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LETTER

The role of domestic and international markets in the loss of nature across Brazil

Damares Lopes Afonso[1,*], **Fernando Salgueiro Perobelli**[2], **Weslem Rodrigues Faria**[2] and **Erasmus Zu Ermgassen**[1]

[1] Earth and Life Institute, UCLouvain, Place Pasteur 3, 1348 Louvain-la-Neuve, Belgium
[2] Department of Economics, Federal University of Juiz de Fora (UFJF), Juiz de Fora Campus, José Lourenço Kelmer Street, s/n, Juiz de Fora, Minas Gerais, Brazil
[*] Author to whom any correspondence should be addressed.

E-mail: damaresalopes@gmail.com

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Abstract

Humans have converted a vast area of nature—forests, savannahs, wetlands, and grasslands—for agriculture. Though domestic markets account for more than 70% of global agricultural production and land use change, domestic supply chains and end-uses are rarely mapped. Here, we present an inter-regional input–output model for Brazil, a major agricultural producer and market with an active agricultural frontier, experiencing 70 Mha hectares of vegetation conversion since 2000. We capture the drivers of conversion in each of Brazil's six biomes from 2010–2015, linking them to 36 economic sectors and 47 Brazilian regions and four external trading partners: the European Union, the United States, China, and the Rest of the World. We find that 37.8% of conversion was driven by local (within-state) consumption, 35.2% driven by demand from other Brazilian states, and the remaining 27% for international trade. Overall, the area of non-forest conversion exceeded that of forests, notably for the domestic market and exports to China. Our approach reveals how conversion percolates throughout the economy, with many sectors indirectly sourcing conversion-associated products and by-products. Notably, we link 10.3% of conversion to dairy consumption and 7.9% of conversion to service sectors, such as Horeca (hotels, restaurants, and cafés). While current environmental governance efforts largely focus on zero-deforestation pledges and first-mile traceability (e.g. from farms to slaughterhouses) our results provide a basis for accountability efforts to look upstream, engaging the retail, dairy, leather, and processed food sectors which use products linked to the loss of nature across each of Brazil's biomes.

1. Introduction

Human activities have transformed a large share of the Earth's ice-free land surface, primarily for agricultural production. Croplands and grazing areas occupy nearly half of this area, followed by managed forests (22%), relatively intact natural ecosystems (28%), and urban infrastructure (1%) (IPCC 2019). This conversion has come at high environmental cost: the loss of native vegetation is the main driver of global biodiversity loss (Díaz *et al* 2019) and accounts for 11% of anthropogenic greenhouse gas emissions (Nabuurs *et al* 2023). It undermines progress toward the Sustainable Development Goals, notably SDG 15 ('Life and land'), representing a net loss of societal value as nature and its contributions to people are eroded (Carrasco *et al* 2017, Leite-Filho *et al* 2021). Recent evidence further underscores the need to conserve and restore ecosystems, with the IPCC recommending the effective protection of 30%–50% of land, freshwater, and marine areas to safeguard biodiversity and enhance climate resilience (IPCC 2023).

One of the reasons why vegetation conversion remains difficult to address is that its drivers often operate through telecoupling, defined as the socioeconomic and environmental interactions linking distant human-environment systems through flows of commodities, capital, information, and people

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(Liu *et al* 2013). Rather than viewing land-use change as a purely local process, the telecoupling perspective emphasizes how consumption, production, and environmental impacts are increasingly connected across space through domestic and international supply chains. As a result, demand generated in one region can influence production decisions and ecosystem conversion in another, often distant, location. These spatially separated connections involve multiple actors, sectors, and jurisdictions, making governance more challenging due to limited supply-chain transparency, diffuse responsibilities, and fragmented policy frameworks between producing and consuming regions (Cotta *et al* 2022). Often telecoupling is framed as an international phenomenon, with land use decisions driven by demand from international markets, while telecouplings within domestic markets receive relatively less attention, despite important intra-national teleconnections, notably between urban consumers and rural producers (Seto *et al* 2012). Consistent with this perspective, our analysis examines how both domestic and international markets contribute to vegetation conversion across Brazilian biomes, revealing telecoupled connections that would remain largely hidden in conventional place-based approaches.

Telecoupling is, however, far from a neutral process. Global trade patterns often reproduce and reinforce socio-economic inequalities, with poorer frontier regions supplying raw materials and ecosystem services to wealthier core regions (Dorninger *et al* 2021). Historically, countries in the Global North have driven land-use conversion and appropriated value from countries in the Global South, generating substantial losses of natural capital through processes described as ecologically unequal exchange—costs that remain largely invisible in conventional monetary accounting systems (Chang *et al* 2016, Hickel *et al* 2021). At the same time, trade can contribute to economic development by expanding export opportunities, generating foreign exchange earnings, and strengthening productive capacities, particularly when accompanied by effective industrial and development policies (Siddiqui 2015). These contrasting outcomes highlight the importance of improving transparency and environmental governance across supply chains, as well as fostering greater environmental responsibility among consumers. Indeed, such measures are central to three of the eight 'leverage points for transformative change' identified by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) as essential for addressing global sustainability challenges (Díaz *et al* 2019, Chan *et al* 2020).

Despite extensive research over the past 10–15 years to develop the data and methods necessary to track telecouplings from production landscapes through to (distant) consumers, this literature has three main limitations. First, it prioritizes forests over other natural vegetation, despite high conversion rates in savannahs, grasslands, and wetlands (Kan *et al* 2025). This bias is reflected in global governance initiatives such as the Consumer Goods Forum's zero-deforestation target the New York Declaration on Forests, and the EU Deforestation Regulation (European Parliament 2023), as well as in empirical studies (Pendrill *et al* 2019a, 2019b, Kastner *et al* 2021), with few exceptions (Hong *et al* 2022). Second, most studies focus on primary commodities and inadequately capture processing and inter-sectoral transformations, relying largely on FAOSTAT-based physical trade models (Laroche *et al* 2024). Third, research emphasizes international trade, although only 12%–26% of agricultural products are globally traded (D'Odorico *et al* 2014, Geyik *et al* 2021, Li *et al* 2022), while domestic markets account for 61%–71% of deforestation and 73% of land-use emissions (Pendrill *et al* 2019b, Hong *et al* 2022). Intra-national telecouplings and the potential for ecologically unequal exchange within countries receive comparatively less research and policy attention.

