The origin, supply chain, and deforestation risk of Brazil's beef exports

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Though the international trade in agricultural commodities is worth more than $1.6 trillion/year, we still have a poor understanding of the supply chains connecting places of production and consumption and the socioeconomic and environmental impacts of this trade. In this study, we provide a wall-to-wall subnational map of the origin and supply chain of Brazilian meat, offal, and live cattle exports from 2015 to 2017, a trade worth more than $5.4 billion/year. Brazil is the world's largest beef exporter, exporting approximately one-fifth of its production, and the sector has a notable environmental footprint, linked to one-fifth of all commodity-driven deforestation across the tropics. By combining official per-shipment trade records, slaughterhouse export licenses, subnational agricultural statistics, and data on the origin of cattle per slaughterhouse, we mapped the flow of cattle from more than 2,800 municipalities where cattle were raised to 152 exporting slaughterhouses where they were slaughtered, via the 204 exporting and 3,383 importing companies handling that trade, and finally to 152 importing countries. We find stark differences in the subnational origin of the sourcing of different actors and link this supply chain mapping to spatially explicit data on cattle-associated deforestation, to estimate the "deforestation risk" (in hectares/year) of each supply chain actor over time. Our results provide an unprecedented insight into the global trade of a deforestation-risk commodity and demonstrate the potential for improved supply chain transparency based on currently available data.

transparency | governance | trade | livestock | sustainability

The production and trade of agricultural commodities, such as soy, oil palm, coffee, cocoa, and beef, can be key drivers of local livelihoods and development (1, 2), but are also associated with profound social and environmental challenges. Commodity production causes almost one-third of global forest loss (3), more than 20% of global greenhouse gas emissions (4, 5), is a major driver of biodiversity declines (6), and has been linked to several high-profile cases of land grabbing and forced labor (7, 8).

Sustainability governance of commodity supply chains is challenging, not least because there is often a spatial disconnect between places of production and consumption. Commodities are traded and processed along complex supply chains which move products from producers via a variety of processors, traders, logistics companies, and retailers before finally reaching consumers. This complexity makes it difficult for companies, consumer countries, and international investors to quantify risks associated with their purchases, let alone identify the origin of their products, and complicates the attribution of responsibility for impacts embedded in supply chains.

Despite a growing body of research, we still have a poor understanding of the impact of commodity supply chains on socioeconomic outcomes and environmental impacts in producer regions (9), the relative role of international and domestic markets in driving these impacts (10), and whether supply chain initiatives, such as corporate sustainable sourcing practices or zero deforestation commitments are achieving improvements on the ground (11). Previous research efforts have relied on data that are limited either in scale or in detail (12), being case studies of a specific company's supply chain or global analyses using coarse national-level statistics and lacking detail on supply chain configurations—the companies who mediate the production, processing, storage, and trade of these products and are key to the implementation of more sustainable trade and sourcing practices.

There is therefore an urgent need for data on commodity supply chains that identify subnational sourcing regions, include information on supply chain actors, and provide wall-to-wall coverage for all export markets (9, 12). These data can: 1) generate more accurate assessments of the role of international trade in driving positive and negative impacts, including development, land use change, biodiversity loss, and carbon emissions; 2) reveal the connection between supply chain actors and specific places where their sourcing and operations have a significant footprint; 3) guide engagement by key companies and consumer markets who have leverage for driving improvements on the ground; and 4) improve monitoring of actors' impacts over time and their progress on efforts to implement sustainable sourcing practices (11).

In this study, as part of the Transparency for Sustainable Economies (Trase) initiative (www.trase.earth), we mapped exports of Brazilian beef, offal, and live cattle, identifying the municipalities where cattle are raised for export markets, the

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Significance

The trade in agricultural commodities is a mainstay of the globalized economy, though the complex nature of commodity supply chains makes it difficult to identify the origin of and impact embedded in products. We brought together detailed data on trade, agriculture, and logistics to produce a subnational map of the origin of Brazil's exports of beef, offal, and live cattle. Brazil is the world's largest beef exporter, exporting one-fifth of its total production, and the sector is a major driver of deforestation. We traced cattle from 2,800 municipalities through to 152 importing countries, via thousands of companies handling their export and import. Our work gives an unprecedented insight into the origin of food and impacts embedded in global supply chains.

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businesses slaughtering those cattle, handling their export, and the international markets purchasing those products.

Brazil is the world's second largest producer of beef, with 2.5 million farmers operating mostly pasture-based production systems where 87 to 90% of cattle are finished on pasture and approximately 10 to 13% finished in feedlots (13–15). The sector also has a notable environmental impact, not least as a major driver of deforestation. Two-thirds of cleared land in the Amazon and Cerrado biomes have been converted to cattle pasture (16), making the Brazilian cattle sector responsible for one-fifth of all emissions from commodity-driven deforestation across the entire tropics (17).

This dynamic is well studied—cattle ranching, which was historically concentrated in the south and coastal regions of Brazil has shifted inland since the 1970s (18), driven by waves of human migration, rising competition for land, improvements in animal disease control and sanitation, and growth in demand from both domestic and export markets (19, 20). Notably, Brazil has become the world's largest beef exporter, exporting two million tons in bovine carcass weight each year, approximately one-fifth of its production, a trade worth more than $5.4 billion per year (in freight-on-board value).

Though studies have tried to link the rise of Brazil's beef exports to deforestation (10, 21, 22), most analyses are limited to specific regions, notably the Amazon, and it remains unclear where in the country exports actually originate from and how this differs from the domestic market, what the relative role of export versus domestic markets is in driving deforestation and the clearance of native vegetation across Brazil's biomes, and ultimately which actors (companies and consumer markets) have the greatest exposure to and responsibility for deforestation on the ground.

Several companies within the cattle sector have made commitments to zero or zero-illegal deforestation (23). Though we know that 75% of export-approved slaughterhouses in the Amazon have signed these commitments (24), we similarly do not know what proportion of exports originate from signatory slaughterhouses versus from nonsignatories and to what degree these locally focused commitments (which apply only to the Amazon) reduce international markets' exposure to deforestation.

In this study, we therefore address four questions:

1) How are Brazilian cattle export supply chains structured and how consolidated is this trade? For example, which regions and companies are responsible for the majority of exports?

2) Where do major consumer markets source Brazilian beef from, and how does this differ from the domestic market?

