# Mechanisms of reduced supply chain policy effectiveness and leakage in the Brazilian cattle sector

Samuel Levy, Matthieu Stigler, Erasmus zu Ermgassen, Vivian Ribeiro, Rachael Garrett

**Abstract**: Spillovers of deforestation activities to untargeted actors and regions have the potential to greatly reduce the effectiveness of zero-deforestation supply chain commitments (ZDCs). While understanding of the direct impacts of supply chain policies has increased, the degree to which deforestation "leakage" occurs remains unclear due to methodological challenges and limited data availability. Focusing on the beef cattle sector, the largest driver of tropical deforestation globally, we use newly assembled temporally and spatially explicit property-level data on cattle sales and deforestation for the Brazilian state of Pará to better understand the processes leading to low ZDC effectiveness and local leakage. We find that incomplete adoption of ZDCs among cattle buyers allows producers to avoid ZDC policies and continue deforesting, accounting for 74% (450,273 ha) of the deforestation detected in our study. Yet laundering, whereby indirect suppliers to ZDC companies to whom ZDCs are not yet implemented continue to deforest and sell through "clean" direct suppliers is also linked to 96,311 ha of deforestation. This laundering appears to drive policy leakage, as direct suppliers of ZDC companies are significantly more likely to switch to an indirect ZDC supplier role after deforesting than direct ZDC suppliers who do not deforest. These results suggest that enforcing ZDC requirements among indirect suppliers is critical to meet the direct goals of supply chain policies. Yet they also suggest that to increase the broader effectiveness of ZDCs and end cattle-driven deforestation, increasing the adoption of ZDCs is more pressing than expanding their scope in the Amazon.

## 1.1 Introduction

The trade of agricultural commodities such as soybeans, cattle, palm oil, coffee, and cocoa is a cornerstone of the global economy and contributes to both economic development and rural livelihoods in producing regions (FAO, 2018). However, commodity production also drives nearly a third of global deforestation (Curtis et al., 2018), 30% of global greenhouse gas emissions (Xu et al., 2021), widespread biodiversity loss (Green et al., 2019), and has been linked to numerous cases of social conflict and land grabbing (Russo Lopes et al., 2021; Vos, 2016). There is, therefore, an urgent need to reduce the environmental impacts of commodity production while meeting rising global demand for food.

The firms which purchase these commodities from producers are relatively few, making these multinational companies a key leverage point to alter the behavior of the millions of producers they source from (Folke et al., 2019). In response to civil society pressure about their ongoing environmental impacts, an increasing number of these firms have made zero-deforestation commitments (ZDCs). These are commitments to not source products produced on recently cleared lands. ZDCs are commonly implemented using a market exclusion mechanism. This is where a company seeks to prevent deforestation from entering its supply chain by monitoring its suppliers, henceforth referred to as “ZDC suppliers”. If a ZDC supplier is identified as having cleared land, market access is blocked and the supplier can no longer sell to this firm (Garrett et al., 2019). By preventing the sale of deforestation-linked goods, it is hoped that the incentives to expand agriculture at the expense of native vegetation will be reduced, thereby resulting in conservation gains (Lambin et al., 2018).

There is growing evidence that with high sectoral coverage and rigorous monitoring and exclusion mechanisms, ZDCs can achieve significant reductions in deforestation among targeted suppliers. Studies have estimated that the Soy Moratorium ZDC in the Brazilian Amazon reduced soy-driven deforestation significantly (Gollnow et al., 2022; Heilmayr et al., 2020). In Indonesia, RSPO certification (a key tool by which ZDCs are implemented in the region) reduced deforestation on palm oil plantations by 33% (Carlson et al., 2018).

However, ZDCs are only effective as a large-scale conservation mechanism if the deforestation reductions they generate across amongst their suppliers are not offset by “leakage”, negative land use spillovers to non-targeted actors, commodities, and regions (Garrett et al., 2019; Meyfroidt et al., 2020). Opportunities to avoid policies, particularly through incomplete adoption or implementation, reduce the effectiveness of ZDCs at both local and global scales (Levy et al., 2021; Moffette and Gibbs, 2021; Pereira et al., 2020; Villoria et al., 2022). We define *incomplete adoption* of ZDCs as the presence of alterative buyers in a sector who have not committed to zero-deforestation. This likely reduces ZDC effectiveness by allowing farmers who sell to these uncommitted buyers to keep deforesting without being penalized (Garrett et al., 2019). We define *incomplete implementation* of ZDCs as the presence of substitutable land uses, regions, or actors outside of the scope of a ZDC. This allows actors not included in ZDC scope to continue deforesting, potentially while participating in ZDC supply chains (Garrett et al., 2019). Both of these processes allow pre-existing deforestation to persist despite ZDCs and also provide mechanisms by producers can evade policies, thereby driving leakage (Meyfroidt et al., 2018).

Both of these challenges are present in the cattle sector of the Brazilian Amazon. They are also particularly pronounced in comparison to the Soy Moratorium, the ZDC governing soy-driven deforestation in the biome, which has higher market coverage and less exposure to indirect suppliers than the Amazonian cattle sector (Moffette and Gibbs, 2021). It is possible that this may explain why ZDCs in the Amazonian cattle sector generated a 15% reduction in cattle-driven deforestation (Levy et al., 2021), while the Soy Moratorium achieved a 57% reduction in soy-driven deforestation (Gollnow et al., 2022).

Partial implementation of ZDCs in the Amazonian cattle sector has previously been linked to cattle laundering, a phenomenon whereby cattle reared on deforested land enter ZDC supply chains by passing first through intermediary “clean” farms who meet the firm’s sale requirements (Gibbs et al., 2016; Pereira et al., 2020). Indirect suppliers of ZDC firms, those producers who sell via intermediaries, were found to be 42% more likely to deforest their properties than direct suppliers, indicating substantial laundering (Skidmore, 2020). However, to date no paper has examined the role that ZDCs have on indirect suppliers' deforestation behavior, nor the leakage associated with this.

Partial adoption of ZDCs, while identified as a limitation of both soy and cattle ZDCs in the Amazon, is a more severe issue in biome's cattle sector where ZDCs' market share is lower than for soy (Gollnow et al., 2022; Levy et al., 2021). In both sectors it appears that non-ZDC firms purchase a substantial quantity of deforestation-linked products, a process this paper refers to as "ZDC avoidance". While studies have investigated partial ZDC adoption, no paper has yet managed to differentiate property-level deforestation in ZDC versus non-ZDC supply chains (i.e., the scale at which policies are implemented) to isolate ZDC avoidance, nor identify whether this process facilitates leakage for cattle or soy.

Several papers have investigated supply chain policies using property-level data (Rajão et al., 2020; Skidmore, 2020; Skidmore et al., 2021), but none of them have been able to isolate the impacts of local leakage processes at this scale. Alix-Garcia and Gibbs (2017) were able to identify the occurrence of local leakage due to differences in deforestation between early and late adopters of ZDC requirements. However, they were unable to determine the mechanism by which this leakage occurred. Additionally, Klingler et al. (2018) identified large numbers of non-compliant cattle producers but did not show that this non-compliant production entered ZDC supply chains. Skidmore (2020; 2021) found indirect suppliers to be linked to high deforestation, but not was not able to isolate whether this behavior was a ZDC induced spillover.

Here, we leverage newly assembled property-level, land use, and supply chain data related to cattle supply chains to substantially advance understanding regarding the mechanisms by which ZDC effectiveness is reduced in multi-tiered supply chains and the role of leakage within these processes. We do this by addressing the following questions: i) To what degree are supply chain policies reducing deforestation amongst direct ZDC suppliers in the Brazilian cattle sector?, ii) What are the characteristics that enable ZDC avoidance and cattle laundering?, iii) What is the relative contribution of each of these mechanisms to deforestation?, and iv) Can evidence be found that farmers who deforest take advantage of these mechanisms to avoid ZDC rules? To answer these questions, we focuse on the Brazilian Amazon cattle sector, which drives 70% of all deforestation in the Brazilian Amazon (Macedo et al., 2012; Project MapBiomas, 2020), and is the largest driver of tropical deforestation globally (Pendrill et al., 2019).

In our analyses we treat ZDC avoidance as all deforestation associated with non-ZDC suppliers. Likewise, we treat cattle laundering as all deforestation associated indirect ZDC suppliers. This therefore constitutes the total deforestation occurring via each mechanism, inclusive of business-as-usual (BAU) deforestation and leakage. We seek to determine both the scale of the deforestation associated with each mechanism and whether resultant leakage can be identified. The study encompasses the entire state of Pará, which has the largest cattle herd and the highest deforestation rates within the Amazon biome (IBGE, 2021a; INPE, 2021). This paper focuses on the impacts of the G4 Agreement, the only ZDC in the Brazilian cattle sector identified as employing monitoring and exclusion mechanisms, or associated with avoided deforestation (Gibbs et al., 2016; Levy et al., 2021) (See Methods for more information regarding ZDCs in the Brazilian cattle sector). Additionally, we analyze land use behavior between 2009-2020 and temporal changes in supply chain participation between 2014-2020.

## 1.2 Theoretical framework: local leakage, ZDC avoidance, and cattle laundering's impact on ZDC effectiveness

For leakage to occur, a policy must induce some direct behavior change that reduces the ease of deforestation, thereby indirectly triggering land use change elsewhere (Meyfroidt et al., 2018). We hypothesize **(H1)** that ZDCs have reduced deforestation among direct suppliers within ZDC supply chains. However, we also expect that both ZDC avoidance and cattle laundering both result in i) **BAU deforestation** (reduced additionality) **(H2, H3)**, as well as ii) **leakage** in the Brazilian cattle sector (**H4**) (Figure 1 .1 & Table 1 .1).

| | Direct supplier (tier 1) | Indirect supplier (tier 2+) |
|---|---|---|
| ZDC supply chain | Lower deforestation due to **policy effectiveness** | Higher deforestation via **laundering (BAU and/or leakage)** |
| Non-ZDC supply chain | Higher deforestation via **ZDC avoidance (BAU and/or leakage)** | Higher deforestation via **ZDC avoidance (BAU and/or leakage)** |

*Figure 1.1: Expected effect of ZDC implementation on deforestation by supply chain tier and policy segment ZDCs in the Brazilian cattle sector as well as the mechanism facilitating this effect. Laundering refers to cattle suppliers selling deforestation-linked cattle via compliant intermediaries into ZDC supply chains. ZDC avoidance refers to direct ZDC suppliers shifting to non-ZDC supply chains to avoid zero deforestation rules. Where this laundering/ZDC avoidance is a change from BAU, we consider it to be leakage. All lower/higher statements are considered relative to pre-ZDC implementation conditions*

Disentangling BAU deforestation (i.e., limited additionality) from leakage is challenging. Supply chains involve numerous actors and locations, with policy treatment varying at very local levels. This makes it difficult to distinguish treated and non-treated actors and BAU conditions (Arima et al., 2011; Meyfroidt et al., 2018).

Here, we argue that when BAU deforestation among non-treated farmers is allowed to continue, ZDC avoidance occurs, reducing ZDCs' additionality (Gollnow et al., 2022; Levy et al., 2021). ZDC avoidance drives leakage when producers who wish to evade ZDCs *change* from a ZDC to a non-ZDC supply chain specifically to avoid ZDC companies' deforestation penalties (Figure 1 .1 & Figure 1 .2). This evasion would increase deforestation in non-ZDC supply chains relative to BAU conditions. This could result in a bifurcation of the market, whereby supply chain membership is rearranged so that deforestation becomes a feature of non-ZDC production, potentially nullifying any additionality associated with ZDCs.

We further argue that when BAU deforestation among untreated indirect suppliers continues to enter ZDC supply chains, cattle laundering occurs, reducing ZDCs' additionality. Cattle laundering results in leakage when treated actors seek to become untreated, that is, when producers previously selling directly to ZDC firms who wish to deforest become indirect suppliers, selling their deforestation-linked cattle via intermediaries. If all deforestation which would have occurred among direct suppliers without ZDC adoption merely shifts upstream to indirect suppliers, it would completely nullify the additionality of the ZDC.

