Potential pathways to reconcile forest conservation and cattle production in Brazil

By

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Abstract

Cattle ranching is the leading cause of deforestation in Brazil, and concerns about the effects of this conversion, such as carbon emissions and habitat destruction, have prompted renewed efforts to strengthen the implementation of public sector policies such as the Brazilian Forest Code (FC) and private sector zero-deforestation commitments (ZDC), including the Cattle Agreements (CA). However, overall FC compliance is limited, and a lack of information about cattle supply chains and the sector has made it difficult to achieve strong forest conservation outcomes from the CA. My dissertation addresses these information gaps regarding Brazil's cattle supply chains to better understand the connections between forest conservation and cattle production. On Chapter 1, I proved an overview of land available in the Amazon and Cerrado biomes for production and for forest conservation under different policy scenarios. Then on Chapter 2 and 3, I focused on more detailed analyses of the supply zones an travel distances of the cattle sector in three Brazilian states — Pará, Mato Grosso, and Rondônia — which collectively account for 23% of the deforestation and 30% of the cattle herd in Brazil through 2018. My results indicate that the cattle industry no longer needs to deforest to produce beef and ongoing legal clearing could create additional space for cropland and cattle production beyond the substantial existing stocks of cleared areas but would significantly impair local carbon and biodiversity stocks. In addition, expanding the CAs to include more suppliers and more slaughterhouses is crucial to better control deforestation. Finally, cattle travel twice the distance between the direct suppliers and the nearest slaughterhouses, which could indicate specific intentional sales. And, in most cases, cattle from direct suppliers with deforestation travel further to slaughter than cattle from suppliers without deforestation. The result of my research is relevant to decision-makers and makes important contributions to Land Systems Science.

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Completing this Ph.D. would not have been possible without the collaboration of many people. I will be forever grateful to my advisor Holly Gibbs for welcoming me to her research lab, Gibbs Land Use and Environment Lab (GLUE). Holly supported me in learning about cattle traceability and deforestation in Brazil and collaborating on several projects I was involved in. Also many gratitude to Dr. Lisa Rausch for her excellent reviews and comments on the PhD chapters and to my colleagues at GLUE, especially Jake, Matt, and Ian, for helping me with the data processing and collaborating on various projects. Finally, I extend my thanks to all my committee for sharing their experiences with me during classes and seminars throughout my Ph.D.

I will also be forever grateful to my friends at Imazon. At Imazon, I started my career as a researcher. There I had the experience of writing my first scientific article (Brandao Jr. and Souza Jr., 2006) while I was still an intern in the Amazon Monitoring program coordinated by Carlos Souza Jr. Under Carlos' guidance, I learned a lot about geoprocessing, remote sensing, and the importance of the scientific method as a tool for Amazon's challenges. I also thank Paulo Barreto for introducing me to the subject of traceability, which eventually resulted in my application to study at UW-Madison.

This Ph.D. would not have happened without the immeasurable support of my parents Amintas Brandao and Maria Hortencia G. Brandao, who have constantly encouraged me to pursue my dreams. I also thank my wife Juliana Brandao who, besides giving me my greatest gift, our daughter Clara Brandao, always supported me during the doctorate, and helped me to face several challenges (which were not few!!), among them, living in another country during the worst pandemic of the last century. Furthermore, I thank my sisters, Gisele Brandao and Patricia

Brandao, for their encouragement in all stages of my life and for giving me my nephews, Julia, Heitor, Debora, and Rafael. Finally, thanks to all my colleagues and friends who helped me conclude this journey.

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Introduction

Cattle ranching is the major driver of deforestation in Brazil. By 2018, nearly 75% (192 MHa) of all cleared land in the country was devoted to pasturelands (Mapbiomas, 2018). Concerns over the impacts of this conversion, such as carbon emissions and habitat destruction (Noojipady et al., 2017), have led to renewed efforts to strengthen the implementation of public sector policies such as the Brazilian Forest Code (FC) (Moutinho et al., 2016; Siqueira et al., 2018) and the private sector's zero-deforestation commitments (ZDC) (Gardner et al., 2018; Garrett et al., 2019; Gibbs et al., 2015; Nepstad et al., 2014). However, overall compliance with the FC is still limited (Azevedo et al., 2017), and a lack of political will and information about cattle supply chains and the sector as a whole has made it difficult to achieve strong forest conservation outcomes from the ZDCs (Alix-Garcia and Gibbs, 2017; Gibbs et al., 2016; Klingler et al., 2018). Consequently, there is an urgent demand to pinpoint solutions to policy concerns and to fill critical information gaps about Brazil's cattle ranching sector.

Brazil's Amazon and Cerrado biomes preserve 80% of Brazil's remaining vegetation and are the current deforestation hotspots, with half of the total area deforested in the country through 2018 (Mapbiomas, 2018). Since the mid-2000s, numerous conservation policies have been implemented to reduce deforestation, including governmental plans to control illegal deforestation at the municipal, state, and federal levels (Arima et al., 2014; Assunção et al., 2012; Casa Civil, 2010; Nepstad et al., 2014, 2010; Viana et al., 2016). Remarkable results have been achieved in the Amazon, where the annual rate of deforestation was reduced by 84% between 2004 and 2012 (Arima et al., 2014; Assunção and Rocha, 2014; Nepstad et al., 2014). However, more recent data shows an escalation of deforestation in this biome since 2013, mainly from pasture expansion (Almeida et al., 2016; Mapbiomas, 2018; Moutinho et al., 2016). Clearing has also continued in the Cerrado biome, which is generally afforded less protection than the Amazon, and is often viewed by major commodity companies as an ideal region to expand new crops and pastures (Cerrado-Manifesto, 2017; Dou et al., 2018; Jepson, 2005; MMA, 2013; Rausch et al., 2019; Strassburg et al., 2017). Thus, new solutions need to be leveraged to halt deforestation in these biomes.

The FC is an essential public policy to control deforestation in Brazil. It regulates how farmers should use and preserve the remaining vegetation within their holdings. Launched in 1934 but updated in 1965 and 2012 (Casa Civil, 2012, 1965, 1934), the FC requires that farmers declare the boundaries of their land in a Rural Environmental Registry database (CAR in Portuguese), and indicate what portions are used for farming and for conservation. Farmers are required to have two conservation areas on each farm: a Legal Reserve (LR) and a Permanent Preservation Area (APP). The LR is covered by natural vegetation that cannot be cleared without a permit and may be used only for sustainable approved logging projects or for the collection of nonforest products. To delimitate an LR, farmers must consider the farm's location relative to the Legal Amazon (a political definition that embraces all five northern states and part of two others). Farms within the boundaries of the Legal Amazon may have an LR of through 80% of their area. The LR covers 20% of that territory for farms outside the Legal Amazon. By contrast, the APPs are regions of natural vegetation located along rivers and hilltops and cannot be cleared for any purpose. Despite its innovation and stringency, the FC has received limited compliance and may require partnerships with supply-chain ZDC policies to halt deforestation (Azevedo et al., 2017, 2015; Moutinho et al., 2016).

In theory, supply-chain ZDCs also play an essential role in eliminating deforestation in Brazil. Currently, the country has two ZDCs in place, both of which are only within the Amazon biome (Greenpeace, 2009, 2006). These ZDCs aim to block access to the market by soybean and cattle suppliers associated with recent deforestation. The soy-sector ZDC, implemented in 2006 and known as the Amazon Soy Moratorium (ASM), virtually stopped the deforestation for new soy fields thanks to strong pressure from the industry and an optimized monitoring system that evaluates whether soybean fields have advanced over forest areas (Gibbs et al., 2015; Kastens et al., 2017). In the cattle sector, two Cattle Agreements (CA) were signed starting in 2009, one with Greenpeace (the "G4") and another with the Federal Prosecution Office (the "Beef TAC") (Gibbs et al., 2016; Greenpeace, 2009). The G4 and the Beef TAC have similar objectives: to exclude suppliers who have recently engaged in deforestation from the cattle supply chain. The G4 seeks zero deforestation, while the Beef TAC aims for zero illegal deforestation. However, the effect of the CA in reducing deforestation is not significant yet due to some fundamental limitations.

In contrast to the ASM, the effectiveness of the two CAs in reducing deforestation has been limited due to inadequate monitoring approaches and the leakage and laundering of cattle raised on properties with recent deforestation (Alix-Garcia and Gibbs, 2017; Carvalho et al., 2019; Gibbs et al., 2016; Klingler et al., 2018). While soybean fields are static and annual maps are available to monitor them (Rudorff et al., 2012), cattle move from farm to farm, and there is no precise information about this movement available, making them a challenge to trace (Massoca and Lui, 2017). In the absence of cattle traceability information, suppliers with deforestation can either move the cattle to regions not yet monitored by the CAs (leakage) or send the cattle to farms free of deforestation before sale to a slaughterhouse that has signed the

CA (laundering). To improve the outcomes for forest conservation, we need an improved understanding of the cattle supply chain characteristics, such as the location of supply zones, as well as the land use dynamics within the regions subject to the agreements.

Companies, policymakers, and environmental organizations are now trying to navigate these policy challenges better to understand the relative role of the FC and ZDCs, and what an end to deforestation would mean for agricultural production in Brazil. Previous work at the biome level has suggested that land-use intensification could create conditions sufficient to meet current and future agricultural production demands without further deforestation (Merry and Soares-Filho, 2017; Strassburg et al., 2014). There may be enough deforested land in Brazil to accommodate the demand for cattle expected by 2040, but we still lack essential information, including first, to what extent different regions concentrate the available arable area; next, whether companies have installed the necessary infrastructure; and finally, whether the land is accessible to most farmers.

My dissertation aims to address these information gaps regarding Brazil's cattle supply chains to better understand the connections between forest conservation and cattle production. I focused on core research questions presented in three chapters to achieve this goal. In the first chapter, I provided an overview of land available in the Amazon and Cerrado biomes for production and forest conservation under different policy scenarios. The subsequent two chapters focused on more detailed analyses of the characteristics of the cattle sector in three Brazilian states — Pará, Mato Grosso, and Rondônia — which collectively account for 23% of the deforestation and 30% of the cattle herd in Brazil through 2018 (IBGE, 2018; Mapbiomas, 2018).

The results of my research are relevant to decision-makers and make scholarly contributions to Land Systems Science. My results offer spatial analysis at various scales, including biomes, slaughterhouse supply zones, and farms. Below are the specific abstracts of each chapter:

Ch1: Estimating the Potential for Conservation and Farming in the Amazon and Cerrado under Four Policy Scenarios

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Since 2013, clearing rates have rapidly increased in the Amazon and Cerrado biomes. This acceleration has raised questions about the efficacy of current regional public and private conservation policies that promote agricultural production while conserving remnants of natural vegetation. In this study, we assessed conservation and agricultural outcomes of four potential policy scenarios that represent perfect adherence to private sector, zero-deforestation commitments (i.e., the Amazon soy moratorium—ASM and the Amazon cattle agreements—CA) and to varying levels of implementation of the Brazilian Forest Code (FC). Under a zero-clearing scenario, we find that the extent of croplands as of 2017 within the two biomes (31 MHa) could double without further clearing if agriculture were to expand on all previously cleared land that is suitable for crops. Moreover, at least 47 MHa of land that is already cleared but unsuitable for crops would remain available for pasture. Under scenarios in which only legal clearing under the FC could occur, 51 MHa of additional natural vegetation could be cleared. This includes as many as 1 MHa of nonforest vegetation that could be cleared in the Amazon biome without triggering the ASM and CA monitoring systems. Two-thirds of the total vegetation vulnerable to legal clearing is located within the Cerrado biome, and 19 MHa of this land is suitable for cropland expansion. Legal clearing of all of these areas could reduce

biodiversity persistence by 4% within the two biomes, when compared with the zero-clearing scenario, and release up to 9 PgCO2e, with the majority (75%) coming from the Cerrado biome. However, when we considered the potential outcomes of full implementation of the FC, we found that 22% (11 MHa) of the 51 MHa of vegetation subject to legal clearing could be protected through the environmental quotas market, while an additional 1 MHa should be replanted across the two biomes, predominantly in the Amazon biome (73% of the area subject to replanting). Together, quotas and replanting could prevent the release of 2 PgCO2e that would otherwise be emitted if all legal clearing occurred. Based on our results, we conclude that ongoing legal clearing could create additional space for cropland and cattle production beyond the substantial existing stocks of cleared areas but would significantly impair local carbon and biodiversity stocks.

Ch2: Mapping the current and potential reach of zero-deforestation cattle agreements across the Brazilian Amazon

In preparation to the Land Journal

Historically government and non-government groups have urged meatpacking companies to help decrease deforestation related to cattle produced in the Brazilian Amazon by signing zero-deforestation Cattle Agreements (CA). However, not all meatpackers have signed the agreements, and those that have do not fully implement the CA and lack transparency. CA slaughterhouses monitor only their direct suppliers who send the cattle for slaughter to the slaughterhouses. Several tiers of indirect suppliers, where cattle are born and raised before being sent to the direct suppliers, are not monitored by CA slaughterhouses. This limits the CAs' ability to reduce deforestation since so many farms are not monitored, which increases the risk of laundering or leakage of cattle from properties with deforestation. Expanding the CAs to include more suppliers and slaughterhouses is crucial to better control deforestation. We assessed the potential of this expansion to increase the area under CA influence using property boundaries and cattle traceability data from 2013 to 2018 to map and characterize the slaughterhouse supply zones of direct and indirect suppliers within the states of Pará, Mato Grosso, and Rondônia. Our results indicate that the current CA supply zones covered an area of 160 million hectares (Mha), more than two-thirds (67%) of the total area of the three states analyzed, and more than 98% of the total pasture and deforested areas. As we found that most of the current CA supply zone (>90% of the current area) already overlaps with the potential areas for expansion, expanding the agreements to include more slaughterhouses or to monitor tier-1 indirect suppliers may expand the CA intensity but will not expand its geographical extent. With our findings, we have an accurate image of the regions potentially under the reach of CA slaughterhouses and those not covered by this policy action to stop deforestation.

Ch3: Investigating the spatial relationship between cattle travel distance along roads and deforestation in the Brazilian Amazon.

In preparation for the Environmental Conservation Journal

Trucks are the primary means of transportation for the cattle industry in the Brazilian Amazon. As a result, roads impact economic output and cattle producers' choices in transporting cattle to slaughterhouses. However, there is little, or no information about travel distances through roads within the cattle supply chain, which could help understand how producers make choices leading up to and after deforestation. Here we estimate the shortest connections using the roads that connect all parts of the cattle supply chain and explore the relationship between the distance traveled by cattle from these roads and deforestation. To do so, we combined road maps from Imazon and IBGE with cattle traceability information and deforestation maps available for the states of Pará, Mato Grosso, and Rondônia, and covered the period from 2013 to 2018. Our estimates indicate that cattle traveled 77 to 144 km (median values) from direct suppliers to slaughterhouses in the years between 2013 to 2018. In addition, direct suppliers do not typically (76% of the slaughtered heads) sell to the nearest slaughterhouse due to potential strong connections with the preferred slaughterhouse. And cattle from suppliers with deforestation travel more than from suppliers without deforestation, and cattle travel further after deforestation. Our method has the potential to be replicated in more Brazilian states if the required data is available

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Chapter 1: Estimating the potential for conservation and farming in the Amazon and Cerrado under four policy scenarios

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Abstract

Since 2013, clearing rates have rapidly increased in the Amazon and Cerrado biomes. This acceleration has raised questions about the efficacy of current regional public and private conservation policies that seek to promote agricultural production while conserving remnants of natural vegetation. In this study, we assessed conservation and agricultural outcomes of four potential policy scenarios that represent perfect adherence to private sector, zero-deforestation commitments (i.e., the Amazon soy moratorium—ASM and the Amazon cattle agreements—CA) and to varying levels of implementation of the Brazilian Forest Code (FC). Under a zero-clearing scenario, we find that the extent of croplands as of 2017 within the two biomes (31 MHa) could double without further clearing if agriculture were to expand on all previously cleared land that is suitable for crops. Moreover, at least 47 MHa of land that is already cleared but unsuitable for crops would remain available for pasture. Under scenarios in which only legal clearing under the FC could occur, 51 MHa of additional natural vegetation could be cleared. This includes as many as 1 MHa of nonforest vegetation that could be cleared in the Amazon biome without triggering the ASM and CA monitoring systems. Two-thirds of the total vegetation vulnerable to legal clearing is located within the Cerrado biome, and 19 MHa of this land is suitable for cropland expansion. Legal clearing of all of these areas could reduce biodiversity persistence by 4% within the two biomes, when compared with the zero-clearing scenario, and release up to 9 PgCO2e, with the majority (75%) coming from the Cerrado biome. However, when we considered the potential outcomes of full implementation of the FC, we found that 22% (11 MHa) of the 51 MHa of vegetation subject to legal clearing could be protected through the environmental quotas market, while an additional 1 MHa should be replanted across the two biomes, predominantly in the Amazon biome (73% of the area subject to replanting). Together, quotas and replanting could prevent the release of 2 PgCO2e that would otherwise be emitted if all legal clearing occurred. Based on our results, we conclude that ongoing legal clearing could create additional space for cropland and cattle production beyond the substantial existing stocks of cleared areas but would significantly impair local carbon and biodiversity stocks.

Keywords:

Brazil; Amazon; Cerrado; Forest Code; supply chain; soy moratorium; cattle agreements

1. Introduction

The Amazon and Cerrado biomes are essential to agricultural production in Brazil, but they have different environmental policies in place to control land clearing. These two biomes comprise 70% of Brazil's land area and include much of the remaining native vegetation, more than 53% of the country's cattle herds, and 60% of grain production (CONAB, 2018; IBGE, 2018a). Concerns about the rapid loss of native vegetation from expansion of agribusiness (soy and cattle), led to the implementation of numerous public and private sector policies in the mid-2000s, including the 2004 plan to control illegal deforestation in the Amazon, the 2006 Amazon soy moratorium (ASM), and the 2009 zero-deforestation cattle agreements (CA) (E. Y. Arima et al., 2014; Gibbs et al., 2016; Greenpeace, 2006, 2009; D. Nepstad et al., 2014). Together, these policies contributed to an 84% decline in annual deforestation between 2004–2012 in the Amazon biome (E. Y. Arima et al., 2014; Assunção & Rocha, 2014; D. Nepstad et al., 2014), though questions remain about the relative contribution of any one policy in attaining this reduction (Fearnside, 2017; Moutinho et al., 2016; Stickler et al., 2013). Although a deforestation control plan has covered the Cerrado biome since 2010, in general, the Cerrado is less protected overall than the Amazon. For example, the Brazilian Forest Code (FC)—the federal legislation that regulates land use on rural farms (Soares-filho et al., 2014; Stickler et al., 2013)—allows up to four times more clearing in the Cerrado than in the Amazon. Moreover, the Cerrado has less protected areas than the Amazon (Strassburg et al., 2017) and no ASM or CA supply chain initiatives (Cerrado-Manifesto, 2017).

While some studies suggest that these public policies were the primary drivers of reduced clearing in the Amazon (Alix-Garcia et al., 2018; E. Y. Arima et al., 2014; Assunção et al., 2015; Assunção & Rocha, 2014; D. Nepstad et al., 2009, 2010, 2014), others have emphasized the role of zero-deforestation commitments made by members of the private sector (Gibbs et al., 2015, 2016; Kastens et al., 2017). However, since 2013, clearing rates have again been rising in the Amazon (Moutinho et al., 2016), and pressure to further clear land may be spilling over into the Cerrado (Dou et al., 2018). Concerns are also growing about the impacts of the ongoing agricultural conversion of the Cerrado—much of which is legal under the FC—on the water, climate, and livelihood cycles of the region (Arantes et al., 2016; Ratter et al., 1997; Sano et al., 2010, 2019; Soares-filho et al., 2014; Strassburg et al., 2017). As a result, high-profile negotiations with a particular focus on the soy and meat supply chains are underway to develop new policies and commitments to limit further clearing in the Cerrado (Cerrado-Manifesto, 2017).

Uncertainty over past policy outcomes for the Amazon region and ongoing efforts to improve protections in the Cerrado together raise essential questions about how best to reduce clearing. In this study, we contribute to that discussion by estimating the potential impact of zero-deforestation commitments, including the ASM and the CA, and of the FC on forests, cropland, and pastureland areas in these biomes. We consider the suitability of previously cleared land as well as of new areas that could be legally converted under the FC. We also identify how much land would be needed to attain full compliance with the FC. This would require that most farm owners do some degree of replanting or obtain off-farm reserves. Finally, we compare the implications that these policies have on carbon emissions and biodiversity. Answers to these questions may help us better understand the extent to which cropland and pastureland could be affected by these different policy approaches.

To answer these questions, we assessed four scenarios that represent varying levels of restrictions on new clearing. Our first scenario estimated the amount of land cleared as of 2017 that is suitable for crop and for pasture expansion, assuming no further clearing of any type of natural vegetation. In our second scenario, we estimated the maximum area that could be available for croplands and pasture, including the cleared land from the first scenario and the nonforest vegetation (e.g., savannas) that could be cleared legally under the FC, but without violating the ASM and the CA. Our third scenario estimated the maximum area that could be available for croplands and pasture if all vegetation of any type that could be legally cleared under the FC were to be cleared. Finally, our fourth scenario represents the full legal compliance with the FC, where we estimated, in addition to the areas of the third scenario, the vegetation "deficits"; that is, the cleared area that would either need to be replanted or compensated to meet FC requirements and which ultimately protects the vegetation surplus against the legal clearing. Within these scenarios, we first assumed no additional clearing of any type of vegetation, and then perfect compliance with the FC, the ASM, and the CA, to show their maximum potential impact, even though, in reality, landowners may not always fully comply with policies.

2. Background on the Three Policies Assessed by Our Scenarios

Launched in 1934 (Casa Civil, 1934), and subsequently updated in 1965 (Casa Civil, 1965) and 2012 (Casa Civil, 2012), the FC asks farmers to delineate the boundaries of their farms, as well as areas for "alternative land use" (areas that could be cropped or grazed) and conservation. Conservation areas are intended for environmental preservation and are further divided into areas of permanent protection (APP) and legal reserves (LR). In the case of APPs, which are generally delimited by river width and topographic characteristics, the objective is to protect the environmental functions of areas located along with water bodies and hilltops; thus, APPs do not allow for any economic activities and must always be replanted if cleared. LRs consist of the remaining vegetation that can be economically exploited by sustainable forest management practices (e.g., sustainable logging). They are delineated based on the size of the farm and its location relative to the Legal Amazon—a political entity that encompasses seven Brazilian States in their entirety and two in part. For all farms outside the Legal Amazon, the LR occupies 20% of the farm area. While the entire Amazon biome is located within the Legal Amazon, most of the Cerrado biome (63%) is outside of it. For farms within the Legal Amazon, three situations apply, depending on the type of vegetation that covers the farm: (i) if the farm has forests, the LR must be 80% of the farm area; (ii) for farms with Cerrado vegetation (wooded grasslands), the LR is 35%; (iii) if a farm has open savannas ("campos gerais" in Portuguese) the LR is 20%. If a farm has an LR deficit, farmers can replant to erase the deficit or purchase environmental quotas (CRA in Portuguese) with farms that have an LR surplus and are located in the same biome. All farmers must replant any LR that was cleared after 22 July 2008 without an official permit.

All information about land use on private farms must be declared in the Rural Environmental Registry (CAR in Portuguese). CAR records are available through an online system called the National Rural Environmental Registry System (SICAR in Portuguese), which, as of 2018, contained more than five million declared farms (SFB, 2019). The CAR data allow environmental agencies to assess compliance with the FC, ASM, and CA. For example, some studies have combined the CAR data with land cover maps and found that there is low compliance with the FC (A. A. Azevedo et al., 2017), especially when compared to compliance with the ASM (Gibbs et al., 2015) and CA (Alix-Garcia & Gibbs, 2017; Gibbs et al., 2016; Klingler et al., 2018).

The ASM and the CA are the firsts zero-deforestation commitments implemented in the tropics. It began in 2006 with the ASM (Gibbs et al., 2015), when international pressure led by

Greenpeace influenced a coalition of soy buyers to vow to not buy soy from cleared areas in the Amazon biome (Greenpeace, 2006). Since the ASM was signed, the Amazon biome has been virtually free of new clearing due to soy (Gibbs et al., 2015; Kastens et al., 2017). Similarly, in 2009 the Amazon's largest meatpackers began signing CA with federal prosecutors (the "Beef TAC") and with Greenpeace (the "G4"). Both the G4 and the Beef TAC have similar objectives: To exclude suppliers who have recently engaged in deforestation from the cattle supply chain (Gibbs et al., 2016). The G4 seeks zero deforestation, while the Beef TAC aims for zero *illegal* deforestation.

In contrast to the ASM, though, the effect of the CA in reducing deforestation has not yet been significant due to inadequate monitoring approaches and to the leakage and laundering of cattle raised on properties with recent deforestation (Alix-Garcia & Gibbs, 2017; Carvalho et al., 2019; Gibbs et al., 2016; Klingler et al., 2018). While soybean fields are static and there are annual maps available to monitor them (B. F. T. Rudorff et al., 2012), cattle move from farm to farm, and there is no precise information available about this movement, making them a challenge to trace (Massoca & Lui, 2017). In the absence of cattle traceability information, ranchers with deforestation can either move cattle to regions not yet monitored by the CA (leakage) or send the cattle to farms free of deforestation prior to sale to a slaughterhouse that has signed the CA (laundering). However, recent efforts have tried to connect animal movement data with farm boundaries to better understand the characteristics of Brazil's cattle supply chain and to pinpoint solutions to reduce deforestation for beef production in the country (Alix-Garcia & Gibbs, 2017; Klingler et al., 2018; Proforest, 2017; E. K. H. J. zu Ermgassen et al., 2019).

3. Materials and Methods

Our study region includes the Amazon and Cerrado biomes, which occupy, in whole or in part, 17 Brazilian states (nine in the Amazon and 12 in the Cerrado) (Figure 1). These biomes also contain 57% of Brazil's agriculture-driven clearing (Mapbiomas, 2018), more than 160,000 species of plants, fungi, and animals (Ratter et al., 1997), and serve as essential reservoirs for much of Brazil's water and carbon stocks (Arantes et al., 2016).

