Characterizing compliance in cattle supply chains:

What factors encourage deforestation-free production in the Brazilian Amazon?

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Executive Summary

Emerging governance efforts, including Supply Chain Initiatives (SSIs) and local to national-level public policies, have led to meaningful changes in Brazil's cattle and soy sectors. **Under the Zero-Deforestation Cattle Agreements (hereafter CA), significant progress has been made on monitoring direct suppliers for deforestation, but broader impacts on forest conservation have lagged behind** (Alix-Garcia & Gibbs, 2017; Gibbs et al., 2015; Gibbs et al., 2020b). Progress is also now at risk due to stagnation of the CA, weakening of the Forest Code, declining transparency of public information, and general government support of economic expansion into forests.

Little is known about why some supplying properties have continued clearing under the CA while others have stopped. We rely on exceptionally rich data to provide the first property-level assessment of the main factors that relate to ongoing deforestation in CA supply chains. We find that:

- **Expansion of the CA to include more slaughterhouses is necessary to achieve zero-deforestation goals.** There are many properties that the CA have yet to reach, and these properties were more likely to have deforestation. Properties with deforestation were three times more likely to be completely outside the supply zones of CA slaughterhouses than properties without deforestation. However, it is not enough for a property to be in the supply zone of a CA slaughterhouse, as the property could still sell to slaughterhouses that have not signed the CA. Properties become less likely to deforest as CA slaughterhouses control a larger share of slaughterhouses in their market.
- **Monitoring must include full land holdings, not just single properties.** Owning multiple properties is common in the Amazon, but slaughterhouses only monitor one property out of all those a rancher owns per the requirements of the CA. Thus, ranchers with multiple properties may choose which property they report to slaughterhouses for monitoring – and unmonitored properties have been shown to have higher risk of deforestation. We also find that if a rancher deforests on any of their properties, the remainder of their properties are at higher risk of deforestation. As such, we suggest that monitoring efforts and assistance should be targeted to these remaining properties.
- **Most deforestation occurs on indirect suppliers.** These properties, which do not sell to slaughterhouses, offer a challenge to the CA. Indirect suppliers are not currently monitored for deforestation by the CA, and have higher rates of deforestation than monitored direct suppliers. We found that a property became more likely to deforest as a lower proportion of their sales went directly to a slaughterhouse. Monitoring these indirect suppliers could slow the pervasive deforestation that remains in CA supply chains.
- **Deforestation for cattle production is more likely in remote areas.** Remote areas have very low oversight, and ranchers have a lower risk of being penalized for clearing. This is why all respondents of our field interviews emphasized the role of remote areas as sources of deforestation in cattle supply chains. This local knowledge was confirmed by our data analyses. Properties with deforestation were four times closer to the deforestation frontier, two times farther from the highway, and 56 kilometers farther from a slaughterhouse.
- **Large forested properties are more likely to be cleared.** The percent forest remaining on a property was the single characteristic that best explained whether a property had deforestation between 2010 and 2018. Properties with deforestation were twice as large and had nearly twice as much remaining forest cover. Respondents of our field interviews reported that large

tracts of remaining forest are more likely to be deforested because it is more likely to go unnoticed.

- **High volume of cattle and deforestation pass through a small number of properties.** These high-volume properties purchase large numbers of cattle, including from many non-compliant properties. They then sell these cattle to slaughterhouses, including slaughterhouses that signed the CA. In this way, they funnel hundreds of thousands of hectares of deforestation to slaughterhouses. Confinements and high-volume properties sold 3.9 million head of non-compliant cattle for slaughter between 2013 and 2018, doubling the number of non-compliant heads per year over the same period. As such, we encourage slaughterhouses to work with these properties to find solutions.

The field work and data analysis that we document here offer a roadmap for how to focus efforts to reduce deforestation in the Amazon. We identify portions of the supply chain as well as types of properties that are at highest risk of deforestation, so that efforts may target them for monitoring as well as financial or educational support to preserve forest. We hope that these results may inform companies, policymakers, producer groups, and NGOs.

1. Introduction

Emerging governance efforts including Supply Chain Initiatives (SSIs) and local to national-level public policies have led to meaningful changes in Brazil's cattle and soy sectors. Deforestation rates declined significantly prior to the very recent increase, but progress is now at risk due to stagnation of SSIs such as the Zero-Deforestation Cattle Agreements (hereafter CA), weakening of the Forest Code, and declining transparency of public information and general government support of anti-deforestation efforts. The CA are particularly vital because they help address a major cause of deforestation – clearing for pasture expansion – which often occurs in the forest frontier and is fraught with uncertain land rights, violence, and corruption.[1]

Under the CA, significant progress has been made on monitoring direct suppliers for deforestation, but broader impacts on forest conservation have lagged behind (Alix-Garcia & Gibbs, 2017; Gibbs et al., 2015; Gibbs et al., 2020b). For example, the Amazon's largest meatpacker, JBS, on average reduced its probability of purchasing from properties with recent deforestation across the Amazon biome after the CA, but its actions and adherence were inconsistent across states (Gibbs et al., 2020a). JBS made major reductions in Pará where state government pressures were high, but actually bought from more properties with deforestation after the CA in Rondônia and the Cerrado portion of Mato Grosso where these pressures were lower. Competition from other nearby plants with less stringent monitoring also made it harder for JBS to block properties with deforestation. Further, our econometric models show that evasion of the CA by producers, who altered the names of farms to avoid being matched to deforestation, among other tactics, was highest in Pará, which is where JBS took the most stringent actions to comply with the CA.

Indeed, deforestation has continued to enter supply chains for all meatpacking companies. Gibbs et al. (2020b) show that deforestation has continued on the direct suppliers that sell to CA slaughterhouses. However, the majority of deforestation in CA supply chains occurs on unmonitored indirect suppliers that sell to direct suppliers in earlier parts of the supply chain. In addition, many ranchers own and manage multiple registered properties as a single holding but register sales from only one property that is monitored for deforestation, which leaves them free to continue clearing the auxiliary properties without consequence.

Little is known about why some supplying properties have continued clearing under the CA while others have stopped. We rely on exceptionally rich data to provide the first property-level assessment of this question, which is fundamental to the success of the CA. Our work informs efforts by companies, policymakers, producer groups, and NGOs to communicate with farmers and to support their actions to avoid deforestation.