3) To what extent do deforestation risks vary among buyers, markets, and cattle products, including meat, offal, and live cattle?

4) What proportion of Brazil's exports are covered by zero deforestation commitments and what implications does this have for efforts to reduce deforestation in the country's cattle sector?

We address these questions by providing a comprehensive mapping of the origin of Brazilian beef, offal, and live cattle exports. We do so in three steps: 1) for the period 2015 to 2017, we linked individual shipments of exports back to slaughterhouses and live cattle exporting facilities by crossing detailed customs data against information on slaughterhouse tax registrations, ownership, and their export licenses. 2) We identified the municipalities supplying cattle to these slaughterhouses, using a large dataset of cattle movements between farms and from farms to slaughterhouse and government statistics on the origin of cattle slaughtered in export-approved slaughterhouses. 3) We then intersected remote sensing data on deforestation and pasture expansion to identify cattle-associated deforestation per municipality and linked these data to our supply chain maps, to calculate the deforestation embedded in cattle exports each year. This "deforestation risk" is allocated to specific trading companies and international buyers based on the volumes they source from each jurisdiction.

Results and Discussion

We mapped the flow of cattle from more than 2,800 municipalities where cattle were raised to 152 exporting slaughterhouses where they were slaughtered, via the 204 exporting and 3,383 importing companies handling that trade, and finally to 152 importing countries (Fig. 1).

How Are Cattle Export Supply Chains Structured? Overall, exports made up 19.1% of Brazilian cattle production in 2017 (*SI Appendix*), though four states made a disproportionately large contribution to exports: Rondônia, Mato Grosso, São Paulo, and Mato Grosso do Sul. These four states each exported >25% of their cattle production (Fig. 2*A*), were home to 53% (81 in total) of exporting slaughterhouses, and were the source of 59.0% of exports between 2015 and 2017. The northeast of Brazil (shown in shades of orange in Fig. 2), on the other hand, was not well connected to export markets—supplying only 0.6% of exports, despite being home to 10.9% of cattle production. Divided per biome, 48.1% of exports originated from cattle in the Cerrado, 25.5% from the Amazon, 18.2% from the Atlantic Forest, 5.0% from the Pampas, and 1.9% from the Pantanal and Caatinga.

Exports were consolidated in the hands of a few companies—204 in total between 2015 and 2017. Of these, 39.2% (80 traders) operated in all 3 y, and three companies, JBS, Minerva, and Marfrig (and their subsidiaries), handled 71.7% of exports (*SI Appendix*). These three companies each operated slaughterhouses in the Amazon states of Mato Grosso and Rondônia (*SI Appendix*, Fig. S1), though JBS had a particularly strong presence in the Amazon, handling 40.3% of exports from the biome, with Minerva responsible for 19.4% and Marfrig 9.9%. In contrast, Marfrig controlled a large share of exports from the Pampas (located mostly in the state of Rio Grande do Sul), which was the origin of 21.5% of their exports and 68.3% of all exports from the biome.

For most export supply chains, export companies were vertically integrated—overall, 94.4% of beef and offal exports were handled by 55 companies who operate their own slaughterhouses. These companies have strong control over the origination of their products, at least to the slaughterhouse level. The remaining 5.6% of beef and offal exports were mostly handled by import-export businesses, who specialize in international trade of multiple commodities. The slaughterhouses supplying exporting businesses each sourced cattle from a wide area. Exporting slaughterhouses, on average, directly and indirectly sourced cattle from 60.4 municipalities (±54.2 SD) and 364 municipalities (±193 SD), respectively, though most purchases were more local with 80% of each slaughterhouse's sourcing being from 18.1 municipalities (±16.7 SD), less than 279 km (±175 SD) away (*SI Appendix*, Fig. S2).

Where Do Major Markets Source from? Between 2015 and 2017, the largest export markets for Brazilian beef, offal, and live cattle were China (mainland and Hong Kong), which purchased 30.2% of Brazil's exports by volume (30.1% by value). They are followed by Egypt (12.4% and 10.2% by volume and value, respectively), Russia (10.4% and 8.2%), Iran (7.1% and 7.2%), the European Union (7.1% and 11.9%), Chile (4.4% and 4.8%), Venezuela (3.9% and 4.3%), and the United States (2.3% and 4.9%). These markets have quite distinct and dynamic sourcing patterns (Fig. 2), driven by differing product portfolios, logistics, and food safety requirements.

Though the three largest export markets, China, Egypt, and Russia purchased from a wide area in Brazil (across 16, 14, and

