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

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 activities 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 37.2% of conversion was driven by local (within-state) consumption, 34.8% driven by demand from other Brazilian states, and the remaining 28% 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 10.2% of conversion to dairy consumption and 7.7% of conversion to service sectors: Horeca (hotels, restaurants, and cafés), commerce and other services. 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.

Keywords: Vegetation loss. Domestic trade. International trade. Brazilian biomes. Input-Output.

1. Introduction

Humans have converted a vast area of the planet Winkler & Fuchs (2021), principally for agriculture. Half (49%) of the ice-free surface of the planet is used for croplands and raising livestock, with infrastructure (1%), forestry (22%), and minimally-exploited nature (28%) and making up the rest (IPCC, 2019). This conversion is the basis of modern agriculture, human dwellings, and the extractive economy, but has also come at a huge cost. The conversion of native vegetation – henceforth "conversion" – is the main driver of biodiversity loss globally (Díaz et al., 2019), and a major source of greenhouse gases, with 11% of anthropogenic greenhouse gases stemming from land use change (Nabuurs et al., 2023). Continued conversion undermines progress toward the UN Sustainable Development Goals (not least, SDG17 'Life on land'), presenting a net loss of value to humanity as nature and its contributions to people are eroded (Carrasco et al., 2017, Leite-Filho et al., 2021).

One of the features which makes conversion so persistent and hard to tame is that the drivers of conversion often act at a distance – i.e. through "telecouplings" (Liu et al., 2013). There is a spatial disconnect between the places and actors responsible for production and consumption. Consumer decisions in one place, transmitted via market signals and supply chains, can have profound impacts on land use decisions and the environment elsewhere. The lack of proximity and transparency along supply chains, along with the high number of actors involved and policy incoherence and fragmentation between producer and consumer jurisdictions all complicate the environmental governance of telecoupled systems (Cotta et al., 2022).

Telecoupling is, furthermore, not a neutral process. Patterns of trade between producer and consumer regions reproduce socio-economic inequalities, with poorer "periphery" or frontier regions disproportionately supplying raw material resources to wealthy "core" regions (Dorninger et al., 2021). Historically, northern countries have contributed to conversion and extracted value from southern countries, who have lost substantial natural capital as a result (Chang et al., 2016), in what has been labelled an "ecologically unequal exchange" (Hickel et al., 2021). These losses are not transparent as the asymmetry in the net transfers of resources is not reflected in traditional monetary accounts (Hickel et al., 2021). Transparency, improved governance of telecouplings, and efforts to foster environmental responsibility for consumers are therefore at the core of three of the eight "leverage points for transformative change" identified by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (Díaz et al., 2019, Chan et al., 2020).

While there has been a concerted research effort over the last 10-15 years to enable these leverage points, by developing the data and methods necessary to trace impacts from production landscapes through to (distant) consumers, this literature has three main limitations. It is biased toward the conservation of forests over other natural vegetation (savannahs, grasslands, wetlands, etc); it has focused on primary commodities, with limited consideration of processed or derived products; and it has relied on coarse, national-level data which has resulted in an over-emphasis on the role of international trade, rather than the flows of goods within countries.

The prioritization of forests over other natural vegetation has been a feature of environmental governance of the last 15 years, although ecosystems like grasslands, savannahs, and wetlands face high conversion to agriculture – often comparable to or exceeding forest loss (Kan et al., 2025). In 2010, for example, the Consumer Goods Forum announced its landmark zero-net deforestation target. This was followed by the New York Declaration on Forests in 2014, which again did not include non-forest vegetation. Though the more inclusive concept of "deforestation- and conversion-free" (DCF) commodities achieved greater prominence with the publication of the Accountability Framework initiative in 2019, forests are still prioritized in most fora – not least the European Union's 2023 Deforestation Regulation (EUDR). The EUDR seeks to prohibit the import of deforestation-linked products and will only evaluate extending the regulation's scope to include "other woody vegetation" within one year and "other natural ecosystems" within two years of entry into force (the date of which is currently uncertain) (European Parliament, 2023). This bias toward deforestation is also reflected in the telecoupling literature (e.g. Pendrill et al., 2019a, Pendrill et al., 2019b, Kastner et al., 2021). A rare exception being (Laroche et al., 2024) which quantified all land use emissions embodied in international trade.

While conversion may be for the production of raw commodities like soybeans and cattle, these commodities are fed into complex supply chains, where they are transformed into many derivative products and embedded in sectors across the economy. Leather, for example, is used in the apparel sector for footwear and automotive industry for car seats. Telecoupling studies have heavily relied, however, on physical trade models fed by FAOSTAT data which struggle to capture product transformation and inter-sectoral dependencies (Laroche et al., 2024). A deeper understanding of embodied vegetation conversion requires analytical tools capable of integrating both spatial and sectoral dimensions.

Finally, most studies of telecouplings focus on international trade (e.g. Pendrill et al., 2019a, Pendrill et al., 2019b, Kastner et al., 2021, Dalin et al., 2017, Lenzen et al., 2012, Hong et al., 2022) – however, only 12-26% of agricultural products are internationally traded (Li et al., 2022, D'Odorico et al., 2014, Geyik et al., 2021). The remaining 74-88% are produced and sold within domestic markets – i.e. most food is produced and consumed within the same country. Commensurately, domestic markets are estimated to be responsible for 61-71% of deforestation and 73% of global land use emissions (Pendrill et al., 2019b, Hong et al., 2022). These numbers come, however, from global studies using national-level data, which do not differentiate the responsibilities of different populations within countries. Telecouplings do not only occur along international supply chains – they are also inter-regional (Fan et al., 2022) or urban-rural phenomena (DeFries et al., 2010), though these intra-national connections and the potential for ecologically unequal exchange within countries receive comparatively less research and policy attention.

In this study, we address these gaps by estimating the vegetation conversion embodied in Brazil's domestic and international trade flows, encompassing not only the agricultural sectors directly linked to conversion but also industrial and service activities. 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. To this end, we employ an inter-regional input–output model specifically developed for this research – MIP-Biomas – which covers 36 economic activities across 47 Brazilian regions, including all biomes and states and four external trading partners (the European Union (EU), the United States (USA), China, and the Rest of the World - RoW) for the year 2015. These data are integrated with satellite-based conversion data from MapBiomas (2010-2015) to calculate conversion embodied in both domestic and international trade, adopting a final-demand perspective, in other words, a consumer-based approach capturing telecoupling both within the Brazilian domestic market and abroad.

Globally Brazil is the country with the highest cumulative emissions from land use change (Evans, 2021), because of the conversion of both forest and non-forest vegetation across each of its six biomes (SI Appendix Figure S1). Since 1985 Brazil has lost 25% of the Cerrado savannah, (32.1 Mha), 13% of the rainforests in Amazônia (53.2 Mha), 24% of the Pampa grasslands (2.8 Mha), 11% of the Caatinga dry forests (6 Mha), 10% of the Pantanal wetlands (1.5 Mha), and 7% of the Mata Atlântica's moist broadleaf forests (2.4 Mha).

This conversion represents a massive loss of natural capital. Brazil's biomes – home to 1.7 million indigenous people (IBGE, 2023) – have profound cultural and spiritual significance and host 15-20% of the world's biodiversity (CBD, 2025) while providing a plethora of natural products (Strand et al., 2018), regulating local and regional temperatures and rainfall (Leite-Filho et al., 2021, Butt et al., 2023), and acting as a globally-relevant store of carbon (Strand et al., 2018). Ultimately, these services support the productivity of the very agriculture which is the main driver of conversion (Rattis et al., 2021, de Souza Batista, 2023).

Across Brazil, the expansion of agriculture – especially cattle ranching – accounts for most conversion, with pasture occupying 69% of converted land, followed by croplands (17%), forest plantations (3%), and mixed-use mosaics (11%) (Mapbiomas col. 9). Agricultural products are then transformed into a range of processed products – such as meat, leather footwear, and biofuels – and transported along complex supply chains and integrated into all sectors across the economy. Though Brazil has become a major exporter of agricultural commodities, the domestic market is still dominant in terms of volume and the lackof transparency (zu Ermgassen et al., 2020a). For example, most beef (75%), maize (62%), beans (95%), bananas (99%), and cassava (99%) are sold into the domestic market (Belik, 2020).

The literature which has mapped supply chains in Brazil at subnational scale has to-date focused on the export of single commodities – particularly soybeans and beef (zu Ermgassen et al., 2020a, zu Ermgassen et al., 2020b, Rajão et al. (2020), largely ignoring the role of the domestic market and the end-use of processed products in the wider economy. A notable exception is (Haddad et al., 2024), which evaluated the impacts of domestic and international trade on deforestation in the Legal Amazon, though not accounting for conversion in other regions and the loss of non-forest vegetation. Here we present an inter-regional input–output model for 2015 covering all biomes and natural vegetation types in Brazil to map domestic and international trade flows with high geographic and sectoral disaggregation, accounting for conversion impacts embedded in agriculture, industry, and services.

