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Global Trade and Deforestation: Potential impacts of the EUDR on the Brazilian beef industry.

Comércio Global e Desmatamento: Potenciais impactos da EUDR na indústria de carne bovina brasileira.

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Abstract

This study analyzes the effects of global trade on deforestation. Based on georeferenced data on forest loss and agricultural and livestock production, the amount of deforestation measured between 2006 and 2010 was attributed to 42 agricultural commodities and 3 livestock commodities. A global input-output matrix was used to understand how deforestation propagates through production chains until it reaches final demand. Using input-output theory techniques, two indicators were calculated: one for deforestation generation per additional dollar in final demand, and another for the deforestation footprint of countries. Subsequently, a case study was carried out to estimate the impact of the EUDR on the Brazilian beef market, assuming the regulation had been in force at the end of 2005. The results revealed facts such as the dependence of the demand structure of poorer countries on more extractive sectors, and that richer countries consume deforestation mainly via imports. The simulated EUDR scenario pointed to an annual trade reduction of USD 38,9 million between Brazil and the EU, and a reduction of the EU's deforestation footprint by 202 hectares over five years.

Keywords: International trade, deforestation, agriculture, livestock, EUDR.

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1 Introduction

Deforestation has likely been a constant feature of human history, driven by the need to build villages, cities, agricultural plantations, and exploit mineral resources. Following the Industrial Revolution, technological advancements and industrial activities expanded at an unprecedented rate. Urban development grew alongside these changes, while population increases necessitated the conversion of forests into agricultural land and pastures for livestock. This relentless drive for expansion and resource use has placed immense pressure on forests. Furthermore, the methods of production in modern society, which rely on the burning of fossil fuels, have emerged as a primary contributor to global warming through the intensification of the greenhouse effect, posing severe threats to countless species on Earth, including humanity itself (Mora et al., 2018).

Today, one of the major challenges humanity faces is how to mitigate the effects of climate change. Policies aiming to reduce greenhouse gas (GHG) emissions, such as multilateral agreements and carbon pricing mechanisms, have been created to achieve emission reduction targets. Among the burning of fossil fuels, deforestation also has a significant weight as a source of emissions. Agriculture, Forestry and Other Land Uses (AFOLU) contributes to around 22% of global greenhouse gas (GHG) emissions. Land Use, Land-Use Change and Forestry (LULUCF)—primarily deforestation—is responsible for nearly half of the net AFOLU emissions (IPCC, 2023). Besides this, other negative externalities from deforestation may arise, such as loss of biodiversity, changes in soil absorption of water, changes in rain regime control, and biogeochemical cycle equilibrium (Mitchard, 2018; Foley et al., 2007; Faria et al., 2023; Berenguer, 2024).

However, within forestry governance, multilateral agreements related to forest protection have not seen full development and adherence from countries (Sotirov et al., 2020; Sommer, 2020; Henn, 2021). In this context, the European Union introduced an important regulatory measure to promote the consumption of deforestation-free products. The EU Deforestation Regulation (EUDR) aims to reduce the EU's contribution to global deforestation by restricting trade with market agents operating in deforested areas —

whether legally or illegally — since December 31, 2020. The logic of the regulation is based on the fact that expansion of agricultural land-use (which includes cropland, pastures, and forestry) is the primary cause of deforestation. This fact is adressed in Pendrill et al.,2022. Features such as populational increase and land grabbing are also drivers of deforestation (Fearnside, 2001; Pfaff, 1999; Busch and Ferretti-Gallon, 2017; Araujo et al., 2009).

This dissertation investigates the potential effects of the EUDR, with a focus on the Brazilian beef industry as a case study.[1] The analysis proceeds in three main steps. First, we identify key deforestation-intensive products and commodities by mapping their countries of origin. Second, we examine how deforestation is embedded and transmitted through global value chains. This allows us to construct deforestation indices by product and country. Third, we estimate the potential impact of the EUDR on trade and deforestation in the Brazilian beef sector by applying a sectoral shock. Using the deforestation index and input-output analysis, we simulate a counterfactual scenario in which the EUDR had been in effect since the end of 2005. This approach provides insights into the regulation's long-term implications for trade flows and deforestation patterns. The period analyzed for deforestation outcomes spans from 2006 to 2010.

We draw on multiple data sources for each step of the analysis. In the first step, deforestation is quantified as forest loss at the pixel level using the Global Forest Change (GFC) dataset, covering the period from 2006 to 2010. This dataset, derived from Landsat imagery, provides a spatial resolution of 30 meters. Each deforested pixel is then associated with agricultural and livestock production—also at the pixel level—by allocating forest loss proportionally to the increase in cultivated area for each crop during the same time period. To estimate the global distribution of crops — forming the basis for connecting deforestation to agricultural activity — we use spatial data on production and harvested area from Agro-MAPS and SPAM. These datasets are compiled by the Food and Agriculture Organization (FAO), the International Food Policy Research Institute (IFPRI), and the Center for Sustainability and the Global Environment (SAGE) at the University of Wisconsin-Madison. In addition, we incorporate spatial data on global livestock production and distribution from the FAO's Gridded Livestock of the World (GLW) database to assess the contribution of livestock expansion to deforestation.

In the second step, we analyze how deforestation associated with agricultural

[1]The tools and methods developed in this analysis can be extended to other sectors and countries globally.

and livestock production propagates through global supply chains using input-output analysis. Specifically, we use Release 059 of the GLORIA global environmentally-extended multi-region input-output (MRIO) database (Lenzen et al., 2021), developed by the Global MRIO Lab (Lenzen et al., 2017). GLORIA-MRIO offers a detailed representation of international trade and production linkages, covering 164 regions and 120 sectors, which enables a comprehensive assessment of how deforestation-related commodities move through global markets. This analysis yields two key outputs: (i) global indicators of deforestation intensity—referred to here as deforestation generators—attributed to products and countries, and (ii) national deforestation footprints.

Building on the previous steps, the third step simulates a scenario in which the EUDR had been in effect since 2005, with a specific focus on its impact on the Brazilian beef industry. For this analysis, we use state-level data on rural productivity and exports from the Brazilian Institute of Geography and Statistics (IBGE). We estimate output levels originating from deforested areas, as identified through satellite imagery, linking them to beef production and export patterns. This step integrates the deforestation footprint results with the projected trade impacts of the EUDR, providing insights into how restrictions on deforestation-linked commodities could alter trade flows to the EU and reduce the contribution of EU consumption—particularly of Brazilian beef—to global deforestation.

Our results indicate that for low-income countries, which tend to have more extractive production structures, each additional dollar of final demand is associated with a higher level of deforestation compared to wealthier countries, which consume more industrialized and less land-intensive products. Globally, cattle production emerges as the leading driver of deforestation. Brazil has the largest deforestation footprint, driven by both high domestic consumption and significant meat exports. Developed countries, in turn, tend to "import" deforestation through their consumption of goods produced in deforesting regions, highlighting a link between higher GDP levels and the outsourcing of environmental degradation to less developed countries. The European Union, for example, is a major importer of Brazilian beef. Under a counterfactual scenario in which the EUDR had been in place since the end of 2005, we estimate a potential reduction of USD 38,9 million in trade and a decrease of 202 hectares in the EU's deforestation footprint—underscoring the regulation's capacity to curb deforestation through targeted trade restrictions.

There is a wide body of literature that explores the use of input-output techniques to calculate how physical measures—such as the content of metals, fossil fuels, and biomass (Lenzen et al., 2017; Hong et al., 2022)—and deforestation are accounted for in international trade, introducing concepts such as embodied content and footprint (Sun et al., 2023; Hoang and Kanemoto, 2021). The development of these techniques is essential for ensuring that environmental costs are accurately calculated and properly attributed to the responsible agents.

The main contribution of this work is to develop a methodology for assessing the impact of a commercial regulation focused on reducing deforestation based on the variation of the environmental footprint and the trade volume, with a particular focus on the EUDR over Brazilian beef market. It also adds to the literature a mapping of the sectors and countries that generate most deforestation, and highlights the urgent need for global governance mechanisms to mitigate deforestation through international trade policies.

This study is organized as follows. Chapter 2 provides the background, exploring the historical presence of deforestation in human development, its connections with climate change and international trade, as well as local dynamics in countries such as Brazil, Indonesia, and Russia—highlighting the complexity of the issue. Chapter 3 describes the data sources and their specific characteristics. Chapter 4 outlines the methodologies applied at each stage of the analysis. Chapter 5 presents the results corresponding to each step. Finally, Chapter 6 concludes the study by discussing the implications of the findings, acknowledging limitations, and suggesting directions for future research.

2 Background

The history of civilizations involves the relationship between human beings and their surrounding environment through modifying actions, aiming to adapt it to their needs and according to their understanding of natural cycles. Thus, combined with the evolution of technology, it became possible to improve tools, cultivate food, domesticate animals, and establish settlements with the development of cities, as well as to enable population expansion and territorial disputes. Some indigenous civilizations that inhabited, and still inhabit, forest environments developed an understanding of the forest as something inherent to their very existence (González and Kröger, 2020). Other civilizations, especially those that led technological progress through historical processes driven by economic forces — explained by the profitability obtained through surplus production and market expansion (HUBERMAN, 2009) — culturally lost the connection between the productive process and the natural cycles, and redefined human existence by separating it from a symbiotic state with nature. Consequently, the pursuit of material progress within this human-technological symbiosis, while ignoring the role of the natural cycles that surround us, leads to the depletion of essential resources for maintaining life on the planet. It is a paradox of material development at the expense of environmental resources, because ultimately, all the technological advancements aimed at improving well-being would become useless if natural systems were to collapse (Commoner, 1974) . In 2002, the 1995 Nobel Prize winner in Chemistry, Paul Crutzen, suggested that we were entering a new era he called the Anthropocene, referring to the epoch in which human modification of the environment becomes significant enough to be a dominant force in shaping the planet's biogeophysical processes (Zalasiewicz et al., 2008).

This reflection paves the way for us, in this work, to focus on one part of the challenge humanity faces: protecting natural systems that are under threat from uncontrolled technological progress. We will address forests, which harbor rich biodiversity and play a crucial role in maintaining the biogeochemical balance of gases on the planet. In the following subsections, we will contextualize the problem of deforestation, its relationship with climate change, its causes through commercial levers activated in global production chains, and other causes intrinsic to the geographic dynamics of socioeconomic order.

2.1 Deforestation and climate change

Facing climate change is the major challenge humanity faces in current days. The effect of not taking mitigation and adaptation actions are the intensification of global warming and consequently materials and lives losses due to extreme events, such as droughts, floods and hurricanes, which also threats hydric and food supply systems, affecting the whole economy.

Unequivocally it is clear with high confidence that human activities are responsible for global warming, mainly coming from emissions of fossil fuels combustion. However, deforestation and land use also plays a significant role. According to IPCC, in 2019, AFOLU (Agriculture, Forestry and Other Land Uses) represents approximately 22% of the total greenhouse gases (GHG) emissions, which Land Use, Land-Use Change and Forestry (LULUCF), mainly deforestation, accounts for almost half of the total net AFOLU emissions (IPCC, 2023). The energy sector represents approximately 34% of total emissions, the industry accounts for 24%, 15% from transport and 6% from buildings. This pattern is different for countries where the energy from thermal sources has less share in the energetic balance. In Brazil for example, according to deforestation and land use change corresponds to 46% of it's total emissions in 2023, whereas energy sector share is only 18% (source: SEEG).

Furthermore, recent studies show that tropical forests, which used to work as a neutral carbon source and carbon sink system, are in the process of switching from being approximately neutral to being a net source of carbon (Mitchard, 2018). Beyond the effects of carbon emissions caused by deforestation, other negative externalities may arise from this practice, such as loss of biodiversity, which presents inestimable value to the balance of life on the planet, weather destabilization, proliferation of diseases, etc. Thus, preserve forests is of utmost importance to limit the global warming and to preserve life. Facing this problem involves analyze the main channels and incentives that conduct to the deforestation of an area. It depends on a myriad of geographic and socioeconomic factors. Undestanding well the local dynamics of deforestation can deliver effective policies that blocks the channels of deforestation. According to Pendrill et al., 2022, agriculture, through direct expansion of pastures and cropland into forests, is the main driver of deforestation. Hence, many policies and agreements can be designed in order to tackle supply chains of agricultural and livestock production, and can be scaled up at global trade level.