This study addresses these gaps by estimating vegetation conversion embodied in Brazil's domestic and international trade, including agricultural, industrial, and service sectors. Specifically, we identify how vegetation conversion in Brazil is driven by different consumer markets (local, national, and international) and how this conversion reverberates across various economic sectors. We construct an inter-regional input–output model (MIP-Biomas) covering 36 economic sectors across 47 Brazilian regions and four external trading partners (European Union, United States, China, and the Rest of the World (RoW)) for 2015. These economic data are integrated with satellite-based conversion data from MapBiomas (2010–2015) to calculate conversion embodied in final demand, capturing telecouplings within Brazil and internationally from a consumer-based perspective.

Brazil has the highest cumulative land-use change emissions globally due to extensive conversion across all six biomes (Evans 2021; SI appendix figure S1). Since 1985, the country has lost 25% of the Cerrado, 13% of Amazônia, 24% of the Pampa, 11% of the Caatinga, 10% of the Pantanal, and 7% of the Mata Atlântica. This conversion represents a massive loss of natural capital. These biomes host 1.7 million Indigenous people (IBGE 2023), contain 15%–20% of global biodiversity (CBD 2025), provide vital ecosystem services and natural products (Strand *et al* 2018), regulate climate and rainfall (Leite-Filho *et al* 2021, Butt *et al* 2023), store carbon (Strand *et al* 2018), and support agricultural productivity (Rattis *et al* 2021, de Souza Batista 2023). Agricultural expansion—especially cattle ranching—drives most

conversion, with pasture accounting for 69% of converted land, followed by cropland (17%), forest plantations (3%), and mixed mosaics (11%) (Souza *et al* 2020a).

Although Brazil is a major agricultural exporter, domestic markets dominate consumption, often with limited transparency (Belik 2020, Zu Ermgassen *et al* 2020a). For example, most beef (75%), maize (62%), beans (95%), bananas (99%), and cassava (99%) are consumed domestically (Belik 2020). Existing subnational studies focus on single commodities, principally soy and beef (Rajão *et al* 2020, Zu Ermgassen *et al* 2020a, 2020b), with limited attention to domestic markets, processed products, or non-forest vegetation. A notable exception is Haddad *et al* (2024), which assesses trade-driven deforestation in the Legal Amazon, though not accounting for conversion in other regions and losses of non-forest vegetation. By contrast, this study provides a comprehensive inter-regional assessment of vegetation conversion embedded across Brazil's entire economy, covering all biomes and vegetation types.

The novelty of this study lies not in the application of entirely new modelling techniques, but in the integration of multiple economic and environmental databases within a biome-based multiregional input–output framework. While previous approaches such as Trase focus on selected export commodities and Haddad *et al* (2024) focus on the Brazilian Amazon, MIP-Biomas provides coverage across all Brazilian biomes, economic sectors, domestic markets, and major international trading partners. This integrated framework allows production, consumption, trade flows, and ecosystem conversion to be analysed simultaneously across the entire Brazilian economy, substantially expanding the geographic and sectoral scope of previous assessments.

2. Materials and method

This study developed an interregional input–output matrix, named MIP-Biomas, designed to represent in an integrated manner all Brazilian biomes and their economic sectors. The matrix combines economic and environmental databases to capture the productive heterogeneity that exists across Brazil's states and biomes while maintaining consistency with official national accounts. The structural basis of MIP-Biomas is the Brazilian 2015 input–output Matrix produced by the Brazilian Institute of Geography and Statistics (IBGE 2018), which was regionalized using the Interregional input–output Adjustment System (IIOAS), a methodology widely applied in the construction of interregional input–output models (Dixon and Rimmer 2004, Faria and Haddad 2014, Haddad *et al* 2017).

The regional database follows the procedures adopted by Haddad *et al* (2024) and disaggregates the national economy into 47 biome-state regions (biome-UFs). This regionalization was performed by replacing national sectoral totals with region-specific shares representing each biome-state region's participation in production, value added, final demand, and international trade. Within the IIOAS framework, these regional shares are used to distribute national economic flows across regions while preserving consistency with the original national accounts. As a result, the regional matrix reproduces the official national totals while explicitly identifying the regional location of production, consumption, and trade activities. For more detailed information on the construction and structure of the IIOAS, see SI appendix S1.

Regional shares were derived from official Brazilian databases as presented in table 1. Production shares were obtained from the Agricultural Census for agricultural production and from Relação Anual de Informações Sociais (RAIS) wage-bill data for non-agricultural sectors, a proxy for sectoral production. Value-added shares were estimated by combining regional production levels with national value-added coefficients. Household and NPISH consumption were regionalized using information from the Household Budget Survey (POF), while government consumption and investment were distributed using municipal gross domestic product (GDP) statistics. International exports were regionalized using ComexStat data, allowing export flows to be allocated by economic activity, biome-state region, and destination market. All information was initially processed at the municipal level and subsequently aggregated into biome-state regions. In cases where 2015 data were unavailable, shares were calculated using data from the nearest available years.

Because official information on interregional trade flows is not available at the level of detail required by this study, bilateral trade matrices were estimated using a gravity-based approach (Jain 2026). Under this framework, trade flows are determined by the interaction between regional supply and demand and constrained by transport costs. Consequently, regions with greater productive capacity and demand tend to trade more intensively, while increasing distance reduces the likelihood and magnitude of exchanges. Bilateral trade shares were estimated using regional production, regional demand, and an impedance matrix based on road travel distances between regions (Carvalho *et al* 2021).

This procedure generates a parsimonious and internally consistent representation of interregional trade patterns, but it necessarily abstracts from factors that may influence observed trade relationships. Institutional arrangements, environmental regulations, subsidies, informal economic activities, migration dynamics, and other non-market interactions are not explicitly represented. Likewise, the framework captures economic relationships at a given point in

time and does not account for opportunity costs associated with land-use change or dynamic responses to policy and market shocks. Consequently,estimated trade flows should be interpreted as a structural approximation of interregional exchanges rather than a complete representation of underlying socio-economic and environmental processes.