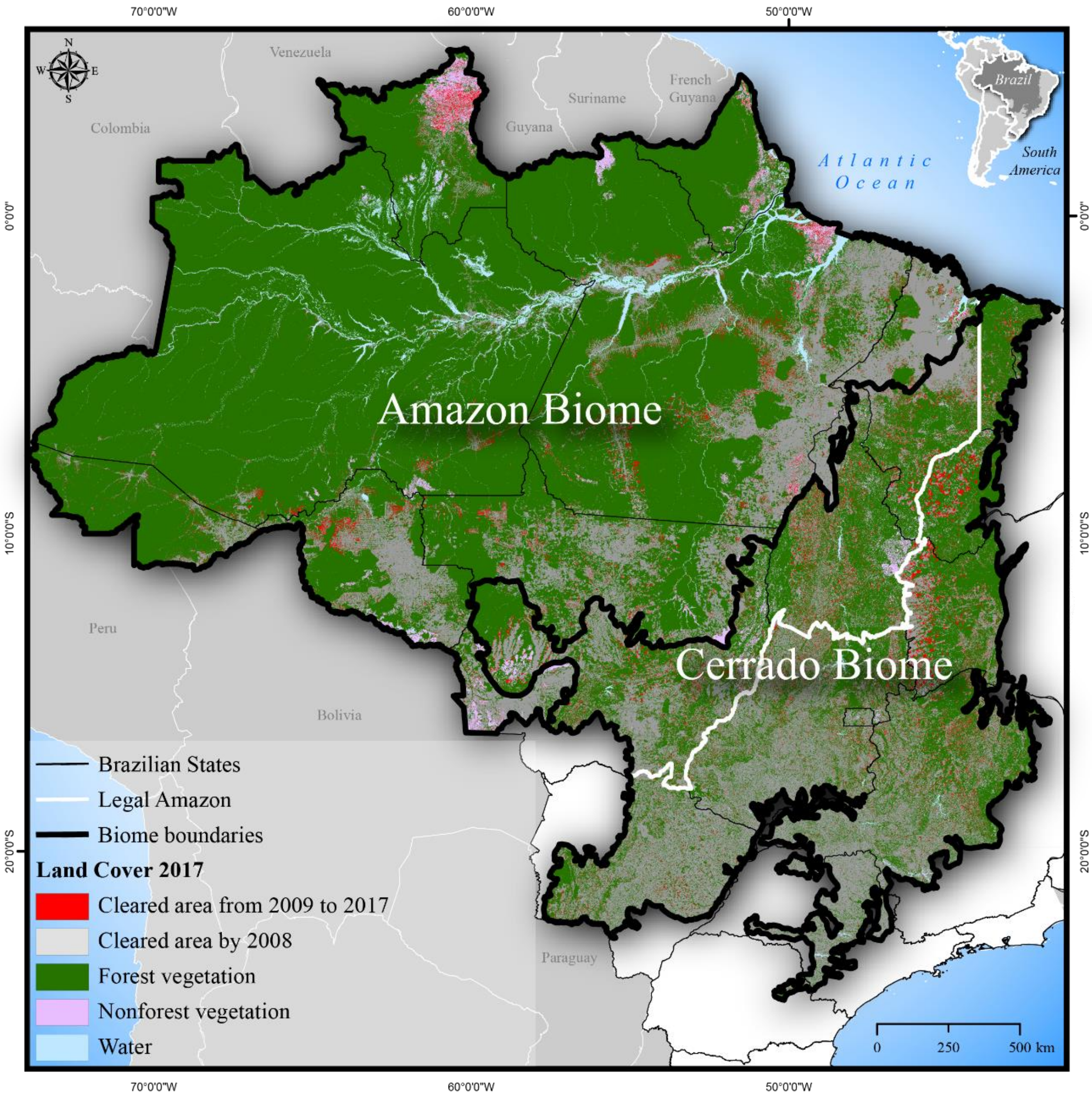

Figure 1. Synthetic land cover map depicting areas of forest, nonforest, and clearing through 2017 within the Amazon and Cerrado biomes and the Legal Amazon. This map was produced

based on PRODES, TERRACLASS, and MAPBIOMAS (collection 2.3) data. More details in Section 3.1.

3.1. Datasets and Data Preparation

Using ArcGIS 10.3, we organized a set of spatial data to generate our four scenarios (Table A1 and Figure A1 in Appendix A). These data portray the land coverage and land use in 2017 in both biomes and are compatible with a scale of 1:100,000 with a pixel size of 60 by 60 m. Before computing these scenarios, the data were prepared using these four steps:

- Step 1. Creation of a synthetic land cover map for 2017.

We built a synthetic land cover map for the Amazon and Cerrado as of 2017 and used it to identify the areas cleared through that year, as well as the remaining forest and nonforest vegetation. Our first step was to create a map of clearings showing (i) the regions cleared by 2008 and (ii) from 2009 to 2017. For the map of cleared areas in the Amazon, we utilized only the data from PRODES Amazon and MAPBIOMAS within the Amazon biome boundary (MMA, 2018). We used MAPBIOMAS data only within areas of nonforest vegetation mapped by PRODES. The clearings map for Cerrado was based on the data from PRODES Cerrado. Next, we identified the remaining forest and nonforest vegetation. For the Amazon, we used PRODES, TERRACLASS, and MAPBIOMAS and began by selecting only the “forest” lands class from PRODES, and the “secondary forest” from TERRACLASS up to 2014. From MAPBIOMAS, we selected only the forest and nonforest classes located within the “nonforest” class mapped by PRODES. Similarly, we identified remaining Cerrado vegetation from the TERRACLASS “natural vegetation” class and the MAPBIOMAS nonforest classes. Finally, we overlaid the map of cleared areas upon that of remaining vegetation to produce a synthetic land cover map for 2017. Secondary forest areas that were located within cleared areas were maintained as “forest”. Areas of remaining nonforest vegetation that overlapped with cleared areas were classified as cleared.

- Step 2. Creation of a mask for the ineligible areas for cropland and pasture.

Land located within protected areas, military areas, urban areas, along roads, mining areas, or water bodies was considered ineligible for cropland and grazing (Soares-filho et al., 2014). These areas were removed from the synthetic land cover map.

- Step 3. Identification of the areas suitable for cropland expansion.

We identified suitable and unsuitable areas for cropland expansion using a map of soy suitability. Soy is the dominant crop in the Amazon and Cerrado biomes; it is planted on 90% of the cropland in the two biomes and can serve as a reasonable proxy for estimating areas most suitable for all types of crops in the region.

We assessed suitability using two soy suitability maps generated by Agrosatélite (B. Rudorff & Oliveira, 2014) and by Soares-Filho et al. (Soares-filho et al., 2014). Both maps cover the Amazon and Cerrado biomes and were merged into a single dataset for our analyses. The Agrosatélite map is based on the EMBRAPA methodology; it identified biophysical restrictions for the occurrence of soy within 30 × 30-m grid cells (B. Rudorff & Oliveira, 2014). We maintained areas of this map where no restrictions on soy production had been reported. The second map, from Soares-Filho et al. (Soares-filho et al., 2014), is also based on environmental conditions and has a 60 × 60 m spatial resolution. For this map, we retained grid cells, with a value for soy higher than 60 (range 0 to 100), which indicates suitability. The two soy suitability maps were then superimposed, and grid cells were classified as “suitable for cropland” if either of the input maps reported suitability. Next, we excluded areas mapped as cropland as of 2017 by

TERRACLASS and Agrosatélite. The remaining areas were classified as “unsuitable for cropland”.

All land unsuitable for cropland was considered suitable for pasture. We assumed that when land is suitable for crops, the farmer will choose to plant rather than use the land for pasture because crops are more profitable than ranching (E. Arima et al., 2005). We also excluded areas considered ineligible for cropland and pasture from our analyses (identified in Step 2). Next, we overlaid our suitability map with the synthetic land cover map for 2017 (from Step 1) to estimate the most suitable areas that could be cleared for cropland or pasture use.

- Step 4. Estimation of Forest Code compliance

We used two datasets to estimate FC surpluses and deficits (Figure A1): (i) 12th order watersheds (a proxy for farms) and (ii) CAR-delineated farms. The rationale for using watersheds as a proxy for farms was to provide a contiguous border-to-border estimate since CAR data only cover an area equivalent to 66% and 46% of the Cerrado and Amazon region that is eligible for cropland and grazing, respectively. This proxy-based approach is comparable to that of Stickler et al. (Stickler et al., 2013) and Soares-Filho et al. (Soares-filho et al., 2014). For the CAR farm dataset, we downloaded farm boundaries declared at the SICAR website in December of 2017 (SFB, 2019). Due to the high level of self-intersection among the CAR farms, we excluded farms whose area overlapped more than 5% of any neighboring farms using the tabulate intersection tool in ArcGIS (Brito, 2017). For both datasets, we considered only farms within the mask of eligible areas. Results from the watershed scale analysis are reported in the main text of this paper and results for the CAR farm dataset can be found in the appendix.

3.2. Generating the Policy Scenarios

Below, we describe the central assumptions of each scenario and how they were estimated in our spatial analysis (Table 1).

Table 1. Summary description of the assumptions considered within the policy scenarios we modeled.

Scenario	Assumption	What Was Modeled
Zero-clearing (ZC)	• No new clearing of any type of vegetation	• Cropland • Current clearing suitable or unsuitable for cropland
Legal clearing of nonforest vegetation (LC-NF)	• Legal clearing of nonforest vegetation	• Areas from the ZC scenario • Legal clearing of nonforest vegetation suitable or unsuitable for cropland
Legal clearing of all types of vegetation (forest and nonforest) (LC-AllVeg)	• Legal clearing of all types of vegetation	• Areas from the ZC scenario • Legal clearing of all types of vegetation suitable or unsuitable for cropland
Full legal compliance (FLC)	• Legal clearing of all types of vegetation • Potential for environmental quotas (CRA) or replanting	• Areas from the ZC scenario • Legal clearing of all types of vegetation suitable or unsuitable for cropland • Potential for CRA or replanting suitable or unsuitable for cropland

- Zero-clearing (ZC)

In this baseline scenario, we show the amount of cleared land that is suitable for cropland and pasture expansion without further clearing of any type of vegetation, whether forest or nonforest. Thus, this scenario divides the total cleared area of the study region into three classes.

The first class represents the area used for cropland by 2017. The second class comprises non-cropland areas that have been previously cleared and are suitable for cropland. The third class consists of non-cropland areas that have been previously cleared that are unsuitable for cropland but may be suitable for pasture. For the second and third classes, we also calculated how much of these areas were devoted to pasture as of 2017.

- Legal clearing of nonforest vegetation (LC-NF)

The intent of this scenario was to calculate the surplus of nonforest vegetation that could be legally cleared under the FC and was suitable or unsuitable for cropland. This surplus of nonforest vegetation could be cleared without triggering the ASM or CA monitoring systems that are currently active in the Amazon. This scenario ultimately points to a reduction in the amount of total native vegetation that could remain, and to an increase in the whole area that could be used for cropland or for pasture, when the surplus areas are combined with the already cleared areas from the ZC scenario. This scenario, when compared with the LC-AllVeg scenario (described below), also assesses the importance of including all types of Cerrado vegetation, should similar agreements be implemented there.

To calculate the surplus of nonforest vegetation that could be legally cleared, we first superimposed the farm or watershed boundaries layers (Figure A1K-L) on our synthetic land cover map for 2017 and calculated the amount of forest and nonforest vegetation within each farm. We then estimated the LR for each farm and the LR surplus and then limited this surplus to the area of nonforest vegetation within the farm. We considered only the vegetation located outside the APPs (Figure A1G) to be LR surplus that could be cleared. For example, in a farm with a 100-hectare LR surplus located outside APPs, with 150 hectares (ha) of nonforest vegetation and 50 ha of forest vegetation, all surpluses would be distributed to nonforest vegetation (100 ha). When there was not enough nonforest vegetation to cover the entire LR surplus, only the nonforest vegetation was allocated for clearing, even if it was less than the total LR surplus. We also assumed that nonforest vegetation in areas suitable for cropland would be cleared before areas that were unsuitable for cropland. The suitability classification of previously cleared areas was the same as in the ZC scenario.

- Legal clearing of all types of vegetation (forest and nonforest) (LC-AllVeg)

Under this scenario, we calculated the surplus of LR of any vegetation that could be legally cleared under the FC. This approach to estimating the LR surplus is similar to that used in the LC-NF scenario above but does not limit the type of vegetation only to nonforest. Again, we estimated how much of this surplus was suitable for cropland. The previously cleared area remained the same as in the ZC scenario.

- Full legal compliance (FLC)

For the final scenario, we estimated the LR deficits that would need to be replanted or compensated using CRA for farms to be fully compliant with the FC, which, in essence, are removed from the total amount of cleared area and LR surplus estimated in the LC-AllVeg scenario. For these estimates, we began by calculating the LR requirements for replanting on each farm. We first estimated the remaining vegetation in 2008 by adding the clearing that occurred from 2009 to 2017 to the vegetation remaining in 2017. We then calculated the LR surplus as of 2008 using the same approach as in the LC-AllVeg scenario. The extent of clearing that occurred after 2009 and exceeded the LR surplus in 2008 was assigned to replanting. For CRA, we combined the farm size (Figure A1J) and the percentage of LR that should be replanted based on the proportion of the municipality where the farm is located that is covered by protected areas (Figure A1I). Finally, we estimated how much of the CRA was suitable or unsuitable for cropland.

3.3. Potential Carbon Emissions and Biodiversity Impacts of Each Scenario

- Carbon emissions

We calculated carbon dioxide (CO_2) emissions using average emission factors for both forest and nonforest vegetation that were either suitable or unsuitable for cropland (Table A2). These emission factors represent the carbon stock in above- and below-ground biomass, as well as the vulnerable fraction of soil organic carbon (SOC) to a depth of 30 cm. To calculate these factors, we overlaid the synthetic land cover map with carbon maps specific to each carbon pool, as described below. We did not calculate CO_2 emissions for the ZC scenario because we assumed that there was no forest or nonforest vegetation cleared in this scenario.

Mean above-ground biomass carbon stocks (AGBC) were calculated from an AGBC map (Englund et al., 2017). Below-ground biomass carbon stocks (BGBC) were derived from a matching map of below-ground BGBC that we created using a regression model (Reich et al., 2014) that predicts BGBC based on covariance with mean annual temperature (MAT), tree phylogeny (angiosperms or gymnosperms), and the history of forest management, as used and described in Spawn et al. (Spawn et al., 2019). Spatial estimates of MAT (1970–2000) were taken from the WorldClimV2 data set (Fick & Hijmans, 2017), and management history was inferred from our synthetic land cover map. In the absence of compatible spatial information on locally dominant forest phylogenies, we assumed that all forests in our study region were dominated by angiosperms.

Committed emissions from SOC stocks to a depth of 30 cm were mapped by spatially applying expected SOC stock change estimates to SOC maps from the SoilGrids250v2 dataset

(Hengl et al., 2017) following the general approach of Spawn et al. (Spawn et al., 2019). Mean stock change estimates represent the fraction of the initial SOC stock that is lost upon conversion to cropland and were taken from Don et al. (Don et al., 2011). Three distinct estimates representing conversion of (i) primary forest, (ii) secondary forest, and (iii) grasslands to cropland were used and spatially stratified according to the pre-conversion landcover type reported by our synthetic landcover map.

Emissions factors in initial units of carbon we converted to CO_2 equivalents using the molar mass ratio (44 g CO_2:12 g C). We then multiplied these average factors by the areas that can be legally cleared as estimated in each of the scenarios. In the case of the FLC scenario, we assumed that the areas of legal clearing potentially protected by CRA would avoid some of the emissions associated with the LC-AllVeg scenario.

- Biodiversity

We analyzed the impact of each policy on biodiversity as the change in the probability that a species will persist due to proportional loss of its extent of suitable habitat (ESH), an approach that allows us to integrate spatially-explicit information on specific anthropogenic land use and the ecology of individual species. ESH describes the intersection of a species' historical geographic range with its environmental preferences (IUCN, 2017), measured based on vegetation cover and elevation (Rondinini et al., 2011).

For each scenario, we assessed potential global extinctions of endemic and near-endemic species of amphibians, birds, and mammals within the Amazon, Cerrado, and the region encompassed by both biomes (hereafter both biomes). The ZC scenario served as the baseline to calculate the biodiversity score. A species was defined as being present in a grid-cell if all of the following conditions were met: (i) the cell was within the range of the species (Birdlife, 2016),

(ii) its local elevation was within the species' elevational range limits, and (iii) its land cover was included on the species list of suitable habitats (Table A3). For migratory species, ESH was mapped considering seasonal differences in their habitat preferences.

Species with ≥70% of their global range inside the Amazon and Cerrado study regions combined were considered endemic. For migratory species, this criterion was applied to their seasonal ranges (resident, breeding, non-breeding, and migratory separately), as the persistence of the species depends on each cyclical scale independently (Wilcove & Wikelski, 2008). For each region, this resulted in the following numbers of ESH models for each vertebrate group: (i) Amazon (N = 284): amphibians (81), birds (124), and mammals (79); (ii) Cerrado (N = 109): amphibians (60), birds (27), and mammals (22); and (iii) both-biomes (N = 458): amphibians (156), birds (191), and mammals (111).

Next, we estimated the effects of the scenarios on the probability of persistence of each species. Following the procedure and analysis from Thomas et al. (Thomas et al., 2004) we calculated the change in persistence of the ESH. For each scenario, we calculated the marginal value of the loss of remaining suitable habitat as:

$$\Delta P_{i,k} = \left(E_{2017,k}\right)^z - \left(E_{scenario\ i,k}\right)^z \qquad (1)$$

where ΔP is the remaining suitable habitat, *i* is each scenario, *k* is the species, E_{2017} is the remaining proportion of ESH in 2017 (including eligible and ineligible land for cropland and pasture, as defined in Section 3.1), $E_{scenario}$ is the remaining proportion of ESH after removing the eligible vegetation vulnerable to a legal clearing (vulnerable vegetation) from E_{2017} according to each scenario, and *z* is a coefficient relating to the probability of persistence to population size.

We assessed the remaining proportion of ESH in 2017 (E_{2017}) against the original ESH of the species. To do this, we used a vegetation map of Brazil, representing pre-industrial times (IBGE, 2004). For migratory species, we calculated an overall marginal value from the $\Delta P_{i,k}$ that was derived separately for the ESH of breeding and non-breeding species and the two values were then combined multiplicatively, as previously suggested by empirical (Lockwood, 2010) and theoretical studies (Iwamura et al., 2013):

$$\Delta P_{i,k,mig} = P_{b,2017} \text{ x } P_{nb,2017} - P_{b,scenario\ i} \text{ x } P_{nb,scenario\ i} \qquad (2)$$

where P_b and P_{nb} are the persistence scores within the breeding and non-breeding ranges, respectively.

For each species, we calculated the $E_{scenario}$ as the sum of vulnerable vegetation ESH across all 12th order watersheds contained within corresponding biomes. The following rules were applied to calculate vulnerable vegetation ESH at watershed or farm level: (i) if ESH is 0 or vulnerable vegetation is 0, then vulnerable vegetation ESH is 0; (ii) if ESH is larger than the vulnerable vegetation, then the vulnerable vegetation ESH was calculated as the ratio of vulnerable vegetation to ESH; and (iii) if ESH less than equal the vulnerable vegetation, then the entire area of ESH was considered vulnerable.

4. Results

4.1. Land Available for Cropland and Pasture

Under the ZC scenario, we found 152 million hectares (MHa) of cleared area as of 2017 across the Amazon and Cerrado biomes (Figure 2). One-fifth of the total cleared area (31 MHa) was used as cropland, and most of this cropland was in the Cerrado biome (26 MHa) (Figure 3C). Of the remaining cleared area, 74 MHa was suitable for cropland (40 MHa in the Cerrado and 34 MHa in the Amazon). Cropland could expand by 238% across both biomes combined (from 31 MHa to 105 MHa), mainly at the expense of pasturelands. A large portion (64 MHa) of the cleared area suitable for cropland was already pasture in 2017.

Opportunities for agricultural expansion without additional clearing were most prevalent in the Cerrado, though there remained a sizeable amount of suitable area in the Amazon as well. In the Cerrado, the current extent of cropland (26 MHa) could expand to as much as 66 MHa, an increase of 40 MHa or 154%. Most of these cleared and suitable areas are in the southern part of the Cerrado biome and in proximity to the “arc of deforestation” along the southern edge of the Amazon biome. In the Amazon, cropland can potentially expand by as much as 680% (from 5 MHa to 39 MHa) on existing cleared areas that are suitable for cropland.

One-third of the total cleared area in the two biomes (47 MHa) was unsuitable for cropland, and, as expected, 36 MHa of this area was already managed as pasture (Figure 3). Two-thirds of this cleared area was concentrated in the Amazon biome (27 MHa), primarily in the northern part of the state of Pará (Figure 2). In the Cerrado biome, up to 20 MHa of these cleared areas were unsuitable for cropland, and most of them were distributed in the north and central portions of the biome.

In the LC-NF scenario, under which the smallest amount of vegetation could be cleared beside the ZC scenario, only 5 MHa could be cleared across both biomes, with the majority of this area (84%; 4.2 MHa) located in the Cerrado. About half of this vegetated land is suitable for crops. In all, the Amazon has 1 MHa of surplus nonforest vegetation under the FC, and neither the ASM nor the CA currently monitors this area, increasing the likelihood that it will be cleared.

The LC-AllVeg scenario allowed for the most additional clearing across both biomes. We found that 51 MHa could be cleared legally under the FC, on top of the areas that were already cleared as of 2017. Nearly 30 MHa of this land with surplus natural vegetation would be suitable for cropland. Due to its lower LR requirements, the Cerrado biome comprises most of the vegetation (76%) that can be legally cleared, and just over half of these surplus areas in the Cerrado are suitable for cropland expansion. In the Amazon biome, 11 MHa of the legally clearable land would be suitable for crops, and only 1 MHa would not. If all farms in the two biomes were to deforest the maximum area of land allowed under the FC, the total potential cleared area could increase from 152 MHa to 203 MHa or 34% over the ZC scenario.

Under the FLC scenario, we found that just over 1 MHa of cleared areas would need to be replanted, and 11 MHa could be compensated under environmental quota schemes in both biomes. Thus, for all farms to achieve FC compliance, there are only 40 MHa (51 MHa–11 MHa) of LR surplus that can be legally cleared. Of these 40 MHa, 21 MHa are suitable for crops and 19 MHa are unsuitable for crops. Thus, the total cleared area under this scenario could be as much as 192 MHa, an increase of 26% compared to the ZC scenario. Results from CAR farm boundary analyses for all scenarios were similar to those reported here at watershed boundaries but were slightly lower because the CAR farms cover a smaller area than the watersheds (details on Appendix B).

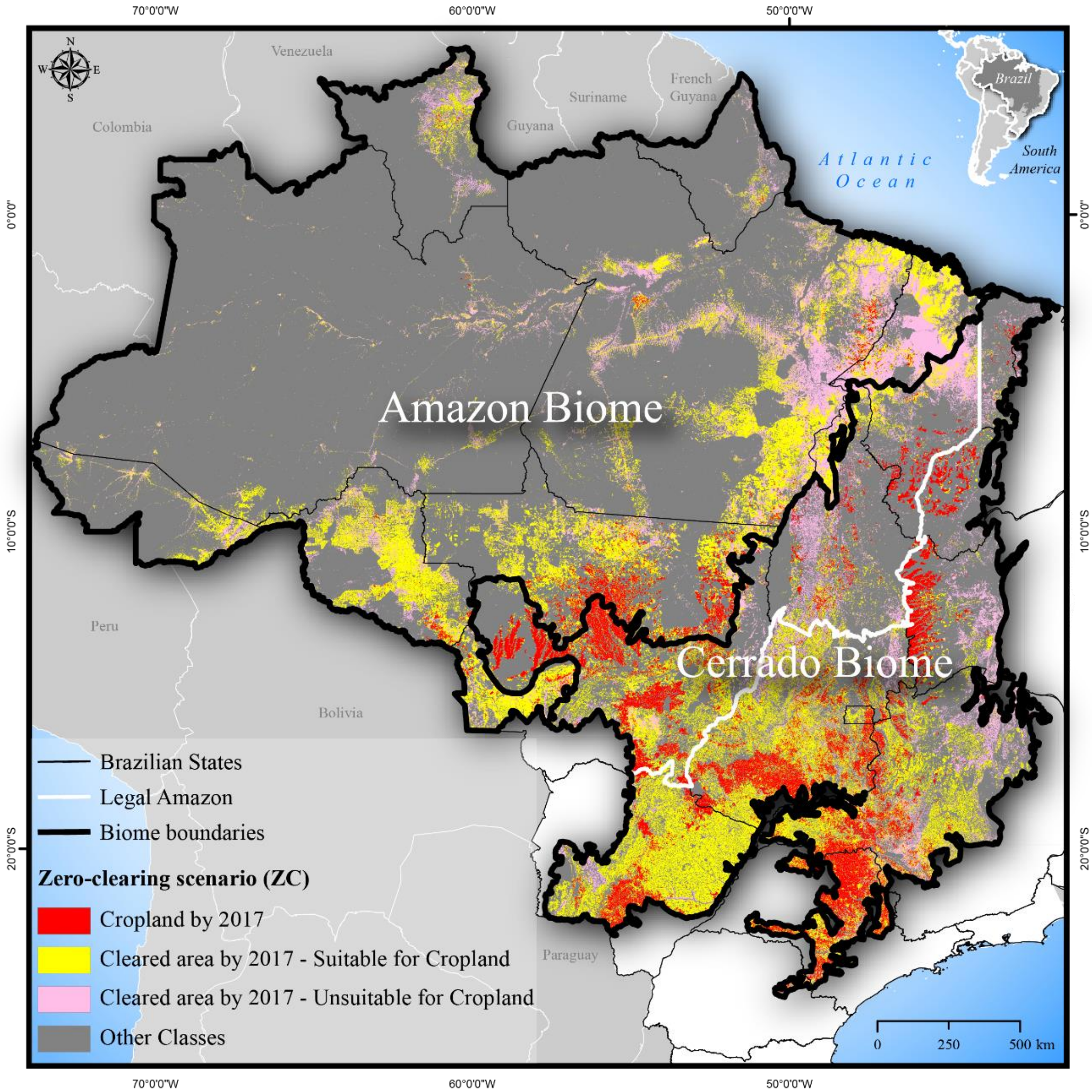

Figure 2. Areas cleared by 2017, calculated under the zero-clearing scenario (ZC).