2.2 Trade, global value chains and deforestation

In this work, we focus on the relationship between trade and deforestation. The main premise of our analysis is that all deforestation is driven by the consumption of certain products whose supply chains activate sectors that generate deforestation to meet final demands originating from multiple regions around the world. To understand this entire chain of relations, we can think of an anecdotal case of the production of an automobile, whose parts are produced in different regions. The high-power engine is forged in Germany, with some parts coming from Japan. The electronics of the futuristic onboard panel were assembled in South Korea, while the beautiful wheels came from Italy, using metals extracted from mines in Australia and Brazil. The fancy beige leather seats and steering wheel originated from a cattle farm deep in Brazil, where, years ago, a large area of native forest was cleared to create pastureland, transforming once dense vegetation into open fields for grazing. Thus, when a final consumer goes to a dealership and buys the vehicle, they indirectly help keep several production chains active. However, the environmental costs embedded in the products they consume are unknown. Furthermore, the ease with which certain products — whose production generates significant environmental damage — enter the market may encourage producers to expand their activities in search of greater profits. Deforestation in tropical forests follows a similar dynamic, where profits from the trade of certain commodities provide an incentive for expanding production (Berman et al., 2023). There are several mechanisms involved in the commercial drivers of deforestation (López and Galinato, 2005; Faria and Almeida, 2016; Busch and Ferretti-Gallon, 2017; Abman and Lundberg, 2020). Understanding local socioeconomic dynamics, conducting good deforestation measurement, and generating detailed trade data allow for better exploration of these mechanisms and the design of agreements and policies to mitigate deforestation, as well as to simulate their effects.

2.3 Local deforestation dynamics

Below, we explain some details of the causes of deforestation in a few of the countries with the highest deforestation levels, with a greater focus on Brazil. For other countries, we recommend exploring the Global Forest Watch website[1].

Brazil

Brazil has approximately 60% of its territory covered by forests. It is also home to the largest tropical forest in the world, the Amazon rainforest. The dynamics of deforestation in Brazil are marked by the predominance of pasture creation. According to Mertens, 2002, the clearing of land for pasture serves three purposes: to provide food for livestock, to facilitate land appropriation, and to increase land value at a low cost in the long term. There is a multiplicity of incentive channels for deforestation, such as the construction of roads, poorly defined property rights, and the existence of food markets in nearby regions (Pfaff, 1999; Walker et al., 2000; Andersen et al., 2002; Reis and Guzmán, 2015; Andersen and Reis, 2015).

In the 21st century, deforestation dynamics in Brazil have experienced significant fluctuations. Between 2004 and 2014, the country recorded consistent declines in deforestation rates, driven by policies such as the Priority Municipalities program, the Soy Moratorium, and the establishment of conservation zones. After 2014, a series of institutional crises and political instability led to weakened enforcement and a surge in deforestation, which peaked again in 2021. More recently, however, deforestation rates have shown a notable decline once more.

Analyzing from a historical perspective, the problem of large-scale deforestation in Brazil began with the arrival of Europeans on the continent in the early 16th century and the exploitation of Pau-Brasil, a native tree with reddish wood that had great utility in the textile industry, which was incipient in England at the time. The enslavement of Indigenous people and the trade of the tree that would give its name to the new territory marked the beginning of a major problem that persists to this day.

Throughout its history, the country has undergone several economic cycles associated with agricultural commodities: the rubber cycle, with the extraction of rubber trees in the Amazon region; the coffee cycle in the southeast, a region of Atlantic Forest; and, more

[1] https://www.globalforestwatch.org/

recently, the expansion of soy in the second half of the 20th century. All of these cycles were accompanied by profound changes in the primary vegetation cover of the territory.

In the early 1960s, during the military regime, the Brazilian government launched a development program for the northern region under the slogan "integrate not to hand over." The idea was to invest in highways to integrate the Legal Amazon with the rest of the country and generate incentives for migration to the region in order to promote economic development. A program of tax incentives, created by SUDAM (Superintendence for the Development of the Amazon), and cheap credit, offered by the Bank of Amazon, for land purchases, led many farmers from the South to sell their properties and buy new lands in the North. In the 1980s, a farmer could buy 14 hectares of land in the North for every 1 hectare sold in the South. In addition to financial incentives, there was much government propaganda promoting cattle production for export at the expense of the forest, which was viewed as a "green hell" to be destroyed. 60.000 km of highways were built, and between 1970 and 1985, the population and GDP grew from 7,3 million to 13,2 million and from US$2,2 billion to US$13,5 billion, respectively (Haddad et al., 2024; Mahar, 1989; Andersen and Reis, 2015).

Figure 2.1: Bank of Amazon advertisement.

Banco da Amazônia (Bank of Amazon) advertisement of cheap land in the North and subsidized credit to invest in cattle raising and make money selling to the USA and Europe.

In more recent times, with technological innovations in agricultural production, soybean cultivation has expanded into a biome with drier soil, the Cerrado, characterized by savanna vegetation. The strength of agribusiness in Brazil's economy and politics has led to the expansion of agriculture and cattle ranching, transforming the country's natural vegetation into monoculture fields. According to Mapbiomas data, soy expanded from 4,4 Mha mapped in 1985 to around 40 Mha in 2023.

However, despite the government's efforts to develop the Amazon region, it remains one of the poorest areas in the country. The border regions with Peru and Bolivia are targets of drug trafficking routes, as well as other criminal activities such as wildlife trafficking. Furthermore, another significant driver of deforestation is land grabbing (Araujo et al., 2009; de Pesquisa Ambiental da Amazônia, 2006; Sant'Anna and Costa, 2021). This practice consists of occupying lands with poorly defined property rights, followed by deforestation and typically the establishment of pasture to simulate some productive activity. The land is then regularized and sold at a higher value. Cases of land invasion and even murders for land theft are also means through which criminal activities profit from regulatory loopholes.

Therefore, we must bear in mind that the incentives for deforestation in Brazil take various forms, but the subsequent creation of pasture for cattle is a very common step, even when the main objective is not cattle production. This pattern of land use in areas recently deforested for pasture creation is observed in the analysis that we will detail below.

Indonesia

According to Global Forest Watch, in 2020 over 50% of Indonesia's territory was covered by natural forests (Mazur et al., 2023). The country is home to one of the largest tropical rainforests in the world, as well as the largest tropical peatlands and mangrove forests globally. In Global Forest Change data (Hansen et al., 2013), the slope of the trend line for forest cover change from 2000 to 2012 shows that Indonesia had the highest annual increase in forest loss among all countries.

The main drivers of deforestation in Indonesia between 2001 and 2016, as identified by Austin et al. (2019), were: oil palm plantations (23%), conversion to grasslands (20%)—primarily due to peaks in fire activity—and small-scale agriculture (22%). They also note that the share of large-scale plantations declined over time; in the early 2000s, they accounted for more than half of all deforestation. Moreover, the study highlights the need for mitigation policies targeting smallholder agriculture, which made a significant contribution to forest loss during the period analyzed.

Russia

From 2001 to 2023, Russia lost 83,7 Mha of tree cover[2] (Brazil lost 68,9 Mha [3]). According to Hansen et al., 2013, Russia experienced the highest forest loss during the observation period. However, when considering forest gain, between 2000 and 2020 Russia gained 37,2 Mha of tree cover (whereas Brazil gained only 8,1 Mha) (Potapov et al., 2022). This is largely because most forest loss in Russia is caused by fires, followed by natural forest regeneration over time—a pattern typical of boreal forests (Curtis et al., 2018).

2.4 Regulation under study: the EUDR

The European Union Deforestation-free Regulation (EUDR) is a regulation that entered into force on June 29, 2023, but its application is scheduled to begin on December 30, 2025, for large and medium-sized companies, and on June 30, 2026, for micro and small enterprises.

Its objective is to minimize the European Union's involvement in the consumption of commodities—cattle, timber, cocoa, soy, palm oil, coffee, rubber—and their main derived products—leather, chocolate, tires, or furniture—associated with global deforestation. The EUDR is an evolution of the EUTR, a regulation that aimed to mitigate deforestation by blocking the consumption of timber and timber-based products originating from recently deforested areas. The fundamental premise for the regulation's success is that deforestation is caused by the expansion of agricultural production (Muradian et al., 2025).

The basic rule for producers and commercial operators of various agricultural commodities and their derivatives entering or exiting the European market is to prove that their products are not cultivated in areas deforested after December 31, 2020, or that their production does not contribute to forest degradation. According to the EU's official page, the regulation's objectives are: "avoid that the listed products Europeans buy, use and consume contribute to deforestation and forest degradation in the EU and globally; reduce carbon emissions caused by EU consumption and production of the relevant commodities by at least 32 million metric tonnes a year; address all deforestation driven by agricultural

[2]Global Forest Watch. "Tree cover loss in Russia compared to other areas." Accessed on 05/20/2025 from www.globalforestwatch.org.

[3]Global Forest Watch. "Tree cover loss in Brazil compared to other areas." Accessed on 05/20/2025 from www.globalforestwatch.org.

expansion to produce the commodities in the scope of the regulation, as well as forest degradation."[4]

From the perspective of this regulation, deforestation is defined as the conversion—whether human-induced or not—of forests into agricultural use. Forests are defined by the FAO as areas with woody vegetation where at least 10% of the canopy is expected to reach a height of 5 meters or more. Therefore, if forested land is converted into urban development or infrastructure, the products extracted from it are not considered to originate from deforested land and thus are not subject to trade penalties. Conversely, products originating from forest destruction due to fires—whether human-induced or not—are considered to originate from deforestation under the regulation. Unless the degraded forest is permitted and able to regenerate: for example, wood products originating from a burned forest whose recovery is assured are not considered non-compliant.[5]

Products originating from areas of forest degradation are also considered non-compliant. Forest degradation includes the following types of conversion: a) primary forests or naturally regenerating forests converted into plantation forests or other wooded land; or b) primary forests converted into planted forests.

Adapting to these new requirements demands that producers and commercial operators invest in technology to track production chains (due diligence), which implies compliance costs. Other concerns include whether the regulation will effectively reduce global deforestation, considering that demand for banned products may be redirected away from the European market. Nonetheless, it is expected that producers will invest in making their supply chains deforestation-free, rather than losing market access and relocating their export destinations.

With the scope of the regulation outlined, the following sections apply the methodology proposed in this study to assess the commercial impacts of the EUDR on Brazil's beef market—a sector that may face significant challenges in complying with the regulation (Cesar de Oliveira et al., 2024)—as well as to estimate the amount of deforestation potentially avoided.

[4] https://environment.ec.europa.eu/topics/forests/deforestation/regulation-deforestation-free-products_en

[5] https://green-business.ec.europa.eu/deforestation-regulation-implementation_en

3 Data

This work can be divided into three phases: geoprocessing to generate the deforestation satellite account, the calculation of the deforestation footprint and generators, and the application of the methodology in a simulation of an economic-regulatory scenario aimed at measuring the impact of the EUDR on the Brazilian beef market. Each phase involves different types of data. In the first, georeferenced files are used to allocate deforestation across various agricultural and livestock productions. In the second, an input-output matrix is used to understand how deforestation is driven by trade interactions within the production chain and to map the countries and sectors most involved in global deforestation. In the final phase, data on beef production, herd sizes, and pasture areas by Brazilian state are used to estimate how much beef is produced per newly deforested hectare. The subsections below will detail each data source and its specifications.

3.1 Global Forest Change (GFC)

The Global Forest Change (Hansen et al., 2013) is the dataset destined to measure variation of forest cover. Its data is composed by Landsat images with resolution of 1 arcsec per pixel (aproximately 30 meters at the equator), and it considers forest as vegetation with more than 5 meters height. In contrast, deforestation is the complete depletion of vegetation at the pixel scale. The files are tiles of 10 x 10 degrees, with coordinates varying from 180W-180E and 80N-60S, totalizing 504 tiles, of which only 243 cover land portions. In our work, we use the rasters files of lossyear, which measure the forest loss of each year. We restricted the dataset from 2006 to 2010. As briefly mentioned above, the resolution is 30m x 30m per pixel. However, as will be described below, other rasters have lower resolution, so it was necessary to aggregate pixels from GFC dataset in order to compatibilize the rasters files.

3.2 Spatial Production Allocation Model (SPAM)

Using a variety of inputs, IFPRI's Spatial Production Allocation Model (SPAM) uses a cross-entropy approach to make plausible estimates of crop distribution within disaggregated units. SPAM dataset is provided by Agro-MAPS, a informal collaborative consortium created in 2002 by Food and Agriculture Organization of United Nations (FAO), IFPRI (International Food Policy Research Institute) and SAGE (Center for Sustainability and the Global Environment, University of Wisconsin-Madison) to satisfy an increasing necessity to have better crop production and land use data to support their respective program. Data encompasses rasters of physical area, yield, production, harvest and production value of 42 cultures and for four types of production systems (according to irrigation method). We use datasets from MapSPAM to map which culture has been produced in each area. We have data for 2005 ((IFPRI) and for Applied Systems Analysis (IIASA), 2016) and 2010 ((IFPRI), 2019) that allow us to analyze the variation of production and to associate the deforestation to agricultural commodities. The SPAM is our reference raster in terms of resolution (5 arc-minutes, approximately 10 km at the equator) and coordinate system (WGS 84). All other rasters had to be made compatible with it in order to avoid mismatching in areas analyses.

