

Deforestation and retail prices of Brazilian beef: a preregistered product-level econometric analysis

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Summary

Background Cattle ranching is the leading proximate driver of deforestation in Brazil. Efforts to eradicate deforestation could incur a trade-off between forest conservation and agricultural production, as conservation constrains the supply of new agricultural land and requires investments in traceability and improved agricultural production, potentially negatively affecting consumer welfare through increased retail prices. We estimated the effect of deforestation on consumer prices using supply chain data for 2980 beef products in Brazil.

Methods We investigated the effect of deforestation on retail prices using a regression model with neighbourhood fixed effects and covariates, including sanitary inspection level, product type, distance from meatpacker to retail store, supply chain monitoring, and retail store size. The model was informed by a directed acyclic graph and the analysis plan was preregistered.

Findings We found no evidence that deforestation rates in regions where beef products were sourced affected retail price (R\$–1.26/kg, 95% CI –2.66 to 0.13 [US\$0.26/kg, 0.515 to 0.025]). Similarly, the implementation of sustainable procurement criteria by meatpackers did not affect prices (R\$–1.71/kg, –4.00 to 0.57 [US\$0.33/kg, –0.78 to 0.11]). The main predictors of price were product type, sanitary inspection, and supply chain length.

Interpretation Beef products with varying deforestation footprints appeared to be marketed through similar supply chains and priced similarly to consumers. This lack of transparency along the supply chain creates a market failure and weakens incentives for sustainable production.

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Introduction

Conversion of forests to pasture accounts for 40% of forest loss worldwide and is most substantial in South America, where the expansion of livestock grazing causes 70% of deforestation.¹ Brazil has one of the world's largest cattle herds and consistently ranks among the top three global producers, exporters, and consumers of beef.² Beef production is one of Brazil's most important economic activities, employing 4.5 million people.³ Historically, however, cattle ranching has also been the main proximate driver of deforestation in Brazil. Over the past three decades, the country lost 70 Mha of natural vegetation and 60% of deforested land was replaced by pastures.⁴ Cattle ranching leads to 1.4 Gt carbon dioxide equivalent (CO₂e) of greenhouse gas emissions per year, making up 57% of the total emissions of the Brazilian economy. Most of these emissions (978 MtCO₂e) relate to land-use change (ie, pasture expansion into forests), with 405 MtCO₂e also from enteric fermentation and manure management.⁵

Existing research has primarily examined the drivers of deforestation and the effectiveness of efforts to constrain the forest loss, with little attention given in comparison to

whether these dynamics carry through to consumer outcomes such as retail prices.

Decoupling cattle ranching from deforestation has been met with mixed success. In the 2000s, the government introduced an Action Plan for the Prevention and Control of Deforestation in the Legal Amazon, which saw deforestation lessen even as cattle production increased.⁶ Around the same time, leading companies adopted commitments to monitor their supply chains,⁷ excluding purchases of cattle from properties with illegal deforestation after 2008. But enforcement of both government command-and-control efforts and corporate sustainability initiatives have been weak.⁸ From the 2010s onwards, government enforcement efforts have been undermined by budget cuts, and gaps in corporate sustainability efforts have become apparent. Notably, these corporate commitments only monitor deforestation on the direct suppliers of slaughterhouses; farms wherein cattle last reside before sale to the slaughterhouse.⁹ This loophole permits deforestation to persist among many indirect suppliers, resulting in low reductions in deforestation rates across the landscapes wherein slaughterhouses source cattle.^{10,11}

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Research in context

Evidence before this study

Previous work has investigated how price incentives to producers affect deforestation, but little research exists on investigating how deforestation affects retail prices. The main driver of deforestation across the tropics is cattle production, wherein land is cleared as a low-cost way to establish new pastures. We conducted a search of CAB Abstracts and Web of Science on June 17, 2025 using the search terms “meat” OR “beef” AND “deforestation” AND “retail prices”, imposing no date or language restrictions. We found no studies with micro-level data on actual retail prices or estimates of the deforestation linked to specific beef products.

Added value of this study

We used sanitary inspection labels to trace beef products back to the slaughterhouse of origin and link this information to remote sensing data of deforestation rates in the landscapes wherein each slaughterhouse sources cattle. This approach allowed us to build an innovative micro-level dataset of the deforestation footprint

and price of beef products sold across Brazil. We then used a directed acyclical graph to inform our model structure and yield results that control for key confounding variables and strengthen causal interpretation. Our analysis plan was preregistered, avoiding post-hoc hypothesis testing, which can otherwise inflate the Type I error rate, or false positives. Although pre-analyses plans are common in clinical research, they remain rare in sustainability science. Our findings indicate that beef with lower deforestation footprint does not cost more for consumers. More important predictors of price were meat quality, level of sanitary inspection, and transport distance from meatpacker to retail point.

Implications of all the available evidence

Our findings suggest that beef products with different deforestation footprints are marketed and priced similarly and that concerns about consumer purchasing power and food security might not, on their own, justify inaction on cattle-associated deforestation.

