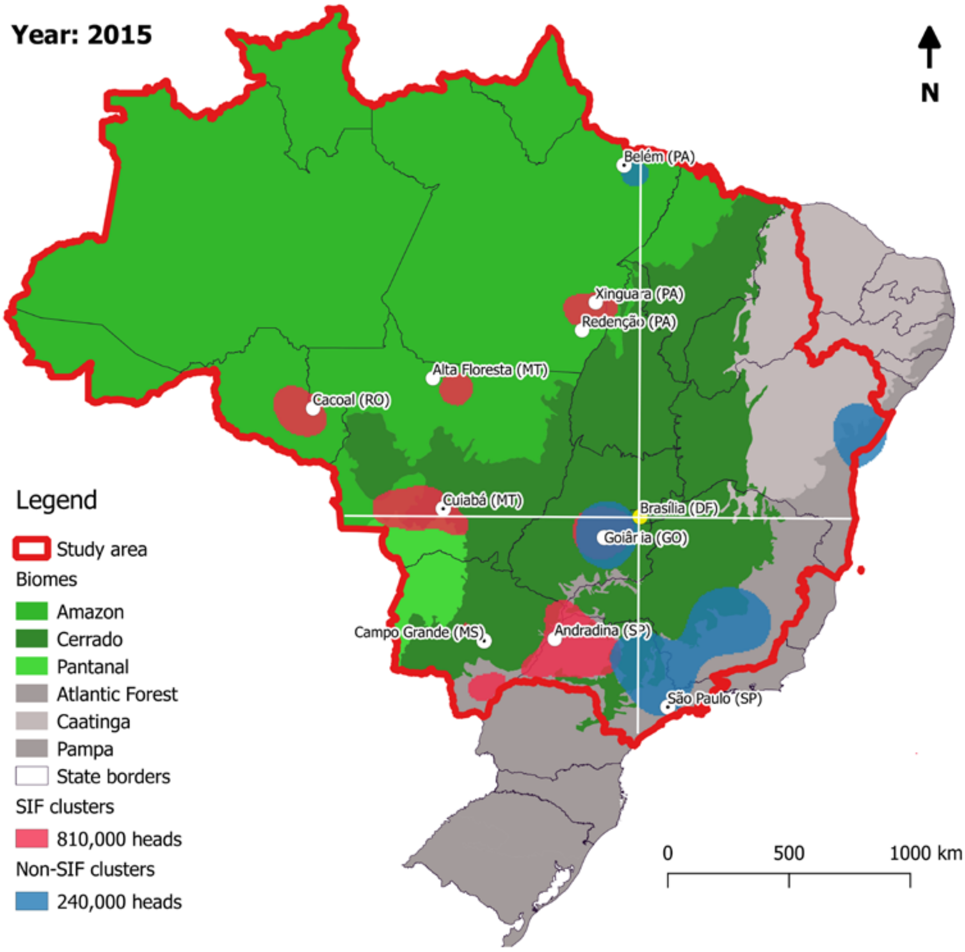

Figure S22. Geographic clustering of federal (SIF) and non-federal inspected slaughterhouses, 2015.

