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Carbon Bias of Tariffs: Are Fossil fuels the Culprits?

Cecilia Bellora, Lionel Fontagné, Christophe Gouel & Youssef Salib

Highlights

- The study finds that the magnitude of the "carbon bias" in tariffs –where carbon-intensive goods face lower trade barriers– is significantly smaller than previously estimated, largely because high tariffs in agriculture counterbalance the under-taxation of fossil fuels when accounting for all greenhouse gases.
- Fossil fuels stand out as the main source of bias because of their consistently low tariffs, yet this effect almost disappears when the model includes natural resource constraints on fossil fuel extraction.
- In non-fossil-producing countries, significant domestic fuel taxes already act much like tariffs, reversing the apparent bias of undervalued fossil fuels.
- Given these findings, policy reforms aimed at harmonizing protection across sectors would have modest, if not negative, global climate benefits.

Abstract

This paper revisits the existence of a carbon bias in trade policies, where emissions-intensive sectors receive lower trade protection than cleaner sectors. Using a stylized general equilibrium model that accounts for greenhouse gas emissions, we confirm the presence of a carbon bias but find it to be significantly smaller than previously estimated. Our analysis reveals that this bias is primarily driven by low tariffs on fossil fuels, particularly crude oil. Incorporating the finite nature of fossil fuel resources into the model reduces the responsiveness of fossil fuel production to tariff changes, effectively neutralizing the carbon bias. Furthermore, when accounting for domestic consumption taxes on fossil fuels in non-producing countries –which act as de facto tariffs– the bias shifts toward a pro-environmental stance. These findings underscore the importance of integrating energy markets' specificities and domestic distortions into trade models to better account for the impact of trade policies on the environment.

Keywords

Fossil Fuels, Greenhouse Gases, International Trade, Tariffs.

JEL

F13, F18, Q40, Q56.

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Centre d'études prospectives
et d'informations internationales
20, avenue de Ségur
TSA 10726
75334 Paris Cedex 07

contact@cepii.fr
www.cepii.fr – @CEPII_Paris
Press contact: presse@cepii.fr

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RESEARCH AND EXPERTISE
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Carbon bias of tariffs: Are fossil fuels the culprits?[1]

Cecilia Bellora,[*] Lionel Fontagné,[†] Christophe Gouel,[‡] and Youssef Salib[§]

1. Introduction

The impact of trade on greenhouse gas (GHG) emissions is typically analyzed through scale, technique, and composition effects (Copeland and Taylor, 1994; Grossman and Krueger, 1994; Copeland et al., 2022). Among these, composition effects—which describe how trade redistributes resources between low- and high-emission industries—are particularly relevant for climate policy. The extent to which trade policies influence this allocation depends on the level and sectoral variation of trade protection in importing countries. In a world with uniform carbon pricing,[2] tariff structures would not affect GHG emissions. However, in reality, both carbon prices and tariff structures vary across sectors and countries, potentially amplifying or mitigating emissions by incentivizing trade in cleaner or dirtier goods. One key feature of trade policy that may contribute to higher emissions is what Shapiro (2021) calls the "environmental bias of trade policies"—where emissions-intensive sectors face lower trade protection. This bias can be attributed to tariff escalation (Antràs and Chor, 2022), a tariff structure in which upstream goods—typically more emission-intensive—are taxed less than downstream products to protect domestic value-added industries (Corden, 1966).

This paper investigates whether current trade policies lead to higher GHG emissions compared to a scenario where tariff structures are harmonized across sectors (where each importer applies the same trade policy across sectors, though not necessarily across partners). Analyzing this requires understanding how tariffs influence trade composition, particularly for emission-intensive industries such as fossil fuels, brown industries, and agriculture. To answer this question meaningfully, however, two key complexities must be considered. First, trade policies do not operate in isolation. Domestic policies, such as taxes on fossil fuel consumption, can counteract or reinforce the effects of tariff structures. For instance, high domestic fuel taxes in importing countries may offset the emissions impact of low fossil fuel tariffs. Second, GHG emissions extend beyond

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[*] CEPII: cecilia.bellora@cepii
[†] PSE: lionel.fontagne@psemail.eu
[‡] INRAE and CEPII: christophe.gouel@inrae.fr
[§] PSE and Ecole des Ponts: youssef.salib@psemail.eu

[2] In this paper, we use the term carbon loosely to designate all greenhouse gases, not just those that are carbon-based.

CO_2. While carbon dioxide is the most studied, methane and nitrous oxide—particularly from agriculture—are also major contributors to global warming. Any meaningful assessment of trade-related carbon bias must account for the full range of GHGs and the distinct emissions profiles of different sectors.

The conjunction of two unrelated sources of heterogeneity—emission intensity and border protection—makes it difficult to predict the overall direction of a potential bias in trade policy. Similarly, domestic taxation and additional GHGs can either amplify, counteract or reverse the intuitive relationship between tariff structures and their impact on GHG emissions. To address these complexities, a general equilibrium model of the world economy is required, one that incorporates GHG emissions and inter-regional input-output relationships. We employ a variant of the standard quantitative trade model developed by Caliendo and Parro (2015), which is also adopted by Shapiro (2021). We extend this model to include GHG emissions, considering both CO_2 emissions from fossil fuel combustion, as analyzed by Shapiro, and other GHGs. Additionally, our model takes into account that fossil fuel production requires sector-specific factors, as highlighted by Baqaee and Farhi (2024). It further incorporates domestic taxation of fossil fuels in importing countries, integrating both border policies (tariffs) and behind-the-border fiscal measures (taxes), which together influence the environmental outcomes of trade.

The model is calibrated using several data sources: trade, input-output, and GHG emissions data from EXIOBASE; bilateral applied tariff data from Market Access Map (MAcMap-HS6); fossil fuel production data from the International Energy Agency; and Net Effective Carbon Rates from the OECD. These diverse datasets allow us to capture the complex inter-sectoral and international relationships that influence GHG emissions. Although our analysis focuses on 2019, our data span the period from 2007 to 2019, which we use for robustness checks. The data indicate that emission intensity is highest in fossil extraction and brown industries for CO_2, and in fossil extraction and agriculture for other GHGs. Regarding the pattern of applied tariffs, the low average protection for fossil fuels and the high protection for agriculture suggest significant effects are likely when harmonizing tariffs across sectors.

Using our model to simulate the harmonization of tariffs across sectors, we assess the overall impact on global GHG emissions, considering both CO_2 and non-CO_2 GHGs. Our results confirm the existence of a carbon bias in tariffs: implementing a uniform tariff across sectors would reduce global GHG emissions, indicating that current tariff structures favor high-emission goods. However, we find that the magnitude of this bias is smaller than previously reported and is largely driven by low tariffs on fossil fuels, particularly crude oil. Meanwhile, other carbon-intensive industries have a negligible or positive impact. To better understand the contribution of fossil fuels to this bias, we explore two alternative extensions. First, by extending the quantitative model to consider the limited availability of natural resources required for fossil fuel extraction, we find the bias shifts close to zero. Second, we argue that domestic taxes on fossil fuels in non-producing countries are equivalent to tariffs. When these taxes—which, on average, are quite high in fossil fuel-importing countries—are accounted for, the bias reverses. Overall, the small size and high sensitivity of the carbon bias suggest that harmonizing tariffs across sectors may not be a priority for climate policy, unlike taxing fossil fuel consumption (or closing other tax loopholes with environmental repercussions, as highlighted by Iovino et al., 2023).

This paper builds on a growing body of research examining how trade policies impact environmental outcomes, especially GHG emissions. While our analysis primarily focuses on the carbon bias of trade policies, this issue fits within a broader literature on the relationship between trade policy and sector-specific emissions. One area of significant attention is the interaction between trade policies and agricultural emissions. This body of work provides important insights into how trade protection and subsidies affect emissions in agriculture, a sector responsible for approximately one-third of global GHG emissions (Crippa et al., 2021). Most studies on agriculture emphasize the sector's high border protection and significant non-CO_2 emissions, highlighting its crucial role in shaping trade-related emissions (Laborde et al., 2021; Guerrero et al., 2022). Our paper contributes to this broader literature by demonstrating that trade policies applied to the agricultural sector are the second-largest driver of the environmental bias in trade policies, with fossil fuel extraction being the largest. Although both sectors are emission-intensive, the agricultural sector tends to be highly protected, whereas the fossil fuels sector has minimal protection. This contrasting protection structure results in opposite changes in emissions when tariffs are harmonized across sectors: an increase for agricultural products and a decrease for fossil fuels.

Another relevant strand of literature explores the optimal taxation of fossil fuels, particularly in the context of international trade. Since the 1960s, studies have examined tariffs as a tool to capture rents from fossil fuel producers, often in the face of imperfect competition (Johnson, 1968; Dixit, 1984; Karp, 1984; Jones and Takemori, 1989). More recently, Rubio (2011) extended this line of research to account for the finite nature of fossil resources. This discussion has gained renewed attention in light of EU sanctions on Russia. Rent-extracting tariffs on fossil fuel imports have been promoted as a way to reduce reliance on Russian energy while mitigating the economic impact on the EU (Gros, 2022a,b; Ockenfels et al., 2022). Additionally, Tahvonen (1995) and others have explored how tariffs can reduce fossil fuel consumption while addressing environmental externalities. Thus, tariffs on fossil fuels resemble carbon taxes in their potential to influence both rent extraction and environmental outcomes—an insight we use in this paper.

Closer to our study, Shapiro (2021), Klotz and Sharma (2023), and Moreira and Dolabella (2024) investigate the existence of an environmental bias in trade policies. Shapiro (2021) addresses this question using two approaches. The first approach employs statistical methods to identify stylized facts about the relationship between trade barriers and emission intensity, while the second uses modeling to quantify the emissions-related implications of removing the identified bias. In his econometric analysis, Shapiro (2021) finds that in 2007, trade protection was lower for dirtier goods, implying that harmonizing tariffs could reduce CO_2 emissions from fossil fuel combustion. Moreira and Dolabella (2024) apply a similar statistical approach, focusing on Latin America and the Caribbean. They extend Shapiro's econometric analysis by including all GHGs, as well as the agriculture and mining sectors. Their findings indicate that the bias is highly heterogeneous across countries, partly because they account for non-fossil fuel emissions. On the other hand, Klotz and Sharma (2023) adopt a modeling analysis focusing specifically on CO_2 emissions from fossil fuel combustion. They find the effect of the tariff bias on emissions to be six times smaller than that reported by Shapiro (2021). However, due to differences in modeling approaches and data, the origin of these discrepancies remains unclear. In this paper, we differ from Shapiro by using updated protection and input-output data from 2019 instead of 2007, and by considering a broader set of GHGs, along with a more detailed regional and sectoral aggregation. We strive to minimize these departures to precisely identify which choices account for any differences in results (see Appendix B).

Importantly, we focus solely on the carbon bias of tariffs, excluding non-tariff measures (NTMs) from our analysis. Although NTMs can represent significant trade barriers, analyzing their potential environmental bias is challenging. First, the heterogeneity of NTMs across sectors makes it difficult to compare their ad valorem equivalents meaningfully. Different types of measures—such as pesticide maximum residue levels and automotive industry standards—operate under fundamentally distinct regulatory logics that resist straightforward harmonization. Second, even if NTMs restrict trade by imposing standards that may be too stringent for some producers, it does not necessarily imply a reduction in welfare, particularly if these standards prevent the export of potentially harmful products (Disdier and Marette, 2010). Therefore, we refrain from considering these barriers in our analysis, as the cross-sectoral standardization of NTMs could introduce unintended risks to public health.

The rest of the paper proceeds as follows. Section 2 introduces the data and presents key stylized facts on trade protection and GHG emissions. Section 3 outlines the quantitative trade model used for the analysis. Section 4 presents the simulation results, highlighting the contribution of different sectors to the carbon bias. Section 5 explores two model extensions to refine the role of fossil fuels. Finally, section 6 concludes.

2. Data and stylized facts

2.1. Data

To generate the stylized facts in the next section and to calibrate the models presented in subsequent sections, we use three main data sources. Trade data are obtained from the EXIOBASE world input-output table version 3.8.2 (Stadler et al., 2018), which represents the global economy with 43 countries, 5 rest-of-the-world aggregates, 163 industries, and 7 final use sectors. Data are available for all years from 1995 to 2021, with projections or provisional estimates for years after 2015. For computational purposes, we aggregate EXIOBASE into 23 regions and 47 industries (see Appendix D).[3]

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[3] To ensure exact replication of Shapiro's (2021) results in Appendix B, we also use the same aggregation scheme with 10 regions and 21 industries.