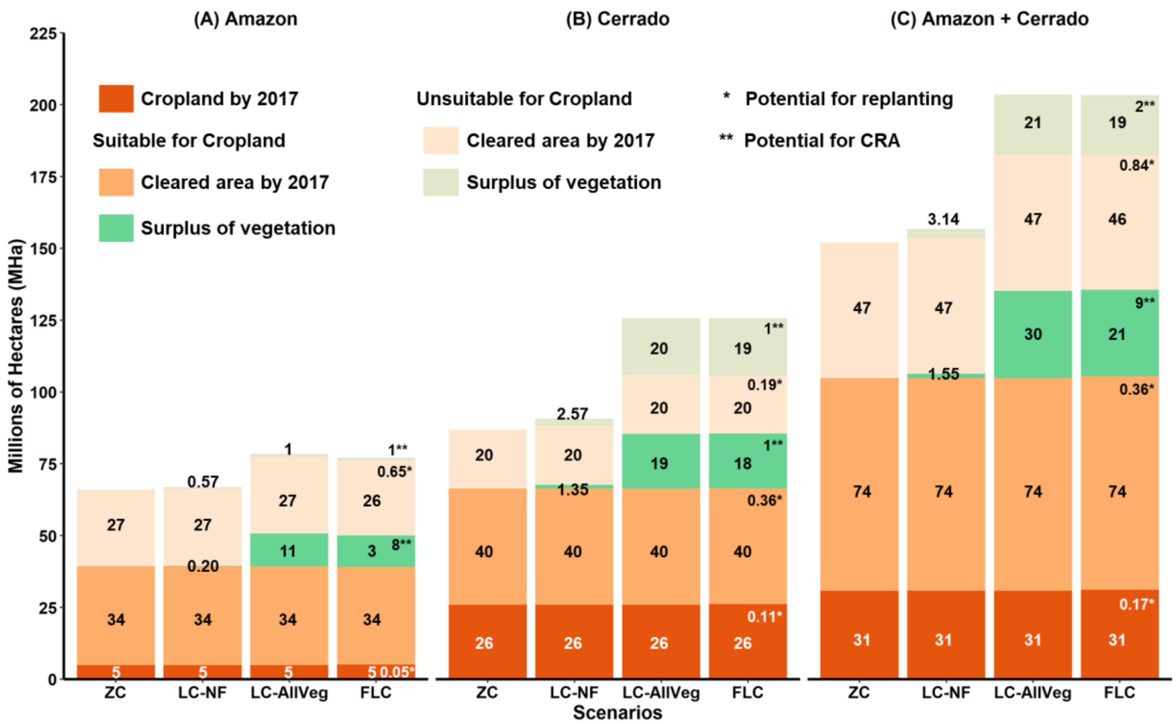

Figure 3. Land areas for the Amazon (A), Cerrado (B), and both biomes combined (C) under four policy scenarios: zero-clearing (ZC), legal clearing of nonforest vegetation (LC-NF), legal clearing of all types of vegetation (forest and nonforest) (LC-AllVeg), and full legal compliance (FLC). The legal clearing presented in this figure was calculated from the border-to-border extent of 12th order watersheds within the areas eligible for crops and pasture.

4.2. Impact of the Four Policy Scenarios on Carbon Emissions

The impacts of even legal clearing on carbon emissions, from the conversion of natural vegetation and subsequent effects on the underlying soil, will increase Brazil's future emissions (Figure 4). Our results show that clearing of all remaining native vegetation that can be legally cleared could result in as much as 9 petagrams of carbon dioxide equivalents ($PgCO_2e$) of emissions, with 25% (2 $PgCO_2e$) coming from the Amazon and the remainder (7 $PgCO_2e$) from the Cerrado. These emissions would be equivalent to 21% of Brazil's cumulative emissions between 1986 and 2017 for the land-use change sector (46 $PgCO_2e$) (T. R. de Azevedo et al., 2018). Limiting clearing of just nonforest vegetation (LC-NF) would reduce emissions by 1 $PgCO_2e$, where 52% (0.52 $PgCO_2e$) could come from the Cerrado where most nonforest vegetation is concentrated, and by 0.48 $PgCO_2e$ from the Amazon biome. Regarding the Amazon biome, the emissions from the nonforest vegetation were equivalent to 85% of the emission from Cerrado due to higher average emission factors (details on Table A2)**.**

However, if CRA schemes were implemented according to the FC (FLC scenario), leading to greater protection for surplus vegetation, potential emissions would fall to 7 $PgCO_2e$ (77% of the emissions from the LC-AllVeg scenario). In the Amazon, the reduction in emissions could be as much as 80% under the FLC scenario compared to the LC-AllVeg scenario. Yet, in the Cerrado, this reduction would be only 3% due to the fact that there is so little illegal clearing in the Cerrado associated with the lower restrictions on clearing of the LR. Thus, even if the FC were fully implemented in the Cerrado, legal clearing alone could result in the emission of 6.79 $PgCO_2e$, almost 400% of the emissions from the Amazon biome without implementing the FC in full.

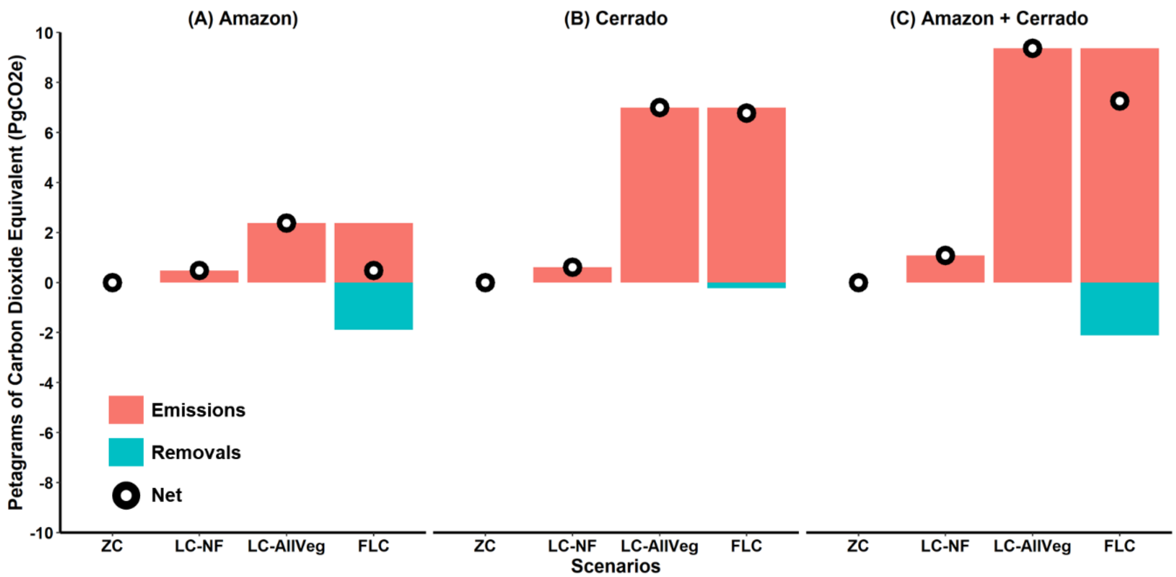

Figure 4. Estimated emissions, removals, and net CO2e emissions for the Amazon (A), Cerrado (B), and both biomes combined (C) under four policy scenarios: zero-clearing (ZC), legal clearing of nonforest vegetation (LC-NF), legal clearing of all types of vegetation (forest and nonforest) (LC-AllVeg), and full legal compliance (FLC).

4.3. Impact of the Four Policy Scenarios on Biodiversity Loss

Clearing of all LR surplus under the LC-AllVeg scenario would lead to a marked decline in biodiversity (Figure 5). Under the LC-AllVeg scenario, the biodiversity persistence score dropped from 0.94 to 0.92, 0.82 to 0.72, and 0.89 to 0.85 in the Amazon, Cerrado, and across both biomes combined, respectively. Likewise, in the LC-NF scenario, clearing of land unsuitable for crops had a higher mean impact on biodiversity than the clearing of similar land within the Amazon by a factor of ten (−0.013 unsuitable vs. −0.0013 suitable), while in the Cerrado the clearing of both types of land had a similar effect on biodiversity persistence (−0.05 unsuitable vs. −0.05 suitable).

Of interest, the observed decline in biodiversity persistence under scenarios LC-NF and LC-AllVeg was reduced under scenario FLC. This happened because under the FLC scenario 4% and 20% of the most vulnerable ESH areas could fall in areas likely to be allocated to CRA in the Amazon and Cerrado, respectively. The recovery of the biodiversity persistence score was more pronounced in the Amazon.

We note that even under the ZC scenario, the accumulated clearing had already affected species' probability of persistence in both biomes (Figure 5, scenario ZC). Scores for the other scenarios show how additional clearing would thus further reduce biodiversity persistence. Without new clearing, the remaining ESH for endemic species was 89% of the pre-industrial times, on average for the Amazon and Cerrado biomes combined. Overall, of the total remaining ESH, 38% across both biomes was suitable for agricultural expansion. Furthermore, 4% of the suitable ESH in the Amazon and up to 25% suitable ESH in the Cerrado was vulnerable to the legal clearing.

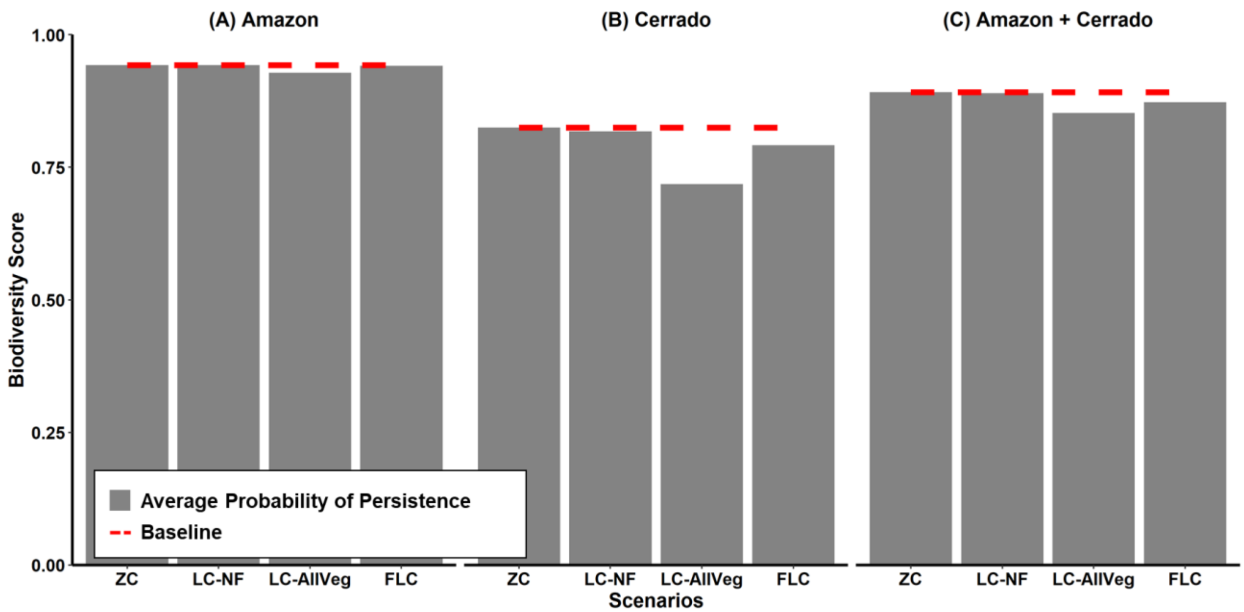

Figure 5. Changes in biodiversity persistence score for endemic vertebrate species under four clearing scenarios for (A) Amazon, (B) Cerrado, and (C) both biomes combined (based on z = 0.25; see Table A3). The biodiversity scores show persistence due to the proportional loss of suitable habitat. The red dashed line is the average probability of persistence without new clearing (ZC Scenario).

5. Discussion

5.1. Challenges to Containing Legal Clearing in the Amazon and Cerrado Regions

As with other studies, we found a considerable amount of land area that could be legally cleared in the Amazon and the Cerrado regions (Martini et al., 2015; Soares-filho et al., 2014; Soterroni et al., 2018). However, our study goes beyond previous studies to quantify the proportion of legally clearable land that is suitable for crops, which sheds light upon the relative risks of cropland expansion in the region. For example, according to the LC-AllVeg scenario, 51 MHa may be legally cleared, with 30 MHa being suitable for cropland. The remaining 21 MHa could be used for pasture; 24% (12 MHa) of the potential area vulnerable to legal clearing is concentrated in the Amazon; the largest share (11 MHa) is suitable for crops, though this area should be afforded at least some protection by the ASM since soy is the most valuable crop produced there. The CA, even with its limitations (Alix-Garcia & Gibbs, 2017; Carvalho et al., 2019; Gibbs et al., 2016; Klingler et al., 2018), could help to protect the additional 1 MHa that is more suitable for pasture, in addition to the areas suitable for crops. In the case of the Cerrado, 39 MHa may be legally cleared, including areas that are suitable for crops and those which are not, which emphasizes the need to expand both the ASM and CA protections for this biome.

Although substantial amounts of vegetation can be legally cleared, the FC includes additional provisions that could help reduce these totals (Soares-Filho et al., 2016). We estimate that as much as 22% (11 MHa) of legal clearing could be avoided under full implementation of the FC where landowners offset vegetation deficits through participation in CRA. However, most of these reductions would take place in the Amazon, where CRA could prevent around 75% (9 MHa) of the legal clearing. The effect on the Cerrado would be small, with 2 MHa of area suitable for CRA (5% of the surplus LR). CRA policy is still being developed but may become a complementary income source for landowners with an LR surplus. Instead of legally deforesting the LR surplus, the landowner would potentially protect the standing vegetation by selling CRA quotas to ranchers that have LR deficits in the same biome (mostly in the Amazon).

However, to halt legal clearing in the Amazon and Cerrado regions, there are still some key challenges. First, current monitoring systems in the Amazon do not cover nonforest vegetation, which limits our ability to measure the clearing of these areas (E. Arima et al., 2016; Rajão et al., 2017). Our results also highlight the significant area of nonforest vegetation left out of the CA and ASM, which both rely on clearing data from INPE’s PRODES to determine compliance. For example, 0.77 MHa of nonforest vegetation is vulnerable to the legal clearing in the Amazon biome (LC-NF scenario) which, consequently, could be legally cleared without violating these agreements. The recently launched PRODES Cerrado, however, does not differentiate between forest and nonforest vegetation, which means that any future agreements in this biome could potentially avoid this concern if they rely on official clearing data like the agreements in the Amazon. Our results show that just under 4 MHa of the total of 39 MHa of vulnerable vegetation in the Cerrado are areas of nonforest vegetation.

Second, the fact that the ASM and CA, which some studies indicate have had a positive effect in the Amazon (Carvalho et al., 2019; Gibbs et al., 2015; Kastens et al., 2017; L'Roe et al., 2016; K. Meijer, 2014; K. S. Meijer, 2015; Svahn & Brunner, 2018; E. K. H. J. zu Ermgassen et al., 2019), are not applied within the Cerrado biome further confounds efforts to regulate clearing. To that end, numerous scientists and key stakeholders have called for new agreements for the Cerrado to stave off clearing in the region, much of which may be permissible under the FC (Cerrado-Manifesto, 2017; Rausch et al., 2019). By allowing up to four times the deforestation within a given farm in the Cerrado compared to in the Amazon, the FC alone is unlikely to control deforestation in this region. Some studies already indicate that zero-deforestation soy production in the Cerrado would be feasible (Rausch et al., 2019; Soterroni et al., 2019), which could prevent the direct conversion of 19 MHa. Likewise, a zero-deforestation approach to cattle production in the Cerrado could potentially prevent at least another 20 MHa from being deforested for pasture.

Third, regardless of the policy approach followed, it will likely remain the case that large extents of Brazil's forestlands are privately owned. Deforestation in the Amazon and Cerrado biomes is mostly driven by commodity production of grains and beef (Curtis et al., 2018;

Margulis, 2003; D. C. Nepstad et al., 2006), which is influenced by price variations and demand for these commodities, as well as conservation policies (Assunção et al., 2015). While some authors suggest that private property may be an effective strategy for combating deforestation because insecure property leads to higher deforestation rates (Koyuncu & Yilmaz, 2013). Others argue that Brazil still needs to improve its land governance to reduce deforestation, given to insecure property rights, especially on public lands that often suffer from land speculation and deforestation to attend market demands (Reydon et al., 2019).

Finally, recent pressure to weaken environmental legislation has been a common practice over the last decade and has undermined the efficacy of existing regulations (Alves et al., 2020; Azevedo-Santos et al., 2017; Bragagnolo et al., 2017; Fearnside, 2016; Ferreira et al., 2014; Loyola, 2014). The Brazilian Congress is majority led by congressmen who are large landowners, known as the “ruralist” bloc (Bragagnolo et al., 2017; Fearnside, 2016), and they have worked to weaken environmental legislation through bills and amendments in exchange for political support (Vieira et al., 2018). One recent effort happened in early 2019, which attempted to revoke the concept of legal reserve determined by the FC (Alves et al., 2020; Projeto de Lei N° 5051, de 2019, 2019). The primary justification for this bill was the fact that the legal reserve collides with property rights, thus affecting agricultural production in Brazil, especially in the Legal Amazon. However, this bill was not approved and was definitively withdrawn from the Brazilian Federal Senate Plenary. If it had been approved, as much as 135 MHa of vegetation could have potentially been cleared in the Amazon and Cerrado biomes (Chiaretti, 2019).

5.2. Cropland Could Expand without Clearing, but Cattle Production Must Intensify

There are large areas in both the Amazon and the Cerrado that are suitable for expanding cropland without additional clearing. The Brazilian Ministry of Agriculture (MAPA in

Portuguese) projects that 9 to 24 MHa of additional land will be necessary by 2028 to meet the domestic and international demands for grains produced in Brazil, a maximum increase of 39% over the total cultivated area of the country in 2017–2018 (MAPA, 2018). That increase could easily be accommodated inside the current 74 MHa of cleared areas that are suitable for crops in the Amazon and the Cerrado regions, without the need for additional clearing and spare the 31 MHa of surplus vegetation suitable for crops and vulnerable to legal clearing, as shown in the LC-AllVeg scenario. However, needs for cropland beyond 2028 could eventually require the full 74 MHa.

In the case of ranching, however, the current cleared area may not be enough for cattle production unless there is substantial intensification. The current cattle herd in the Amazon and Cerrado biomes stands at 111 million head (IBGE, 2018b). Based on MAPA projections, the cattle herd in these two biomes could grow by 13% to 125 million head by 2028 (MAPA, 2018). If we apply historic stocking density averages for the region of 1.64 animal unit per hectare (AU ha^{-1}) (Arantes et al., 2018), a total area of 76 MHa (125 million head/1.64 AU ha^{-1}) would be necessary to accommodate the future herd. If all cleared area suitable for cropland were converted to cropland, the remaining 47 MHa of cleared area unsuitable for cropland that will be available for pasture would not be enough to secure the area required under the MAPA projections without intensification of cattle production. This is because, with the historical stocking ratio, there would be a shortfall of 29 MHa (47 MHa–76 MHa) of area needed for pasture. Given the reduced pasture area that would be available, stocking rates would have to increase from an average of 1.64 AU ha^{-1} to 2.66 AU ha^{-1} (125 million heads/47 MHa), which is well within the potential stocking rates estimated by Arantes et al. (Arantes et al., 2018) under realistic intensification strategies. Without intensification of pastures, clearing for ranching would be likely to encroach on the native vegetation or spill over into other biomes such as the Atlantic Forest or Pantanal. If cropland did not expand beyond the maximum MAPA projections of 55 MHa (31 MHa + 24 MHa), there would be enough pasture area (97 MHa) to accommodate the cattle population requirements in MAPA's projections without additional intensification.

Increasing the intensification of pastures from 1.64 AU ha^{-1} to 2.66 AU ha^{-1} is possible, but it requires investments in technology and technical assistance. Some authors (E. zu Ermgassen et al., 2018) recommend that three conditions could support the intensification of pastures. First, large-scale transfer of knowledge is needed that could enable small and large landowners to learn about new technologies and adopt agricultural practices more focused on intensification. For example, pasture rehabilitation and rotational grazing have the potential to significantly increase the production of beef far beyond 1.7 AU ha^{-1} on average. One challenge, however, is that most projects for intensifying pasture systems require costly technical support (Garcia et al., 2017). Second, financial support for ranching based on sustainability criteria is needed, which would help farmers not only increase production but also improve compliance with environmental policies. Finally, increased transparency in livestock supply chains is essential; slaughterhouses must more rigorously monitor direct and indirect suppliers to eliminate further clearing in their supply chains, which could lead to an intensification of pasture.

5.3. The Forest Code Has a Limited Effect on Reducing Carbon Emissions and Protecting Biodiversity

The FC, ASM, and the CA can complement each other to help avoid new carbon emissions and to protect the biodiversity of the Amazon and Cerrado. To this end, the zero-deforestation premises of the ASM and CA (e.g., blocking of sales from farms with recent clearing) need to be strengthened in the Amazon and expanded to the Cerrado. If the ASM and

CA are expanded to the Cerrado, about 7 PgCO2e of emissions could be avoided by zero-deforestation. In the Amazon, the role of the ASM and CA is less pronounced because the FC is already very restrictive. While C biomass densities are lower in the Cerrado compared to the Amazon, these stocks are, however, extensive, and therefore significant. By allowing four times more clearing within a given farm in the Cerrado than in the Amazon, the FC, on its own, does little to protect them. Expanding the scope of the ASM and CA to include the Cerrado biome could thus complement the FC and help conserve these C stocks that are poorly protected by existing public policies.

The impact of legal clearing on biodiversity and carbon under the FC could also be mitigated through land protection using the CRA. In the Amazon and Cerrado biomes, a decline in biodiversity could be reduced altogether; the guidelines for the recovery of degraded areas through replanting provided for in the FC can help capture carbon and biodiversity. We estimate that replanting vegetation that has been deforested above the limits allowed by the FC can potentially recover about 0.40 PgCO2e in both biomes. Furthermore, the full implementation of CRA could be prioritized in areas with high carbon and biodiversity densities [13,60,88,95].

6. Conclusions

Our scenarios show that there is a maximum of 51 MHa of vegetation in both the Amazon and Cerrado biomes that could be legally cleared under the FC. The legal clearing would create additional room for crops and cattle but could have a significant detrimental impact on local carbon stocks and biodiversity. Thus, expanded efforts to reduce clearing in soy and cattle supply chains are needed. Our findings suggest that without the need for additional clearing, the cropland area in 2017 (31 MHa) could be doubled, which would leave at least 47 MHa of cleared areas that would be likely targets of expansion of pasture intensification projects.

Indeed, without cattle intensification, there would likely be leakage or displacement of cattle ranching to other biomes. Thus, policies that restrict land use in private lands while supporting alternative production modes will be needed to balance production and conservation over the long term in Brazil.

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Appendix A

Table A1. Sources of the data used to calculate the scenarios.

Main Layer	Main Classes	Amazon Biome [References]	Cerrado Biome [References]
Land cover map for 2017	Forest and Nonforest Vegetation, Clearing through 2008 and 2009–2017, Water	TERRACLASS (Embrapa, 2014) PRODES (INPE, 2013) MAPBIOMAS Collection 2.3 (Mapbiomas, 2018)	TERRACLASS (MMA, 2013) PRODES (INPE, 2018) MAPBIOMAS Collection 2.3 (Mapbiomas, 2018)
	Cropland in 2017	Agrosatélite (B. Rudorff & Oliveira, 2014) TERRACLASS (Embrapa, 2014)	Agrosatélite (B. Rudorff & Oliveira, 2014) TERRACLASS (MMA, 2013)
	Pasture in 2017	MAPBIOMAS Collection 2.3 (Mapbiomas, 2018) TERRACLASS (Embrapa, 2014)	MAPBIOMAS Collection 2.3 (Mapbiomas, 2018) TERRACLASS (MMA, 2013)
Areas eligible and ineligible for cropland and pasture	Conservation Units in 2017 Indigenous Lands in 2017 Military Areas in 2017	ICMBio (ICMBio, 2018) FUNAI (FUNAI, 2018)	ICMBio (ICMBio, 2018) FUNAI (FUNAI, 2018)
	Riparian forests Hilltops	(Soares-filho et al., 2014)	(Soares-filho et al., 2014)
Areas suitable and unsuitable for cropland	Suitability for Soy	Agrosatélite (B. Rudorff & Oliveira, 2014) (Soares-filho et al., 2014)	Agrosatélite (B. Rudorff & Oliveira, 2014) (Soares-filho et al., 2014)
Farms	Watershed 12th level Sicar	(Soares-filho et al., 2014) (SFB, 2019)	(Soares-filho et al., 2014) (SFB, 2019)

Table A2. Average emission factors for forested and nonforest vegetation that were suitable or were unsuitable for crops for the Amazon and Cerrado biomes.

Region	**Emission Factors in Mega Grams of Carbon Dioxide Equivalent per Hectare ($MgCO_2eHa^{-1}$)**		
	AGBC	**BGBC**	**SOC30**
Amazon biome			
Forest vegetation unsuitable for cropland	433	102	75
Forest vegetation suitable for cropland	466	108	76
Nonforest vegetation unsuitable for cropland	127	31	70
Nonforest vegetation suitable for cropland	82	20	60
Cerrado biome			
Forest vegetation unsuitable for cropland	106	26	55
Forest vegetation suitable for cropland	96	24	58
Nonforest vegetation unsuitable for cropland	79	20	59
Nonforest vegetation suitable for cropland	72	19	58

AGBC: Above-ground biomass carbon (data from Englund et al. [43]). BGBC: Below-ground biomass carbon (based on the framework from Spawn et al. [45]). SOC30: Soil carbon through 30 cm (based on the framework from Spawn et al. [45]).

Table A3. Mean decline in the probability of persistence for different scenarios with different biodiversity z coefficients. (Mean ± Standard error). Data estimated based on hierarchical habitat classification scheme from the International Union for Conservation of Nature (IUCN) (IUCN, 2012) and the land cover classification from the Brazilian Institute of Geography and Statistics (IBGE) (IBGE, 2013).