One pushback against efforts to constrain deforestation is the perception among some stakeholders, including agribusiness actors and in public discourse, that these efforts will lead to higher prices for consumers and, ultimately, harm food security by restricting economic access to food.^{12,13} In 2022, 15.5% of the Brazilian population was affected by severe food insecurity¹⁴ and the affordability of meat, in particular beef, is of both political and cultural relevance. Although Brazil has ample pasture land on which to increase cattle production sustainably,^{15,16} initiatives to tackle deforestation are framed as increasing the cost of beef because they restrict access to cheap land for agriculture^{15,17} and require investments in machinery, fertilisers, and pasture management.¹⁸ In addition, companies seeking to eliminate deforestation from their supply chains need to also invest in monitoring systems.^{7,19}

Although previous literature has evaluated how price incentives for agricultural producers can stimulate deforestation,^{20–24} and the growing economics literature has examined agricultural trade and supply chain mechanisms,^{25,26} few studies have empirically examined how deforestation and efforts to control the same might affect consumers through retail prices. The little research on this topic is based on macroeconomic, mechanistic modelling to explore how policies to curb deforestation can affect household consumption,²⁷ with no micro-level data on actual retail prices or estimates of how and whether the farm cost-savings from deforestation (which is essentially a technique for ranchers to secure grazing land at low cost) pass through to consumers. Micro-level data are crucial for identifying how deforestation and retail prices are related in reality and for controlling for potential confounders, allowing for a more reliable assessment of the relationship between deforestation and retail prices. We address this gap

using supply chain data detailing the price, origin, and embedded deforestation of beef products sold across Brazil, to evaluate whether deforestation-associated beef is lower cost for consumers, and conversely, whether consumers pay more for products from supply chains monitored for socioenvironmental compliance.

Methods

We developed and preregistered an analysis plan to estimate the effect of deforestation on retail prices.¹⁹ We used a directed acyclic graph (DAG) to map potentially causal pathways for how deforestation affects retail prices (figure 1) and fit regression models controlling for confounding variables. The data and modelling are described in more detail in the following sections.

Beef retail prices

Data on prices of 3767 beef products were collected between June 2022, and August 2023, at supermarkets in five states: Santa Catarina, São Paulo, Mato Grosso do Sul, Pernambuco, and Acre.

The selection of states and municipalities and the sample size in each state were designed to match the population distribution across Brazil's five regions.¹⁹ Within each state, municipalities were selected to ensure a balanced sample of products from across rural and urban municipalities.¹⁹ Within the megacity of São Paulo, data collection was further balanced to include data from across districts of varying income.

Within each municipality or district, a random list of supermarkets was identified by querying the Google Places API for stores listed as food establishments or supermarkets. These stores were visited to collect: the name and location of the store; the type of meat product

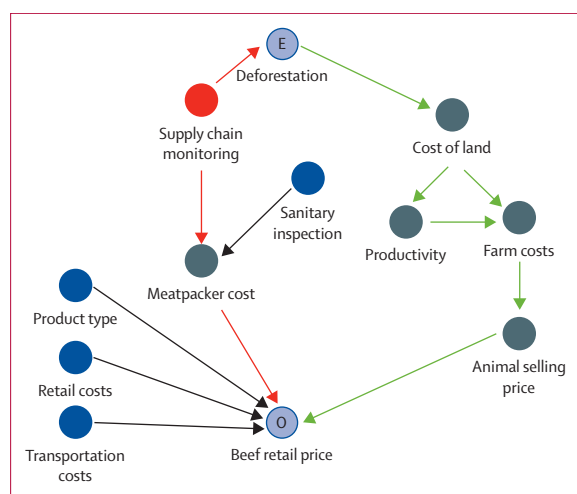


Figure 1: Conceptual representation of the influence of deforestation on beef retail prices in Brazil (directed acyclic graph)

Black arrows=direct causal effect. Blue nodes=covariables. E=explanatory variable. Green arrows=causal path. Grey nodes=unobserved covariables (latent). O=response variable. Red arrows=biasing path.

(ie, hamburger, filé mignon, and meatballs); the retail price of each meat product (either as R\$/kg, or the weight in kg, and the price in R\$); the sanitary inspection code per product; and the sanitary inspection level of each product. Where stores did not sell meat products or the number of beef products available for sale was insufficient, additional stores were visited opportunistically until the data collection was completed.

Deforestation footprint of beef products

In Brazil, products of animal origin are required to undergo sanitary inspection to ensure food-safety standards. These products are labelled with sanitary codes that identify the meatpacking facility of origin. These codes were noted during data collection and deforestation associated with the sourcing of each meatpacking facility (hectares per kilotons carcass) was calculated on the basis of previous work.²⁸ Briefly, the volume of cattle sourced directly and indirectly by each meatpacking facility per municipality was calculated from cattle movement data. The area of deforestation (in hectares) caused by the expansion of cattle ranching was calculated from remote sensing data on deforestation and pasture expansion, and this area was linked with data on cattle production per municipality (in carcass tonnes) to calculate the hectares of deforestation per thousand tonnes of cattle carcass produced in the areas supplying each meatpacker. Deforestation (hectares per year, calculated across 2018–22) and cattle production (kilotons per year) were summed up over a 5-year cattle lifecycle, as cattle live multiple years before slaughter,^{29,30} and then divided one by the other.