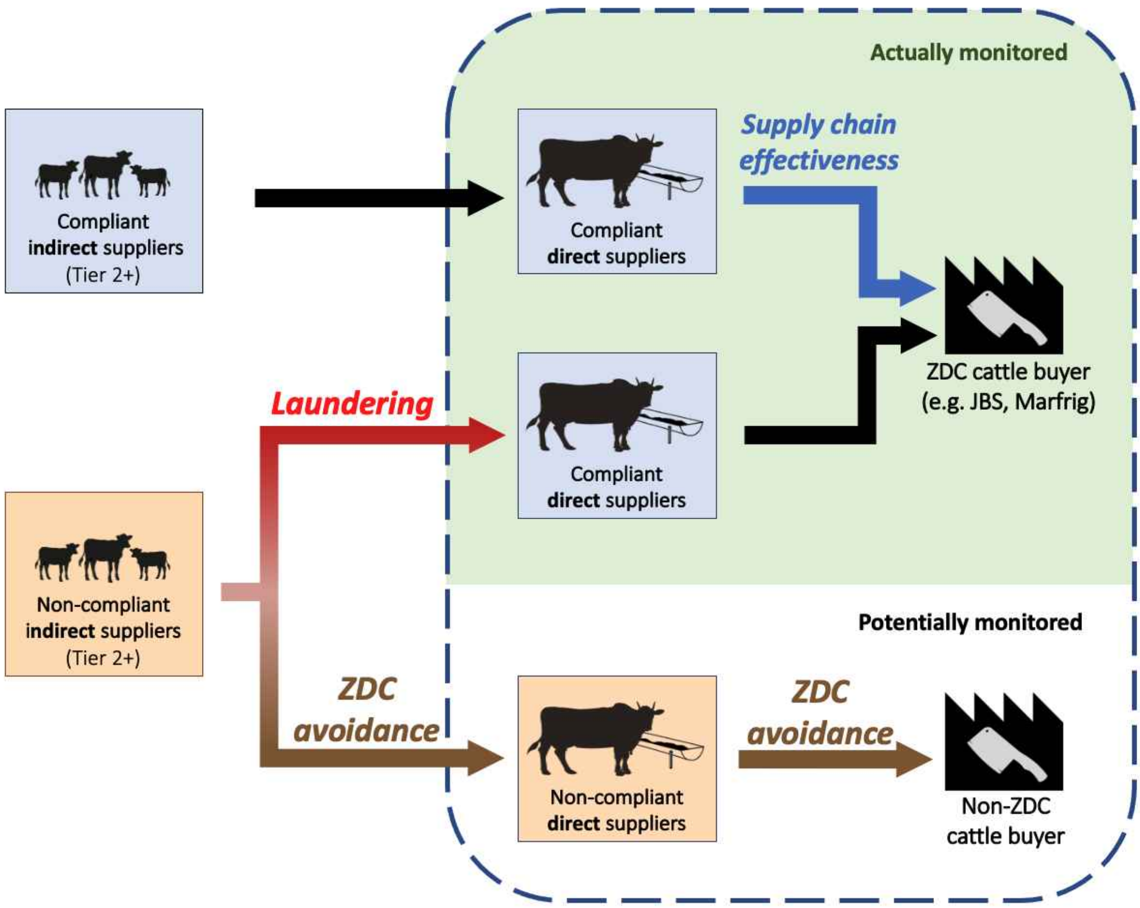


*Figure 1.2: Pathways indicating both the ways that ZDCs are expected to reduce deforestation and by which deforestation is able to continue in the Brazilian cattle sector, adapted from Gibbs et al (2016). Where ZDC avoidance or laundering results in deforestation over what would have been present under BAU conditions, this constitutes leakage.*

## 1.3 Methods & case study context

### 1.3.1 Case study context

We focus on the Brazilian state of Pará as it is a major hotspot for both cattle production and deforestation. Pará is the largest cattle producing state entirely within the Amazon biome, accounting for 24% of the cattle herd and 20% of the cattle slaughtered in the Legal Amazon region in 2020 (IBGE, 2021b, 2021a) as well as 44% of all deforestation within the Amazon biome in the same period (INPE, 2021). The state also accounts for 96% of Brazil’s live cattle exports, which are poorly understood, despite being associated with higher deforestation risks and more complex supply chains (de Sá et al., 2018; Ermgassen et al., 2020a).

Two cattle focused ZDCs exist in the Brazilian Amazon. The first is known as the G4 Agreement and was adopted by the four largest meatpacking companies in the region due to pressure from Greenpeace (Gibbs et al., 2016). The second, known as “Terms of Adjustment of Conduct” or TAC, was created by Brazilian public prosecutors to force meatpackers linked to illegal deforestation to change their behavior (Walker et al., 2013). TAC has been identified as the weaker policy due to slow implementation of monitoring and exclusion mechanisms, as well as the allowance of legal deforestation, all of which severely limit TAC’s ability to identify and exclude direct suppliers that deforest (Mengardo, 2018; Moffette and Gibbs, 2021). Likely as a result, only the G4 has been shown to reduce deforestation (Levy et al., 2021). Due to TAC firms’ failure to reduce deforestation (i.e., lack of additionality), we expect little laundering or market avoidance as a result of the policy and thus focus our analysis on G4.

Pará has moderate coverage with ZDCs, with 32% of cattle production (own calculation using GTAs)  and 45% of exports (Trase, 2020) taking place within G4 supply chains. Additionally, G4 market share has been found to vary substantially across the state, ranging from very high to very low (Levy et al., 2021). No cattle buyer in Pará has a ZDC that includes the monitoring and exclusion of deforestation-linked indirect suppliers as of publication, but due to increasing pressure surrounding the issue, all G4 firms have pledged to expand their policies to indirect suppliers in the future (JBS, 2021a; Marfig, 2020; Minerva Foods, 2020). In the cattle sector, it is the norm for cows to be reared on numerous farms prior to slaughter, so this lack of monitoring of indirect suppliers is expected to substantially limit G4 effectiveness.

Previous studies investigating ZDC effectiveness in Pará have found evidence that both the failure to include indirect suppliers and the presence of non-ZDC companies reduce policy effectiveness (Klingler et al., 2018; Levy et al., 2021; Pereira et al., 2020). However, these analyses were unable to differentiate between continued BAU and leakage, nor to statistically confirm laundering. These conditions make Pará a particularly suitable location to examine local leakage. We substantially advance from past work by being able to separate out laundering and ZDC avoidance processes as contributors to reduced ZDC effectiveness in the Brazilian Amazon cattle sector and by identifying which aspects of laundering and ZDC avoidance may be signals of leakage.

## 1.4 Methods

***Empirical approach***

We seek to identify a) whether ZDCs are effective at reducing deforestation among the treated population direct ZDC suppliers (H1, Table 1 .1), b) whether ZDC effectiveness is being reduced by laundering or ZDC avoidance (H2 & H3, Table 1 .1), and c) whether any of the deforestation associated with either cattle laundering or ZDC avoidance can be considered to be leakage (H4, Table 1 .1).

To establish whether ZDCs firms are effective at reducing deforestation amongst the producers who supply them directly, we examined whether deforestation on direct ZDC suppliers' properties was statistically different from deforestation associated with direct non-ZDC suppliers, both after ZDCs began and prior to their implementation. We did so to understand whether direct supplier deforestation was lower in ZDC supply chains over the study period and to establish whether this is a pre-existing feature of ZDC supply chains or began after policy adoption.

We identified the impact of ZDC avoidance and cattle laundering of ZDC effectiveness by first examining the characteristics of the Brazilian cattle supply chains. We did so to assess how exposed ZDC suppliers are to indirect sourcing and to establish how common it is for a ZDC supplier to shift to supplying non-ZDC companies and vice versa. Second, we quantified the deforestation associated with indirect ZDC suppliers (i.e., cattle laundering) and on the properties of non-ZDC suppliers (i.e., ZDC avoidance).

To establish whether leakage occurred via either of the mechanisms examined, we investigated whether the probability of transitioning to one of these untreated market segments was higher among ZDC producers who deforest. As supply chain data prior to policy introduction or for regions unaffected by ZDCs are unavailable, we lacked a suitable counterfactual that could disentangle leakage from BAU behavior directly. Instead, we examined whether avoidance behaviors exist that would likely not have occurred in absence of ZDC implementation. We did so as this would indicate that producers make use of incomplete ZDC implementation and adoption to evade policies and continue deforesting. We interpreted such evasion as a negative spillover and evidence of indirect land use change.

The procedure used to test each hypothesis is provided in Table 1 .1. To establish the difference between ZDC and non-ZDC suppliers at the direct and indirect level, we used t-tests to determine whether the difference in mean deforestation values was significantly different between groups. As a robustness check, we also used OLS regressions to control for potential confounding variables (Appendix B & Methods). Likewise, to determine the significance of the difference in probability of transitioning to non-treated supply chains after deforesting, we analyzed whether the mean transition probability was significantly different between producers who deforested and those who did not.

| Hypotheses | Mechanism | Test | Confounding/limiting factors |
|---|---|---|---|
| **H1:** ZDC requirements have been **effective** at reducing deforestation among direct ZDC suppliers | Cattle producers who deforest are blocked from sale to ZDC firms, reducing incentives to deforest | 1. Deforestation on direct ZDC suppliers' properties **is lower** than on direct non-ZDC suppliers' properties.<br>2. Prior to ZDC adoption, no difference existed between direct ZDC and direct non-ZDC suppliers | These two tests capture ZDC effectiveness net of ZDC avoidance at the direct supplier level. However, they do not capture laundering effects and thus should only be interpreted as individual (local) supply chain effectiveness as defined by Garrett et al. (2019). |
| **H2:** The presence of non-ZDC cattle buyers reduces effectiveness via **ZDC avoidance** | Cattle producers can continue to deforest and still supply non-ZDC firms | 3. Suppliers regularly move from ZDC to non-ZDC supply chains | While low supply chain stickiness potentially makes avoiding ZDC companies easy, it does not reduce ZDC effectiveness unless deforestation occurs. |
| | | 4. Deforestation is **high** in non-ZDC supply chains | This detects the quantity of deforestation associated with ZDC avoidance. It does not establish whether this was policy-induced |
| **H3:** Failure to monitor indirect suppliers reduces effectiveness via **cattle laundering** | Deforestation-linked cattle can enter ZDC supply chain by passing through a deforestation-free direct supplier's property prior to sale to a ZDC firm | 5. ZDC firms supply chains include large numbers of indirect suppliers | A high indirect supply base increases the likelihood ZDC firms are exposed to laundering. However, effectiveness is not reduced unless deforestation occurs. |
| | | 6. Deforestation is **high** on indirect suppliers' properties | This detects the quantity of deforestation associated with ZDC avoidance. It does not establish whether this was policy-induced |
| **H4:** ZDC avoidance and cattle laundering are being used to evade policies, which drives **leakage** | Producers evade policies by shifting deforestation from treated direct ZDC properties to untreated non-ZDC supply chains or indirect ZDC properties | 7. Likelihood that direct ZDC suppliers who deforest change to be a non-ZDC supplier (direct or indirect) **is higher** than among direct ZDC suppliers who don't deforest.<br>8. Likelihood that direct ZDC suppliers who deforest change to be an indirect ZDC supplier **is higher** than among direct ZDC suppliers who don't deforest. | Both tests only capture a small subset of total leakage as we only measure policy evasion that occurs within a two-year transition window (i.e., deforestation in year t, leading to supply chain change in year t+1). Leakage that occurs through higher level processes (e.g., policy-induced changes in forested land prices) or more complex forms of policy evasion (e.g., changes in supply chain that occur over a three- |

| | |
|---|---|
| | year window or greater) are not identified. |

*Table 1.1: Empirical approach used to identify local leakage due to ZDC avoidance and laundering in the Brazilian cattle sector and key confounding/limiting factors. Tests 3, 7, and 8 pertain to changes over time and tests 1, 2, 4, 5, and 6 pertain to the differences across groups.*

### *Determining the locations and supply chain linkages of cattle producers*

The location and spatial footprint of ranches was determined using property level data obtained through Brazilian rural property registry (CAR) records (SEMAS, 2021; Servico Florestal Brasileiro, 2021). These records contain georeferenced property boundaries, as well as data related to the property owner, property name, land use, and land regularization status and are legally mandated for all rural properties in the Amazon region. The linkages and flows of cattle between properties and from properties to cattle buyers (i.e., slaughterhouses and live exporters) was determined using Guide to Animal Transport (GTA) records, available from the Brazilian Ministry of Agriculture, Livestock and Food Supply (MAPA, 2019) and the Agricultural Defense Agency of Pará websites (ADEPARÁ, 2019). It is required by Brazilian law to register a GTA every time animals are moved from one location to another to ensure compliance with animal health and vaccination standards (Law 12,097; Decree 7,623). Producers are also legally required to register all rural properties in CAR (Law 12,615). For this study GTA data was available from 2014 until 2020, while CAR data was obtained in September 2020 and included all properties registered up to that date, unless deregistration occurred (Servico Florestal Brasileiro, 2021).