The resulting MIP-Biomas includes 47 biome-state regions, 36 economic sectors distributed across agriculture, manufacturing, and services, and four international trading partners: the European Union (EU), the United States (USA), China, and the rest of the World (RoW). The EU, USA, and China were modelled separately because of their importance as destinations for Brazilian exports and their relevance in ongoing debates and policy initiatives related to deforestation-free supply chains. This structure captures the economic heterogeneity of Brazilian regions while explicitly linking production, consumption, and trade flows across biomes. By integrating this framework with vegetation conversion data, it becomes possible to trace how domestic consumption patterns, supply chains, and international markets are associated with ecosystem conversion across Brazil.

Indicators of vegetation conversion embodied in domestic and international trade were estimated by combining monetary flows from MIP-Biomas with land-use change data from MapBiomas[3] Collection 9. To allocate vegetation conversion to final consumers, we applied the complete agricultural land footprint approach (Fan *et al* 2022, explained in SI appendix S2), which traces direct and indirect supply-chain linkages through a multiregional input–output framework. Using the Leontief inverse, the method attributes conversion occurring in producing regions to both domestic consumption and export demand, allowing the identification of final markets associated with ecosystem conversion. The approach also enables the estimation of bilateral embodied conversion flows between regions and the assessment of the relative contribution of domestic and international demand.

Land-use change data were obtained from MapBiomas Collection 9, which processes Landsat satellite imagery at 30 × 30 metre resolution across all Brazilian municipalities. Municipalities were aggregated into biome-state regions, with each municipality assigned to the biome occupying the largest share of its territory. Vegetation conversion was defined as the transition of native vegetation to agricultural land uses, including soybean, sugarcane, rice, cotton, coffee, citrus, oil palm, other perennial crops, pasture, and planted forests.

Vegetation conversion is characterized in this study as the conversion of forest areas and other vegetation types to agricultural activities, such as soybean, sugar cane, rice, cotton, other temporary crops, coffee, citrus, palm oil, other perennial crops, pasture, and forest plantations. One of the advantages of MapBiomas data is its comprehensive definition of forests and other vegetation types, which includes forest formations, mangroves, floodable forests (together 'Forests'), and savanna formations, wooded sandbank vegetation, wetlands, grasslands, hypersaline tidal flats, and herbaceous sandbank vegetations ('Non-forests'), covering all natural vegetation in Brazil's biomes (SI appendix table S2). To ensure consistency between economic and environmental data, we used annualized vegetation conversion estimates derived from the total area converted between 2010 and 2015, allocating conversion evenly across the five-year period rather than assigning all observed transitions to a single year. This approach reflects the gradual nature of land-use change and aligns cumulative environmental impacts with the annual economic structure represented by the 2015 input–output table. For example, if 10 hectares of land were forested in 2010 but detected as soybeans in 2015, then we linked 2 hectares of soybean-driven conversion linked to 2015 consumption (i.e. 10 hectares of conversion allocated across five years). This approach expands on previous analyses which used a one-year allocation period only (Haddad *et al* 2024), potentially over-allocating conversion to cattle production because land is often first converted to pasture before subsequent planting with crops such as soybeans, rice, cotton or maize.

3. Results

We first compare patterns of forest and non-forest conversion, then examine the sectoral footprints underpinning these changes, and finally investigate how local, inter-state (national), and international markets shape vegetation conversion across Brazil.

3.1. Conversion of forest and non-forests

Global consumption in 2015 was associated with the conversion of 3.05 million hectares of native vegetation in Brazil (conversion annualized across 2010–2015, see Methods). Of this total, 44.7% (1,37 million hectares) was deforestation (conversion of forests) and 55.3% (1,69 million hectares) was the conversion of other vegetation types (figure 1). i.e. The area of non-forest vegetation converted was 23.5% larger than the area of forest loss. Nearly three-quarters

[3] MapBiomas provides annual land-use and land-cover data for all of Brazil based on Landsat imagery and automated classification procedures. Differences between MapBiomas estimates and official monitoring systems such as PRODES may arise from differences in scope, definitions, spatial coverage, and methodological approaches. While PRODES is designed primarily to monitor clear-cut deforestation in specific biomes, MapBiomas tracks transitions among multiple land-use classes across the entire country, making it particularly useful for studies linking vegetation conversion to economic activities and land-use trajectories.

Table 1. Database used for the construction of MIP-Biomas in addition to the IBGE IOM for the year 2015.

	Sectors 1–6	Other sectors (7–36)
Intermediate consumption	Agricultural census (2017)	RAIS (2015)
Government consumption	Gross domestic product (GDP) of public administration IBGE (2015)	
NPISH consumption	POF (2017–2018) and RAIS (2015)	
Household consumption	POF (2017–2018) and RAIS (2015)	
Investment	Total GDP IBGE (2015)	
Exports and imports	COMEXSTAT (2015)	

Note: Years in parentheses indicate the reference year of the original dataset used in the construction of the matrix.