3.3 Gridded Livestock of the World (GLW)

Gridded Livestock of the World (GLW) is a database of livestock production and distribution across the world. We utilize it to estimate the size of herds for three species: cattle, sheeps and goats. The database relies on a downscaling methodology whereby census counts of animals in sub-national administrative units are redistributed at the level of grid cells. This downscaling process depends on the version of the database. We use data from 2006 (Robinson et al., 2014) and 2010 (Gilbert et al., 2018), GLW2 and GLW3 respectively. The first employs stratified spatial regressions. The second uses a random-forest method. GLW2 has a better resolution, 30 arcsec, approximately 1km at the equator, while GLW3 has the same resolution as SPAM rasters, 5 arcmin. It means that we had to aggregate cells from GLW2 to make it compatible with our reference raster.

3.4 Gloria-MRIO

Gloria Multi Regional Input-Output (MRIO) (Lenzen et al., 2021) is our input-output matrix data. Developed by the University of Sydney, it integrates primary data from sources such as the United Nations Statistics Division (UNSD), FAOSTAT, the World Trade Organization (WTO), among others.

The database covers 164 regions and 120 economic sectors, providing a comprehensive global representation. This extensive coverage enables a broad analysis of deforestation footprints and their underlying drivers. For our study, we use the 2010 version of the matrix.

3.5 IBGE and MapBiomas

To obtain a measure of the amount of beef produced per hectare—so that we can later calculate the quantity of meat that can be produced in a deforested area—we used various state-level data sources. From the 2010 Municipal Livestock Survey (Pesquisa da Pecuária Municipal 2010) by IBGE, we extracted cattle herd size data. From MapBiomas ("Project MapBiomas - Collection 9 of Brazilian Land Cover & Use Map Series"), we obtained the pasture area corresponding to each state. We also used data from the IBGE's Quarterly Survey of Animal Slaughter (Pesquisa Trimestral do Abate de Animais) for the year of 2010, which allowed us to calculate the average yield in kilograms that one hectare produces. With the results by state, we aggregated them to obtain the national average. The use of these data will be detailed in the methodology section.

4 Methodology

This work itself represents a methodological proposal to measure deforestation driven by commercial forces. However, it can be divided into well-defined stages according to their objectives. The overall methodology aims to pave the way for new ways of measuring the impact of trade on deforestation and to generate insights for policymakers seeking to reduce deforestation through trade-related levers. Each stage explores different techniques to achieve a specific outcome.

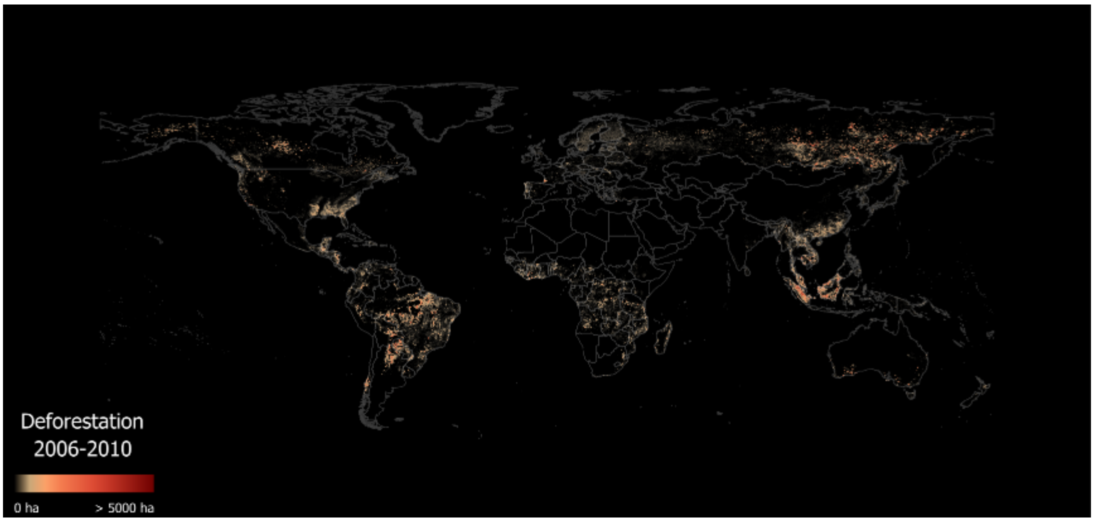
The following subsections will address details of these methodological stages, including their respective theoretical framework, the main assumptions of the methodology, and potential limitations of the method. This level of detail is intended to serve as a foundation for the reader to adapt the techniques, adjusting them to their own assumptions or to different data sources, and generating new results. This section will be divided into three: Deforestation Satellite Account; Deforestation Generators and Deforestation Footprints; Economic Scenario Simulation - EUDR.

4.1 Deforestation Satellite Account

At this stage, the objective is to develop a deforestation satellite account — that is, to assign to each commodity the deforested area corresponding to one cycle of its production. This account will later be integrated into the input-output matrix in order to calculate the deforestation footprint and the generators by sectors and countries. In short, at this phase, the manipulation of georeferenced data plays a central role in the techniques employed.

Initially, raster files from Global Forest Change were processed. Only deforestation that occurred between 2006 and 2010 was marked. The pixels were then aggregated to match the lower resolution of the MapSPAM raster file, and the deforested area per pixel at the new resolution was calculated. In the Figure 4.1 and in the Table 4.1 are displayed the deforestation obtained from GFC rasters between 2006 and 2010.

Figure 4.1: Global Deforestation between 2006 and 2010.



Notes: The figure shows the GFC raster at the MapSPAM resolution (10km x 10km).

Table 4.1: Total deforestation by country (2006-2010)

Ranking	Country	Deforestation (ha)
1	Russian Federation	29.595.992
2	Federative Republic of Brazil	14.801.404
3	United States of America	8.250.002
4	Republic of Indonesia	7.372.385
5	Canada	6.822.232
6	People's Republic of China	5.022.578
7	Democratic Republic of the Congo	2.932.148
8	Argentine Republic	2.821.183
9	Malaysia	2.309.186
10	Republic of Paraguay	2.125.838
11	Plurinational State of Bolivia	1.711.886
12	Commonwealth of Australia	1.426.746
13	Republic of Mozambique	1.158.500
14	Republic of Colombia	1.133.824
15	United Republic of Tanzania	1.047.244
16	Republic of the Union of Myanmar	1.006.079
17	United Mexican States	970.006
18	People's Republic of Angola	964.758
19	Republic of Zambia	740.770
20	Republic of Madagascar	679.797

Notes: The figure shows the top 20 countries with the highest total deforestation — driven not only by agricultural production, but by other sources such as urban development, fires, mining, etc. — between 2006 and 2010.

This process was carried out for all 243 files that contained land portions. Subsequently, the rasters from the Gridded Livestock of the World (GLW) were processed. The 2006 dataset (GLW2) presents animal density per square kilometer, while the 2010 dataset (GLW3) is a raster that contains the number of animals per pixel. The distribution of livestock per pixel within a polygon is done using a dasymetric model (DA), which considers weights calculated by a Random Forest model incorporating spatial predictors such as topography, human population density, vegetation, etc.

GLW2 has a resolution of approximately 1 km × 1 km at the Equator, which indicates the number of animals per pixel in that region. However, this resolution becomes distorted closer to the poles. To make the two datasets compatible, GLW2 was reprojected into a coordinate reference system that preserves area across the entire extent — Equal Earth (EPSG 8867) — to calculate the total number of animals per pixel, considering the approximate 1 km x 1 km size of each cell. Then, the data were aggregated to reach a resolution of approximately 10 km x 10 km, compatible with GLW3. In this way, the number of animals per pixel at the new resolution could be determined. To assign deforested area to livestock production, we used a metric of land area occupied by different types of livestock, including cattle, sheep, and goats.

To estimate the area occupied by livestock, we adopted the reference unit LSU (Livestock Unit), which standardizes the equivalence between species based on their land use impact. One LSU corresponds to the grazing equivalent required to support an adult cow producing 3.000 kg of milk annually. The measure of LSU per hectare (LSU/ha) allows us to estimate the extent of land used by each type of livestock, facilitating compatibility with the deforested areas. FAO data on LSU/ha by country for each type of livestock enabled the calculation of the amount of pasture area occupied by the number of animals in each pixel — simply by dividing the number of animals in the pixel by the LSU/ha value for that region.

With the rasters properly aligned with the reference raster from MapSPAM, the calculation of deforested area distribution by agricultural and livestock commodity was performed. First, the deforested area between 2006 and 2010 was calculated for each pixel. Then, the change in pasture area by livestock type (cattle, sheep, and goats) and the change in cropland area by crop type (42 crops) were calculated per pixel. To understand how deforestation was distributed, suppose the file contains only four pixels. In each pixel, it is possible to measure the forest loss and the area occupied by each crop. Let's consider only four crops for simplicity. In the tables below, we have the measurements in area units (AUs) of forest and production for the four crops. The production area corresponds to the total cropland area.

Table 4.2: Illustration of the deforestation distribution method for 4 pixels.

2006

Pixel	Forest	A	B	C	D	Production Area
#1	36	0	0	0	0	0
#2	18	1	1	1	1	4
#3	9	4	4	4	4	16
#4	3	4	6	8	2	20

2010

Pixel	Forest	A	B	C	D	Production Area
#1	36	0	0	0	0	0
#2	4	1	1	8	2	12
#3	6	3	9	5	3	20
#4	1	9	3	3	1	16

Δ

Pixel	Forest	A	B	C	D	Production Area
#1	0	0	0	0	0	0
#2	-14	0	0	7	1	8
#3	-3	-1	5	1	-1	4
#4	-2	5	-3	-5	-1	-4

Note that only pixels 2 and 3 experienced both forest loss and an increase in cropland area. In these cases, we allocate deforestation proportionally to the positive increments in crop production area—negative changes are not considered. If the total forest loss exceeds the increases in total production area, each crop is assigned a deforestation value equal to its individual area expansion. For instance, in pixel 2, there is a forest loss of 14 area units (AUs) and a total cropland increase of 8 AUs. In this case, the entire 8 AUs of expansion are assumed to have driven deforestation: 7 AUs are attributed to crop C and 1 AU to crop D. The remaining 6 AUs of forest loss are attributed to other causes, such as urban expansion. Conversely, if the forest loss is less than the total increment in cropland area—as seen in pixel 3—we assume that all deforestation was caused by crop expansion. The forest loss is then distributed across crops in proportion to their share of the total positive area increase. In pixel 3, only crops B and C increased in area (5 AUs and 1 AU, respectively). The resulting weights for crops A, B, C, and D are 0, $\frac{5}{6}$, $\frac{1}{6}$, and 0, respectively. In pixel 1, there was no change in total production area nor any forest loss. In pixel 4, although there was a forest loss of 2 units, there was a reduction of 4 units in production. Therefore, we should not attribute the forest loss to the production of crops A, B, C, and D. In such cases, we ignore these pixels.

It is important to highlight that we cannot determine precisely which crop replaced the deforested area, as the pixel resolution is not high enough to attribute deforestation to specific commodities. Instead, what we did was to distribute the forest loss among the crops present in the pixels where the total production area has increased. The deforestation driven by agriculture and livestock production is presented in Table 4.3 , which ranks the most affected countries. Figure 4.2 illustrate the distribution of deforestation by commodity for the top three countries: Brazil, Indonesia, and China.

Table 4.3: Agriculture and livestock deforestation by country (2006-2010)

Ranking	Country	Deforestation (ha)
1	Federative Republic of Brazil	12.910.571
2	People's Republic of China	4.499.273
3	Republic of Indonesia	4.108.603
4	Russian Federation	2.869.077
5	Argentine Republic	2.104.900
6	Republic of Paraguay	1.544.387
7	Plurinational State of Bolivia	1.260.107
8	United States of America	1.240.972
9	Malaysia	1.190.004
10	Republic of Colombia	1.004.758
11	Republic of Mozambique	920.831
12	United Mexican States	853.191
13	Republic of the Union of Myanmar	827.372
14	People's Republic of Angola	798.174
15	Canada	744.392
16	Democratic Republic of the Congo	701.678
17	Republic of Zambia	699.911
18	Commonwealth of Australia	690.628
19	Republic of Madagascar	642.940
20	Kingdom of Thailand	605.240

Notes: The figure shows the top 20 countries with the highest deforestation driven by 42 agricultural and three livestock production between 2006 and 2010.

The resulting deforestation satellite account consists of a vector that stores deforested area by sector and by region. Since the input-output matrix used has 164 regions and 120 sectors, our satellite account is a vector with dimensions of 1 x 19.680. However, we measure deforestation for only 45 commodities (42 agricultural and 3 livestock). And from those 45, when we associate them with the sectors of the GLORIA matrix, we reduce them to only 15 sectors. Thus, most elements of the vector are zero.