Data cleaning

We removed 787 (21%) of the 3767 products from the initial data collection because of missing or invalid values, such as

incorrectly recorded sanitary codes, sanitary inspection at the municipal level, or products with outlier prices. The detailed reasons for exclusions are given in the appendix (p 8), in addition to a comparison between the retained and excluded samples in the appendix (p 8). We identified outliers using a standard IQR rule, classifying observations as outliers when they lay more than $2 \times$ IQR more than the 75th percentile or less than the 25th percentile. For example, with an IQR of 10, values 20 units more than the 75th percentile or 20 units less than the 25th percentile would be flagged as outliers. Based on this rule, 104 (2.8%) of the 3767 beef products were outliers in our sample.

See Online for appendix

Statistical model

We modelled the influence of deforestation on beef retail prices as follows:

$$\begin{aligned} Price_{nri} = & \beta_1 Deforestation_{nri} + \beta_2 Inspection_{nri} \\ & + \beta_3 ProductType_{nri} + \beta_4 Transport_{nri} \\ & + \beta_5 Monitoring_{nri} + \beta_6 RetailSize_{nr} + \alpha_n + \varepsilon_{nri} \end{aligned} \quad (\text{Equation 1})$$

where $Price_{nri}$ is the retail price of beef product $i \in (1, \dots, I)$ sold in retail store $r \in (1, \dots, R)$ located in neighbourhood $n \in (1, \dots, N)$. $Deforestation_{nri}$ is the exposure variable deforestation. $Inspection_{nri}$, $ProductType_{nri}$, $Transport_{nri}$, and $Monitoring_{nri}$ are the product-level variables described in table 1. $RetailSize_{nr}$ indicates whether the retail store belongs to one of the top-10 retailers, is a mid-sized (11–900), or a smaller (>900) retail company. The fixed effect term α_n captures unobserved factors of beef prices that are constant within neighbourhood n , including those correlated to deforestation or to model covariables (table 1). Finally, the model includes the error term ε_{nri} to capture unobserved factors that affect retail prices and vary across neighbourhoods and beef products.

A key assumption for correct statistical inference is that error terms are independent and identically distributed, meaning beef prices are uncorrelated. However, this assumption might not hold, as beef prices within the same neighbourhood are spatially autocorrelated, and larger neighbourhoods show more variability. Consequently, conventional standard errors might be underestimated, producing narrow confidence intervals. To address this issue, clustered standard errors were estimated by neighbourhood, which influences retail prices importantly.

We checked the robustness of our results by running three sensitivity analyses. The first one aims to test the role of supply chain monitoring in explaining beef retail prices. We re-ran the model specified in Equation 1 without controlling for supply chain monitoring. In the second sensitivity analysis, we also re-ran the model for a stratum of data with products sourced from the Legal Amazon, with and without controlling for supply chain monitoring. The Legal Amazon is an administrative region comprising nine states (Acre, Amapá, Amazonas, Pará, Rondônia, Roraima,

Description

Product level

Sanitary inspection	Level of sanitary inspection: Federal (SIF) or State (SIE).
Product type	Products were classified as: premium cuts, non-premium cuts, offal, and processed (including ultra-processed).
Transportation costs	Transport distance (km) between meatpacker and retail store, assuming transport by car along motorways, trunk (main roads), primary, secondary, tertiary roads, and unclassified, residential, living, or service roads, using data from OpenStreetMap and the Open Source Routing Machine. The location of the meatpacker was estimated from sanitary inspection stamp of each meat product, which was then used to calculate the distance to the retail store.
Supply chain monitoring	A dummy variable for slaughterhouses that have adopted supply chain monitoring. Monitoring is defined at the meatpacker level and includes: the Public Livestock Commitment (G4 Agreement) or TAC (Conduct Adjustment Agreement) in the Amazon biome, ³¹ and company-specific zero deforestation commitments by JBS, Minerva Foods, Marfrig Global Foods, and Frigol applied outside the Amazon (appendix p 3).

Retail level

Retail store size	Retail stores were classified as: one of the top 10 supermarket brands, mid-sized supermarket brands (ranking 11–900), and small stores (ranking >900). This information was used as a proxy for retailer costs and market structure (eg, larger stores could benefit from economies of scale).
Retail store neighbourhood	The neighbourhood where the retail store is located. This information was used to control for variations related to the socioeconomic context of the neighbourhood and price variations throughout the data-collection periods within and between states. For instance, rental costs and prices in high-income neighbourhoods are likely to be higher than in other neighbourhoods, and data collection in each state was staggered through June, 2022, to December, 2023. This variable is modelled as fixed effects.

SIE=Serviço de Inspeção Estadual. SIF=Serviço de Inspeção Federal. TAC=Termo de Ajustamento de Conduta.

Table 1: Co-variables considered in the analysis of the association between deforestation and beef retail prices

Tocantins, Mato Grosso, and Maranhão).³² This definition includes the Amazon Biome but extends beyond it as well. This subset was used to assess whether our findings hold in a context wherein supply chain monitoring is most established and deforestation pressures are highest.

The last sensitivity analysis consisted of running the model in Equation 1 for a stratum of the data with products processed by the meatpacking company holding the largest national market share (JBS).³³ The company operates multiple meatpacking facilities across the country, adopting similar business practices (ie, purchasing, processing, and distribution) in its operations nationwide. By fitting the model and analysing the deforestation-price relationship using data from this company only, we held constant differences in business practices between meatpacking companies.