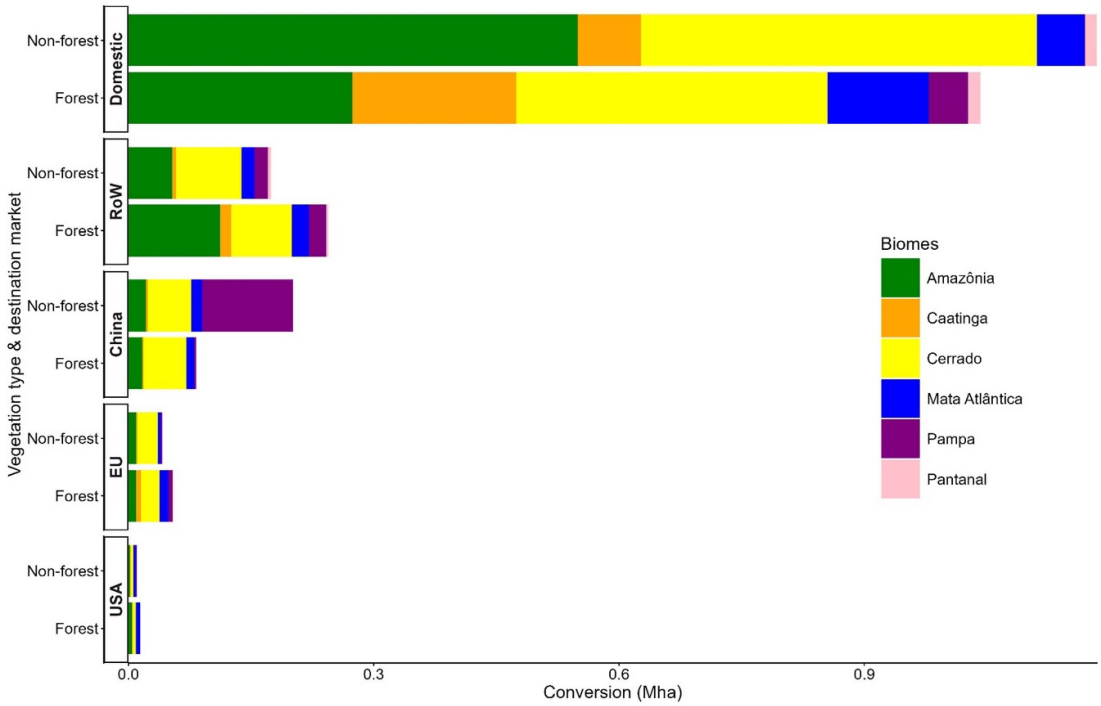


Figure 1. Annualized forest and other vegetation conversion embodied in domestic and international trade in Brazil.

(73%) of total conversion was associated with domestic consumption, although exports to China, the EU, the USA, and the RoW also exerted substantial pressure, accounting for the remaining 27% of total conversion. For conversion linked to Chinese consumption, the area of non-forest vegetation conversion was more than twice as large as forest loss (220 800 ha versus 64 400 ha). Exports to the EU, USA, and RoW were also associated with greater conversion of other natural vegetation (280 800 ha versus 258 800 ha) than forest loss.

3.2. Sectoral footprints

We trace conversion in each biome across the sectors and states where products were transformed, through to destination markets (figure 2). From a consumption perspective, activities linked to animal protein products—beef, pork, chicken, eggs, dairy, hunting services, and live cattle sales—accounted for 66% of conversion in Brazil (figure 3). Overall, 81.6% of this vegetation conversion was for the domestic market, with 18.4% linked to exports—though there were important differences between the market demand behind conversion for different animal products. Exports were more important for chicken, pork, and eggs (43% of conversion linked to exports, 57% for domestic demand) than for cattle products (16.8% exports, 83.2% domestic) or dairy products (1.1% exports, 98.9% domestic). The majority of this conversion occurred in Amazônia (42.7%), the Cerrado (37.9%), and the Caatinga (11.4%).

Other important agricultural product flows included soybean exports to China, and crops like rice, cotton, and coffee for multiple markets (figure 3). China's sourcing of soy was linked to 202 580 ha of conversion—6.6% of all conversion across Brazil—principally in the Pampa (110 250 ha), Cerrado (70 296 ha) and Mata Atlântica (18 000 ha). Other temporary crops, such as rice and cotton, were

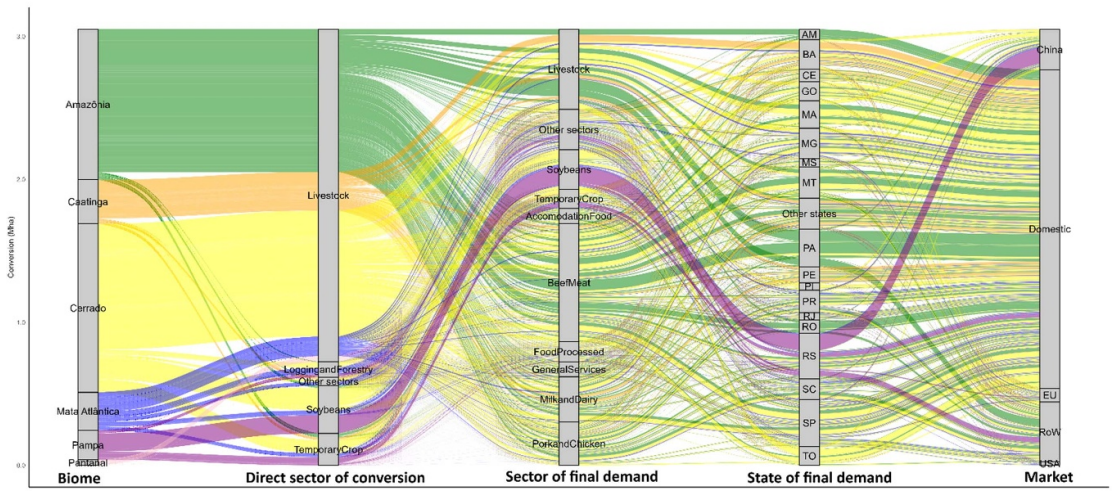


Figure 2. A: Interlinkages of vegetation conversion in Brazilian biomes to their sectors, final destinations and sectors within Brazil and destination markets.

