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Accounting for trade in derived products when estimating European Union's role in driving deforestation

Perrine C.S.J. Laroche [a,1], Manuela Gómez-Suárez [b,1], U. Martin Persson [c], Florence Pendrill [c], Florian Schwarzmueller [b], Catharina J.E. Schulp [a,*], Thomas Kastner [b]

[a] Institute for Environmental Studies, Vrije Universiteit Amsterdam, De Boelelaan 1111, 1081 HV Amsterdam, the Netherlands
[b] Senckenberg Biodiversity and Climate Research Centre (SBiK-F), Senckenberganlage 25, 60325 Frankfurt am Main, Germany
[c] Division of Physical Resource Theory, Dept. of Space, Earth and Environment, Chalmers University of Technology, Gothenburg, Sweden

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ABSTRACT

Governments across the world are increasingly seeking to ensure that the products consumed in their countries meet certain sustainability standards. However, the places of production—where major impacts occur—are often distant from the places of consumption. Physical trade models are suited to estimate the link between consumption and production impacts for individual commodities, but often ignore trade in derived products, obtained by processing primary commodities, especially for non-food products. Derived products which are manufactured using multiple primary commodities, such as shoes containing leather, rubber, as well as other textile materials, pose a special challenge for these models. This can lead to biased assessments of sustainability risks and obscure leverage points to address them. To mitigate the risk of bias, here we present an approach for assessing the importance of accounting for trade in derived products when attributing impacts. We apply the approach to trade in rubber and bovine hide products and associated deforestation to assess the coverage of relevant products included in the European Union (EU) regulation on deforestation-free products (EUDR), as well as to inform future revisions of the regulation's scope. We consider trade flows for 135 types of rubber products and 37 types of products derived from bovine hides. We find that rubber and bovine hides enter the EU at different stages of the supply chain. While natural rubber enters the EU at an early processing stage, through imports of raw natural rubber, most products derived from bovine hides enter the EU either as processed products or as consumer goods. Our results thus highlight that depending on the product, the share of total deforestation attributed to the EU's consumption could be significantly affected by choices in which derived products are accounted for. Weighting the costs and benefits of the inclusion of derived products for each commodity is therefore key to designing demand-side policies that cost-effectively and successfully address the deforestation risk associated with consumption.

1. Introduction

Global trade is a key driver of environmental impacts related to land use activities (Wiedmann and Lenzen, 2018). This calls for innovative modes of governance that transcend traditional political boundaries to protect biodiversity and forests on the global scale (Newig et al., 2019). Such governance approaches draw on the premise that sustainability initiatives in one state or territory often have broad impacts on distant states or territories through systemic effects (Munroe et al., 2019).

In recent years, governments in a number of countries are exploring options of supply-chain legislations to ensure that products consumed within their territories meet certain sustainability standards. A prominent example is the EU regulation on Deforestation-free products (EUDR), which entered into force in June 2023, with the aim to 'minimise consumption of products coming from supply chains associated with deforestation or forest degradation' (EC, 2023), through a requirement on importers of certain forest-risk commodities to carry out due diligence ensuring that products placed on the market are not sourced from recently deforested land.

The list of products covered by the regulation is based on a

* Corresponding author.
E-mail address: nynke.schulp@vu.nl (C.J.E. Schulp).
[1] Equal contribution.

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commodity scope, as well as a product scope. The commodity scope —beef and leather, soybeans, palm oil, coffee, cocoa, rubber, and timber— was established based on an impact assessment, providing insights into the extent and geography of EU demand for agricultural and forest commodities whose expansion has been leading to deforestation and forest degradation in the tropics (EC, 2021). Regarding the product scope, although NGOs and some industry associations called for the inclusion of all derived products from each commodity (EC, 2021; COCERAL, FEDIOL, and FEFAC, 2021), the European Commission decided to limit the scope in order to enhance implementability. Due to limited capacity of the impact assessment, this meant that only the 'main' traded forms for each commodity were included (EC, 2021), typically excluding consumer goods and other highly processed products.

Estimates of how environmental impacts are associated with international supply chains – that provide a quantitative benchmark and have provided justification for the EUDR as well as informed its commodity scope – typically rely on trade data compiled by international organisations such as the Food Agriculture Organisation (FAO), the United Nations (UN), and the World Trade Organisation (WTO). However, in the bilateral trade statistics published by these organisations, the country of origin corresponds to the country from which the product was last shipped (Bruckner et al., 2014), which does not necessarily correspond to the country where the initial land-based activities took place. This issue has been addressed by combining input-output theory (Leontief, 1936; Miller and Blair, 2009) and trade flows in monetary terms (e.g., Kitzes et al., 2009; Moran et al., 2020) or physical terms (Bruckner et al., 2019; Kastner et al., 2011) to track the primary origin of agricultural commodities available for use in a specific country.

Compared to monetary-based trade models—which typically have low sectoral resolution—physical trade models have the advantage of being able to trace flows of specific commodities. This is particularly relevant to address environmental issues related to crop cultivation through supply chain measures. For example, the physical trade-based method developed by Kastner et al. (2011) has been applied to examine the risk of tropical deforestation associated with countries' demand for different primary commodities (Pendrill et al., 2019) and these data have been used in the EU's impact assessment underpinning the EUDR (EC, 2021). The trade database from FAOSTAT has generally been used for this kind of investigation because it contains detailed information on the production and trade of many agricultural commodities (e.g., Bruckner et al., 2019; Pendrill et al., 2019; Arto et al., 2022). However, through their reliance on FAOSTAT trade data, these models are constrained in the inclusion of derived products (see method section).

However, besides trade in their primary forms (e.g., cotton fibre, fruits), many commodities are typically essential inputs for a wide variety of derived products that are also traded. Derived products are products obtained from the transformation of the primary commodity into processed products for industrial use (e.g., yarn, fabrics, juice concentrates) or final consumption (e.g., clothing, fruit juices). The FAOSTAT trade database does include trade flows for many derived products used for food purposes (e.g., fruit juice, bread, sausages), but does not contain such detailed information on derived products that are not used for food purposes (e.g., clothes, tyres, shoes) (Bruckner et al., 2014).

Consequently, the system boundaries of the physical trade models used to link demand for non-food products to place-based environmental impacts are often cut at an early stage in the supply chain, leading to 'truncation errors' (Hubacek and Feng, 2016; West et al., 2022); i.e., errors resulting from values not representing the entire impact of the supply chain, but only representing the impact until the cut-off in terms of product processing. This can be limiting, because demand for derived products may also be used as a leverage point for addressing environmental and social issues related to the production of agricultural commodities (COWI, 2018). Indeed, sustainability initiatives can be taken by a wide variety of supply chain actors, from traders to manufacturers, financiers, and end consumers (Bager et al., 2021). While the issue of incomplete coverage of trade in derived products in the FAOSTAT trade database is well known (Hubacek and Feng, 2016), implications for consumption-based estimates of environmental impacts of non-food land-based products have not been extensively explored.

In this paper, we seek to explore the role of trade in derived non-food products in determining the extent and geography of countries' demand for commodities, as well as associated environmental impacts. We use the case of the EUDR and evaluate the extent to which the EUDR successfully addresses deforestation due to EU demand. We develop an approach for assessing the magnitude of truncation errors in physical trade models which can be applied to a variety of environmental or social impacts and commodities, subject to data availability. We then apply this approach to the case of natural rubber and bovine hides, two central non-food commodities included in the EUDR. Our aim is to understand whether these commodities from different origins enter a country or region – in our example the EU – in unprocessed or processed forms, and how inclusion or exclusion of these trade flows translate into changes in deforestation risk estimates. We finally use these insights to discuss the EUDR scope for natural rubber and bovine hide products and how important the inclusion of derived products is for incentivizing deforestation-free production.

Natural rubber is a relevant commodity, used primarily to support mobility around the globe (Laroche et al., 2021) and included in the EU's list of critical raw materials (EC, 2020). In contrast, although bovine products are primarily used for food and analyses of cattle's impact on deforestation has been widely addressed (e.g., Gerber et al., 2015; Kristensen et al., 2015), the impact on deforestation of the production of hides, a non-food by-product used to manufacture leather products, has been only marginally investigated. However, there is an inextricable link between the leather industry and pasture conversion for cattle ranching, which has been estimated as the largest driver of recent deforestation (Pendrill et al., 2022; Singh and Persson, 2024a) and bovine hides and a number of products derived from them are included in the EUDR.