The magnitude of the effects was presented along with 95% CIs, which were estimated using cluster-robust standard errors. The analysis was performed in R software using the fixest package.

Role of the funding source

The funders had no role in the study design, data collection, data analysis, data interpretation, writing of the manuscript, or decision to submit.

Results

Our analysis included data from 2980 beef products, with 1844 (62%) inspected by the federal system, 1214 (41%) processed by meatpackers with supply chain monitoring commitments, and 1579 (53%) sourced from the Legal Amazon (table 2). The sample included 706 (24%) products from the largest meatpacking company, all under federal inspection system and covered by a supply chain monitoring commitment.

Of 1579 products sourced from the Legal Amazon, 1209 (77%) were marketed by small, regional retailers (ie, not

one of the top-900 retail brands nationally), 898 (57%) were processed by meatpackers under the state inspection system, and 854 (54%) were not covered by public agreements to prevent deforestation (table 2). The proportion of products under state-level sanitary inspection is 3.6-times higher for those sourced from the Legal Amazon (898 [57%] of 1759) than for those sourced elsewhere (238 [17%] of 1401). The proportion of products sourced from the Legal Amazon without commitments for supply chain monitoring (854 [54%] of 1579) is lower than the proportion of products sourced from other areas (912 [65%] of 1401; table 2).

The median beef retail price was R\$34/kg (IQR 24 to 48, or US\$6.59/kg [4.67 to 9.31]), whereas deforestation footprint had a median of 577 ha/kilotons (57 to 1613). Both deforestation and retail prices varied according to market characteristics (tables 3 and 4). Products not covered by supply chain monitoring had higher deforestation footprint (734 ha/kilotons [IQR 57 to 1717]) and lower retail prices (R\$32/kg [23 to 45], or US\$6.21/kg [4.46 to 8.73]) than products monitored for environmental compliance (495 ha/kilotons [260 to 762] and R\$37/kg [26 to 50] or US\$7.18/kg [5.04 to 9.70]). Products from slaughterhouses in the state inspection system had higher deforestation footprint (1613 ha/kilotons [IQR 1408 to 1877]) and lower prices (R\$28/kg [20 to 35] or US\$5.43/kg [3.88 to 6.79]) than products under the federal inspection system (369 ha/kilotons [IQR 57 to 696] and R\$40/kg [27 to 53] or US\$7.76/kg [5.23 to 10.28]).

Median retail prices of products sourced from the Legal Amazon were R\$9/kg (US\$1.75/kg) lower than those sourced elsewhere (tables 2), whereas the median prices for products with supply chain monitoring were R\$5/kg (US\$0.97/kg) higher (table 2). Deforestation footprint did not have a significant effect on prices (R\$–1.26/kg, 95% CI –2.66 to 0.13, [US\$–0.26/kg, –0.515 to 0.025]; figure 2; appendix p 5). These effect sizes suggest that

	Total (N=2980)	Legal Amazon		Largest meatpacker	
		Yes (n=1579)	No (n=1401)	Yes (n=706)	No (n=2274)
Product type					
Premium	951 (32%)	567 (36%)	384 (27%)	222 (31%)	729 (32%)
Non-premium	1118 (38%)	724 (46%)	394 (28%)	240 (34%)	878 (39%)
Offal	190 (6%)	137 (9%)	53 (4%)	51 (7%)	139 (6%)
Processed	721 (24%)	151 (10%)	570 (41%)	193 (27%)	528 (23%)
Retail store state					
Acre	1035 (35%)	1023 (65%)	12 (1%)	80 (11%)	955 (42%)
Mato Grosso do Sul	115 (4%)	11 (1%)	104 (7%)	52 (7%)	63 (3%)
Pernambuco	839 (28%)	332 (21%)	507 (36%)	354 (50%)	485 (21%)
Santa Catarina	277 (9%)	13 (1%)	264 (19%)	10 (1%)	267 (12%)
São Paulo	714 (24%)	200 (13%)	514 (37%)	210 (30%)	504 (22%)
Retail store size					
Top 10	558 (19%)	198 (13%)	360 (26%)	289 (41%)	269 (12%)
Mid-sized (11–900)	591 (20%)	172 (11%)	419 (30%)	113 (16%)	478 (21%)
Small (>900)	1831 (61%)	1209 (77%)	622 (44%)	304 (43%)	1527 (67%)
Sanitary inspection level					
Federal	1844 (62%)	681 (43%)	1163 (83%)	706 (100%)	1138 (50%)
State	1136 (38%)	898 (57%)	238 (17%)	0	1136 (50%)
Supply chain monitoring					
Yes	1214 (41%)	725 (46%)	489 (35%)	706 (100%)	508 (22%)
No	1766 (59%)	854 (54%)	912 (65%)	0	1766 (78%)
Meatpacker to retail store distance (km)	590 (90, 1895)	113 (21, 1686)	899 (227, 2330)	1880 (963, 2355)	184 (71, 1543)
Deforestation footprint (hectare/kiloton)	577 (57, 1613)	1435 (724, 1812)	57 (23, 308)	369 (59, 495)	724 (57, 1717)
Beef retail price (R\$/kg)*	34 (24, 48)	30 (20, 42)	39 (27, 52)	37 (26, 49)	33 (23, 47)
Values are expressed as n (%) or median (percentile 25; percentile 75). *Average exchange rate over 2022: 1R\$≈US\$0.194.					
Table 2: Description of beef products included in the sample by location and brand of the meatpacker that processed the product					

reducing deforestation footprint to zero could increase beef prices by R\$1.29/kg (US\$0.25/kg), representing a 3.5% rise (appendix p 5).