We consider the context in which the CA was implemented, including both factors inherent to the property and to the implementation of the agreements themselves. Factors such as property size, remaining forest, distance to a paved highway, and production volume may be correlated with deforestation

1. The CA are composed of two supply chain agreements: the G4 and TAC. The G4 was negotiated in 2009 between Greenpeace and the largest meatpacking companies (JBS, Marfrig, and Minerva), while the TAC is an agreement between the state-level Public Federal Prosecutors and a larger set of companies, with additional companies joining the TAC each year. Because of the large overlap in the goals and requirements of the two agreements, we refer to them collectively.

independent of the CA. Factors related to supply chain and market context (such as access to non-monitoring slaughterhouses or role in the supply chain) could be correlated with deforestation because they make it easier to evade monitoring. Finally, the influence of complementary policies could help discourage deforestation. Here, we discuss the main factors that have been found to relate to ongoing deforestation in CA supply chains. We also quantify the importance of a small number of high-volume properties in funneling deforestation to CA slaughterhouses.

Our report is structured as follows: Chapter 2 presents our data, sample, and methodology used to examine what factors were associated with deforestation in the cattle supply chain. Chapter 3 focuses on key findings and messages to better target properties with deforestation and improve monitoring. Chapter 4 provides concluding remarks.

2. Methodology

Sample and data. We used our unique and powerful cattle supply chain database, the "Brazilian Bovine dataBase" (B3), to characterize the properties and the parts of the supply chain that had high rates of deforestation after the CA. B3 is based on publicly available data such as the Guide to Animal Transport (GTA) that tracks movements of cattle between properties and to slaughterhouses, property boundaries, and deforestation and legal compliance data. The Brazilian Ministry of Agriculture, Food, and Livestock (MAPA) uses the GTA to ensure animal health standards and track animal vaccinations record, in part to satisfy international trading partners who want to guarantee the health of meat or animals (Bowman et al., 2012). Federal law requires that ranchers register GTA paperwork prior to moving animals between properties or to slaughter (Law 12.097 and Decree 7.623) and it is generally considered reliable (EU Directorate General, 2011; Klingler et al., 2018).

We used entity matching approaches to link the GTA cattle transaction data with the property boundaries to help us understand deforestation on cattle properties.[2] We considered the Amazonian states of Mato Grosso, Pará, and Rondônia, which account for 80 percent of deforestation and 80 percent of the cattle production in the Legal Amazon since 2000 (IBGE, 2019; PRODES, 2020). We analyzed all properties located in the Amazon biome that appeared in the GTA between 2013 and 2018 (2010 and 2018 in Rondônia) and that could be matched to a property boundary. This corresponds to 113,008 properties matched to a property registry. Our sample properties are linked to 47 percent of the transactions registered in the GTA and 55 percent of the heads transported during the period. It accounts for 50 percent of pasture on registered properties in the three states, as well as 29 percent of deforestation and 23 percent of total forest area in 2018. The sample includes all properties, both those exposed to the CA as well as those not exposed.

We categorized each property as a direct or indirect supplier based on its sales history. This is important because direct suppliers are generally larger properties with less remaining forest, and because they are subject to monitoring by the CA while indirect suppliers are not (Gibbs et al., 2020b). We considered properties to be direct suppliers if they sold cattle directly to slaughterhouses at least once. All other properties were considered indirect suppliers. Throughout our analysis, we characterize properties based on their activity in the years they registered cattle movement in the GTA, whether purchasing or selling cattle. From our sample of 113,008 properties with at least two hectares of pasture, 55,522 were classified as direct suppliers and 57,486 as indirect suppliers. Additionally, we gathered information from a set of 30,000 auxiliary properties that did not appear as selling cattle in the GTA, but which shared an owner and municipality with a property in the GTA. Although the auxiliary properties are not part of the main sample, we used them to create three variables characterizing properties in the main sample (main properties).

We used a set of 30 variables that characterize these properties **(SEE TABLE S1 FOR MORE DETAILS)**. The variables fall into eight categories: role in the cattle supply chain, market context, production and productivity, property land characteristics, land use context, public policy context, auxiliary properties, and confinements/ high-volume properties.

2. We provide additional details on how we link GTA transactions and property maps in the Supplementary Information.

Characterizing compliant and non-compliant suppliers. We classified properties in our sample as those with and without deforestation. We used PRODES Amazon deforestation maps from 2010 to 2018. We considered a property to have deforestation if they had at least 6.25 hectares of deforestation[3] in a single year during that period.

We first compared properties with and without deforestation using normalized differences, which compares the average values of two groups in a scale-free way.[4] This initial analysis tested if suppliers with and without deforestation were significantly different in terms of the 30 characteristics of interest. These characteristics were transformed to have a mean of zero and a standard deviation of one, allowing for easier interpretation and comparison. The test reported the difference in means in terms of the standard deviation **(TABLE S2)**. We defined significant differences to be equal to normalized differences greater than 0.05. For each variable, we compared suppliers with and without deforestation.

Regression models to determine the main factors that influence post-CA deforestation. We examined which property characteristics were correlated with deforestation status using regressions. Our main model is a linear probability model that identifies the characteristics that are most related to the decision to deforest. It shows how a single variable was related to the likelihood of deforestation while holding all other variables constant, thereby isolating the relationship between that single variable and deforestation. As in the difference of means test, all variables were normalized to a mean of zero and standard deviation of one. As robustness, we compared the results from the linear probability model with a linear LASSO and a logistic regression. Standard errors were clustered at the municipal level to account for correlation of the error between properties in the same municipality.

Field work. We supplemented our numerical analysis with field surveys of key actors in the cattle supply chain. These eight interviews in six locations were carried out using a convenience sample in the state of Rondônia. Interviewees included a Municipal Minister of the Environment (Rondônia), leaders of local farmers' associations in Rondônia, agricultural extension agents, and university researchers of the Federal University of Rondônia. Respondents were allowed to respond freely to a set of structured questions regarding determinants of deforestation on cattle ranches.

Quantifying the scale of deforestation passing from confinements and high-volume properties to CA slaughterhouses. We examined the role of confinements and high-volume properties in passing deforestation through the supply chain. We totaled the heads that non-compliant suppliers sold to confinements and high-volume properties. We built on the set of confinements identified by Vale et al., 2019 by including the top five percent of properties in our sample in terms of heads sold. Next, we quantified the amount of deforestation passing through these confinements and high-volume properties by tracking deforestation on the properties they buy from. To do this, we totaled the deforestation (ha, post-2009) on those properties we identified as selling to confinements and high-volume properties. We estimated the total deforestation annually, observing all years of deforestation prior to the sale of non-compliant cattle.