While this legal requirement meant coverage of both property and supply chain level data is high, producers are nonetheless known not to register themselves in CAR (Pereira et al., 2020). GTA availability varies over time during our study period (see Ermgassen et al., 2021), but total estimated slaughter was at or above 80% of IBGE slaughter estimates for 2016-2020, with low GTA coverage for the first two study years, 2014 and 2015 (IBGE, 2021b). Some cattle are likely moved without issuing a GTA, particularly between adjacent properties. However, evidence suggests that some laundering can be detected using GTAs (Earthsite, 2020) and external audits determined that GTA fraud is uncommon (EU

Directorate General, 2011). Overall, this means that while we have high confidence in confirmed links to ZDC slaughterhouses, our confidence in a lack of connection is lower, particularly for 2014 and 2015, where GTA coverage was limited. However, our approach to determining supply chain tier and policy treatment requires a single link to be considered a direct supplier, which limits the impacts of such missed links (see below section on identification of suppliers).

The datasets lack a shared identifier and both contain input errors, spelling inconsistencies, and incomplete entries. To resolve these issues, we cleaned both datasets to determine unique properties in each and joined them together using all available shared information. This included data on the municipality, farm name, owner's name, and the owner's unique tax number (CPF or CNPJ in Portuguese). Due to inconsistencies in spelling as well as input errors present in the two datasets, matching was achieved using a restricted Damerau-Levenshtein approximate string matching approach (Boytsov, 2011; Navarro, 2001). Full details regarding cleaning and matching procedures can be found in Appendix B.

Through our approach we identified 139,502 cattle producing properties in the GTA database, of which 56,233 (40%) could be linked to a georeferenced rural property in the CAR database. This corresponds to 794,030 (41%) of the GTAs issued over the study period. Our spatially-explicit cattle supply chain dataset is a small improvement on previous attempts to link GTAs to georeferenced rural property data in Brazil, which matched 37% of properties identified in GTA records in Pará and Mato Grosso (Skidmore, 2020). Properties that were matched in both datasets were on average 300ha in size, with 21% forest cover at the start of the study period (INPE, 2020). This is far below the 80% mandated by Brazil's Native Vegetation Protection Law (Law 23,793; commonly known as the Forest Code). Of these 56,233 properties, 51,975 were linkable directly or indirectly to a slaughterhouse or exporter and therefore were assessable for their supply chain membership. This attrition is likely due to incomplete GTA coverage over the study period (Skidmore, 2020). Amongst the total GTA population, 122,740 properties were linkable to slaughterhouses, meaning our reduced sample accounts for 42% of total number of GTA properties linkable to a slaughterhouse.

Our procedure required a match for both the property (i.e., property name) and the producer (i.e., farmer name and/or tax number) between the two datasets. We did so to avoid erroneous matches, which produced conservative but precise matches. While we only identified 40% of all properties present in the GTAs, the proportion of each supply chain tier and policy supply chain are similar between the spatialized sample and the full GTA population (Appendix B). We therefore expect that attrition primarily occurred due to random inconsistencies in property name/owner/tax number that we were unable to correct between the two datasets. However, there are three relevant groups that we likely unrepresented: rented properties, those who ceased production early in the study period, and indirect suppliers. As property renters usually only lease non-forested areas and/or lack the right to open additional areas (Puppim de Oliveira, 2008), this is unlikely to alter estimates of deforestation significantly. CAR registration has increased over time in Pará and despite being legally mandated is still incomplete, particularly for smaller producers and indirect suppliers. Additionally, some of these producers may not have obtained GTAs whatsoever, leading to them being missed by our approach (Pereira et al., 2020; Skidmore, 2020). This means properties that ceased production at the start of the study and indirect suppliers are both likely to not be registered in CAR. Most importantly, this means our estimates of ZDC impacts on indirect suppliers are likely an underestimate. Full details regarding the linking procedure are available in Appendix B.

### *Identification of direct and indirect supply to ZDC and non-ZDC buyers*

We processed cattle movement and property-level data into a graph database to give a network of properties, exporters, and slaughterhouses, linked by cattle movements. This graph included properties whose spatial footprint had been identified and unspatialized properties to maximize our the ability to link actors together. We determined whether an entity within our supply chain network was a cattle company (i.e., a slaughterhouse or live exporter) based on whether they were the recipient of GTAs designated as either *abate* (slaughter) or *exportação* (export) during the study period. We determined whether an entity was a ZDC signatory or not by comparing the tax numbers identified for each cattle company against tax numbers for known TAC and G4 signatories (Imazon, 2017; Trase, 2021)

We defined ZDC and supply chain tier status annually to capture changes in policy exposure over time. As farmers must comply fully with ZDC requirements to be able to sell any cattle directly to a ZDC company, we treated a producer as direct in every year they sold at least one cow to a ZDC cattle company directly (Figure 1 .3). For the same reason, if a direct supplier sold any cow to a buyer who had signed the G4 agreement, we treated the supplier as a ZDC direct supplier for that year. Thus, only suppliers who sold all of their direct sales in a given year to non-ZDC slaughterhouses were treated as non-ZDC direct suppliers. As indirect suppliers are currently untreated by ZDCs, we defined a ZDC indirect supplier as an indirect supplier who sold over 50% of their production to the direct G4 suppliers. We did so to ensure our categorization of indirect suppliers ZDC status included those actors most likely to be engaging in leakage behaviors. Any producers who did not meet the previous categories and sold at least once to a non-ZDC direct supplier was treated as a non-ZDC indirect supplier. Finally, if a producer sold exclusively to other indirect suppliers within a given year they were classified as Tier 3+ indirect suppliers (Figure 1 .3). Due to the complexity and distance of links involved, we did not link Tier 3+ producers to ZDC or non-ZDC supply chains. For research questions 1-3, which did not examine temporal trends, we characterized each producer’s predominant supply chain tier and ZDC status by the supply chain group they participated in most often between 2014 and 2020. 3,883 (7%) of producers exclusively functioned as Tier 3+ suppliers and were thus excluded from analyses for research questions 1-3.

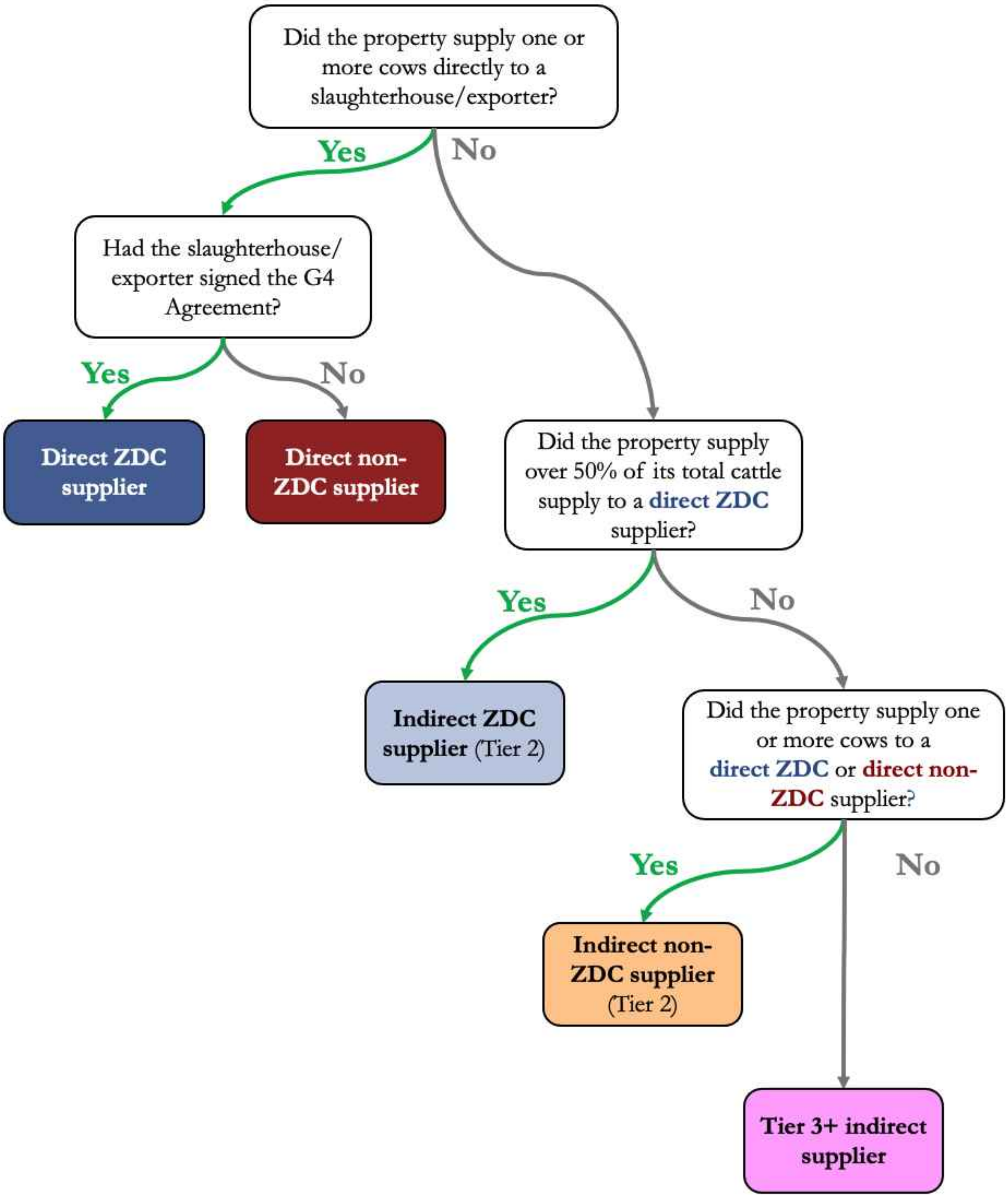


*Figure 1.3: Decision tree indicating how producers' ZDC treatment and supply chain tier were determined. This procedure was completed for every observation for each year providing an annually specific estimate of whether a producer was a direct ZDC, direct non-ZDC, indirect ZDC, indirect non-ZDC, or Tier 3+ indirect supplier. To determine a producers' supply chain tier and ZDC treatment over the whole study period, we assigned each producer to the group*

*they were most commonly a member of over the study period, excluding years where they did not sell and years where they sold at the Tier 3+ level.*

### *Determining property-level deforestation characteristics by supply chain tier*

As the G4 policy studied is concerned with deforestation by the signatories' suppliers in the years after the policy began in late 2009, irrespective of the resultant land use or quantity deforested, we determined the presence of deforestation on each property and the total area deforested since 2010 until 2020 for each property. Additionally, we calculated the total deforestation rate over this period, relative to the initial forest cover in 2009. To identify whether differences in properties' deforestation behavior already existed prior to ZDC implementation, we also estimated whether deforestation occurred on each property and the deforestation rate for 2009, using 2008 forest cover to calculate deforestation rates. Importantly this meant we included land use from years prior to when our supply chain data began, in line with previous studies (Skidmore, 2020). The significance of this is that while we can identify non-compliance with ZDCs (i.e., deforestation), we cannot confirm it was the same land user who we identify in the GTA records between 2014 and 2020. For this reason, we examined a producer's pre-2014 deforestation only for our non-temporal analyses.