2. Materials and Method

2.1 Construction of the Input-Output Matrix for Brazilian Biomes (MIP-Biomas)

This study developed an interregional input-output matrix, named MIP-Biomas, to encompass all Brazilian biomes and economic sectors. The matrix was based on the 2015 Input-Output Matrix (IOM) from the Instituto Brasileiro de Geografia e Estatistica (IBGE, 2018), the most recent official dataset available. Input-output matrices have been widely applied in environmental studies for analyzing land use and deforestation impacts (Pendrill et al., 2019b, Fan et al., 2022, Haddad et al., 2024, Chen & Han, 2015, Marselis et al., 2017, Ali, 2017, Chen et al., 2018, Sun et al., 2020, Franco-Solís & Montanía, 2021, Hoang & Kanemoto, 2021), with analyses ranging across global, national, and regional scales, and addressing various ecological indicators.

The input-output approach was selected for its ability to model domestic trade patterns across all regions and sectors, as highlighted in studies by (Fan et al., 2022) and (Haddad et al., 2024), while also facilitating assessments of international trade, in line with previous research (Pendrill et al., 2019a, Henders et al., 2015). To build the MIP-Biomas matrix, the original IBGE IOM was first converted into a 36-by-36 activity-by-activity framework using the commodity-by-commodity technology assumption (Miller & Blair, 2009), enabling detailed sectoral analyses of agricultural-driven vegetation conversion, at the product level, making the analysis more detailed than at the sectoral level.

Next, the matrix was regionalized using the Interregional Input-Output Adjustment System (IIOAS), which estimated interregional trade flows based on SHIN tables (Dixon & Rimmer, 2004). This technique has been widely applied to regionalize national input-output tables (Haddad et al., 2024, Faria & Haddad, 2014). MIP-Biomas provides regional detail for 47 biome-UFs (biome-state combinations), representing Brazilian biomes subdivided by state, and includes 36 economic activities spanning the primary, industrial, and service sectors. Table 1 presents the regional and sectoral structure, while SI Appendix Figure S1 illustrates the spatial layout of the biomes-UFs.

To carry out the regionalization from IIOAS method, we used national IOM data from IBGE (IBGE, 2018), and shares of each economic activity by region. Intermediate consumption shares were based on sectoral wages from the RAIS database (2015) for activities 7 to 36, while activities 1 to 7 used production values from the 2017 Agricultural Census. Final demand components – including government, household, NPISH consumption, gross fixed capital formation, exports, and imports – were sourced from various national datasets, as summarized in Table 2. All data were collected at the municipal level and aggregated to the biome-UF level, with shares determined by participation in national totals. In the absence of publicly available regional trade flow data, we assume that trade flows follow a gravity model a common approach in SHIN tables (e.g. Haddad et al., 2024, Faria & Haddad, 2014). This approach allows us to estimate interregional trade patterns based on geographic proximity, reflecting the tendency for regions that are closer together to engage in more frequent and intense economic exchanges. Data on road distance was collected from Google Maps and OpenStreetMap APIs (Carvalho et al., 2021).

Table 1. Regional and sectoral definition of the MIP-Biomas

Regions			Activities	
R1	Amazônia-Acre	Amazônia-AC	1	Sugarcane
R2	Amazônia-Amazônias	Amazônias-AM	2	Soybeans
R3	Amazônia-Amapá	Amazônia-AP	3	Other temporary crop products and services
R4	Amazônia-Maranhão	Amazônia-MA	4	Coffee beans
R5	Amazônia-Mato Grosso	Amazônia-MT	5	Other products from permanent crops
R6	Amazônia-Pará	Amazônia-PA	6	Bovine and other live animals, animal products, hunting and services
R7	Amazônia-Rondônia	Amazônia-RO	7	Pigs, poultry and eggs
R8	Amazônia-Roraima	Amazônia-RR	8	Logging and forestry
R9	Amazônia-Tocantins	Amazônia-TO	9	Fishing and aquaculture
R10	Caatinga-Alagoas	Caatinga-AL	10	Extractive activities
R11	Caatinga-Bahia	Caatinga-BA	11	Meat of bovine animals and other meat products
R12	Caatinga-Ceará	Caatinga-CE	12	Pork and poultry meat
R13	Caatinga-Minas Gerais	Caatinga-MG	13	Industrialized fish
R14	Caatinga-Paraíba	Caatinga-PB	14	Milk and dairy products
R15	Caatinga-Pernambuco	Caatinga-PE	15	Other food products
R16	Caatinga-Piauí	Caatinga-PI	16	Beverages
R17	Caatinga-Rio Grande do Norte	Caatinga-RN	17	Tobacco products
R18	Caatinga-Sergipe	Caatinga-SE	18	Manufacture of textiles, clothing and accessories
R19	Cerrado-Bahia	Cerrado-BA	19	Manufacture of footwear and leather goods
R20	Cerrado-Distrito Federal	Cerrado-DF	20	Wood products, excluding furniture
R21	Cerrado-Goiás	Cerrado-GO	21	Cellulose, paper and paper products manufacturing
R22	Cerrado-Maranhão	Cerrado-MA	22	Various industries
R23	Cerrado-Minas Gerais	Cerrado-MG	23	Petroleum refining and coking plants
R24	Cerrado-Mato Grosso do Sul	Cerrado-MS	24	Manufacture of biofuels
R25	Cerrado-Mato Grosso	Cerrado-MT	25	Chemical products
R26	Cerrado-Piauí	Cerrado-PI	26	Fertilizers, pesticides and disinfectants
R27	Cerrado-Paraná	Cerrado-PR	27	Mineral products, steel, metallurgy and related
R28	Cerrado-São Paulo	Cerrado-SP	28	Machinery and equipment
R29	Cerrado-Tocantins	Cerrado-TO	29	Manufacture of transport vehicles, including parts
R30	Mata Atlântica-Alagoas	Mata Atlântica-AL	30	Furniture
R31	Mata Atlântica-Bahia	Mata Atlântica-BA	31	Energy, gas, water, sewage, waste management and other utilities
R32	Mata Atlântica-Espírito Santo	Mata Atlântica-ES	32	Trade
R33	Mata Atlântica-Goiás	Mata Atlântica-GO	33	Transportation
R34	Mata Atlântica-Minas Gerais	Mata Atlântica-MG	34	Warehousing and postal services
R35	Mata Atlântica-Mato Grosso do Sul	Mata Atlântica-MS	35	Hotels, restaurants, and cafés (Horeca)
R36	Mata Atlântica-Paraíba	Mata Atlântica-PB	36	Various services
R37	Mata Atlântica-Pernambuco	Mata Atlântica-PE		
R38	Mata Atlântica-Paraná	Mata Atlântica-PR		
R39	Mata Atlântica-Rio de Janeiro	Mata Atlântica-RJ		
R40	Mata Atlântica-Rio Grande do Norte	Mata Atlântica-RN		
R41	Mata Atlântica-Rio Grande do Sul	Mata Atlântica-RS		
R42	Mata Atlântica-Santa Catarina	Mata Atlântica-SC		
R43	Mata Atlântica-Sergipe	Mata Atlântica-SE		
R44	Mata Atlântica-São Paulo	Mata Atlântica-SP		
R45	Pampa-Rio Grande do Sul	Pampa-RS		
R46	Pantanal-Mato Grosso do Sul	Pantanal-MS		
R47	Pantanal-Mato Grosso	Pantanal-MT		

Table 2. Database used for the construction of MIP-Biomas in addition to the IBGE IOM for the year 2015

	7Activities 1 – 6	Other activities (7 - 36)
Intermediate consumption	Agricultural Census (2017)	RAIS (2015)
Government consumptiom	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)	

2.2 Vegetation Conversion Data Conversion in Brazil

Data on agricultural land use change were obtained from MapBiomas Collection 9, a dataset that processes Landsat satellite images with a resolution of 30 × 30 meters per pixel across all Brazil. MapBiomas provides extensive regional and sectoral disaggregation, ideal for this study’s requirements. Municipalities were aggregated to create biome-UFs, with each municipality assigned to the biome containing the largest share of its land cover when it covered more than one biome.

Agricultural classes in the MapBiomas dataset were directly aligned with the activities in MIP-Biomas, except for the rice, cotton, citrus and palm oil categories. Rice and cotton were grouped under “other temporary crops”, while citrus and palm oil were classified under “other permanent crops”. The pasture areas were allocated to activity 6 of MIP-Biomas, which covers activities related to livestock, animal products, and related services. Forest plantation areas were linked to activity 8, which represents logging and forestry. The areas classified as mosaics of agriculture and pasture were proportionally allocated between agriculture and pasture based on their shares from their original categories in Mapbiomas, to preserve the proportionality observed within each biome-state in the MIP-Biomas model.