	Z = 0.25	**Z = 0.50**	**Z = 1**
Amazon biome			
LC-NF	0.96 ± 0.004	0.92 ± 0.006	0.86 ± 0.01
LC-AllVeg	0.94 ± 0.003	0.90 ± 0.006	0.82 ± 0.009
FLC	0.96 ± 0.004	0.91 ± 0.006	0.86 ± 0.01
Cerrado biome			
LC-NF	0.86 ± 0.010	0.75 ± 0.016	0.60 ± 0.024
LC-AllVeg	0.78 ± 0.014	0. 63 ± 0.018	0.43 ± 0.023
FLC	0.84 ± 0.011	0.72 ± 0.017	0.55 ± 0.024
Both biomes			
LC-NF	0.88 ± 0.007	0.79 ± 0.013	0.65 ± 0.018
LC-AllVeg	0.82 ± 0.01	0.70 ± 0.015	0.52 ± 0.019
FLC	0.87 ± 0.008	0.76± 0.013	0.60 ± 0.019

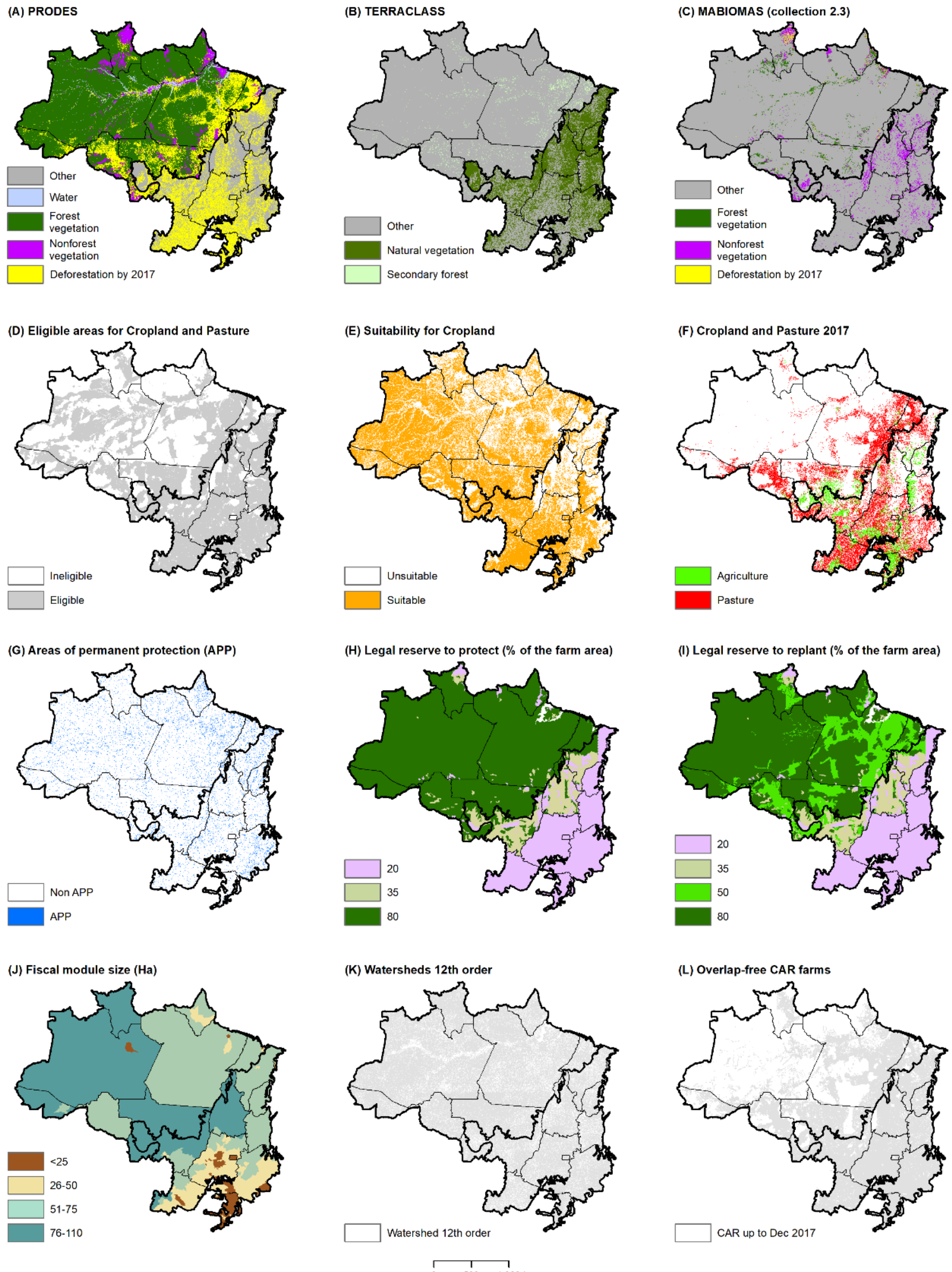

Figure A1. A simplified representation of the main datasets used in this study. Data from: (A) PRODES [92,93]; (B) TERRCLASS [90,91]; (C) MAPBIOMAS [38]; (D) Eligible areas for Cropland and Pasture [12,94,95]; (E) Suitability for Cropland [12,40]; (F) Cropland and Pasture 2017 [38,40,90,91]; (G) Areas of permanent protection (APP)[12]; (H) Legal reserve to protect

(% of the farm area) [12]; (I) Legal reserve to replant (% of the farm area)[12]; (J) Fiscal module size (Ha) [12]; (K) Watersheds 12th order [12]; (L) Overlap-free CAR farms [29].

Appendix B

We found some differences between the LR surplus and deficit calculated for the watersheds versus the CAR property boundaries. We found a surplus of 4 MHa that can be cleared under the FC in the Amazon (3.7 MHa suitable for cropland), compared to 12 MHa using the watersheds. One potential source of this difference is the fact that watersheds are a border-to-border proxy for property boundaries. Thus, the watersheds show potential LR surplus and deficits in regions with low CAR coverage, such as the extreme western region of the Amazon Biome and where the CAR did not take effect until December 2017. In the Cerrado, the difference was lower, with 26 MHa of LR surplus calculated with the property boundaries compared to 39 MHa estimated with the watersheds. The differences in the Cerrado region were most notable in the southern portion of the biome. In this region, the watersheds had a smaller average size than the rural farms, which may have increased the LR surplus. Regarding the LR deficit, the difference was 2 MHa in the Amazon biome (9 MHa calculated with the watersheds compared to 11 MHa for the properties). In the Cerrado, the difference in the LR deficit was almost 2 MHa, with nearly 5 MHa calculated with the properties and 3 MHa with the watersheds.

Chapter 2: Mapping the current and potential reach of zero-deforestation cattle agreements across the Brazilian Amazon

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Abstract

Government and non-government groups have urged meatpacking companies to help decrease deforestation related to cattle produced in the Brazilian Amazon by signing zero-deforestation Cattle Agreements (CA). However, not all meatpackers have signed the agreements and those that have track only those cattle from properties that sell cattle directly to their slaughterhouses, leaving their indirect suppliers unmonitored. This limits the CAs' ability to reduce deforestation since so many farms are not monitored, which increases the risk of laundering or leakage of cattle from properties with deforestation. Expanding the CAs to include more suppliers and more slaughterhouses is crucial to better control deforestation. We assessed the potential of this expansion to increase the area under CA influence using property boundaries and cattle traceability data from 2013 to 2018 to map and characterize the slaughterhouse supply zones of direct and indirect suppliers within the states of Pará, Mato Grosso, and Rondônia. Our results indicate that the current CA supply zones covered an area of 160 million hectares (Mha), a more than two-thirds (67%) of the total area of three states analyzed, and most of the pasture and deforested areas. As we found that most of the current CA supply zone (>90% of the current area) already overlaps with the potential areas for expansion, expanding the agreements to include more slaughterhouses or to monitor tier-one indirect suppliers may expand the CA intensity but will

not expand its geographical extent. With our findings, we have an accurate image of the regions potentially under the reach of CA slaughterhouses and those not covered by this policy action to stop deforestation.

Keywords: Brazil, Amazon, Deforestation, Cattle, Traceability, Supply Zones

1. Introduction

Brazil's Amazon rainforest is home to the world's largest cattle herd, which has grown rapidly in size since the first ranchers arrived in the region in the late 1960s. In three decades, the Brazilian Amazonian cattle herd has jumped sixfold, from 15 million head in 1985 to 93 million head in 2020, which is comparable to the entire U.S. cattle herd for that year (IBGE, 2021; USDA, 2021). The area of pasture also increased drastically for the same period – from 23 million hectares (Mha) to 70 Mha – occupying 80% of the Amazon's deforested area in 2020 (Mapbiomas, 2021). This aggressive increase in the herd and pasture area in the region has motivated many governmental and private policies to minimize deforestation in the Brazilian Amazon (Lambin et al., 2018; Boucher et al., 2013; Nepstad et al., 2009, 2014). These policies helped contribute to an 84% reduction in the deforestation rate (mostly for soy), from 2.78 Mha in 2004 to 0.46 Mha in 2012 (the region's lowest deforestation rate), but deforestation rates rebounded by roughly 80% from 2013 to 2021, averaging 0.82 Mha per year during that time period. While soy deforestation has slowed (Heilmayr et al., 2020; Gibbs et al., 2015), pasture deforestation has continued to surge.

Since 2008, Brazil's Federal Prosecution Service (known by the acronym MPF in Portuguese), Greenpeace, and other non-governmental organizations (NGOs) have pressured and encouraged companies to sign Zero-Deforestation Cattle Agreements (CAs) to halt deforestation caused by cattle farming in the Brazilian Amazon. The agreement with the MPF is an extrajudicial Term of Adjustment of Conduct (also known as the Beef TAC) that emphasizes blocking suppliers who engage in illegal deforestation in the Legal Amazon as defined by the Brazilian Forest Code (FC) or that have other socio-environmental violations of the law (forced labor, environmental embargoes, and overlap with protected areas) (Imaflora, 2021; Pereira et al. 2020;

Barreto et al. 2017; Gibbs et al., 2016). The Greenpeace agreement, known as the Public Live-stock Commitment or as the “G4”, is a voluntary commitment that was signed in 2009 with the region's four largest slaughterhouses (Greenpeace, 2009). The G4 follows the Beef TAC's criteria but emphasizes blocking suppliers with any deforestation (zero-deforestation criteria) and only applies in the Amazon biome. By 2016, approximately half of the state and federal slaughterhouses in the Brazilian Amazon, accounting for 70% of the region's slaughter capacity that year, had signed the CAs (Barreto et al., 2017; Amaral, 2016).

Despite evidence that CA slaughterhouses with monitoring systems avoid buying from properties with deforestation, research suggests that the CAs have not resulted in decreased deforestation after more than a decade of implementation (Alix-Garcia & Gibbs, 2017; Gibbs et al., 2016). One reason is that half of the major slaughterhouses in the Amazon, representing at least 30% of the slaughter market share, have still not signed onto the CAs. This means that many direct suppliers with deforestation can avoid monitoring by selling to a non-CA slaughterhouse, creating competition between the slaughterhouses that do and those that do not monitor for deforestation (Moffette, 2018). In addition, the supply chain is complex, and animals may move through various properties before slaughter, but the main source of data that could improve traceability across multiple farms is difficult to access (Skidmore et al. 2020, 2021; Rajao et al., 2020; Carvalho et al. 2019; Klingler et al., 2018). As a result, slaughterhouses can only monitor the suppliers from those they purchase directly, leaving out the indirect suppliers, who often rear and fatten the cattle before slaughter (Gibbs et al., 2016). In some cases, this complex supply chain facilitates laundering, a process in which non-compliant suppliers purposefully transport animals or modify documentation to compliant suppliers before ultimate sale to a CA slaughterhouse (Skidmore et al., 2020; Klinger et al., 2018; Gibbs et al., 2016). Expanding the CA to more slaughterhouses and more suppliers is crucial to increase the influence of the agreement on halting deforestation.

Although it is presently difficult to access, various recent studies have demonstrated the potential for combining cattle traceability documentation from the Animal Transit Guide (GTA in Portuguese) with property boundaries from the Rural Environmental Registry (CAR in Portuguese) to provide improved information on indirect suppliers (Skidmore et al. 2020, 2021; Rajao et al., 2020; Slob et al., 2020; Klingler et al., 2018; Proforest, 2017; Gibbs et al., 2016). The GTA was launched in 2006 by the Brazilian government under the country's Unified Agricultural Health Care System to control the spread of animal diseases (MAPA, 2006). GTAs are required documentation that must be provided if one or more animals are moved from one property to another within Brazilian territory. A GTA record comprises tabular information on the groups of animals being transported (such as the number, sex, and age of animals for example) and details regarding the transaction's origin and destination places. The CAR data are spatial databases introduced nationally in 2012 to help in environmental management and planning against deforestation in the country as part of the revised Brazilian Forest Code (FC) (Casa Civil, 2012; SICAR 2020). They include geographically precise property boundaries in addition to information on landowners. While linking GTA and CAR data may increase visibility into the cattle supply chain, there are also important limitations to this approach due to errors and inconsistency in the data and the prevalence of complex property ownership structures that neither dataset is designed to address (Skidmore et al. 2021; Rajao et al., 2020; Rausch & Gibbs 2016). That means that not all farms with sales registered in the GTAs can be connected with CAR properties, which may reduce our capacity to map regions impacted by CAs and areas where the agreements' geography or intensity could expand.

Supply zones, continuous areas comprising suppliers to one slaughterhouse, can overcome some of these challenges by providing information about the level of risk surrounding slaughterhouses and may also be a solution for augmenting the information derived from property-level traceability based on the GTA. Many sourcing zone approaches have been developed previously in other studies, with methods to estimate zones from buffers around slaughterhouse coordinates (Alix-Garcia & Gibbs, 2017), maximum purchasing distances from roads and grazing areas (Barreto et al., 2017), and trip lengths (Santos and Costa, 2018). Although innovative, these studies lacked data on direct and indirect suppliers, reducing the precision of the zones they defined. Here we establish slaughterhouse supply zones based on the GTA-CAR characteristics' spatial autocorrelation. Our technique first identifies the spatial autocorrelation of the GTA-CAR suppliers and then creates a uniform shape around them.

We used our supply zones, comprised of direct and indirect suppliers, to evaluate the following research questions: (i) Between 2013 and 2018, how large were the supply zones of direct and indirect suppliers of CA and non-CA slaughterhouses? (ii) What are the characteristics of these zones and suppliers in terms of overlap between them, land use, and deforestation? (iii) How would CA supply zones change if the first layer of indirect suppliers the monitored? How would they change if more slaughterhouses joined the CA? Our findings provide a comprehensive picture of the geography of the cattle supply chain across current and potential CA supply zones for slaughterhouses in the three most important cattle producing states in the Brazilian Amazon.

2. Materials and Methods

2.1. Study area

Our area includes the states of Pará, Mato Grosso, and Rondônia (Figure 1), which encompass nearly one-third of Brazil's total area (239 Mha of 849 Mha) and produce nearly and 80% of the region's slaughtered cattle, respectively (IBGE, 2021). This study area contains portions of three Brazilian biomes: the Amazon, Cerrado, and Pantanal. The Amazon biome covers 82% of the land, followed by the Cerrado with 15% and the Pantanal with 3%. More than half of the Amazon and Pantanal biomes and 17% of the Cerrado biomes are within our study area.

In 2018, the study region's land use was distributed as follows (based on data from Souza Jr. et al., 2020). Natural vegetation occupied 172 Mha (72% of the 239 Mha), while cleared pasture, soybeans, and other land use types (other crops, urban areas, etc.) covered 67 Mha (28%). About half of natural vegetation (55% of 172 Mha) is within protected or military areas. On the other hand, the non-protected natural vegetation, where private deforestation is more common, occupied 77 Mha (45%of 172 Mha). Within cleared areas, pasture was the most predominant land use, accounting for 49 Mha, which represented 73% (of 67 Mha) of total cleared land within the study area and about 26% of all pastures in Brazil in 2018. Soybeans accounted for 10 Mha of the total cleared land (15% of 67 Mha) and other land use classes for 8 Mha (12% of 67 Mha).

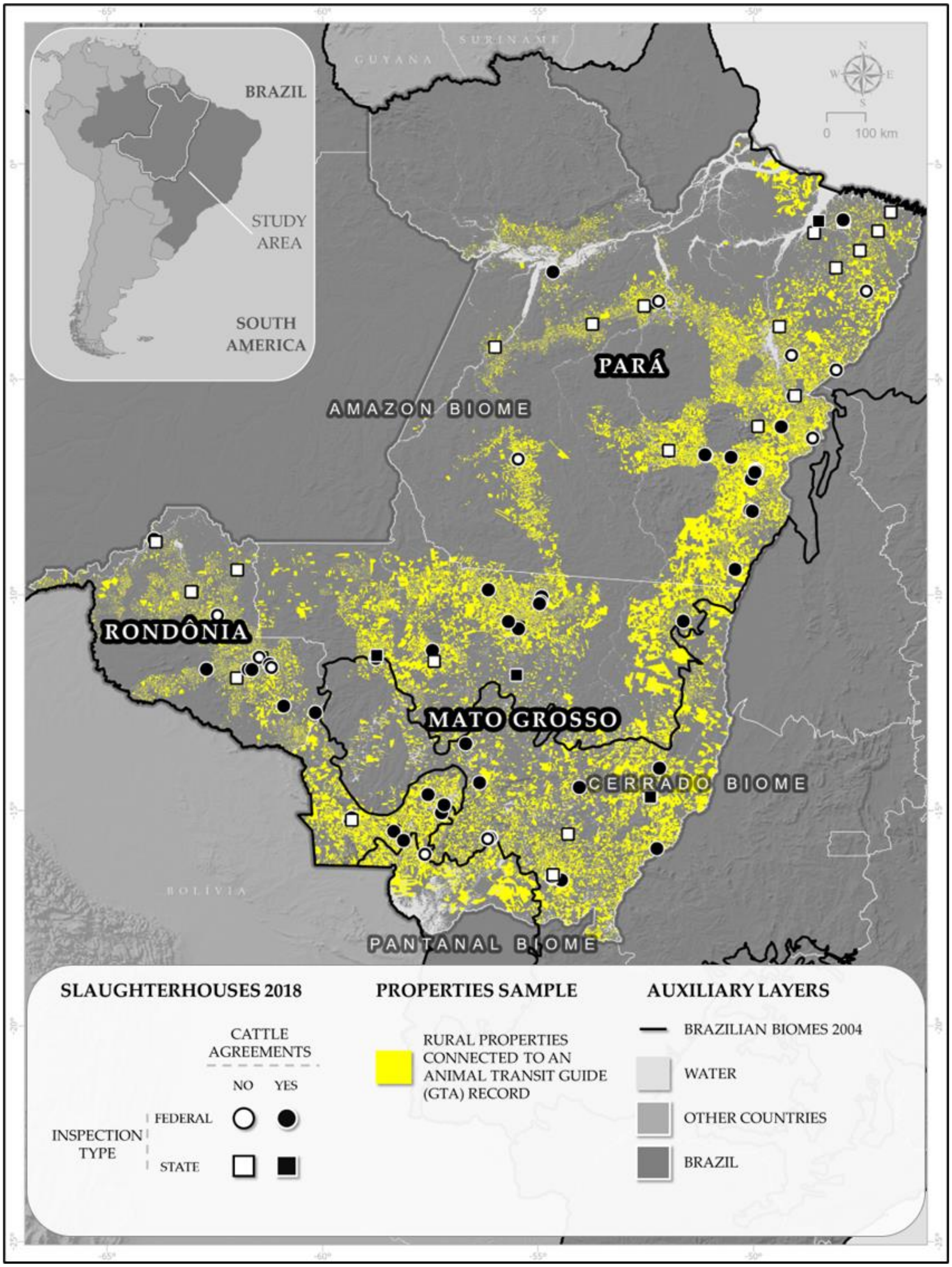

Figure 1. Slaughterhouses and rural properties connected to animal transit guide record in 2018.

2.2 Processing the GTA-CAR data

We downloaded roughly ten million GTA transactions from the websites of the state animal sanitation offices in Pará, Mato Grosso, and Rondônia, as well as the Brazilian Ministry of Agriculture, Livestock, and Food Supply (MAPA in Portuguese). These GTA transactions took place between January 2013 and December 2018. We also downloaded property boundaries from each state's environmental agency and two federal systems (System of Rural Environmental Registry-SICAR and Land Management System-SIGEF, both acronyms in Portuguese).

We identified 439,469 unique properties based on the property and owner attributes in the downloaded GTA transactions, which moved a total of 239 million heads between 2013 to 2018. We linked the GTA and CAR properties by applying the matching methods described in Skidmore et al. 2020, 2021, which involve matches based on common landowner and property information found in both databases (full methods description in Appendix C). We identified 149,491 GTA farms (34% of 439,469) associated with unique CAR properties, referred to here as matched GTA properties (Figure 1).

The matched GTA properties sample covered 40 Mha, representing 26% of the total area covered by property boundaries within Pará, Mato Grosso, and Rondônia, and moved 155 million heads, representing 65% of the total cattle volume (239 million heads) traded within our full set of GTA transactions (matched and unmatched). Almost one-third (45 of 155 million heads) of the cattle that originated in the matched GTA properties were sold for slaughter.

2.3 Mapping the slaughterhouse supply zones

In our analysis, we defined slaughterhouse supply zones as uniform shapes around slaughterhouses' direct or indirect tier-1 suppliers. Our sample contains 142 GTA-listed slaughterhouses that slaughtered more than 1,000 heads per year and had a health inspection code. Around half (54%, or 77) of slaughterhouses were part of Brazil's Federal Inspection System (SIF in Portuguese), which allows export out of state and to other countries. Another 38 slaughterhouses (27%) were licensed under the State Inspection System (SIE in Portuguese), meaning that the meat can only be sold within the state of slaughter. The 27 plants (29%) that did not appear on the SIF or SIE lists are referred to as Other. The slaughter volumes identified from the matched GTA properties are equivalent to more than 90% of the total slaughter heads measured by the Brazilian Institute of Geography and Statistics (IBGE) for the study area and period (IBGE, 2020).

We used ArcGIS Pro to map the slaughterhouse supply zones. For each year between 2013 and 2018, we began by identifying the direct suppliers and the first tier of indirect suppliers (tier-1 indirect suppliers) who sold at least 16 heads of cattle per unique transaction per year, resulting in 97,085 GTA properties for the whole period. We wanted to exclude suppliers selling very small numbers of heads and based the minimum heads sold criterion on the findings of Skidmore et al., 2021, who showed that it takes 16 to 18 animals to fill a single cattle truck. We defined direct suppliers as those properties that sold cattle for slaughter to the 142 slaughterhouses in our sample. Tier-1 indirect suppliers were those who never sold as direct suppliers during our study period but sold to the direct suppliers for non-slaughter purposes within the same year of the direct supplier's transaction.

In the second step, we estimated annual slaughterhouse supply zones based on the spatial autocorrelation among direct and among tier-1 indirect suppliers. Our assumption is that spatially clustered suppliers are the ones that make up the supply zone. Those suppliers that are too distant are of less importance in defining the zone. We begin by calculating the maximum spatial autocorrelation distance between cattle suppliers. We determine the maximum geographical autocorrelation distance by controlling for the number of animals sold by the supplier. The influence of a particular supplier in calculating the maximum distance is proportional to the quantity of animals sold. Then, we aggregate these cattle suppliers according to the distance with the greatest spatial autocorrelation. For the creation of the slaughterhouse supply zones, we used the Incremental Spatial Autocorrelation (ISA) and aggregate polygon functions available in ArcGIS (ESRI, 2020a). More specifics are in Appendix A.

2.4 Defining the CA and non-CA slaughterhouse supply zones

Next, we defined supply zones based on their relevance to the CA. We first identified the slaughterhouses that signed the CA between 2013 and 2018, building upon the lists of CA slaughterhouses compiled by Amaral (2016) and Barreto et al. (2017). We found 81 slaughterhouses that had signed the CA, accounting for 57% (of 142) of all slaughterhouses in our sample. A large percentage of CA slaughterhouses (n = 59; 42% of 142) were SIFs, accounting for 77% of the total SIF facilities in Mato Grosso, Pará, and Rondônia. Seven CA slaughterhouses were SIEs (18% of total SIEs). Based on this information, we defined four groups of suppliers and applied the methods described above to delineate annual supply zones for each group (Table 1).

Table 1. Slaughterhouse supply zone definitions.

Slaughterhouse supply zone types	Suppliers used to define the zone boundary	Suppliers monitored by the CA? (YES/NO)	Zone definition
CA slaughterhouse supply zone of direct suppliers (CA direct supply zone)	CA direct suppliers	Yes	Defined as a generalized polygon surrounding CA direct suppliers
CA slaughterhouse supply zone of tier-1 indirect suppliers (CA tier-1 indirect supply zone)	CA tier-1 indirect supplier	No	Defined as a generalized polygon surrounding CA tier-1 indirect suppliers
Non-CA slaughterhouse supply zone of direct suppliers (non-CA direct supply zone)	Non-CA direct suppliers	No	Defined as a generalized polygon surrounding non-CA direct suppliers
Non-CA slaughterhouse supply zone of tier-1 indirect suppliers (non-CA tier-1 indirect supply zone)	Non-CA tier-1 indirect supplier	No	Defined as a generalized polygon surrounding non-CA tier-1 suppliers

2.5 Estimating the potential expansion of supply zones monitored by the CA

We then investigated three pathways to expand the CA supply zone area: 1) CA slaughterhouses expand monitoring to include tier-1 indirect suppliers, 2) Non-CA slaughterhouses begin monitoring directs suppliers, and 3) Non-CA slaughterhouses begin monitoring directs and also include tier-1 indirects. We first aggregated all CA direct supply zones onto a single map.

Then, to consider the expansion from monitoring indirect suppliers (pathway 1), we added the CA tier-1 indirect supply zone to the CA direct supply zones. For pathway 2, we added the zone maps from the non-CA direct suppliers. And for pathway 3, we added the non-CA tier-1 indirect suppliers to the non-CA direct suppliers and CA direct and indirect supplier maps.

2.6 Characterizing the slaughterhouses' supply zones

We quantified a series of characteristics of each slaughterhouse supply zone to provide a comprehensive understanding of the geographic features, land use, deforestation, and related carbon emissions, as well as median values of what a typical CA direct supply zone. Appendix B has further information on how we compute these characteristics.