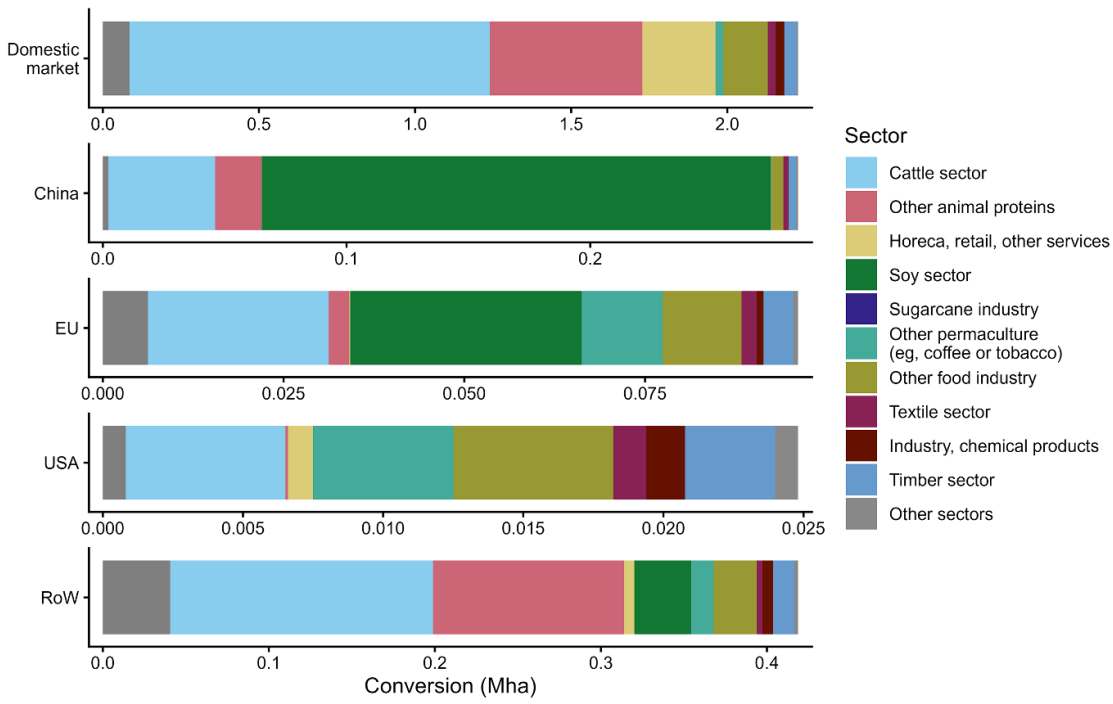


Figure 3. Total conversion of vegetation in Brazilian domestic and international trade by sector, biome of origin and final market linked to 2015 consumption. The 36 modelled sectors are aggregated here for easier interpretation, full names are detailed in table S1.

linked to 223 800 ha of total conversion (7.3% of the total), mostly linked to conversion in the Cerrado and Pampa (91 600 ha and 58 000 ha, respectively), 92% of which was destined for the domestic and RoW markets.

Our approach also reveals how conversion percolates throughout the economy, even into what might be considered as non-food sectors. Horeca (hotels, restaurants, and cafés), retail and wholesale, and other services, were associated with 241 200 ha (7.9%) of conversion, and textiles and timber-related sectors (including paper, wood products and furniture) were, respectively, linked to another 34 000 ha and 62 300 ha of conversion (1.11% and 2.04% of the total). We note that our estimates of conversion for timber only include the expansion of tree plantations into other land uses, and not extraction of native wood, which would be considered as forest degradation, rather than land use conversion (see Methods). We can highlight the movement and processing of products within Brazil, prior to export (SI appendix figure S4). For example, 90% of the conversion linked to exports of footwear and leather goods—8000 ha, principally in the Amazônia and

the Cerrado—involved supply chains where products were internally-displaced before export. These patterns confirm the importance of traceability efforts back to the farm or landscape of origin, notably required under the EU Deforestation Regulation, as checks based on the location of the registered exporters would miss the true origin and impacts of products.

3.3. Disaggregating the domestic market

Within the domestic market, we differentiate the conversion driven by both local and national markets, which was evenly split: 37.8% all conversion was linked to within-state consumption (e.g. forest loss in Pará state linked to consumption in Pará), and 35.2% of conversion driven by demand from other Brazilian states (here defined as national or interstate markets)—the remaining 27% of conversion being linked to international trade, as previously discussed. The proportion of conversion linked to local, national, or international markets varied, however, across biomes (figure 4). The Pampa biome stands out for its strong connection to global markets, with half (53.3%) of all conversion linked to Chinese imports of soybeans.

The heterogeneity in footprints within Brazil is again seen in state-level data (figure 5(a)). More than four-fifths (84.1%) of the conversion linked to consumption in Amazônia's two most populous states, Pará and Amazonas, occurred locally (within-state), highlighting the role of the Amazonian economy in driving deforestation. For Rio de Janeiro and São Paulo, however, largely situated in the Mata Atlântica biome, the picture was very different. Only 24% of the Mata Atlântica's forest cover remains, with much of the vegetation conversion occurring in the wake of Portuguese colonization in the 1500s. More than 90% of the conversion linked to the economies of Rio de Janeiro and São Paulo occurs elsewhere—notably in the Cerrado (141 290 ha) and Amazônia (82 240 ha). States with high GDP tend to have higher imports of conversion to meet their consumption (figure 5(c)). Notably, we see that the economies of the Mata Atlântica biome, which is home to 70% of the Brazilian population and 80% of the national GDP (39), has the highest levels of embodied vegetation conversion (figure 5(c)). This finding highlights the notion of unequal exchange within the Brazilian economy, where poorer regions experience ongoing vegetation conversion to supply populations in wealthier regions.

4. Discussion and conclusion

We trace the market drivers of vegetation conversion across all six Brazilian biomes: Amazônia, Caatinga, Cerrado, Mata Atlântica, Pampa, and Pantanal. Our analysis covers both domestic and international markets, drawing on a novel input–output model, MIP-Biomas, which disaggregates Brazil into 47 internal regions and 36 economic sectors spanning agriculture, manufacturing, and services. The model also captures trade flows with major global partners, including the EU, the USA, China, and the RoW. Furthermore, we differentiate between forest and non-forest vegetation types to more accurately characterize biome-specific ecological impacts.

Our modelling approach is based on a regionalized input–output framework that traces environmental pressures embodied in supply chains within Brazil and abroad. As with any modelling exercise, the results should be interpreted as estimates of likely patterns of responsibility rather than direct observations of physical commodity flows. Nevertheless, our findings broadly align with studies using national-scale data and physical trade models (Pendrill *et al* 2019a, 2019b), subnational supply-chain mapping from the Trase initiative (Zu Ermgassen *et al* 2020a, 2020b), and input–output analyses for the Legal Amazon (Haddad *et al* 2024) (SI appendix figures S5–S8). The consistency of these different approaches suggests that the model captures the main structural drivers of vegetation conversion in Brazil.

Notably, we reproduce several findings reported in the literature, including the importance of soy production in the Pampa and Mata Atlântica (Ribeiro and Guedes Pinto 2023, Amaral *et al* 2025, Pereira and Bernasconi 2025) and the export of live cattle from Amazônia (zu Ermgassen *et al* 2024). While our findings suggest that consumers within Amazônia and those elsewhere in Brazil have roughly equal importance in driving conversion in the region, Haddad *et al* (2024) find that intra-national trade is more important—responsible for 59.7% of deforestation in the Legal Amazon (with 16.8% linked to local consumption) (SI appendix figure S8). These differences stem largely from different framings of responsibility. Our approach allocates conversion proportional to final consumption (Fan *et al* 2022), while Haddad *et al* employ a hypothetical extraction method that allocates responsibility according to the marginal effect of removing demand. Despite these differences, both approaches point to the importance of domestic demand as a major driver of vegetation conversion.