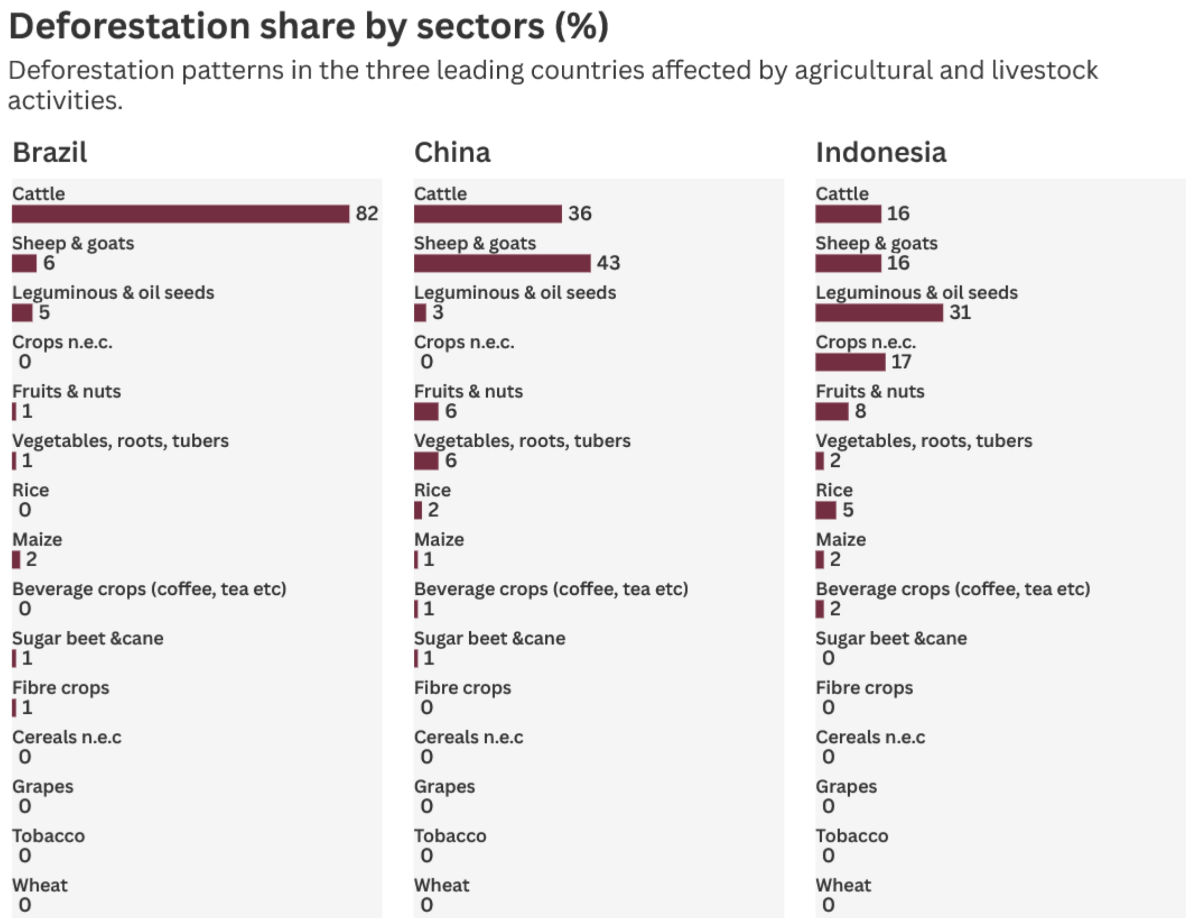
Finally, to close this subsection, we want to address an important discussion in the work, which is what a satellite account represents. A satellite account represents the flow of a process inherent to the annual production of a sector in the industry represented in the input-output matrix. For example, there may be satellite accounts for water use or CO_2-equivalent emissions. However, the reader may have noticed that the deforestation we measure in this work is the stock of deforestation generated over five years. Years later, this deforested land will still be part of the productive cycle of the agricultural industries and may even be used for different sectors than those for which the deforestation initially took place (for example, an area that right after deforestation hosted cattle may, within a few years, become an area for soybean production).

This gives rise to a conceptual compatibility issue in satellite accounting that needs to be mentioned in this work: how can we transform the measured deforestation stock into a flow measure? This, in itself, could give rise to another extensive study, as it involves knowledge of the productive cycles of various soil types for different sectors and regions. One way to simplify would be to assume a fixed duration of land use by all sectors and divide the measured deforestation value by this number. For example, if we fix the average land use time per sector at 20 years, we could say that the (flow) deforestation inherent to annual production corresponds to $\frac{1}{20}$ of the measured deforestation stock.

To make this clearer, we can draw a fanciful analogy with a chemical industry that, instead of emitting a certain amount of CO_2 into the atmosphere in each annual production cycle, emitted all the CO_2 from its current and future production at once. That is, if we measured the total accumulated stock of emissions, how could we transform it into a flow corresponding to one year? The simplified proposal would be to consider an average lifetime for these industries and divide the measured stock by each year of their production. This is the issue we are addressing here in relation to deforestation.

However, to stay focused on the purpose of this study — which is to present a methodology for measuring the amount of deforested area due to trade forces — we will present the results obtained based on five years of deforestation. The conversion to a flow measure could be carried out if there is a need to refine the results by region and sector. We just wanted to highlight this point to acknowledge our awareness of the strict conceptual framework of a satellite account. Therefore, when we talk about generators and footprints, it should be understood that the deforestation generated corresponds to a stock accumulated over five years.

Figure 4.2: Deforestation profile in Brazil, Indonesia and China.



Notes: Deforestation profile associated with the fifteen GLORIA commodity sectors in the three main countries that deforest for agricultural and livestock production.

4.2 Deforestation Generators and Deforestation Footprints

The tools applied in this section are based on input-output theory, developed by the economist Wassily Leontief (1906–1999). Below, we illustrate the structure of the matrices we work with, derive the fundamental identity of the Leontief model using a bit of linear algebra, and apply the method to compute deforestation generators and footprints using the satellite account derived in the previous subsection.

Let $\mathbf{Z}$ be the intermediate consumption matrix between regions:

$$\mathbf{Z} = \begin{bmatrix} \mathbf{Z^{11}} & \cdots & \mathbf{Z^{1R}} \\ \vdots & \boxed{\mathbf{Z^{rs}}} & \vdots \\ \mathbf{Z^{R1}} & \cdots & \mathbf{Z^{RR}} \end{bmatrix} \tag{4.1}$$

Each block $\mathbf{Z^{rs}}$ is itself a matrix that captures the intersectoral trade from region r to region s:

$$\mathbf{Z^{rs}} = \begin{bmatrix} Z_{11}^{rs} & \cdots & Z_{1N}^{rs} \\ \vdots & \ddots & \vdots \\ Z_{N1}^{rs} & \cdots & Z_{NN}^{rs} \end{bmatrix} \tag{4.2}$$

The element Z_{ij}^{rs} indicates the amount, in monetary units, that sector i in region r sells to sector j in region s. Thus, $\mathbf{Z}$ is a matrix of matrices, which represents the intermediate consumption across the R regions and N sectors.

To incorporate deforestation data into the interregional input-output framework, we construct a satellite account which has the form of a row vector. This vector represents the deforested area attributed to the production activities of each region that links environmental pressure to economic structure. The satellite account structure is represented at the bottom of the matrix $\mathbf{Z}$ below:

$$\left[\begin{array}{ccc} \mathbf{Z^{11}} & \cdots & \mathbf{Z^{1R}} \\ \vdots & \ddots & \vdots \\ \mathbf{Z^{R1}} & \cdots & \mathbf{Z^{RR}} \\ \hline \mathbf{d^1} & \cdots & \mathbf{d^R} \end{array}\right] \quad \textit{Deforested area in each of the R regions.}$$

As mentioned previously, a satellite account enables the integration of environmental indicators into economic models, allowing for an assessment of environmental impacts along regional production chains. In this representation, each element of the vector is also a vector of N elements, representing the N sectors of a specific region r.

$$\mathbf{d^r} = [d_1^r \quad \cdots \quad d_N^r]$$

The elements of this vector in the present work were obtained as described in the previous subsection. Now that we have in mind the structures of the global input-output matrix and the deforestation satellite account vector, we will develop the model that leads to the basic identity of the input-output theory (Miller and Blair, 2009).

We start from the basic input–output model, which states that the gross output is equal to the sum of intermediate consumption and final demand consumption.

$$\mathbf{x} = \mathbf{Z} \cdot \mathbf{i} + \mathbf{y} \tag{4.3}$$

In an interregional model with N sectors and R regions, we have:

- $\mathbf{x}$ is the total output vector ($NR \times 1$);
- $\mathbf{Z}$ is the intermediate consumption matrix ($NR \times NR$);
- $\mathbf{i}$ is a column vector with all elements equal to 1 ($NR \times 1$);
- $\mathbf{y}$ is the final demand vector ($NR \times 1$).

Now, we define the matrix of technical coefficients. Let $\mathbf{A}$ be the matrix of technical coefficients given by

$$\mathbf{A} = \mathbf{Z} \cdot \widehat{\mathbf{X}}^{-1} \tag{4.4}$$

Where $\widehat{\mathbf{X}}$ is the diagonal matrix formed with the elements of $\mathbf{x}$. That is, $\widehat{X}_{ii} = x_i$. Therefore,

$$\widehat{\mathbf{X}}^{-1} = \begin{bmatrix} \frac{1}{x_1} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \frac{1}{x_N} \end{bmatrix} \tag{4.5}$$

Thus, we can rewrite equation 4.3 in the form:

$$\mathbf{x} = \mathbf{A} \cdot \mathbf{x} + \mathbf{y} \iff (\mathbf{I} - \mathbf{A}) \cdot \mathbf{x} = \mathbf{y} \tag{4.6}$$

Provided that the matrix $(\mathbf{I} - \mathbf{A})$ is invertible, we solve the equation for $\mathbf{x}$:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1} \cdot \mathbf{y} \tag{4.7}$$

Equation 4.7 is the fundamental equation of the input–output model. The meaning of this equation is that final demand drives total production by activating sectors across the input chains. We use this idea to calculate how a shock in final demand results in deforestation, CO_2 emissions, water consumption, and other environmental impacts.

We therefore define the matrix $\widehat{\mathbf{D}}$, with dimensions $NR \times NR$. It is a diagonal matrix, i.e., all off-diagonal elements are equal to zero. Each diagonal element of this matrix is defined as:

$$\widehat{D}_{ii}^{rr} = \frac{d_i^r}{x_i^r}; \ \forall i \in \{1,...,N\} \ , \ r \in \{1,...,R\} \tag{4.8}$$

Where:

- d_i^r is the deforestation (in hectares) of sector i in region r;
- x_i^r is the production (in dollars) of sector i in region r.

$$\widehat{\mathbf{D}} = \begin{bmatrix} \frac{d_1^1}{x_1^1} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \frac{d_N^R}{x_N^R} \end{bmatrix} \tag{4.9}$$

The unit of $\widehat{D}$ is $\frac{\text{ha}}{\text{US\$}}$.
Pre-multiplying both sides of equation 4.7 by $\widehat{\mathbf{D}}$, we obtain:

$$\widehat{\mathbf{D}} \cdot \mathbf{x} = \widehat{\mathbf{D}} \cdot (\mathbf{I} - \mathbf{A})^{-1} \cdot \mathbf{y} \iff \mathbf{d} = \widehat{\mathbf{D}} \cdot (\mathbf{I} - \mathbf{A})^{\mathbf{-1}} \cdot \mathbf{y} \tag{4.10}$$

The interpretation of equation 4.10 is analogous to that of equation 4.7: the vector $\mathbf{d}$ expresses the total deforestation (in hectares) associated with the production structure required to meet the demand $\mathbf{y}$.
We define the matrix resulting from the multiplication of the deforestation coefficient matrix by the Leontief inverse as the deforestation generation matrix, denoted by $\mathbf{G}$.

$$\mathbf{G} = \widehat{\mathbf{D}} \cdot (\mathbf{I} - \mathbf{A})^{\mathbf{-1}}$$

From this matrix, we can calculate the global deforestation generated by a one-unit monetary increase in final demand. In this case, the values expressed in the GLORIA matrix are in units of 1.000 US dollars.

To obtain the total deforestation generated by a unitary increase in demand in sector j of a given region s, we sum the elements in the column of $\mathbf{G}$ corresponding to that sector and region.