3. 6.25 hectares corresponds to the minimum mappable unit for PRODES.
4. Normalized difference has two main advantages. First, in comparison to a standard t-test, the normalized difference is not sensitive to the sample size. Second, the result of the normalized difference is directly interpretable in terms of how much average standard deviation is the mean from one sample to the mean of the other sample (Imbens & Wooldridge, 2009).

3. Key Findings and Messages

Expansion of CA to include more slaughterhouses is necessary to achieve zero-deforestation goals

Properties, both those that sell cattle directly and those that sell indirectly, were less likely to have deforestation when they were more exposed to CA. We defined exposure as the percent of federally inspected slaughterhouses (SIFs) within 145 kilometers that had signed the CA. Properties with deforestation, on average, had an exposure of 40 percent; properties without deforestation had an exposure of 58 percent **(FIGURE 1, TABLE S2)**. We found that the CA have yet to reach many properties, and this failure was correlated with deforestation. Thirty-six percent of properties with deforestation were not within 145 kilometers of a single slaughterhouse that signed the CA, compared to only 13 percent of properties without deforestation.

Properties are less likely to have deforestation when the market is dominated by slaughterhouses that have signed the CA.

However, it was not enough for a property to be in the supply zone of a single CA slaughterhouse if the property could still sell to slaughterhouses that had not signed the CA. Indeed, our model found that a property in a market that was fully controlled by the CA was ten percent less likely to deforest than a property with no exposure to the CA, after controlling for all other property characteristics **(FIGURE 2)**. Complementary to these findings, higher levels of exposure to the CA have been shown to increase the likelihood that a property increases productivity and investment (Moffette et al., 2020). These results demonstrate the importance of having not just one, but many slaughterhouses signed onto the CA in each region. This suggests that increasing the market share of CA slaughterhouses could make significant progress toward zero-deforestation goals by adding to the overall pressure to avoid deforestation and by reducing leakage of properties with deforestation to non-CA slaughterhouses (Alix-Garcia & Gibbs, 2017; Gibbs et al., 2020a).

FIGURE 1

Exposure to the CA by properties with and without deforestation

Boxes represent the 25th percentile, the median and the 75th percentile. Circles represent the mean.

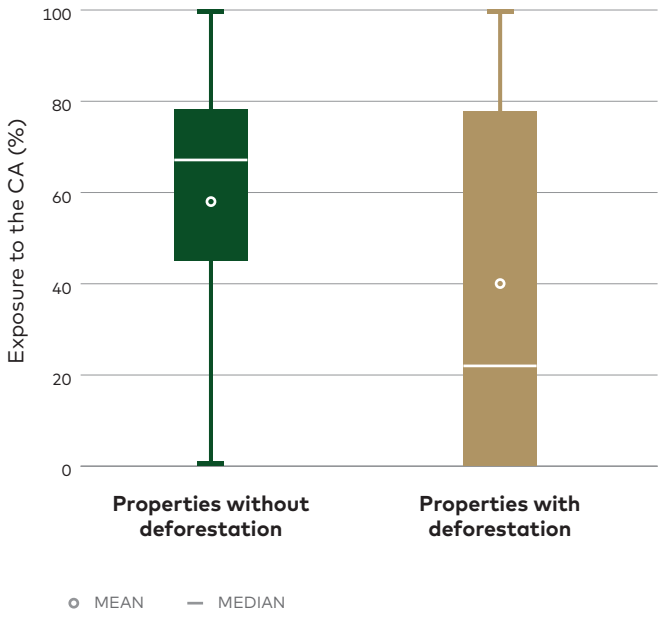


FIGURE 2

Results from regression models

We present coefficients with p-values smaller than 10% using a linear probability model that correlates deforestation with 26 property characteristics. Positive values are associated with more deforestation, negative values are associated with less deforestation, and coefficients larger in an absolute value are more correlated with deforestation. Coefficients extracted from LASSO and logistic regression are also presented as robustness.

Property characteristics associated with deforestation

Monitoring must include full holdings, not just single properties

Among all direct and indirect suppliers, one-third had more than one property. Owning multiple properties allows ranchers flexibility at the time of sale, as slaughterhouses only monitor one property out of all those a rancher owns (hereafter holding) per the requirements of the CA. Thus, ranchers with multiple properties may choose which property they report in the GTA, which determines which property the slaughterhouse monitors. This creates loopholes in the CA, as ranchers could choose to selectively report properties without deforestation, keeping those with deforestation outside the scope of monitoring. Of the properties that sold directly to the CA, 58 percent of direct suppliers were part of a larger holding.

After a rancher deforests one property, they are more likely to deforest the rest of their properties. These remaining properties should be targeted for monitoring and assistance.

Previous work has shown that deforestation is higher on the properties that ranchers do not use to sell cattle (hereafter auxiliary properties) (Gibbs et al., 2020b). Auxiliary properties that are co-owned with properties that sell directly to CA slaughterhouses have more than twice as much deforestation as the direct supplying properties themselves. Indeed, while 12 percent of direct suppliers have deforestation, 30 percent are a part of a holding that contains deforestation. This suggests that ranchers use the "cleanest" portions of their holdings to sell cattle, as it increases their likelihood to pass monitoring requirements. As a result, monitoring the entire holding is necessary to achieve zero-deforestation supply chains.

Respondents in the field also emphasized that we cannot limit our understanding of deforestation to the property-level; we should rather think about it as "cultural" and a "cycle." Indeed, interview respondents believed that a key determinant of whether a property was deforested was its rancher, and whether they subscribed to this "culture" of deforestation. To test for this pattern of deforestation by the same rancher, we compared the likelihood of finding deforestation on the main property that was listed in the GTA based on whether its auxiliary properties had deforestation. We found that deforestation in the main property and auxiliary properties go hand in hand. While 48 percent of main properties with deforestation had deforestation on an auxiliary property;

only 16 percent of main properties without deforestation had deforestation on an auxiliary property (TABLE S2). Consequently, while main properties are less likely to have deforestation overall, there are differences between the main properties that are part of a holding where the auxiliary properties do or do not have deforestation. The main property is more likely to have deforestation if it is owned by a rancher who deforests its auxiliary properties than if these auxiliary properties are also free of deforestation.

Properties that sell cattle directly to slaughterhouses are less likely to deforest than those that sell earlier in the supply chain.

The importance of monitoring full holdings is thus doubly important. First, deforestation will remain in CA supply chains until ranchers are also accountable for deforestation on their auxiliary properties. Second, auxiliary properties tell an important story about whether a rancher is likely to deforest their other properties. When a rancher deforests anywhere in their holding, the remainder of their properties are at higher risk of deforestation, and monitoring efforts and assistance should be targeted to them.