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, savanna formations, mangroves, floodable forests, wooded sandbank vegetation, wetlands, grasslands, hypersaline tidal flats, and herbaceous sandbank vegetations, covering all the vegetation in Brazil's biomes. We define “forest” as forest formations together with mangroves. All other vegetation types are classified as “other vegetation” as defined by Trase (68) To align with the 2015 base year of the input-output database and account for the multi-year time lag between the clearing of land and the establishment of agriculture (Pendrill et al., 2019a, Pendrill et al., 2019b, zu Ermgassen et al., 2020a, Graesser et al., 2018), we identified the proximate driver of deforestation based on an allocation period of 5 years, from 2010 to 2015, using the conversion annualized per year. 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.

2.3 Measuring Vegetation Conversion Embodied in Domestic and International Trade

To estimate vegetation conversion embodied in domestic and international trade, we adopt the complete agricultural land footprint (CALF) methodology described by (Fan et al., 2022). This approach redistributes total vegetation conversion across end-users based on the demand-supply chain structure. In this study, we distinguish between domestic and international end-users. Domestic end-users are represented by domestic absorption (f), which includes household consumption, government consumption, NPISH consumption, and investment. International end-users are represented by exports (e). The vegetation conversion of one area that is allocated to part of the vegetation conversion footprint of another area is considered the vegetation conversion embodied in trade, inherent to the links in the demand-supply chain.

To facilitate the explanation of the analytical techniques, Table S1 serves as a synthesis of the MIP-Biomas structure, comprising n regions (biomes-UFs), each with m economic activities and t elements of final demand. In this framework:

- z_{ij}^{sd} represents the monetary value of goods or services purchased from activity i in region s for the intermediate use of activity j in region d.
- f_{it}^{sd} denotes the monetary value of goods or services from activity i in region s destined for region d, to meet final demand element t, consumed domestically through government consumption, NPISH consumption, household consumption, or investment.
- e_i^s refers to the portion of final demand exported abroad from activity i in region s, disaggregated by destination country or external region (k).
- y_i^s is the total final demand for activity i in region s.
- p and c represent the vectors of imports and taxes, respectively.
- w_j^d indicates the value added by activity j in region d.
- x_i^d is the total output of activity i in region d.
- r_j^d captures the vegetation conversion footprint associated with activity j in region d, measured in hectares (ha).

All these measurements are in monetary units, except r_j^d which are in hectares (ha). The intersectoral flows of the input-output model can be represented as follows: a) the equilibrium expressed by total demand, equation 1, which represents the sum of intermediate demand (z) and domestic (f) and exported (e) components of final demand; b) the equilibrium given by total supply, with the sum of intermediate consumption plus value added, as shown in equation 2.

$$x_i^s = \sum_{s=1}^{n} \sum_{j=1}^{m} z_{ij}^{sr} + f_i^s + e_i^s \quad (1)$$

$$x_j^d = \sum_{s=1}^{n} \sum_{i=1}^{m} z_{ij}^{sd} + w_j^d \quad (2)$$

Where total demand (equation 1) is equal to total supply (equation 2) in the model. Coefficients of production, representing production technology, are assumed to be fixed, that is, the output of each product is a function of a fixed combination of the intermediate input components:

$$a_{ij} = \frac{z_{ij}}{x_j} \quad (3)$$

Whither technical coefficients represent the quantity of inputs i required to produce one unit of the activity's output j. Substituting equation 3 in equation 1:

$$x_i^s = \sum_{s=1}^{n} \sum_{j=1}^{m} a_{ij}^{sr} X_j + f_i^s + e_i^s \quad (4)$$

Replacing total demand (y) as the sum of domestic demand (f) and exports (e) and considering the system in matrix form, we have:

$$\boldsymbol{X} = \boldsymbol{AX} + \boldsymbol{Y} \quad (5)$$

The solution for total output (X) is a function of the Leontief inverse $((I - A)^{-1})$ and the total final demand (Y) which is exogenous to the model.:

$$\boldsymbol{X} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{Y} \quad (6)$$

This system indicates the output required, directly and indirectly, in each activity i when final demand increases by one monetary unit. In addition to these equations from the traditional model, the MIP-Biomas makes use of h, a coefficient of direct vegetation conversion footprint, calculated separately, per unit of product, x, by activity j in the region of origin d:

$$h_j^d = \frac{r_j^d}{x_j^d} \quad (7)$$

The interpretation of h_j^d regarding vegetation conversion can tell us how much vegetation conversion activity j produces per monetary unit of output produced in this activity. Crop agriculture, livestock, and logging and forest activities are direct drivers of vegetation conversion (activities 1 to 6 and 8; Table 1), the direct vegetation conversion footprint, r_j^d, of all industries other than agricultural ones are zero – the same occur with the coefficient h_j^d. Thus, the conversion of vegetation embodied into activities other than agriculture is caused by indirect links in the supply chain.

Considering the separation of national and international end users in MIP-Biomas, equation 6 can be rewritten as:

$$X = (I - A)^{-1}(\sum f^s + \sum e^s) \quad (8)$$

In which X denotes the total output, A is the direct consumption coefficient matrix between the domestic regions; f^s denotes the domestic absorption; and e^s denotes the international final use given by exports of region s. Replacing the Leontief matrix as $B = (I - A)^{-1}$, equation 8 becomes:

$$X = B(\sum f^s + \sum e^s) \quad (9)$$

Taking the direct vegetation conversion, h^d, and considering equation 9, we can calculate the vegetation conversion embodied in domestic trade:

$$Domestic\ trade\ footprint = h * X = h * B * (\sum f^{il}) \quad (10)$$

$$h * X = (h^1 \ldots h^s \ldots h^n) * \begin{bmatrix} b^{11} & \cdots & b^{1n} \\ \vdots & \ddots & \vdots \\ b^{n1} & \cdots & b^{nn} \end{bmatrix} * (\sum f^s) \quad (11)$$

Where b^{sd} denotes the block matrix in the Leontief inverse matrix. The footprint in area s is then expressed by:

$$Domestic\ trade\ footprint^s = h^s * \sum_l \sum_i b^{si} f^{il} \quad (12)$$

Which represents the vegetation conversion footprint of region s caused by domestic absorption (f), considered as domestic trade, being i the activities and l the regions. In the same way, we have vegetation conversion embodied into international trade:

$$International\ trade\ footprint = h * X = h * B * (\sum e^i) \quad (13)$$

$$h * X = (h^1 \ldots h^s \ldots h^n) * \begin{bmatrix} b^{11} & \cdots & b^{1n} \\ \vdots & \ddots & \vdots \\ b^{n1} & \cdots & b^{nn} \end{bmatrix} * (\sum e^s) \quad (14)$$

Then, the international footprint in area s is then expressed by:

$$International\ trade\ footprint^s = h^s * \sum_k b^{sk} e^k \quad (15)$$

In this way, we measure the vegetation conversion embodied in international trade in region s caused by the exports (e) to the EU, US, China and the rest of the world (RoW), which are calculated separately for these foreign regions and represented by k.

In domestic and international trade, we also map the bilateral flows of vegetation conversion within Brazilian regions, from the region of origin s to its final region inside Brazil, d, for each final market – which can be the domestic region itself (in the case of domestic trade) or exports to the EU, USA, China, or the rest of the world. The bilateral regional trade pattern for each market can be expressed as:

$$Bilateral\ trade\ footprint^{sd} = h^s * \sum_i b^{si} f^{id} \quad (16)$$

Symmetrically, the vegetation conversion in region d allocated to region s is:

$$Bilateral\ trade\ footprint^{ds} = h^d * \sum_i b^{di} f^{is} \quad (17)$$

Our modelled results closely align with the conversion to agricultural production present in the MapBiomas database, showing differences of -3.04% for all vegetation formations (SI Appendix Table S2). These small discrepancies are mainly due to the exclusion of stock variation as a component of final demand.

Finally, we investigate Ecological Unequal Exchange within the Brazilian economy by calculating the net embodied exchange for each region. This indicator is defined as the difference between the vegetation conversion embodied in all products consumed by the Brazilian Federation Units (FUs), called Brazilian states, and the conversion that occurred within each state itself, also considering all products. The analysis relates this net exchange to the GDP per capita of each state in 2015, calculated from IBGE (IBGE, 2025) data as total GDP divided by population for the same year.

3. Results

Global consumption in 2015 was associated with the conversion of 3.09 million hectares of native vegetation in Brazil (conversion annualized across 2010-2015, see Methods). Of this total, 47% (1,46 million hectares) was deforestation and 53% (1,63 million hectares) the conversion of other vegetation (Figure 1). i.e. The area of non-forest vegetation converted was 11.6% greater than that of forest loss. Almost three-quarters (72%) of conversion was linked with domestic consumption, although export flows from China, the EU, the USA and the rest of the world (RoW) also exert significant pressure: 28% of all conversion. For China, the area of non-forest vegetation loss was double the area of forest loss (201,855 ha vs 83,390), while the EU, USA, and RoW were responsible for more forest loss than conversion of other natural vegetation (336,780 ha vs 244,150 ha).