Additionally, all emission data from sources other than fossil fuel combustion (e.g., other CO_2 emissions[4] and non-CO_2 emissions[5]) come from EXIOBASE satellite data, which exclude emissions associated with land-use changes. Non-CO_2 emissions are converted to CO_2-equivalents (CO_2eq) using global warming potentials with a 100-year time horizon from the IPCC Sixth Assessment Report (2023).

Tariff data is sourced from the Market Access Map HS6 (MAcMap-HS6) database developed at CEPII (Guimbard et al., 2012) based on raw data provided by ITC (UNCTAD-WTO). MAcMap-HS6 provides ad valorem tariffs for bilateral trade flows for virtually all countries at the Harmonized System (HS) 6-digit level. We use the version of MAcMap-HS6 that is used to estimate trade elasticities in Fontagné et al. (2022). In this version, the protection provided by tariff rate quotas is represented by the outside rate. We average the tariffs, using trade weights, to obtain ad valorem tariff equivalents at the EXIOBASE country and sectoral level. Since only the years 2007, 2010, 2013, 2016, and 2019 are available in MAcMap-HS6, we linearly interpolate to obtain the other years.

Our third main source of data is the International Energy Agency (IEA). We use IEA fossil production data (IEA, 2022) to calculate the quantities of fossil fuels (primary coal, primary oil, and natural gas) extracted in each country. Using emission factors from the Emission Factor Database (EFDB) from IPCC (2021), we calculated the CO_2 embedded in fossil fuel production. Fossil CO_2 emissions are thus tracked from the point of their extraction, a methodological choice (identical to Shapiro, 2021) that will be explained in section 3.3.

Beyond the three main data sources listed above, we use a few others. We use the same trade elasticities as in Shapiro (2021). Since our sectoral aggregation implies more sectors than in Shapiro (2021), we keep the same trade elasticities but apply them to the more detailed sectors. In the extension presented in section 5.1, we use data from GTAP (Aguiar et al., 2022) on the share of the natural resource rents in the production cost of fossil fuel extraction. In section 5.2 for complementary analysis, we use OECD Net Effective Carbon Rates (OECD, 2022) and BP Statistical Review of World Energy (BP, 2020).

2.2. Stylized facts

In this subsection, we provide some stylized facts. They cannot replace the model's results, as they are very stylized, aggregated at the world level, and neglect equilibrium effects. However, they are useful for gaining an intuitive understanding of the potential environmental bias of trade policies and the associated impact of tariff harmonization. By harmonization, we mean that each country establishes, for each trade partner, only one tariff value for all sectors (by taking the trade-weighted average of former values). The mathematical formalism will be introduced in

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[4] Cement and lime production processes, peat decay, and waste.

[5] Excluding the emissions associated with land-use changes, the coverage of GHG emissions is comprehensive, encompassing CH_4, HFCs, PFCs, N_2O, and SF_6.

section 4.

To simplify the presentation, we have grouped all sectors into five: Agriculture, Fossil Extraction, Brown Industries, Manufacturing n.e.s., and Services. The composition of these five sectors in relation to EXIOBASE sectors is given in Appendix D. Importantly, the Fossil Extraction sector contains only sub-sectors extracting fossils from the ground and excludes sectors refining fossils. Refining sectors are in the Brown Industries category. This distinction is important because tariffs on refined fossils can be high, while they are usually very low or even absent on crude oil and gas. Moreover, fossils refined locally do not need natural resources to be produced but are dependent on the availability of crude fossils.[6] Following a trade policy logic, services are defined as the sectors that are not covered by the Harmonized System of the World Customs Organization, which means that they include some brown industries such as construction and transport.[7]

2.2.1. Sectoral trade exposure and tariff structure

Understanding the distribution of trade exposure and tariff protection across sectors is crucial for assessing the environmental bias in trade policy. Since tariffs influence sectoral resource allocation, they can either reinforce or counteract emissions incentives embedded in trade flows. Varying levels of trade exposure interact with the different tariff structures applied to each sector, creating potential environmental implications. In this section, we categorize sectors based on their trade exposure and tariff protection levels, setting the stage for analyzing the potential emissions impact of trade policy reform.

Trade exposure and sectoral share Sectors vary significantly in their exposure to international trade, shaping the extent to which tariff structures influence emissions. For coherent comparisons, we compare imports with aggregate supply, as imports are often reused in downstream products. We also use aggregate supply to account for sectors that are used mainly as intermediate consumption but play an important role in value chains. Table 1 provides an overview of imports as a percentage of aggregate supply across five broad sectoral categories. Fossil Extraction is the most trade-exposed, with 47% of its production being internationally traded, making it particularly sensitive to tariff changes. Manufacturing n.e.s. follows, with 29% of its supply imported, accounting for 39% of total imports. Brown Industries, which include emissions-intensive sectors such as chemicals and metals, exhibit a similar degree of trade exposure, with 25% of their aggregate supply imported. In contrast, Agriculture remains relatively shielded from trade, with imports making up only 13% of its supply. While trade exposure determines how much a sector is affected by tariff changes, its role in shaping emissions also depends on initial tariff levels and emission intensity, two points we address below.

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[6] This will be especially relevant for a model extension analyzed in section 5.1.

[7] We classify the Electricity sector in services, despite the existence of an HS code (271600) for this sector, because this heading is optional and trade in electricity is generally covered by special arrangements that do not involve tariffs.

Table 1 – 2019 descriptive trade statistics

Sector	Imports % in sector aggregate supply	Sector % in total aggregate supply	Sector % in total import	Average tariff (%)
Agriculture	13.5	3.5	3.9	6.8
Fossil Extraction	47.1	1.5	5.9	0.3
Brown Industries	25.1	15.3	31.5	1.9
Manufacturing n.e.s.	28.6	16.7	39.1	3.0
Services	3.8	63.0	19.5	0

Sources: EXIOBASE and MAcMap-HS6.

Tariff structure These varying levels of trade exposure interact with the different tariff structures applied to each sector, creating potential environmental implications. Overall, the trade-weighted average tariff in 2019 is 2.6%. Among sectors, Agriculture faces the highest average tariff (6.8%), reflecting longstanding protectionist policies. In contrast, Fossil Extraction faces virtually no tariffs (except for coal in some countries), despite being the ultimate source of all CO_2 emissions from fossil combustion. Brown Industries and Manufacturing n.e.s. are subject to moderate tariffs, close to the global average, especially for Manufacturing n.e.s.

2.2.2. Emission intensity across sectors

The final important parameter in the decomposition of the impact of tariff policy on emissions is the carbon content of the sectors. Sectors are not only very heterogeneous in tariffs but also very heterogeneous in their carbon emissions. Because of our focus here on emissions associated with production, the statistics displayed in this subsection exclude those emitted at the time of final consumption.

We distinguish CO_2 emissions from fossil fuel combustion from other GHG emissions (CO_2 emissions from processes and emissions of other GHGs). If we consider CO_2 emissions from fossil fuel combustion, table 2 shows first that Fossil Extraction is the most emissive sector per EUR of output, followed by Brown Industries.[8] Agriculture, other manufacturing industries, and Services display much lower CO_2 emission intensities. Second, Services are responsible for more than half of the emissions. This is because of the large economic size of this aggregate, which includes, in our setup, emission-intensive sectors such as electricity generation, transport, and waste treatment. Brown Industries constitute the bulk of the remaining CO_2 emissions.

The perspective is very different when considering GHG emissions other than CO_2 from combustion. In this case, Agriculture and Fossil Extraction are strong emitters, particularly in terms of

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[8] Table 2 sources all emissions from EXIOBASE. In the model, emissions come from the IEA for CO_2 from combustion and EXIOBASE for other GHGs. However, the accounting of emissions in the model, which follows Shapiro (2021), makes it complex to recover direct sectoral emissions (see section 3.3), leading us to adopt another source for this table.

Table 2 – Direct emissions from production in 2019

	CO_2 from fossil fuel combustion		Other GHG emissions (CO_2eq)	
Sector	Total (Gt)	Intensity (kg/EUR)	Total (Gt)	Intensity (kg/EUR)
Agriculture	0.70	0.13	6.60	1.19
Fossil Extraction	1.67	0.69	3.08	1.28
Brown Industries	7.35	0.31	2.84	0.12
Manufacturing n.e.s.	1.84	0.07	0.08	0.00
Services	17.07	0.17	0.77	0.01

Sources: EXIOBASE.

emission intensity, making these two aggregates the most emission-intensive sectors in terms of all GHGs. This illustrates the importance of accounting for all GHGs, given the differences in emission patterns.

Excluding services, Brown Industries are the largest emitters. However, as previously mentioned, Brown Industry tariffs are typically close to the global average. Unless there is a significant negative correlation between the tariff and the carbon content of different brown industries or production locations, removing the sectoral heterogeneity in the tariffs should not significantly impact brown industry emissions. Agricultural emissions, however, are likely to be affected because harmonizing tariffs across sectors would imply a strong liberalization in a sector that is highly emission-intensive.

This statistical measure of carbon content does not fully characterize the emission impact of a given sector. Indeed, it does not account for the input–output linkages. For example, higher tariffs and prices on fossil products would result, as in other sectors, in a decrease in fossil production, which would reduce the total emissions of the fossil production sector. However, more importantly, this decrease means that downstream sectors will use less fossil fuel and reduce their total emissions. Such considerations highlight the central importance of the Fossil Extraction sector despite its lower contribution to total direct emissions compared to Brown Industries.

To summarize these stylized facts, Fossil Extraction and Agriculture are the sectors where most of the effect of tariff harmonization on emissions can be expected. Brown Industries and other manufacturing sectors face average tariffs close to the world average tariff, which makes any effect more dependent on the heterogeneity within these sectors. Both this internal heterogeneity among the five large sectors and heterogeneity across countries are ignored in this preliminary analysis but will be better accounted for in the model.

3. Quantitative model

Our general framework is a multi-country, multi-sector Armington trade model with intermediate consumption. This framework is a small generalization with GHG emissions of the simple quantitative trade model of Caliendo and Parro (2015), also used in Shapiro (2021). We have extended the standard Caliendo and Parro (2015) framework so that fossil fuel production requires the use of specific factors (an approach also used inter alia in Baqaee and Farhi, 2024).[9] We follow the same approach as Shapiro (2021) and adopt an extraction-based accounting for CO_2 emissions from combustion, where emissions are counted at the place of extraction. Other GHG emissions are taken to be proportional to the output of the emitting sector.

3.1. Model setup

The world is composed of regions indexed $i, j \in \mathcal{I}$ each composed of sectors indexed $k, l \in \mathcal{K}$. We denote $\mathcal{G} \subset \mathcal{K}$ the subset of goods, which exclude services. Factors are indexed $f \in \mathcal{F}$.

Households In country j, the representative household supplies a fixed quantity of factors and has Cobb–Douglas preferences over composite final goods:

$$U_j = \prod_{k \in \mathcal{K}} \left(D_{j,k}^{\mathrm{FC}}\right)^{\theta_{j,k}^{U}}, \tag{1}$$

where $D_{j,k}^{\mathrm{FC}}$ is the final demand for the composite good of industry k in country j and $\theta_{j,k}^{U}$ is the share of expenditure spent on industry k varieties. The household faces a budget constraint given by

$$GNE_j = \sum_{f \in \mathcal{F}} w_{j,f} L_{j,f} + \Xi_j + \Delta_j, \tag{2}$$

where $GNE_j = \sum_{k \in \mathcal{K}} p_{j,k} D_{j,k}^{\mathrm{FC}}$ is the nominal Gross National Expenditure, $p_{j,k}$ is the price of a consumption good, $w_{j,f}$ is the factor return to factor f, $L_{j,f}$ is factor supply, Ξ_j is a lump-sum transfer from the government, and Δ_j is the trade deficit.

Composite final goods are represented by a CES (Armington assumption),[10] and the same CES aggregator is used for final and intermediate consumption:

$$D_{j,k}^{\mathrm{FC}} = \left[\sum_{i \in \mathcal{I}} \beta_{ij,k}^{1/\sigma_k} \left(D_{ij,k}^{\mathrm{FC}}\right)^{(\sigma_k - 1)/\sigma_k}\right]^{\sigma_k/(\sigma_k - 1)}, \tag{3}$$

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[9] Given that the shocks analyzed here are of small magnitude, using more general functional forms than the Cobb–Douglas used in Caliendo and Parro (2015) and Shapiro (2021) has little effect. A model with CES functions calibrated following the elasticities used in Baqaee and Farhi (2024) and Bachmann et al. (2024) generates very close results and is analyzed in Appendix C.3.