Deforestation Generator

$$G_j^s = \sum_r \sum_i G_{ij}^{rs}$$

This sum allows us to identify the sectors and regions that exert the most pressure on deforestation for each dollar added to their demand. We can take the aggregated view by sector—that is, how much deforestation is caused by a 1.000 US dollar increase in the demand for a given sector—or the aggregated view by region. For this, the 1.000 US dollars are distributed proportionally according to the structure of demand, as explained below:

- How much deforestation is generated worldwide by a 1.000 US$ increase in the demand for sector j: We increase the demand for sector j by 1.000 US$, distributing this amount proportionally across the regions that make up the demand for this sector.

$$G_j = \frac{\sum_s G_j^s \cdot y_j^s}{\sum_s y_j^s} \tag{4.11}$$

- How much deforestation is generated worldwide by a 1.000 US$ increase in the demand for region s: We increase the demand for region s by 1.000 US$, distributing this amount proportionally across the sectors that make up the demand for this region.

$$G^s = \frac{\sum_j G_j^s \cdot y_j^s}{\sum_j y_j^s} \tag{4.12}$$

Deforestation Footprint

We adopt the approach proposed by Kanemoto et al. (2011). To enable an analysis that accounts for multiple sources or destinations of final demand, we generalize the final demand vector $\mathbf{y}$ into a final demand matrix $\mathbf{Y}$, where each column corresponds to the final demand vector of one of the R regions:

$$\mathbf{Y} = \left[\mathbf{y}^{(1)}\ \mathbf{y}^{(2)}\ \cdots\ \mathbf{y}^{(R)}\right] \tag{4.13}$$

Thus, we have:

$$\mathbf{x} = \mathbf{Z} \cdot \mathbf{i} + \mathbf{y}^{(1)} + \mathbf{y}^{(2)} + \cdots + \mathbf{y}^{(R)} \tag{4.14}$$

$$\mathbf{x} = \mathbf{Z} \cdot \mathbf{i} + \mathbf{Y} \cdot \mathbf{i} \tag{4.15}$$

- $\mathbf{Y}$ is the final demand matrix $(n \times R)$;
- each $\mathbf{y}^{(k)}$ represents a column of final demand from origin or use k.

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1} \cdot \mathbf{Y} \cdot \mathbf{i} \tag{4.16}$$

Then,

$$\mathbf{d} = \widehat{\mathbf{D}} \cdot (\mathbf{I} - \mathbf{A})^{-1} \cdot \mathbf{Y} \cdot \mathbf{i} \tag{4.17}$$

Instead of working with the aggregated deforestation vector **d**, we can decompose it into components that reveal where the deforestation was ultimately consumed—that is, we can allocate the deforestation generated according to the specific final demand it was intended to meet.

To do this, we modify equation 4.17 by omitting the summation vector **i**. We then obtain:

$$\mathbf{F_D} := \widehat{\mathbf{D}} \cdot (\mathbf{I} - \mathbf{A})^{-1} \cdot \mathbf{Y} \tag{4.18}$$

$$\mathbf{F_D} = \begin{bmatrix} \mathbf{G^{11}} & \cdots & \mathbf{G^{1R}} \\ \vdots & \ddots & \vdots \\ \mathbf{G^{R1}} & \cdots & \mathbf{G^{RR}} \end{bmatrix} \cdot \begin{bmatrix} \mathbf{y}^{(1)} & \mathbf{y}^{(2)} & \cdots & \mathbf{y}^{(R)} \end{bmatrix} = \begin{bmatrix} \mathbf{F_D^{11}} & \cdots & \mathbf{F_D^{1R}} \\ \vdots & \ddots & \vdots \\ \mathbf{F_D^{R1}} & \cdots & \mathbf{F_D^{RR}} \end{bmatrix} \tag{4.19}$$

Application and Interpretation

- The elements along the **diagonal** represent deforestation that is **produced and consumed** domestically within the country.
- Summing an entire **column**, excluding the diagonal element, yields the **deforestation imported by the region**.
- Summing an entire **row**, excluding the diagonal element, yields the **deforestation exported by the region**.

Calculating the Deforestation Footprint

The total **deforestation footprint** of a region is calculated as:

$$Footprint = D_{\text{Dom}} + D_{\text{Imp}} - D_{\text{Exp}} \tag{4.20}$$

Where:

- D_{Dom} represents domestic deforestation (diagonal element);
- D_{Imp} represents deforestation embodied in imports (column sum excluding the diagonal);
- D_{Exp} represents deforestation embodied in exports (row sum excluding the diagonal).

We conclude this section by reiterating the distinction between deforestation generators and deforestation footprints.

Based on input-output theory, when we multiply the vector of deforestation coefficients—calculated as the ratio between the deforested area and the gross production value of a given region and sector—by the Leontief inverse matrix, we obtain the generator matrix. Summing the columns of this matrix yields the generator vector, where each element indicates the amount of deforestation generated worldwide as a result of a 1.000 US$ increase in final demand in a given region and sector. To attribute this value across regions (or sectors), we apply regional (or sectoral) weights to distribute the 1.000 US$ according to the structure of demand. In this sense, it is a measure expressed in hectares per US$ ($\frac{ha}{US\$}$).

On the other hand, when we multiply the generator matrix by the final demand matrix, we obtain a matrix that reflects the actual deforestation generated by existing final demand (rather than a marginal increase in demand). Summing the rows of this matrix gives us exported deforestation, while summing the columns gives imported deforestation. The diagonal elements represent the domestic consumption of deforestation. By adding domestic and imported deforestation and subtracting exported deforestation, we obtain the deforestation footprint measure.

4.3 Regulatory scenario simulation – EUDR

Based on the regulatory mechanism described in Section 2.4, this study aims to apply the methodology presented so far to estimate the impact of the EUDR, in terms of trade and deforestation mitigation, on the Brazilian beef industry. In 2010, accoding to ComexStat data, beef and other meat products exported approximately US$ 6,5 billions and 15,9% was to EU. According to GLORIA data, Brazilian beef exports the equivalent of US$ 3,4 billions, approximately 20% of this amount was to EU. The methodology applied here will also serve as a model for application in other commodity markets. Since the data used in this work cover the period from 2006 to 2010, we simulate a scenario in which the regulation applies to products originating from areas deforested after December 31, 2005, and estimate its impact on the Brazilian beef market.

What we will do is derive, from the cattle production in deforested areas measured by georeferenced data, the amount of beef that would have been produced. This beef, therefore, would be prevented from entering European markets due to the EUDR. The main assumptions of the methodology we will apply are: 1) the yield of the land (in kg/ha) in the deforested area will be equal to the average yield of already productive land; 2) the export rate to the EU of the production in question will be equivalent to the average export rate of the total production. In other words, we assume that producers will not reallocate production to meet the demands of different markets. This would be an irrational choice, given that the expected reaction of producers facing a potential market loss would be to redirect production from illegal areas to serve markets that do not have deforestation regulations like the EU's EUDR. Calculating the effect while accounting for optimal reallocation choices by producers would be extremely complex, involving market data collection, land ownership information, and microeconomic modeling. By disregarding this reaction from producers, the impact we estimate can be interpreted as an upper bound of the real effect. And this also holds significant value. Below, we detail the calculations used to estimate the impact of the EUDR on the Brazilian beef industry.

Based on the yield Y (kg/ha) of each state (i), the production Z of the commodity (k) in the deforested area D is calculated as follows:

$$Z^D_{k,i} = Y_{k,i} \cdot D_{k,i} \tag{4.21}$$

Thus, we can calculate the share of total production that comes from deforested areas:

$$s_{k,i}^D = \frac{Z_{k,i}^D}{Z_{k,i}} \tag{4.22}$$

This will be the shock factor to be applied in the input-output data.

For derived products, we need to determine how much of the derived product industry consumes from the original commodity (in quantity) for its production. From this, we can generate a yield measure for the derived product per hectare. The following subsession illustrates how we proceeded in the case of the tranformation from cattle to beef.

Beef Production in 2010

The Table 4.4 presents data on beef production by each of the 27 states of Brazil. These data are essential for calculating how much beef is produced per hectare. The cattle stock figures are sourced from IBGE's Municipal Livestock Survey, while the pasture area data come from MapBiomas, a land cover and land use database. The ratio of cattle to pasture area yields the Head Yield (head/ha). Additionally, IBGE's Quarterly Survey of Animal Slaughter provides data on slaughter numbers and beef production in kilograms, enabling the calculation of Beef Yield (kg/ha). With these indicators, we can estimate the amount of beef being produced in recently deforested areas simply by multiplying the beef yield (kg/ha) by the deforested area (ha). The result is displayed in Table 4.5.

Table 4.4: Brazilian beef production by state.

State	Cattle (head) (1)	Pasture Area (ha) (2)	Head Yield (head/ha) (3)	Slaughter (head) (4)	Beef Production (kg) (5)	Slaughter Rate (6)	Avg. carcass Weight (kg/head) (6)	Beef Yield (kg/ha) (7)
Mato Grosso	28.757.438	21.702.555	1,33	4.082.705	1.030.711.870	0,14	252,5	47,5
Minas Gerais	22.698.120	22.918.549	0,99	2.393.057	559.345.190	0,11	233,7	24,4
Mato Grosso do Sul	22.354.077	15.497.306	1,44	3.298.044	796.638.088	0,15	241,5	51,4
Goiás	21.347.881	14.596.336	1,46	2.612.313	656.052.878	0,12	251,1	44,9
Pará	17.633.339	18.295.133	0,96	2.105.467	499.488.696	0,12	237,2	27,3
Rio Grande do Sul	14.469.307	20.300.000	1,40	1.938.588	426.564.677	0,13	220,0	41,4
Rondônia	11.842.073	7.323.925	1,62	1.902.369	443.204.227	0,16	233,0	60,5
São Paulo	11.197.697	6.251.195	1,79	3.532.524	887.134.205	0,32	251,1	141,9
Bahia	10.528.419	15.314.625	0,69	1.177.361	268.871.913	0,11	228,4	17,6
Paraná	9.411.380	3.580.204	2,63	1.459.406	338.599.312	0,16	232,0	94,6
Tocantins	7.994.200	7.125.250	1,12	906.479	211.868.603	0,11	233,7	29,7
Maranhão	6.979.844	7.479.471	0,93	589.678	134.078.898	0,08	227,4	17,9
Santa Catarina	3.985.661	981.102	4,06	509.350	116.125.890	0,13	228,0	120,5
Acre	2.578.460	1.690.434	1,53	485.166	109.324.332	0,19	225,3	64,7
Ceará	2.546.134	2.330.974	1,09	332.225	64.043.929	0,13	192,7	27,5
Pernambuco	2.383.268	2.691.353	0,89	401.028	91.018.191	0,17	227,0	33,8
Espírito Santo	2.195.406	2.172.597	1,01	380.421	89.118.238	0,17	234,3	41,0
Rio de Janeiro	2.160.727	1.841.313	1,17	228.771	47.548.109	0,11	207,8	25,8
Piauí	1.679.957	1.660.056	1,01	147.484	26.683.121	0,09	180,9	16,1
Amazonas	1.360.800	1.444.419	0,94	178.358	40.537.354	0,13	227,3	28,1
Paraíba	1.242.579	1.654.931	0,75	74.285	11.446.558	0,06	154,1	6,9
Alagoas	1.219.578	1.399.248	0,87	193.518	44.218.003	0,16	228,5	31,6
Sergipe	1.177.765	1.533.347	0,73	95.791	25.217.923	0,09	263,3	16,4
Rio Grande do Norte	1.064.575	1.270.257	0,84	107.547	21.707.655	0,10	201,8	17,1
Roraima	577.000	682.189	0,85	73.284	16.492.191	0,13	225,0	24,2
Amapá	114.773	76.331	1,50	0	0	0	0	0
Distrito Federal	100.600	89.135	1,13	0	4.471.851	0	0	0
Brazil	209.541.109	181.902.436	1,15	29.205.319	6.960.511.902	0,14	238,3	38,3

Notes: The ratio between columns 1 and 2 provides results in the Head Yield, in column 3. The slaughter rate, in column 6, is the ratio between columns 4 and 1. The average carcass weight, in column 7, is the ratio between columns 5 and 4. It is the average weight of the animal's cold body, without hide, paws, head and entrails. Finally, the Beef Yield is the product of columns 3, 6 and 7. It indicates the average quantity of beef (in kg) produced per hectare.

Table 4.5: Deforested area (ha) by state and its production (kg).

State	Deforested Area (ha)	Deforested Area Production (kg)
Pará	2.671.401	72.933.853
Mato Grosso	1.800.205	85.496.521
Rondônia	900.019	54.464.257
Minas Gerais	821.119	20.040.059
Maranhão	820.913	14.715.900
Bahia	783.433	13.754.382
Tocantins	421.842	12.543.441
Mato Grosso do Sul	385.880	19.836.150
Amazonas	316.271	8.876.072
Goiás	311.884	14.018.058
São Paulo	192.293	27.289.133
Acre	190.416	12.314.618
Santa Catarina	157.197	18.606.233
Paraná	146.748	13.878.742
Piauí	128.233	2.061.162
Roraima	118.311	2.860.211
Rio Grande do Sul	105.450	4.361.442
Ceará	60.658	1.666.591
Espírito Santo	53.388	2.189.926
Pernambuco	46.700	1.579.328
Sergipe	45.952	755.739
Amapá	32.622	0
Paraíba	31.688	219.171
Alagoas	25.460	804.562
Rio Grande do Norte	21.928	374.735
Rio de Janeiro	15.423	398.222
Distrito Federal	854	0
Brazil	**10.606.285**	**406.038.510**

Notes: The table shows the deforested areas for cattle raising and the estimated beef production for these areas by each of the 27 Brazilian states.