We trace conversion in each biome across the sectors and states where products were transformed, through to destination markets (Figure 2a). From a consumption perspective, activities linked to animal protein products – beef, pork, chicken, eggs, dairy, hunting services, and live cattle sales – accounted for 65.4% of conversion in Brazil (Figure 2b). Overall, 81.2% of this vegetation conversion was for the domestic market, with 18.8% 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 (17.3% exports, 82.7% domestic) or dairy products (1.1% exports, 98.9% domestic). The majority of this conversion occurred in Amazônia (42.6%), the Cerrado (38.2%), and the Caatinga (11.2%).

Other important agricultural product flows included soybean exports to China, and crops like rice, cotton, and coffee for multiple markets (Figure 2b). China's sourcing of soy was linked to 208,780 ha of conversion - 6.7% of all conversion across Brazil - principally in the Pampa (111,250 ha), Cerrado (,250 ha) and Mata Atlântica (18,700 ha). Other temporary crops, such as rice and cotton, were linked to 230,520 ha of total conversion (7.5% of the total), mostly linked to conversion in the Cerrado and Pampa (93,400 ha and 58,800 ha, respectively), 89% 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), commerce and other services, were associated with 239,000 ha (7.7%) of conversion, and textiles and timber-related sectors (including paper, wood products and furniture) were, respectively, linked to another 34,450 ha and 62,910 ha of conversion (1.11% and 2.03% 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 S3). For example, 90% of the conversion linked to exports of footwear and leather goods – 8,500 ha, principally in the Amazônia and the Cerrado – involved supply chains where products were internally-displaced before export. For example, the transaction of cattle hides within Brazil means that footwear and leather products exported from the southern states of Rio Grande do Sul, Paraná, and Santa Catarina (located within the Pampa and Mata Atlântica biomes where a substantial portion of Brazil's tannery sector is located) were linked to 2,100 hectares of conversion across Amazônia and the Cerrado. 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.

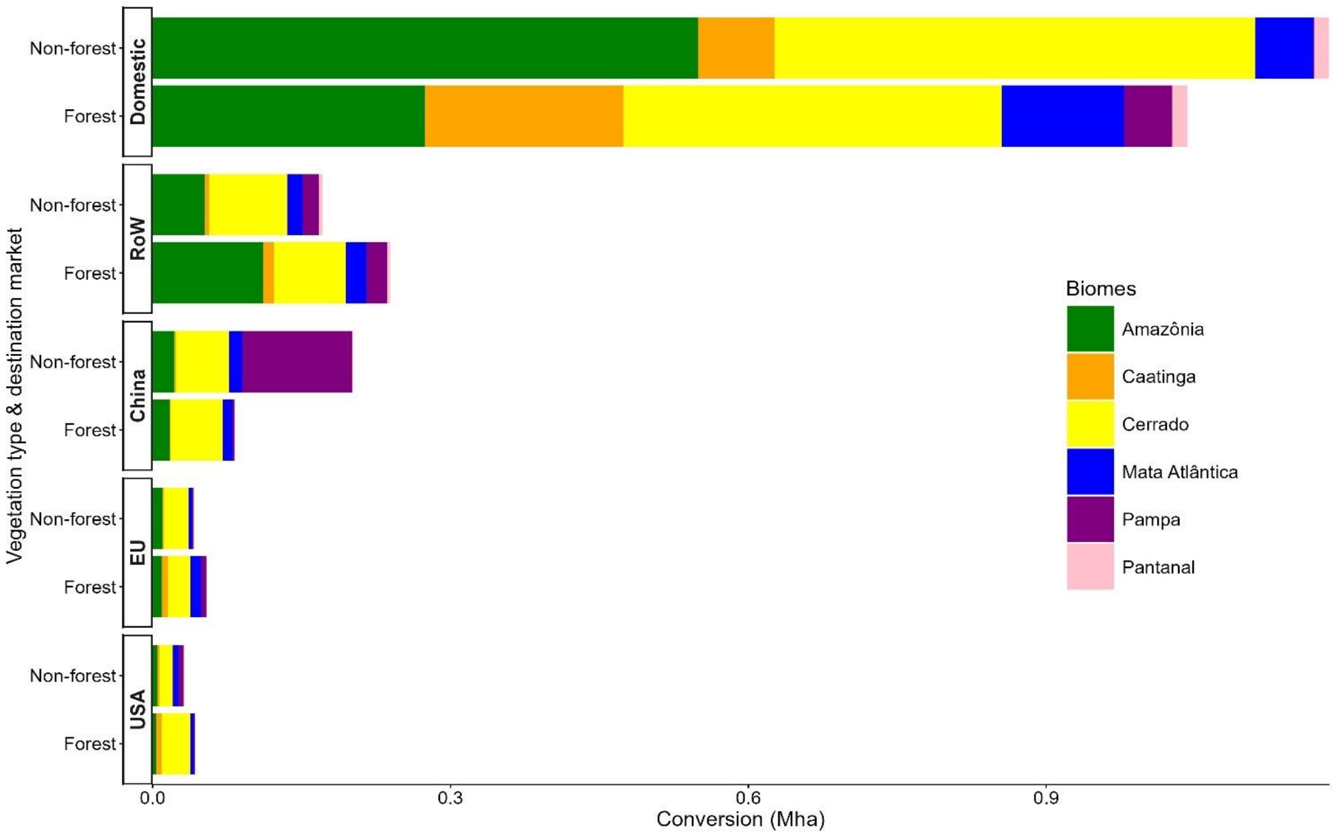

Figure 1. Annualized forest and other vegetation conversion embodied in domestic and international trade in Brazil

Disaggregating the domestic market

Within the domestic market, we differentiate the conversion driven by both local and national markets, which was evenly split: 37.2 % all conversion was linked to within-state consumption (e.g. forest loss in Pará state linked to consumption in Pará), and 34.8% of conversion driven by demand from other Brazilian states – the remaining 28% 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 3). The Pampa biome stands out for its strong connection to global markets, with half (52.7%) of all conversion linked to Chinese imports of soybeans.

The heterogeneity in footprints within Brazil is again seen in state-level data (Figure 4a). 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 loss 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 4c). 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 4c). 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

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 rest of the world. Furthermore, we differentiate between forest and non-forest vegetation types to more accurately characterize biome-specific ecological impacts.

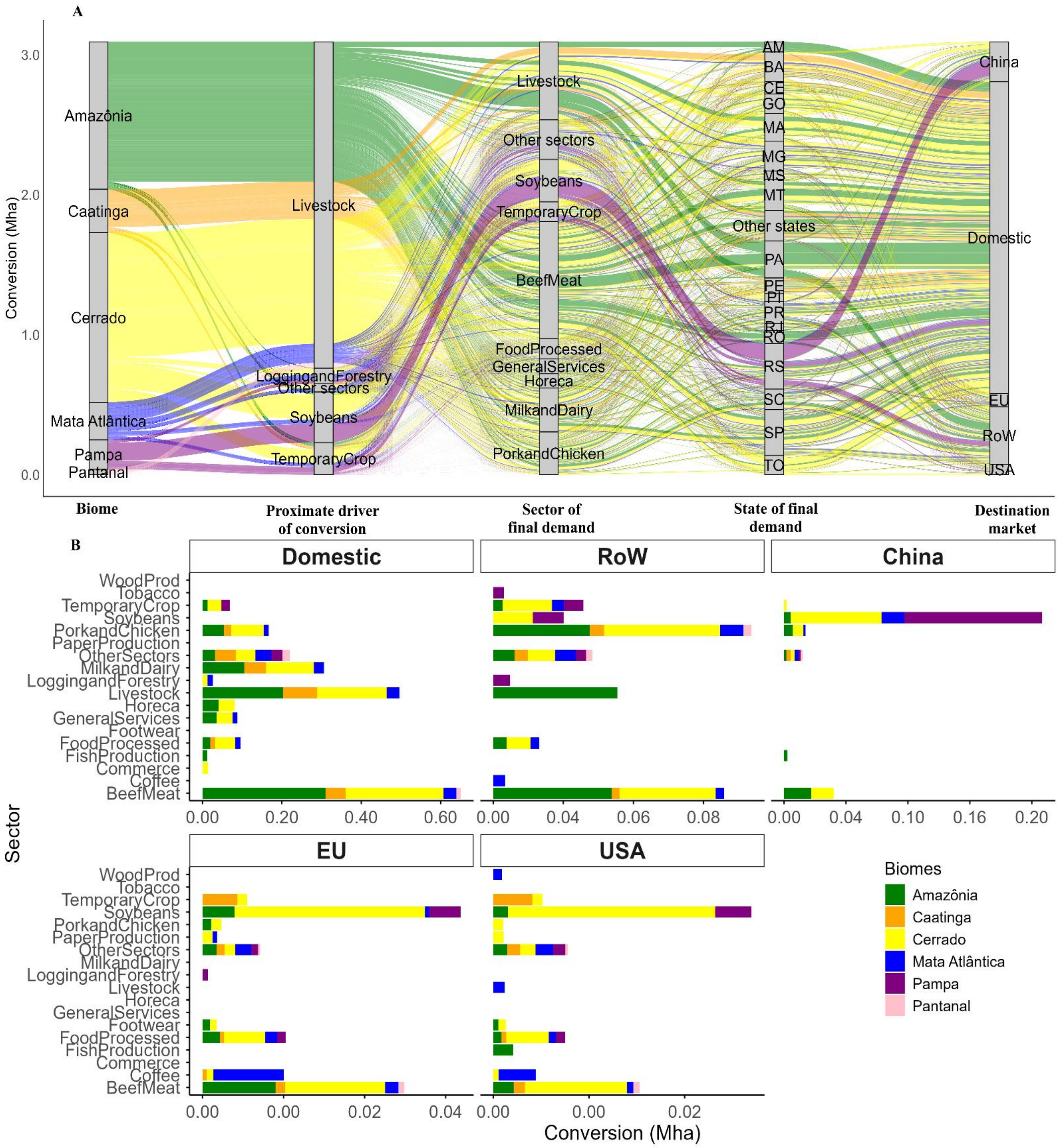

Figure 2. A: Interlinkages of vegetation conversion in Brazilian biomes to their sectors, final destinations and sectors within Brazil and destination markets (panel A), total conversion of
vegetation in Brazilian domestic and international trade by sector, biome of origin and final market (panel B). Average hectares (ha) from 2010 to 2015.