[10] Caliendo and Parro (2015) model is originally based on Eaton and Kortum (2002), but since for counterfactual purposes an Eaton–Kortum model is equivalent to an Armington model, we adopt the Armington assumption to simplify the exposition.

where $\beta_{ij,k}$ is a demand shifter (common to final and intermediate consumption), $\sigma_k > 1$ is the elasticity of substitution among varieties, and $D^{\mathrm{FC}}_{ij,k}$ is the import by j from i for final consumption.

From (3), the price of the composite good is

$$p_{j,k} = \left(\sum_{i \in \mathcal{I}} \beta_{ij,k} p_{ij,k}^{1-\sigma_k} \right)^{1/(1-\sigma_k)}, \tag{4}$$

with $p_{ij,k}$ the sector k price index of country j imports from country i.

Trade policy and trade costs Two types of bilateral trade costs are considered: iceberg costs and ad valorem tariffs. $\tau_{ij,k} \geq 1$ units must be shipped from country i to country j in order to sell one unit of a variety of sector k, and an ad valorem tariff denoted by $T_{ij,k} = 1 + t_{ij,k}$ must be paid, with $t_{ij,k}$ being the tariff rate. Tariffs are only applied to goods, so for $k \in \mathcal{G}$. Tariff revenue is fully rebated to the consumer budget as a lump sum. In all specifications, no tariff is levied on intra-regional trade, i.e., $t_{ii,k} = 0$. The import price is given by

$$p_{ij,k} = T_{ij,k} \tau_{ij,k} c_{i,k}, \tag{5}$$

where $c_{i,k}$ is the unit production cost.

Production costs Production combines factors and intermediate inputs according to a Cobb–Douglas technology. The unit costs of production can be written as:

$$c_{i,l} = \prod_{f \in \mathcal{F}} \left(\frac{w_{i,f}}{\theta^{w}_{i,f,l}} \right)^{\theta^{w}_{i,f,l}} \prod_{k \in \mathcal{K}} \left(\frac{p_{i,k}}{\theta_{i,kl}} \right)^{\theta_{i,kl}}, \tag{6}$$

where $\theta^{w}_{i,f,l}$ is the budget share of factor f in production costs and $\theta_{i,kl}$ is the budget share of good k in the production costs of good l.

3.2. Market clearing and equilibrium conditions

Market clearing and budget constraint In equilibrium, total expenditure must equal total demand for final and intermediate consumption in each market:

$$E_{j,k} = \theta^{U}_{j,k} GNE_j + \sum_{l \in \mathcal{K}} \theta_{j,kl} c_{j,l} Q_{j,l}, \tag{7}$$

where

$$Q_{i,l} = \sum_{j \in \mathcal{I}} X_{ij,l} / c_{i,l} \tag{8}$$

is the production from sector l, and $X_{ij,k}$ is the value of bilateral trade exclusive of tariff.

Clearing in factor markets implies

$$w_{j,f} L_{j,f} = \sum_{l \in \mathcal{K}} \theta^{w}_{j,f,l} c_{j,l} Q_{j,l}, \tag{9}$$

Gross Domestic Product is defined as the sum of value added and tariff revenue:

$$GDP_j = \sum_{f \in \mathcal{F}} w_{j,f} L_{j,f} + \Xi_j, \tag{10}$$

where tariff revenue is $\Xi_j = \sum_{i \in \mathcal{I}} \sum_{k \in \mathcal{G}} t_{ij,k} X_{ij,k}$.

Gravity equation Given that final and intermediate demands are based on the same CES aggregator, tariff-inclusive trade values follow a simple gravity equation:

$$T_{ij,k} X_{ij,k} = \beta_{ij,k} \left(p_{ij,k} / p_{j,k} \right)^{1-\sigma_k} E_{j,k}. \tag{11}$$

Equilibrium definition Based on the above, the market equilibrium can be characterized as a vector of the price of composite goods ($p_{j,k}$), the unit production costs ($c_{i,k}$), factor return ($w_{i,f}$), sectoral production ($Q_{i,k}$), sectoral expenditure ($E_{j,k}$), income (GDP_j), gross national expenditures (GNE_j), trade flows ($X_{ij,k}$), and import prices ($p_{ij,k}$) such that equations (2), (4)–(11) hold. Additionally, to close the model, we assume that trade balances remain constant in terms of global nominal GDP.

Exact hat algebra We calibrate the model by expressing all variable in deviation from benchmark, the so-called exact hat algebra approach. Appendix A.1 details the equations under this form and the calibration.

3.3. Emissions accounting in the model

CO_2 emissions from combustion and other GHG emissions are accounted for differently. The accounting of CO_2 emissions from combustion follows the methodology outlined in Shapiro (2021). We compute the quantities of fossil fuel extracted and multiply them by the emission intensity of the respective fuel. To perform these calculations, we utilize data from IEA (2022) and the EFDB (IPCC, 2021) to determine the quantity of CO_2 released through the combustion of each fossil fuel produced in a particular country (for more details, refer to Appendix A.2). We operate under the assumption that the emission factor remains constant regardless of fluctuations in the quantity of fossil fuel extracted. Based on this methodology, the CO_2 emissions attributed to combustion resulting from the extraction of fossil fuels in country j can be expressed as:

$$\mathrm{CO_2}_j = \sum_{k \in \text{fossil}} f_{j,k}^{\mathrm{CO_2}} Q_{j,k}, \tag{12}$$

with $f_{j,k}^{\mathrm{CO_2}}$ the emission factor of the fossil fuel k produced in country j.

For the other anthropogenic GHGs (including CO_2 emissions associated with production processes such as steel and cement manufacturing, but not with combustion), the approach used for combustion emissions is not applicable. However, these emissions are significant, accounting for 25% of total GHG emissions. To address this, we adopt a different method from that used for combustion-related emissions. Specifically, we account for these emissions by distinguishing between those from production and those from final consumption. Emissions from a specific production sector in a given country are assumed to be proportional to the level of production, reflecting the fact that these emissions are linked to the production process rather than to a particular input. This results in a unique emission factor $f_{j,k}^{\mathrm{OtherGHG}}$, enabling us to express these emissions as follows:

$$\mathrm{OtherGHG}_{j,k} = f_{j,k}^{\mathrm{OtherGHG}} Q_{j,k}. \tag{13}$$

In order to account for other GHGs in final consumption, we must resort to an approximation. The EXIOBASE data provides information on other GHGs emitted by households, but it does not associate these emissions with specific products. As a result, we are left with the assumption that emissions of other GHGs from final consumption fluctuate in proportion to the Laspeyres quantity index of final consumption, denoted $Q_{j,\mathrm{FC}}$:

$$\mathrm{OtherGHG}_j^{\mathrm{FC}} = f_{j,\mathrm{FC}}^{\mathrm{OtherGHG}} Q_{j,\mathrm{FC}}. \tag{14}$$

The inclusion of non-combustion GHG emissions distinguishes our study from that of Shapiro (2021). This distinction is particularly significant in the context of the agricultural sector, which accounts for 50% of these emissions. Within this sector, non-combustion emissions make up 90% of the sector's total emissions. Emissions of other GHGs resulting from final consumption are relatively insignificant, contributing to just 1% of other GHG emissions. It's important to note that our model, being stylized and lacking explicit representation of land use, does not account for emissions associated with changes in land use. The scenario we evaluate involves substantial liberalization of the agricultural sector—a scenario that could spark an expansion of agricultural land use primarily in countries abundant in land. This expansion could, in turn, lead to higher emissions associated with land-use change (Guerrero et al., 2022). Consequently, our model's neglect of this mechanism potentially accentuates any environmental bias in trade policies.

4. Results

Once the model is calibrated, we run counterfactual scenarios. In the main text, we use 2019 data aggregated into 23 regions and 47 industries. In the Appendix, we analyze robustness across multiple years and different regional and sectoral aggregations. In this section, we consider only one production factor that can be freely reallocated across sectors within a given country. An extension with several production factors will be considered in section 5.1.

The model described in section 3.1 is used to calculate the general equilibrium effects of replacing the sector-heterogeneous tariffs $t_{ij,k}$ imposed by importing country j on exports from country i in sector k with the trade-weighted average value for all sectors (excluding services), $\bar{t}_{ij} = \sum_{k \in \mathcal{G}} t_{ij,k} X_{ij,k} / \sum_{k \in \mathcal{G}} X_{ij,k}$. In the rest of the paper, this shock will sometimes be referred to as "harmonization of tariffs across sectors." In Appendix C.2, we analyze a WTO-compatible tariff harmonization for robustness, in which the harmonization is done multilaterally instead of bilaterally.

4.1. The environmental impact of tariff harmonization

Our results indicate a small carbon bias in tariffs. Harmonizing tariffs across sectors within each country dyad leads to a reduction in total GHG emissions of -0.58%. This finding contrasts with Shapiro's (2021) result of a -1.75% decrease in emissions after tariff harmonization in 2007. The smaller reduction in emissions observed in our analysis can be attributed to three main factors. First, we incorporate a broader range of GHGs, extending beyond CO_2 emissions from fossil fuel combustion. Second, we consider more countries and sectors, allowing us to keep separate countries and sectors with very different emission intensities and tariff profiles. Lastly, the year of analysis has a slight impact; across different years, the bias remains small but transforms into a small positive number in 2007 when all GHGs are considered (yearly results are presented in Appendix C.1). Appendix B provides a detailed, step-by-step explanation of the differences between our results and those of Shapiro.

Including all sources of GHG emissions is crucial for characterizing the carbon bias in trade policy. While CO_2 emissions from fossil fuel combustion constitute the majority of total GHG emissions, other GHGs also play a significant role. These other GHGs are particularly concentrated in a few sectors, as illustrated in table 2, and show limited correlation with emissions from fossil fuel combustion. This underscores the importance of considering sectoral heterogeneity in both emissions and trade policy.

Including all GHGs in the analysis reduces the carbon bias to -0.58%, mainly due to the positive impact of tariff heterogeneity on methane emissions. High tariffs on agricultural products, which are methane-intensive, play a significant role. Harmonizing tariffs across sectors lowers the tariffs on agricultural goods, which increases demand for and production of these goods, in turn leading to higher methane emissions. This finding is consistent with previous research on the environmental effects of agricultural trade policies (e.g., Laborde et al., 2021; Guerrero et al., 2022).

This overall modest level of bias warrants a more detailed analysis of its sectoral origins. In the following subsection, we show that the carbon bias of tariffs can be decomposed by sector, with fossil fuel extraction and agriculture contributing the most to this bias.

4.2. Decomposing sectoral contributions

In this subsection, we decompose the results at the sectoral level. To simplify the presentation, we consider the same five large groups of sectors as those presented in section 2 for stylized facts. The conclusions also hold with more granular sectors.

One finding from our sectoral analysis is that the effect of tariff harmonization on each group of sectors is nearly independent of its effect on other sectors, in terms of total emissions. Let Δx represent the change in CO_2 or GHG emissions when tariffs are bilaterally harmonized across all sectors (as described in the second paragraph of section 4), and let Δx_a denote the change in emissions when tariffs are bilaterally harmonized only across the sectors of category a (i.e., when, in each bilateral relationship, only tariffs applied to sectors in category a are adjusted to match the average value of tariffs $\bar{t}_{ij}$). We observe that the sum of the changes in emissions when the shock is applied to each category closely approximates the result for the shock on the entire economy. In other words, $\sum_a \Delta x_a \approx \Delta x$. This approximation holds in our reference scenario table 3 and applies to all model specifications tested. For example, as shown in figure A1, which depicts the decomposition of the shock for the years 2007–19, $\sum_a \Delta x_a / \Delta x - 1$ mostly remains below 5%.

From a modeling point of view, this result is a consequence of the small size of the shock and of the use of Cobb–Douglas production and utility functions, which greatly limit the nonlinearities. This quasi-independence of the sectoral effects allows us to decompose the results by sector. In terms of all GHG, the tariff shock applied only to Fossil Extraction leads to a decrease of emissions of 1.27%. This sector is the main responsible of the carbon bias, and in its absence in the shock the bias would be positive. The agricultural sector contributes in the other direction, with two competing effects that co-exist. CO_2 emissions from combustion decrease in this sector, but they represent a small share of the agricultural emissions and other GHG emissions increase a lot.