We used PRODES (INPE, 2021) to determine deforestation and forest cover, as this is the product used by ZDC companies to monitor their suppliers for deforestation and implement their commitments (Greenpeace International, 2009; MPF, 2020). PRODES uses 30x30 meter pixels, with a minimum deforestation patch size of 6.25ha (INPE, 2021). As ZDCs also do not accept producers who are embargoed by the Brazilian Institute of the Environment and Renewable Natural Resources (IBAMA) or whose properties are within conservation units or indigenous lands, we also determined which properties were spatially overlapping with embargoed regions or protected areas (IBAMA, 2021; MAPA, 2021) (Appendix B).

To establish additional characteristics of each property that could confound results, we also determined the properties: a) smallholder status, b) if they had cropland, c) if they had secondary or “auxiliary” properties for which no GTA was issued but potentially were also used to rear cattle (Skidmore, 2020), d) if they were within a protected area, e) if they had a forest area greater than the legally determined minimum area (i.e., greater than 80%), f) the distance to a G4 or federally inspected (SIF) slaughterhouse, g) the forest area prior to ZDC adoption in 2009, h) the presence of degraded pasture. We also calculated i) whether a property was within a municipality which had been prioritized by the Brazilian government as a location for which additional anti-deforestation measures were required, j) whether the property was ever embargoed by IBAMA, k) the percentage of each property’s pasture area which was degraded, and l) the percentage of each property that was secondary forest. Full methods for the calculation as well as further details on the reason for inclusion are available in Appendix B.

## 1.5 Results

### 1.5.1 Supply chain polices are likely reducing deforestation amongst direct ZDC suppliers

We found that direct ZDC suppliers were 18% less likely to deforest than those directly supplying non-ZDC firms since ZDCs began in 2010 (34% vs. 40%, p-value <0.001) (Table 1 .2). Additionally, ZDC suppliers’ deforestation rates over the same period were 63% lower than their non-ZDC counterparts (9% vs. 14% of initial forest area, p-value <0. 001). Our results also indicate that prior to the implementation of ZDCs, no statistical difference was present in either the likelihood of deforestation occurring or deforestation rates between properties we identified as selling primarily to direct ZDC and direct non-ZDC suppliers (Table 1 .2). However, direct ZDC suppliers did have a lower and significantly different initial forest cover remaining as a proportion of their total property area (16% vs. 23%, p<0.001). As both of direct ZDC and non-

ZDC suppliers' remaining forest proportions were significantly lower than the legal requirement in the region (80%), we do not expect any difference regarding ZDC suppliers' incentives to deforest legally.

| | Direct suppliers | | | Indirect suppliers | | |
|---|---|---|---|---|---|---|
| Variable | Non ZDC | ZDC | Diff | Non ZDC | ZDC | Diff |
| No. properties | 20499.0 | 2434.0 | | 19332.0 | 5823.0 | |
| **Deforestation 2010-2020**: | | | | | | |
| Deforestation rate | 13.9 | 8.5 | -5.42*** | 19.5 | 21.7 | 2.19*** |
| % with deforestation | 40.3 | 34.2 | -6.06*** | 47.7 | 49.9 | 2.16* |
| **Deforestation 2009**: | | | | | | |
| Deforestation rate | 2.5 | 2.1 | -0.32 | 3.4 | 3.9 | 0.42 |
| % with deforestation | 13.5 | 12.6 | -0.96 | 16.1 | 18.4 | 2.39*** |
| **Additional characteristics**: | | | | | | |
| % smallholder | 31.6 | 13.8 | -17.78*** | 47.8 | 41.7 | -6.16*** |
| % small property | 77.4 | 51.6 | -25.77*** | 91.0 | 85.5 | -5.47*** |
| % with forest surplus | 20.4 | 14.8 | -5.56*** | 22.5 | 19.0 | -3.49*** |
| % ever embargoed | 4.7 | 6.0 | 1.28. | 5.8 | 7.0 | 1.17* |
| % within protected area | 2.1 | 1.4 | -0.68 | 2.0 | 2.0 | -0.02 |
| % in priority municipality | 42.0 | 65.1 | 23.17*** | 51.2 | 67.9 | 16.62*** |
| % with auxiliary properties | 29.7 | 35.0 | 5.3*** | 17.3 | 16.7 | -0.62 |
| % with degraded pasture | 97.9 | 99.1 | 1.14** | 98.2 | 98.9 | 0.67** |
| % with cropland | 21.1 | 26.4 | 5.31*** | 13.9 | 13.1 | -0.84 |
| % of property forested in 2009 | 23.3 | 15.6 | -7.72*** | 26.9 | 23.5 | -3.46*** |
| % of pasture degraded | 49.6 | 51.0 | 1.37 | 46.6 | 48.7 | 2.03*** |
| % of property secondary forest | 6.4 | 3.7 | -2.66*** | 6.5 | 4.6 | -1.87*** |
| Distance to nearest G4 SH (km) | 285.5 | 81.3 | -204.25*** | 237.3 | 119.1 | -118.24*** |
| Distance to nearest SIF SH (km) | 84.1 | 58.7 | -25.36*** | 86.0 | 72.7 | -13.24*** |

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; $.p < 0.1$. P-values adjusted for multiple testing using Holm (1979) procedure.

*Table 1.2: Equivalence of means tests for differences in deforestation occurrence and deforestation rates of ZDC and non-ZDC producers along with who are direct suppliers and indirect suppliers. P-values were calculated using t-tests and corrected for multiple testing following Holm, (1979). The method by which each variable was calculated can be found in the Methods and Appendix B.*

In contrast, indirect ZDC suppliers were 5% more likely to deforest than non-ZDC indirect suppliers (50% vs. 48%, p-value <0.05) and deforestation rates were 11% higher among indirect ZDC suppliers than indirect non-ZDC suppliers (22% vs 20%, p-value <0.001) (Table 1 .2). Importantly, it appears that indirect ZDC suppliers were also more likely than indirect non-ZDC suppliers to deforest prior to ZDC implementation, indicating parallel deforestation pre-trends may not have been present for indirect ZDC and indirect non-ZDC suppliers.

These results for the role of ZDC supply chain membership on direct and indirect supplier deforestation behavior are robust to alternate estimations where we control for differences in initial forest area, total property size, smallholder status, whether a property was within a protected area, distance to the nearest federally-inspected slaughterhouse, and whether a farm was linked to auxiliary properties (additional properties linked to the same farmer which did not appear in the GTAs) (Appendix B). These findings show that farmers directly supplying ZDC companies have reduced their deforestation relative to direct non-ZDC suppliers and that such a difference in deforestation behavior did not exist prior to ZDC adoption. Additionally, we find that deforestation remains high in non-ZDC supply chains and amongst indirect ZDC suppliers, likely due to cattle laundering and ZDC avoidance.

### 1.5.2 Indirect sourcing and sale to non-ZDC firms are widespread and sourcing relationships and supply chain position are highly fluid

Both the sale of cattle to ZDC firms via intermediaries and to non-ZDC firms are found to be commonplace in Pará's cattle sector. 100% of slaughterhouses and exporters had indirect suppliers within their supply base and 76% of individuals, 69% of the total land area and 67% of cattle sales occur within non-ZDC supply chains (Figure 1 .5). On average, cattle buyers were supplied by 12 suppliers directly and 73 suppliers indirectly per year (Appendix B). Amongst ZDC slaughterhouses this trend increases, with each ZDC slaughterhouses buying from an average of 41 direct suppliers and 428 indirect suppliers per year. The chain broadens out even further at the first tier. We found that direct suppliers were connected to an average of 4.6 indirect suppliers per year and that 93% of direct suppliers source cattle from at least one indirect supplier.

Actors often changed supply chain tier over the study period, with only 7,297 producers (14%) exclusively selling directly throughout the study period. 23,170 (45%) supplied consistently indirectly, and 21,508 (41%) changed between direct and indirect supply over time. Producers also often changed between participating in ZDC and non-ZDC supply chains, however less commonly than they changed supply chain tier. 3,155 (7%) were exclusively ZDC supply chains members, 36,325 (76%) exclusively sold to non-ZDCs and 8,612 sold to both ZDCs and non-ZDCs over the study. This means that while 19% of non-ZDC suppliers also participated in ZDC supply chains, 73% of ZDC suppliers were, directly or indirectly, involved in both ZDC and non-ZDC supply chains. These linkages indicate a highly intertwined sector with low segregation between supply chain tiers and moderate segregation between ZDC and non-ZDC supply chains. Additionally, producers sold on average for 3.4 years out of the 7-year study period, with non-sequential sale years common, potentially reflecting the multi-year nature of cattle production processes.

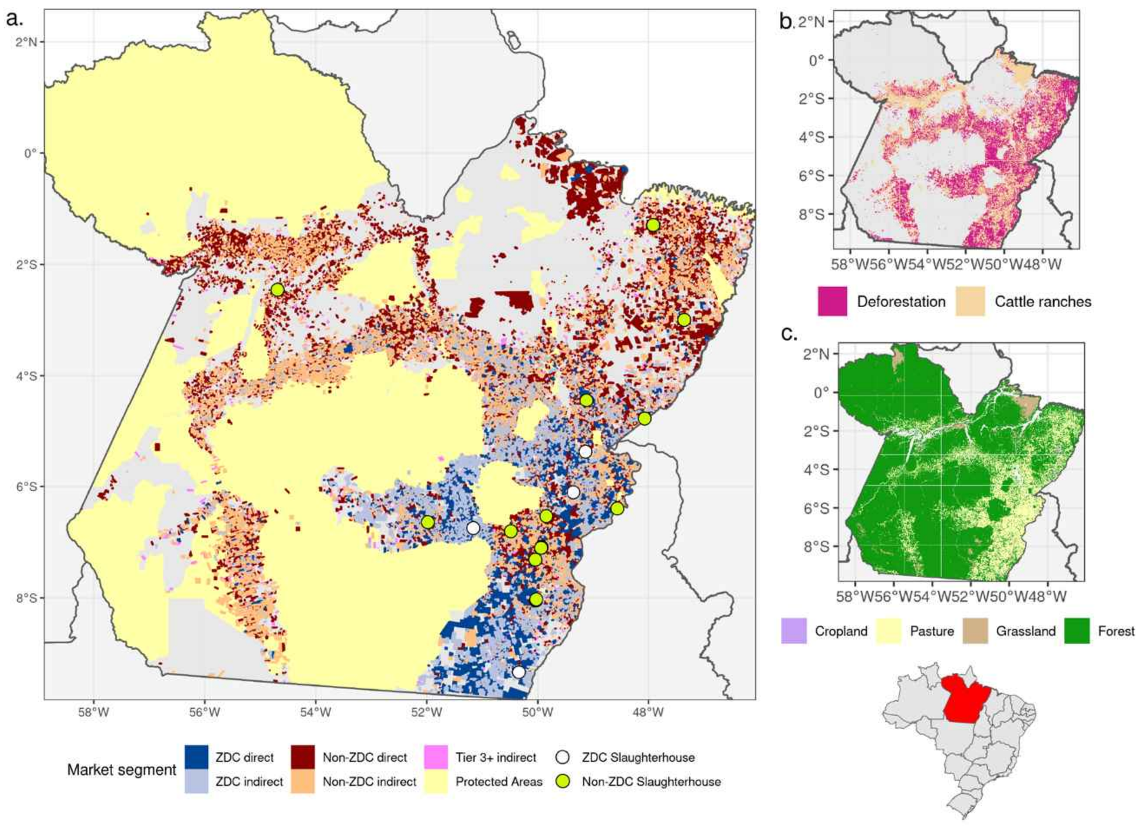


*Figure 1.4: Cattle ranches by supply chain tier and market segment (a.), cattle-driven deforestation since 2000 (b.) and land use cover in 2020 (c.), for Pará state, Brazil. ZDC producers are concentrated in Southwest Pará and indirect suppliers from both supply chains are closer to frontier regions with high levels of recent deforestation. Only federally inspected slaughterhouses (SIFs) are included on the map. Protected areas include indigenous reserves and federal conservation units (MMA 2021), deforestation and land cover are provided by*

*Mapbiomas (2021). Slaughterhouses and their ZDC status are provided by Trase (2021)*

Despite the fluidity between chains and tiers, there are strong spatial patterns to both supply chain tier and ZDC supply chain segment (Figure 1 .4 & Table 1 .2). ZDC suppliers are concentrated in the southwest of Pará, close to G4 slaughterhouses. We found Non-ZDC suppliers dominated in the north and west of Pará and Tier 3 and higher indirect suppliers were found across the state. Indirect suppliers are more likely to be close to protected areas and land deforested since 2010 in both ZDC and non-ZDC supply chains, particularly amongst indirect ZDC suppliers.