2. Method

This paper studies the relevance of including trade in derived products when estimating the contribution of the EU's consumption to rubber- and bovine hides-related deforestation. In this methodological section, we illustrate how primary commodities flow through trade in derived products (2.1), and present three calculation steps to quantify the effect of including trade in derived products on the estimated contribution of a country's apparent consumption to environmental impacts (2.2). We then present data sources for exploring the case of rubber- and bovine hides-related deforestation (2.3).

2.1. Framework and definitions

The relevance of including trade flows of derived products when estimating the extent and impacts of consumption will depend on their contribution in relation to trade in the primary commodity and will vary across countries and commodities. Fig. 1 illustrates how a primary commodity flows between different countries through trade in the primary commodity itself, but also through trade in derived products. We provide a supplementary excel file to allow exploration of the effects under different data configurations (Supplementary material 2).

'Apparent consumption' refers to the quantity of a primary commodity available for use in a country, where use corresponds to either intermediate (i.e., as a production input) or final consumption (UN, 2016). It can be estimated from data on the production of the primary commodity and data on trade in the primary commodity and products derived from it in physical terms, using the method of Kastner et al. (2011). This

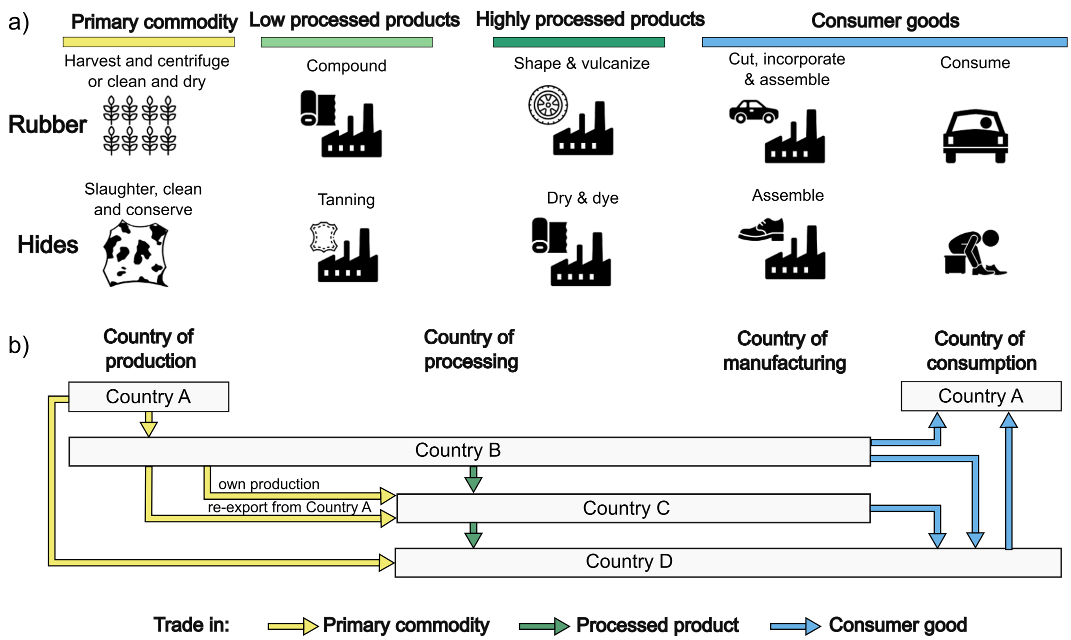

Fig. 1. a) Simplified representation of the supply chain of natural rubber and bovine hides, and b) diagram illustrating how these products (i.e. primary commodity, processed products and consumer goods) can flow between countries through trade. In the example, Country A and country B produce the primary commodity. Country A exports the primary commodity to countries B and D, and country B exports the primary commodity to country C. However, the exports from country B partly consist of re-exports from country A (i.e. export it in the exact same form as it was imported), as well as exports from its own production (note that this also applies and is accounted for for downstream trade flows in the diagram but is only shown in the first stage for the sake of simplicity). Country B, C and D process and manufacture the primary commodity into consumer goods. Country B exports processed products to country C, and country C exports processed products to country D. Finally, countries B, C and D export consumer goods to country A and D, where consumption takes place. Including trade in processed products or consumer goods affects apparent consumption estimates in countries that produce and export such goods (e.g., decreasing apparent consumption in country B), or import processed goods (e.g., increasing apparent consumption in countries C and D).

method allows for tracing the origins of a primary commodity—in this case, the country of crop cultivation or the country of livestock rearing—using information on the proportional composition of the supply of trading partners (domestic production and imports). As a result, it quantifies the mix of origins of a primary commodity's apparent consumption in a country. Results can then be used to link resource use at the national level with impacts occurring in specific locations (Chaudhary and Kastner, 2016; Dalin et al., 2017).

'Trade flows' are determined by the spatial patterns of *'production'*, *'processing'* and *'final consumption'* of the primary commodity and the products derived from it at different processing stages. A *'primary commodity'* corresponds to the first tradeable form of a crop or animal product, obtained by applying only basic treatments after harvest or slaughter (e.g., cleaning, drying). *'Processed products'* are derived products resulting from further processing of the primary commodity (e.g., seeds processed into vegetable oil, fibres processed into yarn, tanning of hides into leather), which may involve blending with other materials (e.g., cotton fibre may be blended with one or more other fibres before it is spun into yarn). *'Consumer goods'* are also derived products, but come as marketable items intended for end users, often obtained from combining various processed products derived from different materials (e.g., shoes, furniture, or tyres). The amount of primary commodity that derived products contain (primary content) is commonly expressed in proportion to their weight and decreases through processing stages. Differences in production processes between countries and firms can result in differences in the composition of similar products.

2.2. Calculation steps

Omitting or including trade in derived products affects estimates of the role of countries in the environmental impact associated with the production of a commodity. This effect can be quantified through three calculation steps:

(1) estimate countries' apparent consumption by accounting for trade flows of either (i) primary commodity only, (ii) primary commodity and processed products, or (iii) primary commodity, processed products and consumer goods.
(2) calculate the difference between these apparent consumption estimates. The effect of including trade in processed products on apparent consumption is then indicated by the difference between (ii) and (i), and that of including trade in consumer goods by the difference between (iii) and (ii). The overall effect of the inclusion of trade in derived products is shown by the difference between (iii) and (i).
(3) estimate countries' contribution to environmental impacts. A country's contribution to the environmental impact occurring in a producing country is calculated by multiplying the share of the producing country's total production (of e.g., natural rubber) apparently consumed in the country by an indicator of impact in the producing country (e.g., deforestation caused by natural rubber).

The R code to reproduce the calculation steps of this study is provided at https://zenodo.org/records/11085412.

2.3. Data sources

We decompose the supply chain of natural rubber and bovine hides into four main stages (Fig. 1a). For rubber, the *primary commodity* is natural rubber, harvested in liquid or coagulated (cup lump) forms and centrifuged or cleaned, formed into sheets or blocks, and air-dried near the plantations to reach its first tradeable form (Priel, 2022). It must then undergo a series of processing steps to meet specific uses. Liquid latex is used to manufacture thin rubber items such as pharmaceutical gloves and condoms, or mattresses, while cup lumps are used for tyres and technical rubber items (e.g., tubes, pipes). Natural rubber is usually blended with other ingredients (e.g., synthetic and/or reclaimed rubber and carbon black) to obtain a compound (i.e., *low-processed products*) that meets the technical requirements of end uses. This compound is then eventually combined with other materials (e.g., steel), shaped and vulcanised into *highly processed products* (e.g., tyres) (Priel, 2022). Highly processed products are then marketed to industries to support the manufacturing process (e.g., conveyor belts, tubing), or incorporated into *consumer goods* (e.g., vehicles, textiles, shoes) intended for end users. Some highly processed products are sold to end-users as spare parts (e.g., tires) and some consumer goods serve as inputs to industrial processes (e.g., vehicles). However, the physical trade matrices provided by international organisations (e.g., FAOSTAT, 2024; Comtrade, 2024) do not distinguish between types of consumption users, leaving the potential fates of these products unknown. Our distinction between highly processed products and consumer goods can therefore solely be based on product categories.