3. Results

3.1 CA and non-CA slaughterhouse supply zones occupied virtually the same extent

Slaughterhouses, especially CA slaughterhouses, influenced a remarkable amount of land across Mato Grosso, Pará, and Rondônia. In 2018, slaughterhouses influenced an area spanning 170 Mha, including both direct and tier-1 indirect supply zones to CA and non-CA slaughterhouses, accounting for 71% of total area of these states (Figure 2 and Figure 3). The CA direct supply zone along covered 94% of this area (160 Mha of 170 Mha). The supply zones identified based on properties not monitored by CAs (CA tier-1 indirect and non-CA direct and tier-1 indirect zones) encompassed 96% of the 170 Mha total area, or 163 Mha. About 95% of the direct supply zones of the CAs coincided with these zones that were not monitored by the CAs.

The reach of the slaughterhouse supply zones varied by state (Figure 3). Approximately 93% of Mato Grosso was covered by slaughterhouse supply zones, with 90% in CA direct supply zones. Most of this state (86%) was situated in areas where CA direct supply zones overlapped with zones not monitored by CAs. In Rondônia, slaughterhouse supply zones encompassed 80% of the state's area, with 79% in regions covered by CA direct supply zones and 76% in areas of overlap between CA direct supply zones and other zones. In the case of the more forested state of Pará, slightly over half (53%) of the state fell within slaughterhouses supply zones, with 48% in CA direct supply zones, and 46% in overlapping regions.

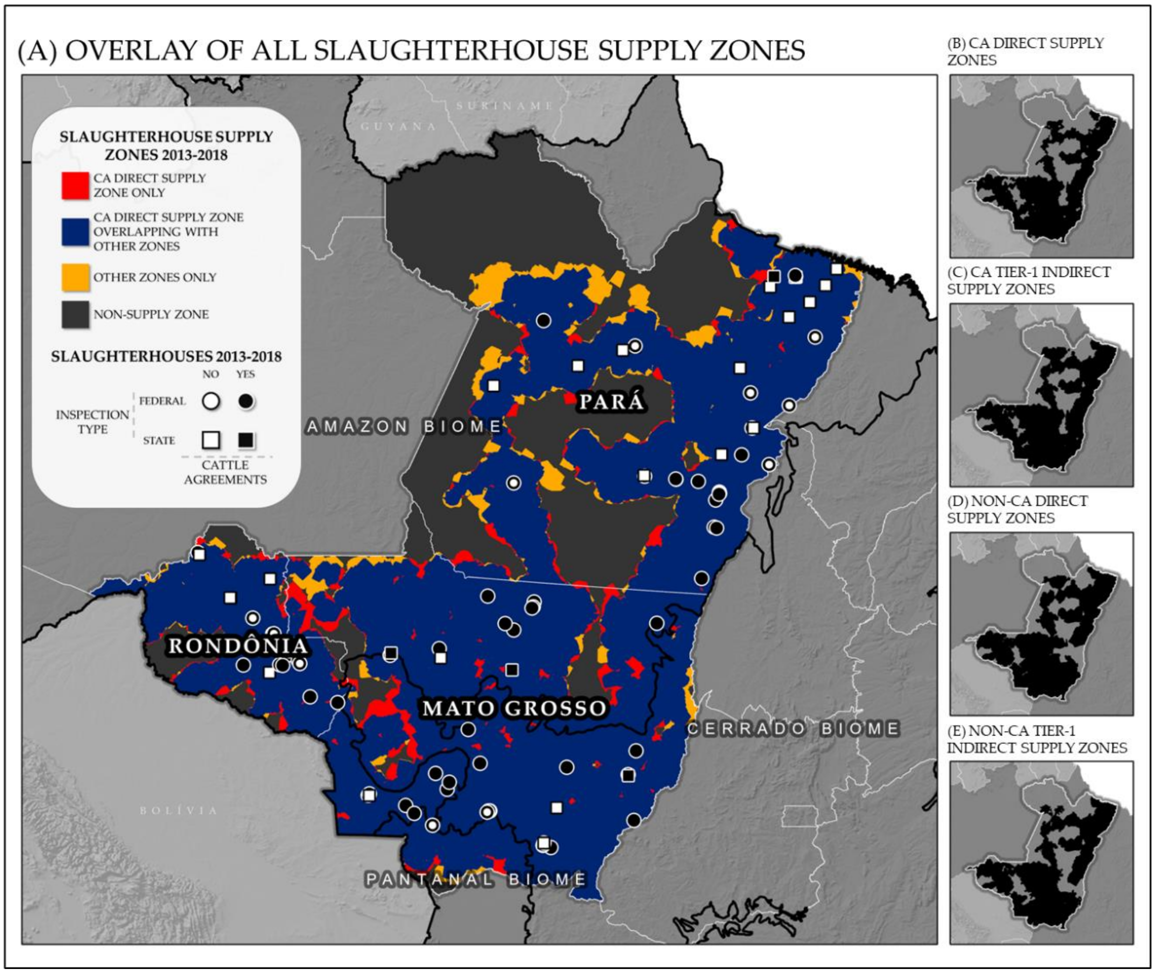

Figure 2. Spatial overlap of all slaughterhouse supply zones (A) and their individual spatial configuration (B-E).

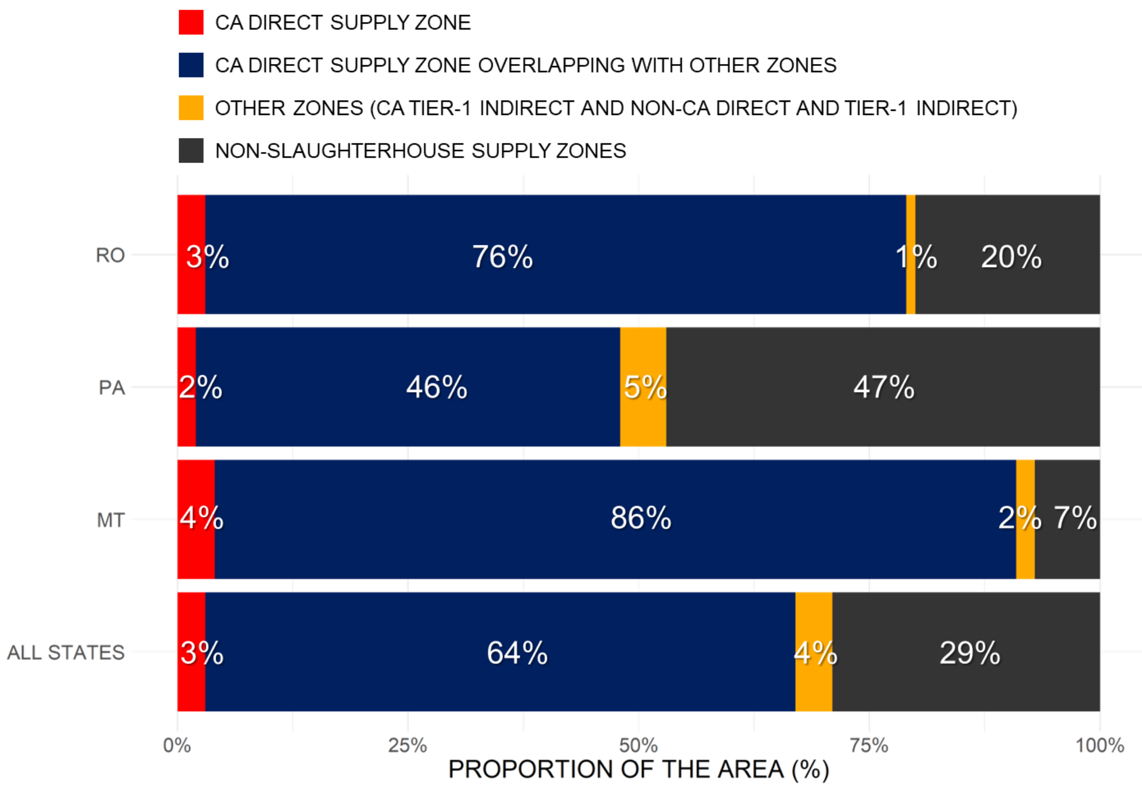

Figure 3. Proportion of slaughterhouse supply zones considering different types of overlaps between CA direct supply zones and other zones.

3.2 CA slaughterhouses' direct supply zone characteristics

3.2.1 CA slaughterhouses' direct supply zones were stable over time

The coverage of CA direct supply zone was relatively stable between 2013 and 2018. We observed that 96% of the total extent was in locations that had been the same for two or more consecutive years and 71% of the area persisted for all years. Approximately 25% of the CA direct supply zone persisted between two to five years, and 4% appeared only in one year. In Mato Grosso, 82% of the CA direct supply zone persisted all six years, 16% between two to five years, and only 2% were included in only one year. In Pará, these levels were 63%, 29%, and 8%, respectively. Rondônia was the state with the lowest persistence over time, with half of that state's CA direct supply zone persisting between two and five years, 46% in all six years, and 3% included in just one year.

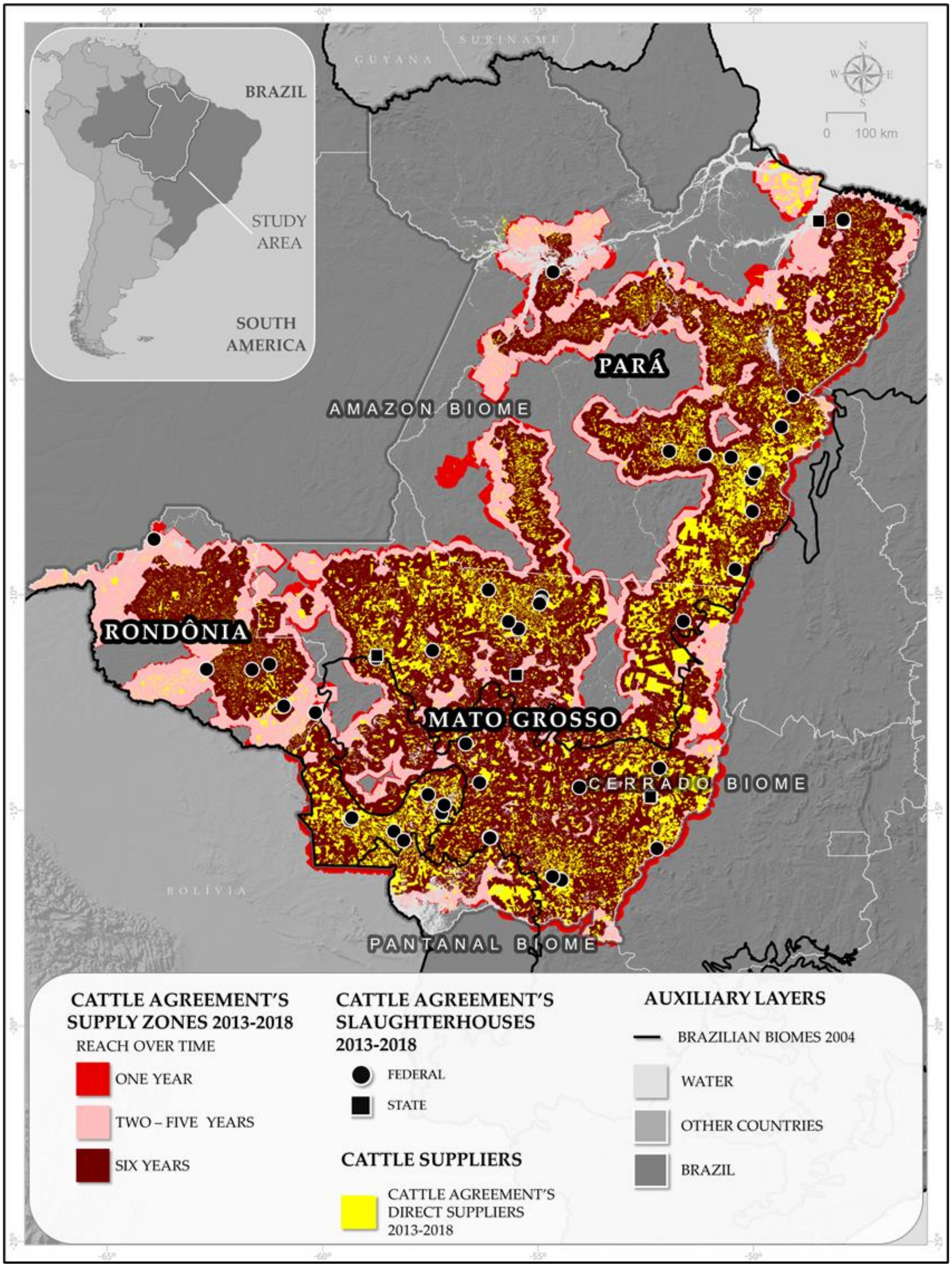

Figure 4. Stability of CA direct supply zone over time from 2013 to 2018.

3.2.2 Most of pasture, natural vegetation, and deforestation is within CA slaughterhouses' direct supply zones

We observed that practically all the pasture in our study region (99% of 49 Mha) was within CA direct supply zones, though almost all this area also overlapped with other zone types. Supply zones from non-monitored suppliers (non-CA direct and tier-1 indirect suppliers, as well as CA tier-1 indirect suppliers) that did not intersect with CA direct supply zone accounted for less than 1% of the pasture. The concentration of pasture in CA direct supply zones was almost 100% in Mato Grosso, 99% in Rondônia, and 96% in Pará.

In addition, 86% of natural vegetation situated outside of protected areas (Conservation Units, Indigenous Lands, and Military Areas) in 2018 fell within CA direct supply zones. In Mato Grosso, Rondônia, and Pará, respectively, this proportion was 98%, 90% and 71%. Even though the CA direct supply zones covered most of the unprotected vegetation, we observed that 84% of this vegetation was also included inside other types of zones (CA tier-1 indirect, non-CA direct, or indirect). In Mato Grosso, Rondônia, and Pará, this percentage was 94%, 88%, and 70%, respectively.

The CA direct supply zone likewise covered nearly all of the deforested area across the three states. We observed that approximately 99% (61 Mha) of the cumulative deforestation by 2007 and 97% (7 Mha) of the yearly deforestation between 2008 and 2018 was within the CA supply zones.

3.3.3 Individual CA slaughterhouse direct supply zones cover areas comparable to large Amazonian municipalities

A typical CA direct supply zone covers an area equivalent to that of a large cities in the Brazilian Amazon. We found that each CA direct supply zone covers an area of roughly 12 Mha (mean: 16 Mha) (Figure S1 in the SM). This size is comparable to Altamira or São Félix do Xingu, which occupy 16 Mha and 8 Mha of area, respectively, which are both in Pará and are the largest municipalities within the Brazilian Amazon. The CA direct supply zone area also varied by state: the median size of zones in Mato Grosso reached nine Mha, followed by seven Mha in Pará, and two Mha in Rondônia. In additional, CA zones size also vary according to the level of health inspection. State slaughterhouse zones (SIE) were often bigger, spanning 24 Mha (mean 18 Mha). Federal slaughterhouses have zones of 14 MH (mean 17 Mha), whereas Other slaughterhouses have zones of 4 Mha (mean 10 Mha). There was no significant difference ($p<0.05$) between the CA supply zone sizes of direct or tier-1 suppliers and between non-CA suppliers for most health inspection types. We found significant difference only when comparing the CA zones of direct and tier-1 indirects of federal and state non-CA slaughterhouses.

Natural vegetation covers nearly half of a typical CA direct supply zone based on data from Mapbiomas. Natural vegetation (close and open canopy vegetation) represents 55%, pasture accounts for 38%, soybeans for 3%, and other land uses for 4% (Figure S2 in SM). Typically, 32% of a typical CA direct supply zone area was unprotected natural vegetation located in private lands. These proportions vary somewhat depending on the type of zone. For example, state CA slaughterhouses had three times more soybean area (9%) than a typical zone. Other CA slaughterhouse zones, on the other hand, had slightly more pasture area (42%). The zones of federal CA slaughterhouses (SIF) did not vary much from a typical CA zone.

The median CA direct supply zone has deforested 48% of its zone area by 2018. Deforestation in 2007 accounted for majority of the overall deforestation (43%) in each CA direct supply zone. Deforestation from 2008 to 2018 covered almost 5% of the zone's area (median). The median annual deforestation within a typical CA direct supply zone in this period was 0.04 Mha which emitted 12.45 MtCO2 each year (Figure S3 in SM).

3.3.4 CA direct suppliers represented less than one-fifth of our CA direct supply zones

The 39,439 CA direct suppliers used to define the slaughterhouses' supply zones for CA direct suppliers covered 17% (28 MHa of 160 MHa) of the total zone’s area and 70% of the total GTA properties area. The remaining 83% (132 MHa of 160 MHa) was composed of 120 MHa (75% of 160 MHa) area not within our GTA properties sample, and 12 MHa of other GTA properties (8% of 160 MHa).

CA direct suppliers have multiple roles in the supply chain. We found that 12% of total cattle moved by CA direct suppliers are slaughtered in CA slaughterhouses, 7% are slaughtered in non-CA slaughterhouses, and 78% are sent to other properties for purposes other than slaughter (Figure S2 in SM). Based on medians, we discovered that direct suppliers from SIF slaughterhouses delivered around 11% to 17% of cattle for slaughter to a CA slaughterhouse, vs 4% to 11% to a non-CA slaughterhouse. CA direct suppliers from state slaughterhouses and others in Mato Grosso sent the bulk of their cattle (more than 90%) for non-slaughter transactions.

Most deforestation within CA direct supply zones was outside the CA direct suppliers. In 2007, two-thirds (66% of 61 MHa) of the deforestation occurred outside of our GTA-CAR sample, 24% (15 MHa) on CA direct suppliers, and 10% (6 MHa) on other GTA properties. Similarly, the non-GTA areas accounted for the majority of the deforestation from 2008 to 2018 (78% or 5 MHa of 7 MHa), with CA direct suppliers accounting for 11% (1 MHa) and other GTA properties contributing to just over 1 MHa (11% of 8 MHa), with CA indirect suppliers comprising for 1 MHa (9%).

3.4 Expanding the agreements to more slaughterhouses or more suppliers could increase their intensity.

Clustering of slaughterhouses and direct and indirect suppliers means that expanding the CA to non-CA slaughterhouses or to tier-1 indirect suppliers will not significantly increase CA direct supply zone area. As we reported earlier 96% of the accumulated area of CA direct supply zones overlapped with the non-CA supply zones. If all non-CA slaughterhouses had signed the agreements, the increase in area covered by the CA supply zones would have been only 3 Mha or 4%. The level of increase would have been greatest in Pará, at 14%, followed by Rondônia at 7%. In highly consolidated Mato Grosso, the area covered by supply zones if all slaughterhouses signed the CA would have increased by only 1%. If only the zones of CA tier-1 indirect suppliers would have been added to the CA direct supply zones the increase of CA slaughterhouses' reach would have been 5%. In Mato Grosso and Rondônia, this increase would have been 2% and less than 1%, respectively. In Pará, this increase would have been a little higher, at 11%.

The area covered by expansion could be increased by larger amounts if we consider the more precise coverage of the individual properties with registered transactions in the GTA within the more generalized zones. Expanding the CAs to include all non-CA slaughterhouses and their direct suppliers would result in an increase of 7% of the current CA direct supplier’s area. Expanding the agreements to cover tier-1 CA indirect suppliers would increase the area of monitored properties (estimated from GTA data) by 34%. If all slaughterhouses had monitored their direct and tier-1 indirect suppliers, the increase would have been 42%.

Although CA direct supply zones occupied most of the maximum potential reach of all slaughterhouses (94% of 170 Mha), the intensity of the exposure varied across the study area (Figure 5-A). Regions with more exposure to CA slaughterhouses, that is, where several CA direct supply zones overlap spatially, were in three main portions of the states of Pará, Mato Grosso, and Rondônia: (i) in central-west Pará; (ii) in northwestern Mato Grosso; and (iii) in southwestern Mato Grosso. In these areas, at least ten CA direct supply zones overlap spatially. On the other hand, the portions with lower exposure intensity, where three or fewer CA direct zones overlap, were in northwestern Pará. Just under half (48%) of the area occupied by CA direct supply zones had exposure intensity levels ranging from six to nine. In other words, they are accessible to at least six and at most nine CA slaughterhouses simultaneously. In addition they have an average area of 21 Mha. Approximately one-third of CA direct supply zones had intensity levels ranging from one to five. The average area of these regions was 10 Mha. The areas with the highest level of exposure intensity (greater than ten) represented 23% (37 Mha) of the total area of CA direct supply zones.

The intensity of CA exposure would have increased by expanding the CA expanding to more suppliers or more slaughterhouses (accessible to more than nine CA slaughterhouses). For example, if zones of tier-1 CA indirect suppliers have been added to the CA direct supply zones, the areas with high intensity would have been 40% higher (Figure 5-B). If this expansion had occurred for all non-CA slaughterhouse direct suppliers, the increase would have been 32% (Figure 5-C). And if the indirect tier-1 non-CA zones had also been added the high intensity areas would have been 53% (Figure 5-D).

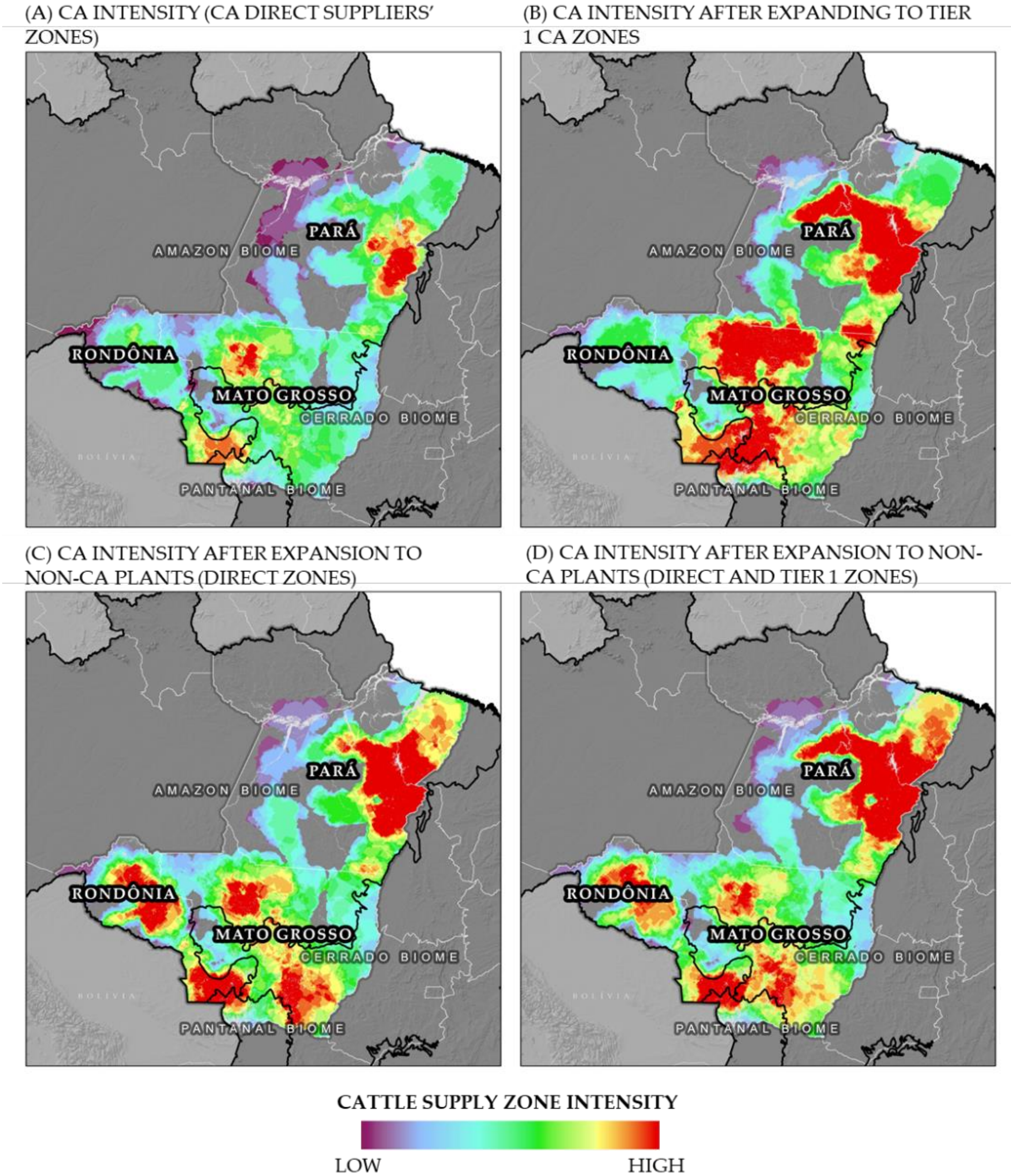

Figure 5. Exposure intensity to CA supply zones during the period 2013 to 2018 in the States of Pará, Mato Grosso, and Rondônia. The higher the intensity the more CA supply zones from different CA slaughterhouses overlap in the same area.

4. Discussion

4.1 Supply zones are more narrow than previously estimated.

Our supply zones, based on registered cattle transactions, produced more precise and smaller zones than previous work. We found that the buffers approach, which is the most widely used approach (Levy, 2022; Skidmore 2020; Alix-Garcia and Gibbs, 2017), generally tended to produce larger slaughterhouse zones than our method—by 34% in total area of all zones combined and 33% per zone (median). The cost-distance approach from Barreto et al. (2017) also overestimated zone boundaries compared to our results, by including regions covered by rivers and without cattle suppliers, and 12% regarding the median area of each zone. Policies and studies using more generalized approaches should keep in mind that they may be overestimating the area involved. Our approach represents a methodological advance in the use of GTA traceability data for estimating cattle supply chains and associated deforestation risk. The method we developed can be expanded to other states in the country where cattle transaction and property boundary data are available.

4.2 CA slaughterhouses' direct supply zones are long-term stable regions that concentrate much of the unprotected vegetation.

Our results suggest that the CA slaughterhouses are important agents in land use in Pará, Mato Grosso, and Rondônia. The CA direct supply zones are time-stable and individually comparable to large Amazonian municipalities; thus, companies and managers of each slaughterhouse have a significant reach to influence land use decisions. Additionally, virtually all vegetation found outside Indigenous Lands, Conservation Units, and Military Areas is within the CA direct supply zones. Recognizing that decision-making about deforestation ultimately rests with landowners such as cattle ranchers, and slaughterhouses can influence tdecision-makingking with their sourcing criteria, such as those defined in the CA. We posit that slaughterhouses can impact vegetation regions beyond their suppliers (Borgatti and Li, 2009), but within their supply zones. Also, we argue that locations with a high intensity of CA slaughterhouses — those accessible to many slaughterhouses at the same time may— be more influenced to comply with CA requirements which could help to reduce deforestation.