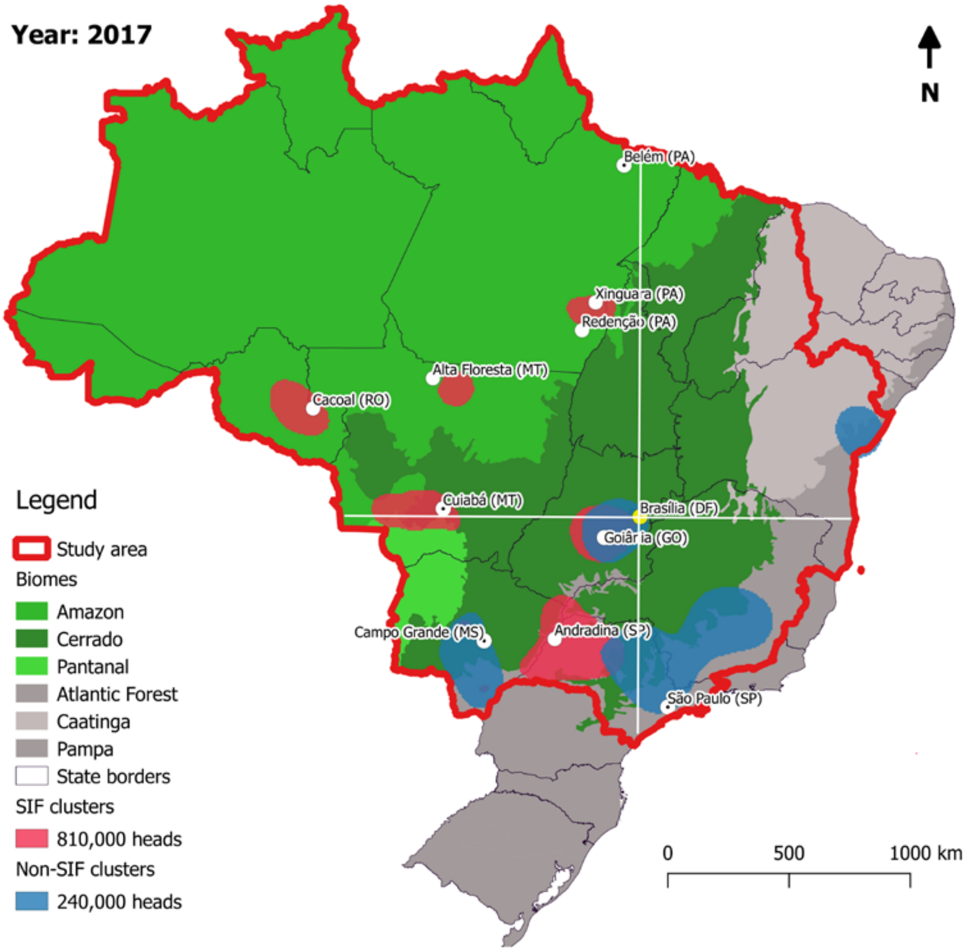

Figure S23. Geographic clustering of federal (SIF) and non-federal inspected slaughterhouses, 2017.

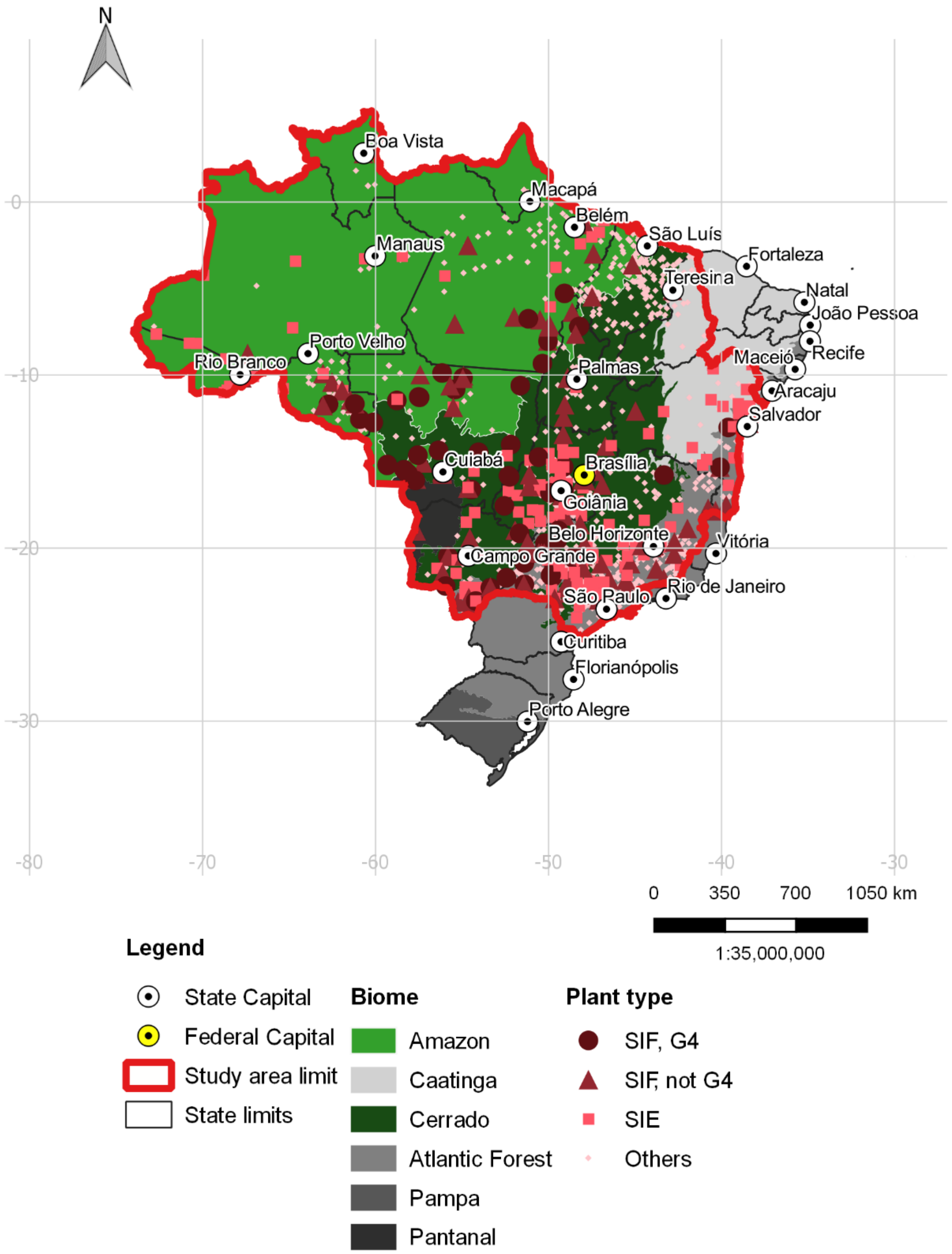

Figure S24. Slaughter units mapped in the study area. The G4 plants are those with voluntary commitments to remove deforestation in the Amazon biome from their supply chains. They are a subgroup of the federally-inspected (SIF) plants. The "other" category includes plants inspected at the municipality level and plants without food sanitation inspection.

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