For bovine hides, the *primary commodity* is raw hides, cleaned, cured and conserved after the slaughter of the animal. This prevents the hides from decaying, ensuring that they can be safely transported to tanneries, where they are processed into *low processed products* (i.e. wet-blue or tanned hides). During this process, the hides undergo several mechanical and chemical treatments to remove unwanted materials, like keratinous structures and fats. At the end, the hides are treated with mineral tanning agents (mainly salts of chromium) to stabilize collagen fibres. After tanning, hides are rinsed, dried, and eventually split, dyed, or further enhanced (*highly processed products*) (IFC, 2007). The leather produced in this step is finally manufactured into *consumer goods* (e.g. shoes, clothes, bags) intended for end users.

For our assessment of rubber and bovine hides, we focus on the period 2018–2020. We focus our analyses on the EU, i.e. the 27 EU Member States (as of 2024) that are targeted by the EUDR. Results for all countries for the years 2012–2022 are available at https://zenodo.org/records/11085412.

2.3.1. Production data

We use production data from FAOSTAT (2024), the only comprehensive open-access global data source for natural rubber and bovine hides. Production figures for rubber refer to stabilised or concentrated liquid latex and coagulated rubber latex (cup lump) in dry weight, corresponding to 60% of liquid weight. Inconsistent reporting by rubber-producing countries (see Laroche et al., 2021 – Table S8) introduces potential inaccuracies in the FAO rubber production figures that are currently difficult to quantify. For hides, production refers to raw (conserved) hides and skins. We included hides from cattle and buffaloes, as the trade data up until highly processed products explicitly refers to bovine hides and leather, including buffalo hides (See Section 2.3.2). Cattle and buffalo hides account for ~76% of global hide production (FAOSTAT, 2024).

2.3.2. Trade data

We use bilateral trade flow data from the BACI (2024) database which, in contrast with the FAOSTAT (2024) trade database, covers a large number of non-food products at different levels of processing (Table 1 and Table 2). Regarding rubber and leather, FAOSTAT (2024) only covers the primary commodity, i.e. natural rubber under the item codes 836 and 837, and raw hides and skins under the item codes 919 and 957. These codes correspond to the HS 4-digit codes 4001 and 4101 respectively (Tables 1 and 2).

Both FAOSTAT (2024) and BACI (2024) are based on the harmonisation records of the United Nation's Comtrade (2024) database on bilateral import and export flows to eliminate inconsistencies due to differences between countries' currencies and reliability. While BACI (2024) retains the product coverage of the United Nation's Comtrade (2024) database, FAOSTAT (2024) presents a version with harmonized classifications of agricultural and forestry products that are reported based on production numbers.

Table 1
Rubber product categories included in the analysis, listed by corresponding HS 4-digit code, description, and supply chain stage. A detailed list of all 135 products at the HS 6-digit code is provided in the Supplementary materials (Table S1). Product categories marked in **bold** are included in the EUDR (EC, 2023). Product categories marked with an asterisk (*) are included in the trade data from FAOSTAT (2024).

Product category HS 4-digit code	Product category description	Supply chain stage
4001*	**Raw natural rubber**	**Primary commodity**
4005	**Compounded rubber**	**Low processed products**
4006	**Other forms (e.g., camel back)**	**Low processed products**
4007	**Thread, cord**	**Highly processed products**
4008	**Plate, sheets, strip, rods**	**Highly processed products**
4009	**Tubes, pipes, hoses**	**Highly processed products**
4010	**Conveyor, transmission belts, beltings**	**Highly processed products**
4011	**Pneumatic tyres**	**Highly processed products**
4012	**Retreaded or used pneumatic tyres**	**Highly processed products**
4013	**Inner tubes**	**Highly processed products**
4014	Hygienic or pharmaceutical articles	Consumer goods
4015	**Articles of apparel and clothing accessories**	**Consumer goods**
4016	**Other articles (e.g., mats, gaskets)**	**Consumer goods**
4017	**Hard rubber in all forms**	**Highly processed products**
3405	Scouring pastes	Consumer goods
3506	Prepared adhesives	Consumer goods
5604, 5607, 5806, 5906, 5911, 6002, 6113, 6116	Textile with rubber parts	Consumer goods
6401, 6402, 6403, 6404, 6406	Footwear with rubber sole	Consumer goods
6506	Headgear with rubber part	Consumer goods
8701, 8702, 8703, 8704, 8705, 8711, 8712, 8716	Vehicles	Consumer goods
9404	Mattresses made of rubber	Consumer goods
9615	Combs, hair-slides and similar with rubber parts	Consumer goods

Table 2
Bovine hides product categories included in the analysis, listed by corresponding HS 4-digit code, description, and supply chain stage. A detailed list of all 37 products at the HS 6-digit code is provided in the Supplementary materials (Table S2). Product categories marked in **bold** are included in the EUDR (EC, 2023). Product categories marked with an asterisk (*) are included in the trade data from FAOSTAT (2024).

Product category HS 4-digit code	Product category description	Supply chain stage
4101*	**Raw hides and skins**	**Primary commodity**
4104	**Tanned hides**	**Low processed products**
4107	**Leather**	**Highly processed products**
4114, 4115	Leather	Highly processed products
4201	Saddlery and harness	Consumer goods
4202	Cases and handbags	Consumer goods
4203, 4205	Textile containing leather	Consumer goods
6403, 6404, 6405	Footwear containing leather	Consumer goods

The product resolution in BACI (2024) corresponds to the traded good level (HS 6-digit code[2]). We identified a total of 135 traded goods containing 'rubber' in their HS description, belonging to 40 different product categories (HS 4-digit level[1]). We allocate these 40 product categories to the four supply chain stages (Table 1).

We identified 16 traded goods containing either 'bovine hides' or 'bovine leather', as well as 21 traded goods which contain 'leather' in their HS description, but do not specify the animal origin of the primary commodity (i.e. hides). However, as buffalo and cattle hides account for up to 76% of the worldwide produced hides (FAOSTAT, 2024), we assume that at least three-quarters of these traded goods are manufactured from bovine hides. This sums up to a total of 37 traded goods, belonging to 12 product categories (HS 4-digit level). We allocate these 12 product categories to the four supply chain stages (Table 2).

Our approach is flexible in terms of the allocation of the products into different categories. It can be modified to e.g. reflect the inclusion of the products in environmental regulations, thus allowing an exact assessment on the possible benefits of including specific derived products in the scope of such regulations.

2.3.3. Primary commodity content in traded products

The primary content of rubber products is expressed as a proportion of their weight and is assumed to be uniform within a product category (HS 4-digit code[2]), except for categories 4011 and 4012 (tyres). For these product categories, we determine the primary content by product (HS 6-digit code[2]) to account for differences between vehicle types (e.g., passenger cars, trucks). However, potential differences in production processes between countries and firms are not accounted for because such information is not available for global-scale analyses.

Uncertainty about the primary commodity content of products is high and increases along the supply chain, as the number of materials involved increases. For rubber, we used conversion factors from Laroche et al. (2021) as a basis, and contacted an expert working in consultancy (Shaw, 2022) to verify and gain additional insights. We shared the list of product categories (Table 1) with this expert and asked him to indicate a range of potential primary content (natural rubber) of the products (Table S1). For bovine hides, we calculated conversion factors as described in the Supplementary materials, based on the report presented on the mass balance in leather processing by the United Nations Industrial Development Organisation (Buljan et al., 2000), as well as on the information provided by a leather manufacturer regarding ranges in the amount of material needed to produce leather goods (Damm, 2022).

We quantify uncertainties regarding the composition of derived products by calculating results with the mean (Figs. 2, 3 and 4), minimum and maximum conversion factors (Tables S4, S5 and S6).

2.3.4. Deforestation data

We use average figures of forest area lost due to the expansion of natural rubber plantations into forests (gross deforestation) per country and per year from the Deforestation Driver & Carbon Emission (DeDuCE) model (Singh and Persson, 2024a, 2024b), the most comprehensive deforestation attribution dataset currently available. Other estimates of rubber-related deforestation have been derived from spatially explicit approaches but cover a limited number of rubber-producing countries (Table S3).