Meatpacker commitment to monitor the supply chain also did not affect retail prices (R\$–1.71/kg, 95% CI –4.00 to 0.57 or US\$0.33/kg [–0.78 to 0.11]). Aside from product type (premium, non-premium, or offal), sanitary inspection level was one of the strongest predictors of price, with products under state inspection system being R\$7.78/kg (95% CI 2.35 to 13.20, or US\$1.50/kg [–0.46 to 2.56]) cheaper than those under federal inspection system (figure 2; appendix p 5). Another strong predictor of prices is the distance between the meatpacker and the retail store, with prices dropping by R\$2.86/kg (95% CI 1.35 to 4.38 or US\$0.56/kg [0.26 to –0.85]) for one SD increase in distance between the meatpacker and retail store (appendix p 1).

The results are stable across various sensitivity analyses (figure 3 and appendix pp 6–7). The estimated effect of deforestation on retail prices remained close to zero across sensitivity analyses that did and did not include supply chain monitoring or were fit to subsets of data from the Legal Amazon and Brazil's largest meatpacking company. For products from the Legal Amazon, the effect of sanitary inspection in influencing prices was no longer significant, with no difference in price observed between meat products from federal-level and state-level slaughterhouses in the region. For the subset with products from the largest

meatpacking company, transport distance was not a significant predictor of prices.

Discussion

The strongest predictors of beef retail prices are the type of meat (premium and non-premium cuts) and the degree of food-safety controls. Our finding of higher retail prices for beef produced under the federal inspection system is consistent with the assumptions in our conceptual framework (figure 1), as federal facilities have more demanding food-safety standards. In addition, beef sourced from the Legal Amazon tend to have higher deforestation footprints and lower retail prices, although deforestation is not a predictor of prices.

Although the level of sanitary inspection is a key predictor of prices in the full sample, the same is not true for products sourced from the Amazon, suggesting that the lower prices from the region are explained by other factors. This finding could reflect the fact that cattle ranching in the Amazon is characterised by low-productivity, extensive grazing. As a result, cattle take longer to reach a slaughter weight. Although younger animals tend to have higher meat quality, in particular meat tenderness,³⁴ the older cattle ages at slaughter could result in lower quality, reflected in the lower retail prices from the region. Our analyses control for differences in the cuts of meat, but variation in meat quality is otherwise unobserved.

	Total	Legal Amazon		Largest meatpacker	
	N=2980	Yes (n=1579)	No (n=1401)	Yes (n=706)	No (n=2274)
Product type					
Premium	577 (243; 1613)	1408 (673; 1812)	59 (22; 369)	452 (308; 673·25)	779 (155; 1738)
Non-premium	1242·5 (256; 1800)	1613 (1408; 1877)	57 (22; 303)	452 (308; 687)	1408 (243·75; 1812)
Offal	1408 (308; 1809)	1613 (1281; 1877)	185 (57; 308)	426 (308; 762)	1613 (577; 1877)
Processed	57 (57; 594)	724 (724; 724)	57 (57; 184)	57 (57; 369)	57 (57; 724)
Retail store state					
Acre	1738 (1408; 1877)	1800 (1408; 1877)	57 (48·5; 166·5)	482 (482; 482)	1800 (1613; 1877)
Mato Grosso do Sul	369 (94·5; 439·5)	724 (452; 724)	369 (84; 369)	369 (369; 369)	246 (57; 574·5)
Pernambuco	369 (57; 655)	724 (577; 894)	57 (57; 308)	369 (57; 696)	243 (57; 632)
Santa Catarina	22 (22; 22)	905 (724; 929)	22 (22; 22)	308 (308; 431·25)	22 (22; 22)
São Paulo	260 (57; 721)	724 (650; 779)	59 (57; 369)	369 (59; 491)	248 (57; 724)
Retail store size					
Top 10	369 (57; 724)	724 (543; 762)	59 (57; 369)	369 (280; 543)	184 (57; 724)
Mid-sized (11–900)	57 (22; 587)	779 (633·5; 1717)	22 (22; 57)	369 (59; 543)	22 (22; 587)
Small (>900)	1392 (256; 1800)	1613 (1408; 1877)	57 (57; 308)	369 (57; 482)	1408 (447; 1812)
Sanitary inspection level					
Federal	369 (57; 696)	724 (543; 883)	59 (57; 369)	369 (59; 495)	256 (57; 724)
State	1613 (1408; 1877)	1800 (1613; 1923)	22 (22; 22)	*	1613 (1408; 1877)
Supply chain monitoring					
Yes	495 (260; 762)	724 (577; 1629)	143 (57; 369)	369 (59; 495)	724 (577; 1800)
No	734 (57; 1717)	1717 (1408; 1923)	57 (22; 184)	*	734 (57; 1717)

Values are expressed as median (percentile 25; percentile 75). *All products from the largest meatpacker are inspected at the federal level and covered by supply chain monitoring.