### 1.5.3 Both ZDC avoidance and cattle laundering occur in the Brazilian cattle sector and are associated with high levels of deforestation

Non-ZDC supply chains were associated with higher deforestation levels than ZDC supply chains over the study period (Figure 1 .5). Between 2010 and 2020, 74% of all deforestation in the cattle sector occurred in non-ZDC supply chains. 450,273 ha of ZDC avoidance deforestation was identified on the properties of non-ZDC suppliers over this period, in comparison to 119,306 ha on the properties of ZDC suppliers. Deforestation rates in ZDC supply chains were 2.76% over the 10-year study period, in comparison with 4.11% by non-ZDC suppliers.

Indirect suppliers in ZDC supply chains were associated with a far higher share of deforestation than indirect non-ZDC suppliers. In ZDC supply chains, 81% of all deforestation occurred via cattle laundering, with 96,311 ha of forest loss occurring on the properties of indirect ZDC suppliers (Figure 1 .4). In non-ZDC supply chains, indirect suppliers were associated with 50% of all deforestation, totaling 227,599 ha. Amongst ZDC direct suppliers, we found 22,996 ha of forest had been cleared since 2010, with a total deforestation rate of 0.9% over the study period. On the properties of indirect ZDC suppliers 96,311 ha of deforestation occurred at a rate of 5.48%. Non-ZDC direct suppliers cleared 222,674 ha of forest at a rate of 2.99%, while the indirect suppliers they purchased from deforested at a rate of 6.46% over the study period.

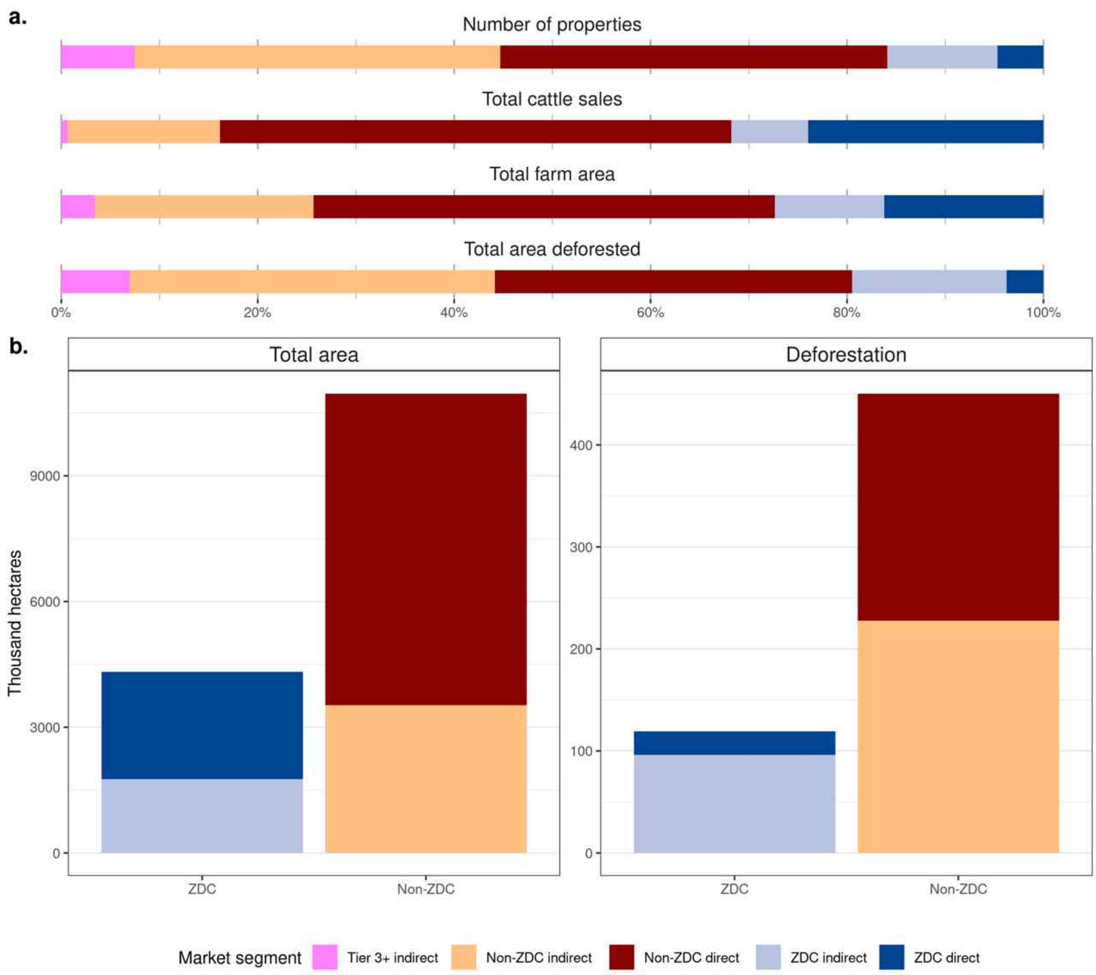


*Figure 1.5: Proportion of properties, cattle sales, total farm area, and deforested area by supply chain tier and ZDC segment (a.) and total area and total area deforestated by supply chain tier and segment in thousand hectares (b.) Tier 3+ indirect suppliers are omitted from plot b. Supply chain tier and policy treatment over the study period were determined by a producers' predominant supply chain position as described in the Methods. Deforestation is provided by PRODES (INPE 2021) and includes all deforestation from 2010 until 2020, which constitutes all full years since the G4 policy began in Pará.*

### 1.5.4 Direct ZDC suppliers who deforest evade ZDCs by shifting to indirectly supplying ZDC firms, but not by shifting to non-ZDC supply chains

We found that while a direct ZDC supplier who deforested was 18% less (45% vs. 54%, p<0.05) likely to remain a direct ZDC supplier than a deforestation-compliant producer, 45% still sold to a ZDC buyer the following year, indicating unexpectedly high levels of non-compliance amongst ZDC buyers (Figure 1 .6 & Table 1 .3). For non-ZDC direct suppliers, we found that deforestation had no effect on any of the transitions investigated and deforestation appeared to be entirely uncorrelated with producers' decisions regarding whom to supply the subsequent year (Figure 1 .6 & Table 1 .3).

| | Probability of transition from ZDC Direct | | | Probability of transition from Non-ZDC Direct | | |
|---|---|---|---|---|---|---|
| Transition to: | No deforestation | With deforestation | Diff | No deforestation | With deforestation | Diff |
| ZDC D | 54.39 | 44.79 | -9.6* | 1.97 | 1.86 | -0.107 |
| ZDC I | 3.67 | 10.43 | 6.764*** | 2.36 | 2.51 | 0.15 |
| Non-ZDC D | 16.55 | 12.27 | -4.279 | 49.25 | 50.65 | 1.403 |
| Non-ZDC I | 2.72 | 5.52 | 2.806* | 14.27 | 13.87 | -0.398 |
| Non-ZDC D/I | 19.26 | 17.79 | -1.473 | 63.52 | 64.53 | 1.006 |
| T3+ | 1.51 | 1.23 | -0.28 | 3.36 | 3.63 | 0.271 |
| No sales | 21.18 | 25.77 | 4.588 | 28.79 | 27.47 | -1.32 |

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; $.p < 0.1$

*Table 1.3: Probability in percentage points of transitioning from direct ZDC and non-ZDC supply to alternative supply tier and policy segments, distinguishing producers who deforested from those who did not. In the transition to column, "D" refers to direct suppliers, "I" to indirect suppliers, "D/I" to direct or indirect suppliers, and "T3+" to suppliers at the tier 3 or beyond level. The Diff column shows the difference between the transition probabilities together with the significance level, indicating whether this difference is statistically different from zero. Individuals who deforested after ZDCs commenced in 2010, but before supply chain data is available in 2014 were excluded.*

28% of direct ZDC producers who became non-compliant switched to supplying ZDC companies indirectly (10%) or to supplying non-ZDC companies (18%), either directly or indirectly. For direct ZDC suppliers who deforested, the chance of becoming an indirect ZDC supplier was 184% higher than amongst direct ZDC suppliers who had not deforested (10% vs.4%, p<0.001).

Unexpectedly, we found no conclusive evidence than non-compliant direct ZDC suppliers were more likely to switch to non-ZDC supply chains than those who had not deforested since 2010. While producers who deforested were more likely to become indirect non-ZDC suppliers, we found that, overall, no significant difference existed between G4 direct suppliers' likelihood to switch to non-ZDC supply chains due to deforestation (18% vs. 19%, p>0.1)

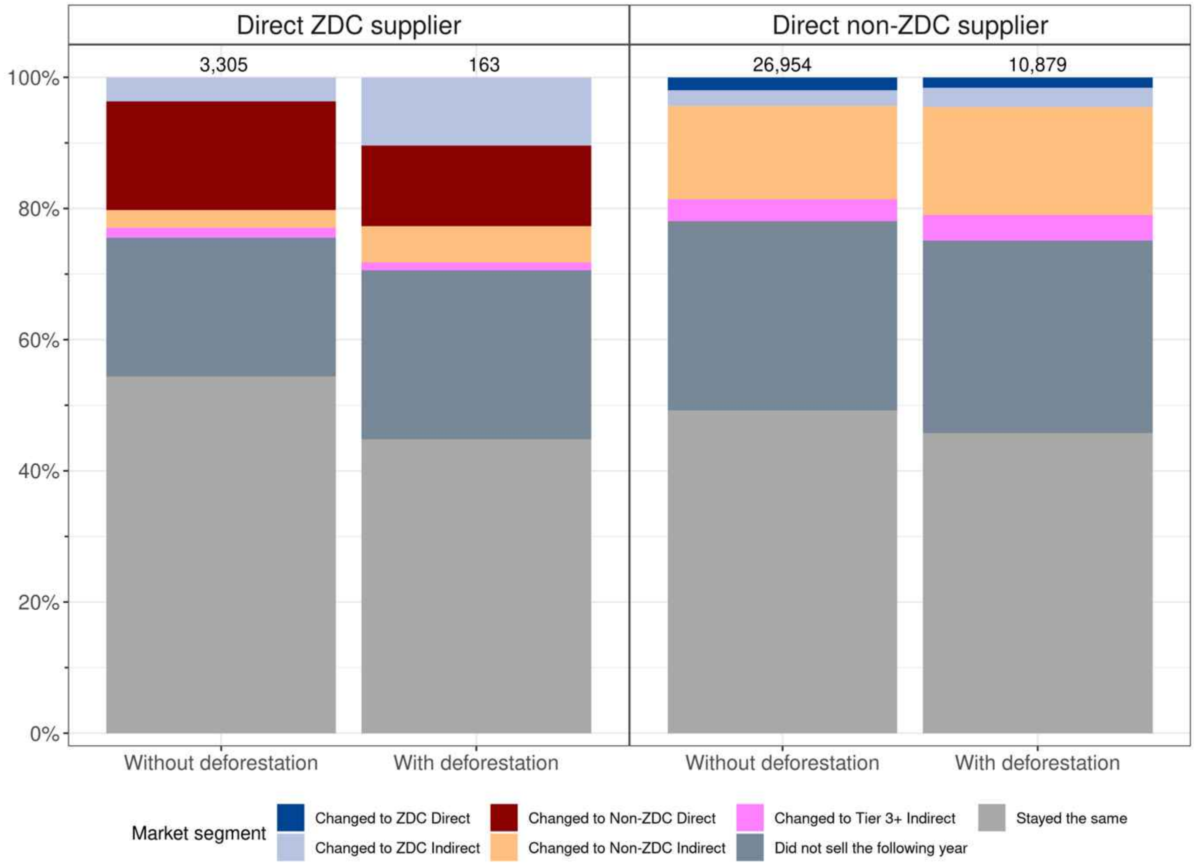


*Figure 1.6: Direct ZDC and non-ZDC supplier probability of transitioning to alternate supply chain tiers and policy segments, distinguishing between those who deforested (columns 2 & 4) and those who did not (1 & 3). The number of individuals in each group is shown at the top of each column. Individuals who deforested after ZDCs commenced in 2010, but before supply chain data is available in 2014 were excluded.*

## 1.6 Discussion

This paper sought to identify the role that incomplete adoption and incomplete implementation of cattle ZDCs have had on the effectiveness of these policies, through the mechanisms of ZDC avoidance and cattle laundering. We found that while ZDCs appear to be effective at reducing deforestation amongst the direct ZDC suppliers, the availability of non-ZDC firms and the exclusion of indirect suppliers from the scope of commitments allowed for large numbers of producers to continue deforesting, reducing the overall effectiveness of ZDCs. We were also able to identify that some of the reduced effectiveness of ZDCs is likely occurring due to leakage via cattle laundering. This is evidenced by our finding that direct ZDCs are more likely to transition to indirect ZDC supply after deforestation than those who did not deforest or those who supplied non-ZDC firms. However, we found no evidence for similar leakage behavior to be occurring via ZDC avoidance as producers were not more likely to transition to non-ZDC supply chains after deforestation.