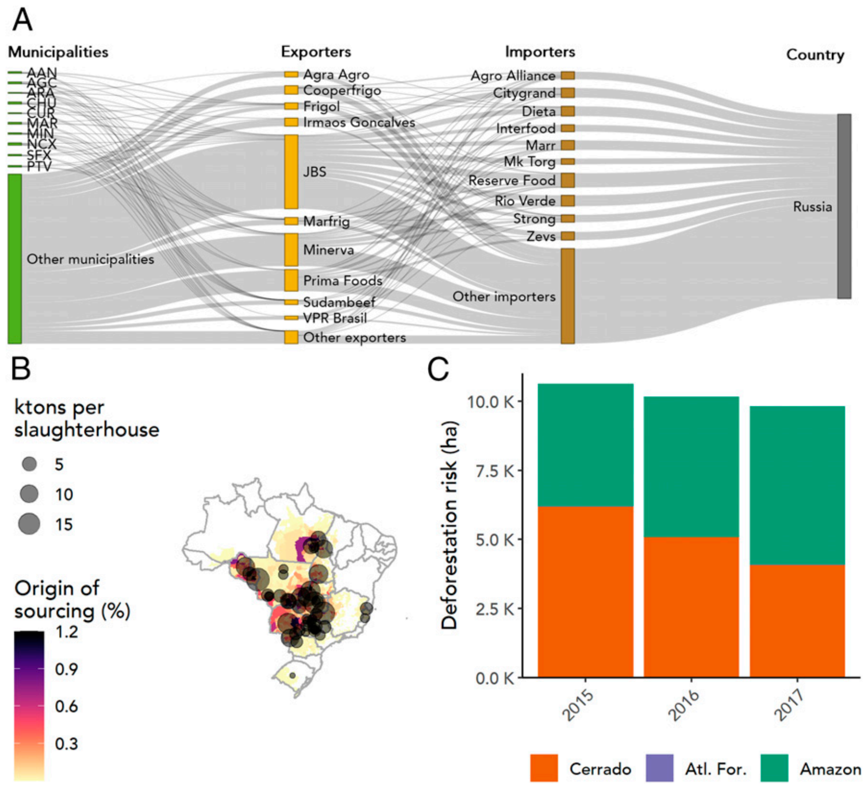

Fig. 1. Example trade flow for Brazilian beef to Russia, the third largest importer between 2015 and 2017. (*A*) The flow of exports in 2015 from municipalities where cattle were raised (shown in green), via intermediary exporting (orange) and importing companies (beige), into Russia (grey). The top 10 actors are displayed in each case. (*B*) The origin of these 2015 exports, per municipality and slaughterhouse (shown as gray circles). (*C*) Supply chain data can be crossed with indicator data, such as deforestation risk, to calculate the risks associated with each actor's sourcing, here shown per biome/year. Abbreviations: AAN, Agua Azul do Norte; AGC, Agua Clara; ARA, Alto Araguaia; CHU, Chupinguaia; CUR, Curionópolis; MAR, Marabá; MIN, Mineiros; NCX, Nova Crixas; SFX, São Felix do Xingu; PTV, Porto Velho; and Atl. For., Atlantic Forest.

11 states, respectively), imports into the United States and the United Kingdom were concentrated in the states of Mato Grosso do Sul, São Paulo, and Rio Grande do Sul. The latter pattern arises because the United States and the United Kingdom almost exclusively (>90%) imported processed meat products, such as beef jerky and corned beef, which have historically been produced in facilities in the consolidated central-west and south of Brazil (*SI Appendix*, Fig. S3), near to Brazil's major urban markets which they also serve. In contrast, 69.7% of Venezuela's sourcing came from states in Brazil's Legal Amazon, with 16.0% imports from the state of Pará. This is because they were a major buyer of live cattle, purchasing 58.5% of all Brazil's live cattle exports in 2015, more than three-quarters of which were exported through the port of Barcarena in Pará, drawing on cattle from surrounding municipalities (25) (*SI Appendix*, Fig. S3). This particular trade pattern is driven in part by simple logistics—ports in the north have the shortest shipping distances to Venezuela. These trade patterns are, however, not static: Venezuela's imports declined from $644.0 million in 2015 to $5.7 million in 2017, linked to the country's economic recession (26), and the United States' sourcing shifted notably between July 2016 and July 2017, when they temporarily lifted restrictions on imports of fresh and frozen beef from Brazil (Fig. 3). These restrictions were again lifted in February 2020, setting the scene for another boost in US beef imports and deforestation risk.

European Union countries, on the other hand, accepted only fresh and frozen beef from facilities in 10 states in Brazil's south, southeast, and central-west, some of the first to be designated as free of foot-and-mouth disease (FMD) (*SI Appendix*, Fig. S4). EU sourcing is, however, expanding northwards—in 2016, in recognition of Brazilian efforts to eradicate FMD, the European Union approved 14 additional states for exports of processed meat, including five states in Brazil's Legal Amazon: Acre, Rondônia, Pará, Tocantins, and Maranhão. In 2017, Rondônia was the first of these to sell processed meat to the EU market, supplying 55 tons of processed offal to Denmark and Italy.

How Are Deforestation Risks Distributed? Overall, we identified 73,000 to 74,700 ha/year deforestation risk linked to cattle exports each year, assuming a 1-y amortization period (*Materials and Methods*), out of a total of 480,000 to 520,000 ha/year of cattle-associated deforestation risk. Of the deforestation linked to cattle exports, 40,200 to 41,900 ha/year (55.0 to 56.6%) arose from municipalities in the Amazon, 30,100 to 32,200 ha/year (40.7 to 43.0%) in the Cerrado, and 100 to 130 ha/year (0.1 to 0.2%) in the Atlantic Forest.

Our approach reveals how exposure to deforestation risk is far from uniform—as is implicitly assumed in environmental footprint analyses or life cycle assessments which rely on national-level or representative footprints, (e.g., refs. 17 and 27) (*SI Appendix*, Fig. S5).

Among exporters, deforestation risks vary greatly depending on where companies operate slaughter and processing facilities. The meat packer Irmãos Conçalves, for example, has the fifth-highest total deforestation risk of all major exporters (2,100 to 3,500 ha/year), and the highest relative deforestation risk (Fig. 4*A*). Irmãos Conçalves operates a slaughterhouse in the Amazon state of Rondônia which had, as of July 2020, not made

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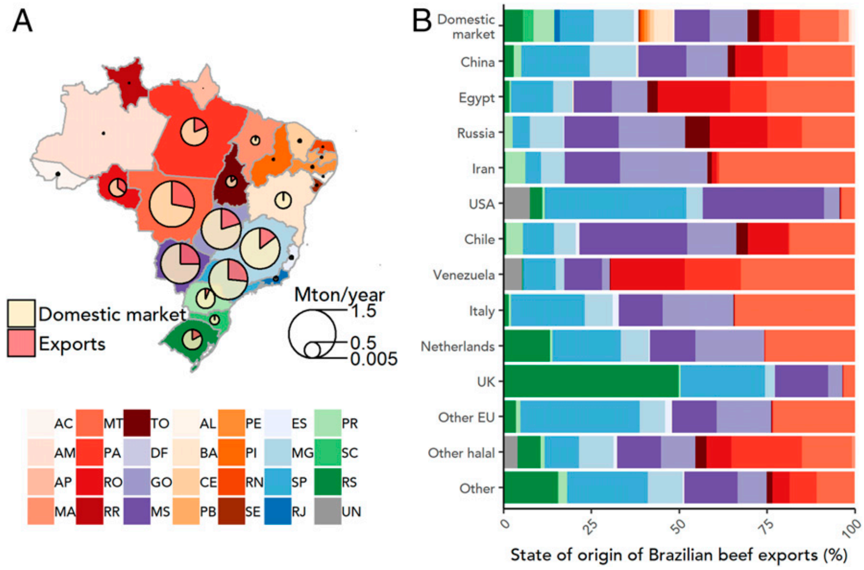