Table 3: Deforestation footprint (hectares/kilotons) of beef products in the sample according to select characteristics

	Total (N=2980)	Legal Amazon		Largest meatpacker	
		Yes (n=1579)	No (n=1401)	Yes (n=706)	No (n=2274)
Product type					
Premium	46 (35; 60)	43 (33; 53)	50 (40; 66)	48 (38; 60)	46 (35; 60)
Non-premium	27 (20; 36)	24 (19; 29)	37 (29; 49)	34 (27; 47)	26 (20; 33)
Offal	16 (13; 18)	15 (13; 17)	19 (16; 30)	16 (14; 21)	16 (13; 18)
Processed	36 (25; 47)	40 (34; 50)	33 (23; 46)	30 (24; 42)	36 (26; 50)
Retail store state					
Acre	27 (19; 34)	27 (19; 34)	31·5 (22·5; 38)	33·5 (21·75; 42·75)	26 (19; 33)
Mato Grosso do Sul	40 (27·5; 54)	27 (24·5; 35)	42 (29·75; 55·25)	44 (31·75; 56)	38 (26·5; 52)
Pernambuco	34 (22; 46)	39 (27; 48·25)	29 (21; 43)	32 (21·25; 45·75)	36 (22; 46)
Santa Catarina	37 (30; 48)	40 (31; 59)	36·5 (30; 47·25)	39 (31·75; 49·25)	36 (30; 47·5)
São Paulo	48 (36; 62)	49 (35·75; 60)	47 (36; 63·75)	43 (34; 50)	50 (37; 67)
Retail store size					
Top 10	43 (32; 56)	39 (30·25; 53)	44 (32; 58·25)	39 (30; 50)	46 (34; 61)
Mid-sized (11–900)	39 (30; 50)	39 (30; 50)	39 (30; 50)	40 (30; 49)	39 (30; 50·75)
Small (>900)	30 (20; 42)	28 (19; 38)	36 (24; 50)	32 (22·75; 44)	29 (20; 41)
Sanitary inspection level					
Federal	40 (27; 53)	39 (28; 53)	40 (27; 54)	37 (26; 49)	41 (29; 58)
State	28 (20; 35)	26 (19; 32)	34·5 (29; 42·75)	*	28 (20; 35)
Supply chain monitoring					
Yes	37 (26; 50)	37 (26; 50)	39 (26; 50)	37 (26; 49)	38 (26; 54)
No	32 (23; 45)	27 (19; 35)	39 (28; 54)	*	32 (23; 45)

Values are expressed as median (percentile 25; percentile 75). Average exchange rate over 2022: 1 R\$≈0·194 US\$. *All products from the largest meatpacker are inspected at the federal level and covered by supply chain monitoring.

Table 4: Retail prices (R\$/kg) of beef products in the sample according to select characteristics

Lower quality of meat from the Amazon (distant to major consumer markets in Brazil's south and southeast) could also explain the negative association between transport distance and retail prices. Another possible mechanism is through economies of scale in longer supply chains, suggesting that upstream production and procurement dynamics could outweigh transport costs in shaping retail prices. For example, federally inspected meatpackers benefit from fiscal incentives on interstate shipment of processed goods, due to which transporting finished products from meatpackers to distant retailers becomes economically feasible. These mechanisms are potentially corroborated by the insignificance of transport distance, when analysing only products supplied by the largest meatpacking company, wherein meat quality and economies of scale will be likely standardised.

We also find that meat from slaughterhouses with supply chain-monitoring commitments has lower deforestation footprints. However, no significant association between products' deforestation footprint and retail price could stem from multiple mechanisms. In theory, deforestation commitments could be costless to firms or have no effect on deforestation, although we consider these explanations unlikely. Concrete costs exist for supply chain monitoring, as meatpackers pay for satellite monitoring of direct supplier properties. These commitments are publicly audited and have been shown to change slaughterhouse sourcing behaviour.^{35,36} Moreover, multiple studies point towards reductions (although not elimination) of deforestation in the supply-shed of committed slaughterhouses.^{11,37} These mechanisms are, therefore, accounted for in our DAG and modelling framework (figures 1–3). A more plausible explanation is that the acquisition of cheap land through deforestation is a cost-saving that is absorbed along the supply chain. Our data do not allow us, however, to pinpoint at what level of the supply chain this margin is retained, whether at the level of producers, meatpackers, or retailers.

Ultimately, our study provides evidence that beef with varying deforestation footprints is marketed through similar supply chains and priced similarly to consumers. This evidence contrasts with the findings of consumer surveys which suggest that many consumers in Brazil value information on the origin and sustainability of beef products, and express a willingness to pay more for verified sustainable products.³⁸ The lack of transparency and differentiation between beef produced by farmers who deforest illegally and those who adopt sustainable practices prevents market incentives to reward sustainable production, which could hinder the transition to a deforestation-free livestock sector. Deforestation is still profitable and the decision to convert forest into pastures is driven by potential economic gains.²³ Despite the latest advances, cattle production in Brazil, and in particular in the Amazon, is still mainly characterised by low on-farm investments, because ranchers are generally averse to risk and the adoption of new production technologies, posing a barrier to the modernisations of production and improvements in