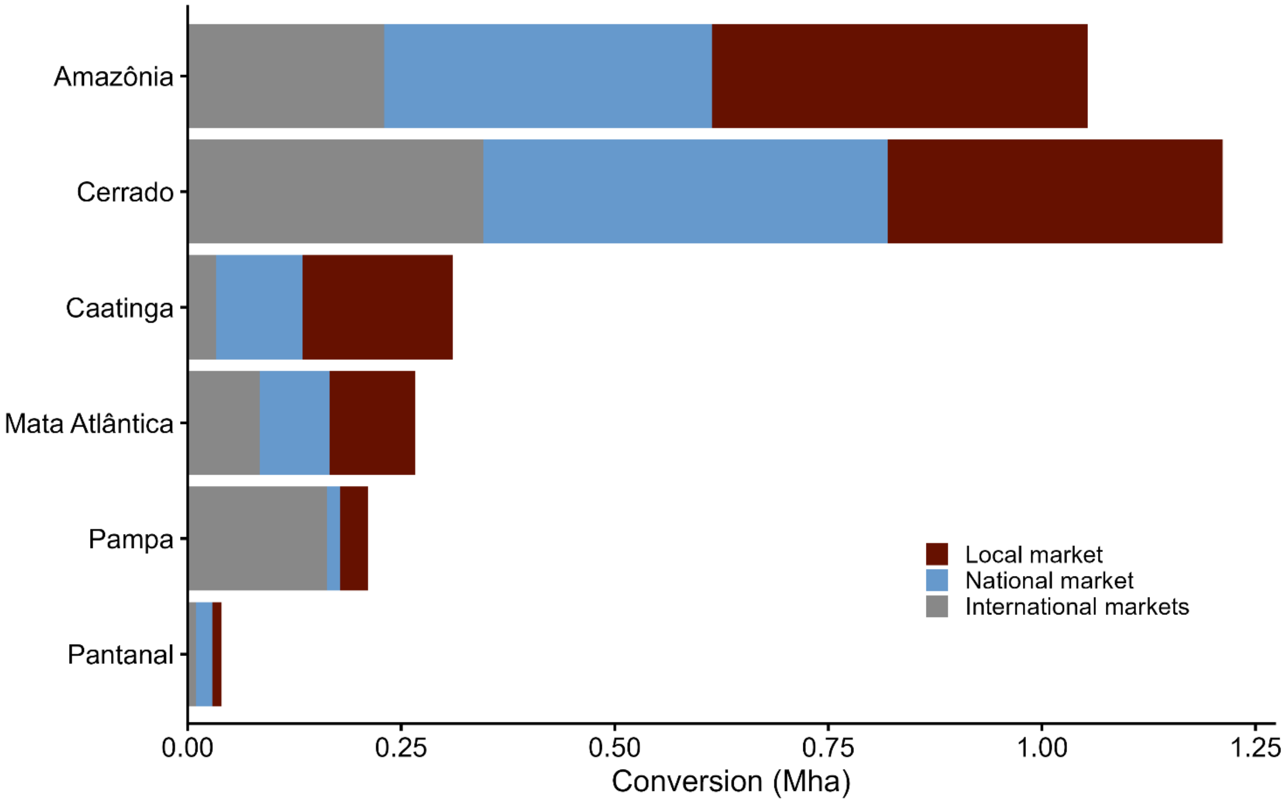

Figure 3. Conversion in each biome is driven by local markets (i.e. consumption within the same state where conversion occurred), national markets (consumption in a state different from where the conversion took place) as well as international markets

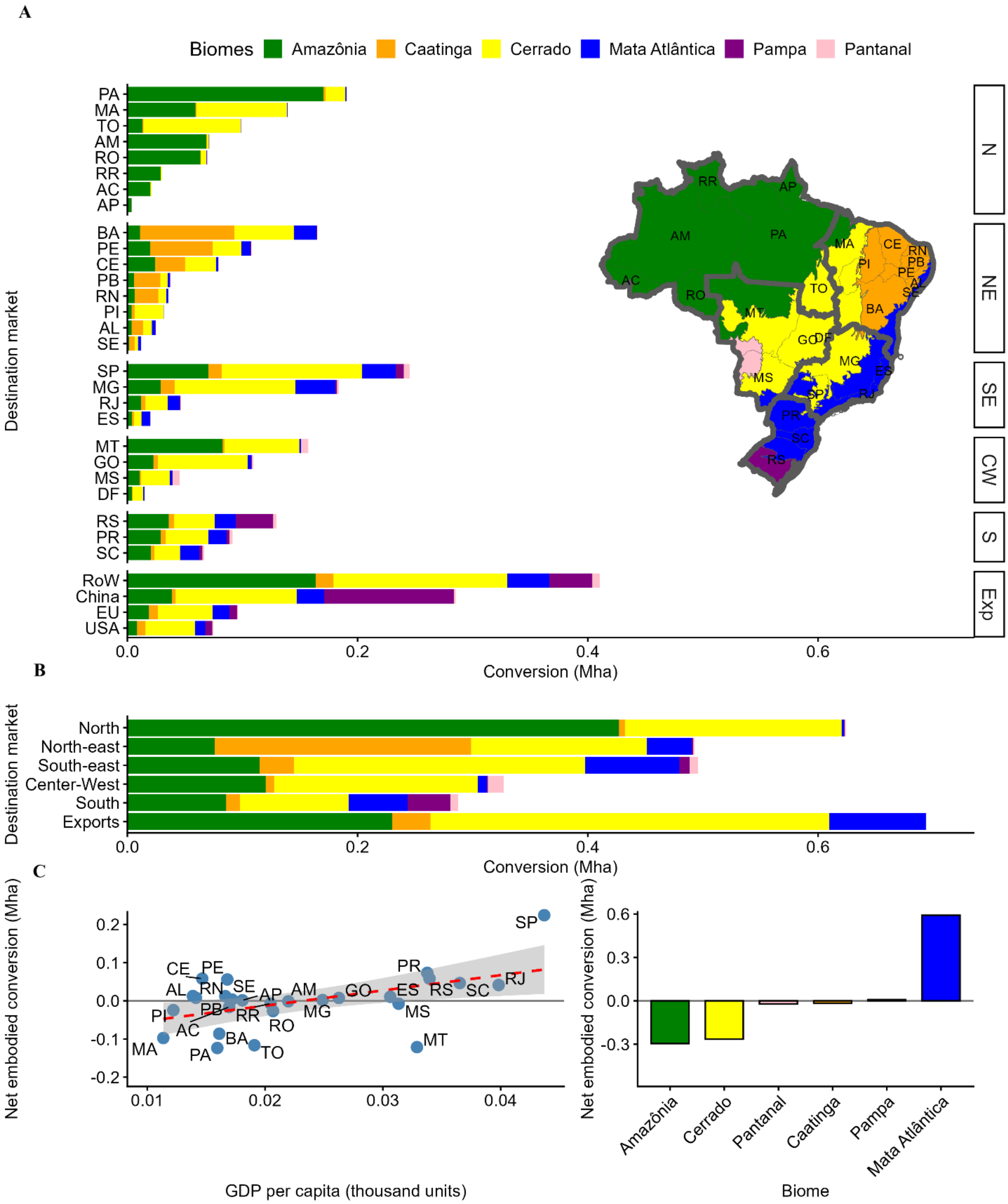

Figure 4. The vegetation conversion (per biome) embodied in the consumption of each state (panel A), and region (panel B), as well as exports. Panel (C) shows the correlation between state GDP and net embodied conversion (left) at the state level (left) and the net embodied conversion across biomes (right). Panel (A) region abbreviations: N = North, NE = North-east, SE = South-east, S =South, CW = Center-West, Exp = Exports.