The effect of fossil fuels can itself be further decomposed as contributions from each type of fossil fuels. This is done in the middle panel of table 3. Tariffs on crude oil, which are initially low and largely increase because of the shock, are the main contributor to the bias.

Brown Industries contribute only marginally to the bias, with a decrease of all emissions of 0.17%. If we disaggregate more, the sectors in Brown Industries where most of the emission reduction occurs are heavy industries: iron and steel, manufacture of metal products, machinery

Table 3 – Sectoral results of tariff harmonization

Sector	All GHG	CO_2 from combustion	Other GHG
Agriculture (A)	0.61	−0.17	0.78
Fossil Extraction (F)	−1.27	−1.18	−0.09
Brown Industries (B)	−0.17	−0.15	−0.02
Manufacturing n.e.s. (M)	0.27	0.10	0.17
Coal (C)	−0.39	−0.36	−0.03
Oil (O)	−0.78	−0.73	−0.06
Gas (G)	−0.09	−0.09	−0.01
All	−0.58	−1.40	0.82
All except Fossil Extraction	0.70	−0.20	0.91
A + F + B + M	−0.56	−1.40	0.85
A + B + M	0.72	−0.22	0.94

Notes: The first column is the % change in emissions compared to the calibrated emissions. The two other columns are contributions to the total effect (i.e., All GHG = CO_2 from combustion + Other GHG). The three intermediate lines display a breakdown of the Fossil Extraction sector. The last four lines display simulations applying the tariff shock to several sectors ("All" and "All except Fossil Extraction") and sum of sectoral simulations.

and equipment, manufacture of coke oven products, Other metals production, petroleum refinery, fertilizers and chemicals not elsewhere classified.

To sum up, the carbon trade bias of trade is mostly due to the absence of tariffs on fossil fuels, or more precisely crude oil, which makes an eventual trade policy reform much simpler and smaller in scope.

4.3. The role of sector upstreamness in tariff-induced emissions

Shapiro (2021) provides a political economy explanation for the carbon bias. He notes that carbon-intensive industries are often upstream industries. Upstreamness refers to a sector's relative position in the global value chain. A higher degree of upstreamness means that a sector primarily supplies inputs to other industries rather than producing final goods. Politically, upstream industries may benefit from lower tariffs because downstream industries, which depend on these inputs, lobby for reduced costs in their supply chains.

Complementing the former argument consistent with the theory of effective protection, this paper underlines the specific role of fossil fuel extraction for CO_2 emissions and agriculture (especially cattle and rice) for other GHG emissions. We analyze here how upstreamness and emissions interact in our model.[11] To proceed, we exploit the previously identified property that the sum of shocks to individual sectors is nearly equal to the aggregate shock. Thus, we run

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[11] Like Shapiro (2021), we use the upstreamness measure defined in Antràs et al. (2012). As per the appendix in

32 counterfactual simulations—one for each of our non-service sectors. Figure 1 displays the relationship between reductions in GHG emissions, divided by the sector's initial global output, and its upstreamness.

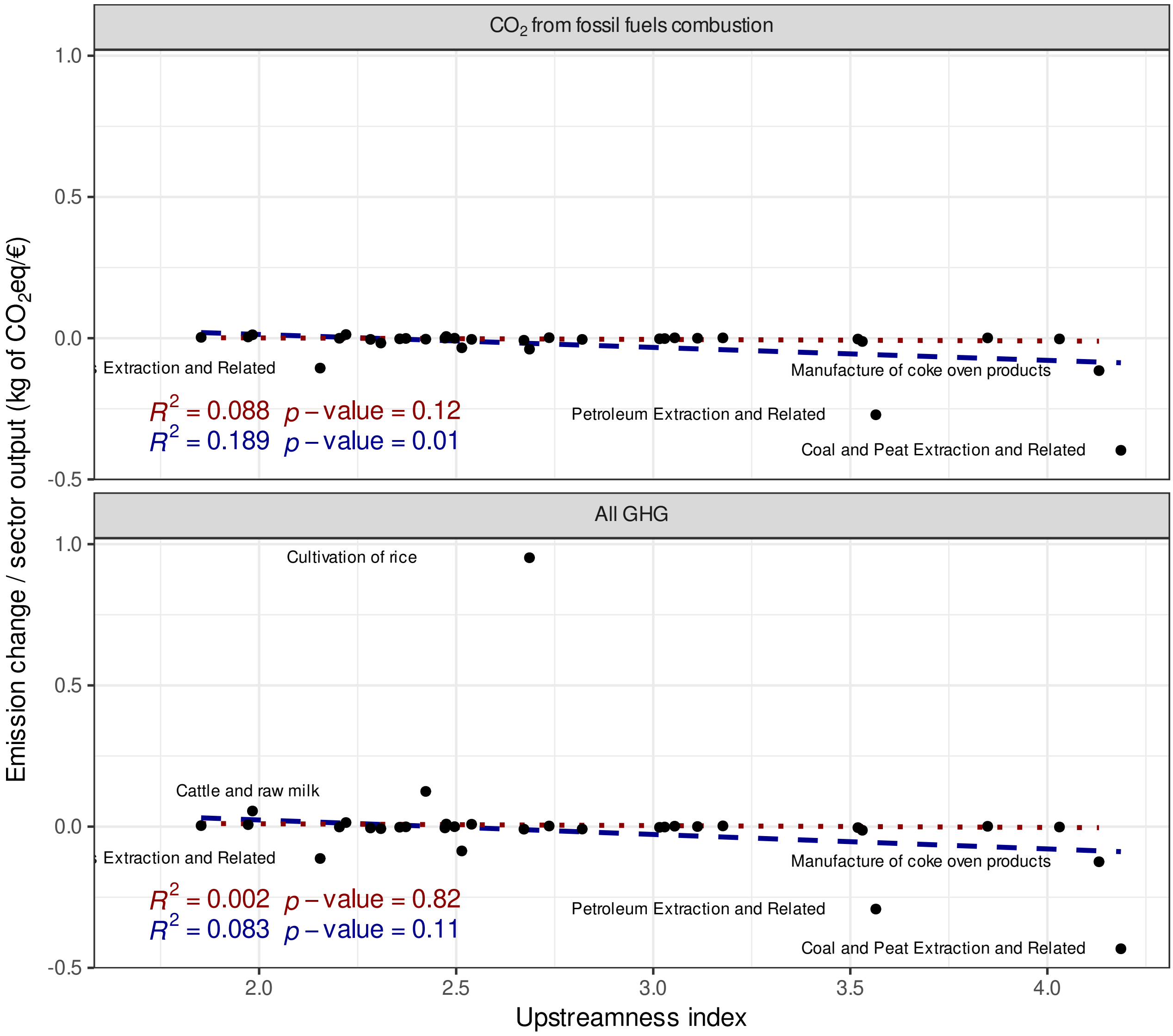

Figure 1 – Relation between emissions changes and upstreamness.
Notes: Each point corresponds to the counterfactual result obtained from applying the tariff harmonization shock on a single sector. The lines are regression lines using as weight the initial sector output with associated statistics displayed on the bottom left. The blue dashed lines use the all sample, and the red dotted lines exclude the fossil fuel sectors.

Antràs et al. (2012), upstreamness can be calculated as the line by line ratio between $[\mathbf{I}-\mathbf{A}]^{-1}\mathbf{x}$ and $\mathbf{x}$, where $\mathbf{x}$ is the total output vector, $\mathbf{A}$ is the technical coefficient matrix, and $\mathbf{I}$ is the identity matrix. For this measure, sectors with a higher value are considered more upstream.

Figure 1 shows a negative correlation between upstreamness and CO_2 emission reductions. We measure this relationship statistically by regressing the change in emissions per sector output on the upstreamness index, weighted by the benchmark value of sector output. This relationship is tenuous and is primarily driven by fossil fuel extraction sectors. When fossil fuels are removed from the analysis, the relationship between upstreamness and emissions becomes statistically insignificant, suggesting that the carbon bias is largely driven by the unique combination of high upstreamness and CO_2 intensity in fossil fuel sectors. When including all GHG emissions, the relationship is statistically insignificant even with the fossil fuel sectors.

This analysis confirms the dominant role of fossil fuel extraction sectors in driving the carbon bias and shows that, if upstreamness affects general equilibrium results, it does so primarily through these sectors.

5. Refining the modeling of fossil fuels

The results presented so far reveal that the carbon bias of trade is largely driven by low tariffs on fossil fuels, particularly crude oil. However, the model's reaction to changes in fossil fuel tariffs raises two important concerns. First, the assumption that local production of fossil fuels can increase substantially in response to higher tariffs may not be realistic, as it overlooks the natural constraints on fossil fuel extraction. Second, the treatment of fossil fuel taxes, especially in countries that do not produce these resources domestically, merits closer scrutiny. Domestic taxes on fossil fuels in non-producing countries can function similarly to tariffs, and their exclusion from the analysis might lead to an incomplete picture of the carbon bias.

This section addresses these issues by refining the model in two key ways. First, we introduce a modification that accounts for the finiteness of natural resources, limiting the ability of countries to increase domestic fossil fuel production in response to tariff changes. Second, we explore the equivalence between domestic taxes and tariffs on fossil fuels in non-producing countries, adjusting the model to reflect the broader fiscal policy environment. These refinements provide a more nuanced understanding of the role fossil fuels play in the carbon bias of trade policies, and offer insights into the potential limitations of using tariffs as an environmental policy tool.

5.1. Accounting for resource constraints

The baseline model follows Shapiro and assumes the same production function for fossil fuels as for other sectors: a Cobb–Douglas combination of labor and intermediate inputs. This assumption can lead in the model to strong reactions of production to changes in fossil fuel tariffs because if the domestic price increases in response to higher tariffs, it is always possible to bring more labor to produce additional fossil fuels. However, this setting ignores the natural constraints on fossil fuel extraction. Fossil fuel reserves are finite, and rapid increases in extraction could only be achieved by tapping into less accessible and more expensive reserves. Furthermore, the costs associated with extraction would increase significantly as producers move to exploit these less accessible resources.

To address this issue, we use a more general but still highly stylized model in which the production of fossil fuel requires the use of a sector-specific factor representing the finiteness of natural resources (see Baqaee and Farhi, 2024 and Bachmann et al., 2024 for recent applications of such an approach). This extension is included in the model presented in section 3, where nothing prevents a factor from being used in only one sector. We use the GTAP 11c database to calibrate the cost share of natural resources. The finite resource extension acknowledges that the marginal costs of extracting additional fossil fuels rise with supply.[12]

Table 4 compares the results of the standard model and the finite natural resources extension. In the extended model, the impact of tariff harmonization on GHG emissions is very different. The bias becomes negligible at -0.04%. This modeling change primarily affects the emissions associated with the Fossil Extraction sectors, with an emission reduction that decreases from -1.27% to -0.53%. However, it also affects all sectors that emit CO_2 from fossil fuel combustion, albeit to a lesser extent. Because of the strong reduction in emission changes from fossil fuels and the relative stability of those from the other sectors, the increased emissions in the agricultural sector weigh much more in these simulations.

Table 4 – Results of tariff harmonization for the standard and the finite natural resources model. % change in GHG emissions compared to the calibrated emissions.

Sector	Standard model	Finite natural resources
Agriculture (A)	0.61	0.41
Fossil Extraction (F)	−1.27	−0.53
Brown Industries (B)	−0.17	−0.11
Manufacturing n.e.s. (M)	0.27	0.22
Coal (C)	−0.39	−0.19
Oil (O)	−0.78	−0.30
Gas (G)	−0.09	−0.04
All	−0.58	−0.04
All except Fossil Extraction	0.70	0.49

In reality, the ability of fossil fuel producers to respond to tariff-induced price changes is limited by the physical availability of resources, and this must be accounted for in any comprehensive policy assessment. Note that in all the sensitivity analyses done in the Appendix, the small negative bias found here turns positive when accounting for finite natural resources. This is the case for

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[12] For parsimony, we maintain here a Cobb–Douglas assumption for the production function, but Appendix C.3 provides a robustness check using a CES specification, which would allow matching fossil fuel supply elasticities from the literature.

all years except 2019 (figure A3), and when the Cobb–Douglas production function is replaced by nested CES functions (Appendix C.3).