The patterns identified in our analysis should also be interpreted within the broader governance context that shapes land-use outcomes across Brazilian biomes. Brazil has developed one of the most comprehensive environmental governance frameworks among tropical commodity-producing countries, combining command-and-control policies, satellite monitoring systems, protected areas, environmental licensing, rural property registration systems, and private-sector initiatives. Programs such as PRODES,

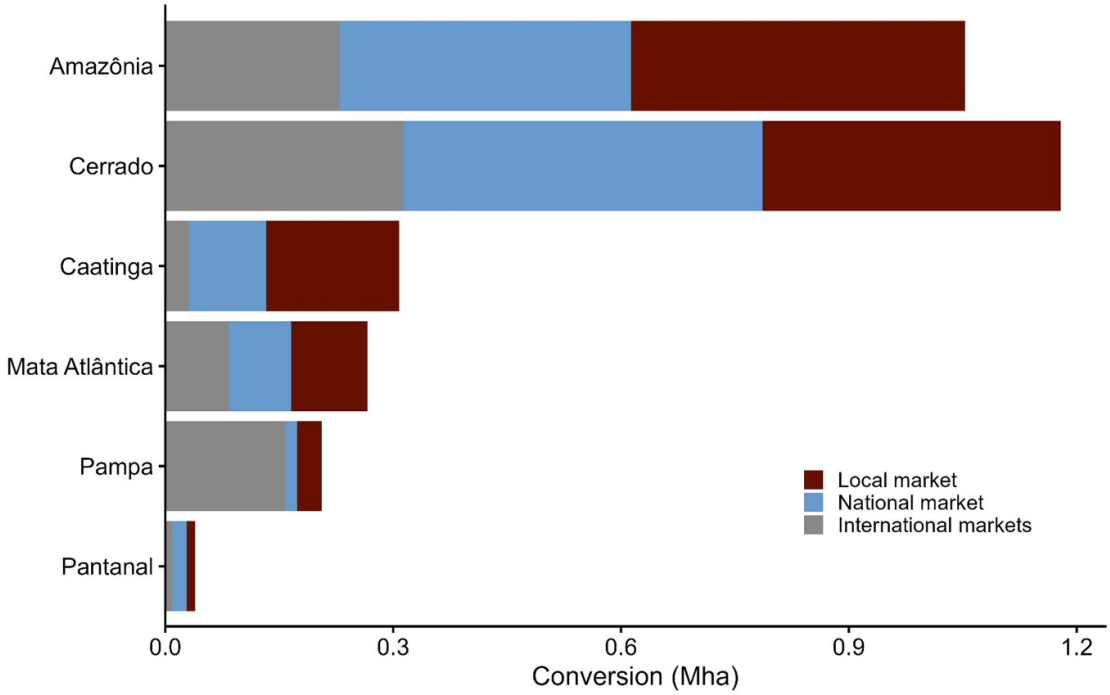


Figure 4. Conversion in each biome is driven by local markets (i.e. consumption within the same state where conversion occurred), national markets (consumption in a state different from where the conversion took place) as well as international markets.

protected areas, and the enforcement of environmental legislation have played an important role in reducing deforestation pressures in several periods, particularly in Amazônia. However, Brazil's biomes are governed under substantially different regulatory regimes, enforcement capacities, and private-sector arrangements. Consequently, observed differences in vegetation conversion reflect not only variations in market demand, but also differences in governance effectiveness and regulatory coverage.

We find that the conversion of non-forest vegetation—including savannahs, wetlands, and grasslands—is linked to all markets and, for some destinations, exceeds the area of forest conversion. Historically, however, conservation efforts have focused more strongly on forests, particularly the Amazon rainforest. This priority is reflected in the Brazilian Forest Code, which mandates larger conservation areas on private properties in Amazônia (80% of private lands) compared with Cerrado areas within the Legal Amazon (35%) and other biomes across the country (20%). The national and international focus on Amazônia is also reflected in conservation funding, monitoring systems, and scientific research. As a result, forests have generally received greater institutional attention than non-forest ecosystems, despite growing evidence of biodiversity loss and ecosystem degradation in savannahs, wetlands, and natural grasslands.

A similar pattern can be observed in private-sector sustainability initiatives. Within Brazil, initiatives such as the Amazon Soy Moratorium and the Cattle Agreements have played an important role in improving traceability and reducing deforestation associated with agricultural expansion in the Amazon biome, though they may have increased conversion in the neighbouring Cerrado (Moffette and Gibbs 2021). More recently, other initiatives have sought to expand governance beyond forests, including the Cerrado Manifesto, the Agriculture Sector Roadmap to 1.5 °C, the Consumer Goods Forum Forest Positive Coalition, and the Science Based Targets Network Land Target. Similarly, growing attention has been given to deforestation- and conversion-free (DCF) sourcing commitments and the protection of non-forest ecosystems in corporate sustainability strategies.

Nevertheless, important asymmetries remain. Forest 500 data, for example, indicate that companies are still more than three times more likely to adopt zero-deforestation commitments than broader zero-conversion commitments (Thomson 2025). This suggests that forests continue to receive substantially greater attention than other native ecosystems. Some authors have argued that non-forest regions have effectively functioned as 'sacrifice frontiers' for forest conservation (Levy *et al* 2024). While attention to non-forest ecosystems has increased considerably in recent years, our results suggest that these ecosystems remain exposed to substantial conversion pressures from both domestic and international markets. The adoption of a 'Cerrado Protocol' for sustainable cattle sourcing and the growing emphasis on DCF commodities are therefore welcome developments,