Most deforestation occurs on indirect suppliers

Deforestation in the cattle supply chain is highest on indirect suppliers. These properties, which sell to slaughterhouses infrequently or not at all, offer a challenge to the CA. In all supply chains, both CA and non-CA, properties were less likely to have deforestation if they sell directly to slaughterhouses more frequently. We found that a property became less likely to deforest as a higher proportion of their sales went directly to slaughterhouses, and properties that only sold directly were four percent less likely to deforest than properties that never sold directly. Even a single direct sale distinguished the likelihood that a property will deforest; 17 percent of properties that ever sold directly had deforestation, compared to 19 percent of those that never did.

FIGURE 3 shows the locations of direct and indirect suppliers with and without deforestation.[5] Notably, direct and indirect suppliers were collocated. Additionally, the same regions had high density of properties with deforestation for both direct and indirect suppliers. Direct suppliers are larger than indirect suppliers, so each property appears more prominently on the map.

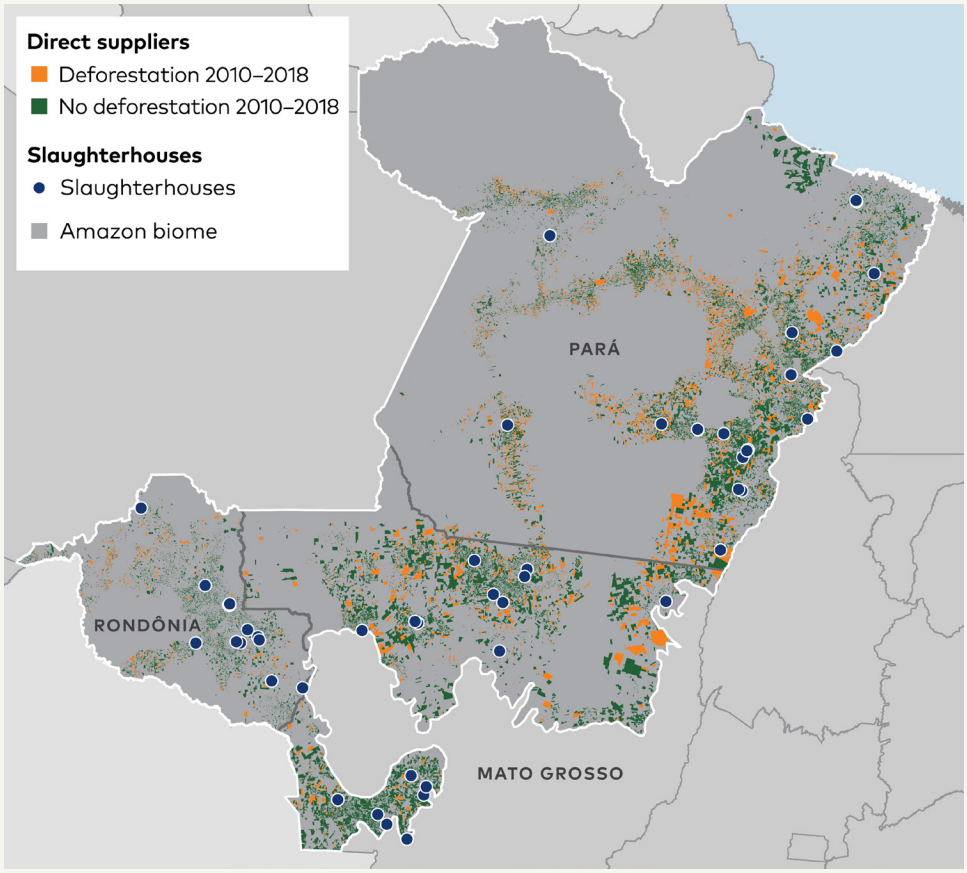
In CA supply chains, the difference between direct and indirect suppliers is even greater. Gibbs, et al. (2020b) show that 12 percent of direct suppliers to the CA had deforestation that violated those agreements, compared to 17 percent of indirect suppliers. Moreover, indirect suppliers deforested at least twice as much area as direct suppliers. Critically, direct suppliers in CA supply chains are monitored for deforestation, while indirect suppliers are not. This means that monitoring should be expanded to this part of the supply chain, as failing to consider indirect suppliers allows deforestation to continue in the cattle supply chain.

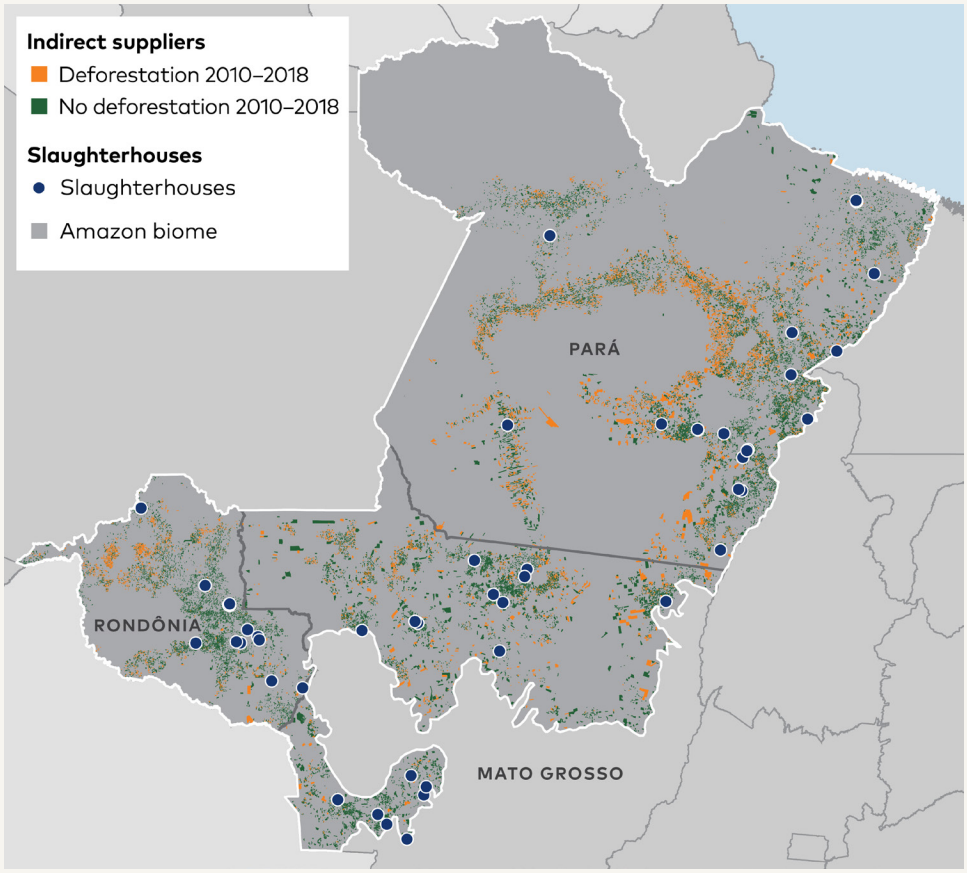
5. Here we categorize properties as direct suppliers if they ever sold directly to a slaughterhouse; all others are indirect suppliers. In our regression analysis, we use a continuous definition based on the percent of sales that go directly to a slaughterhouse.