### 1.6.1 ZDCs appear to be reducing deforestation amongst direct suppliers, but ZDC avoidance and cattle laundering limit effectiveness

Direct ZDC supply chains were associated with an 18% lower likelihood of deforestation than non-ZDC direct suppliers, a figure similar to previous estimates of the impacts of cattle ZDCs (Levy et al., 2021). While this estimate of ZDC effectiveness does not account for the impact of laundering, it does capture the process of both intentional (i.e., leakage) and unintentional ZDC avoidance by direct suppliers. We find that this overall ZDC avoidance (deforestation among direct and indirect non-ZDC suppliers) was associated with nearly five times as much deforestation as cattle laundering (deforestation among indirect ZDC suppliers) between 2010 and 2020, with 450,273 ha of primary forest loss occurring in non-ZDC supply chains and 96,311 ha on the properties of indirect ZDC suppliers. This suggests that ability of suppliers to simply avoid ZDC policies is the greatest challenge to their broader effectiveness.

While indirect ZDC suppliers were linked to 81% of the deforestation in ZDC supply chains, this equated to only 16% of total deforestation. It is important to note that while our results likely underestimate the impact of indirect suppliers, this underestimate occurs in both ZDC and non-ZDC supply chains (See Methods & Appendix B). It is therefore unlikely that this could explain the difference in the scale of deforestation associated with laundering and ZDC avoidance.

Despite these major weaknesses identified due to incomplete implementation and adoption of supply chain policies, our results provide compelling property-level and supply chain specific evidence that ZDCs are having some conservation impact Brazilian Amazon. Specifically, that they are likely resulting in reduced deforestation on the properties of direct ZDC suppliers. This overall reduction in deforestation among direct ZDC suppliers appears to be greater than the amount of increased deforestation among indirect ZDC suppliers and among all non-ZDC suppliers, indicating some net additionality of the policy. However, as this paper potentially under sampled indirect suppliers, further work needs to be done to confidently establish such additionality.

### 1.6.2 Laundering drives leakage, while non-ZDC markets facilitate BAU deforestation

We found strong evidence that laundering is a mechanism by which leakage occurs in the Brazilian cattle sector. Direct ZDC suppliers who deforest appear to be evading ZDC restrictions by switching from supplying ZDC firms directly to supplying them indirectly after deforestation. While we found suppliers in non-ZDC supply chains to be more likely to deforest than those in ZDC supply chains, we found no evidence that farmers are using the non-ZDC market to evade ZDCs and we are therefore unable to differentiate such deforestation from BAU behavior. It is possible that for farmers who wish to avoid commitments, the transaction costs of shifting upstream are lower than shifting to new suppliers. Non-ZDC slaughterhouses and exporters are associated with lower prices, either by paying less per kilo of estimated carcass weight or by downscaling animals' estimated carcass weights (Cammelli et al., 2022; de Oliveira et al., 2017). Additionally, should alternative buyers be further away than ZDC buyers, this would also incur additional transport costs (Boechat and Parré, 2018). We expect these low transaction costs associated with laundering to be particularly true for farmers who possess multiple properties, or kinship/friendship networks that allow access to deforestation-free properties for the purpose of cattle laundering (Skidmore, 2020).

Previous work has suggested that supply chain leakage should be more likely where stickiness, the maintenance of supply chain configurations over time, is low. This is because under such conditions producers can easily shift between supply chain tiers or policy segments to avoid a ZDC (Meyfroidt et al., 2018; Reis et al., 2020). Our work finds compelling evidence for this hypothesis within Pará as we find stickiness to be low between supply chain tiers, where leakage is observed, but is higher (although still relatively low) between ZDC and non-ZDC supply chains, where leakage is not observed. ZDC buyers are concentrated in the southwest of Pará and in this region, a large number of producers participate in ZDC supply chains (Figure 1 .4). Previous work found that the market share of ZDCs in southwestern Pará is very high (Levy et al., 2021). Therefore, for producers in this region, it may be challenging to switch to non-ZDC supply chains, providing additional evidence for ZDC supply chain stickiness, but not supply chain tier stickiness.

By not including indirect suppliers, ZDCs are incentivizing producers who wish to deforest to move upstream in ZDC supply chains as opposed to simply allowing this behavior to continue. While we can identify that leakage occurred due to laundering, we were unable to quantify the share of total cattle laundering attributable to leakage. This is because we lacked sufficient supply chain data prior to ZDC implementation for a counterfactual that could allow us to disentangle the quantity of leakage from BAU indirect supplier deforestation. However, as our analyses are mechanism specific, laundering induced leakage within our sample can be no greater than the total deforestation associated with indirect ZDC suppliers (96,311 ha). Therefore, while leakage due to cattle ZDCs' failure to monitor or exclude indirect suppliers due to their deforestation, the impact of this leakage is far smaller than ZDC avoidance.

This is significant as considerable pressure, including from international media (e.g., The Economist, 2020; The Guardian, 2020), has been put on ZDC suppliers to increase their commitments to indirect suppliers to eliminate cattle laundering. Resultantly, all companies within the G4 Agreement have pledged to expand their commitments to indirect suppliers, with JBS having already begun monitoring some of its indirect supplier base (JBS, 2021b). Our findings indicate that this will potentially result in major conservation gains. However, previous research has identified that indirect suppliers are unlikely to have the resources, information or documentation to comply with ZDCs (Pereira et al., 2020) and that expanding ZDCs to indirect suppliers is likely to have major negative livelihood impacts (Cammelli et al., 2022). This work lacks detailed socioeconomic data regarding the characteristics of the suppliers within our supply base, however we similarly find that indirect suppliers were smaller, closer to the forest frontier, and sold less cattle than direct suppliers, particularly relative to those selling to ZDC companies (Figure 1 .5 & Table 1 .3). While limited, our findings provide quantitative support for arguments that expanding ZDCs to indirect cattle suppliers may pose effectiveness-equity tradeoffs.

Indeed, given that we find that in Pará alone 29,041 properties primarily function as indirect cattle suppliers, corporate actions that have significant negative impacts on the wellbeing of these producers are likely to face high levels of resistance, which could undermine the acceptability of ZDCs in the Brazilian cattle value chain. Achieving a sustainable and equitable cattle sector in the Amazon likely requires ZDCs that can combat leakage while not excluding small-scale producers from potential financial benefits associated with production. Previous research suggests that such actions include capacity building, producer engagement, as well as both financial and in-kind support for marginal producers (Grabs et al., 2021). Such measures would help manage the transition for indirect suppliers to zero-deforestation production and close the leakage loophole they currently present for supply chain commitments.

## 1.7 Conclusion

Addressing commodity-driven deforestation requires conservation policies that can alter producers’ behavior at scale, despite these actors being spread across great distances and participating in complex, multi-tier supply chains. These characteristics make it challenging not just to govern deforestation, but also to assess the interventions themselves. This is particularly true for private policies, as they are implemented on a property-by-property basis. This local scale of implementation occurs as a producer is only treated if they sell to a company with a deforestation policy. Here, by determining both the supply chain tier and ZDC policy treatment of rural properties in the Brazilian Amazon, we were able to improve understanding regarding two of the key limitations of supply chain policies, incomplete adoption, and policy implementation. Additionally, we were also able to provide the first evidence whether leakage can be identified due to either of these loopholes.

Our findings suggest that efforts to increase the adoption of ZDCs, such as the G4, which are able to monitor and exclude non-compliant producers are expected to have greater additionality than efforts to reduce cattle laundering. Efforts that seek to align alternative ZDCs in the Brazilian cattle sector, namely TAC, with the G4, as are being attempted by the Brazilian Public Prosecutors Office (MPF, 2020) are likely to have major positive impacts for conservation. We found ZDC coverage to vary across the study region, with ZDCs particularly dominant in southwestern Pará. However, as this paper and previous work identified, much of the cattle sector of Pará and the wider Amazon region is currently not covered by an effective ZDC, such as the G4 (Ermgassen et al., 2020b; Levy et al., 2021). While increasing ZDC coverage may impact indirect suppliers' livelihoods, it is unlikely to have as negative an impact as efforts to increase ZDC scope to cover indirect suppliers, which they are most likely unable to meet (Cammelli et al., 2022; Pereira et al., 2020). We suggest, therefore, that reducing opportunities for ZDC avoidance is likely to be a particularly promising policy option to increase the effectiveness of ZDCs without significant negative equity impacts.

However, increased ZDC adoption would likely also increase the incentives for producers to launder cattle. Our findings indicate that laundering does not nullify the impact of ZDCs, but by placing indirect suppliers outside the scope of ZDCs laundering nonetheless both facilitates substantial deforestation. Additionally, this mechanism provides direct suppliers, who are usually well capitalized with largescale operations (Cammelli et al., 2022), the ability to conceal their behavior by moving upstream. Therefore, efforts that expand both the coverage and scope of ZDCs are of vital importance to avoid surpassing irreversible planetary boundaries, such as Amazon dieback (Lapola et al., 2018). But to avoid negative livelihood impacts, such implementation and adoption improvements should also be accompanied by additional measures by companies to support more marginal producers to comply with ZDCs. Our findings provide substantial evidence that ZDCs' effectiveness is limited. Nonetheless, it appears that these weaknesses do not nullify the deforestation reductions to direct suppliers. Therefore, while urgent improvements are needed to increase the rigor and coverage of ZDCs, these policies contribute to reduced tropical deforestation, likely conserving biodiversity, and carbon stocks in the process.

# Appendix

## A. Mechanisms of reduced supply chain policy effectiveness and leakage in the Brazilian cattle sector

### A.1 Standardization of GTA and CAR data

Before linking GTA and CAR data, we first processed both datasets to remove errors, standardize the data and to maximize the likelihood of accurate matches between the two datasets. This was achieved by a) removing all accents and special characters from farmer and property name data, b) capitalizing all text in farmer and property name data, c) removing repeated whitespace from all text strings, as well as any whitespace from the start and end of text data, and d) correcting common errors and standardized farm names (e.g., “FAZENDA”, “FAZ.” “FAZINDO” and “FAZEND” became “FAZ). Additionally, where data appeared to be in the incorrect variable (e.g., “FAZENDA X” listed under farmer name & “MR X” under property name), these data were moved to the expected variables. Where data contained long strings of text that appeared to pertain to various matching variables (e.g., a property name string containing information pertaining to a property, a farmer and the farmer’s tax number) and it was possible to split this data (e.g., via the presence of dashes), we did so. We also corrected tax number data by removing non-numeric characters. In 1% of GTAs, a unique CAR identifier was present, which was extracted and standardized to unsure string length and substring separators were consistent.