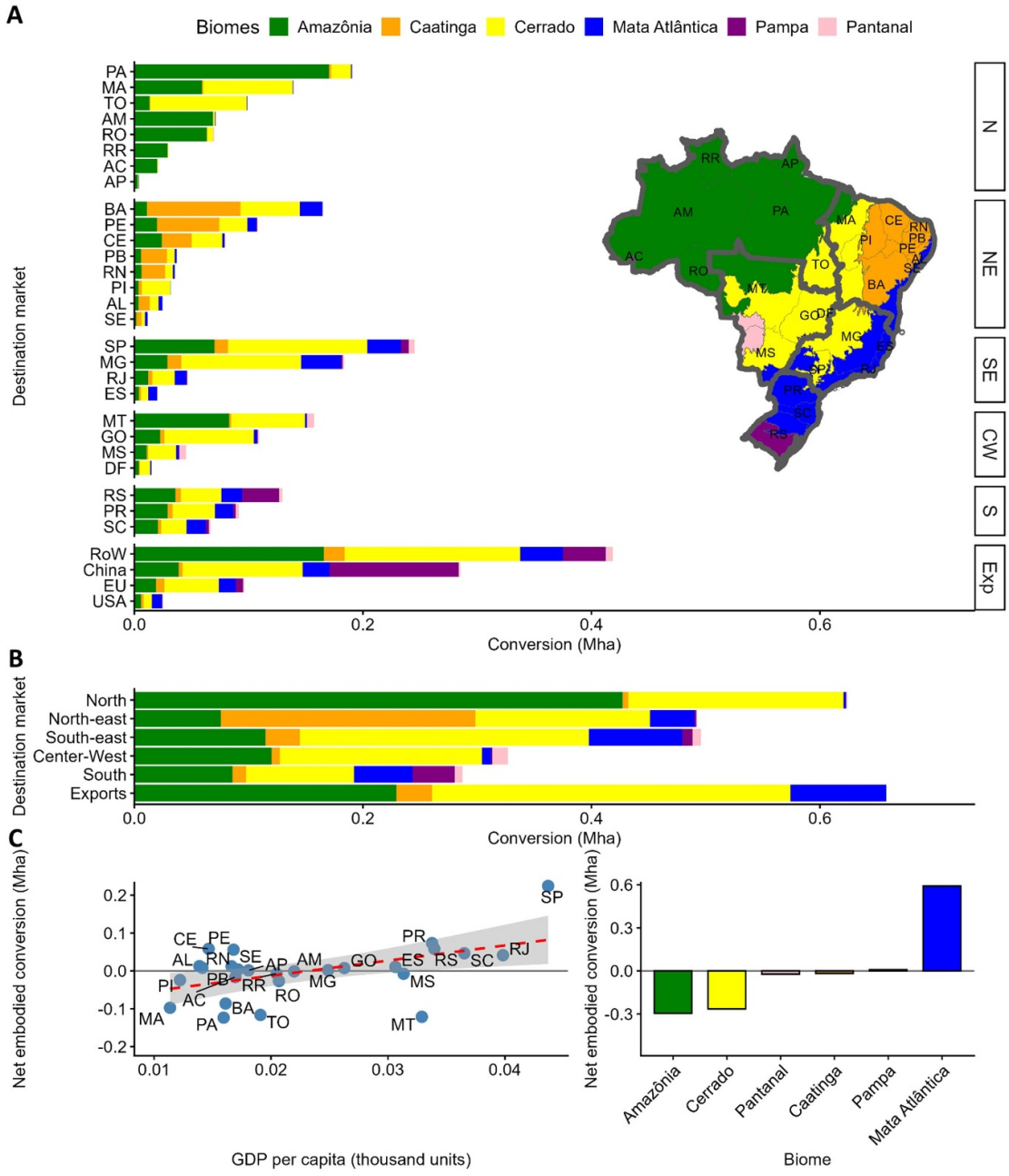


Figure 5. The vegetation conversion (per biome) embodied in the consumption of each state (panel A), and region (panel B), as well as exports. Panel (C) shows the correlation between state GDP and net embodied conversion (left) at the state level (left) and the net embodied conversion across biomes (right). Panel (A) region abbreviations: N = North, NE = North-East, SE = South-East, S =South, CW = Center-West, Exp = Exports.

although broader implementation will be required for these initiatives to achieve impacts consistent with the scale of conversion identified in our analysis (AFi 2024, Zu Ermgassen *et al* 2025).

Our results also highlight the importance of the domestic market, which is associated with 73% of vegetation conversion across Brazil, most of it linked to livestock products (figures 2 and 3). This finding suggests that strategies focused exclusively on exports are likely to overlook a substantial share of the demand associated with land-use change. While environmental governance efforts have often concentrated on improving traceability between farms and slaughterhouses (Gibbs *et al* 2016), our results indicate that downstream sectors such as retail, dairy, leather, and other users of livestock by-products also play an important role in shaping conversion outcomes.

The dairy sector provides a notable example. Although it has generally received less attention in discussions of agricultural sustainability than beef and soy, we estimate that 10.3% of vegetation conversion is associated with dairy consumption. Almost 40% of this conversion occurred in the Cerrado, followed by 33.7% in Amazônia and 17.8% in the Caatinga. The relevance of livestock by-products is

also consistent with recent studies drawing attention to deforestation and labour concerns associated with tallow-derived biofuels from Amazônia (Pajolla and Borges 2025). These indirect connections of the livestock sector may become increasingly important in light of recent commitments to expand biofuel production announced around COP30 in Belém (Brazil 2025).

We further disaggregate the domestic market into local (within-state) and national consumption, finding that both play an important role in vegetation conversion, accounting for 37.8% and 35.2%, respectively, of natural vegetation loss across Brazil. The relative importance of these markets varies considerably across regions and biomes (figure 4). Consumption in the North region is predominantly associated with local conversion (84.9% local versus 15.1% elsewhere), whereas states in the South-East predominantly drive conversion beyond their borders (76.3% versus 23.7% locally).

These patterns point to two important dimensions of land-use change in Brazil. First, despite the frequent representation of Amazônia as a remote wilderness or resource frontier, it is largely an urbanized region, with more than 70% of the population living in cities (Brondizio 2025). Demand from local urban centres therefore represents an important driver of vegetation conversion. Beef consumption in urban areas, for example, is substantially higher than in rural areas both on a per-capita basis and in aggregate terms (IBGE 2021). Second, interregional trade redistributes environmental pressures across the national economy. A significant share of the environmental impacts associated with resource-intensive production occurs in regions that differ from those where final consumption takes place. This reflects long-standing patterns in which natural resources from poorer and environmentally vulnerable regions support economic activity and consumption in wealthier parts of the country.