The DeDuCE model aims to attribute deforestation—the permanent replacement of natural forests by other land-uses—across the globe to commodities produced on expanding croplands, pastures, and forest plantations. It does so by overlaying satellite data on forest loss with maps of specific crops (e.g., soybeans, oil palm, cocoa, and rubber) or of broader land-uses (e.g., croplands, forest plantations, and pastures) or deforestation drivers. Through a procedure that prioritizes data with higher spatiotemporal accuracy and detail, the model identifies where deforestation occurs and attributes this directly to a commodity using spatial data or to a broader land-use (e.g., agriculture or commodity production). Where deforestation cannot be spatially attributed to a specific commodity, the model uses non-spatial agricultural and forestry statistics to assess commodity-driven deforestation in a two-step procedure: first, the deforestation attributed to broad land-uses is further subdivided between cropland, pastures, and forest plantations based on their relative (gross) expansion in a region (typically at country-level); second, deforestation attributed to cropland expansion (either based on cropland maps or statistics) is further allocated between different crop commodities in proportion to their respective increase in harvested area.

For rubber, the model includes maps of plantation extent in eight countries in Southeast Asia in year 2021 from Wang et al. (2023), based on satellite remote sensing data. Together these countries accounted for over 90% of total (globally) estimated rubber deforestation in the period 2001–2022, and thus the data on deforestation embodied in rubber presented here are primarily based on high-resolution spatial data (rather than non-spatial agricultural statistics). Similarly, the estimates of deforestation attributed to leather products below are primarily based on high-resolution maps of pasture extent in in twelve South American countries from MapBiomas Project (2022), that together account for over 80% of estimated global pasture-related deforestation in the same time period.

To attribute deforestation for a given land use—in this case rubber plantations or pastures—to commodities the DeDuCE model uses a 5-year amortization period, reflecting the fact that once land is cleared, it will typically produce commodities over multiple years. In practice, this means that deforestation attributed to rubber or bovine hide production in a given year is an average of the deforestation attributed to the corresponding land-use in the preceding 5 years (see Singh and Persson, 2024b for details). Further, for bovine hides-related deforestation, we need to allocate the deforestation attributed to pasture expansion between meat and hides. We do this by calculating the average mass of produced bovine hides in relation to the average mass of produced beef for the years 2018 to 2020 (FAOSTAT, 2024), which comes down to 11%. This factor is in line with the mass allocation done by Notarnicola et al. (2011), who used a share of 12%. Additionally, we compared these factors with the reported market value of a hide in relationship with the market value of a bovine (e.g. Walker et al., 2013; ICT, 2017; Sothmann, 2021), which ranges from 5 to 15%. Based on this information, we attribute 10% of total pasture expansion deforestation to cattle and buffalo hides.

3. Results

The results below present average figures per year for the EU27, calculated using production, trade, and deforestation data for the period 2018–2020 and mean conversion factors. Additional results using the minimum and maximum conversion factors are available in the Supplementary materials (Tables S4, S5 and S6). Results for all countries for the years 2012–2022 are available at https://zenodo.org/records/11085412. We compare the EU's contribution to total rubber- and bovine hides-related deforestation with that of major producing and consuming countries for each commodity. In this section, when we refer to hides, we are referring solely to bovine hides.

3.1. Apparent consumption

The apparent consumption of both commodities in the European Union varies with the level of inclusion in traded products (Fig. 2).

For natural rubber, trade in the primary commodity is the main channel for it to enter the EU, resulting in the net entry of 1457 thousand

[2] The Harmonized System (HS) is one of the two main international reporting systems for trade statistics. Traded goods are classified using a 6-digit code and grouped into product categories indicated by a 4-digit code, and broad chapters indicated by a 2-digit code.

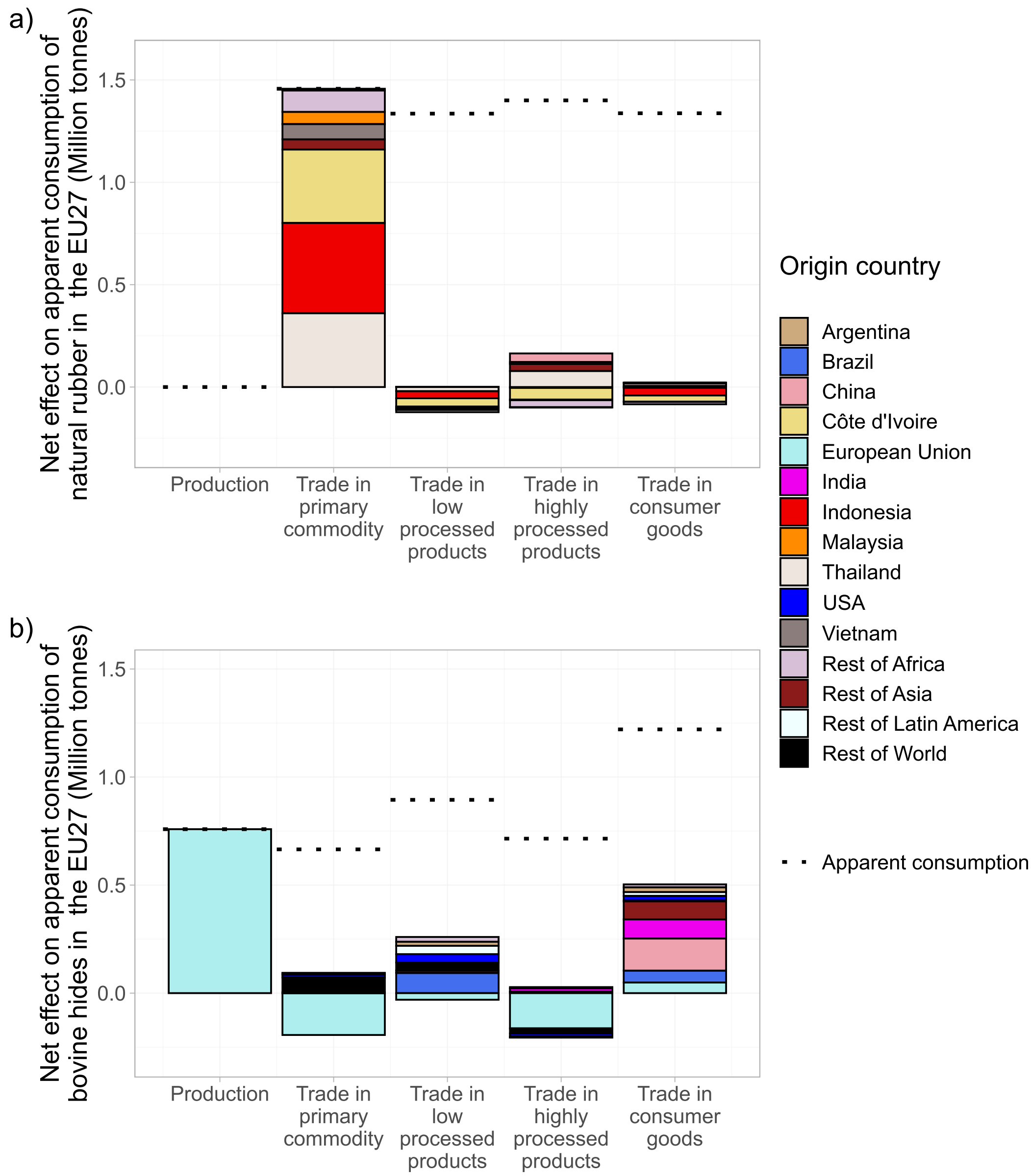

Fig. 2. Net effect of trade in primary commodity and derived products on EU's apparent consumption of a) natural rubber and b) bovine hides from different origins. Dashed lines indicate the EU's total apparent consumption estimates at each processing level and are cumulative, i.e. they include trade in the prior processing levels.

tons of natural rubber into the EU market (Fig. 2a). One-third of this natural rubber originates from Indonesia, 23% from Thailand, 18% from Côte d'Ivoire, and the remaining quarter comes mainly from Vietnam, Malaysia, Nigeria and Cameroon. Including trade in low-processed products (mainly rubber compounds) results in a net decrease of EU apparent consumption, down to 1335 thousand tons. Further including trade in highly processed products leads to a slight net increase in EU apparent consumption of natural rubber from Thailand, China and India, but also to a net decrease of EU apparent consumption of natural rubber from African countries, particularly Côte d'Ivoire. The EU's apparent consumption of natural rubber is then 1400 thousand tons. Finally, including trade in consumer goods causes a net decrease in the EU's apparent consumption of natural rubber, down to 1337 thousand tons. This is 9% lower than the figure obtained when accounting for trade in the primary commodity alone.