Due to the potential for the presence of numerous, non-identical recordings in both GTA and CAR datasets, we also sought to determine unique individuals in each dataset. This was done through two procedures. First, for both GTA and CAR data, observations were grouped by farmer and property characteristics (i.e., a match for both property name and farmer name and/or tax number). Due to the potential for continued errors and inconsistencies remaining despite our cleaning procedure, we also grouped properties by non-exact string matches using a restricted Damerau-Levenshtein approximate string matching approach (Boytsov, 2011; Navarro, 2001), allowing for up to two character insertions, deletions, substitutions or transpositions to determine a string match. For all GTA or CAR grouped observations, a new unique identifier was provided that is specific to the dataset and unique at the grouped level (i.e., each property we determined to be unique gained a unique CAR identifier and a unique GTA identifier). Tax number links had to be exact and no approximate string matches were accepted for this variable.

Second, for the CAR dataset only (as this is the only dataset with spatial information), we also determined spatial matches, to further group the data and also remove instances of double counting land use across two observations. Where the overlapping area of two properties was 80% or greater than the area of both of the overlapping properties individually, a match was determined, and the data were grouped. For CAR data matched through either method, the spatial data was unioned to ensure one spatial footprint per property.

## A.2 Linking of GTA and CAR data

In the 1% of data where a unique CAR identifier was present in the GTA data, this identifier was used to link the data, for all other data, we used the same procedure as to determine unique CAR and GTA properties. Using the cleaned and grouped GTA and CAR data as described above, we matched observations across the two datasets when we were able to identify a match for both a property identifier (i.e., property name) and a farmer identifier (i.e., tax number and/or farmer name). Where no match was found through an exact match, we then used Damerau-Levenshtein approximate string matching approach to determine inexact matches for property name and/or farmer name, while requiring an exact tax number match between the two datasets. Through this approach we were able to link 56,233 properties, of which 4,067 properties were unconnected to any slaughterhouse of cattle exporter and 191 properties also slaughtered cattle. In both cases, we excluded these observations, leaving 51,975 matched properties within our sample.

Failed matches occurred due to several factors, some of which have the potential to introduce some bias into results. First, we were unable to identify producers who were not registered in CAR as of 2020, when data was obtained. Although CAR registration is legally required in Pará, coverage is still incomplete, particularly for smaller producers and indirect suppliers (Pereira et al., 2020), meaning we likely over sample direct suppliers. Further, properties in the GTAs early in the study period which ceased to be present by the date CAR was obtained (i.e., due to purchase, abandonment or amalgamation with another property) may be missing from our CAR dataset should the property have been deregistered. Examination of the CAR data indicates many former properties that should have been removed from CAR were retained (e.g., locations fully covered by later registered properties), however we cannot fully determine the scale of deregistration due to a lack of suitable CAR data from earlier in the study period. Second, errors and inconsistencies in property identifiers (i.e., property name, owner name, tax number) between the two datasets likely caused attrition in the number of matches despite the matching procedure used. However, the prevalence of such errors is expected to be random and therefore not bias results (Skidmore, 2020).

Finally, as our procedure required matches for both property (i.e., property name) and producer (i.e., farmer name and/or tax number) to avoid erroneous matches (e.g., linking two different properties with the same property name), we were unable to link properties where the owner of the cattle established in the GTAs was not listed as the owner of a property in CAR, such as when the land used for cattle production was leased, an increasingly common occurrence in the Amazon (Assunção, 2008; Lima, 2020). Farmers who lease land often only rent the non-forest areas and/or lack the right to open additional areas however (Puppim de

Oliveira, 2008), meaning our failure to capture this population is unlikely to alter estimates of deforestation significantly. Our matching procedure therefore produces conservative but precise matches that likely underrepresent indirect suppliers and those properties which only traded early in the study period.

## A.3 Comparison of spatialized population to full GTA characteristics

To gain an indication of how representative the sample used within this study is, relative to the total cattle selling population (as recorded by the GTAs), we compared our results for the 51,975 matched properties against the full sample of 122,740 properties which could be linked at least once to a slaughterhouse during the study period (out of a total of 141,861 properties) for the number of links per slaughterhouse, the proportion of individuals in each group (ZDC direct/indirect, non-ZDC direct/indirect, T3+) and for the proportion of total sales each group accounted for. We found that we estimate a similar percentage of individuals for all groups except T3+ indirect suppliers and direct ZDC suppliers. T3+ suppliers were estimated to be 7% of the market in the sample, while the GTA data indicates that these suppliers were 11% of the individuals within the sector. For direct ZDC suppliers, which the sample estimates to be 4.7% of the total number of actors, the full dataset shows only 2.7% (Table A .2:). Sales proportions were highly similar across groups, with T3+'s contribution again being underestimated. Sampled sales indicate T3+ accounted for 0.7% of total sales, while the full dataset indicates 1.6%. Direct G4 sales were more similar here, with the sample estimating G4 directs account for 24% of sales and the full sample indicating 20.6% The number of individuals linked per slaughterhouse appears to be a slight overcount in general, with the proportion of individuals each slaughterhouse sources from slightly higher in the sample, compared to the overall population (Table A .1:).

While some differences exist in the supply chain characteristics sampled relative to the total GTA population, these differences appear minor. In particular, as the largest discrepancies appear to be among Tier 3+ indirect suppliers, who we do not link to either ZDC or non-ZDC slaughterhouses, this is unlikely to affect our results. It is possible, however, that the lack of difference found is due to the large number of properties in both the full and reduced datasets that cannot be linked to slaughterhouses. While the extent of this issue is unknowable, it does reflect the incomplete nature of the GTA records themselves in Pará, which has been found by other authors (Skidmore, 2020).

## A.4 Supplementary tables & figures

| | ALL SLAUGHTERHOUSES | | G4 SLAUGHTERHOUSES | |
|---|---|---|---|---|
| | All GTA properties | CAR-linked properties | All GTA properties | CAR-linked properties |
| Tier 1 | 18.80 | 11.85 | 51.81 | 40.95 |
| Tier 2 | 128.39 | 72.85 | 699.03 | 428.41 |
| Tier 3 | 502.55 | 284.27 | 4185.00 | 2378.32 |
| Tier 4+ | 35,620.98 | 17,819.39 | 46,243.45 | 22,916.18 |

*Table A.1: Mean annual number of properties sourced from per slaughterhouse. Number of suppliers are differentiated by supply chain tier, with Tier 1 being direct suppliers, and Tiers 2 onwards being indirect suppliers. Tier 2 is equivalent to ZDC and non-ZDC indirect suppliers. Tier 3 and Tier 4+ are equivalent to Tier 3.*

| Supply chain Segment | Total sales (%) | | No. individuals (%) | |
|---|---|---|---|---|
| | All GTAs | CAR-linked | All GTAs | CAR-linked |
| ZDC direct | 20.6 | 24.0 | 2.7 | 4.7 |
| ZDC indirect | 9.2 | 7.8 | 12.0 | 11.2 |
| Non-ZDC direct | 49.2 | 52.0 | 33.5 | 39.4 |
| Non-ZDC indirect | 19.4 | 15.5 | 40.5 | 37.5 |
| Tier 3+ indirect | 1.6 | 0.7 | 11.3 | 7.5 |

*Table A.2: Proportion of total sales and total number of individuals by ZDC policy treatment and supply chain tier, with results shown for both the total population of GTAs and for the sample used in this paper that were linked to*

*CAR. Results are broadly similar, but Tier 3+ indirect suppliers are undercounted, and the number of ZDC direct suppliers are over counted*

| Variable | Description & Calculation | Unit | Years | Source |
|---|---|---|---|---|
| Is smallholder | Any property with an area less than one Brazilian fiscal module, equivalent to legal definition of a *minifúndio* | 0/1 | NA | (Embrapa, 2018) |
| Is small property | Any property with an area less than four Brazilian fiscal modules, equivalent to legal definition of a *pequino propriedade* | 0/1 | NA | (Embrapa, 2018) |
| Has forest surplus | Any property where mean forest area over the study period was 80% of the total property area or greater, indicating compliance with the Brazilian natural vegetation requirements (the Forest Code) | 0/1 | 2008 - 2020 | INPE (2021) |
| Embargoed | Any property embargoed by IBAMA for breaching Brazilian environmental regulations, determined by intersecting embargo point/polygon data with CAR data during the study period. Any embargoes lacking spatial data were excluded. | 0/1 | 2008 - 2020 | (IBAMA, 2021) |
| Within protected area | Any property which intersects with a protected area, including all conservation units and indiginous reserves listed by the Brazilian Ministry of the Environment, excluding *Áreas de Proteão Ambiental*, the weakest protected areas where cattle production is often allowed (Marques and Peres, 2015) | 0/1 | NA | (MAPA, 2019) |
| Within priority municipality | Any property within a municipality that was included on the Brazilian Ministry of the Environment’s list of municipalities requiring additional monitoring and interventions due to high deforestation during the study period | 0/1 | 2008 - 2020 | (Ministério do Meio Ambiente, 2020) |
| Has auxiliary property | Any property where the tax number identified is shared with additional CAR properties for which no GTA could be matched, indicating both properties are part of the same portfolio, but only the linked property issued GTAs, potentially a form of indirect supplier leakage (Skidmore, 2020) | 0/1 | NA | (ADEPARÁ, 2019; SEMAS, 2021; Servico Florestal Brasileiro, 2021) |
| Has degraded pasture | Any property which had pasture designated as either moderately or severely degraded pasture during the study period. | 0/1 | 2008 - 2020 | (Project MapBiomas, 2020) |
| Percentage pasture degraded | The ratio of degraded pasture (either moderately or severely) over the total pasture area. Both degraded pasture area and total pasture area were calculated as the mean value over the study period | % | 2008 - 2020 | (Project MapBiomas, 2020) |
| Has cropland | Any property which was identified as having annual crops (including soy) during the study period. | 0/1 | 2008 - 2020 | (Project MapBiomas, 2020) |
| Initial forest cover | Forest area in the last year prior to ZDC implementation (2009) over total property area | % | 2008 - 2020 | INPE (2021) |
| Secondary forest | Mean secondary forest area over study period (defined as any forest vegetation that has been cleared and/or converted to human use at least | % | 2008 - 2020 | Project MapBiomas, 2020) |

| | | | | |
|---|---|---|---|---|
| | once) over total proterty area | | | |
| Distance to nearest G4 SH | Distance in km to the nearest G4 slaughterhouse that was operational during the study period | Km | NA | (Trase, 2021) |
| Distance to nearest SIF SH | Distance in km to the nearest federally inspected slaughterhouse (SIF) that was operational during the study period | km | NA | (Trase, 2021) |