Fig. 2. The origin and destination of Brazilian beef. (*A*) Cattle production (Mtons/year) and the proportion exported per state in Brazil, shown for 2017. (*B*) Breakdown of the origin of sourcing per major market. "Other EU" refers to other EU markets and "Other halal" are other halal markets, as defined in *SI Appendix*. States are colored by region, states in the Legal Amazon are in shades of red (AC, Acre; AM, Amazonas; MA, Maranhão; MT, Mato Grosso; PA, Pará; RO, Rondônia; RR, Roraima; and TO, Tocantins), the central-west in purple (DF, Distrito Federal; GO, Goiás; and MS, Mato Grosso do Sul), the northeast in orange (AL, Alagoas; BA, Bahia; PB, Paraíba; PE, Pernambuco; PI, Piauí; RN, Rio Grande do Norte; and SE, Sergipe), the southeast in blue (ES, Espirito Santo; MG, Minas Gerais; SP, São Paulo; and RJ, Rio de Janeiro), and the south in green (PR, Parana; SC, Santa Catarina; and RS, Rio Grande do Sul), with unknown (UN) origin shipments shown in grey.

any commitment to monitor their suppliers for deforestation (see below *Coverage of zero deforestation commitments*). In contrast, Frisa Frigorifico Rio Doce ("Frisa") and Pampeano Alimentos, a subsidiary of Marfrig, had low deforestation risks. Frisa sourced from facilities in Minas Gerais, Espírito Santo, and Rio Grande do Sul, where deforestation rates are lower, and Pampeano

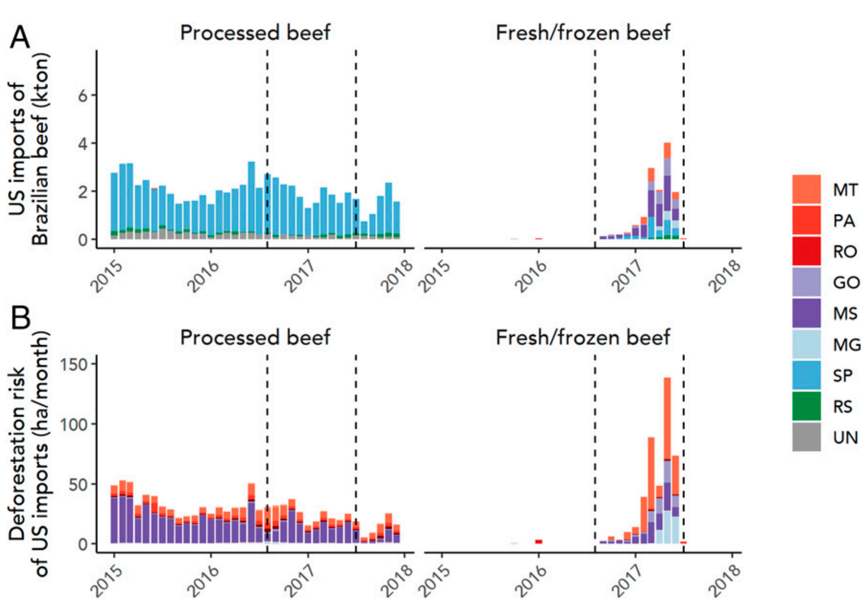

Fig. 3. US deforestation risks have fluctuated notably over time, driven by changes in the products imported. The UnitedStates has historically had low deforestation risk (430 to 850 ha/year) importing processed meat products originating from meat packing facilities in São Paulo (*A*, *Left*) and sourcing cattle from municipalities where there was little recent deforestation (*B*, *Left*). The United States has historically not permitted fresh meat imports from Brazil because of concerns over bovine spongiform encephalopathy (BSE) and food safety in Brazil; from July 2016 onwards, however, the United States did permit fresh meat imports, and this led to a doubling in the Brazil-US beef trade (*A*, *Right*), before the Carne Fraca meat scandal broke and imports were banned again in July 2017 (trade window demarcated by vertical dotted lines). The slaughterhouses which met this new demand for fresh meat in 2016 were located across the country—with 14% of exports originating from facilities in the Legal Amazon region. These exports carried a higher deforestation risk than the previous imports (*B*, *Right*). Note: this plot does not include deforestation risk linked to "unknown" sourcing, and excludes 13.7% of US sourcing, where the month of shipment was unknown. State abbreviations are listed in Fig. 2 legend.