For hides, most hides processed in the EU have their origin in countries within the EU, which produce a total of 758 thousand tons of hides (Fig. 2b). Including trade in the primary commodity results in a net decrease of EU apparent consumption, where 193 thousand tons of hides produced in the EU leave the region, resulting in an apparent consumption of 665 thousand tons. Including trade in low processed products (tanned hides) leads to a net increase in EU apparent consumption through hides originating from Latin America, particularly from Brazil and Argentina, as well as from the United States of America (USA) and China. The EU's apparent consumption of hides at this stage is 894 thousand tons. Further including trade in highly processed products (leather) leads to a net decrease in EU apparent consumption of hides from the EU, Brazil, and the USA, and to a slight increase in EU apparent consumption of hides from India. The EU's apparent consumption of hides is then 714 thousand tons. Finally, including trade in consumer goods causes a net increase in the EU's apparent consumption of hides to 1220 thousand tons. One-third of these hides originates directly from the EU, 13% from Brazil, 12% from China, 8% from India, and the remaining third is distributed between Asian and Latin

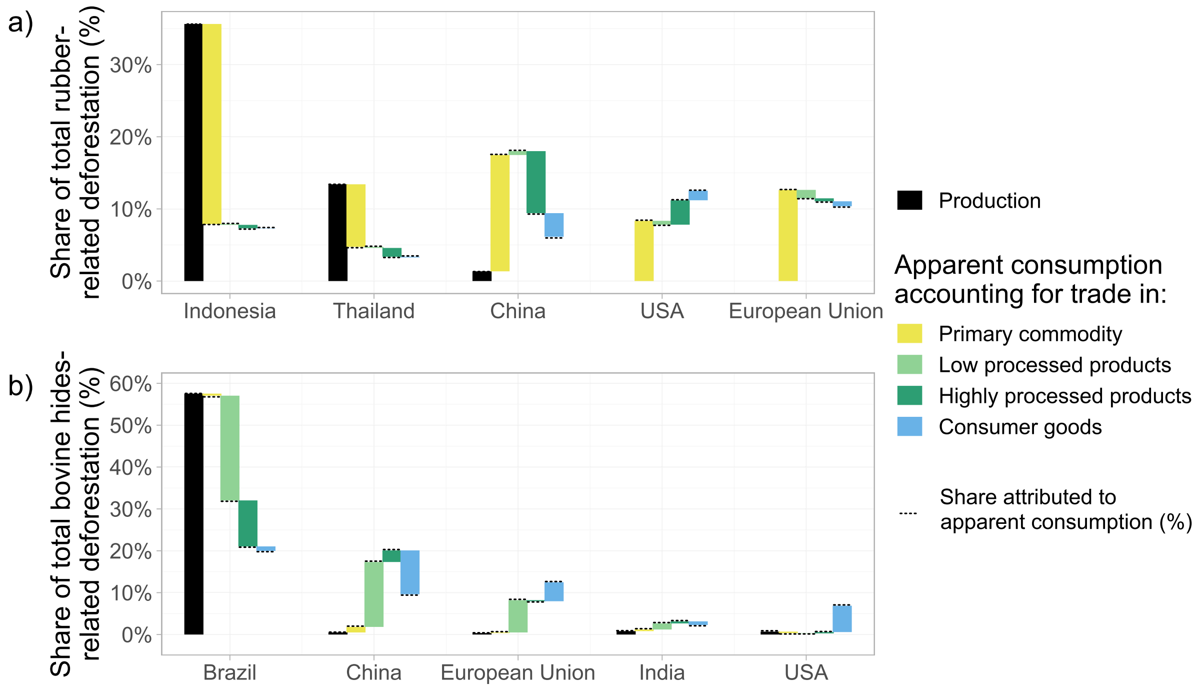

Fig. 3. Share of total deforestation based on production or apparent consumption estimated under different levels of inclusion in traded products. a) Share of rubber-related deforestation attributed to the top two rubber producers (Indonesia and Thailand) and the top three rubber consumers (China, the US, and the EU). b) Share of bovine hides-related deforestation attributed to the top bovine hides producers and consumers (Brazil, China, EU, India, and the USA).

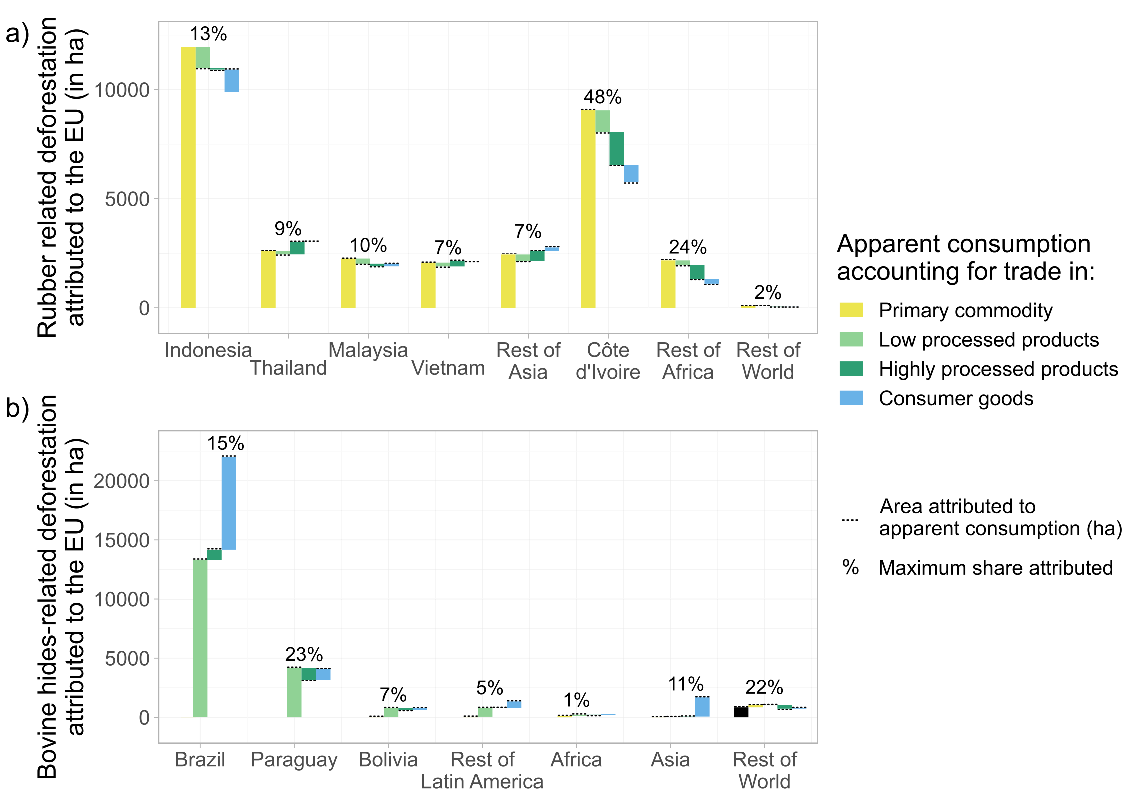

Fig. 4. a) Rubber- and b) bovine hides-related deforestation in specific producing countries attributed to the EU's apparent consumption (in absolute terms) under different levels of inclusion in traded products in absolute and relative terms (maximum value only).

American countries, mostly from Argentina, Pakistan and Bangladesh. The EU's apparent consumption at this stage is 45% higher than the figure obtained when accounting for trade in the primary commodity alone.

For both commodities, applying minimum or maximum conversion factors results in only small differences, lessening or increasing the EU apparent consumption estimates by around 1% (Table S4a and S4b). The difference is slightly larger when looking at the EU's apparent consumption of natural rubber from specific producer countries, but remains small overall (Table S5a and S5b). This indicates that conversion factors are not a large source of uncertainty in the case of the EU, as trade in derived products contributes only marginally to EU net imports of natural rubber. For other countries with other trade structures this might be a larger source of uncertainty.