*Table A.3: Description of additional producer characteristics displayed in Table 1 .2, and used as covariates in Table A .4 and Table A .5, including the temporal coverage, data source and details of how the variable was calculated.*

| | Deforestation rate, 2010-2020 | | % with deforestation, 2010-2020 | | Deforestation rate, 2009 | | % with deforestation, 2009 | |
|---|---|---|---|---|---|---|---|---|
| | Raw | Controls | Raw | Controls | Raw | Controls | Raw | Controls |
| (Intercept) | $13.92^{***}$ | $7.93^{***}$ | $40.28^{***}$ | $25.37^{***}$ | $2.45^{***}$ | $2.05^{***}$ | $13.53^{***}$ | $8.37^{***}$ |
| | (0.18) | (0.36) | (0.34) | (0.68) | (0.07) | (0.15) | (0.24) | (0.49) |
| ZDC direct | $-5.42^{***}$ | $-2.37^{***}$ | $-6.06^{***}$ | $-2.68^{**}$ | $-0.32$ | $-0.07$ | $-0.96$ | $-0.80$ |
| | (0.55) | (0.55) | (1.05) | (1.02) | (0.23) | (0.23) | (0.73) | (0.74) |
| Property area (ha) | | $-0.00^{***}$ | | $-0.00$ | | $-0.00^{*}$ | | $0.00^{***}$ |
| | | (0.00) | | (0.00) | | (0.00) | | (0.00) |
| Was smallholder | | $1.51^{***}$ | | $-14.00^{***}$ | | $-0.35^{*}$ | | $-6.63^{***}$ |
| | | (0.37) | | (0.69) | | (0.16) | | (0.50) |
| Initial forest area (ha) | | $0.00^{***}$ | | $0.00^{***}$ | | 0.00 | | 0.00 |
| | | (0.00) | | (0.00) | | (0.00) | | (0.00) |
| Within Protected Area | | $-4.54^{***}$ | | 2.42 | | $-1.00^{*}$ | | 1.35 |
| | | (1.17) | | (2.17) | | (0.49) | | (1.57) |
| Had auxiliary property | | $-1.80^{***}$ | | $-3.01^{***}$ | | $-0.37^{*}$ | | $-1.77^{***}$ |
| | | (0.36) | | (0.67) | | (0.15) | | (0.49) |
| Distance to SIF SH (km) | | $0.00^{***}$ | | $0.00^{***}$ | | $0.00^{***}$ | | $0.00^{***}$ |
| | | (0.00) | | (0.00) | | (0.00) | | (0.00) |
| Had cropland | | $-0.26$ | | 1.50 | | 0.02 | | $2.39^{***}$ |
| | | (0.42) | | (0.78) | | (0.18) | | (0.56) |
| $R^2$ | 0.00 | 0.04 | 0.00 | 0.10 | 0.00 | 0.00 | 0.00 | 0.03 |
| Adj. $R^2$ | 0.00 | 0.04 | 0.00 | 0.10 | 0.00 | 0.00 | 0.00 | 0.03 |
| Num. obs. | 22933 | 22933 | 22933 | 22933 | 22933 | 22933 | 22933 | 22933 |

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

*Table A.4: OLS regression results indicating the impact of ZDC supply chain participation on* ***direct*** *supplier deforestation rates and deforestation occurrence, both for 2010-2020, the years since ZDCs were implemented (columns 1 & 2) and in 2009, the year prior to ZDC implementation. "Raw" columns do not include covariates, while "Controls" columns include covariates controlling for variation in property area, smallholder status, initial forest area (in 2009), whether a property was within a protected area or not, the presence of auxiliary properties, the presence of cropland, and the distance to the nearest federally-inspected or "SIF" slaughterhouse.*

| | Deforestation rate, 2010-2020 | | % with deforestation, 2010-2020 | | Deforestation rate, 2009 | | % with deforestation, 2009 | |
|---|---|---|---|---|---|---|---|---|
| | Raw | Controls | Raw | Controls | Raw | Controls | Raw | Controls |
| (Intercept) | 19.55*** | 9.06*** | 47.74*** | 28.22*** | 3.45*** | 2.29*** | 16.05*** | 9.96*** |
| | (0.22) | (0.46) | (0.36) | (0.72) | (0.09) | (0.20) | (0.27) | (0.57) |
| ZDC Indirect | 2.19*** | 4.10*** | 2.16** | 5.21*** | 0.42* | 0.62** | 2.39*** | 3.18*** |
| | (0.45) | (0.44) | (0.75) | (0.69) | (0.19) | (0.20) | (0.56) | (0.55) |
| Property area (ha) | | −0.00*** | | −0.00* | | 0.00 | | 0.00 |
| | | (0.00) | | (0.00) | | (0.00) | | (0.00) |
| Was smallholder | | 1.95*** | | −13.25*** | | 0.88*** | | −5.93*** |
| | | (0.39) | | (0.61) | | (0.17) | | (0.48) |
| Initial forest area (ha) | | 0.00*** | | 0.00*** | | −0.00 | | 0.00** |
| | | (0.00) | | (0.00) | | (0.00) | | (0.00) |
| Within Protected Area | | −7.66*** | | 0.25 | | −1.14 | | −0.47 |
| | | (1.34) | | (2.10) | | (0.59) | | (1.67) |
| Had auxiliary property | | −2.71*** | | −4.26*** | | −0.59** | | −2.22*** |
| | | (0.49) | | (0.77) | | (0.22) | | (0.61) |
| Distance to SIF SH (km) | | 0.00*** | | 0.00*** | | 0.00*** | | 0.00*** |
| | | (0.00) | | (0.00) | | (0.00) | | (0.00) |
| Had cropland | | −0.52 | | 2.05* | | −0.02 | | 1.73* |
| | | (0.55) | | (0.87) | | (0.24) | | (0.69) |
| $R^2$ | 0.00 | 0.05 | 0.00 | 0.15 | 0.00 | 0.00 | 0.00 | 0.04 |
| Adj. $R^2$ | 0.00 | 0.05 | 0.00 | 0.15 | 0.00 | 0.00 | 0.00 | 0.04 |
| Num. obs. | 25155 | 25155 | 25155 | 25155 | 25155 | 25155 | 25155 | 25155 |

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

*Table A.5: OLS regression results indicating the impact of ZDC supply chain participation on* ***indirect*** *supplier deforestation rates and deforestation occurrence, both for 2010-2020, the years since ZDCs were implemented (columns 1 & 2) and in 2009, the year prior to ZDC implementation. "Raw" columns do not include covariates, while "Controls" columns include covariates controlling for variation in property area, smallholder status, initial forest area (in 2009), whether a property was within a protected area or not, the presence of auxiliary properties, the presence of cropland, and the distance to the nearest federally-inspected or "SIF" slaughterhouse.*

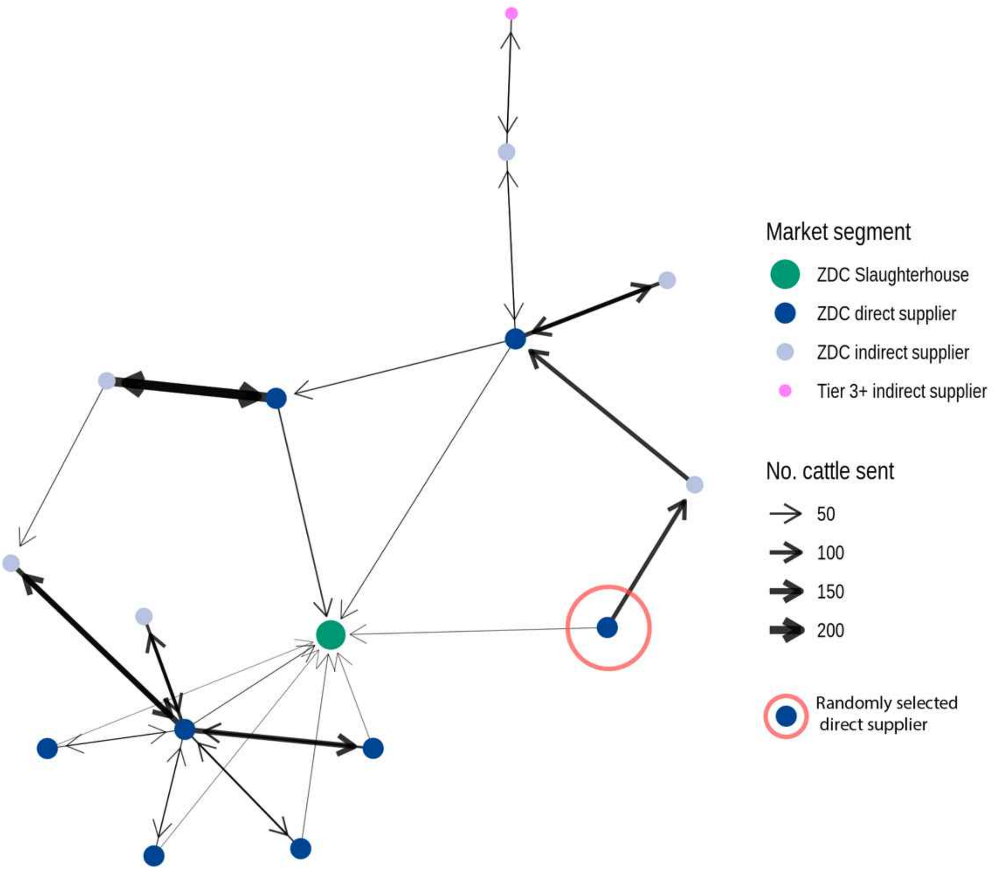


*Figure A.1: Example supply chain configuration, generated by randomly selecting a direct ZDC supplier (indicated with a red circle) and determining all links between this property and its trading partners in 2015. The direction of cattle movement is indicated by arrow direction, with two-way movements indicated by arrows pointing in both directions. Arrow width indicates the number of cattle moved. ZDC slaughterhouse is indicated in green, direct ZDC supplier in dark blue, ZDC indirect supplier in light blue and Tier 3+ indirect suppiers in pink.*

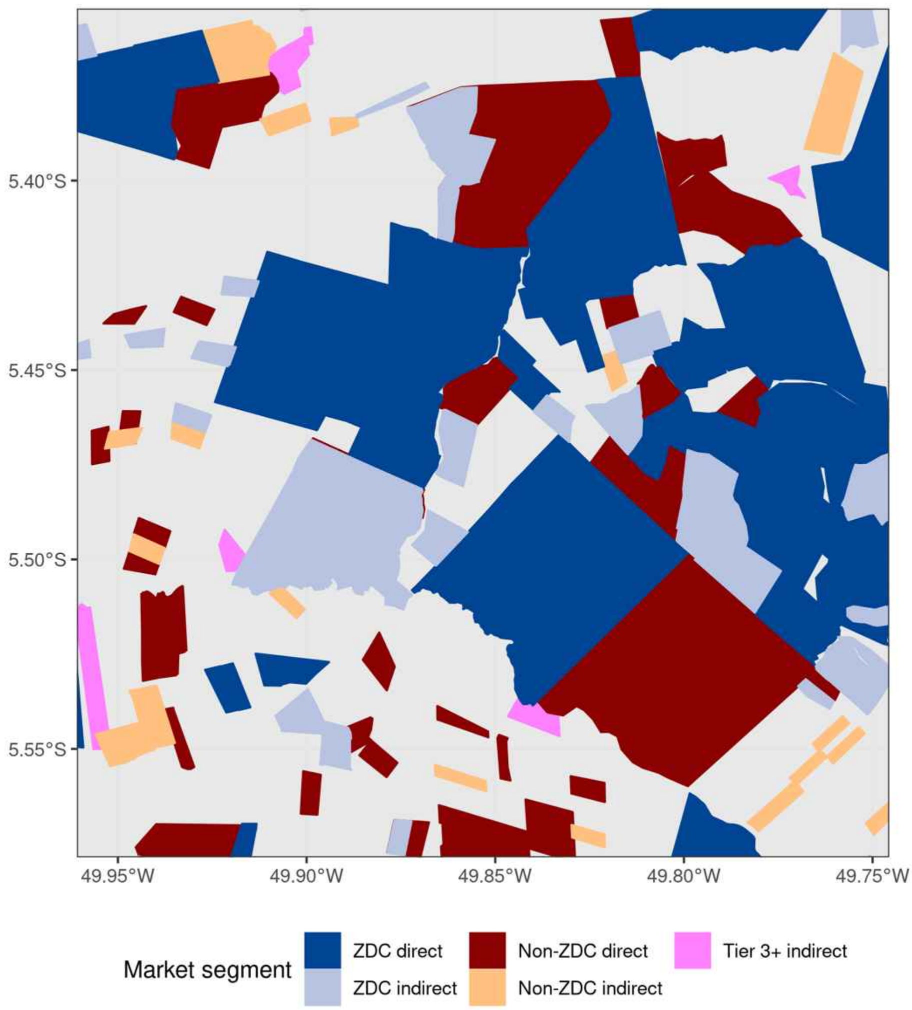


Figure A.2: Example landscape in Pará, showing the diversity of supply chain arrangements present. Direct ZDC suppliers are shown in dark blue, indirect ZDC suppliers in light blue, direct non-ZDC suppliers in dark red, indirect non-ZDC suppliers in light red, and Tier 3+ suppliers in pink.

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