The proportion of Brazilian beef production originating from deforested areas, relative to the country's total beef production, is:

$$s^D_{\text{beef}} = \frac{Z^D_{\text{beef}}}{Z_{\text{beef}}} = \frac{406.038.510}{6.960.511.902} \Rightarrow s^D_{\text{beef}} = 5{,}8\% \tag{4.23}$$

This amount of 5,8% will be reduced from Brazilian beef exports to the 27 EU member states, then the deforestation footprints will be recalculated. The shock will be applied both to the intermediate consumption and the final demand. The Table 4.6 shows the GLORIA estimates of exports from the Brazilian beef industry to EU countries, broken down into final demand and intermediate consumption and its respective shares in the country's total consumption. It also indicates each country's share in the total EU consumption.

Table 4.6: EU consumption pattern of Brazilian beef.

EU Country	Final Demand	Intermediate Consumption	Total Consumption	% of EU Consumption	% Final Demand	% Intermediate Consumption
Italy	144.553	45.429	189.981	28%	76%	24%
Germany	91.736	29.833	121.569	18%	75%	25%
Netherlands	103.770	9.847	113.617	17%	91%	9%
France	57.567	21.081	78.648	12%	73%	27%
Spain	56.790	1.247	58.037	9%	98%	2%
Romania	46.868	0.37	46.905	7%	100%	0%
Ireland	9.684	4.355	14.039	2%	69%	31%
Sweden	2.848	7.948	10.797	2%	26%	74%
Bulgaria	7.790	215	8.005	1%	97%	3%
Finland	6.048	330	6.377	1%	95%	5%
Belgium	1.567	399	4.966	1%	32%	68%
Denmark	0.22	347	3.369	1%	1%	99%
Greece	2.124	3	2.127	0%	100%	0%
Portugal	1.909	195	2.104	0%	91%	9%
Poland	1.113	220	1.333	0%	84%	16%
Malta	1.137	54	1.190	0%	95%	5%
Slovakia	1.046	62	1.107	0%	94%	6%
Czech Republic	0.654	177	0.831	0%	79%	21%
Cyprus	0.629	2	0.631	0%	100%	0%
Lithuania	0.464	34	0.499	0%	93%	7%
Austria	243	126	370	0%	66%	34%
Hungary	253	14	266	0%	95%	5%
Croatia	120	7	127	0%	94%	6%
Slovenia	71	5	76	0%	94%	6%
Latvia	21	8	29	0%	72%	28%
Estonia	24	2	26	0%	92%	8%
Luxembourg	6	0	6	0%	98%	2%
EU - 27	**539.055**	**127.977**	**667.032**	**100%**	**81%**	**19%**

Notes: The figure shows the consumption of the Brazilian beef industry in EU countries (in thousands of US dollars) divided into final demand and intermediate consumption. Final demand accounts, on average, for 81% of total consumption.

The results related to this simulation will be presented in the next section.

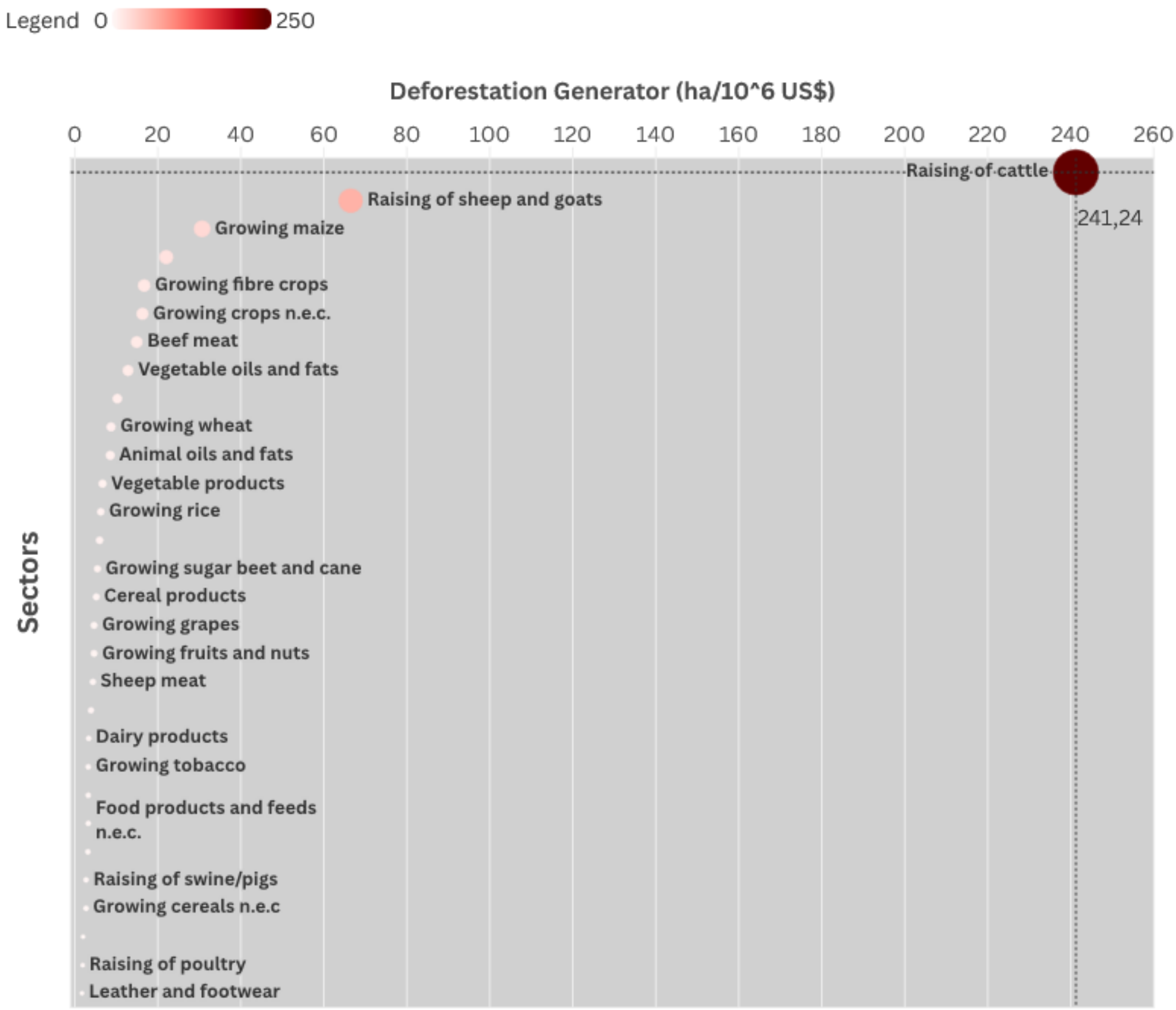
5 Results

First, we present the main drivers of deforestation by sector and region, followed by an analysis of deforestation footprints by region. This concludes the section on deforestation indicators. We then discuss the results of the EUDR economic scenario by comparing the EU's deforestation footprints with and without the regulation.

5.1 Deforestation Generators

Sectoral results: This sector-specific index measures the amount of deforestation caused by a US$ 10^6 increase in final demand. It highlights the most extractive sectors—those that contribute most significantly to global deforestation, both directly and indirectly through the activation of other sectors along their supply chains.

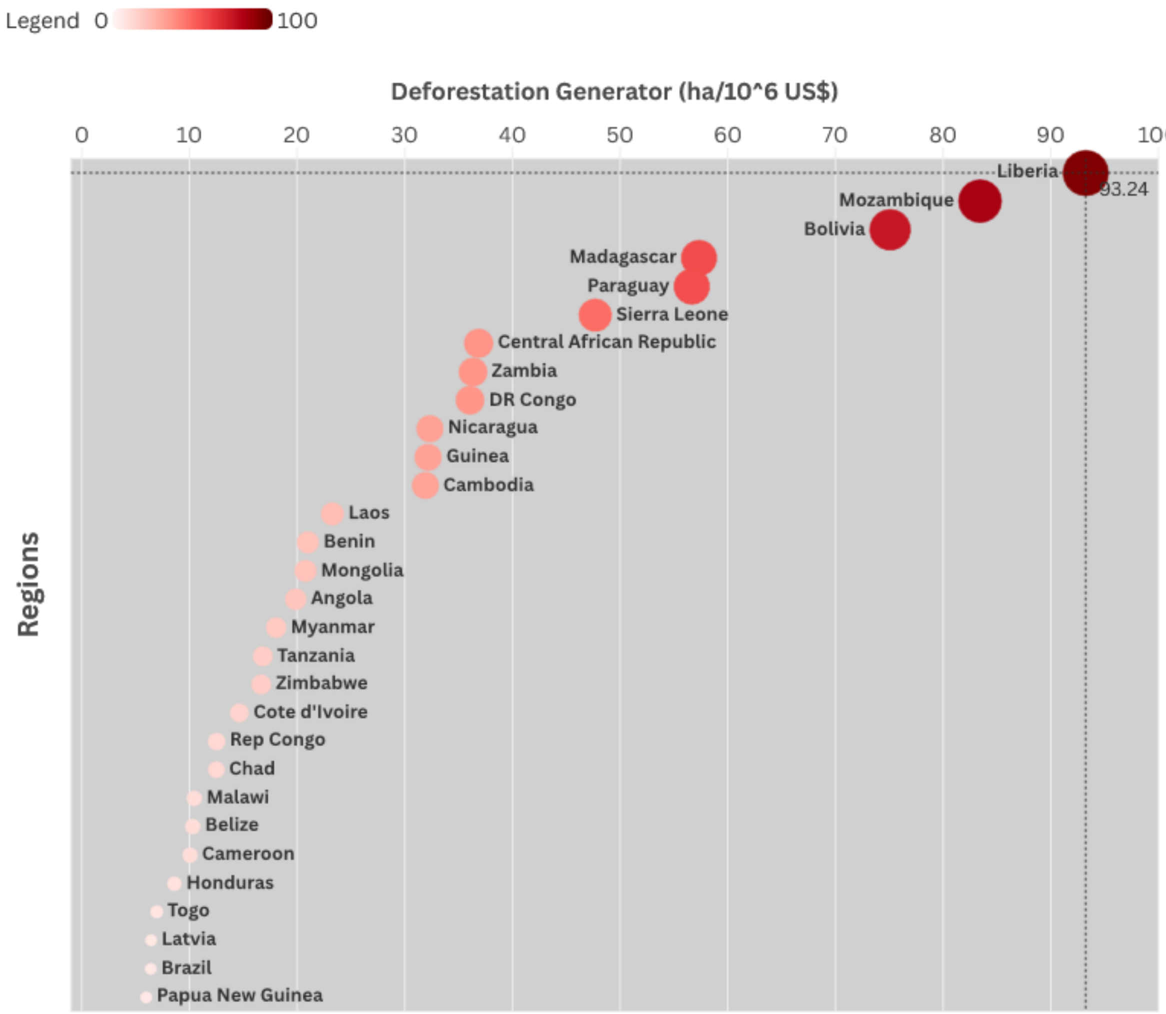
Figure 5.1: Deforestation generator by sector.



Notes: This chart presents the 30 most deforestation-intensive sectors among the 120 analyzed from GLORIA-MRIO. It reveals that an increase of US$ 1.000.000 in the final demand for the cattle raising sector leads to 241,24 hectares of deforestation worldwide.

Regional results: This region-specific index measures the amount of deforestation generated by a US$ 10^6 increase in a country's final demand. It highlights the most extractive regions — those that contribute most, both directly and indirectly, to global deforestation through their demand and the activation of supply chains. However, it is important to note that this is a relative metric. It reflects the extractive intensity of a country's demand structure. For instance, a poorer country whose economy relies heavily on directly deforesting extractive sectors will tend to have a higher index than a wealthier country, whose demand is more concentrated in industrialized goods.

Figure 5.2: Deforestation generator by region.