3.2. Contribution to rubber- and bovine-related deforestation

We estimate that the EU demand for natural rubber is accountable for the loss of ~26,000 to 32,000 ha of forest annually, depending on the inclusion of derived products in the apparent consumption estimate. The share of total rubber-related deforestation attributed to the EU's apparent consumption represents 10 to 12% of total global rubber-related deforestation and varies only slightly with the level of inclusion in traded products (Fig. 3a). In comparison, the share attributed to apparent consumption in the USA increases from 7% to 12%, i.e., by more than a third, when accounting for trade in all rubber derived products, mainly as a result of including trade in consumer goods. China's apparent consumption share is even more sensitive to the inclusion of derived products. It is highest when trade is considered only down to low-processed products (18%) and lowest when trade is considered down to consumer goods (6%), indicating that China's exports of consumer goods are relatively high compared to its imports. The main rubber-producing countries, Indonesia and Thailand, where respectively 35% and 13% of total rubber-related deforestation takes place, are attributed less than 7% of total rubber-related deforestation due to consumption whether or not trade in derived products is accounted for (Fig. 3a, Table S6a).

Furthermore, we estimate that the EU demand for hides is accountable for the loss of ~1200 to 31,000 ha of forest annually, depending on the inclusion of derived products in the apparent consumption estimate. The share of total deforestation attributed to the EU's apparent consumption of hides represents 0.3 to 12% of total global deforestation due to cattle pasture expansion and in contrast to rubber, varies greatly with the level of inclusion in traded products (Fig. 3b, Table S6b). It increases up to 8% when accounting for trade in low processed products and increases again up to 12% when accounting for trade in consumer goods, indicating that EU's imports of consumer goods are relatively high compared to the import of hides in all other processing stages. The share attributed to apparent consumption in the USA is low when accounting for trade in hides, low and highly processed products, but increases from 0.5 to almost 7% when accounting for trade in consumer goods. Similar to the rubber-case, China apparent consumption's share of hides is sensitive to the inclusion of derived products. It is highest when accounting for highly processed products (20%), but already 17% are attributed to low processed products and decreases to 10% when accounting for consumer goods. Although Brazil and India produce relative similar amounts of hides (990 and 934 thousand tons respectively), the share of total deforestation attributed to the production of hides in Brazil accounts for over half of the deforestation attributed to hides production globally (57%), while for India we estimate 0.8% of deforestation due to hides production.

The share of rubber- and hides-related deforestation attributed to the EU's apparent consumption can be much higher than 12% when focusing on specific producing countries and is more sensitive to the level of inclusion in the products traded (Fig. 4).

For rubber, it is particularly high in Côte d'Ivoire (up to 48%), and other African rubber-producing countries when only trade in primary commodity is accounted for. Including trade in derived products results in a decrease of the share attributed to the EU's apparent consumption, reflecting that the EU exports of processed products contain raw natural rubber from Africa. The contribution of the EU's apparent consumption to rubber-related deforestation in Asian producer countries is high in absolute terms, but relatively low compared to other geographies like Africa. It increases a bit with inclusion of derived products in Thailand and Vietnam.

For hides, including trade in derived products results in an increase of the share attributed to the EU's apparent consumption, mostly in Latin American countries, like Paraguay (23%) and Brazil (15%). This increase is highest when accounting for trade in consumer goods. For example, in the case of Brazil, the absolute amount of deforestation due to the EU's apparent consumption of hides goes up to 22,000 ha per year. 7.

4. Discussion

This study extends previous estimates of countries' accountability for the environmental impacts associated with trade and consumption of non-food commodities. We propose an approach using three calculation steps to quantify how estimates of a country's or region's consumption of non-food commodities are affected by the inclusion (or exclusion) of trade in derived products. Ultimately, such assessments can inform the scope of legislation aimed at ensuring due diligence or other restrictions on imports of commodities associated with major environmental impacts. As an example, we explored the case of natural rubber and bovine hides within the scope of the EUDR.

Our results suggest that the inclusion of trade in derived products in the trade model leads to significant changes in the EU's apparent consumption estimates for bovine hides, but not for natural rubber. The EU's apparent consumption of bovine hides increases greatly with the inclusion of trade in derived products, as the EU imports large quantities of leather-based consumer goods (shoes, bags, etc.) that are manufactured elsewhere (Fig. 2). In contrast, the EU's apparent consumption of natural rubber is not very sensitive to trade in derived products, as most of the natural rubber found on the EU market enters through raw rubber imports (Fig. 2).

Accounting for trade in derived products reveals indirect links between the EU and countries that produce the primary commodities, that are missed when only looking at trade in primary products, for both natural rubber and bovine hides. EU imports of natural rubber harvested in China and India only occur at a later stage in the value chain, through imports of highly processed products (Fig. 2). In the case of bovine hides, the EU's link with production in the USA, Latin America and Africa only becomes visible when trade in low-processed products is factored in, and the link with production in China, India and other Asian countries is revealed when trade is considered up to the level of consumer goods (Fig. 2).

Furthermore, estimates of deforestation embodied in EU apparent consumption depend on the geographical location of deforestation risks linked to specific commodities. In the case of bovine hides, the inclusion of trade in low-processed products and consumer goods reveals links with sourcing locations that are hotspots for deforestation linked to cattle farming (i.e. Argentina, Brazil, and Uruguay). As a result, estimates of EU embodied deforestation are increasing (Fig. 3). In the case of natural rubber, China, and India are not hotspots for rubber-related deforestation. Consequently, the link to additional sourcing locations revealed by the inclusion of trade in derived products does not translate into higher estimates of EU embodied deforestation (Fig. 3).

4.1. Implications for the EUDR

The approach presented in this paper can be valuable for increasing the cost effectiveness of policies, like the EUDR. By clarifying the role of

EU's imports of derived products as drivers of deforestation, it can inform the product scope of due diligence legislations. This is important, as the complexity and cost of implementing due diligence increases with the level of processing of commodities (Tuladhar et al., 2024). Scoping out the derived products that do not present a real risk of deforestation may increase the acceptability and cost-effectiveness of the policy.

As the EUDR aims to minimise the EU's contribution to deforestation worldwide (Marín Durán and Scott, 2022), it is crucial that the major parts of EU trade and consumption of commodities driving deforestation are covered by the policy. Our study suggests that the current regulation falls short of this, as some leather and all leather-based products (saddles, bags, textiles, footwear, etc.) are excluded from the scope of application (EC, 2023, Annex I), while being associated with a significant part of the EU's contribution to deforestation risk for leather (Fig. 3). To address a relevant part of the deforestation risk associated with EU demand for leather products, due diligence should be requested on imports of derived products up to the consumer goods. The conclusion is different for natural rubber, as this study suggests that EU's imports of rubber-derived products covered by the legislation (e.g. tires, clothing) carry only a limited risk of deforestation (Fig. 3). Hence, including only raw rubber within the scope of the EUDR could deliver the same outcome in terms of tackling deforestation (EC, 2023).

Implementing the EUDR requires substantial investment from the companies and governments involved in the targeted trade flows (Bager et al., 2021). This investment primarily focuses on establishing and enforcing robust traceability and assurance systems (Gardner et al., 2019). Our observation that minimal quantities of natural rubber enter the EU market through imports of processed products (Fig. 2) suggests that most consumer goods containing rubber circulating in the EU are manufactured domestically. Considering this, it raises the question of whether the EU should prioritize verifying the compliance of raw natural rubber alone, rather than extending controls throughout the downstream agents of the value chain. The resources saved in terms of time, money, and capacity could be redirected towards monitoring retailers' compliance with their imports of leather-based products, as our findings indicate that such products present a risk of being linked to deforestation (Fig. 3).

The EUDR's scope could potentially have an impact on the dynamics of international trade. Limiting due diligence requirements to imports of raw natural rubber could encourage EU operators to shift their imports towards rubber compounds or tyres from regions such as China. EU demand could therefore persist as a driver of deforestation unless all regions of the world do their due diligence on their raw rubber imports (Newig et al., 2020). This scenario does not seem very likely, given that the tyre industries are major players in the EU economy (ERTMA, 2021) and have already made sustainability commitments (GPSNR, 2020, 2022). Conversely, the extension of due diligence mandates to retailers of leather goods could lead to a major shift in sourcing patterns in favour of regions or producers that already have advanced traceability systems. While this may be desirable from a consumption perspective, it could also have detrimental effects by driving sustainability initiatives away from the places with the weakest levels of environmental governance (Gardner et al., 2019).