FIGURE 3

Locations of direct and indirect suppliers with and without deforestation

Locations of direct suppliers with and without deforestation (top) and indirect suppliers with and without deforestation (bottom)





Deforestation for cattle production is more likely in remote areas

During field surveys, local farmers, government officials, and extension agents all emphasized the role of remote areas as sources of deforestation in cattle supply chains. They reported that deforestation occurs in remote frontier areas with large areas of remaining forest, with little occurring in settled "old frontiers." Remote areas, they explained, have very low oversight. Therefore, ranchers have a much lower risk of being punished for clearing.

Frontiers often overlap with areas that are poorly connected to the supply chain, i.e., far from slaughterhouses. Thus, respondents noted that ranchers have little incentive not to deforest. This was evidenced by the lesser influence of slaughterhouses that monitor for deforestation in frontier regions. Moreover, respondents noted that remote areas are often populated with indirect suppliers, whose weak ties to the supply chain undermine financial incentives.

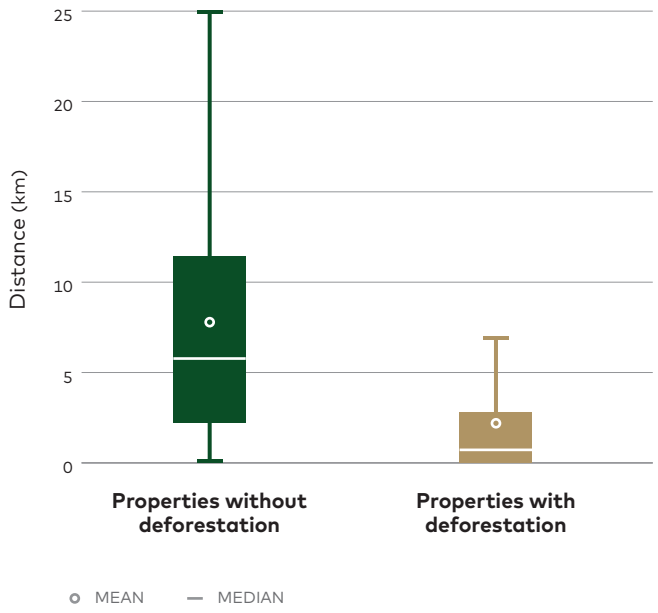
Properties with deforestation were four times closer to the deforestation frontier, two times farther from the highway, and 56 km farther from a slaughterhouse.

This local knowledge was confirmed by our analyses. Cattle suppliers with deforestation were farther from slaughterhouses and highways, and closer to the deforestation frontier.[6] On average, properties with deforestation were only two kilometers from the deforestation frontier **(FIGURE 4, TABLE S2)**, 27 kilometers from a highway **(FIGURE 5A, TABLE S2)**, and 279 kilometers from a non-CA slaughterhouse **(FIGURE 5B, TABLE S2)**. In comparison, properties without deforestation were eight kilometers from the deforestation frontier, 12 kilometers from a highway, and 223 kilometers from a non-CA slaughterhouse. Notably, distance to the deforestation frontier and distance to the nearest highway were two of the variables that most correlated with deforestation status **(FIGURE 2)**.

Additionally, properties with deforestation were more likely to be located in a municipality on the Priority List, which is a federal list that targets enforcement to municipalities with high levels of deforestation. Properties with deforestation had a 54 percent likelihood of being in a Priority Municipality, while properties without deforestation only had a 26 percent likelihood of being in a Priority Municipality **(TABLE S2)**. These municipalities are often located in frontier regions, further confirming that deforestation occurs in these remote areas.

FIGURE 4

Distribution of distances to the deforestation frontier among properties with and without deforestation



6. Deforestation frontier was defined as the patches greater than 25 ha of the aggregated recent deforestation (3 years, PRODES Amazon).

Large forested properties are more likely to be cleared

The percent forest remaining on a property was the single characteristic that best explained whether a property had deforestation between 2010 and 2018 **(FIGURE 2)**. Properties with deforestation, on average, still were 41 percent forested in 2009, while properties without deforestation were only 24 percent forested **(FIGURE 6A, TABLE S2)**. This corroborates our field surveys which suggest that ranchers with large tracts of remaining forest are more likely to deforest because it is more likely to go unnoticed, compared to a rancher who clears their last piece of remaining forest. Properties with deforestation were also twice the size of properties without deforestation. They were 451 hectares, on average, while properties without deforestation were 223 hectares **(FIGURE 6B, TABLE S2)**.

FIGURE 5: Distribution of distances

Distribution of distances to (a) the nearest highway and (b) nearest non-CA slaughterhouse among properties with and without deforestation