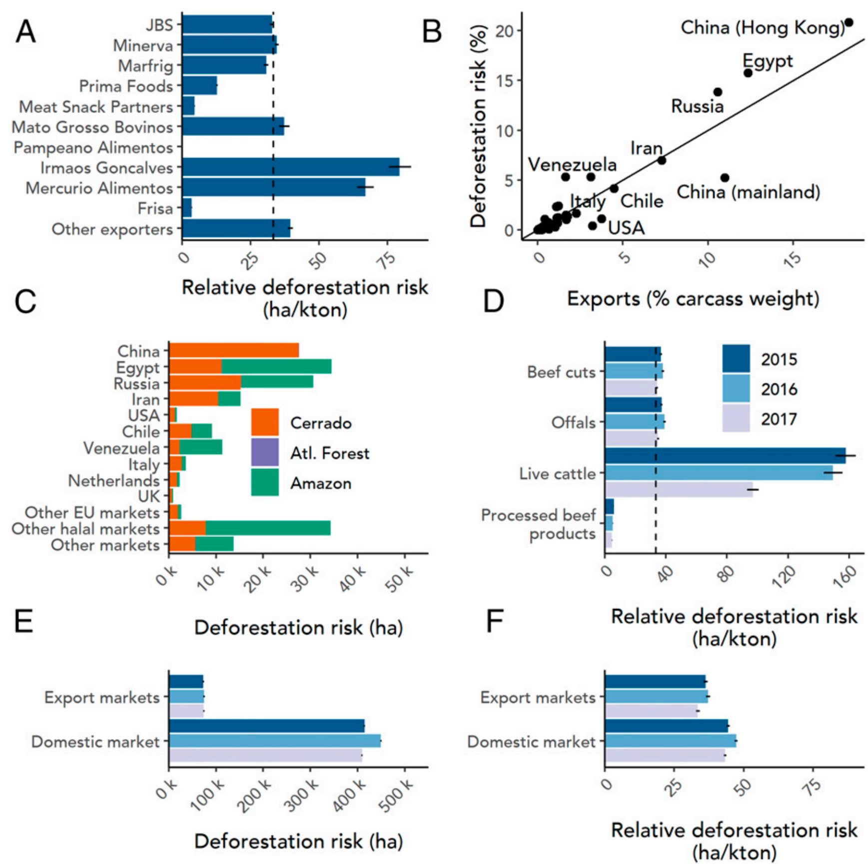

Fig. 4. The deforestation risk of different actors' purchases of Brazilian beef. (*A*) The relative deforestation risk of major exporters, with the market average risk for exports in 2017 shown as a dashed vertical line. (*B*) The deforestation risk of major markets (as a percentage of all export-associated deforestation risk), plotted against their market share (% of exports). (*C*) The deforestation risk of major markets (2015 to 2017) in the Amazon, Cerrado, and Atlantic Forest biomes. (*D*) The relative deforestation risk of different products—live cattle exports carry a disproportionately high risk. The total (*E*) and relative (*F*) deforestation risk linked to exports and the Brazilian domestic market. Error bars show 95% confidence intervals, accounting for key parameter uncertainty (*Materials and Methods*).

Alimentos also operated a processing facility in Rio Grande do Sul, in the Pampas—a nonforested biome (*SI Appendix*).

Among importing countries, we also see stark differences in deforestation risk (Fig. 4*B* and *SI Appendix*, Fig. S6). China, for example, carried the greatest exposure to deforestation: 15,900 to 23,000 ha/year (21.7 to 31.1% of all export-associated deforestation risk), with a notable difference in deforestation risk of imports arriving into ports in mainland China versus Hong Kong (Fig. 5), driven by disparities in their sanitary requirements and slaughterhouse approval processes (*SI Appendix*). These risks are also dynamic—in June 2019, China licensed more than 20 additional cattle slaughterhouses for export to the Chinese mainland; these slaughterhouses had double the deforestation risk of slaughterhouses previously supplying the mainland (70.5 ha/kton ± 81.8 SD vs. 31.0 ha/kton ± 36.1 SD), though these slaughterhouses already supplied 14.2% of exports to Hong Kong between 2015 and 2017.

Different countries' risks arise in different regions (Fig. 4*C*). International markets for halal products (including Egypt, Iran, and the United Arab Emirates) sourced 30.8 to 39.5% of their imports from municipalities in the Amazon, which were responsible for 60.9 to 64.5% of their deforestation risk (15,000 to 20,700 ha/year of 24,600 to 32,100 ha/year across all biomes). The European Union's deforestation risk, in contrast, was concentrated in the Cerrado: 2,100 to 2,600 ha/year, 72.9 to 75.2% of their total deforestation risk (2,900 to 3,600 ha/year). There is no evidence that differences in deforestation risk between countries arise from "preferences" for low or high deforestation risk—before the data presented here were assembled, the deforestation risk of each countries' sourcing was unknown, precluding any informed efforts by downstream actors to reduce their sourcing risks within Brazil. Instead, sourcing patterns have historically been determined by a combination of disease control requirements, product preferences, sanitary requirements, and logistics (see above). A major application of our analyses is therefore to provide a tool for downstream actors (companies and governments) to differentiate sourcing risks, as exemplified by the breakdown of slaughterhouses newly licensed for export to the Chinese mainland (Fig. 5*C*).

Our results also draw attention to Brazil's export of live cattle. This trade in live cattle is comparatively understudied, despite its large size (more than 200,000 animals worth >$200 million are exported each year), implications for animal welfare given the necessary long-distance transport, and disproportionate deforestation risk—live cattle exports are concentrated in the Amazon state of Pará and make up 3.9% of Brazilian cattle exports by value, but 11.6% of deforestation risk (Fig. 4*D*). Seventeen companies handled live cattle exports, of these Minerva was the most important, handling 47.3% of all trade. Beyond Venezuela, mentioned above, other major markets for live cattle were Turkey, Lebanon, Jordan, and Iraq, where cattle are both used as breeding stock and raised for slaughter.

By spatially mapping cattle exports, we also elucidate the proportion of cattle-associated deforestation which is linked to