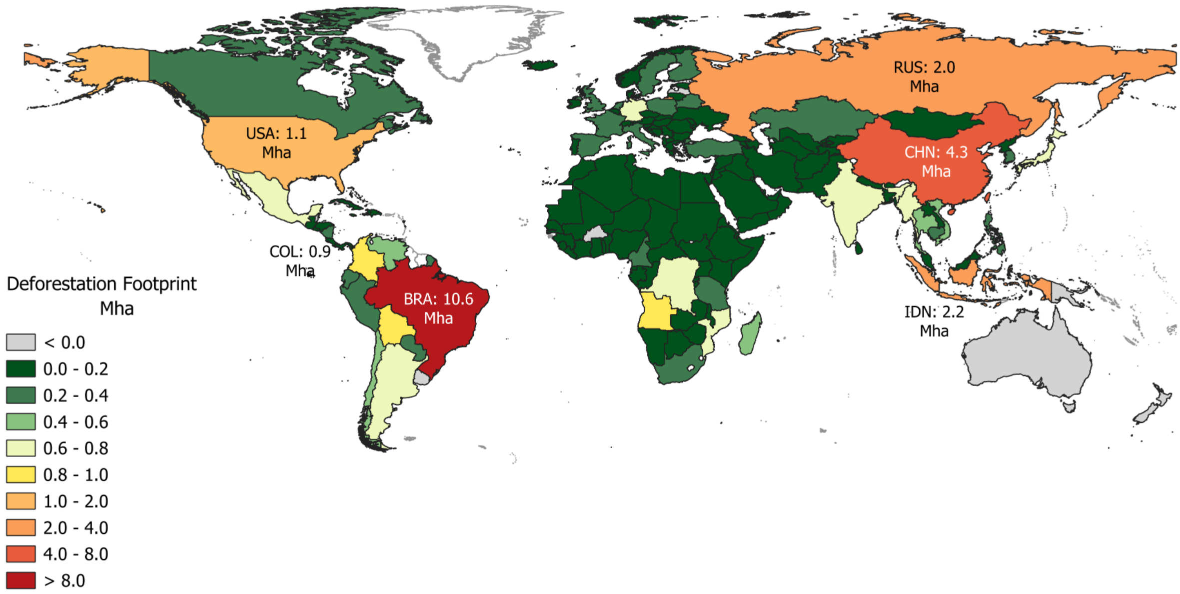
This chart presents the 30 most deforestation-intensive regions among the 164 analyzed from GLORIA-MRIO. It reveals that an increase of US$ 1.000.000 in Liberia's final demand generates 93,24 ha of deforestation in the world.

We can see that the poorest countries lead the ranking of the relative index of deforestation generation. To measure how much deforestation each country has actually caused globally through its final demand, we use the concept of deforestation footprint, which attributes responsibility for deforestation to the volume of a country's consumption (domestic and imported).

5.2 Deforestation Footprints

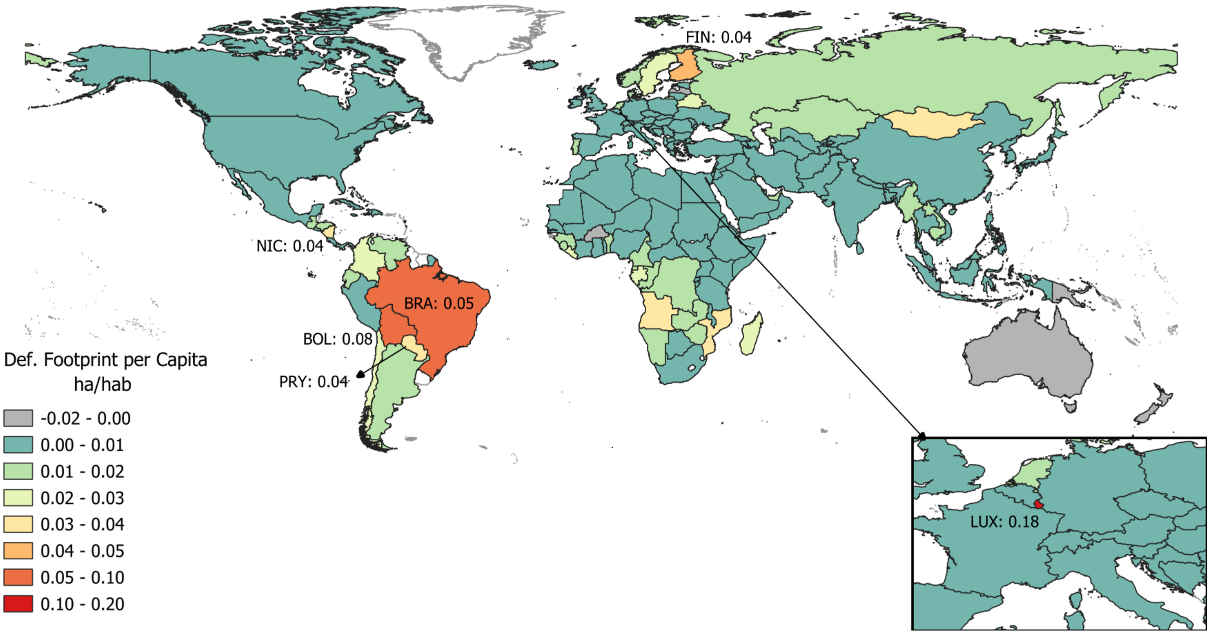
The footprints represent how much deforestation is embedded in the products consumed by each country. It is a country-specific measure. To calculate it, the final demand vector must be decomposed into multiple vectors according to their origin. This allows us to assess how much deforestation a country consumes domestically, how much it imports, and how much it exports through its products. It is a measure with area units. Next, we present maps highlighting global deforestation footprints, as well as per capita footprints, deforestation consumed domestically, imported and exported deforestation.

Figure 5.3: Deforestation footprint in millions of hectares (Mha).



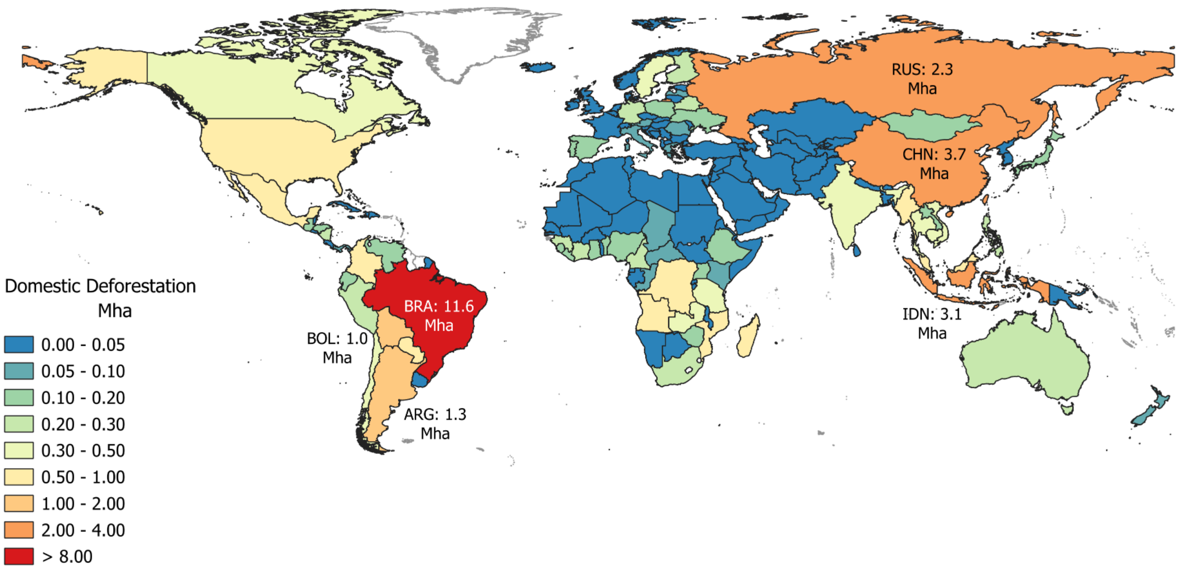
The countries highlighted on the map, ranked from highest to lowest deforestation footprint, are: Brazil, China, Indonesia, Russia, USA and Colombia.

Figure 5.4: Deforestation footprint per capita in ha/hab.



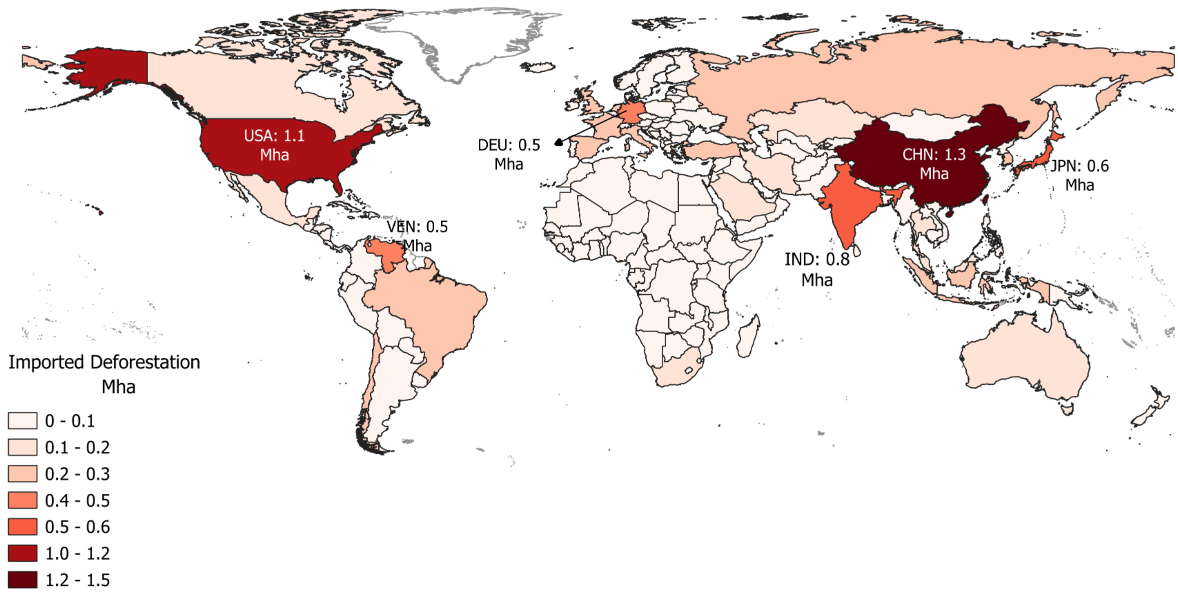
The countries highlighted on the map, ranked from highest to lowest deforestation footprint per capita, are: Luxembourg, Bolivia, Brazil, Finland, Nicaragua, and Paraguay.

Figure 5.5: Deforestation consumed domestically in millions of hectares (Mha).



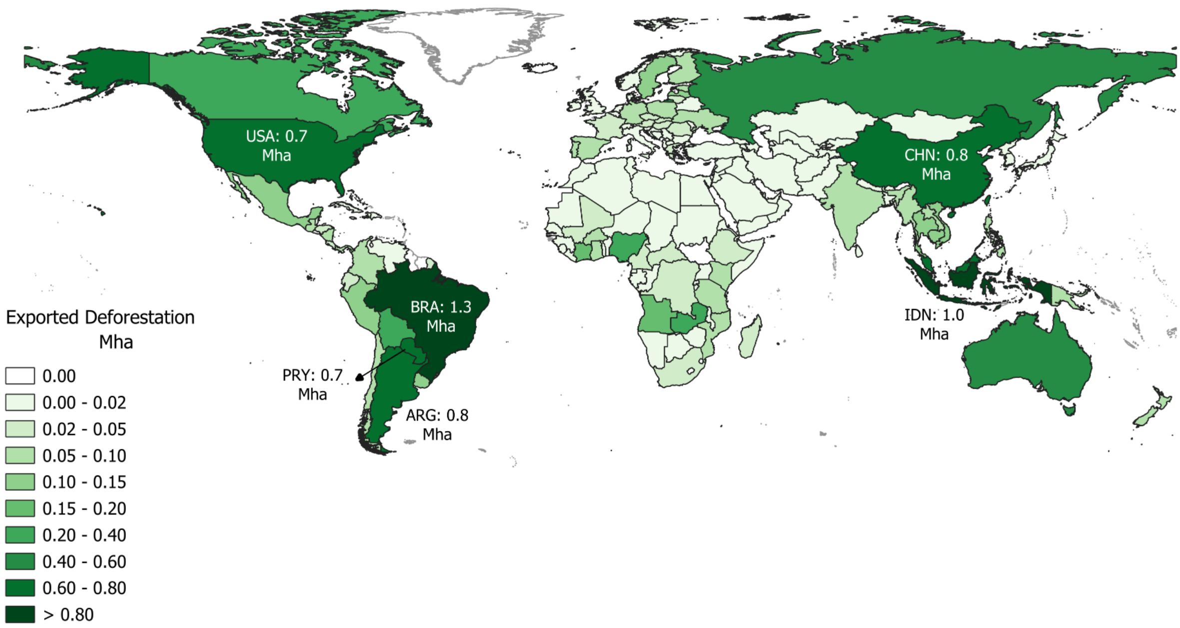
The countries highlighted on the map, ranked from highest to lowest in domestically consumed deforestation, are: Brazil, China, Indonesia, Russia, Argentina, and Bolivia.

Figure 5.6: Imported deforestation in millions of hectares (Mha).