5.2. Treating domestic fuel taxes as tariffs

5.2.1. When do domestic fuel taxes act as tariffs?

The low tariffs on fossil fuels play a crucial role in the carbon bias of tariffs. However, these low tariffs represent only part of the overall picture. Specifically, if a country does not produce a particular good domestically, a domestic consumption tax or a uniform tariff on all exporters can serve as equivalent policy tools; these instruments raise the domestic price and reduce consumption by similar amounts. In globalized fossil fuel markets, non-producing countries generally lack incentives to favor specific exporters, making domestic taxes a more natural instrument that is not constrained by international commitments (such as the WTO and Free Trade Agreements) and can therefore be used more freely to address externalities like air pollution and GHG emissions. In addition, for coal and oil that may require refining before being used, low tariffs on the extractive sectors combined with higher tariffs on the refined sectors incentivize domestic refining through tariff escalation. These taxes also enable importers to capture a portion of the resource rents extracted by exporters (Dixit, 1984; Karp, 1984; Jones and Takemori, 1989; Rubio, 2011).

For fossil fuels, many non-producing countries implement sector-specific domestic taxes that significantly impact fossil fuel consumption and emissions. While in this setting these taxes have similar effects to tariffs, they are not typically considered in trade policy discussions focused on tariffs alone. Ignoring these taxes in trade policy analysis underestimates the effective protection applied to fossil fuels in non-producing countries. Importantly, the equivalence between domestic taxes and tariffs does not apply to fossil fuel-producing countries, where tariffs provide additional protection to local industries. For instance, in the US, tariffs on oil have been debated as a means of supporting domestic industries (Loris, 2020), whereas domestic taxes in non-producing countries act more like uniform tariffs across all suppliers. Moreover, many fossil fuel exporting countries have fossil fuel subsidies (IEA, 2023), which are known to be a widespread impediment to GHG emissions mitigation. This issue of instrument equivalence is particularly important given that, aside from the relatively small tobacco sector, fossil fuels are unique in having sector-specific taxes and many non-producing countries.

The overall fiscal burden on fossil fuels is a combination of various instruments: carbon taxes, excise taxes, and emissions trading schemes. In addition, some countries provide fossil fuel subsidies, which can counteract the effect of tariffs and taxes. We use the OECD's (2022) Net Effective Carbon Rates data to capture the overall tax burden on fossil fuels for 71 countries, 39 of which are included individually in EXIOBASE. We use the year 2018, which is the closest available year to our 2019 reference year. We put these taxes in perspective with the countries' fossil fuel import rate, calculated from BP (2020) Statistical Review of World Energy, which limits our sample to 39 countries.[13] Figure 2 plots, for countries with net imports exceeding −30% (which truncates two countries), the ad valorem crude oil (the main driver of the bias) level of taxation—derived from the OECD net effective energy tax rate—as a function of net imports. Focusing on countries entirely dependent on imports, there are still large variations in levels of taxation, but these countries have a minimum level of taxation around 20% (the conclusions would be similar for coal and gas). Findings by Mahdavi et al. (2022) show that the determinants of fossil taxation comprise revenue needs, income per capita, but also fossil endowment, which confirms the trade relevance of these taxes.[14]

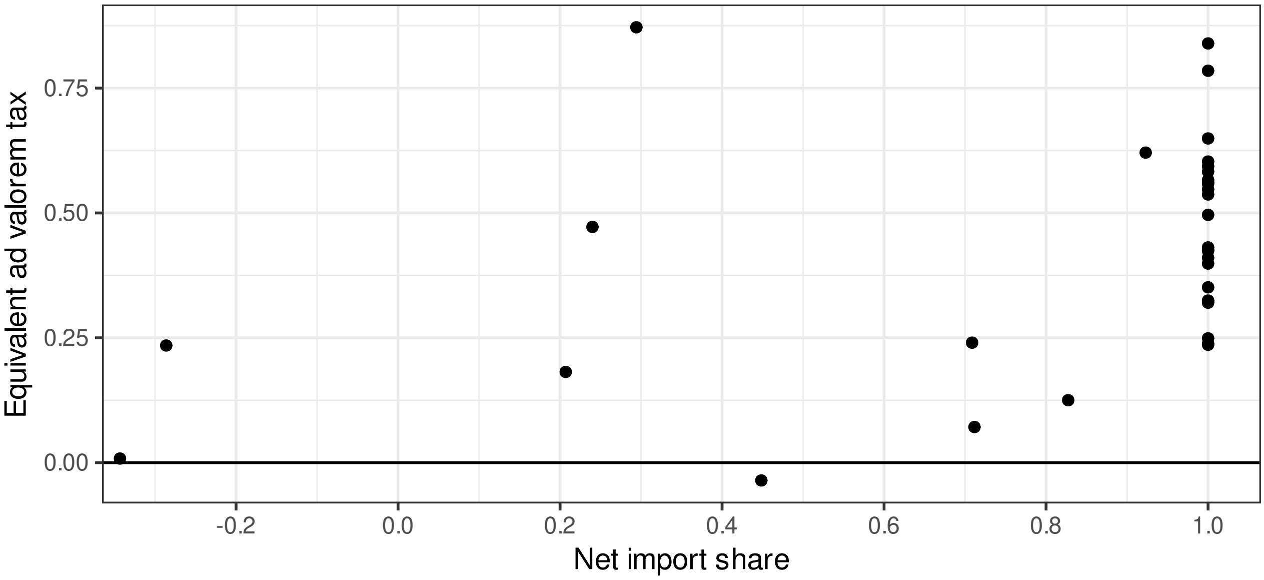

Figure 2 – Net effective energy tax rate as a function of net import share for crude oil in 2018, by country.
Sources: Taxation calculated using OECD and EXIOBASE, and net imports calculated from BP.

The above argument shows that the conclusion of section 4 is incomplete. Indeed, section 4 shows that most of the carbon bias is explained by the very low levels of tariffs on fossil fuels. This conclusion may change if domestic fossil fuel taxes that are functionally equivalent to tariffs are also considered as tariffs. In the extension presented here, we provide an order of magnitude for the change in the carbon trade bias if fossil fuel taxes are treated as such.

For the countries that extract fossil fuels, there is no equivalence between a tariff and a domestic tax. Therefore, we focus our analysis on non-producing countries, defined as those that import more than 99% of their fossil fuel consumption. For these countries, we assume that the theoretical equivalence between a tariff and a domestic consumption tax holds, and we aggregate

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[13] As explained by Bellora et al. (2022), standard trade data are often imprecise for energy products. BP data are thus used to obtain reliable information on energy production and trade.

[14] Crude oil is a special case, as it is often refined before use. Section A.2 expands in more detail on the equivalence between tax and tariff for crude oil.

the net tax presented in figure 2 to our regions in the model. 12 out of the 23 regions in our model can be considered non-producing countries. Their ad valorem equivalent net taxes are displayed in table 5. This level of taxation is not comparable to typical tariffs; it is much higher, especially for fossil fuel extraction sectors, for which in most of these countries, the tariffs are at zero or close to zero.

Table 5 – Ad valorem equivalent net tax (%) on fossil fuels for the regions with import shares above 99%

Region	Coal	Oil	Gas
Belgium, Netherlands, and Luxembourg	82.3	23.8	–
Eastern EU countries in OECD data	–	50.1	–
France	31.8	78.5	29.9
Germany	–	56.6	–
Italy	69.7	–	–
Japan	12.0	23.6	83.9
Korea	66.5	24.9	36.6
Non EU European countries	–	49.8	17.4
Nordic countries in the EU	59.2	–	–
Norway	7.4	–	–
Other EU countries in OECD data	–	56.5	65.4
Spain	–	55.8	49.1

Note: "–" indicates that for this fuel the region's import share is below 99%. See table A6 for the country mapping.
Sources: Taxation calculated using OECD and EXIOBASE and net imports calculated from BP.

5.2.2. Quantifying the effect of domestic fuel taxes

To understand quantitatively the consequences for the carbon bias of tariffs of treating domestic fossil taxes as equivalent to tariffs, we add the tax rates presented in table 5 to the existing tariffs and apply the sectoral tariff harmonization shock.

The results are shown in table 6, where the impact of the policy shock is compared to the baseline scenario without domestic taxes included. The results are completely opposite to the benchmark: there is a pro-environmental bias driven by the tariffs on fossil fuel sectors. Previously, because fossil fuels had tariffs below the average, the shock increased fossil fuel tariffs and decreased their consumption. Here, two effects compete. First, since in some non-producing countries fossil fuel tariffs have become higher than the average tariffs, the sectoral tariff harmonization shock will reduce tariffs on those fossil fuels. This reduction will lower the price of these fossil fuels and increase their usage and production, mechanically increasing the corresponding emissions. Secondly, in these countries, the average tariff has increased, which affects the other sectors. However, since fossil fuel sectors represent a limited share of trade, this second effect is negligible compared to the first one.

Table 6 – Impact of the sectoral tariff harmonization shock taking into account domestic fossil fuel taxes. % change in emissions compared to the calibrated emissions.

Scenario	All	Agriculture	Fossil Extraction	Brown Industries	Manufacturing n.e.s.
Fossil tax not included (benchmark results)	−0.58	0.61	−1.27	−0.17	0.27
With fossil tax for net imports > 99%	2.14	0.65	1.25	−0.12	0.36

These results show that, considering behind-the-border taxes on fossil fuels as tariffs, the bias of tariffs becomes pro-environmental, unfavorable to carbon emissions.

6. Conclusion

This paper revisits the policy relevance of a recently identified stylized fact: the existence of a carbon bias in trade policies, where dirtier sectors face relatively lower border protection compared to cleaner sectors. Using counterfactual simulations in a stylized general equilibrium model accounting for all GHG emissions, we confirm the presence of a carbon bias in 2019. However, our results suggest it is much smaller than previously estimated. Crucially, our analysis reveals that this bias is primarily explained by the low tariffs on fossil fuels, particularly crude oil. Additionally, the effects of these low tariffs are counteracted by high tariffs on agricultural products, a sector where comprehensive modeling of all GHG emissions is crucial.

The central role of fossil fuels warrants further scrutiny due to the unique characteristics of these sectors. We explored two key factors: the finite availability of natural resources required for their extraction and the widespread use of fossil fuel consumption taxes in non-producing countries. Firstly, fossil fuel sectors are constrained by finite natural resources, which are unevenly distributed across countries. When we adjust the model to account for this constraint, the carbon bias vanishes. This alternative modeling reduces the supply elasticity of fossil fuel sectors, limiting their capacity to react to small tariff increases. The sensitivity of the bias to this simple modeling change emphasizes the uncertainty surrounding its actual magnitude and policy significance.

Secondly, non-producing countries often impose nearly zero tariffs on fossil fuels while levying significant consumption taxes, which, in this context, function as equivalent to tariffs. When these taxes are considered in the analysis, the carbon bias shifts toward a pro-environmental stance. In our case, the carbon bias is minimal enough to be more than offset by these often overlooked taxes. This suggests that the observed bias originates more from differences in fiscal instruments than from a structural under-taxation of polluting sectors.

These findings underscore the importance of integrating the specificities of energy markets and domestic distortions into trade models to more accurately account for the impact of trade policies on the environment.