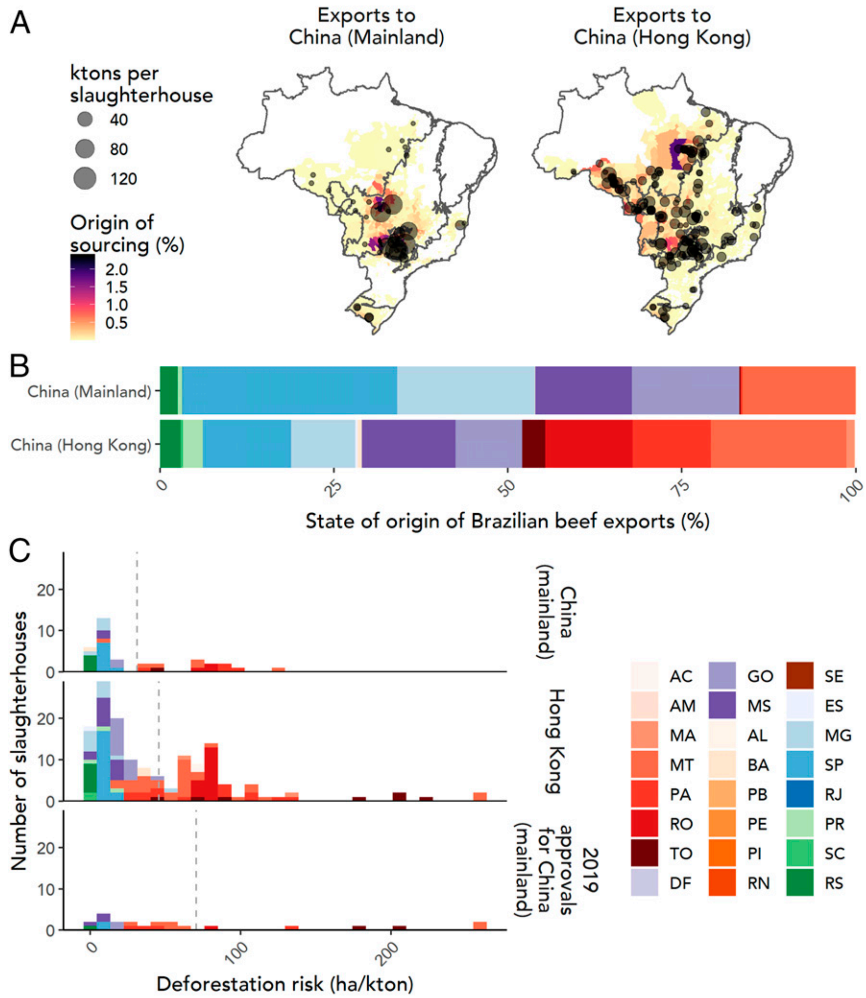

Fig. 5. The origin of Brazilian beef exports to Mainland China and Hong Kong. (*A*) Slaughterhouses are shown as points scaled by the volumes exported, with the percentage of exports originating per municipality in the background. (*B*) The state of origin of cattle supplying each market. (*C*) The deforestation risk of slaughterhouses exporting to China. There is a notable difference in deforestation risk between slaughterhouses exporting to Hong Kong and the Chinese mainland and between slaughterhouses previously exporting to the mainland and those recently licensed for export to the mainland. Among newly licensed slaughterhouses, the top five with deforestation risks >100 ha/kton are located in Mato Grosso (two), Tocantins (two), and Pará (one).

consumption by the Brazilian domestic market. The Brazilian domestic market purchased 80.9 to 82.4% of Brazil's beef across 2015 to 2017, incurring 85.8 to 86.8% of deforestation risk each year, while export markets purchased 17.9 to 19.1% of Brazil's beef, shouldering 13.2 to 14.2% of deforestation risk (Fig. 4*E*). The lower relative risk of export markets (Fig. 4*F*) is not because they do not source cattle from the Amazon, as sometimes suggested (28, 29). Overall, 17.2 to 21.5% of the Amazon's cattle production was exported each year. Rather, within each biome, exports tend to originate from relatively consolidated municipalities, which have well-developed agricultural sectors (higher agricultural gross domestic product [GDP]) and where deforestation is less recent (lower remaining natural vegetation cover), than municipalities supplying the domestic market (*SI Appendix*, Fig. S7).

Clarifications in the Attribution of Deforestation Risk. The attribution of deforestation risk to actors and specific markets comes with some clarifications. First, we use the term deforestation risk, though our data include some nonstrictly forested vegetation types, particularly in the Cerrado, where we used the PRODES-Cerrado dataset on natural vegetation loss. This dataset captures the conversion of a gradient of natural ecosystems, including forest, shrub, and savannah into "anthropic" land uses. We intersect these (and other) data on natural vegetation loss with maps of pasture expansion to limit our analyses to cattle-associated land use change (*SI Appendix*).

When reporting deforestation risk, we included only the footprint of pasture expansion, not other sources of feed. Around 10 to 12% of cattle are finished in feedlot systems. These systems are expanding into frontier regions in Brazil (30), though they ultimately still represent a small proportion of total feed demand, considering that cattle spend at most a few months in feedlots before slaughter. We also do not account for illegality in meat processing and export, though we believe this has a negligible effect on our results (*SI Appendix*).

Each actor's deforestation risk represents the risk of sourcing cattle products from recently deforested land, given their subnational origin, and does not mean that that amount of deforestation was directly "caused" by the production they are purchasing. Rigorous estimates of how much deforestation is caused by each actor or market would ideally account for indirect effects, which could be substantial. For example, although beef exports tend to originate from areas with lower deforestation risk than domestic consumption, exports grew 30% from 2010 to 2017 and may drive expansion in frontier regions by displacing domestic demand elsewhere (31). A spike in late 2019 in beef prices within Brazil, resulting in large part from a surge in demand by the Chinese market, lends support to the idea that changes in exports do have knock-on effects on the domestic market (32). Looking beyond the cattle sector, the pasture area in Brazil has been relatively stable since 2005, at approximately 180 Mha (33). Cropland, in particular soy and sugar cane, expanded by 19.2 Mha between 2005 and 2017 (34), with the majority of expansion occurring onto pasture, which, in turn, has expanded into forest. This complex dynamic makes the relative role of cropland and pasture expansion in driving vegetation loss in Brazil an area of active research and debate.

Overall, each year between 2000 and 2017, cattle-associated deforestation ranged between 0.26 and 1.8 Mha, which on average made up 41% (±3% SD) and 17% (±2% SD) of all deforestation in the Amazon and Cerrado, respectively (*SI Appendix*, Fig. S8). These estimates of cattle-associated deforestation are conservative for two reasons. Firstly, our approach, which intersects remote sensing data on deforestation, pasture expansion, and soy planting, leaves 62% (±47% SD) of deforestation in the Amazon and Cerrado unattributed to a subsequent land use. While some of this deforestation may be attributed to other drivers (e.g., mining, swidden agriculture, other cropland expansion), it also reflects uncertainties in the classification of pasture in remote sensing products. Secondly, we try to limit our calculation to deforestation that is motivated by cattle production, per se, rather than speculative clearing, where vegetation is removed to valorize land, in particular for selling it for soy farming later on. We therefore excluded areas which were planted with soy within 5 y, as well as pasture which was detected more than 5 y postclearance. The latter assumes that the clearance of deforested areas which are idle for 6 or more years before productive use are driven more by speculation, than directly for cattle ranching (even if they then go on to be used for cattle ranching).

Finally, though our results are consistent across different assumptions about cattle slaughter rates, carcass weights, and property sizes, our results are sensitive to the amortization period chosen. Using a 1-y amortization, we estimate 73,000 to 74,700 ha of deforestation risk each year; a 10-y amortization period, on the other hand, increases this to 120,100 to 160,100 ha of deforestation risk each year, because cattle-associated deforestation rates were higher in the early 2000s, and 10-y amortization allocates some deforestation in this period to current exports. Though the overall quantity of deforestation linked to imports in 2015 to 2017 increases substantially, the relative importance of different actors remains similar (*SI Appendix*, Fig. S9), giving confidence to the relevance of our results for differentiating the risk exposure of different markets and buyers.

Coverage of Zero Deforestation Commitments. The deforestation risks embedded in the purchases of companies and countries can be mitigated through government and corporate efforts to regularize land use in the sector. There are two commitments made by slaughter businesses in the Brazilian cattle sector, both initiated in 2009: 1) the Terms of Adjustment of Conduct (TAC) are legally binding commitments signed by individual slaughterhouses to not purchase cattle from properties with illegal deforestation within the Legal Amazon (the nine states making up the Amazon basin); 2) the G4 is an agreement from the three largest meat packing companies, JBS, Minerva, and Marfrig, to not purchase cattle from properties in the Amazon biome who cleared land post-2009.