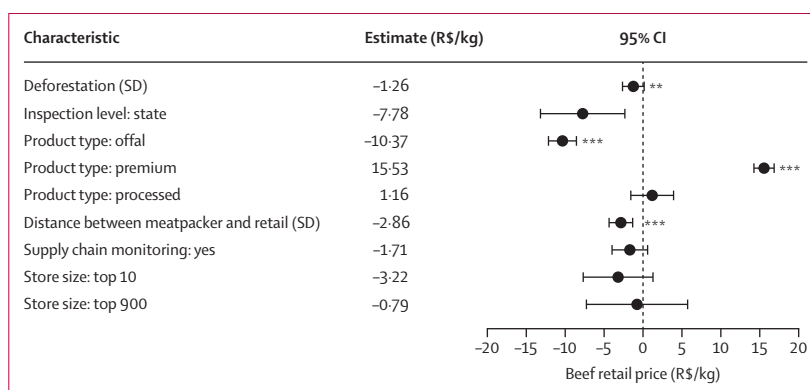


Figure 2: Coefficient estimates from the regression of beef retail prices in Brazil

Estimates of deforestation on beef retail prices considering covariables are given. For numeric variables (deforestation and distance), estimates are interpreted as changes in beef retail prices associated with 1 SD change. For categorical variables, the estimates are relative to prices for inspection level=federal, product type=non-premium, supply chain monitoring=no, and store size=smaller stores. Average exchange rate over 2022: R\$1≈US\$0.194. **p<0.01, ***p<0.001.

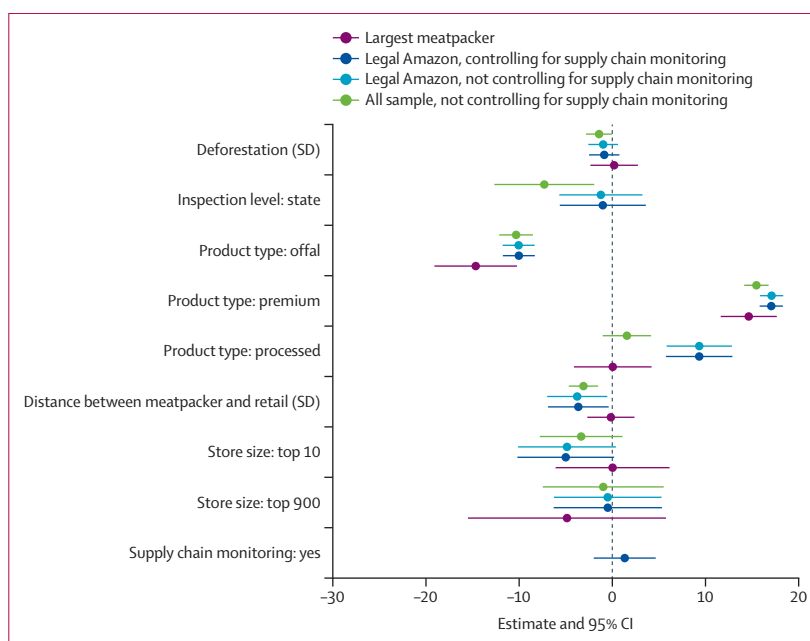


Figure 3: Sensitivity analyses of supply chain monitoring, Legal Amazon, and largest meatpacker in explaining retail prices

Estimates of deforestation on beef retail prices considering covariables are given. For numeric variables (deforestation and distance), estimates are interpreted as changes in beef retail prices associated with 1 standard deviation change. Average exchange rate over 2022: 1R\$≈US\$0.194. For categorical variables, the estimates are relative to the prices for inspection level=federal, product type=non-premium, supply chain monitoring=no, and store size=smaller stores.

sustainability.³⁹ In addition to expanding supply chain monitoring to discourage deforestation among meatpackers' direct and indirect suppliers, financial incentives could support ranchers in transitioning away from deforestation by making sustainable production more profitable or restricting the economic gains from unsustainable practices. One way is to apply taxes on unsustainable production that result in beef with high emissions or with a large land footprint. Such taxation could increase consumer prices by

2%,⁴⁰ a similar magnitude to our estimates of the cost of eliminating deforestation. Specifically, our estimates suggest that eliminating deforestation would result in a price increase of 3.5%. These numbers are notably smaller than the inflation in beef prices that rose by 21–47% between 2020 and 2023.

Caution should be taken when extrapolating our findings. The causal interpretation relies on the assumption that the DAG captures all relevant confounders or that remaining unobserved factors are absorbed by the neighbourhood fixed effects, assumptions that are ultimately untestable. In addition, our estimates are based on current agricultural practices and supply chain monitoring, which is restricted to direct suppliers. These monitoring systems are estimated to have reduced deforestation in the Amazon by only 15%, with a potential to reduce deforestation by half, should they be more widely and effectively adopted by meatpacking companies.¹¹ However, their effectiveness remains constrained in practice, particularly due to the low coverage of indirect suppliers and incomplete adoption across supply chains. Fully eliminating deforestation from cattle supply chains will require closing these gaps. Improvements in traceability could incur additional costs beyond those captured in our estimates, which reflect the supply chain monitoring practices currently in place. Overall, our results suggest that concerns about impacts on consumer purchasing power and its implications for food security might not justify inaction on cattle-associated deforestation.