In addition, our results highlight those areas of natural vegetation outside the reach of slaughterhouses may be designated for other reasons, such as the creation of new protected areas or limited use areas, without affecting cattle production in the studied states. Several studies have shown that Protected Areas have been one of the most effective ways to contain deforestation in the Amazon (Soares-Filho and Rajão, 2018; Soares-Filho et al., 2010). Furthermore, cattle production can expand without the need for new deforestation, if new investments in intensified cattle ranching are expanded in the Amazon (Brandao Jr. et al., 2020).

4.3 Although the CA direct supply zones cover the majority of the states studied, the high overlap (> 90%) with other supply zones may stimulate competition and laundering.

Our findings show a high degree of overlap (>90%) between CA direct supply zones and other zone types (CA tier-1 indirect suppliers and non-CA direct and tier-1 indirect suppliers). Although this result is generally consistent with other studies that found a large overlap between zones of slaughterhouses that signed the agreements and zones of slaughterhouses that did not sign (Moffette, 2018; Barreto et al., 2017; Alix-Garcia and Gibbs 2017), our study also found different types of overlap between direct and indirect supplier zones of slaughterhouses that signed and did not sign the agreements. These findings provide a fresh knowledge of the possible risk of competition and cattle laundering operations, which limit the efficiency of the agreements in reducing deforestation.

Competition with other non-CA slaughterhouses and cattle laundering are activities that may occur in isolation or in tandem. Competition arises when CA slaughterhouses often cannot locate enough cattle from complying suppliers within their supply zones to satisfy their demand because suppliers are selling cattle to non-CA slaughterhouses, potentially resulting in a cow shortfall (Moffette, 2018). Cattle laundering may occur when non-compliance tier-1 indirect suppliers can sell to compliant CA direct suppliers without triggering the CA slaughterhouse's monitoring systems (Carvalho et al., 2021; Gibbs et al., 2016).

Expanding the CA to include additional non-CA slaughterhouses would assist to mitigate these risks by lowering the economic burden incurred by CA slaughterhouses due to higher buying regulations, as well as limiting the potential for competition and laundering (Pereira et al., 2020; Raoni et al., 2020; Barreto et al., 2017; Gibbs et al., 2016). Without an expansion of CA to more slaughterhouses and more suppliers, we believe there is an imminent risk that cattle suppliers will once again deforest to produce cattle. With increased competition and cattle laundering it is likely that CA slaughterhouses will be forced to buy cattle coming from deforested farms, which could further decrease the effectiveness of CA in forest conservation.

Some recent alternatives have been discussed to expand CA monitoring to more suppliers and more slaughterhouses. Recently, the MPF has strengthened its partnership with non-governmental agencies and universities to harmonize the methods of analysis and audit of CA slaughterhouses (Mengardo, 2018). In addition, new tools have been launched to help slaughterhouses to understand the deforestation contamination level of their supply chain. Among these tools, we highlight a few: Selo Verde, Visipec, Beef on Track and Trase. The Selo Verde, launched in the state of Pará, is the first public tool in Brazil that has as its main objective to provide information on compliance with the Forest Code and estimates of contamination of the cattle supply chain (Agencia Para, 2022). Visipec, was developed in partnership with civil society and the University of Wisconsin-Madison to help the cattle industry to estimate the contamination with deforestation of indirect suppliers (VISIPEC, 2021). It also includes ways to include indirect suppliers in the monitoring based on Best Practices criteria, validated by industry representatives and indirect suppliers (GTFI, 2021). And finally, Beef on Track and Trase has been helping to increase transparency with information about the cattle sector at Brazilian Amazon and Global scales, respectively. As these tools are still in their early years of implementation in the Brazilian cattle sector, it is still too early to estimate their effectiveness in curbing deforestation and CA expansion. However, strategies such as these may accelerate the expansion of CAs through social or market pressure potentially created by the information generated from these instruments.

5. Conclusions

Using property boundaries and cattle traceability data from 2013 to 2018, we mapped and characterized the slaughterhouse supply zones of direct and indirect suppliers in the Brazilian states of Pará, Mato Grosso, and Rondônia for the purpose of assessing the potential of this expansion to increase the area under CA influence. Our findings reveal that the present CA supply zones include an area of 160 million hectares (Mha), which is more than two-thirds (67%) of the entire area of the three investigated states and most pasture and deforested lands. As more than 90% of the present CA supply zone overlaps with possible expansion regions, increasing the agreements to include additional slaughterhouses or to monitor tier-one indirect suppliers may raise the CA intensity but will not expand its geographical reach. With our results, we have a clear picture of the locations possibly within the reach of CA slaughterhouses and those not protected by this deforestation-prevention legislation.

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Appendix A

Incremental Spatial Autocorrelation (ISA) Steps

"Everything is related to everything else, but near things are more related than distant things." (Tobler, 1970). With this assumption in mind, we calculated the distances between cattle suppliers that had the highest spatial autocorrelation. We utilized the ISA module in ArcGIS Pro v2.8 to do this. We used Python to create a script that first determined the distance with the highest spatial correlation. The Aggregate Polygons method is then used to construct uniform polygons from this distance (ESRI, 2020b). Several uniform polygons were created for the same suppliers from the same slaughterhouse in numerous situations. This is because suppliers are often scattered throughout many areas and grouped together based on the ideal distance computed by ISA. As a result, we chose the polygons that included more than 80% of the providers.

Appendix B

Supply Zones Characteristics.

Below a series of characteristics that we calculated for each supply zone from this study. The data used here is organized on Table B1. First, we classified the zones based on the health inspection classification (SIF, SIE, Others), agreements (CA or non-CA), and supplier type (direct or tier-1 indirect). Second, we calculated geographical characteristics such as the area in hectares and the overlap with other zones. We computed a set of summary statistics based on the zone's areas (average, median, and range) and how they vary at the state level. In addition, we calculated the cumulative area of each zone by year and the overlap of these cumulative areas over the years 2013 to 2018. A further analysis was the overlap of the cumulative areas of CA and non-CA zones for the entire period (2013-2018). Finally, we calculated the intensity of the overlap for CA zones. In other words, the cumulative number of CA zones per slaughterhouse for the period 2013-2018 overlapped with each other. This last metric (overlap intensity) served to map whether there are zones that are exposed to CAs.

Third, we assessed the land use based on Mapbiomas collection 6 data (Souza Jr et al. 2020). First, we reclassified the original 30+ land-use classes from Mapbiomas for the year 2018 into four main classes: (i) pasture, (ii) natural vegetation (forest or non-forest vegetation); (iii) soybean, (iv) and other. The output here was the total zone percentage and total area in Mha covered by each of the land-use for 2018.

The following characteristics were deforestation and associated carbon emissions. We first calculated deforestation using PRODES data for the Amazon and Cerrado biomes (INPE, 2020). The PRODES measures the clear-cut of forest areas. We excluded deforestation below

6.25 hectares from the PRODES Amazon and one hectare from the PRODES Cerrado since these figures are the minimum mapping unit according to their methodologies (INPE 2020). Zones within the Pantal biome were excluded from our assessment since the PRODES Pantanal is still preliminary (INPE, 2021). The PRODES data were grouped into one category for deforestation through 2007 and a second category for annual deforestation between 2008 and 2018. To quantify carbon emissions from deforestation, we overlaid deforestation data on the above and below ground biomass carbon per hectare map from Soto-Navarro et al. (2020) to calculate the total carbon dioxide equivalent (CO2) emission in mega (10^6) metric tons (MtCO2e) using the committed flow method outlined in Brandao Jr et al. (2020).

Table B1. Datasets used to assess the supply zones' characteristics.

Data	Source	Period	Link to access the data
Deforestation	PRODES Amazon PRODES Cerrado	Accumulated deforestation 2007 and annual deforestation 2008-2018	http://terrabrasilis.dpi.inpe.br/en/download-2/
Land-use	Mapbiomas collection 6.0	2013 and 2018	https://mapbiomas.org/en/download
Carbon stock	Soto-Navarro et al. (2020)	2010	https://developers.google.com/earth-engine/datasets/catalog/WCMC_biomass_carbon_density_v1_0

Appendix C

Mapping cattle supply chains by linking GTA and property records

This text was adapted from the matching description written by Lisa Rasch, Jake Munger, and Matt Christie

Our research team established coding rules based on years of testing and the professional knowledge of team members and other specialists to match GTA and CAR data. These rules match fields from each record. When any of the criteria are satisfied, two records match (see Table C1 for details). Each matched pair of documents is granted a unique ID ("property ID") that shows they belong to the same property.

Thus, our technique is distinct from string or entity matching systems that allow mismatches (i.e., fuzzy matching). Instead, our rule-based method establishes matching requirements that have been established and validated over time to optimize recall (the number of matches made) and decrease false matches in the data. Our method matches property borders in 80% of Pará transactions, 73% in Mato Grosso, and 34% in Rondônia. Based on manual assessment of random pairings, accuracy estimates are >90%.

For each property group that contains a CAR record ("matched properties"), we may correlate spatial and land-use features, such as yearly deforestation areas from PRODES (Brazil's official deforestation mapping product), that can be obtained from maps. For data that mention a slaughterhouse, we also include CA tables (Gibbs et al. 2016) painstakingly prepared by archival research and collaboration with Brazilian authorities. Once matching is complete, the data are grouped into tables in PostgresSQL (v.9.5). We design tables to facilitate various sorts of analysis while keeping enough information to connect each item to the source data.

For this investigation, we utilized SQL scripts to query the database for PA-related transactions. For transactions whose destination was another property, we looked for transactions from those properties that happened after the PA-origin transaction. In both situations, whether PA livestock moved via another farm or not, we identified slaughterhouses that received them. We retrieved PRODES yearly deforestation statistics for each property, as well as pasture cover from MapBiomas collection 4.0 (https://mapbiomas.org/). The results of our queries were a transaction-level dataset that included the GTA dates, information about the properties involved in the transaction, including annual deforestation areas and overlap with Protected Areas, and the slaughterhouse name and CA status for slaughtering transactions from direct suppliers.

Table C1. Rules for matching records in GTA and property databases.

Rule Description	Notes
Match on property name, municipality, and CPF.	CPF is the Brazilian Social Security Number.
Match on property name, municipality, and CNPJ.	CNPJ is the Brazilian Federal Tax Identification Number.
Match on property identifier, municipality, and similar property name.	Examples of property identifiers: *Código do estabelecimento* (GTA), SICAR number, state CAR number, *Código do imóvel* (INCRA), etc.
Match on municipality and property boundary.	
Match on property name, municipality, and owner name.	Applied when the CNPJ number is missing.

Rule Description	Notes
Match on property name, municipality, and owner name under different circumstances.	Applied when the CNPJ number is available.
Match on municipality, person/company, and "property name containment."	"Property name containment": when one name contains the other as a substring. Example: BOA VISTA contains the name VISTA
Match on property name, person/company, and neighboring municipality.	
Match on person/company, municipality, and property name with numerals removed.	
Match on person/company, neighboring property boundary, and property name with numerals removed.	
Match on property name and coordinates falling within the property boundary.	
Match on property name, municipality, and coordinates.	
From the property maps, match on the best GTA property with a similar owner name using a random forest classifier.	In addition to the CAR, the matching also included the INCRA and *Terra Legal* databases. Together, we refer to sources that provide property boundaries as *property maps*.

Rule Description	Notes
From the GTA, match on the best property with pasture with similar owner name using a random-forest classifier.	The random forest is trained on familiar attributes like municipality, property name, etc.
From the MT-GTA, match on the best MT-CAR property with a similar owner name using a random-forest classifier.	Mato Grosso state (MT).
From the GTA, match RO properties to the CAR on municipality, owner, and similar address information.	Rondônia state (RO). Address information extracted: "LINHA," "GLEBA," "LOTE," "BR," and "KM."
Match on CAR number if the geometries are within 1km of each other.	
For CAR records without a geometry, match on CAR number and most similar property name to records with a geometry.	
For GTA records that list a CAR number in their notes, match on CAR number and most similar property name.	
For CAR records that only provide a geometry, match to JBS traceability data on intersecting coordinates.	More information available at: https://jbs.com.br/en/press/releases-en/blockchain-platform-developed-by-jbs-begins-operation/

Supplementary Materials – SM

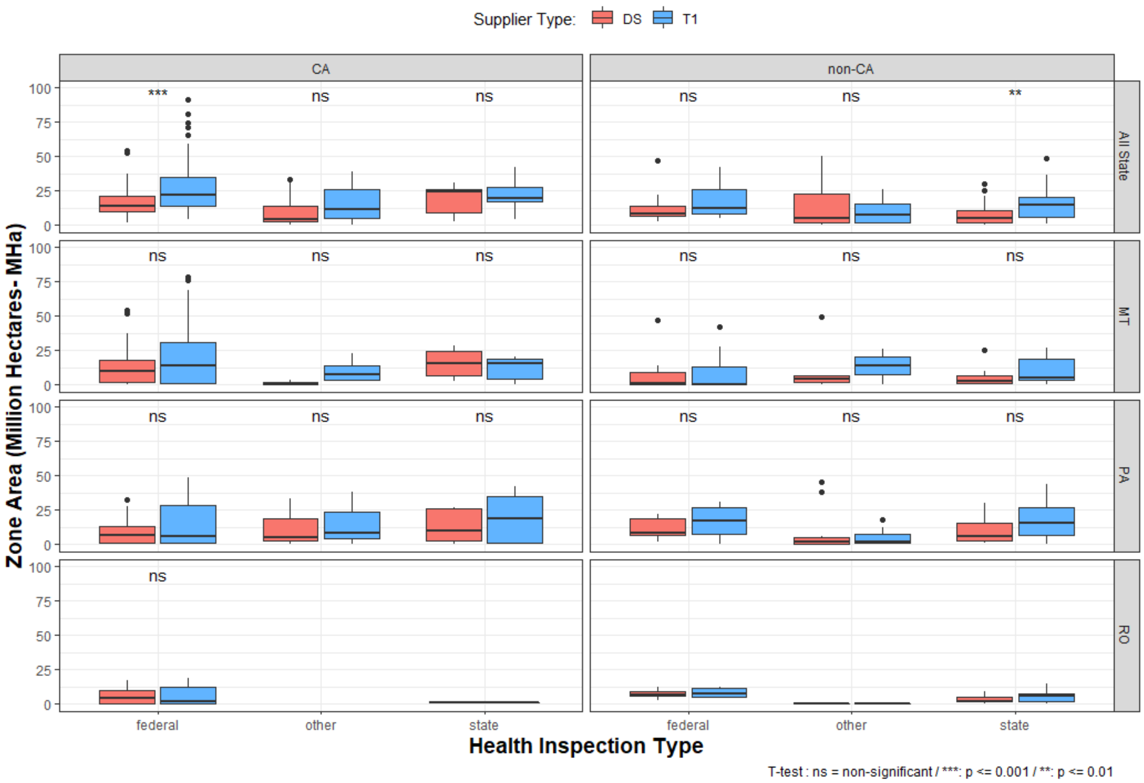

Figure S1. Box-plot showing the supply zone areas per health inspection type, per CA, per state for direct (red) and tier-1 indirect (blue) suppliers.

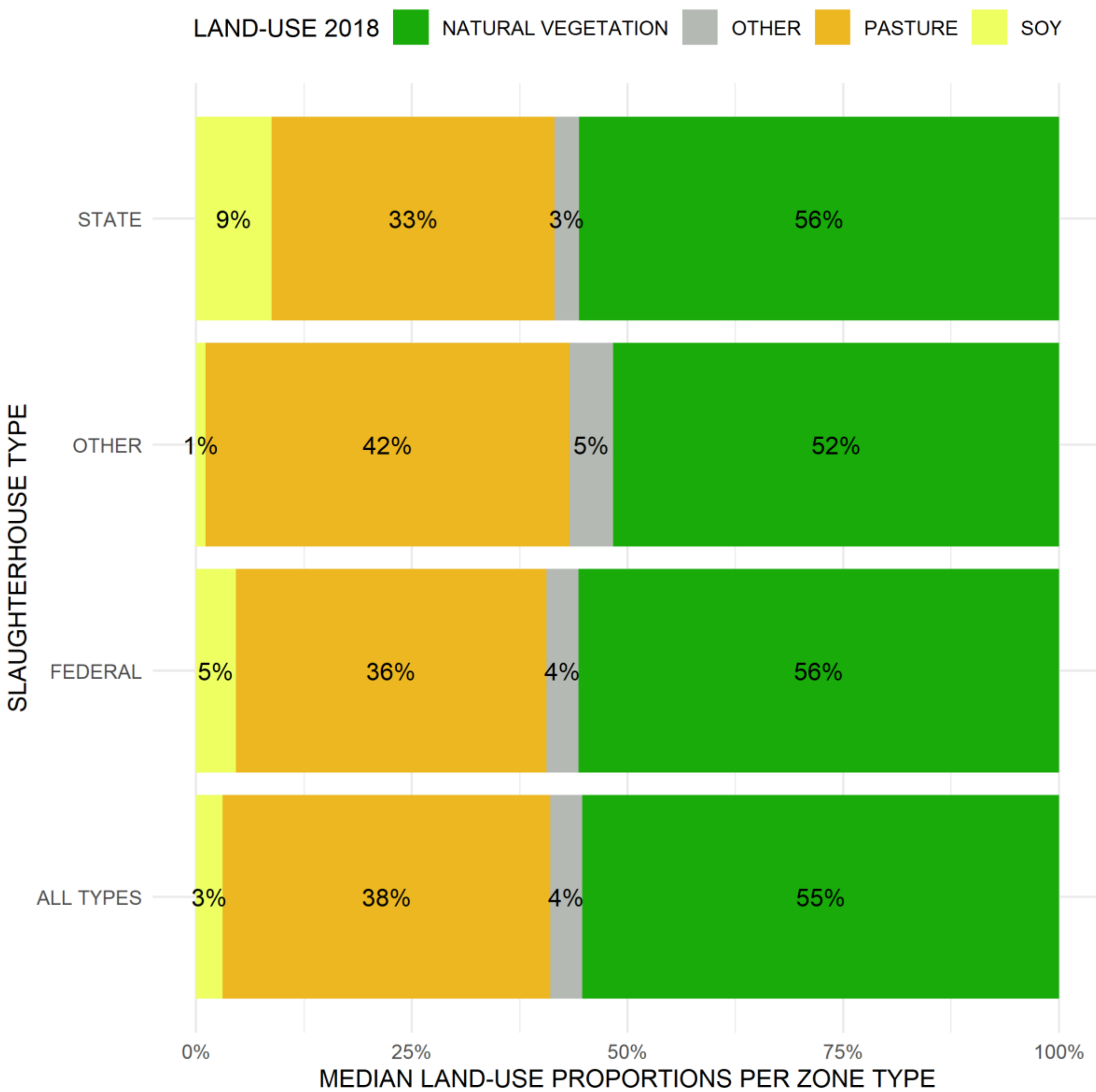

Figure S2. Median percent land-use 2018 proportion within the CA supply zones.

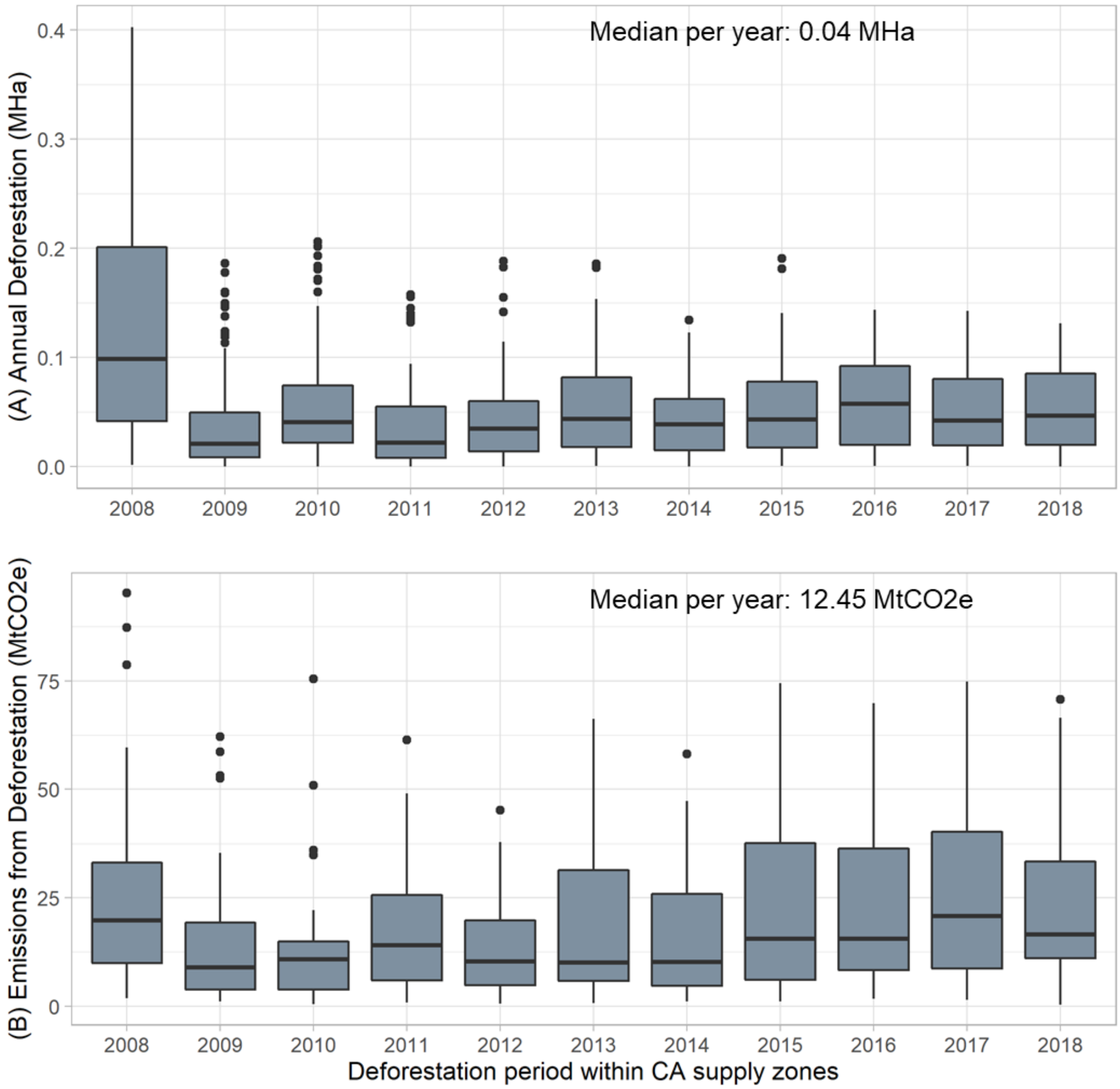

Figure S3. Box-plot showing the annual deforestation (A) and associated carbon emissions (B) within the CA supply zones.

Chapter 3: Exploring the spatial relationship between the cattle's travel distance through roads and deforestation in the Brazilian Amazon

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Abstract

Trucks are the primary means of transportation for the cattle industry in the Brazilian Amazon. As a result, roads impact economic output and cattle producers' choices in transporting cattle to slaughterhouses. However, there is little or no information about travel distances through roads within the cattle supply chain, which could help understand how producers make choices leading up to and after deforestation. Here we estimate the shortest connections using the roads that connect all parts of the cattle supply chain and explored the relationship between the distance traveled by cattle from these roads and deforestation. To do so, we combined road maps with cattle traceability information and deforestation maps, available for the states of Pará, Mato Grosso, and Rondônia, and cover the period from 2013 to 2018. Our estimates indicate that cattle traveled 77 to 144 km (median values) from direct suppliers to slaughterhouses in the years between 2013 to 2018. In addition, direct suppliers do not typically (76% of the slaughtered heads) sell to the nearest slaughterhouse. And cattle from suppliers with deforestation travel more than from suppliers without deforestation, and cattle traveled further after deforestation occurrences. Our method has the potential to be replicated in more Brazilian states if the required data is available

Keywords: Roads, Deforestation, Brazilian Amazon, Cattle, Cattle Agreements, Accessibility

1 Introduction

Roads are important drivers of development and environmental impacts in tropical forest regions. On the one hand, roads also increase the economic growth and social well-being of isolated populations by providing access to health and education services that are generally available in large commercial centers and by reducing transportation costs between producers and centers of processing and consumption of agricultural products (Schielein et al., 2021; Weiss et al., 2018; Perz et al., 2007). However, without sufficient environmental enforcement, roads also promote deforestation, forest fragmentation, and fires, reductions in tropical biodiversity, increased greenhouse gas emissions, and overall alter tropical ecosystems (Laurance et al., 2009; Trombulak and Frissell, 2000; Forman, 1998). These effects have historically occurred across the tropics, including in the Brazilian Amazon (Schielein et al. 2021; Fontanilla-Diaz, et al., 2020; Pfaff et al. 2018; Barber et al. 2014; Freitas, et al., 2010; Brandão Jr. and Souza Jr. 2006).

A great expansion of roads in the Brazilian Amazon occurred between the 1960s and 1970s. At that time a series of government programs fostered the integration of the region's natural resources with Brazil's large centers, which resulted in the main road axes in the Amazon (Transamazonica, Cuiabá-Santarém, Cuiabá-Porto Velho, and Belém-Brasília) (Fearnside, 2015). Other government programs also encouraged the occupation of the region through the creation of rural settlements with road crossings along the major highways, as well as tax incentives to attract agricultural and mineral production to the region. Major road construction and improvement continue in the Amazon today, notably the paving of BR-163, known as the "soy highway," between Cuiabá and Santarém, paving of a state highway that bisects the Xingu Park, and major improvements to the highway between Porto Velho and Manaus. In addition to the official roads, unofficial roads constructed without government inspection or incentives are quickly expanding in the Amazon area (Nascimento et al., 2021; Souza Jr. et al., 2020; Perz et al., 2007; Brandão Jr. and Souza Jr. 2006; Asner et al., 2006; Arima et al., 2005). These roads are developed to expose forests to exploitative activities like logging, but they lead to new colonization, forest fragmentation, and many environmental impacts (Ferrante et al., 2021; Ahmed et al., 2013; Arima et al., 2008; Laurance et al., 2006; Cochrane, 2003; Nepstad et al., 2001; Verssimo et al., 1995). Consequently, deforestation in the Brazilian Amazon jumped from almost 28 thousand km^2 in 1975 to 53 thousand km^2 in 2000 (89% increase in 25 years), and then to 81 thousand km^2 in 2020 (53% increase over 2000) (INPE, 1989, 2020)

Various studies indicate that most (>90%) of the Amazon's deforestation is concentrated along the region's roads (Barber et al., 2014; Pfaff et al., 2007; Brandao Jr et al., 2007; Kirby et al., 2006), with much of this deforestation (~80%) being pasture and soy (~8%) soybean (Mapbiomas, 2022). However, while deforestation for new soybean areas virtually stopped after 2006 due to several public policies to combat deforestation and the private agreement known as the Soy Moratorium, deforestation for pasture continues, even with the commitments made by the cattle sector in the Cattle Agreements (CA) (Kastens et al., 2017; Alix-Garcia and Gibbs, 2017; Gibbs et al., 2016).