We find that the conversion of non-forest vegetation – savannahs, wetlands, and grasslands – is driven by all markets and even exceeds the area of forest loss linked to the domestic market and China. National and international conservation efforts have, however, historically prioritized forests. Notably, the Brazilian Forest Code mandates larger conservation areas on properties in Amazônia (80% of private lands) compared to Cerrado areas within the Legal Amazon (35%) and other biomes across the country (20%). Though reform of the Forest Code to bring non-forests on equal parity with forests seems politically unlikely, it is essential that existing protections for non-forests are not weakened further – as seen by the recent permission of cattle grazing in ecologically sensitive areas on private properties in the Pantanal (SOS Mata Atlântica, 2023). The same asymmetry is found in corporate sustainability initiatives. Global companies are 2-3 times more likely to adopt zero-deforestation than zero-conversion commitments (Thomson, 2025). Within Brazil, the flagship Amazon Soy Moratorium and Cattle Agreements have protected the Amazon rainforest only (Moffette & Gibbs, 2021) – leading some to argue that non-forests have been used as 'sacrifice frontiers' for forest conservation (Levy et al., 2024). The adoption of a 'Cerrado Protocol' for sustainable cattle sourcing and increased emphasis on deforestation and conversion-free (DCF) commodities are therefore welcome though both initiatives still need large growth in adoption to have meaningful impact (zu Ermgassen et al., 2025, Afi, 2024).

Our results also highlight the important role of the domestic market – responsible for 72% of vegetation conversion across Brazil, most of which was linked to the production and consumption of livestock products (Figures 2 & 3). While environmental governance efforts to date have largely focused on improvements in traceability from farms to slaughterhouses (Gibbs et al., 2016), accountability efforts should seek to engage the retail, dairy, and leather sectors as well as other sectors which make use of livestock by-products. For example, though the dairy sector is largely under-the-radar in discussions of agricultural sustainability and land use change usually focused on beef and soy, we find 10.2% of conversion linked to dairy consumption. Almost 40% of this conversion took place in the Cerrado, followed by 33.7% in Amazônia, and 17.8% in the Caatinga. The importance of cattle by-products is also confirmed by recent work drawing attention to deforestation and forced labour for tallow-derived biofuels from Amazônia (Pajolla & Borges, 2025). These indirect connections of the livestock sector have become even more important considering new pledges to increase biofuels made at COP30 in Belém (Brazil, 2025).

We disaggregate the domestic market into local (within-state) and national consumption, finding that both play an important role in conversion, responsible for 34.7% and 37.3%, respectively, of natural vegetation loss across Brazil. The role of different markets varied, however, across biomes and regions (Figure 4). Consumption in the North region mostly led to local conversion (84.9% local vs 15.1% of conversion elsewhere), while states in Brazil's South-East were the opposite, mostly driving conversion in other regions (76.3% vs 23.7% of conversion locally). This pattern flags two important dynamics of land use change in Brazil. First, though Northern Brazil, particularly Amazônia, is often imagined as an "untouched wilderness" or "resource frontier", it in fact a largely urbanized economy, with more than 70% of the population living in cities (Brondizio, 2025). Demand from local urban centers is therefore an important driver of conversion, as the consumption of beef in urban areas is 30% higher per-capita and 3-fold higher (in total) than in rural areas (IBGE, 2021). Second, inter-regional trade leads to an important spatial redistribution of environmental impacts within the domestic market. This reflects an economic structure where natural resources in lower-income "peripheral" regions are consumed by more wealthy regions, often far from the sites of degradation.

This unequal exchange is also reflected in Brazil's international trade patterns. Notably, 49.7% of export-driven conversion is linked to the export of raw commodities (e.g. soybeans), rather than derived, higher-value products (e.g. soybean meal or processed foods). This trade pattern is a legacy of both China's investments in their domestic processing industry, which now requires a large and stable supply of raw beans, plus also tax incentives in Brazil. The Kandir Law in Brazil encourages the export of primary and minimally-processed goods by exempting them from the ICMS (Tax on the Circulation of Goods and Services). Recent fiscal reforms, however, in Brazil may finally change this, as exports of processed products will now also be tax-exempt (Gala, 2025). This shift in incentive could boost processing and value-capture within Brazil, prior to export.

Our modelling approach is based on a regionalized input–output model, tracing impacts within the Brazilian economy and abroad. Our findings are a complement to and closely match results from studies using national-scale data and physical trade models (e.g. Pendrill et al., 2015, Pendrill et al., 2016), studies using subnational supply chain mapping of individual commodities from the Trase initiative (zu Ermgassen et al., 2020a, 2020b) or input-output analyses based on individual biomes (Haddad et al., 2024) (SI Appendix Figures S4-6). We identify new hotspots of conversion, for example, linked to the dairy and non-food sectors, not seen in other work, while also reproducing key findings from previous studies – despite the differences in our underlying methods and data. For example, we identify the impacts of soy production in the Pampa and Mata Atlântica (Amaral et al., 2025, Ribeiro & Guedes Pinto, 2023, Pereira & Bernasconi, 2025) and the export of live cattle from Amazônia (zu Ermgassen et al., 2024a). 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). These differences stem from different framings of responsibility – our approach allocates conversion proportional to actual consumption (Fan et al., 2022), while Haddad employs a hypothetical extraction method, where responsibility is allocated based on the marginal effect of removing demand. Regardless of the underlying assumptions, local consumption remains important, rivalling exports as a driver of conversion.

Our work inevitably comes with some caveats. First, as mentioned above, the footprint of the timber and pulp-and-paper industries captured in our analysis represents only a fraction of their environmental impact, because we do not consider their impacts on forests through logging (which is a land use degradation, rather than a conversion, per se). Second, the input-output matrix represents a snapshot of the economy for a specific year (2015) and does not fully capture the multi-year life-cycle of some products. For example, though the livestock sector is arguably always an input into other sectors (notably the meat sector), we map 18% of conversion for final demand to the livestock sector (Figure 2). This occurs because the Brazilian input-output matrix is calculated from financial transaction data, which includes transactions within the livestock sector within the year (i.e. farm-to-farm sales in 2015), and so the livestock sector also appears as a demand from itself. This feature of the input-output model arguably makes our estimate of inter-regional flows conservative, because these farm-farm transactions are mostly local (99% within-state). In comparison, 67.2% of the flows from the livestock sector into other sectors were inter-state or towards international markets. 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 tonnes/year to 1.5 million tonnes. An update to the input-output model would therefore capture an increase in Chinese imports, replacing 'rest of the world' 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).

5. Conclusion

Though domestic markets are responsible for three-quarters of all food production and the majority of the environmental impacts of the food system, they tend to be treated as a single homogenous unit in telecoupling and environmental governance studies. Here, we present a regionalized input–output model for Brazil, tracing the origin and impact of consumption in 47 Brazilian regions and four international markets, linking conversion to primary, industrial, and service sectors. Altogether, our results on the distribution of responsibility across urban and rural, local, regional, and international markets, and across sectors suggests that we need not just a focus on supply chains, rural producers, and territorial governance, but a combination of measures which improve traceability, a deliberate attempt to guide urban growth and consumption in a sustainable manner, and address the inequalities which underpin much of the extractive economy across each of Brazil's diverse biomes (Brondizio, 2025).

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Table S1 - Representation of the MIP-Biomas

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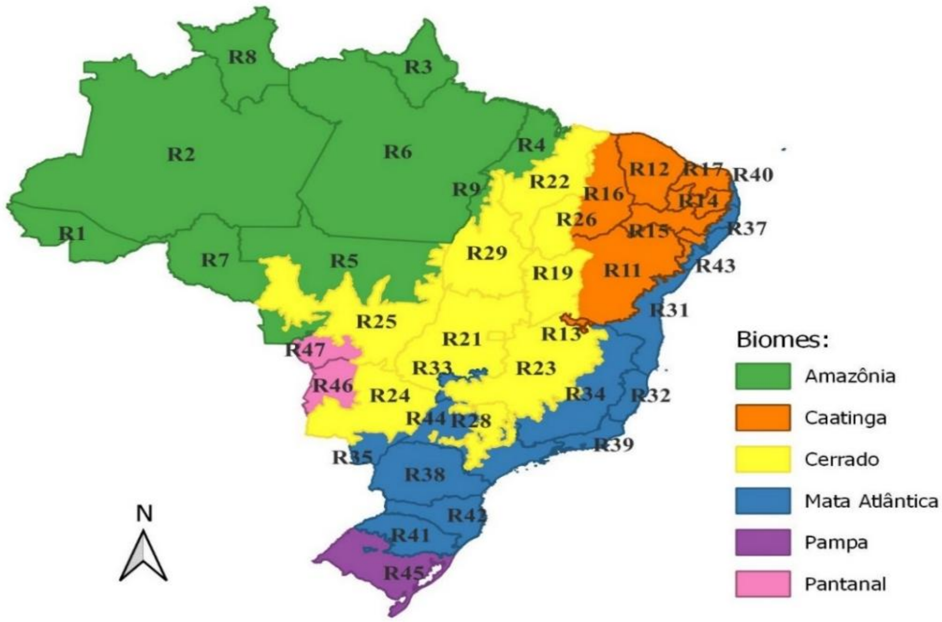

Source: elaborated by the author based on the MIP-Biomas.