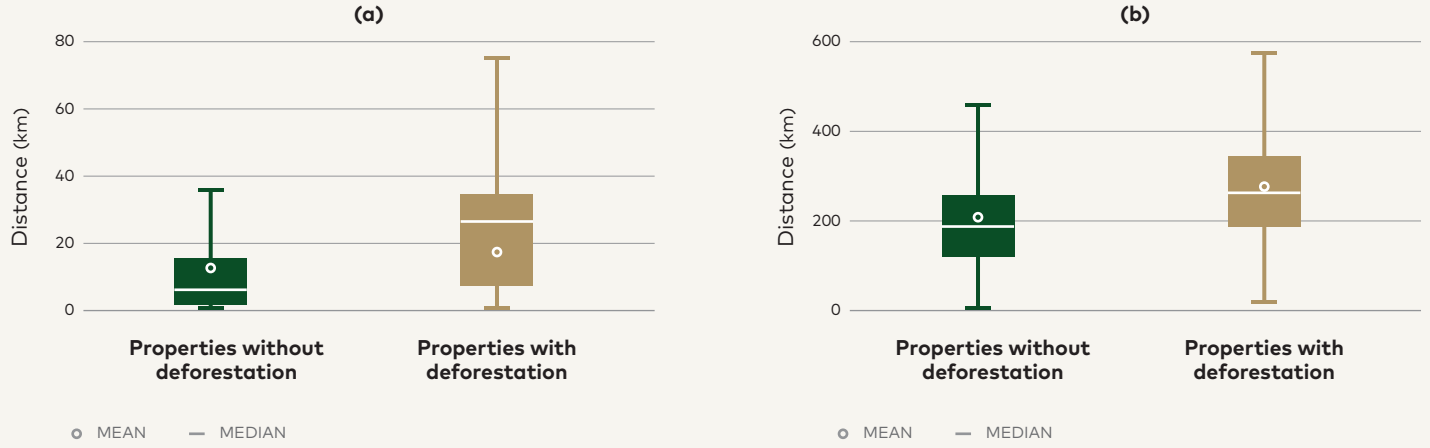
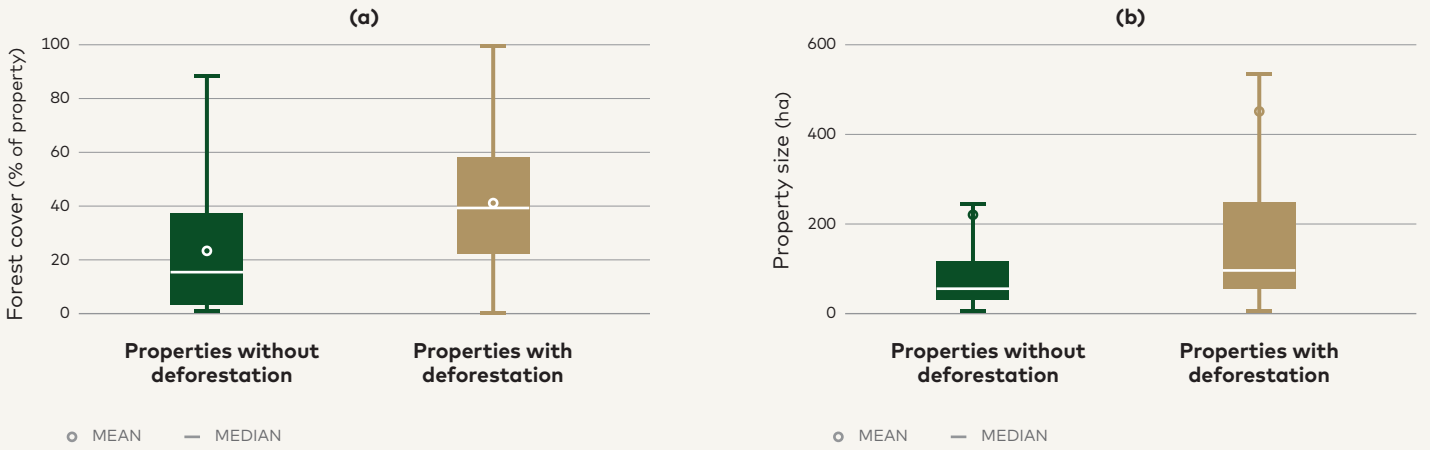


FIGURE 6: Distribution of forest cover

Distribution of forest cover (a) and property size (b) among properties with and without deforestation



Properties with deforestation were twice as large and had nearly twice as much remaining forest cover. Deforestation is less likely to be noticed when it occurs in large tracts of forest, according to field surveys.

Similarly, properties with 80 percent or more area in Legal Reserve, a signal that the property is likely in compliance with the Forest Code, were less likely to have deforestation (FIGURE 2). This suggests that, even though properties with large tracts of forest were more likely to deforest, those that still are compliant with the Forest Code had an additional incentive not to deforest. This is consistent with previous work that shows the effectiveness of public policy in slowing deforestation (Assunção et al., 2015; Alix-Garcia et. al, 2018).

Local respondents also explained that ranchers are likely to clear when their existing pasture becomes degraded. Because soil in the Amazon is relatively unsuited for agriculture, soils degrade quickly if care is not taken to maintain quality. Indeed, 40 percent of soils in the Amazon are considered moderately or highly degraded (zu Ermgassen et al., 2018). Because resources (both financial and educational) for soil investment remain scarce and land is abundant and inexpensive, expanding pasture is often more attractive than improving it. We find that 14 percent of the pasture is degraded on properties with deforestation, compared to ten percent on properties without deforestation (TABLE S2). However, this result is not significant when we control for other variables, including property size. This could be due to the fact that bigger properties generally have more pasture degradation.

These results suggest the importance of breaking the cycle of deforestation. Deforestation in the last ten years was not focused on small slivers of forest, but rather occurred on large properties that still had significant areas of remaining forest. These large tracts of forest are vital to the Amazon biome, and responsible supply chains should both support and monitor the ranchers that control them.

High volume of cattle and deforestation pass through a limited number of properties

A small number of properties purchase large numbers of cattle from non-compliant properties. They then sell these cattle to slaughterhouses, including slaughterhouses that signed the CA. In this way, they funnel hundreds of thousands of hectares of deforestation to slaughterhouses.

We investigated the role of the top five percent of properties in terms of their total outflow of cattle during our study period. This amounted to 5,648 properties, from which 227 never sold directly to slaughterhouses and 5,421 sold directly to slaughterhouses. Of the 5,421 high-volume properties that sold directly to slaughterhouses, 94 percent (5,112) sold to CA slaughterhouses.

The 227 high-volume indirect suppliers had a high deforestation footprint; 33 percent had non-compliant deforestation on their properties and they sold 719,000 heads of cattle during our study-period. High volume direct suppliers had an even higher deforestation impact on the supply chain. In the same period, they bought 3.9 million heads of cattle from properties with deforestation. The annual number of non-compliant heads passing through direct confinements and high-volume properties doubled over the period, from 385,000 in 2013 to 740,000 in 2018. Moreover, the hectares of non-compliant deforestation passing through these confinements increased by 140 percent between 2013 and 2018 (164,000 vs. 395,000 hectares). Importantly, 98 percent of this non-compliant area was potentially sold through a confinement or high-volume properties that supplied CA slaughterhouses.