The lack of transparency in supply chains suggests that consumers might be unaware that they pay a similar price for meat with different deforestation footprints. Further studies need to explore whether informing consumers about the environmental implications of their beef consumption choices—at constant prices—would encourage different attitudes. Consumer's decisions are tied to the alternatives offered to them by retailers. Hence, retailers have an important role to play in marketing products from environmentally responsible supply chains, which could be done by adopting sustainable sourcing protocols to avoid selling meat from slaughterhouses supplied directly or indirectly by farms associated with deforestation.³¹ Our results indicate that the top-ten retailers have high deforestation footprints, but smaller retailers have even greater exposure per tonne of beef sold. Till date, only three retail companies have committed to not purchasing beef from deforested areas, and implementation of these commitments has been incomplete, again focusing on monitoring slaughterhouses' direct suppliers. The Brazilian Public Prosecutors Office has indicated that it will begin to take action against retailers commercialising products linked to deforestation,⁴¹ which could prompt wider uptake of these commitments.

Among all the stakeholders in the supply chain, meatpackers have the greatest influence and ability to monitor ranchers for social-environmental compliance, because they are the entry point to the market. However, traceability

remains challenging with each slaughterhouse plant sourcing from more than 3000 farms to meet the annual demand for cattle.⁴² Despite the latest progress, meatpackers in the Legal Amazon still have a low degree of control and transparency in their supply chains, particularly regarding indirect suppliers. Moreover, supply chain commitments are largely restricted to slaughterhouses in the Amazon, ignoring pasture expansion in other biomes—such as the Cerrado—and many smaller slaughterhouse plants inspected at the state level or municipal level have not yet adopted commitments.⁴³ Tackling deforestation requires that large and smaller slaughterhouses alike adopt measures to control their direct and indirect suppliers.

Among the products sourced from the Legal Amazon, we observed a large proportion of products under state-level inspection. Although official statistics suggest that around 90% of inspected slaughter in the Legal Amazon occurs under the federal system,⁴⁴ in our sample, less than half of beef originated in the Legal Amazon were under federal inspection. This occurrence could be due to a possible overrepresentation of state inspection in our sample from Acre, where 31% of our retail data were collected.¹⁹ In Acre, more than 20% of cattle are slaughtered in the state-level slaughterhouses,⁴⁴ who tend to sell their meat locally, rather than to other Brazilian states or to international markets.⁴⁵ This context suggests that the higher deforestation footprint observed among state-inspected slaughterhouses in the Legal Amazon sample (table 3) reflects the concentration of state-inspected beef in Acre (a high deforestation state) rather than a systematic difference between federal and state sanitary inspection (appendix p 9).

Our sample also did not include beef products sourced from municipal-inspected slaughterhouses, nor clandestine slaughter. These smaller slaughterhouses have few sanitary controls, let alone supply chain monitoring for deforestation. Our results suggest that the sanitary inspection level is a key predictor of prices, but the deforestation footprint of beef sourced from smaller slaughterhouses is unlikely to be systematically different from the state-level or federal-level slaughterhouses in our sample, as these slaughterhouses only monitor their direct suppliers, in any case, with no mechanisms to control deforestation linked to their many indirect supplier properties. By some estimates, half of all cattle slaughtered in the Amazon are contaminated by deforestation occurring among slaughterhouses' indirect suppliers.⁴⁶

To account for this large share of unmonitored slaughterhouse sourcing, we follow other work in calculating the deforestation footprint of each slaughterhouse based on deforestation occurring within their supply-shed, using deforestation rates in the municipalities where they source cattle.^{28,43,47–49} Although property-level analyses would, in theory, give more precise estimates of the deforestation footprint of a given product, we favour supply-shed approaches because, in practice, property-level traceability

is flawed and incomplete. Current traceability data and approaches can only track the purchase of cattle from properties responsible for 29% of deforestation and 50% of the pasture area.⁹ The remaining 71% of deforestation and 50% of pasture occurs outside confirmed supplier properties, although this deforestation is captured by supplyshed.⁴⁷ We note this mapping of slaughterhouses' sourcing,⁵⁰ which calculate supply chain impacts, for example, land-use change and scope-3 emissions, within jurisdictional sourcing regions.

We find that cattle production associated with lower deforestation footprint does not translate to higher prices for consumers; nor does supply chain monitoring implemented by meatpacking companies to restrict market access for deforestation-linked cattle. Our findings also add to the evidence suggesting that forest conservation can encourage the adoption of more sustainable agricultural practices, increasing value-add across the cattle supply chain.

Contributors

Conceptualisation: JTdS and EzE. Investigation (data collection): AMdC, FC, and EzE. Data curation: AG and EzE. Formal analysis: JTdS. Funding acquisition: EzE. Methodology: JTdS, VG, and EzE. Writing—original draft: JTdS. Writing—review and editing: JTdS, VG, AMdC, AG, FC, DM, RdOS, and EzE. JTdS, AG, and EzE accessed and verified the underlying data. JTdS and EzE had the final responsibility for the decision to submit for publication.

Declaration of interests

We declare no competing interests.

Data sharing

The data analysis plan is available online. Data and code used in this study are available online.

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For more on **Data analysis plans**, see <https://osf.io/vrwz3/overview>

For more on **data and code**, see https://github.com/silvajacqueline/Deforestation_BeefPrices

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