Figure S1 – Regions of the MIP-Biomas.

Table S2 –Mapbiomas and MIP-Biomas' data on the origin of vegetation conversion

Biome	Mapbiomas	MIP-Biomas	Difference (%)
Amazônia	1069436.56	1053602.89	-1.48
Caatinga	414324.54	310225.31	-25.13
Cerrado	1197785.63	1211724.70	1.16
Mata Atlântica	260817.61	266351.77	2.12
Pampa	204605.37	211177.87	3.21
Pantanal	39744.55	39695.67	-0.12

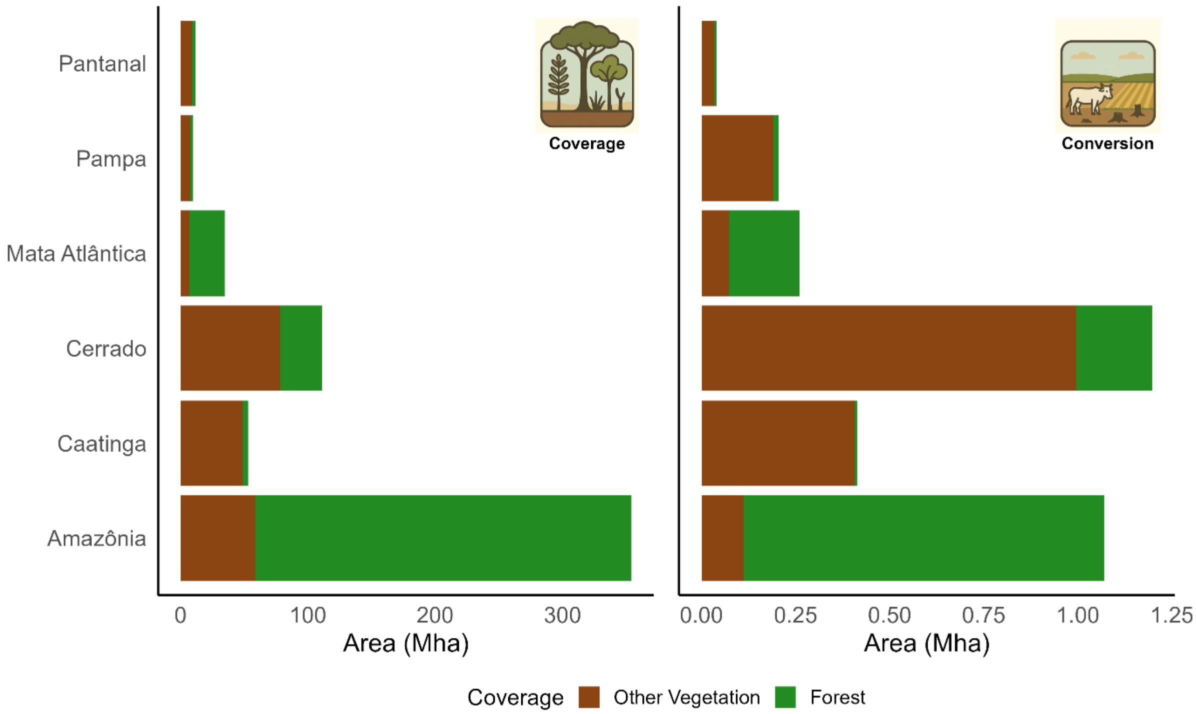

Figure S2 – The coverage and conversion of natural vegetation – both forests and other vegetation across each of Brazil's biomes. The conversion area is the annualized average from 2010-2015, the time period analysed in the MIP-Biomas model in this study. Data from MapBiomas Collection 9.

SI Appendix Figure S1 illustrates the coverage and conversion of forest areas – defined as forest formations plus mangroves – and other vegetation types across Brazil's six biomes. This visualization helps differentiate the distribution of these vegetation types and their transformation into agricultural land. Coverage refers to the extent of forest and other vegetation types within each biome, while conversion indicates the portion of these areas that have been repurposed for agricultural uses. The composition of native vegetation varies significantly among biomes. Amazônia and Mata Atlântica are predominantly covered by forest formations, whereas Cerrado, Caatinga, Pampa, and Pantanal are mainly composed of other vegetation types, such as savannas, grasslands, and wetlands. This distinction is essential for understanding the dynamics of native vegetation loss linked to trade.

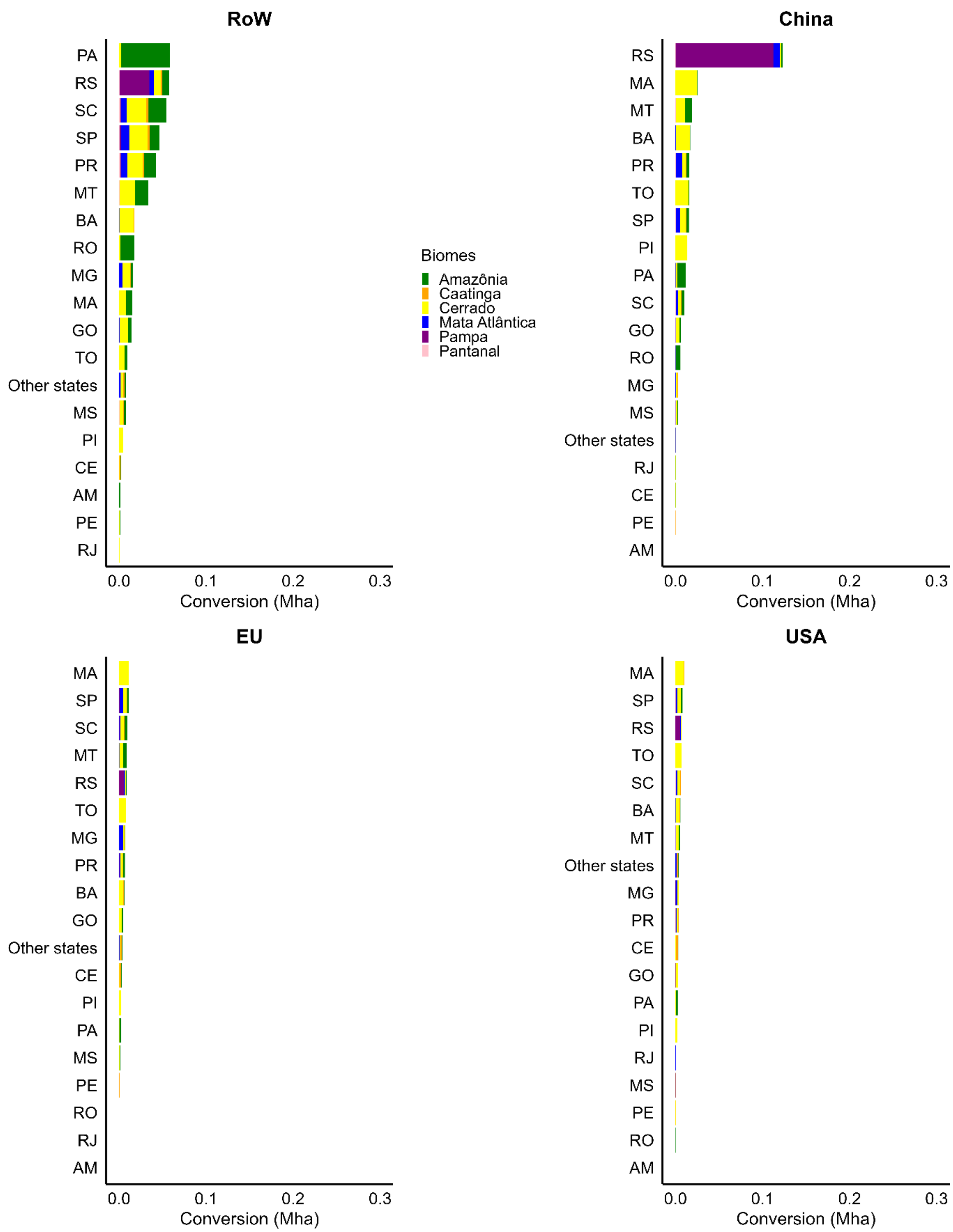

Figure S3 – Total conversion of vegetation in Brazilian international trade by state of sale in Brazil and biome of origin of conversion