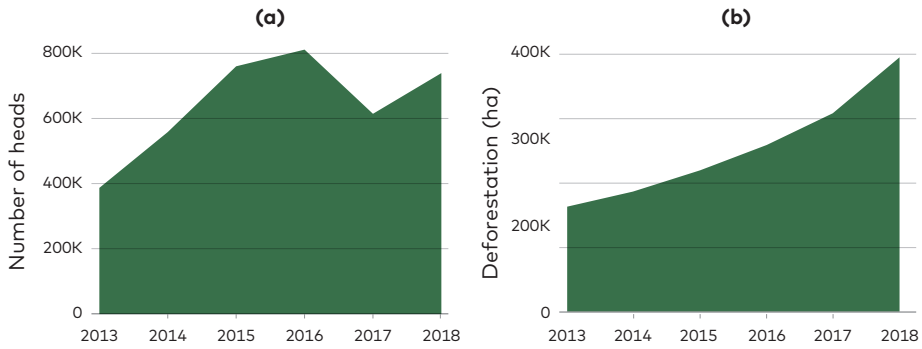
Similarly, Gibbs et al. (2020b) find that the top five percent of suppliers to CA slaughterhouses supplied 58 percent of the head of cattle linked to deforestation in CA supply chains. Since only 12 percent of high-volume CA suppliers are non-compliant, the integration of deforestation is not coming from themselves, but rather through deforestation by the indirect suppliers from which they buy. Indeed, they purchase from more than 100 indirect suppliers, on average, making it very likely that they purchase from a non-compliant supplier.

The importance of confinements and high-volume properties to cattle supply chains makes them a key component of efforts to reduce deforestation; they are relatively small in number, but they have an extraordinarily outsized role in supply chains. Enlisting them in the effort to monitor deforestation and ensuring they only purchase from clean suppliers could make inroads toward deforestation-free cattle arriving at slaughterhouses. Slaughterhouses should focus on solutions for these high-volume suppliers and support them in their efforts to purchase cattle from compliant indirect suppliers.

FIGURE 7

Heads with deforestation

Heads with deforestation (a) and total deforestation (b) sold to confinements and high-volume properties



4. Concluding Remarks

Deforestation remains in cattle supply chains, despite over ten years of zero-deforestation commitments in the sector. However, our results highlight the potential of expanded monitoring to reduce this deforestation and help companies meet their commitments. Since deforestation is most prevalent in specific contexts and can be addressed with changes to current monitoring strategies and requirements, we offer these suggestions for greener supply chains:

- Monitor all indirect suppliers and auxiliary properties of both direct and indirect suppliers.
- Ramp up attention in remote properties that are isolated from highways and/or slaughterhouses and that are close to the forest frontier.
- Target large forested properties for education and incentives to preserve forest as well as monitoring.
- Expand the CA to include all slaughterhouses.
- Ensure that high-volume direct suppliers have the information needed to avoid buying from their suppliers with deforestation and encourage slaughterhouses to work with these properties to find solutions.

Broader implementation of the CA to include all companies and all suppliers (direct and indirect) would likely enhance the forest conservation impacts. However, it is unlikely that ranchers and meatpackers will lead such transformations by themselves. Additional mechanisms beyond the CA are required to address some properties, particularly those that are more remote and less connected to the supply chain. Our results suggest that successful Supply Chain Initiatives should rely on complementarity and synergies between governmental and private actors. However, in the context of weakening of the Forest Code, declining transparency of public information, and general government support of economic expansion into forests, additional international market pressures and support are needed.

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Supplement

1. Supplementary methodology

Brazilian Bovine database (B3). This work builds on B3, a database that uses the Guide to Animal Transport (GTA), which tracks all movement of cattle for animal health purposes for the states of Mato Grosso, Pará, and Rondônia.[7] We downloaded, archived, standardized, and linked these GTA records with the CAR (Rural Environmental Registry) and other property maps, using sophisticated Data Science techniques including automated information extraction, string and entity matching, and machine learning.

The B3 database includes more than 500,000 properties and more than 10,000,000 transactions. B3 reveals a complete picture of the supply chain (including which supplier sells to whom, inflows and outflows of cattle from individual properties, and the purposes of movements from one property to another, etc.), and allows assessment of deforestation and legal violations such as forced labor.

Matching details. We identified properties in the GTA and property maps by their unique combination of municipality, farm name, and owner identification number (CPF or CNPJ). We matched properties in the two datasets using these unique combinations. Because we used multiple property registries, it is possible for a GTA transaction to match property maps in multiple registries. In cases where properties were matched with more than one map, we followed Sparovek et al. (2019) and prioritized data from the Terra Legal database (Ministério do Desenvolvimento, 2019), followed by the INCRA CCIR database (INCRA, 2019) followed by boundaries registered in the CAR (Sistema Nacional de Cadastro Ambiental Rural, 2019). We excluded properties that had an average of less than two hectares of pasture in the years they sold cattle, corresponding to one percent of the sample; these are likely to be cases where the single property map that we matched does not represent the full extent of the production area.

Sample representativeness. Since we aimed to compare properties with and without deforestation, we preferred to have a high degree of accuracy within our sample rather than higher coverage of the region. While other matching techniques result in higher coverage, these techniques result in some erroneous matches, which would bias our analysis. Our results are based on a sample composed of properties with well-documented property maps and GTA records that can be carefully matched. While our matching technique may over-sample properties that are highly connected to the supply chain (such as direct suppliers and key indirect suppliers) and under-sample new properties or those that sell infrequently, it remains the matching technique with the highest level of accuracy.

7. The Guide to Animal Transport documents all movement of livestock within Brazil in accordance with Law 12.097 and Decree 7.623. These records are stored by state sanitation agencies to ensure animal health standards and track animal vaccinations records, in part to maintain international trading partners who want to guarantee the health of meat or animals, particularly after some trading partners blocked Brazil following a Foot and Mouth Disease outbreak in 2000 (Bowman et al., 2012).