4.2. Limitations and future research

Although this study presents an empirical case for the EUDR, the results must be considered in light of the uncertainties associated with the input data.

Despite efforts to include the widest range of derived products possible, we acknowledge that our list is not exhaustive. For example, natural rubber is also used for the underside of mats (Evers, 2022) but as 'rubber' does not appear in the corresponding HS description we did not include mats. Nevertheless, as 70–85% of global natural rubber is used in tyres (Millard, 2019), we are confident that we capture most natural rubber flows by including flows of tyres and vehicles. For hides, leather is for example also used as upholstery and as material for vehicle seats, but as 'leather' is not specified in the HS description of these products, we did not include them in the analysis. Yet, the included products account approximately for 78% of traded leather' consumer goods (Jones et al., 2010).

Another large level of uncertainty comes from estimating the amount of – in our case – natural rubber and bovine hides, contained in traded products. While we use a very detail product resolution, spent considerable time finding appropriate factors and perform a sensitivity analysis using minimum and maximum estimates for the content factors (Table S4, S5 and S6), the actual amount of – for instance – natural rubber contained in a pneumatic tyre (ERTMA, 2019) will depend on many factors, including the type of vehicle it is used for and can only be roughly estimated for global level analysis.

Additionally, deforestation associated with rubber and leather production is still highly uncertain. Since 2019, when the cost-benefit analysis was carried out by the European Commission to decide on the scope of the regulation, estimates of rubber-related deforestation have increased 7-fold thanks to the efforts of Wang et al. (2023) to quantify this phenomenon in Southeast Asia using remote sensing data. In the case of leather, the share of deforestation attributed to leather products compared with meat is difficult to establish (see method section) but will have large impact of the results estimate.

Finally, the success of policies like the EUDR depends on many of factors beyond the selection of the commodities covered. Addressing, for instance, societal, economic and land-use issues is crucial for achieving sustainable consumption and production (Warren-Thomas et al., 2023). Future research efforts could explore how these factors can be integrated into policy design and implementation alongside considerations of commodity selection.

5. Conclusion

Governments across the world are increasingly using results from trade-based attribution of environmental impacts to assess their responsibility and design governance approaches. Omitting flows of derived products in trade models may or may not result in considerable impacts being neglected. Quantifying and understanding this effect for specific cases can support the design of effective demand-side policies. The framework and calculation steps presented in this study provide a simple and reproducible tool to evaluate the role of derived products in introducing sustainability risks to markets and to better attribute environmental impacts along supply chains for informing the design of supply-chain measures.

CRediT authorship contribution statement

Perrine C.S.J. Laroche: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Manuela Gómez-Suárez:** Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **U. Martin Persson:** Conceptualization, Methodology, Resources, Writing – review & editing. **Florence Pendrill:** Conceptualization, Formal analysis, Resources, Software, Writing – original draft, Writing – review & editing. **Florian Schwarzmueller:** Formal analysis, Investigation, Writing – review & editing. **Catharina J.E. Schulp:** Funding acquisition, Methodology, Project administration, Writing – review & editing. **Thomas Kastner:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Software, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare no competing interest. This work does not necessarily reflect the view of the EU and in no way anticipates the Commission's future policy.

Data and code availability

All data used in this paper can be found open access online. The code for reproducing the results and figures presented in this study as well as the complete results generated are available at: https://zenodo.org/records/11085412.

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Appendix A. Supplementary data

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References

Arto, I., Cazcarro, I., Garmendia, E., Ruiz, I., Sanz, M.J., 2022. A new accounting framework for assessing forest footprint of nations. Ecol. Econ. 194, 107337 https://doi.org/10.1016/j.ecolecon.2021.107337.

BACI, 2024. International Trade Database at the Product-Level. Retrieved from. http://cepii.fr/cepii/en/bdd_modele/bdd_modele_item.asp?id=37.

Bager, S.L., Persson, U.M., dos Reis, T.N.P., 2021. Eighty-six EU policy options for reducing imported deforestation. One Earth 4 (2), 289–306. https://doi.org/10.1016/J.ONEEAR.2021.01.011/ATTACHMENT/DD03AD45-6FB0-4F9E-B187-683F5336B815/MMC1.PDF.

Bruckner, M., Giljum, S., Fischer, G., Tramberend, S., 2014. Review of Land Flow Accounting Methodologies and Recommendations for Further Development, March, pp. 1–58.

Bruckner, M., Wood, R., Moran, D., Kuschnig, N., Wieland, H., Maus, V., Bö, J., 2019. FABIO: the construction of the food and agriculture biomass input−output model. Environ. Sci. Technol. 53, 11302–11312. https://doi.org/10.1021/acs.est.9b03554.

Buljan, J., Reich, G., Ludvik, J., 2000. Mass Balance in Leather Processing. United Nations Industrial Development Organization. Retrieved from. https://www.unido.org/sites/default/files/2009-05/Mass_balance_in_leather_processing_0.pdf.

Chaudhary, A., Kastner, T., 2016. Land use biodiversity impacts embodied in international food trade. Glob. Environ. Chang. 38, 195–204. https://doi.org/10.1016/j.gloenvcha.2016.03.013.

COCERAL, FEDIOL & FEFAC, 2021. Mandatory Due Diligence as a part of the Smart Mix of EU Measures to tackle Deforestation and Human Rights Issues. Retrieved from. https://www.coceral.com/data/162192986321ENV047%20COCERAL-FEDIOL-FEFAC_Due%20Diligence%20position_210423.pdf.

Comtrade, 2024. International Trade Statistics Database. Retrieved from. https://comtrade.un.org/.

COWI, 2018. Feasibility Study on Options to Step up EU Action against Deforestation. https://doi.org/10.2779/97793.

Dalin, C., Wada, Y., Kastner, T., Puma, M.J., 2017. Groundwater depletion embedded in international food trade. Nature 543 (7647), 700–704. https://doi.org/10.1038/nature21403.

Damm, D., 2022. Leather Atelier. Personal Communication. https://danieladamm.de/home/.

EC, 2020. Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability. Retrieved from. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0474&from=EN.

EC, 2021. Impact Assessment: Minimising the Risk of Deforestation and Forest Degradation Associated with Products Placed on the EU Market. Retrieved from. https://ec.europa.eu/environment/system/files/2021-11/SWD_2021_326_1_EN_impact_assessment_part1_v4.pdf.

EC, 2023. Regulation (EU) 2023/1115 of the European Parliament and of the Council of 31 May 2023 on the making available on the Union market and the export from the Union of certain commodities and products associated with deforestation and forest degradation and repealing Regulation (EU) No 995/2010. Retrieved from. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32023R1115.

ERTMA, 2019. Natural Rubber Supply Chain. Retrieved from. https://www.etrma.org/natural-rubber-supply-chain/.

ERTMA, 2021. The European Tyre and Rubber Industry Statistics Report. Retrieved from. https://www.etrma.org/wp-content/uploads/2021/11/20211030-Statistics-booklet-2021VF.pdf.

Evers, H., 2022. Sustainability Manager at Weber & Schaer. Retrieved from. https://www.weber-schaer.com/english/products/natural-rubber-latex/sustainability.html.

FAOSTAT, 2024. FAO Statistical Database. Retrieved from. http://www.fao.org/faostat/en/#home.

Gardner, T.A., Benzie, M., Börner, J., Dawkins, E., Fick, S., Garrett, R., Wolvekamp, P., 2019. Transparency and sustainability in global commodity supply chains. World Dev. 121, 163–177. https://doi.org/10.1016/J.WORLDDEV.2018.05.025.

Gerber, P.J., Mottet, A., Opio, C.I., Falcucci, A., Teillard, F., 2015. Environmental impacts of beef production: review of challenges and perspectives for durability. Meat Sci. 109, 2–12. https://doi.org/10.1016/j.meatsci.2015.05.013.

GPSNR, 2020. GPSNR Policy Framework for Sustainable Natural Rubber Production and Sourcing. Retrieved from. https://rubberplatform.sharepoint.com/sites/GPSNRMembers/SharedDocuments/Forms/AllItems.aspx?id=%252Fsites%252FGPSNRMembers%252FSharedDocuments%252FOld%252F04_MembershipRequirements%252FGPSNRPolicyFramework.pdf&parent=%252Fsites%252FGPSNRMembers%252FSharedDocuments%252.