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Appendix

A. Model details and calibration

A.1. Exact-hat algebra formulation

In this appendix, we express the model equations in relative changes. The counterfactual value of a variable ν is denoted ν' and the relative change with respect to the baseline equilibrium is denoted $\hat{\nu} = \nu'/\nu$. Manipulating the equilibrium equations presented in section 3 makes it possible to derive a set of equations where all variables are expressed in relative changes and where the information required to characterize the initial equilibrium is made explicit:

$$\hat{p}_{ij,k} : \hat{p}_{ij,k} = \hat{T}_{ij,k}\hat{\tau}_{ij,k}\hat{c}_{i,k}, \tag{A1}$$

$$\hat{c}_{i,l} : \hat{c}_{i,l} = \prod_{f\in\mathcal{F}} (\hat{w}_{i,f})^{\theta^{w}_{i,f,l}} \prod_{k\in\mathcal{K}} (\hat{p}_{i,k})^{\theta_{i,kl}}, \tag{A2}$$

$$\hat{w}_{j,f} : w_{j,f}L_{j,f}\hat{w}_{j,f} = \sum_{l\in\mathcal{K}} \theta^{w}_{j,f,l} R_{j,l}\hat{c}_{j,l}\hat{Q}_{j,l}, \tag{A3}$$

$$\hat{E}_{j,k} : E_{j,k}\hat{E}_{j,k} = \theta^{U}_{j,k} GNE_j\widehat{GNE}_j + \sum_{l\in\mathcal{K}} \theta_{j,kl} R_{j,l}\hat{c}_{j,l}\hat{Q}_{j,l}, \tag{A4}$$

$$\hat{Q}_{i,k} : \hat{c}_{i,k}\hat{Q}_{i,k} = \sum_{j\in\mathcal{I}} \theta^{R}_{ij,k}\hat{X}_{ij,k}, \tag{A5}$$

$$\hat{X}_{ij,k} : \hat{T}_{ij,k}\hat{X}_{ij,k} = \hat{p}_{ij,k}^{1-\sigma_k}\hat{p}_{j,k}^{\sigma_k-1}\hat{E}_{j,k}, \tag{A6}$$

$$\hat{p}_{j,k} : \hat{p}_{j,k} = \left(\sum_{i\in\mathcal{I}} \theta^{X}_{ij,k}\hat{p}_{ij,k}^{1-\sigma_k}\right)^{1/(1-\sigma_k)}, \tag{A7}$$

$$\widehat{GNE}_j : GNE_j\widehat{GNE}_j = GDP_j\widehat{GDP}_j + \Delta_j\hat{\Delta}_j \tag{A8}$$

$$\widehat{GDP}_j : GDP_j\widehat{GDP}_j = \sum_{f\in\mathcal{F}} w_{j,f}L_{j,f}\hat{w}_{j,f} + \sum_{i\in\mathcal{I}}\sum_{k\in\mathcal{K}} t'_{ij,k}X_{ij,k}\hat{X}_{ij,k}, \tag{A9}$$

$$\widehat{\mathrm{CO}_2}_j : \widehat{\mathrm{CO}_2}_j = \sum_{k\in\mathrm{fossil}} \frac{\mathrm{CO}_{2j,k}}{\mathrm{CO}_{2j}}\hat{Q}_{j,k}, \tag{A10}$$

$$\widehat{\mathrm{OtherGHG}}_{j,k} : \widehat{\mathrm{OtherGHG}}_{j,k} = \hat{Q}_{j,k}, \tag{A11}$$

$$\widehat{\mathrm{OtherGHG}}^{\mathrm{FC}}_{j,k} : \widehat{\mathrm{OtherGHG}}^{\mathrm{FC}}_{j,k} = \hat{Q}_{j,\mathrm{FC}}, \tag{A12}$$

where the θ indicates initial budget shares, $\theta^{R}_{ij,k} \equiv X_{ij,k}/R_{i,k}$ is the share of the bilateral export flow from j to i in sector revenue, $\theta^{X}_{ij,k} = T_{ij,k}X_{ij,k}/E_{j,k}$ is the (tax inclusive) share of expenditure in sector k in country j devoted to imports from country i, and $R_{i,k} = \sum_{j\in\mathcal{I}} X_{ij,k}$ is the initial total revenue from sector k. Calibrating this model for counterfactual simulations requires inputting two sets of parameters: behavioral parameters (σ_k) and initial values that are directly observable in multi-regional input-output databases.

The default closure is to assume that trade balances remain constant in terms of global GDP, which is expressed as $\Delta_j\hat{\Delta}_j = \theta_j^{\Delta}\sum_i GDP_i\widehat{GDP}_i$.

Note that equations (A1) and (A6) can be substituted away to render more compact the model.

A.2. Calibration data

Economic data The calibration is done on EXIOBASE 3.8.2. Prior to calibration, we first remove all negative values of final demand (corresponding to negative inventory changes) keeping the input/output coefficients constant to retrieve the production levels corresponding to the new final demand levels.

As EXIOBASE does not include information about tariffs, in the presence of tariffs in the benchmark equilibrium it is necessary to do some adjustments. EXIOBASE provides information about transaction values in basic prices, so corresponding to the costs borne by the producer. So, we proceed as follows to extend the database for information about tariffs. Denoting $\mathbb{X}_{ik,ju}$ the original matrix of intermediate and final consumption with $u \in \mathcal{U} = \mathcal{I} \cup \mathcal{Y}$ indexing uses, which gathers sectors of intermediate consumption ($\mathcal{I}$) and categories of final demand ($\mathcal{Y}$), we calculate sectoral tariff expenditures as

$$\Xi_{j,l} = \sum_{i\in\mathcal{I},k\in\mathcal{K}} t_{ij,k}\mathbb{X}_{ik,jl} \text{ for all } l \in \mathcal{I}, \tag{A13}$$

final demand as

$$D^{\text{FC}}_{j,k} = \sum_{i\in\mathcal{I},y\in\mathcal{Y}} (1 + t_{ij,k})\,\mathbb{X}_{ik,jy}, \tag{A14}$$

where y indexes the various final demands, intermediate consumption as

$$D^{\text{IC}}_{j,kl} = \sum_{i\in\mathcal{I}} (1 + t_{ij,k})\,\mathbb{X}_{ik,jl}, \tag{A15}$$

value added as

$$VA_{i,k} = \sum_{j\in\mathcal{I},u\in\mathcal{U}} \mathbb{X}_{ik,ju} - \sum_{i'\in\mathcal{I},k'\in\mathcal{K}} \mathbb{X}_{i'k',ik} - \Xi_{i,k}, \tag{A16}$$

trade as

$$X_{ij,k} = \sum_{u\in\mathcal{U}} \mathbb{X}_{ik,ju}, \tag{A17}$$

and GNE as

$$GNE_j = \sum_{k\in\mathcal{K}} D^{\text{FC}}_{j,k}. \tag{A18}$$

The other variables can be easily derived from there. For high tariffs, this approach may generate negative value added which has to be checked.

Note that we have not used the information provided about trade and transport margins. This is consistent with the model for which we have assumed iceberg trade costs. However, we have to keep in mind that trade flows in EXIOBASE are expressed as free on board and neglecting the margins implies underestimating the value of demand.

CO_2 emissions from fossil fuel combustion The calibration of CO_2 emission is done in two steps. We use IEA (2022) data to know the quantity in TJ of each fossil primary energy product—there are 24 of them—that is extracted in each country. The carbon content of these TJ is calculated using the conversion values in the EFDB (IPCC, 2021). Then, the 24 energy products are aggregated into the three EXIOBASE extraction sector corresponding to coal, oil, and gas. Thus, we ascertain how much CO_2 is emitted from the extraction in each country to each of these fossil fuels. The IEA countries are aggregated to the countries/regions in the model. In counterfactuals, as in Shapiro (2021), if the oil extraction sector in any given country increase by x% in volume, an increase in x% is also deemed to happen in the associated CO_2 emissions.

Other GHG emissions The other GHG emissions are directly taken from EXIOBASE and aggregated to our sectors and regions.

Domestic taxes on fossil fuels To calculate the values of the domestic taxes on fossil fuels, we rely on two sources: the OECD's (2022) net effective carbon rates and EXIOBASE. The OECD database provides data, for 2018 and 2021 and for different fuel sources, on subsidies and carbon, fuel, and electricity taxes (in currency per GJ). Their total leads to a net effective energy tax rate. The database also gives the potential tax base of these taxes in TJ. These two pieces of information gives us the total revenues of the taxes. We combine this information with the consumption value of each fuel from EXIOBASE to obtain an ad valorem equivalent tax.

The OECD database provides information on consumption taxes, so for petroleum, it concerns the various transformed products (diesel, gasoline, . . .). To calculate the tax on transformed oil, the diversity of oil derivatives must be circumvented. We do this by subtracting from the total taxation on fossil fuels the total taxation on gas and coal. We then divide by the corresponding tax base to obtain the net tax on transformed oil.

A second issue, also specific to oil, is that taxes are applied to transformed products while oil trade mostly concerns crude oil. To solve this issue, we chose the rough approximation of considering that these taxes on transformed oil are similar to equivalent tariffs, being applied to crude oil. This rough approximation has a two-fold justification. First, the approximation does not imply any large trade distortions, as these taxes mostly apply to transformed oil that has been produced using imported crude oil. Indeed, the countries concerned by the tax-tariff equivalence, i.e., countries that import more than 99% of their crude oil, import only a small percentage of their refined oil, usually from neighboring countries with similar policies. The net imports of refined oil are about −5% on average in the selected subset of countries, and the (non-net) imports of refined oil are also small, at 29%.[15] Secondly, a tariff on crude oil would have a very high pass-through to the price of refined oil, and almost no impact on other sectors as crude oil must be refined before use. Reciprocally, a change in such a tax would have a similar impact on the price of crude oil as a tariff reduction, but only a marginal impact on other components of the value added, which have multiple usages. Because crude oil constitutes only part of the total value added of petroleum products—around 50%—fixing the ad valorem tariff at the same level as the tax is in reality an underestimation. The approximate character of the exercise does not imperil the results of this extension. Indeed, this extension does not intend to give a precise figure but only to show that the central value obtained for the carbon trade bias, mostly due to fossil, should be considered carefully and does not necessarily point to an abnormally low tarification on crude oil.

B. Reconciling differences with Shapiro (2021)

This section clarifies any difference between ours and Shapiro's results. To do this, we start by exactly replicating Shapiro's results, then we introduce differences step by step (table A1). Table A1 reads as follows. The first line is a replication of Shapiro's setup with our implementation of the same model. Then, each line adds one difference allowing us to identify what is driving differences in the counterfactual results. The last line replicates the benchmark results presented in section 4.1.[16] Shapiro studies a joint harmonization of tariffs and NTBs, while our focus is on tariffs only. So, our point of comparison is Shapiro's Appendix Table VIII, Panel 1, row 3, which reports the effect of harmonizing tariffs only. Using Shapiro's data, but our implementation of the model, we obtain the same results: −1.75% of CO_2 emissions (from fossil fuels combustion). On the whole the results are convergent and differ mainly because of updates in data and differences in scopes that we detailed below.

Even though our data sources are the same, our calibration data are different from Shapiro's data, because these data have been revised. An example of data difference is given by the setting 2 in which we use the most recent version of EXIOBASE, version 3.8.2, instead of Shapiro's version 2.2.2 and use our processing of MAcMap-HS6 tariff data. These changes barely affect the bias, increasing to it −1.77% for CO_2 emissions.

In setting 3, we keep the recent EXIOBASE data and update the initial CO_2 emissions. The

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[15] This share of refined oil import is mostly concentrated in the EU single market, where most countries are crude oil importers with similar levels of oil taxation. Japan and South Korea, the largest included countries outside the EU, have lower (non-net) imports, respectively 10% and 20%.

[16] Note that we do not present the results as before (e.g., in table 3), where changes in CO_2 emissions are presented as their contribution to all GHG emissions. Here, to be consistent with Shapiro, we present the changes in CO_2 emissions relative to their initial values.

Table A1 – Comparison of counterfactual emissions changes (%) from a tariff harmonization with Shapiro (2021). Setting 1 corresponds to Shapiro's data and results (for CO_2 only), and each subsequent setting introduces one difference with the previous one.

	CO_2		All GHGs	
Setting	All	Fossils	All	Fossils
1. Shapiro (2021): Shapiro's data, shock, and aggregation, year = 2007	−1.75	−1.51	−1.03	−1.10
2. Updated economic calibration data (excluding CO_2)	−1.77	−1.02	−1.18	−0.75
3. Update calibration data (including CO_2)	−1.50	−0.73	−0.98	−0.54
4. No shock on services	−1.72	−0.99	−1.16	−0.74
5. Our sectoral aggregation (10 regions, 47 sectors)	−1.38	−0.99	−0.52	−0.75
6. Our sectoral and geographical aggregation (23 regions, 47 sectors)	−1.68	−1.11	0.31	−0.85
7. Our benchmark results: our data, shock, and aggregation, year = 2019	−2.02	−1.70	−0.58	−1.27

initial CO_2 emissions are built by combining IEA information on fossil fuel production with IPCC information on emission factors. We use a more recent version of IEA's energy balances than Shapiro. Updating fossil fuel production leads to significant changes in CO_2 emissions and to the associated bias, for the year 2007, the year Shapiro (2021) uses. Many small differences are introduced by this data update. In terms of initial emissions, the three most important changes are the decrease of the emission from the combustion of Indian coal (−31%), the increase in emissions from Northern European oil (+139%) and the decrease in emission from coal from the Rest of the World (−28%). The decrease in the before-shock emissions from Indian coal largely explain the lower bias (emissions decrease by −1.5%) when using the new CO_2 data.[17]

The difference between settings 3 and 4 comes from the counterfactual shock. In Shapiro, the tariff harmonization is applied to all sectors including services. Since services are not subject to tariffs in reality, we think it is inappropriate to apply tariffs to them in this analysis, and we do not do it in this paper, except in settings 1–3 for comparison sake. This correction aggravates the CO_2 bias from −1.5 to −1.72%. Having tariffs on services makes these sectors comparatively more expensive and reduces their final consumption—albeit by a limited amount as they are overwhelmingly produced locally. As, services are some of the least carbon-intensive sectors, reallocating service consumption to other sectors tends to increase carbon emissions. Moreover, as services currently have no tariff, including them in the analysis lowers the average level of tariffs, which reduces the amplitude of the shock on fossil fuels. Thus fossil fuel consumption goes down by a lesser amount than for the shock excluding services. In other words, our exclusion of services tends to increase the carbon bias of tariffs.