Comparison with other studies

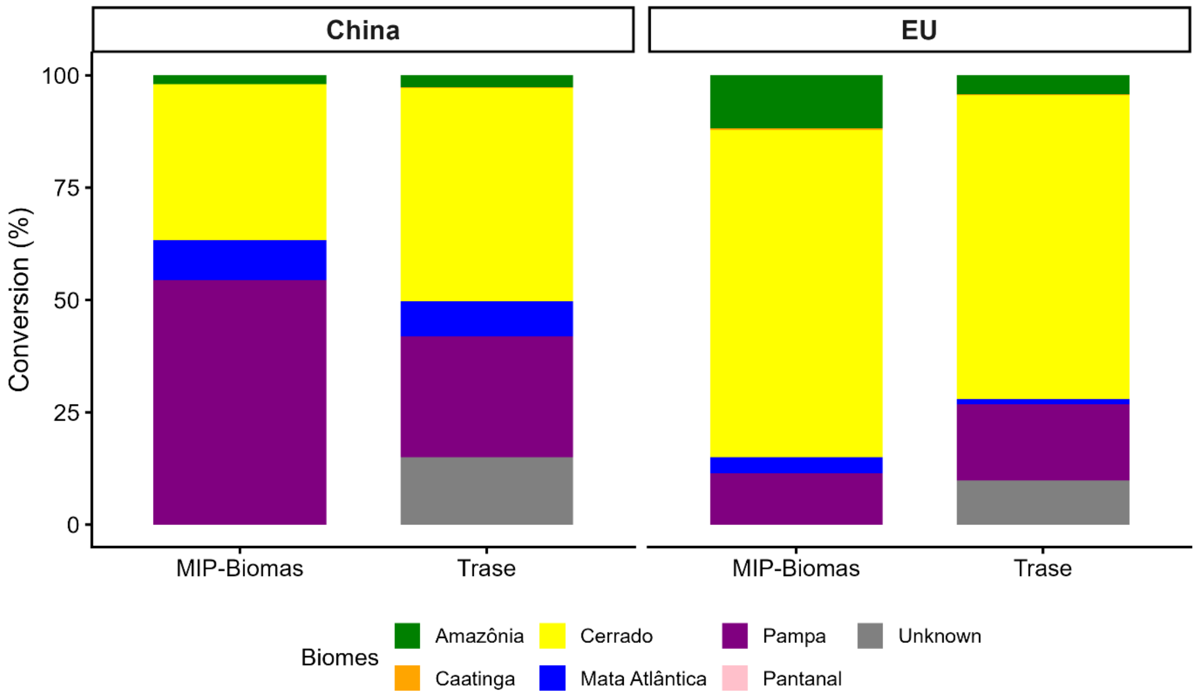

Figure S4 – Comparison of Trase and MIP-Biomas' data on conversion linked to international soy trade.

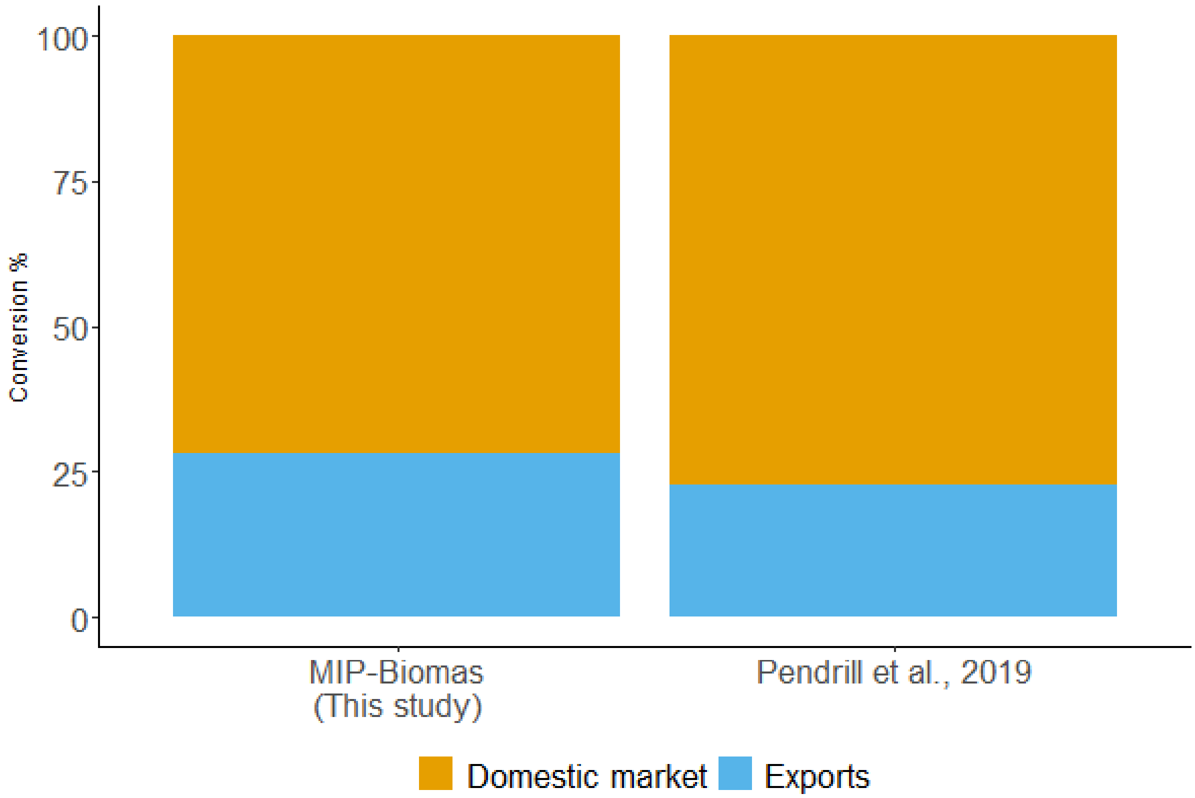

Figure S5 – Comparison of Pendrill et al. 2019b and MIP-Biomas' data on conversion in Brazil linked to the domestic and export markets.

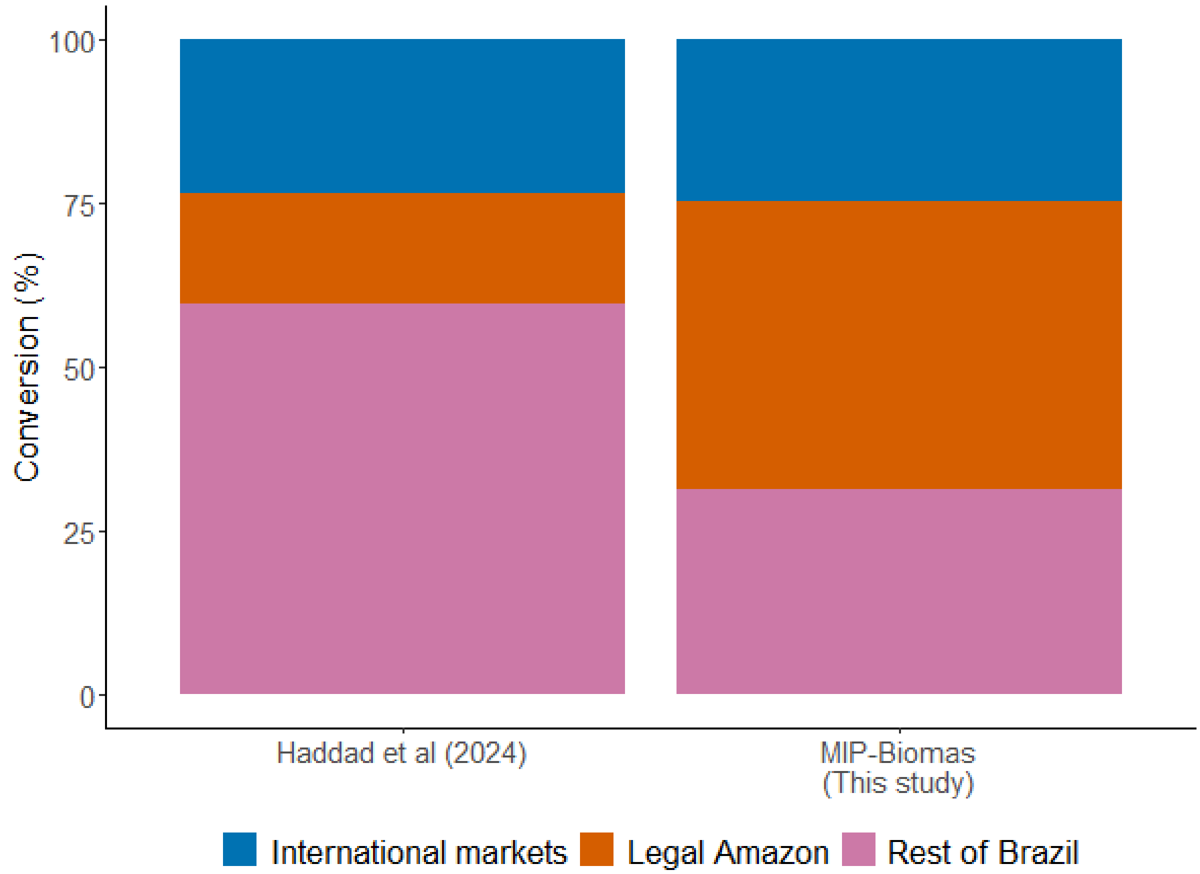

Figure S6 – Comparison of Haddad et al. and MIP-Biomas' data on conversion in the Brazilian Legal Amazon linked to the international markets, and consumption within the Legal Amazon or the rest of Brazil.