2. Supplementary tables

Table S1

CHARACTERISTICS OF IMPLEMENTATION CONTEXT	VARIABLES	DETAILED DATA DESCRIPTION	DATA SOURCE
Role in cattle supply chain	1. Direct supplier	Heads sold directly to slaughterhouse as a percent of all heads sold by the property.	B3 Guide to Animal Transport (GTA) Database
	2. Number of slaughterhouses they supply	Average of the number of slaughterhouses they supply, across active GTA years.*	B3 Guide to Animal Transport (GTA) Database
	3. Sales to high-volume slaughterhouse	Average percent of volume of sales to MAPA category AB1 or AB2 slaughterhouses, across active GTA years.*	B3 Guide to Animal Transport (GTA) Database
Market context	1. Exposure to CA slaughterhouses	The percent of slaughterhouses within 145 km of the property that have signed the TAC or G4. We average the exposure for 2010-2018.	Alix-Garcia and Gibbs (2017)
	2. Early exposure to CA slaughterhouse (2009/2010)	Dummy variable (0/1) indicating whether the property fell within 145 km of a CA slaughterhouse in either 2009 or 2010.	Alix-Garcia and Gibbs (2017)
	3. Distance to closest non-CA slaughterhouse	Average minimum distance (2010-2018) from a non-CA slaughterhouse.	Alix-Garcia and Gibbs (2017)
	4. Distance to nearest highway	Distance to nearest highway.	DNIT
Production and productivity	1. Outflow (heads) per year	Average volume of sales (cattle outflow) per year, across active GTA years.*	B3 Guide to Animal Transport (GTA) Database
	2. Inflow (heads) per year	Average volume of cattle purchases (cattle inflow) per year, across active GTA years.*	B3 Guide to Animal Transport (GTA) Database
	3. High volume of sale per transactions	Dummy variable (0/1) indicating whether the average sale volume per transaction per year, across active GTA years, is higher than 16 heads (the typical capacity of a truck to a slaughterhouse).*	B3 Guide to Animal Transport (GTA) Database
	4. Transactions per year	Average number of transactions per year, across active GTA years.*	B3 Guide to Animal Transport (GTA) Database
	5. Flow per hectare of pasture	Average outflows (heads) per hectare of pasture per year, across active GTA years.* Hectares of pasture are calculated for each year and based on the MapBiomas pasture and mosaic categories.	B3 Guide to Animal Transport (GTA) Database, MapBiomas
Property land characteristics	1. Property size	Property size in hectares.	Terra Legal, INCRA, SICAR, CAR
	2. Forest cover	Forest/natural vegetation area as a percent of property area as of 2009.	PRODES
	3. Degraded pasture area	Average percent of pasture area which is classified as degraded pasture in 2010, 2012, and 2014.	TerraClass
	4. Suitability for potential production	Potential capacity, sustainable animal units per hectare.	LAPIG

** Across active GTA years: years in which the property appears in the GTA with transactions either as a buyer or seller.*

Table S1 (continued)

CHARACTERISTICS OF IMPLEMENTATION CONTEXT	VARIABLES	DETAILED DATA DESCRIPTION	DATA SOURCE
Land use context	1. Distance to deforestation frontier	Distance to patches greater than 25 hectares of aggregated recent deforestation (2015–2018) (km).	PRODES
	2. Distance to nearest protected areas	Distance to nearest protected area (km).	MMA and FUNAI
	3. Regional grain production	Average municipal grain output (2010–2018) - corn and soymeal.	IBGE
	4. Soy	Area of soy production in hectares.	Rudorff and Risso (2015)
Public policy context	1. Forest code compliance (proxy)	Dummy variable (0/1) indicating whether the property reaches the natural vegetation requirement (% forest = 80% in the Amazon biome).	PRODES
	2. Forced labor	Dummy variable (0/1) indicating whether the property has ever been accused of forced labor.	Ministerio do Trabalho e Emprego (2018)
	3. Priority List	Percent of years the municipality was on the Ministry of the Environment's Priority List (also named "blacklist) from 2010–2018.	Ministério do Meio Ambiente (2018)
	4. Pará	Dummy variable (0/1) indicating whether any of the owners of a given property owns an additional property (where owners are either listed on the specific, selected property boundary or on the GTA transactions)	Ministério do Meio Ambiente (2018)
Auxiliary properties	1. Multiple property ownership	Total number of properties from all the owners of a given property (where owners are either listed on the specific, selected property boundary or on the GTA transactions).	Terra Legal, INCRA, SICAR, CAR
	2. Soy/Crop on auxiliary properties	Dummy variable (0/1) indicating whether an auxiliary property owned by the rancher has soy greater than 50 hectares	Rudorff and Risso (2015)
	3. Deforestation on auxiliary properties	Dummy variable (0/1) indicating whether an auxiliary property owned by the rancher has deforestation greater than 6.25 hectares in a single year	PRODES
Confinements	1. Distance to nearest high-volume property	Average minimum distance to a high-volume property across active GTA years.*	Vale, Gibbs et al. (2019), GTA, CAR
	2. Percent of sales to high-volume properties	Average percent of sales to high-volume property across active GTA years.*	Vale, Gibbs et al. (2019), GTA, CAR

** Across active GTA years: years in which the property appears in the GTA with transactions either as a buyer or seller.*

Table S2

	NO DEFORESTATION	DEFORESTATION	NORMALIZE DIFFERENCES
Supply chain characteristics			
Direct supplier (% of heads)	0.158	0.129	-0.087
Number of slaughterhouses they supply	0.343	0.241	-0.137
Average heads sold to high volume slaughterhouses	13.066	8.397	-0.023
Market context			
Exposure to the CA, 145 km	0.582	0.401	-0.380
Early exposure to the CA, 145 km	0.667	0.376	-0.431
Distance nearest non-CA slaughterhouse	210.284	278.907	0.391
Distance to nearest highway	12.439	26.869	0.438
Production and productivity			
Outflow (heads) per year	121.509	125.861	0.005
Inflow (heads) per year	112.466	110.480	-0.002
High volume per transaction (0/1)	0.441	0.523	0.117
Transactions per year	5.833	4.904	-0.040
Flow per hectacre of pasture	2.349	1.458	-0.039
Number of active selling years	4.463	3.883	-0.200
Property land characteristics			
Property size, ha	222.711	451.478	0.095
Forest cover (% of property)	23.904	41.412	0.527
Degraded pasture (% of total)	0.102	0.138	0.172
Suitability for potential production	3.630	3.454	-0.186
Land use			
Distance of deforestation frontier (km)	7.736	2.185	-0.697
Distance nearest protected area	33.950	24.346	-0.278
Regional grain production	0.065	0.040	-0.108
Soy (ha)	4.374	6.112	0.012
Public policy context			
Forest code compliance (proxy)	0.031	0.060	0.100
Forced labor	0.001	0.002	0.023
Priority List	0.260	0.539	0.445
Pará	0.472	0.677	0.299
Auxiliary properties			
Owner owns multiple properties (0/1)	0.334	0.332	-0.002
Soy/Crop on auxiliary properties (0/1)	0.041	0.048	0.024
Deforestation on auxiliary properties (0/1)	0.159	0.483	0.522
Confinements			
Distance to nearest high volume direct	5.166	7.441	0.185
Sales to high volume direct (%)	0.173	0.186	0.037
Observations	92,983	20,025	113,008