We find that, in total, 31.2% and 17.8% of Brazil's cattle exports were covered by the TAC and G4 agreements, respectively. These proportions rose to 82.6% and 69.6% of exports from the Amazon biome. Despite the high coverage of these commitments, we found 123,200 ha of deforestation risk linked to exports from the Amazon biome between 2015 and 2017, with G4 companies (and their subsidiaries) linked to 75,600 ha of deforestation risk within the Amazon, and 147,700 ha nationwide. This mismatch between high zero deforestation coverage and considerable deforestation risk arises because of several factors.

First, these commitments are only partially implemented (*SI Appendix*). Second, deforestation commitments are implemented at the level of properties (ranches), but we map supply chains and calculate deforestation risk at the municipal level. While animal movement data can be used to trace cattle back to individual properties, these data were not available for all slaughterhouses (*Materials and Methods*); property boundary data with identifying information (required for making the link with movement data) are not available nationwide, and meat packing companies are not otherwise forthcoming about the origin of their cattle purchases (*SI Appendix*). Monitoring risks at the municipal scale also brings advantages. While committed companies can and do make efforts to avoid deforestation-linked cattle entering their supply chains (23), in practice they only monitor their direct suppliers; they therefore miss the bulk of deforestation associated with their sourcing which arises from their network of indirect suppliers—properties which rear cattle, sell them on to other properties, who may fatten them before sending them to the slaughterhouse. The municipal-level approach taken here captures these landscape-level risks and provides the most complete picture possible, using publicly available data, of their exposure to deforestation nationwide. Previous research indeed suggests that though committed companies have reduced their purchases from properties with post-2009 deforestation, this has not led to landscape-level reductions in deforestation (23, 24, 35). Ultimately the success of commitments needs to be judged against overall changes in deforestation rather than changes in the direct exposure of individual companies. Finally, irrespective of the resolution of the analysis, G4 companies carry considerable deforestation risk also because of the limited geographical scope of their commitment: 47.1% of these companies' deforestation risk arose from sourcing cattle in the Cerrado (*SI Appendix*, Fig. S10), where the G4 does not apply, and 17.2% of their deforestation risk stemmed from sourcing cattle outside the Legal Amazon, where TACs are not in place.

Conclusion

We present a wall-to-wall mapping of the origin and supply chain of Brazil's beef, offal, and live cattle exports, an international trade which supplies more than 150 countries worldwide. Our approach and data, which can be visualized at https://trase.earth/, can be extended to other years, commodities, and countries. These data provide a powerful foundation for understanding the net impacts of international trade, increasing accountability for actors along the supply chain, and can be used by companies and consumer markets to identify hotspots of risk in their supply chains, targeting engagement efforts to deliver improvements on the ground. Potential research applications include quantifying the success of zero deforestation agreements in reducing local deforestation rates, the development of spatially disaggregated carbon, biodiversity, and land use footprints for the cattle sector, and improved corporate carbon accounting (36).

Here we linked these supply chain data to data on deforestation risk, revealing a wide heterogeneity in sourcing patterns and risks between different supply chain actors and highlighting the importance of subnational data for accurate environmental footprinting. Our results draw attention to hotspots of deforestation risk (e.g., linked to specific traders or the trade in live cattle) and reveal the disproportionate deforestation risk associated with the Brazilian domestic market, driven by the fact that export markets tend to source more from postfrontier and consolidated regions.

Though efforts to improve the governance of cattle supply chains often focus on export markets, in particular EU imports (22, 37), clearly efforts to increase accountability within the domestic market, for example among major retailers, are critical (38, 39), given the domestic market's size and deforestation risk (Fig. 4 *E* and *F*). Ultimately, to set the cattle sector onto a more sustainable footing, improvements in the transparency and governance of both domestic and export supply chains are required. Exports are increasing, and we observe that with each new export market opportunity, exports have expanded into areas with more, not less, deforestation risk—as exemplified by renewed exports of fresh meat to the United States and the licensing of new slaughterhouses to the Chinese mainland (Figs. 3 and 5). The major exporting firms are all also major players in the domestic market—any policies implemented to address demands from international customers inevitably have knock-on effects for sustainability risks feeding into the domestic market. Export market requirements have historically been critical in driving improvements across the meat industry, notably in sanitary standards (*SI Appendix*). The leverage of export markets comes in large part from their key role in the financial viability of the sector—margins across the sector are typically low and exports are particularly high value, making up a large share of meatpacker revenues. In 2018, exports were responsible for approximately 45%, 50%, and 65% of JBS, Marfrig, and Minerva's revenues in Brazil, respectively (40–42).

Though some of Brazil's international customers, notably in China, Russia, and the Middle East, are typically thought of as markets which are more concerned with securing a stable supply of imports than the deforestation impacts of those products, the Chinese market, in particular, has shown an increasing awareness of food security and climate risks, including deforestation (43). The lingering potential for an EU-Mercosur trade deal also gives EU markets continued leverage, despite making up only 11.9% of Brazil's beef exports by value. Recent movement (in 2020) by major traders toward improved supply chain monitoring arguably reflects increased scrutiny from multiple directions, including international markets, civil society, and the finance sector.

Brazil's cattle agreements have successfully encouraged ranchers to georeference properties and reduce deforestation rates among properties directly supplying signatory slaughterhouses (23, 24). Achieving landscape level reductions in deforestation will require these governance efforts to expand in coverage—to include a greater proportion of slaughterhouses (supplying both domestic and export markets), extend to regions beyond the Legal Amazon, and to monitor both direct and indirect suppliers (24, 44, 45) (*SI Appendix*). Governance efforts cannot, however, rely only on the private sector. Government enforcement of forest conservation in Brazil was one of the major environmental success stories of the 2000s (46), reducing deforestation even while raising the productivity of cattle ranching (47, 48). Recent moves to cut spending for forest conservation and give amnesty for deforestation on public land have, however, facilitated a resurgence in deforestation rates (49, 50). Ultimately, supply chain sustainability efforts are most likely to succeed when supported by complementary government policy, at national and local levels (24, 44, 45, 50). Only then are these efforts likely to achieve large-scale reductions in the deforestation risk associated with purchases of Brazilian cattle products.