The CA, which began in 2009, compels participating slaughterhouses to block purchases of cattle coming from suppliers that have been deforested since 2008. To do so, the slaughterhouses that signed the agreements must use environmental monitoring systems to check whether their suppliers had deforestation or other socio-environmental infractions. Even after more than ten years of implementation, the CA has had little effect on average deforestation rates in cattle-producing regions (Alix-Garcia and Gibbs, 2017; Gibbs et al., 2016). Three main reasons may be related to the low effectiveness of the CA in curbing deforestation for cattle. First, current compliance monitoring is limited to direct suppliers, who deliver cattle for finishing at CA slaughterhouses. This narrow method of monitoring leaves out thousands of indirect suppliers who manage the cattle before shipping them to the direct cattle suppliers. Second, only half of Amazon's slaughterhouses have signed CAs, leaving unmonitored at least one-third of the market share of the region (Barreto et al., 2017). Finally, the traceability data needed to allow a complete supply chain monitoring has a low transparency level, limiting all efforts to control deforestation for cattle production. These three factors together raise the risk of cattle laundering, a process where non-compliant indirect suppliers send cattle to compliant direct suppliers without the control of CA slaughterhouses (Rajao et al., 2020; Gibbs et al., 2016). Therefore, expanding the CA to more slaughterhouses and more suppliers associated with more transparent traceability data is needed to enable better implementation of the CA, as well as a better understanding of the movement of cattle through the Brazilian Amazon.

Animal traceability documents (GTA) combined with rural property boundaries (Cadastro Ambiental Rural or CAR) have been used by some studies to increase understanding of the impact of the Amazon cattle chain on deforestation and implementation of CA (Skidmore et al., 2020, 2021; Raoni et al., 2020; Kingle et al. 2018;). From this GTA-CAR data one can identify the direct and indirect suppliers, combine them with deforestation and other requirement from the agreements to assess their compliance, as well as estimate the flow of cattle within these suppliers until the finishing at the slaughterhouses. While many GTA-CAR studies have focused on characterizing suppliers' compliance with CAs, there is still an information gap on the relationship between spatial characteristics of the cattle supply chain and deforestation that needs to be explored, including travel distances.

Roads are the main means used to transport cattle from the Amazon. Although many studies have estimated the impact of roads on deforestation, there is little or no information about how roads are selected, and which roads are used for the transport of specific commodities like cattle. Specifically, more information about travel distances in the cattle supply chain is needed to increase understanding of how producers make choices leading up to and following deforestation that renders them out of compliance with policies like the CA. For example, understanding under what conditions CA suppliers travel further if they have deforestation could help improve policy design or motivate efforts to increase coverage of the CAs. In addition, tracking travel distances could help identify laundering in response to policy implementation. Do suppliers with deforestation travel further after deforestation to avoid detection from CA slaughterhouses? Finally, understanding if suppliers sell to the nearest plant or travel farther than this could tell us something about how they make decisions and could indicate the strength of relationships between suppliers and slaughterhouses. Therefore, awareness of how travel distances vary and their relationship to deforestation is important to advance our knowledge about the Brazilian cattle supply chain.

Here we present a unique analysis to estimate the distance traveled by cattle that connect all parts of the cattle supply chain. We build our analysis on a GTA-CAR database that links ten million records of cattle transactions to thousands of property boundaries for the Amazonian states of Pará, Mato Grosso, and Rondônia for the period 2013-2018 (Brandao Jr. et al.; in preparation; Skidmore et al., 2020, 2021). This database allows us to track both direct and indirect suppliers to slaughterhouses, with the GTAs included indicating that 90% of the cattle moved in these states occur via roads. We also used a database of official and unofficial roads produced by IBGE and Imazon for the year 2017 and 2012 using Landsat images, respectively (IBGE, 2018; Imazon, 2012). We developed a method to estimate the shortest connection using roads (named "cattle roads" in this paper) between the direct suppliers and the slaughterhouses, and between the tier-1 indirect suppliers and the direct suppliers.

Here we explore three core topics: 1) How far do cattle travel to reach slaughterhouses via the road network? 2) Do suppliers usually sell to the nearest slaughterhouse or travel farther to other slaughterhouses? 3) Do cattle from suppliers with deforestation travel further than cattle from suppliers without deforestation? Do travel distances change over time due to the occurrence of deforestation?

2 Methods

2.1 Study area and data pre-processing

We explored the spatial relationship between cattle's travel distance through roads and deforestation in the states of Pará, Mato Grosso, and Rondônia, which cover roughly one-third of Brazil's extent. We used a series of roads, cattle traceability, and deforestation to perform these assessments (Figure 1).

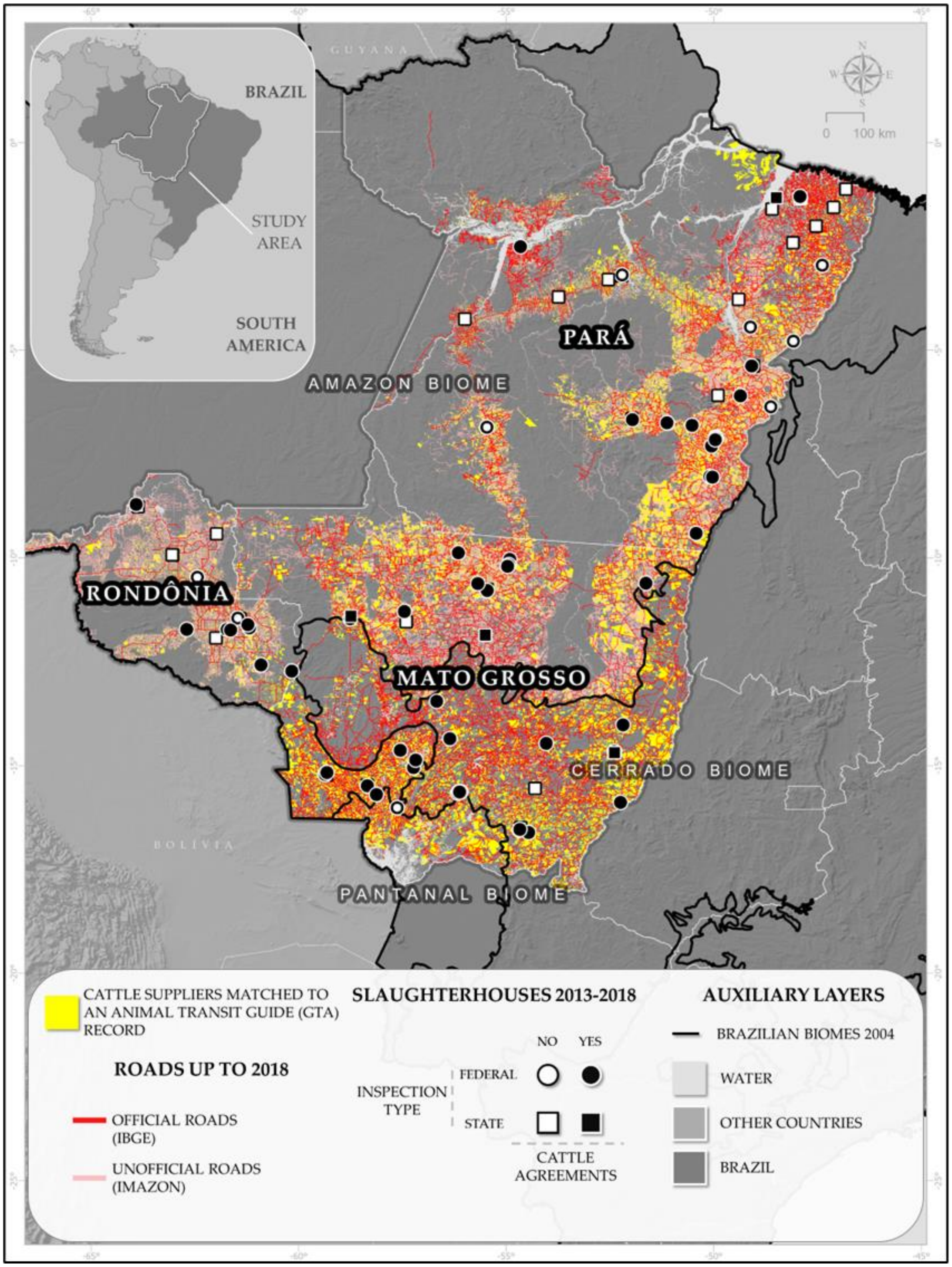

Figure 1. Study Area with the roads, slaughterhouses, and suppliers.

- Roads network. We combined the Landsat-based maps of official and unofficial roads networks produced by the Brazilian Institute of Geography and Statistics (IBGE in Portuguese) and by the Amazon Institute of the People and the Environment (Imazon), respectively, to create a network of approximately 450 thousand km of roads, of which 4% was official (federal or state highways) and 96% unofficial. The IBGE map that we used was produced by the Brazilian government and contains the paved and unpaved roads federal and state highways identified on a scale of 1:250,000 for the year 2017 (IBGE, 2017). As the IBGE map does not include unofficial roads, we also used the detailed map (scale of 1:50,000 for the year 2012) of official and unofficial roads from Imazon available for the Amazon biome (Imazon, 2012). The Imazon roads map was produced following the approach developed by Brandao Jr. and Souza Jr. (2006).
- Cattle traceability database. This database has the locations of slaughterhouses and their direct and tier-1 indirect suppliers as well as the mode of transport. We used the database from Chapter two (Brandao Jr. et al., in preparation) based on GTA records from 2013 to 2018, which was matched to rural properties in Pará, Mato Grosso, and Rondônia. Our sample has about 97,000 cattle suppliers and 142 slaughterhouses (more details in the Chapter two) that moved cattle via roads according to the GTA. We limited our sample to direct and tier-1 indirect suppliers because they make up more than 84% of all the cattle suppliers in the GTA.
- Deforestation and natural forest vegetation data. The deforestation and natural forest data was produced by the Brazilian National Institute for Space Research (INPE in Portuguese) under the Brazilian Amazon Forest Satellite Monitoring Program (PRODES in Portuguese) and following the methodology developed by Almeida et al. (2021). Using

data from Landsat, PRODES has been making maps of past deforestation within the Brazilian Amazon biome since 1997. For our study, we selected the classes forest and annual deforestation, for the period 2013-2018, respectively.

2. Estimating the cattle's travel distance through roads

We estimated the shortest connections using the roads between direct suppliers and slaughterhouses and between tier-1 indirect suppliers and direct suppliers using the Cost Path as Polyline function available in ArcGIS Pro, based on the assumption that ranchers will attempt to minimize the distances traveled by cattle whenever possible. This function makes an output polyline feature that shows the least costly path from a source to its destination, based on a friction surface that contains the "cost" for each cell in the map. The first step in running this function was to create the source and destination points. The centroids of all cattle supplier properties were the source, and the slaughterhouse locations the destination points.

In the second step, we create a friction surface based on the roads network map that contains an estimated cost for each road cell in the map. In this process, we first converted the official IBGE road maps and the unofficial roads map from Imazon to a raster format, using the Feature to Raster function, with a 200 x 200-meter of cell size. For the IBGE road map, we use the attributes paved and unpaved as cell identifiers. We assumed that all unofficial Imazon roads were unpaved. After this conversion to a raster format, we reclassified the paved and unpaved road cells to cost estimates based on the study by Schielein et al. (2021). Schielein and colleagues cataloged and organized average speed estimates in kilometers per hour (km/h) for trucks traveling on paved and unpaved roads in the Brazilian Amazon. We used a value of 81 km/h for paved roads and 27 km/h for unpaved roads as our annual average speed estimate (See details on the SM). Then, using equation (1) we adjusted the average speed to 1 and 4 (paved and unpaved roads, respectively) in the friction map to reflect the assumption that the higher the speed, the lower the friction cost in the map. All surface types other than roads (i.e., forests, rivers, and others) were reclassified with a value of 10,000, i.e., a high cost to be crossed.

$$FV = \frac{1}{AS} \times 100 \quad (1)$$

Where:

FV. The friction value used on the friction map.

AS. Average annual speed value (km/hour)

In the final step was we estimated the cattle's travel distance in kilometers through roads for each combination of direct supplier – slaughterhouse and tier-1 indirect supplier – direct suppliers. For each of the direct suppliers, we identified the shortest paths using the roads between these suppliers and the slaughterhouse (named as potential cattle roads of direct suppliers), as well as between the tier-1 indirect suppliers and the direct ones (potential cattle roads of tier-1 indirect suppliers). We refer to roads selected by our model as "potential" because we do not have field data to validate if the shortest paths through the roads were actually used by the cattle suppliers to transport the animals.

2.4 Assessing distance between direct suppliers and slaughterhouses

To identify whether direct suppliers sold cattle to the nearest slaughterhouses, we estimated the shortest distance a direct supplier could travel by road to reach the nearest slaughterhouse. We then compared this data with the distance identified from the traceability data (item 2.3). We also examined the type of slaughterhouse (federal, state, or other) and whether it was in CA or not.

2.5 Estimating travel distance of suppliers with and without deforestation

In this analysis, we seek to test two main hypotheses. First, direct suppliers with deforestation travel greater distances on average than direct suppliers without deforestation. Second, direct suppliers with deforestation travel greater distances after deforestation occurred. Both of our hypotheses are based on research showing that most CA slaughterhouses are monitoring and implementing some degree of controls on direct suppliers to comply with the CA, so sellers with deforestation may have to seek out other options following deforestation. However indirect suppliers are not yet monitored by any slaughterhouses, so we do not anticipate changes in travel distances due to deforestation. We use the non-parametric Wilcoxon test to check the statistical significance of these comparisons.

To test the first hypothesis, we selected the suppliers who shipped cattle to slaughterhouses between 2013 and 2018. We then selected those suppliers who had more than 6.25 hectares of forest in 2013, according to PRODES Amazonia data. Lastly, we selected two subgroups of cattle suppliers from the previous step: (i) those who deforested more than 6.25 hectares of forest in any year between 2014 and 2018; and (ii) those who never deforested between 2014 and 2018.

For the second hypothesis, we selected only direct suppliers with some deforestation between 2014 and 2018 from the sample of the first hypothesis. We then compared whether the average annual distance traveled before deforestation occurred was greater than the average annual distance after deforestation occurred.

3 Results

3.1 Direct suppliers are farther from slaughterhouses than from their tier-1 indirects.

Across all states and between 2013 to 2018, our estimates indicate that cattle traveled 77 to 144 km (median values) from direct suppliers to slaughterhouses (Figure 2-A). When selling to the largest SIF slaughterhouses (Figure 2-A-SIF), suppliers typically traveled 80 to 86 km (8% variation) across all years, and they traveled 77 km to 92 km when selling to the medium-sized SIE slaughterhouses for the same period (Figure 2-A-SIE). We noticed a large range in distance traveled by the direct suppliers selling to Other slaughterhouses (Figure 2-A-Other). They typically traveled 104 km in 2013, and even farther by 2018 when they traveled up to 144 km. In all years, suppliers selling to Other slaughterhouses traveled farther than those selling to the larger SIE and SIF slaughterhouses.

The median distance traveled by cattle between tier-1 and direct suppliers was eight times (21 km) less than the median distance traveled between direct suppliers and slaughterhouses (Figure 1-B). We did not observe a large variation in the distance traveled by cattle between tier-1 indirect suppliers and direct suppliers to any of the three types of slaughterhouses analyzed (SIF, SIE, and others).

Disaggregated by state, we find that cattle travel less in Rondônia than in Pará and Mato Grosso (Figure S1). In Rondônia, cattle arriving at the SIE and SIF slaughterhouses traveled about 39 km and 75 km respectively (median values). In Pará and Mato Grosso, our results showed median values of 114 and 70 for SIE slaughterhouses in these two states, and 90 and 84 km for SIF slaughterhouses. Cattle slaughtered in Other slaughterhouses traveled about 124 and 104 km in Pará and Mato Grosso. Cattle from tier-1 suppliers traveled an estimated 22 km and 26 km for tier-1 suppliers located in Mato Grosso and Pará, and less than 15 km in Rondônia (Figure S2).

For the most part, cattle slaughtered by CA slaughterhouses traveled longer distances (Figure S3 and Figure S4). In Pará, the median distance traveled was 109 km for CA slaughterhouses, which was 53% greater than the 71 km traveled by cattle traveling to non-CA slaughterhouses. In Mato Grosso and Rondônia, the results were similar, with cattle slaughtered by CA slaughterhouses traveling 23% to 31% further than cattle slaughtered in non-CA slaughterhouses.

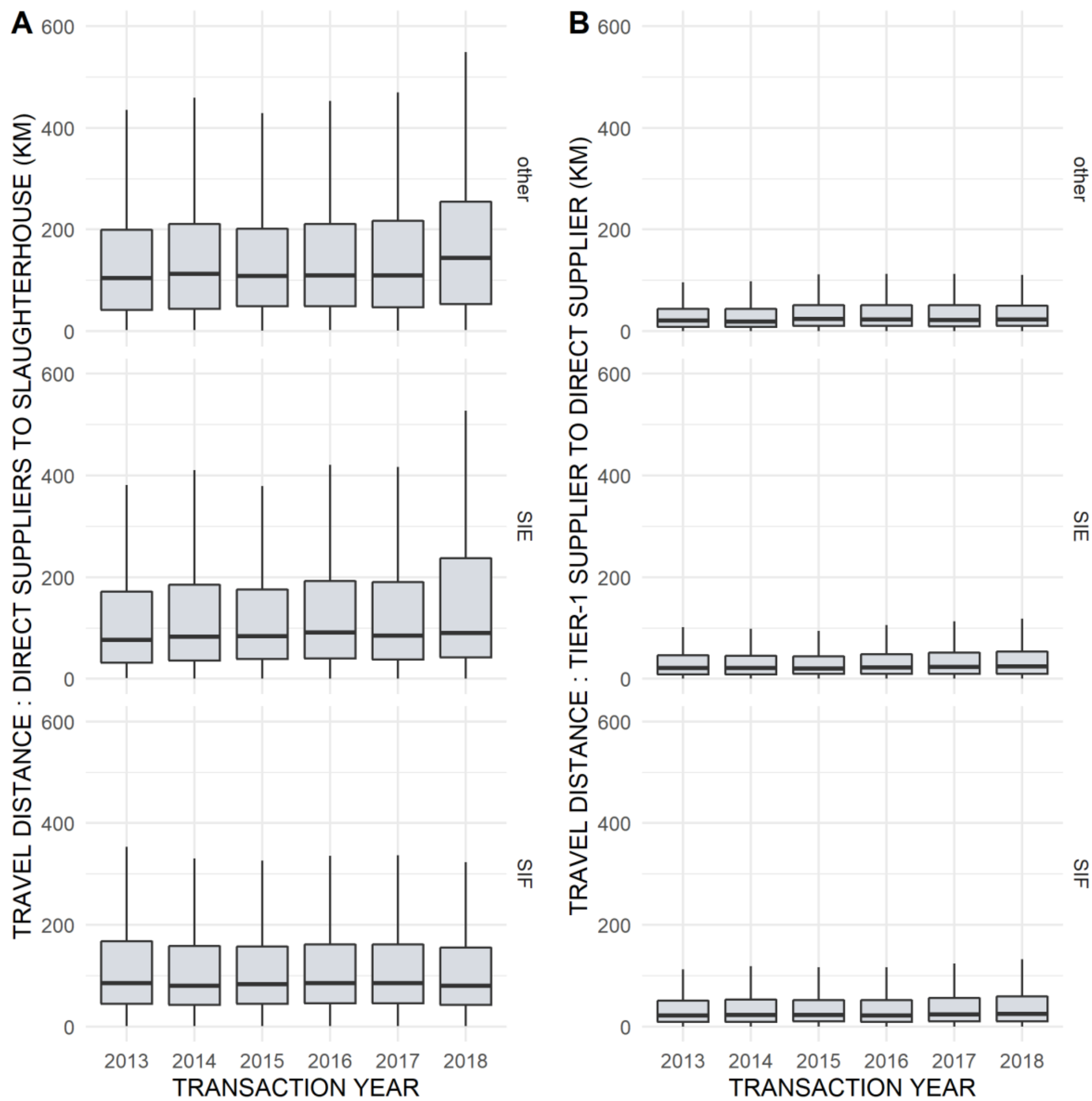

Figure 2. Distance traveled by cattle between direct suppliers and slaughterhouses (A) and indirect tier-1 to direct suppliers (B) from 2013 to 2018 per slaughterhouse type (other, SIE, SIF).

3.2 In general, cattle travel twice as far to sell to preferred slaughterhouse.

Direct suppliers do not typically sell to the nearest slaughterhouse if we include all types—SIF, SIE, Other. We estimate that about 40 million head of cattle were slaughtered between 2013 and 2018 in the states of Pará, Mato Grosso, and Rondônia by the slaughterhouses in our sample, and 76% of the cattle slaughtered were transported beyond the nearest slaughterhouse. Indeed, cattle typically traveled twice the distance as they would need to travel between the direct supplier and the nearest slaughterhouse. The median distance along the shortest path on roads between direct suppliers and the nearest slaughterhouses was 42 km. However, the median shortest path distance over roads between direct suppliers and the slaughterhouses they sold to was 85 km.

CA and non-CA slaughterhouses of the same type (SIE or SIE) are located at different distances from the direct suppliers. CA slaughterhouses of type SIE and SIF are at 107 km and 77 km (median) from the direct suppliers, against 42 km and 52 km from the non-CA slaughterhouses of these same types. When comparing these distances with the nearest CA of non-CA, SIFs, or SIEs, we noticed that cattle traveled more to reach non-CA slaughterhouses when the nearest one was a CA. Figure 3 illustrates travel distances using roads based on the slaughterhouses' status. Cattle go roughly twice as far to reach a non-CA slaughterhouse when the closest slaughterhouse has signed the CA when compared to the distance to the GTA-listed slaughterhouse. When both the closest slaughterhouse and the slaughterhouse listed in the GTA are part of the CA, the difference in the distances is only 50 km. State direct suppliers (SIE) reported a non-significant 3% more. When neither the nearby slaughterhouse nor the GTA-listed slaughterhouse signed the CA, the animals also traveled further (16% further). When the closest slaughterhouse was non-CA and the slaughterhouse listed in the GTA was party to the CA, cattle went the furthest farther (about 270% more).

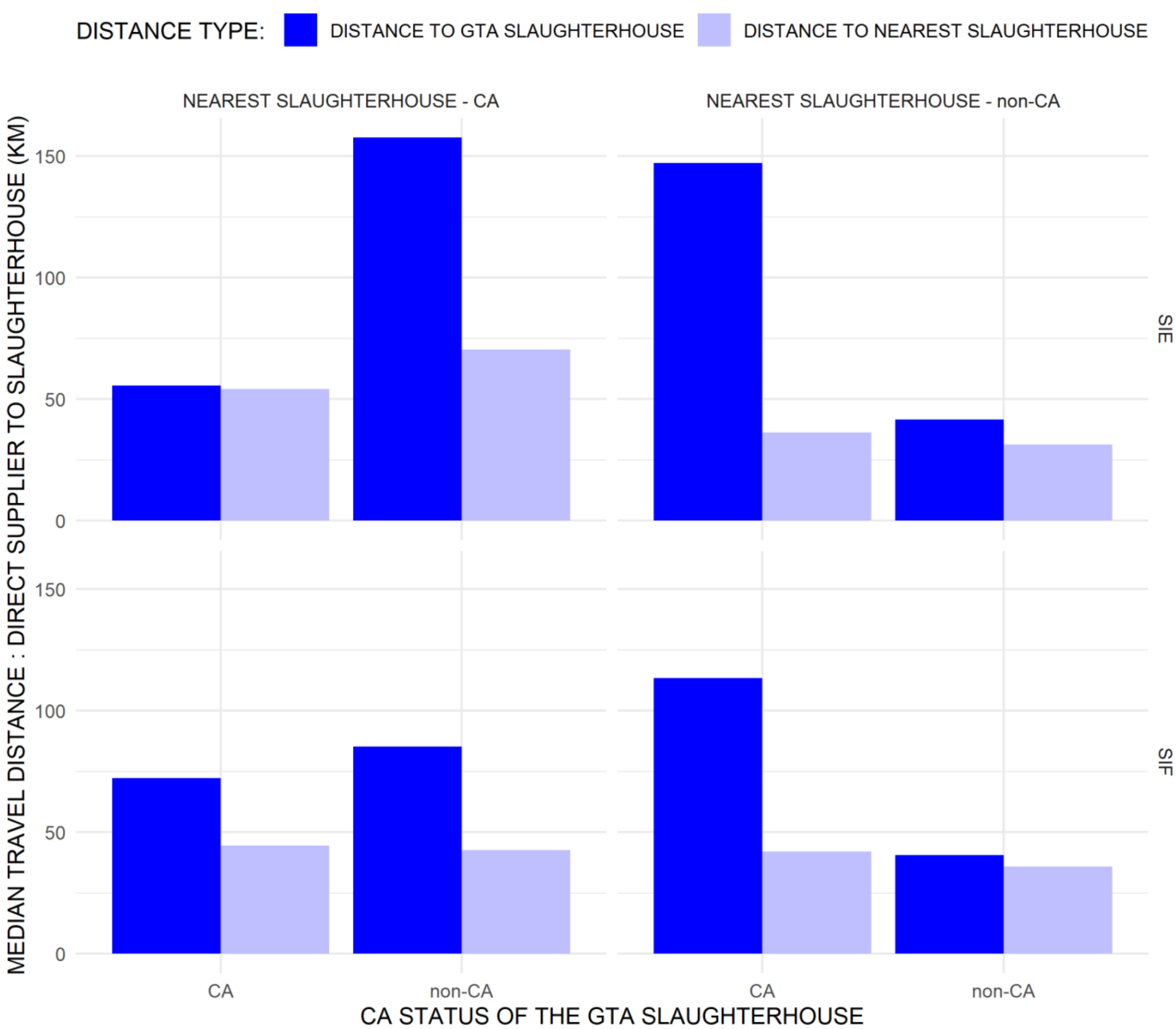

Figure 3. Comparison of the median travel distance between the nearest slaughterhouses (light blue) and the GTA-listed slaughterhouses (dark blue) by type of CA status (CA and non-CA) for the states of Pará, Mato Grosso, and Rondônia and ranging from 2013 to 2018, per slaughterhouse type (SIE, SIF).