The countries highlighted on the map, ranked from the largest to the smallest importer of deforestation, are: China, United States, India, Japan, Germany and Venezuela.

Figure 5.7: Exported deforestation in millions of hectares (Mha).

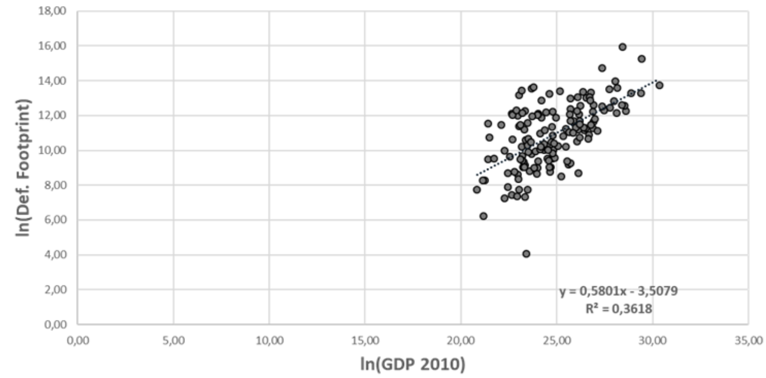


The countries highlighted on the map, ranked from the largest to the smallest exporter of deforestation, are: Brazil, Indonesia, China, Argentina, Paraguay, and USA.

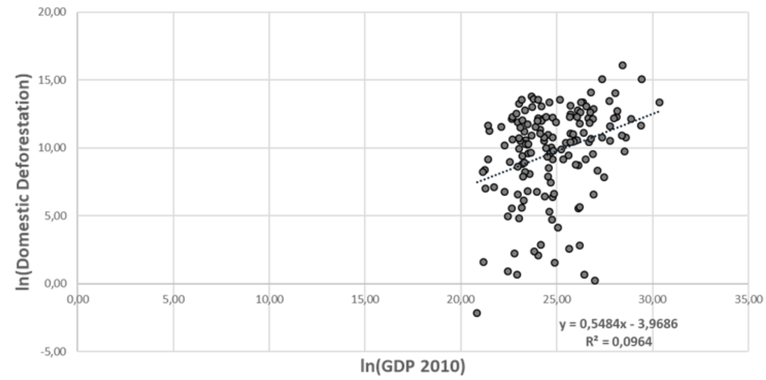
It is evident that Brazil stands out in terms of both absolute and per capita deforestation footprints. This result is mainly driven by domestic deforestation consumption.

This fact was addressed by Haddad et al. (2024), in a paper showing that meat consumption by Brazilians is one of the main drivers of deforestation in the Amazon. Other countries such as Indonesia and China also have large footprints due to domestic consumption. China's footprint is further aggravated by imported deforestation. Brazil and Indonesia stand out as major exporters of deforestation. This is more related to the stock of forests these countries possess. From the deforestation import perspective, a country's level of wealth explains the volume of deforestation it imports. This makes sense, as wealthy countries consume larger quantities of products, particularly commodities that come from extractive economies and are later industrialized in their own territories. To observe these correlations between extractivism and wealth levels, we plotted graphs showing the correlation between deforestation measures and GDP. We used logarithmic scales on the axes to facilitate the visualization of patterns.

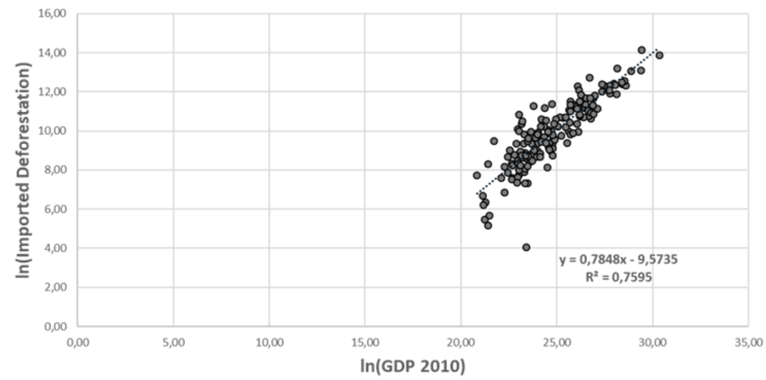
Figure 5.8: Correlations of deforestation indicators and GDP.



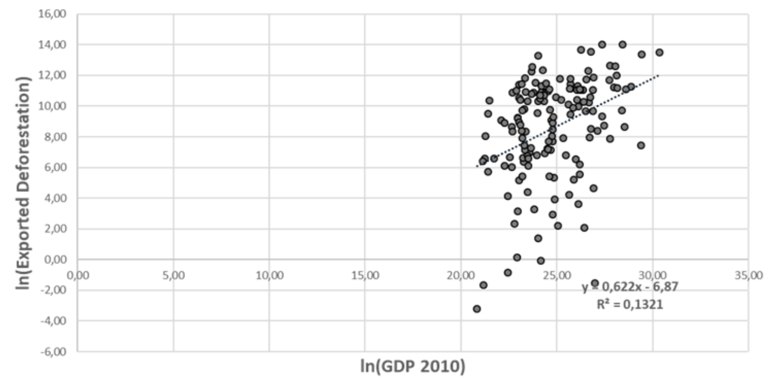
(a) Log of Deforestation Footprint x log of GDP.



(b) Log of Domestic Deforestation x log of GDP.



(c) Log of Imported Deforestation x log of GDP.



(d) Log of Exported Deforestation x log of GDP.

The scatter plot that shows the strongest correlation with GDP is, as mentioned above, the one of deforestation imports. The export plot is noisier because deforestation exports—as well as domestic consumption—depend heavily on a country's forest stock rather than on its income. Since the footprint is composed of both export and domestic consumption components, it ends up being "contaminated" by them.

5.3 EUDR Impact on Brazilian Beef Industry and Deforestation

We applied the shock value obtained from Equation 4.23 to both final demand and intermediate consumption to assess the trade impact. The corresponding values are shown in Table 4.6. The reduction in exports due to the final demand shock amounts to US$31,4 million, while the shock to intermediate consumption leads to a further reduction of US$7,5 million.

Although we assess the trade shock on both intermediate consumption and final demand, only the final demand shock is used to calculate the deforestation impact, as explained in Section 4.3.

We detail the final demand shock used to estimate the effect of the EUDR on deforestation footprints in Table 5.1.

Table 5.1: Final demand shock by country.

Countries	**Final Demand**	**Shock**	**New Final Demand**
Italy	144.553	8.432	136.120
Germany	91.736	5.351	86.385
Netherlands	103.770	6.053	97.716
France	57.567	3.358	54.209
Spain	56.790	3.313	53.477
Romania	46.868	2.734	44.134
Ireland	9.684	0.565	9.119
Sweden	2.848	0.166	2.682
Bulgaria	7.790	454	7.335
Finland	6.048	353	5.695
Belgium	1.567	91	1.476
Denmark	0.22	1	0.21
Greece	2.124	124	2.001
Portugal	1.909	111	1.797
Poland	1.113	65	1.048
Malta	1.137	66	1.070
Slovakia	1.046	61	0.985
Czech Republic	0.654	38	0.616
Cyprus	0.629	37	0.592
Lithuania	0.464	27	0.437
Austria	243	14	229
Hungary	253	15	238
Croatia	120	7	113
Slovenia	71	4	67
Latvia	21	1	19
Estonia	24	1	22
Luxembourg	6	0	5
EU-27	**539.055**	**31.446**	**507.609**

Final demand, shock value and new final demand of EU-27 countries (in thousands of US dollars).

After obtaining the new values of the EU's final demand for Brazilian beef, we recalculated the deforestation footprint. The updated values of the EU's deforestation footprint are presented in Table 5.2. This reduction of 202 hectares in the EU's footprint comes exclusively from the import channel, which declined due to the blockage of beef produced in deforested areas in Brazil between 2006 and 2010.

Table 5.2: Impact of EUDR on the EU Deforestation Footprint (ha).

Region	Without EUDR	With EUDR	Δ
Germany	612.784	612.749	-34
Netherlands	212.599	212.56	-39
France	224.154	224.133	-22
Italy	307.305	307.251	-54
Spain	365.957	365.936	-21
Romania	77.874	77.857	-18
Ireland	4.103	4.1	-4
Austria	61.999	61.999	0
Finland	220.624	220.622	-2
Sweden	251.435	251.434	-1
Bulgaria	8.236	8.233	-3
Czech Republic	39.753	39.753	0
Belgium	79.239	79.238	-1
Greece	86.599	86.598	-1
Portugal	119.211	119.21	-1
Slovakia	4.546	4.546	0
Cyprus	6.361	6.36	0
Poland	215.516	215.515	0
Denmark	85.742	85.742	0
Malta	1.622	1.622	0
Lithuania	21.237	21.237	0
Slovenia	13.331	13.331	0
Hungary	7.352	7.352	0
Croatia	14.733	14.733	0
Luxembourg	93.13	93.13	0
Estonia	3.925	3.925	0
Latvia	-5.778	-5.778	0
EU-27	**3.133.588**	**3.133.386**	**-202**

The table shows the impact of the EUDR on the EU's deforestation footprint linked to the Brazilian beef industry. The regulation results in a reduction of 202 hectares, driven by decreased EU demand for Brazilian meat sourced from deforested areas used for cattle production. The overall effect would likely be much larger if all commodities and trading partners were taken into account.

6 Conclusion

The work presented here proposed a methodology for measuring global deforestation driven by trade, with a particular application to assessing the potential impact of the EUDR on the Brazilian beef market. It is crucial to develop methodologies to measure environmental indicators in order to propose policies that mitigate climate change and to simulate and assess the effectiveness of such policies.

Our results highlighted facts such as the dependency of poorer countries like Liberia, Mozambique, and Bolivia on extractive sectors, which leads to more deforestation per dollar added to their demand structure. The most extractive sectors are those that directly generate deforestation or that most activate, in their production chains, the sectors that deforest directly—thus, they deforest indirectly. In our study, the sectors responsible for direct deforestation are those producing agricultural and livestock commodities. This deforestation was measured using georeferenced data on agricultural production and forest loss. Therefore, sectors that consume more from these tend to have higher deforestation indices.

The analysis of the deforestation footprint provided relevant insights for designing regulations such as the EUDR, as it shows a strong correlation between deforestation driven by imports and GDP. On the other hand, the export of deforestation content depends not on income, but on forest stock. Mechanisms like the EUDR aim to reduce the deforestation footprint of the countries implementing it, primarily by decreasing imported or domestically consumed deforestation. It is a way to extend local regulation to the global scale and "educate" market agents. However, its effectiveness depends on minimizing effects such as production relocation, or "deforestation leakage"—when producers export products from deforested areas to unregulated markets. This is a likely outcome, considering the costs of complying with the regulation, the so-called compliance costs. Moreover, since it is a regulation not yet in force at the time of writing, it is not possible to assess its ex-post impacts. What can be done, then, is to simulate impact scenarios, as we did for beef produced in Brazil. Disregarding producer responses, we obtained an estimated impact of approximately US$ 38,9 million in reduced trade flow of Brazilian beef to the EU—US$ 31,4 million in final demand and US$ 7,5 million in intermediate consumption. The impact on deforestation was a reduction of the EU's footprint by 202 hectares, due to the final demand shock. If the shock to intermediate consumption is also considered, the footprint reduction could be between 200 and 300 hectares, based on a simple proportionality analysis, but not calculated via input-output techniques. Considering intermediate consumption shocks for impact calculation opens up avenues for future research.

Indeed, the scope of this work aligns with the magnitude of the issue. Despite its different local dynamics, deforestation is a global-scale problem that also requires globally conceived solutions. However, due to the breadth of the work, many details could be further explored. What we have so far is a prototype of a deforestation generation calculator based on trade shocks, but it can be enhanced and refined to incorporate more details and explore additional applications.

For future research, this work offers some natural extensions. Some relate to physical measurement improvements, aimed at enriching the satellite account: both by including other sectors that can cause deforestation—such as mining and construction—and by increasing satellite image resolution to more accurately allocate deforestation to commodities. The study also sheds light on important issues regarding how deforestation is measured within the production cycle. In this regard, it paves the way for research that could propose new methods of accounting for both deforestation and reforestation flows, taking into account the land-use cycle for different crops over the years, thereby avoiding absolving crops that subsequently occupy deforested areas of responsibility.

As for the economic analysis, other approaches could be used, such as general equilibrium models, which incorporate agents' decision-making and account for market reallocations-aspects omitted in our analysis—as well as econometric approaches to measuring shocks in other markets and bilateral trade flows, estimating trade elasticities and calculating tariff effects to support the design of deforestation reduction policies.

In addition to robust technical tools, it is important to consider new deforestation mitigation policies that do not further penalize the poorest countries. Those who deforested long ago and who now consume products originating from deforested areas also bear responsibility. The sustainable use of environmental resources must transcend notions of political boundaries. It is a challenge for our species.

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