Materials and Methods

Linking Customs Data to Slaughterhouses. We linked customs data for Brazilian beef and live cattle exports between 2015 and 2017 back to slaughterhouses using a logic-based decision tree (*SI Appendix*, Fig. S11). The decision tree triangulated information in customs data with internal trade data to map flows back first to a specific state and then to individual slaughterhouses. Exports were linked to slaughterhouses by crossing the information in the customs data against asset-level tax registrations provided by the National Registry of Legal Entities (Portuguese acronym: CNPJ) and official lists of slaughterhouse export permissions (i.e., to which countries each slaughterhouse is licensed for export). The decision tree also made use of asset ownership data (e.g., JBS' slaughterhouses) and subsidiary relationships between companies (*SI Appendix*).

Identifying the Source of Cattle Slaughtered per Slaughterhouse. Cattle were traced back to the municipalities where cattle were raised using two approaches. First, records of cattle movements, known as Guia de Trânsito Animal (GTA) records, were downloaded from state and federal sources (*SI Appendix*). The GTA data detail the movement of batches of cattle between properties, listing the date of each movement, the farms or slaughterhouse sending and receiving cattle, the number of cattle, and their ages and gender. In total, 16.7 million cattle GTA documents were downloaded, covering cattle movements from 2012 to 2017 for 23 states in Brazil. These data were cleaned, duplicates removed, and records with errors in the dates or locations were discarded, resulting in a sample of 15.6 million GTAs (*SI Appendix*, Fig. S12). We then identified the network of properties and animal movements which supplied each slaughterhouse, by loading these data into a graph database and doing traversal searches on a network of animal movements (*SI Appendix*). The networks of properties supplying each slaughterhouse included so called "indirect suppliers." The network of GTAs was converted into liveweight movements (in kilograms) using conversion factors for cattle of different ages (51). We then identified how much of each slaughterhouse's supply originated from each municipality, by adapting input-output methods previously used for studying the origin of international trade flows (*SI Appendix*, Fig. S13). This slaughterhouse-specific approach was used to map 51.4% of exports back to municipalities of cattle production (*SI Appendix*, Fig. S14). No identifying information about the properties supplying each slaughterhouse is published.

Where GTA data were not available for a given slaughterhouse, but the state of slaughter was known, we used municipal-level data on the origin, the number, and the ages of cattle slaughtered in export-approved (SIF) slaughterhouses per state (52). We converted cattle heads into liveweights and calculated the proportion of SIF slaughter per state (between 2015 and 2017) which originated in each municipality (*SI Appendix*, Fig. S14). These data differ from our slaughterhouse-specific mapping in that they do not account for indirect suppliers. A total of 47.7% of exports were mapped back to a municipality of production using this approach.

Cattle-Associated Deforestation per Municipality. Cattle-associated deforestation (ha/ton carcass) was calculated by intersecting annual deforestation maps in the Amazon, Cerrado, and Atlantic Forest biomes with pasture maps (33, 53–55), summing the area per municipality, and dividing by the municipal cattle production. We used a 5-y allocation period to link deforestation and pasture expansion, i.e., if a polygon of pasture expansion overlapped a deforestation polygon that was cleared less than 5 y previously, then this was identified as cattle-associated deforestation. We used this 5-y allocation for two reasons: 1) land cleared for cattle ranching may not be identified as pasture immediately postclearance because of delays between deforestation and the first planting of grasses or its detection by remote sensing, and 2) some clearance is driven by land speculation more than cattle production, per se, and to try to capture this dynamic we exclude areas where there is a more than 5-y delay between deforestation and the first sign of its productive use (i.e., sowing with pasture). This 5-y cutoff excludes 16% of areas where pasture was detected on land deforested between 2000 and 2017. We also excluded areas that were planted with soy within 5 y of clearance, to account for cases where pasture is used to prepare the soil before planting soy (56). Altogether, we identified 0.26 to 1.8 Mha of cattle-associated deforestation each year, between 2000 and 2017 (*SI Appendix*, Fig. S15). We calculated cattle-associated deforestation using both a 1-y and a 10-y amortization period (*SI Appendix*, Figs. S6 and S9), though we focus on 1-y amortized results in the main text.

Cattle production per municipality (tons of carcass and offal per year) was calculated by multiplying the number of cattle per municipality by state-specific slaughter rates and carcass weights (*SI Appendix*). The slaughter rate was calculated as the herd size divided by the number of cattle slaughtered per state (57, 58). Carcass weights were calculated using state- and year-specific data, dividing the total production of cattle carcasses per state by the number of slaughtered heads (59), and accounting for offal.

As cattle live multiple years, cattle-associated deforestation was calculated over the animal's lifecycle. We assume a cattle lifecycle of 5 y, because the Brazilian cattle herd as a whole has an offtake rate of approximately 20% (14), and so the herd is effectively replaced every 5 y. For 2017 exports, for example, cattle-associated deforestation (in hectares) and cattle production (in tons) were therefore calculated over the 2013 to 2017 period.

Deforestation Risk in Cattle Exports. Deforestation linked to Brazil's cattle exports in each year (deforestation risk) was calculated as the volume of cattle carcass in exports per municipality, multiplied by the deforestation per ton of carcass occurring in the municipalities which supplied each export flow (*SI Appendix*). For the 1% of exports where the state of origin was not known, exports were allocated nationwide in proportion to each municipality's contribution to total production, and the deforestation risk was calculated as above. The deforestation risk of the domestic market was calculated by subtracting exports per municipality from total production and multiplying by deforestation per ton of carcass, as above.

Slaughterhouses were listed as TAC signatories according to ref. 60. When calculating proportions of exports covered by zero deforestation commitments, we considered subsidiaries to be covered by their parent company commitment.

Sensitivity Analysis. We included parameter uncertainty for three key variables: the slaughter rate and carcass weights (both used to estimate cattle production per municipality) and the property herd size (used when identifying the municipal origin of cattle). We conducted a 1,000-iteration Monte Carlo sampling of distributions for each of these parameters and propagated each uncertainty throughout the analysis (*SI Appendix*) to generate 95% confidence intervals.

Data Availability. The .rdata file data have been deposited in Zenodo (10.5281/zenodo.3949782) and code to replicate reported results and figures is available at GitHub, https://github.com/ErasmuszuE/zuErmgassen_2020_PNAS.

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