3.3 Cattle from suppliers with deforestation travels more than from suppliers without deforestation

Our results indicated that direct suppliers without deforestation (n = 8,234) traveled about 91 km (median) to access a slaughterhouse when considering all types of slaughterhouses. This was 15% less than the 105 km (average) traveled by suppliers with deforestation (n = 1,714). These average distances are statistically different (P-value <0.5).

Disaggregating this comparison by type of slaughterhouse (SIF, SIE, or other) and by state, we find two main results (Figure 4). First, that we found a statistically significant difference in travel distances on properties with and without deforestation (P-value <0.5) in all combinations, except for the Other slaughterhouses in Pará.

In addition, we found that cattle traveled further after deforestation occurrences (Figure 5). In most states, this increase in travel was small but statistically significant for SIF and SIE slaughterers. In Rondônia this difference was more apparent where cattle had to travel about 50 and 30 km more to the SIF and SIE slaughterhouses after deforestation, respectively.

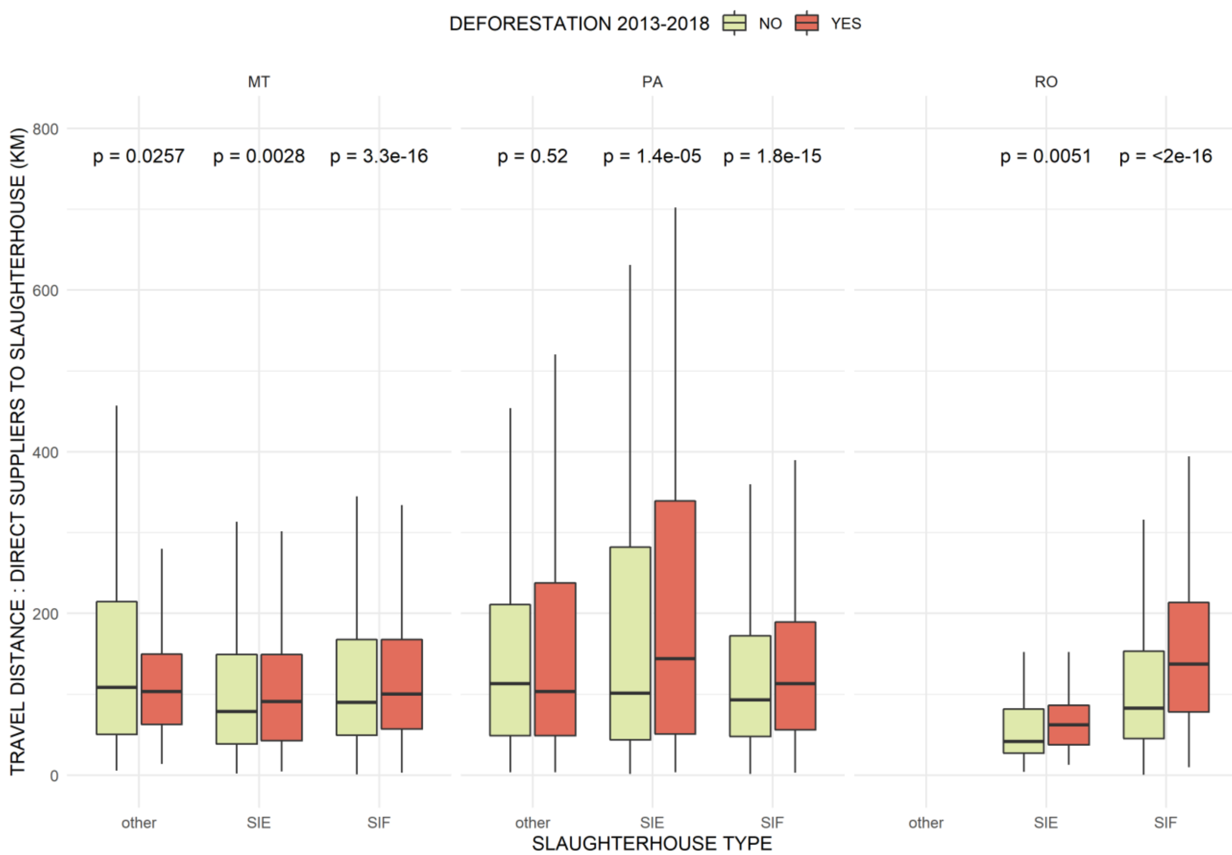

Figure 4. Comparison of median travel distances by slaughterhouse type and by state for direct suppliers with no deforestation from 2013 to 2018 (light green) and with some deforestation (orange) in that period. P-value less than 0.5 is significant according to the Wilcoxon test.

Figure 5. Comparison of median travel distances before (light green) and after (orange) the occurrence of deforestation at direct suppliers to CA and non-CA slaughterhouses by type of slaughterer (SIE, SIF) and by state.

4 Discussion

4.1 High proximity between tier-1 and direct suppliers via roads can favor environmental illegality

The short travel distances between tier-1 suppliers and direct suppliers can be an indicator of many processes. First, this result is consistent with Chapter two (Brandao Jr et al. in preparation), where we found a large overlap between the supply zones of direct and indirect tier-1 suppliers. For example, the transportation cost for a direct supplier to sell cattle to another cattle supplier is much lower than to another slaughterhouse that has not signed the agreements. Without expanding the agreements to include indirect suppliers, as suggested by Skidmore et al., (2020; 2021), Barreto et al. (2017), and Gibbs et al. (2016), the risk of cattle laundering is unlikely to decrease.

Second, that suppliers may organize themselves spatially into groups of the same family, or the same organizational group. There is a vast literature in social networks that communities tend to organize themselves in groups that present similar behavior (Müller-Hansen et al., 2019; Mertens et al., 2008, 2015). This may have been captured by the travel distances, indicating that tier-1 suppliers may be socially connected to direct suppliers. However, more research is needed using social network concepts to better understand these connections.

4.2 Direct suppliers do not always sell to the nearest slaughterhouse, which is counterintuitive

Our results indicated that direct suppliers do not sell to the nearest slaughterhouses. This result is counterintuitive from the standpoint of spatial and typical relationships between suppliers and processing centers. There is a large literature based on Von Thünen models that suggests that the closer the processing centers the lower the associated transportation cost and therefore the higher the profitability of the sale (Walker 2021; Schielen and Borner 2018; Walker and Homma, 1996). This may be an indication of intentional sales that contradicts the literature. Or perhaps, there may be other factors that were not analyzed such as the size of the slaughterhouses, the price of the cattle, among others, that were not captured by the travel distances. Thus, more research could be done on this topic to understand which variables could be associated with the suppliers' intentions in selling cattle.

4.3 Suppliers with deforestation traveled more than suppliers without deforestation

Our study provides important information about an increase in travel distances on deforested cattle ranches, especially after deforestation has occurred. Some factors may be associated with this increase, such as the search for non-CA slaughterhouses more distant than the CA slaughterhouses. Changes in cattle prices, not captured by travel distances. Or even, changes in the buying patterns of slaughterhouses. These results could be interpreted as a direct impact of CA implementation.

However, our results should be interpreted with caution as we have not done a full econometric analysis (Athley and Imgens, 2017) of the effect of deforestation to assess the causal impact on travel distances. To generate this robust econometric analysis, we would need a set of field data representing the sales behavior of suppliers before and after the occurrence of deforestation, as well as historical conditions of cattle prices, and transportation cost, among others, which was not the focus of this research.

5 Conclusions

In this study, we estimated the travel distances of cattle through roads. Our results indicated that cattle travel between 77 and 144 km (median values) from direct suppliers to slaughterhouses and approximately 21 km (median value) between tier-1 indirect suppliers and direct suppliers. We also analyzed whether suppliers usually sell to the nearest slaughterhouse or travel farther to other slaughterhouses and found that 76% of cattle were not slaughtered at the nearest slaughterhouses. Finally, we found potential evidence that cattle coming from suppliers with deforestation travel further than suppliers without deforestation, and cattle travel longer distances after deforestation has occurred. Our approach has the potential to be replicated in other states in Brazil if data on suppliers, traceability, and roads are available.

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SUPLEMENTARY MATERIAL – SM

Table S1. Annual average speed for paved and unpaved roads and friction values used to estimate the potential cattle roads.

ROAD TYPE	**DATA FROM: SCHIELEIN ET AL. 2021**		**ANNUAL AVERAGE (KM/H)**	**FRICTION VALUE**
	TRAVEL-SPEED DRY SEACON IN KM/H	TRAVEL-SPEED WET SEASON IN KM/H		
PAVED ROADS	81	81	81	1.00
UNPAVED ROADS	49	5	27	4.00

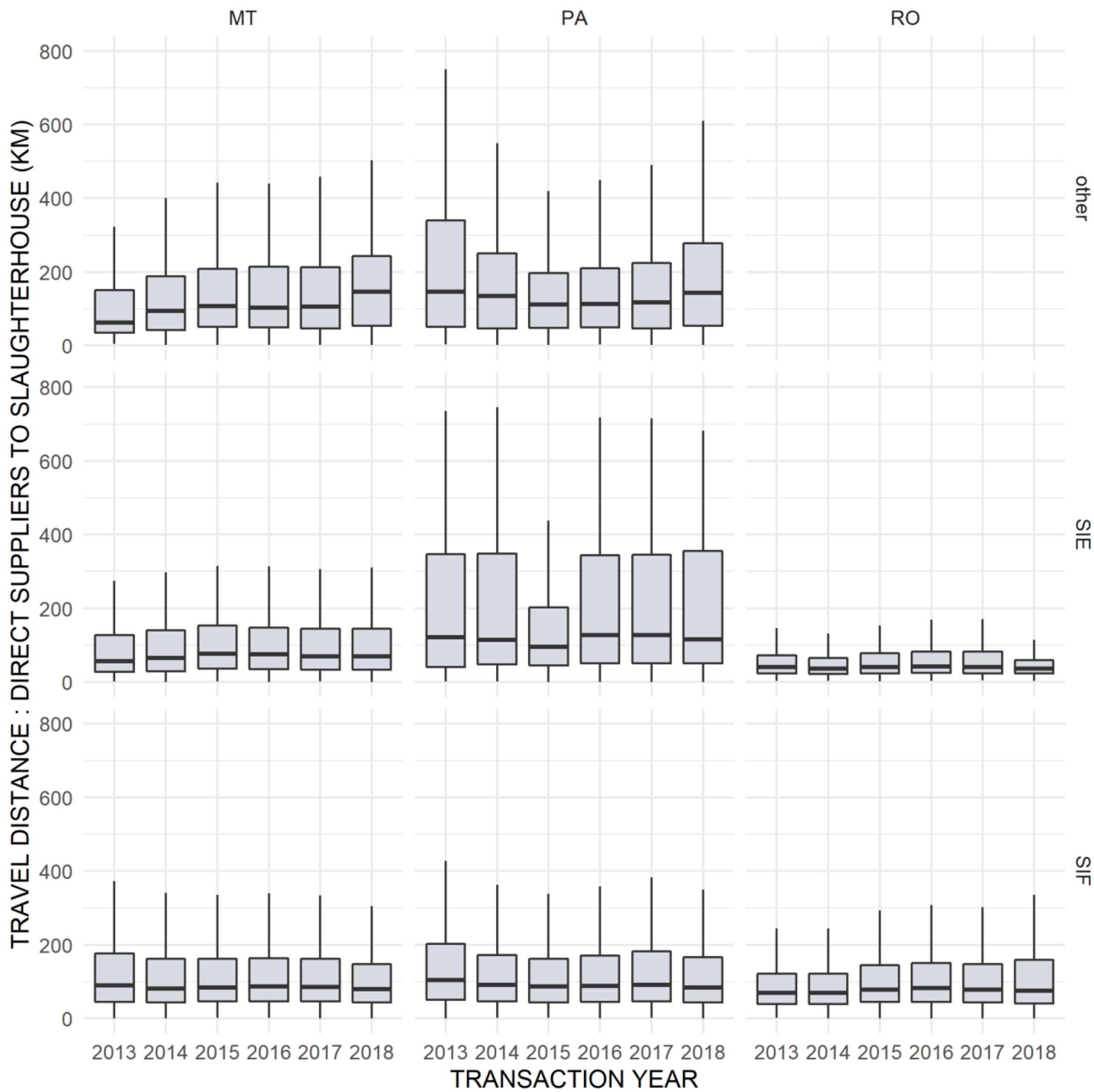

Figure S1. Estimated distance from roads that cattle traveled between direct suppliers and slaughterhouses located in Mato Grosso (MT), Pará (PA), and Rondônia (RO), by type of slaughterhouse (other, SIE, SIF), within the period from 2013 to 2018.

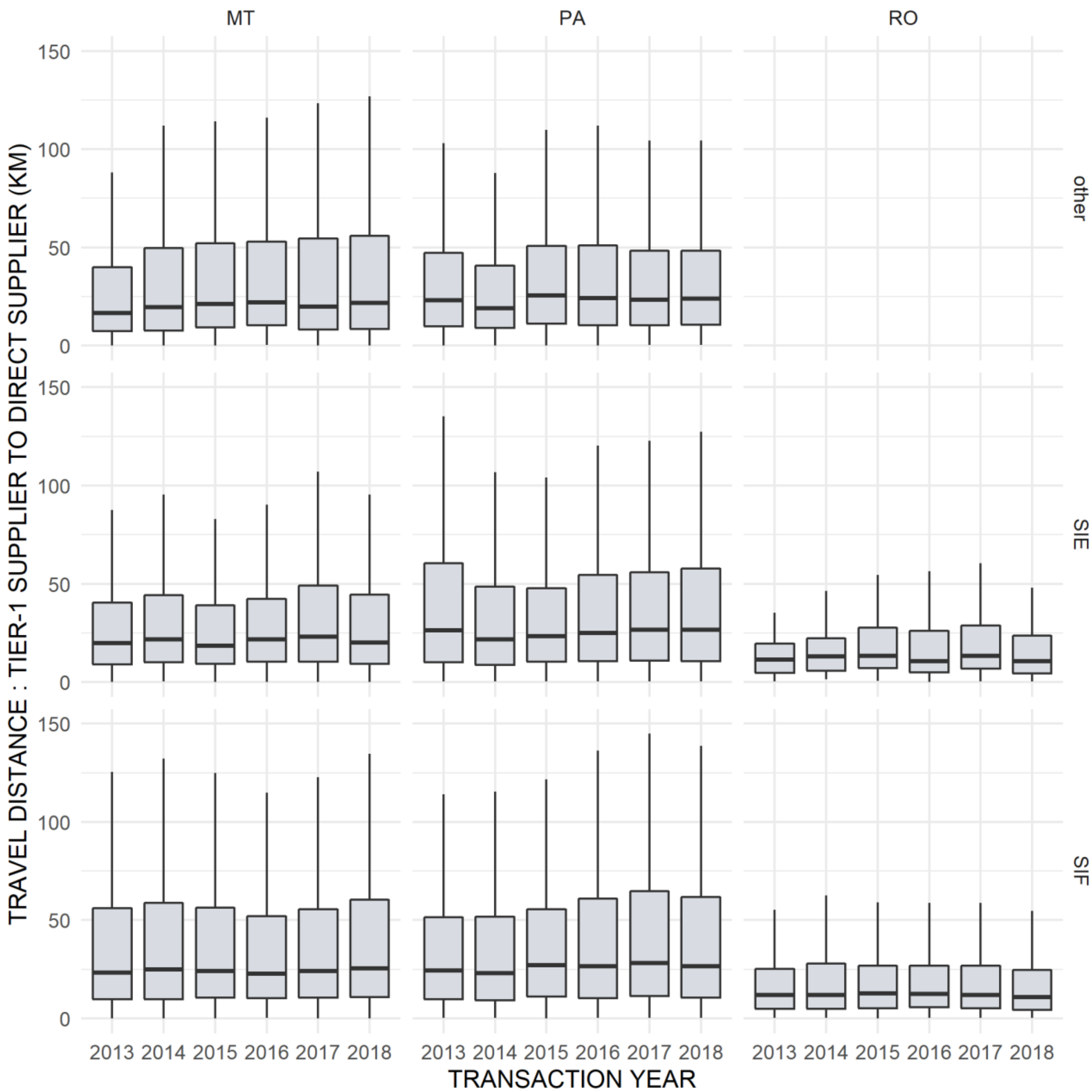

Figure S2. Estimated distance from roads that cattle traveled between tier-1 indirect suppliers an direct suppliers from slaughterhouses located in Mato Grosso (MT), Pará (PA), and Rondônia (RO), by type of slaughterhouse (other, SIE, SIF), within the period from 2013 to 2018.

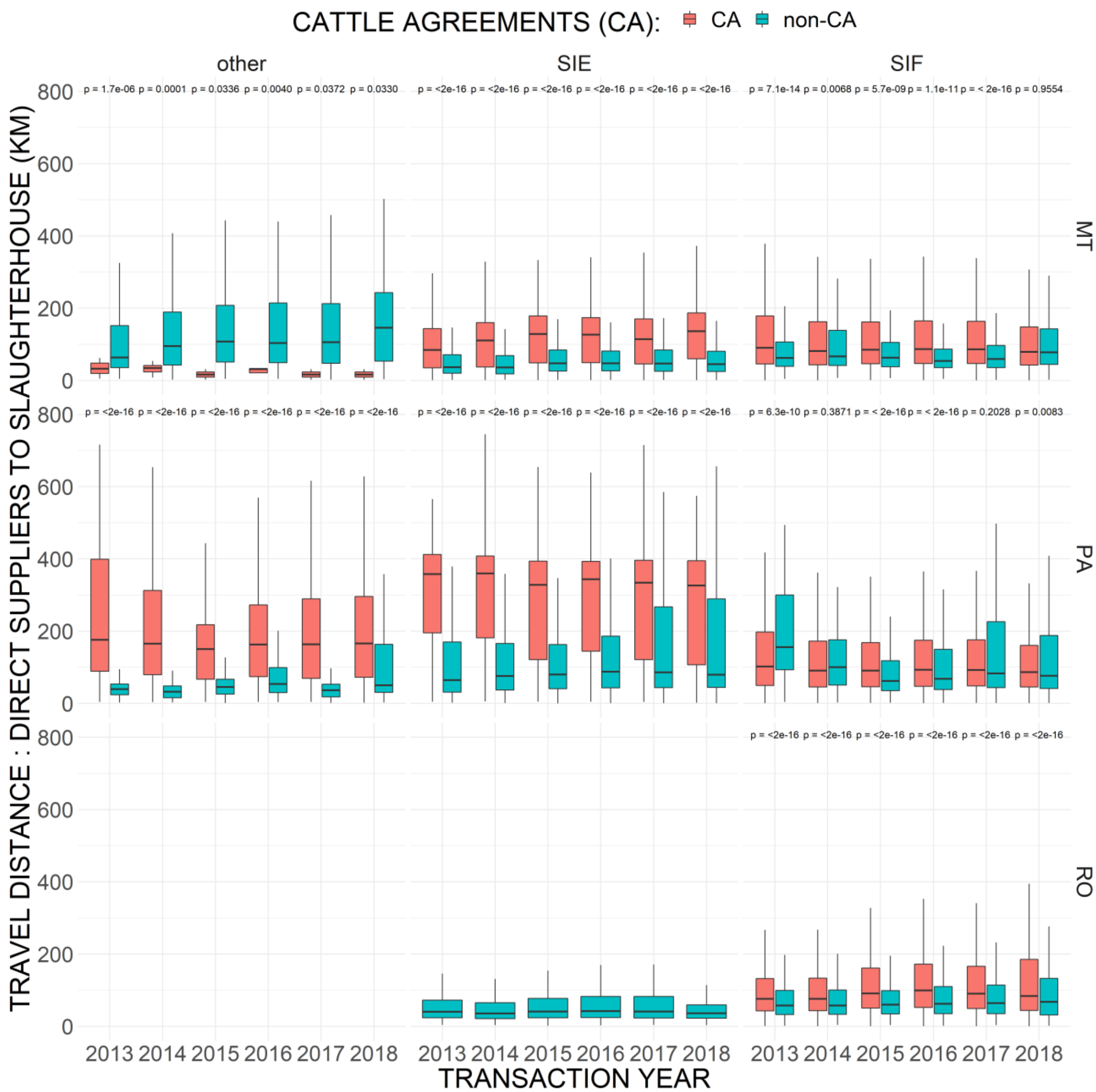

Figure S3. A comparison of the travel distances between direct suppliers and slaughterhouses that signed Cattle Agreements (CA) in red and those that didn't (non-CA) in blue, by state (MT, PA, RO) and by type of slaughterhouse (other, SIE, SIF). The p-values (significance if p<0.5) above each pair of travel distance of CA and non-CA were estimated using the Wilcoxon test.

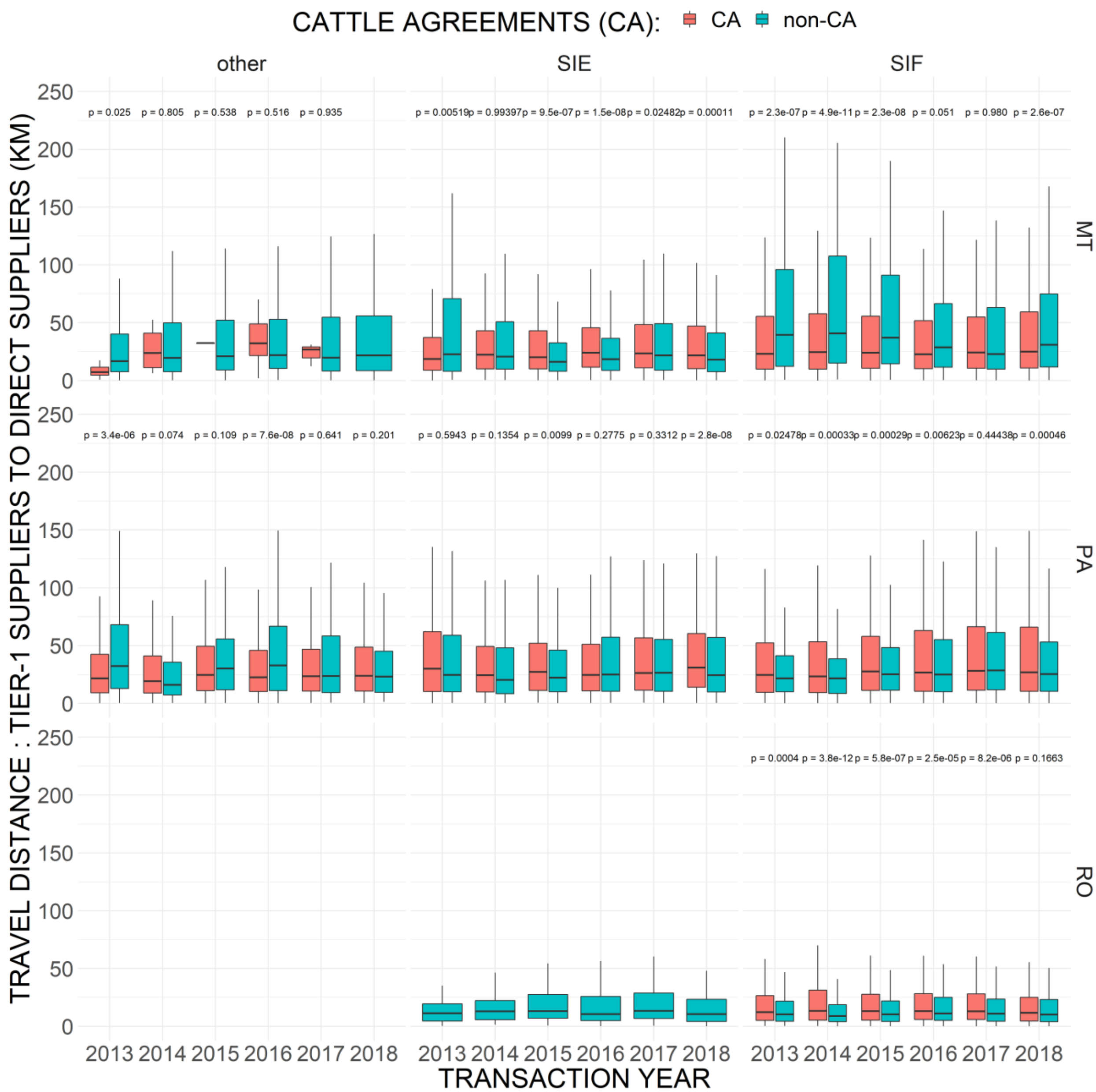

Figure S4. A comparison of the travel distances between tier-1 indirect suppliers and direct suppliers of slaughterhouses that signed Cattle Agreements (CA) in red and those that didn't (non-CA) in blue, by state (MT, PA, RO) and by type of slaughterhouse (other, SIE, SIF). The p-values (significance if $p<0.5$) above each pair of travel distance of CA and non-CA were estimated using the Wilcoxon test.

Table S2. Median distance, mean and standard deviation for estimated travel distances between direct suppliers and CA and non-CA slaughterhouses by state, nearest geographically and identified by GTA data.

STATE	CATTLE AGREEMENT (CA)	TYPE OF TRAVEL DISTANCE	DIRC. SUPP. (N)	MEDIAN (KM)	MEAN (KM)	SD (KM)
MT	CA	Distance to Gta Slaughterhouse	20,046	86	119	105
		Distance to Nearest Slaughterhouse		46	57	42
	non-CA	Distance to Gta Slaughterhouse	6,632	70	111	110
		Distance to Nearest Slaughterhouse		43	54	41
PA	CA	Distance to Gta Slaughterhouse	13,296	109	168	157
		Distance to Nearest Slaughterhouse		38	46	31
	non-CA	Distance to Gta Slaughterhouse	10,611	71	130	135
		Distance to Nearest Slaughterhouse		37	43	28
RO	CA	Distance to Gta Slaughterhouse	6,949	85	116	96
		Distance to Nearest Slaughterhouse		41	51	35
	non-CA	Distance to Gta Slaughterhouse	5,886	58	83	82
		Distance to Nearest Slaughterhouse		38	46	31