In setting 5, we move from Shapiro's sectoral aggregation with 21 industries to our aggregation with 47 industries (see tables A4 and A5 for the sectoral mappings). This finer aggregation allows us to separate sectors with very different emission intensities and trade protections, which could otherwise bias the results. One example is rice cultivation, which generates significantly higher emissions than other crops. Refining the sectoral aggregation is crucial for our paper's

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[17] In both scenarii, the shock induces a similar decrease in percentages of Indian coal emissions, but in the newer data the initial stock is lower which translates into a lower total impact on world emissions.

results, which focus on all GHGs—precisely because of the need to separate certain agricultural activities—with the bias in all GHGs being more than halved by this change. On the other hand, the reduction in bias is much smaller when adopting Shapiro's focus on CO_2 emissions.

In setting 6, we move from Shapiro's geographical aggregation with 10 regions to our aggregation with 23 regions (see table A6 for the geographical mappings). Among the key differences is the fact that we can isolate some large countries, as well as fossil-fuel-producing and agricultural-exporting countries, and avoid grouping together European Union countries with countries outside the EU (which leads to the imposition of tariffs between EU countries when they are bundled with non-members). This change aggravates the bias in terms of CO_2 emissions but reverses the bias when considering all GHGs. Indeed, the composition effects related to the country aggregation can go in opposite directions depending on the gas under consideration, given the very different country specializations. One intuition for the increase in the bias in terms of CO_2 is that when fossil-fuel-producing countries are separated from non-producing countries, the latter are more forced to decrease their fossil-fuel consumption under a tariff harmonization, since they cannot compensate by increasing domestic production, which reduces emissions further.

Moving to setting 7 brings us to our benchmark results by changing the year of the data from 2007 to 2019. The change of reference year matters for several reasons, which we do not try to disentangle precisely (see section C.1 for more information on yearly results): tariff rates, fossil fuel prices (changes in sectoral price levels influence emission intensity), agricultural prices, trade and input-output data. This changes increases a lot the bias to -2.02% for CO_2 emissions.

We have focused the above discussion on CO_2 emissions to clarify the differences with Shapiro, who analyzes these emissions. However, in this paper, we are primarily interested in all GHG emissions, and it is also important to understand what choices could have affected the associated bias. Table A1 makes it clear that compared to Shapiro's setting, the two choices of importance are the sectoral and country aggregation and the analyzed year. Keeping more countries and sectors reduces the composition biases that appear when countries and sectors with different emission intensities are mixed together.

Finally, the main finding of our paper is that if there is a carbon bias of tariffs, it is mostly explained by the fossil fuel extraction sectors. The two columns "Fossils" in table A1 make clear that this conclusion holds for all the variants studied here.

C. Sensitivity analysis

This appendix addresses potential concerns related to the paper's results. First, that the reference year used, 2019, is peculiar (e.g., in terms of agriculture and fossil fuel prices) leading to an smaller environmental bias. To address this concern, section C.1 presents yearly results. Second, that the tariff harmonization is not realistic since it is not WTO compliant (section C.2). Third, that the model behaves too linearly (section C.3).

C.1. Yearly results

In this section, we analyze how the carbon bias of tariffs has evolved over time, starting from 2007, the first year in our sample and the year used in Shapiro (2021), to 2019, our reference year. We also examine the sectoral contributions to the bias over this period. Here, we employ the stylized model used in section 4 in which fossil fuel production does not rely on specific factors. Additionally, we use the model with finite natural resources. However, due to the lack of annual data on net carbon rates, we do not analyze the case of domestic fossil taxes. Figure A1 illustrates the emission changes over time following a tariff harmonization. It indicates that the carbon bias associated with CO_2 emissions has increased over time, rising from -1.68% to -2.02%. For all GHGs, the bias has fluctuated between 0.31% and -1.15%, showing an increase up to 2016, followed by a decline that returned the bias to -0.58% in 2019.

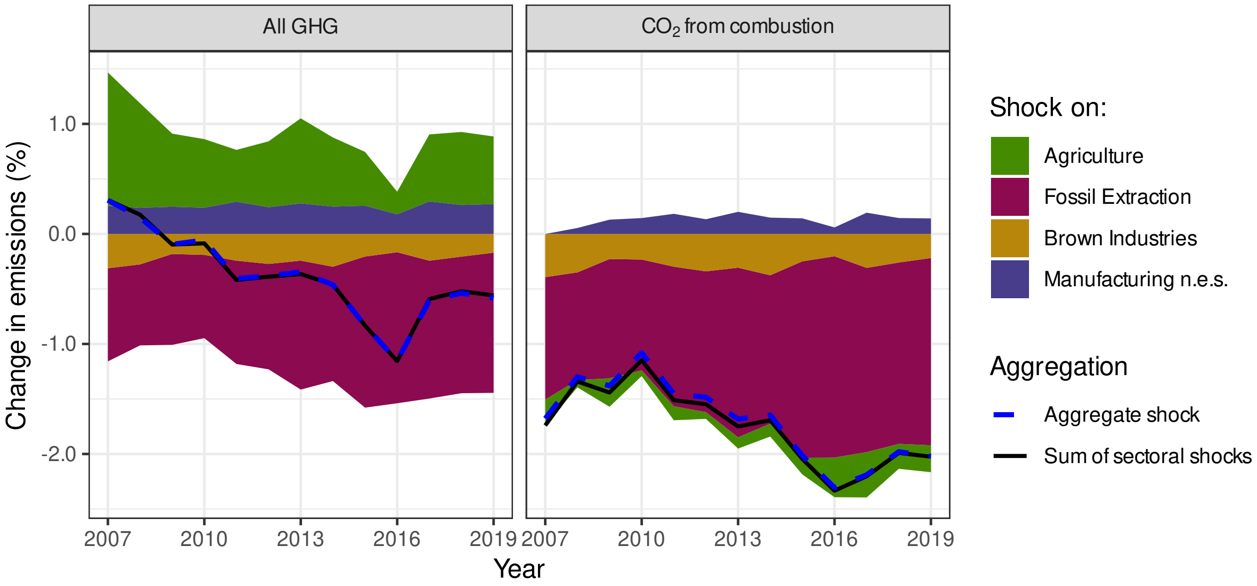

Figure A1 – Yearly results of tariff harmonization.
Notes: Each color corresponds to the change in GHG emissions when the shock is applied to a given sector. If the effect is positive, it is stacked above the zero line, and if the effect is negative, it is stacked below it. The sum of the shocks across all sectors is represented by the black line. The shock applied to all sectors simultaneously is represented by the dashed blue line.

In terms of sectoral contributions, the previous conclusions hold true for the entire period. Fossil fuel extraction sectors are the primary drivers of the bias. Their contribution to the bias has tended to increase over time. It is also worth noting that, over the period, the sum of sectoral contributions is very close to the result obtained when the shock is applied to all sectors simultaneously. Figure A2 further breaks down the contribution of fossil fuels into their respective sectors, showing that crude oil is the main driver of the increase in the bias.

The evolution of the bias over time has multiple causes: changes in tariffs (and consequently in the harmonization shock), trade structure, emission intensity, sectoral price levels (particularly

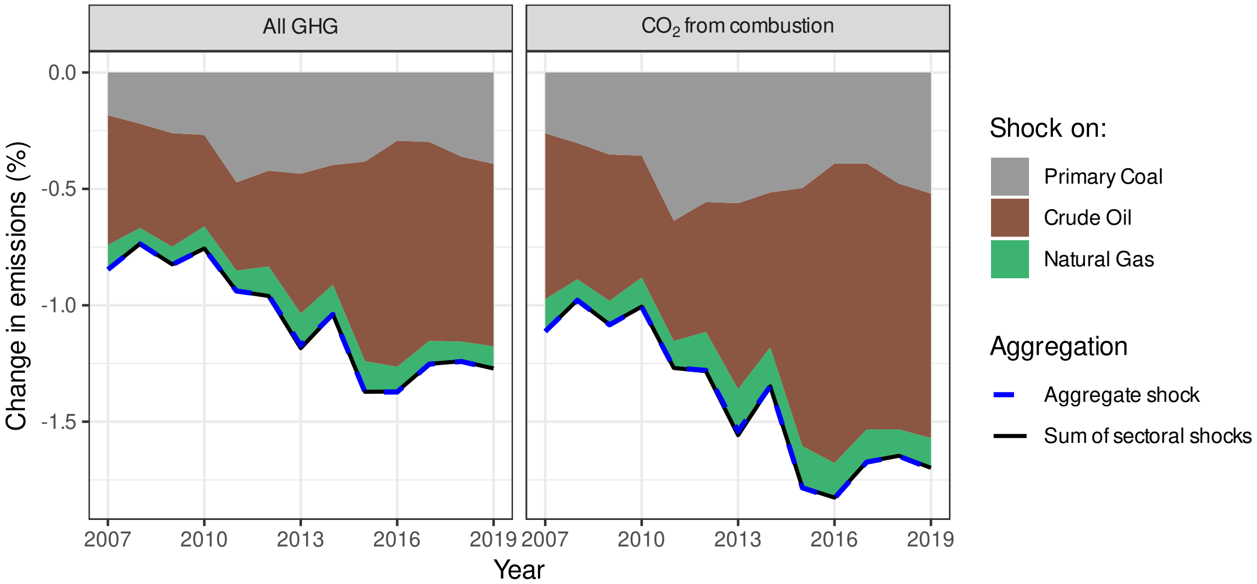

Figure A2 – Yearly results of tariff harmonization for Fossil Extraction sectors.
Notes: Each color represents the change in emissions when the shock is applied exclusively to coal, oil, or gas extraction. The black line indicates the total change, while the blue dashed line represents the outcome of the simultaneous shock.

fossil fuel prices), and more. These factors could only be disentangled by simulating the model while keeping one determinant fixed at its initial level. However, since EXIOBASE is only available in current prices, most of these simulations cannot be performed; for example, emission intensities cannot be isolated from changes in sectoral price levels, which carries significant implications given the considerable fluctuations in fossil fuel prices over time. Therefore, we can only propose suggestions regarding the factors driving the observed patterns.

Tariffs did not change drastically between 2007 and 2019 but generally decreased. The trade-weighted global average tariff dropped from 3.1% in 2007 to 2.6% in 2019. However, the average tariff in the crude oil sector decreased more significantly, from 0.8% to 0.2%. As a result, the magnitude of the simulated harmonization shock on oil increased from a 1.6% to a 2.3% rise. This increase in the shock's magnitude is an important driver of the bias's growth over time, as it implies a stronger counterfactual reduction in oil imports and larger associated emissions.

The residual variations unexplained by the tariff changes are likely due to price fluctuations. We calculate an oil price deflator using the value and the volume of oil consumption, respectively, from EXIOBASE and IEA. The inferred price peaks in 2012 at 164% of its 2007 reference level, then decreases to 84% of the reference level by 2016, and slightly rises again to 116% of the reference level in 2019. To quantify the contribution of oil prices to the bias, we construct a normalized measure of the carbon bias. We divide the percentage change in CO$_2$ emissions by the benchmark share of oil in these emissions—thus attributing all changes to this sector. This quantity is further divided by the share of trade in the sector and the average Laspeyres simulated change in tariffs for the oil sector. Our proxy price and the normalized measure of the bias due to the oil extraction sector exhibit a 64% correlation, indicating that oil price movements are a significant driver of the bias.

Indeed, as oil prices increase, the budget share of oil in inputs becomes higher.[18] Because of the Cobb–Douglas production function, this higher share means a lower substitution effect between oil and other inputs after the shock. This results in a smaller decrease in oil consumption and, therefore, a smaller decrease in CO_2 emissions.

Some of the fluctuations in the impact of agriculture can as well be explained by tariff and price movements. A lot of the border protection in the agricultural sector is provided by specific tariffs. Consequently, their conversion to an ad valorem equivalent depends on prevailing agricultural good prices, which vary a lot over time. So, even a constant trade policy can lead to very different trade protection depending on the economic situation. This effect is compounded by the fact that agricultural trade flows are quite variable, which affects any trade-weighted tariff aggregation.