A similar dynamic can be observed in Brazil's international trade patterns. We estimate that 49.7% of export-related conversion is associated with exports of primary commodities, such as soybeans, rather than processed and higher-value products. This pattern reflects both China's expansion of domestic processing capacity and Brazilian tax incentives that have historically favoured exports of primary and minimally processed goods. The Kandir Law, for example, exempts many exported products from the ICMS tax. Recent fiscal reforms may alter these incentives by extending tax advantages to processed exports (Gala 2025), potentially increasing domestic value addition before export. Whether increased processing within Brazil would reduce or intensify pressures on natural ecosystems, however, remains uncertain.

Land conversion in Brazil cannot be understood solely as an environmental issue because it is closely intertwined with economic development objectives. The agricultural sector plays a strategic role in the Brazilian economy, contributing approximately 3% of formal employment, 5.6% of GDP, and around 30% of Brazilian exports when considering raw agricultural commodities alone. Including the food industry raises this share to over 40%, highlighting the sector's contribution to economic growth, foreign exchange earnings, and trade balance. Our results suggest that effective governance requires accounting for connections among consumers, producers, and ecosystems across multiple regions and supply chains rather than focusing solely on individual production areas (Meyfroidt *et al* 2020).

Against this backdrop, growing international pressure to reduce deforestation has intensified debates over the compatibility of agricultural expansion and environmental conservation. Although agricultural expansion and land conversion have supported economic growth, employment, export earnings, and income generation in many frontier regions, they have also become the main drivers of tropical deforestation, biodiversity loss, greenhouse gas emissions, and ecosystem degradation (Tilman *et al* 2001, Gibbs *et al* 2010, IPCC 2019, IPBES 2019). Consequently, policies aimed at reducing deforestation are often discussed in terms of trade-offs between environmental conservation and economic development.

Studies suggest that restricting land conversion may reduce agricultural production, income, and regional economic growth where agricultural expansion remains an important development strategy (Ferreira Filho and Horridge 2012, Ferreira Filho *et al* 2015, Carvalho *et al* 2016, Souza 2022). However, these trade-offs are not necessarily unavoidable, as complementary policies that promote productivity gains, technological innovation, and regional development can substantially reduce the economic costs of conservation (Foley *et al* 2011, Carvalho *et al* 2016, Souza *et al* 2020b). Furthermore, recent evidence indicates that forest conservation may also generate direct economic benefits by maintaining regional climate regulation. Amazon deforestation has been shown to reduce precipitation and depress soybean yields in southern Brazil, implying that continued forest loss can erode agricultural productivity itself through biophysical feedbacks, thereby weakening the presumed conflict between conservation and agricultural development (Li *et al* 2026). Understanding who benefits from land conversion, who bears its environmental costs, and which sectors ultimately drive deforestation and other vegetation conversion is therefore essential for designing effective and equitable conservation policies.

Our contribution complements this literature by focusing on the demand-side drivers of vegetation conversion. Rather than estimating the economic costs of conservation policies, the input–output

framework identifies how environmental pressures are embodied in supply chains and ultimately linked to different forms of final demand. Our results indicate that responsibility for vegetation conversion extends beyond export markets and is predominantly associated with domestic demand. Within domestic demand, household consumption accounts for 75.21% of total conversion, followed by investments (22.78%), government consumption (1.88%), and NPISH consumption (0.12%) (SI appendix figure S9). These findings provide a complementary perspective on the economic-environmental trade-offs associated with land-use change in Brazil.

Our work inevitably comes with some limitations. First, the footprint of the timber and pulp-and-paper industries represents only a fraction of their environmental impacts because we do not account for forest degradation associated with logging activities. Second, the results should be interpreted as estimates derived from a regionalized input–output framework rather than direct observations of commodity movements. Although the broad patterns identified are consistent with previous studies and external datasets, uncertainty increases when interpreting specific supply-chain pathways, individual trade relationships, or highly localized hotspots.

Third, the input–output matrix represents a snapshot of the Brazilian economy in 2015 and does not fully capture the multi-year life cycle of some products. For example, the livestock sector appears partially as a consumer of its own output because financial transactions include farm-to-farm sales within the same year. This characteristic may make estimates of interregional trade conservative, as these transactions are overwhelmingly local. In comparison, most flows from livestock production to other sectors occur between states or through international trade. This study is also subject to the inherent limitations of static input–output models, which assume fixed production structures and therefore do not capture technological change, substitution effects, or dynamic responses to shocks over time. These limitations should be considered when interpreting the results.

Finally, the baseline year of the model (2015) is the most recently available, though it is worth reflecting on how our results might map to the Brazilian economy today. Though the structural changes in the Brazilian economy over the last decade have been limited (Haddad *et al* 2024), one notable change is in the share of trade with China. From 2015–2024, exports of beef to China and Hong Kong grew 3.9-fold, from 374 000 t yr^{-1} to 1.5 million tonnes. An update to the input–output model would therefore capture an increase in Chinese imports, replacing 'RoW' countries as the main export market (figure 4). Despite the impressive growth in China's imports, this does not change the conclusion that the domestic market is still dominant—in 2024, 72% of beef was consumed domestically, versus 80% in 2015 (Zu Ermgassen *et al* 2020a, ABIEC 2024). Although specific trade relationships may evolve over time, the broader structural patterns identified here remain consistent with recent evidence, including findings from Trase (supplementary material S5 and S6).

Altogether, our findings show that responsibility for vegetation conversion is shared across domestic and international markets, and multiple sectors of the economy. They further suggest that land-use outcomes emerge from the interaction between market demand and a governance landscape that varies substantially across biomes, vegetation types, and supply chains. This highlights the need for responses that extend beyond producer-level interventions and export-oriented policies. Reducing vegetation conversion will require stronger traceability and accountability throughout value chains, continued improvements in environmental governance, greater protection of non-forest ecosystems, and policies that promote sustainable consumption while addressing the regional inequalities that continue to shape patterns of production and resource use across Brazil's diverse biomes.

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Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.21821440.

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Author contributions

Damares Lopes Afonso 0000-0001-6579-4946
Conceptualization (equal), Formal analysis (equal), Methodology (equal), Writing – original draft (equal)

Fernando Salgueiro Perobelli
Conceptualization (equal), Supervision (equal), Writing – review & editing (equal)

Weslem Rodrigues Faria
Conceptualization (equal), Methodology (equal), Supervision (equal), Writing – review & editing (equal)

Erasmus Zu Ermgassen 0000-0002-9168-6057
Project administration (equal), Validation (equal), Writing – original draft (equal)

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