GPSNR, 2022. Global Platform for Sustainable Natural Rubber. Retrieved from. https://sustainablenaturalrubber.org/.

Hubacek, K., Feng, K., 2016. Comparing apples and oranges: some confusion about using and interpreting physical trade matrices versus multi-regional input-output analysis. Land Use Policy 50, 194–201. https://doi.org/10.1016/j.landusepol.2015.09.022.

ICT, 2017. World Leather Congress. Retrieved from: https://web.archive.org/web/20180804104737/http:/www.leathercouncil.org/introtoleather.htm.

IFC, 2007. Environmental, Health, and Safety Guidelines for Tanning and Leather Finishing. Retrieved from, World Bank Group. http://documents.worldbank.org/curated/en/874161491555046600/Environmental-health-and-safety-guidelines-for-tanning-and-leather-finishing.

Jones, B., Redwood, M., Sinturel, P., 2010. The Future Trends and Expected Status of the World Leather and Leather Products Industry and Trade. United Nations Industrial Development Organization. Retrieved from. https://downloads.unido.org/ot/26/09/26092957/FutureTrends_b.pdf.

Kastner, T., Kastner, M., Nonhebel, S., 2011. Tracing distant environmental impacts of agricultural products from a consumer perspective. Ecol. Econ. 70 (6), 1032–1040. https://doi.org/10.1016/j.ecolecon.2011.01.012.

Kitzes, J., Galli, A., Bagliani, M., Barrett, J., Dige, G., Ede, S., Wiedmann, T., 2009. A research agenda for improving national ecological footprint accounts. Ecol. Econ. 68 (7), 1991–2007. https://doi.org/10.1016/j.ecolecon.2008.06.022.

Kristensen, T., Aaes, O., Weisbjerg, M.R., 2015. Production and environmental impact of dairy cattle production in Denmark 1900–2010. Livest. Sci. 178, 306–312. https://doi.org/10.1016/j.livsci.2015.06.012.

Laroche, P., Schulp, C., Kastner, T., Verburg, P., 2021. Assessing the contribution of mobility in the European Union to natural rubber expansion. Ambio 51, 770–783. https://doi.org/10.1007/s13280-021-01579-x.

Leontief, W.W., 1936. Quantitative input and output relations in the economic systems of the United States. Rev. Econ. Stat. 18 (3), 105–125. https://doi.org/10.2307/1927837.

MapBiomas Project, 2022. Annual Series of Land Use and Land Cover Maps of Brazil. retrieved from. https://brasil.mapbiomas.org/en/.

Marín Durán, G., Scott, J., 2022. Regulating trade in forest-risk commodities: two cheers for the European union. J. Environ. Law 34 (2), 245–267. https://doi.org/10.1093/jel/eqac002.

Millard, E., 2019. Recent experiences from the natural rubber industry and its movement towards sustainability. In: Schmidt, M., Giovannucci, D., Palekhov, D., Hansmann, B. (Eds.), Sustainable Global Value Chains, 1st ed. Springer International Publishing, pp. 499–520. https://doi.org/10.1007/978-3-319-14877-9_27.

Miller, R.E., Blair, P.D., 2009. Input-Output Analysis: Foundations and Extensions, 3rd ed. Cambridge University Press, Cambridge. Retrieved from. https://books.google.nl/books/about/Input_Output_Analysis.html?id=viHaAgAAQBAJ&redir_esc=y.

Moran, D., Wood, R., Hertwich, E., Mattson, K., Rodriguez, J.F.D., Schanes, K., Barrett, J., 2020. Quantifying the potential for consumer-oriented policy to reduce European and foreign carbon emissions. Clim. Pol. 20 (sup1), S28–S38. https://doi.org/10.1080/14693062.2018.1551186.

Munroe, D.K., Batistella, M., Friis, C., Gasparri, N.I., Lambin, E.F., Liu, J., Nielsen, J.Ø., 2019. Governing flows in telecoupled land systems. Curr. Opin. Environ. Sustain. 38 (January), 53–59. https://doi.org/10.1016/j.cosust.2019.05.004.

Newig, J., Lenschow, A., Challies, E., Cotta, B., Schilling-Vacaflor, A., 2019. What is governance in global telecoupling? Ecol. Soc. 24 (3) https://doi.org/10.5751/ES-11178-240326.

Newig, J., Challies, E., Cotta, B., Lenschow, A., Schilling-Vacaflor, A., 2020. Governing global telecoupling toward environmental sustainability. Ecol. Soc. 25 (4) https://doi.org/10.5751/ES-11844-250421.

Notarnicola, B., Puig, R., Raggi, A., Fullana i Palmer, P., Tassielli, G., De Camillis, C., Mongelli, I., Rius Carrasco, A., 2011. Life Cycle Assessment of Italian and Spanish Bovine Leather Production Systems. Retrieved from. https://repositori.udl.cat/server/api/core/bitstreams/ef613928-30b8-4e26-8d14-22e09116d215/content.

Pendrill, F., Persson, M., Godar, J., Kastner, T., Moran, D., Schmidt, S., Wood, R., 2019. Agricultural and forestry trade drives large share of tropical deforestation emissions. Glob. Environ. Chang. 56 (February), 1–10. https://doi.org/10.1016/j.gloenvcha.2019.03.002.

Pendrill, F., Gardner, T.A., Meyfroidt, P., Persson, U.M., Adams, J., Azevedo, T., West, C., 2022. Disentangling the numbers behind agriculture-driven tropical deforestation. Science 377 (6611). https://doi.org/10.1126/science.abm9267.

Priel, L., 2022. Head of Rubber Projects at Einhorn. Retrieved from. https://einhorn.my/einhoerner-about-us/.

Shaw, D., 2022. Chief Executive of Tire Industry Research. Personal Communication. https://tireindustryresearch.com/news/.

Singh, C., Persson, U.M., 2024a. DeDuCE: agriculture and forestry-driven deforestation and associated carbon emissions from 2001-2022 (1.0.0) [data set]. Zenodo. https://doi.org/10.5281/zenodo.10674962.

Singh, C., Persson, U.M., 2024b. Global patterns of commodity-driven deforestation and associated carbon emissions. Preprint Earth ArXiv. https://doi.org/10.31223/X5T69B.

Sothmann, S. (2021). Hide economics: Leather's status as a byproduct. Leather & Hide Council of America. Retrieved from https://www.usleather.org/press/Hide-Economics-Leather-Status-as-Byproduct.

Tuladhar, A., Rogerson, M., Engelhart, J., Parry, G.C., Altrichter, B., 2024. Blockchain for compliance: an information processing case study of mandatory supply chain transparency in conflict minerals sourcing. Supply Chain Manag. https://doi.org/10.1108/SCM-11-2023-0585.

UN, 2016. Definition "Apparent Consumption" in the United Nations Environment Glossary. Retrieved October 27, 2022, from. https://unstats.un.org/unsd/environmentgl/gesform.asp?getitem=116.

Walker, N.F., Patel, S.A., Kalif, K.A.B., 2013. From Amazon pasture to the high street: deforestation and the Brazilian cattle product supply chain. Tropic. Conserv. Sci. 6 (3), 446–467. https://doi.org/10.1177/194008291300600309.

Wang, Y., Hollingsworth, P.M., Zhai, D., West, C.D., Green, J.M., Chen, H., Hurni, K., Su, Y., Warren-Thomas, E., Xu, J., Ahrends, A., 2023. High-resolution maps show that rubber causes substantial deforestation. Nature 623 (7986), 340–346. https://doi.org/10.1038/s41586-023-06642-z.

Warren-Thomas, E., Ahrends, A., Wang, Y., Wang, M.M., Jones, J.P., 2023. Rubber's inclusion in zero-deforestation legislation is necessary but not sufficient to reduce impacts on biodiversity. Conserv. Lett. 16 (5), e12967 https://doi.org/10.1111/conl.12967.

West, C., Croft, S., Titley, M., Ebrey, R., Gollub, E., Simpson, J., Smythe, J., 2022. Assessing tropical deforestation in Germany's agricultural commodity supply chains Intelligence for sustainable trade. https://doi.org/10.48650/PV1P-Q331.

Wiedmann, T., Lenzen, M., 2018. Environmental and social footprints of international trade. Nat. Geosci. 11 (5), 314–321. https://doi.org/10.1038/s41561-018-0113-9.