Figure A3 presents the same analysis using the finite natural resources model used in section 5.1. The figure shows that the evolution of the results in the two models tends to be parallel, both in aggregate and for each sector. In 2019, the results from the finite resources model exhibit a slight negative bias. However, this bias is consistently positive throughout the rest of the period.

Overall, the main results remain robust when varying the time period. In the main model, the bias is present in most years, except the first two. It diminishes when non-combustion GHG emissions are considered, and is consistently driven by fossil fuel extraction sectors. In the model with finite natural resources, the bias is negligible and mostly positive.

C.2. A more WTO-compliant harmonization

The tariff harmonization implemented here (and by other authors) is a theoretical exercise to understand the carbon bias of tariffs. However, such a tariff reform violates one of the most important WTO commitments, inherited from the GATT: the Most-Favored-Nation rule, which stipulates that the same tariff on a given product must be applied to all member countries, except for specific exceptions such as Free Trade Agreements, Customs Unions, and antidumping measures. Here, we simulate a tariff harmonization across sectors that respects this rule by assuming that each country imposes a single average tariff on all its imports (for EU countries, this excludes intra-EU trade): $\bar{t}_j = \sum_{i\in\mathcal{I}\&i\neq j,k\in\mathcal{G}} t_{ij,k}X_{ij,k}/\sum_{i\in\mathcal{I}\&i\neq j,k\in\mathcal{G}} X_{ij,k}$.

Table A2 displays the results of this simulation along with the benchmark bilateral tariff harmonization. It shows that results are quite close between the two scenarii, and the role of the

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[18] The correlation between the share of the oil extraction sector in the total economy and the oil price deflator is 95%. This observation contradicts our Cobb–Douglas assumption for the production function, but it is addressed by the CES extension in Appendix C.3.

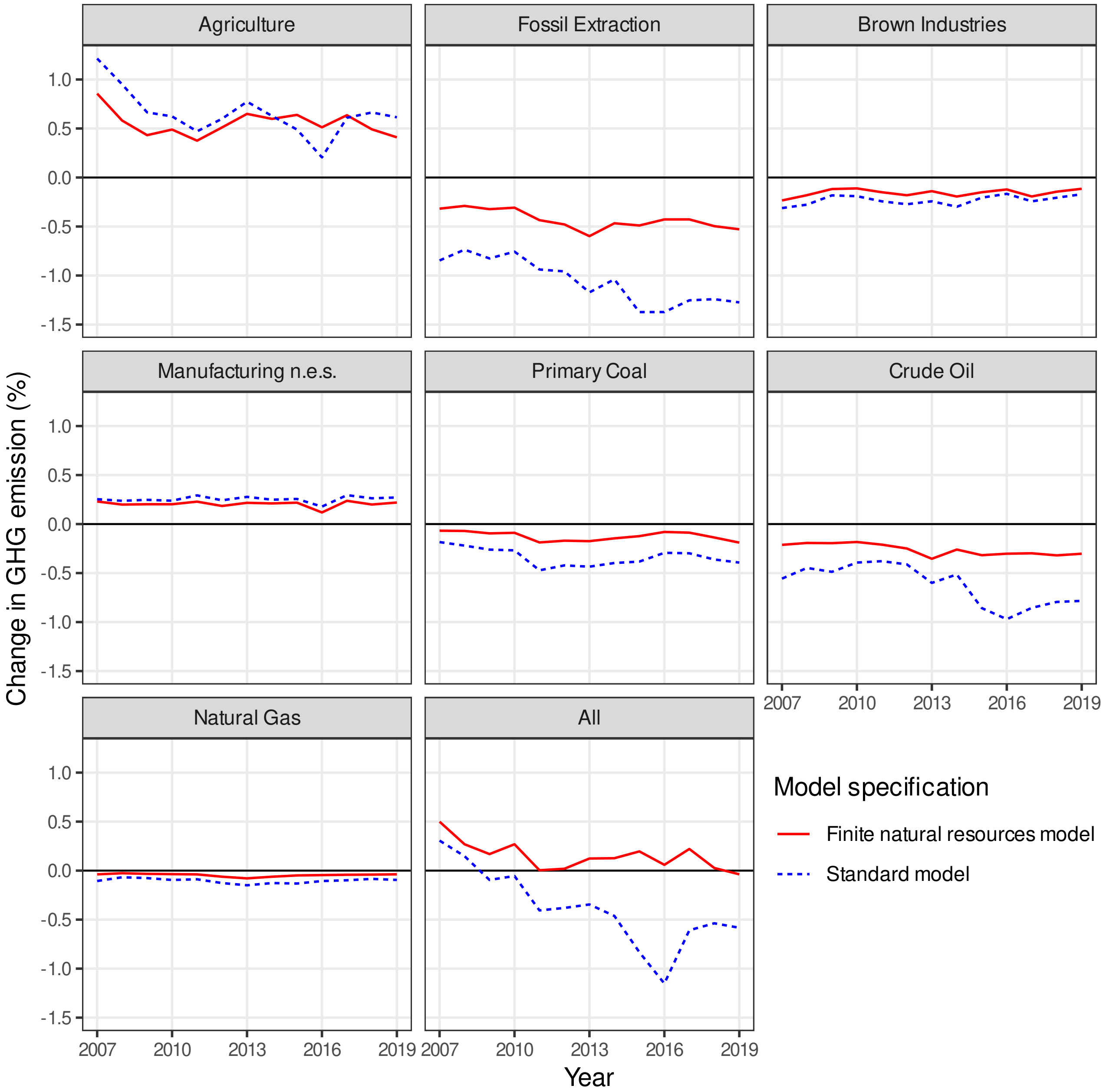

Figure A3 – Impact by sector of tariff harmonization on GHG emissions over time, with the natural resources extension

fossil-fuel tariffs is even reinforced by this choice.

Table A2 – Results of tariff harmonization for two harmonization scenarii. % change in GHG emissions compared to the calibrated emissions.

Tariff scenario	All	Fossils
Bilateral harmonization (benchmark results)	−0.58	−1.27
Multilateral harmonization	−0.51	−1.49

C.3. Model with more non-linearities

In this section, we analyze whether our results are sensitive to the degree of product substitution. To do this, we replace the Cobb–Douglas functions in the model with CES functions. This change affects the utility function (1), the production function (6), and the associated demand functions. We denote σ^U as the substitution elasticity for utility. For the production function, we assume a two-tiered nested CES structure. At the top tier, there is a CES with elasticity σ^Q between value added and intermediate inputs. At the lower tiers, there is a CES with elasticity σ^{IC} among intermediate inputs and a CES with elasticity σ^{VA} between factors (only the finite natural resources extension involves more than one factor). Since CES equations are standard, we do not display the model's equations with CES here.

For calibrating these elasticities, we adopt Baqaee and Farhi (2024)'s central calibration and follow Bachmann et al. (2024) for less elastic variants. Baqaee and Farhi (2024)'s central calibration implies lower elasticities than in our benchmark Cobb–Douglas model, with $\sigma^U = 0.9$, $\sigma^Q = 0.5$, $\sigma^{\mathrm{IC}} = 0.2$, and $\sigma^{\mathrm{VA}} = 0.5$.

Table A3 displays the results for the standard model and the model with finite natural resources. When using the standard model, the results show very little sensitivity to calibration, with the overall bias not changing by more than 0.03 percentage points across the specifications. The contribution of fossil fuels is more sensitive to calibration, but this effect is offset by compensatory changes in the agricultural sector. It is only when the model accounts for the need to use natural resources to produce fossil fuels that the results become sensitive to calibration. This sensitivity is mostly explained by the elasticity between factors, σ^{VA}, as it reduces the supply elasticity of fossil fuels and thus their role in the overall bias. For any set of elasticities below the Cobb-Douglas case, the bias turns positive for the finite natural resources model.

These results confirm our main conclusion that under the standard model, there is a small negative bias, while under the model accounting for natural resources, the sign of the bias is very sensitive to the model parameters.

Table A3 – Results of tariff harmonization for various model calibration. % change in GHG emissions compared to the calibrated emissions.

Model	Parameterization $(\sigma^U, \sigma^Q, \sigma^{\mathrm{IC}}, \sigma^{\mathrm{VA}})$	All	Fossils
Standard model	Benchmark $(1, 1, 1)$	-0.58	-1.27
	as Baqaee–Fahri $(0.9, 0.5, 0.2)$	-0.60	-1.21
	low elasticities $(0.9, 0.1, 0.2)$	-0.61	-1.17
	very low elasticities I $(0.9, 0.05, 0.05)$	-0.61	-1.16
	very low elasticities II $(0.1, 0.05, 0.05)$	-0.59	-1.09
Finite natural resources	Benchmark $(1, 1, 1, 1)$	-0.04	-0.53
	as Baqaee–Fahri, except for σ^{VA} $(0.9, 0.5, 0.2, 1)$	0.00	-0.46
	as Baqaee–Fahri $(0.9, 0.5, 0.2, 0.5)$	0.09	-0.36
	low elasticities $(0.9, 0.1, 0.2, 0.5)$	0.13	-0.30
	very low elasticities I $(0.9, 0.05, 0.05, 0.5)$	0.14	-0.29
	very low elasticities II $(0.1, 0.05, 0.05, 0.5)$	0.13	-0.26

D. Supplementary tables

Table A4 – Our sectoral mapping with EXIOBASE

Five main sectors	Our sectors	EXIOBASE sectors
Agriculture	Cattle and raw milk	Cattle farming Raw milk
	Cultivation of crops nec	Cultivation of vegetables, fruit, nuts Cultivation of oil seeds Cultivation of sugar cane, sugar beet Cultivation of plant-based fibers Cultivation of crops nec Wool, silk-worm cocoons Manure treatment (conventional), storage and land application Manure treatment (biogas), storage and land application
	Cultivation of rice	Cultivation of paddy rice
	Cultivation of wheat and cereals nec	Cultivation of wheat Cultivation of cereal grains nec
	Forestry and fishing	Forestry, logging and related service activities (02) Fishing, operating of fish hatcheries and fish farms; service activities incidental to fishing (05)
	Other meat and animal farming	Pigs farming Poultry farming Meat animals nec Animal products nec
Fossil Extraction	Coal and Peat Extraction and Related	Mining of coal and lignite; extraction of peat (10)
	Natural Gas Extraction and Related	Extraction of natural gas and services related to natural gas extraction, excluding surveying
	Petroleum Extraction and Related	Extraction of crude petroleum and services related to crude oil extraction, excluding surveying
Brown Industries	Casting of metals	Casting of metals
	Ceramic goods, bricks, tiles, clay products	Manufacture of ceramic goods Manufacture of bricks, tiles and construction products, in baked clay
	Energy NEC	Extraction, liquefaction, and regasification of other petroleum and gaseous materials Processing of nuclear fuel
	Fertilisers and chemicals nec	N-fertiliser P- and other fertiliser Chemicals nec
	Iron and steel	Manufacture of basic iron and steel and of ferro-alloys and first products thereof Re-processing of secondary steel into new steel

	Manufacture of cement, lime and plaster	Manufacture of cement, lime and plaster
		Re-processing of ash into clinker
	Manufacture of coke oven products	Manufacture of coke oven products
	Manufacture of metal products, machinery and equipment	Manufacture of fabricated metal products, except machinery and equipment (28)
		Manufacture of machinery and equipment n.e.c. (29)
	Manufacturing n.e.c.	Manufacture of other non-metallic mineral products n.e.c.
	Mining of chemical and fertilizer minerals	Mining of chemical and fertilizer minerals, production of salt, other mining and quarrying n.e.c.
	Mining of iron ores	Mining of uranium and thorium ores (12)
	Mining of other ores	Mining of iron ores
		Mining of copper ores and concentrates
		Mining of nickel ores and concentrates
		Mining of aluminium ores and concentrates
		Mining of precious metal ores and concentrates
		Mining of lead, zinc and tin ores and concentrates
		Mining of other non-ferrous metal ores and concentrates
	Other metals production	Precious metals production
		Re-processing of secondary preciuos metals into new preciuos metals
		Aluminium production
		Re-processing of secondary aluminium into new aluminium
		Lead, zinc and tin production
		Re-processing of secondary lead into new lead, zinc and tin
		Copper production
		Re-processing of secondary copper into new copper
		Other non-ferrous metal production
		Re-processing of secondary other non-ferrous metals into new other non-ferrous metals
	Petroleum Refinery	Petroleum Refinery
	Plastics, rubber and glass	Plastics, basic
		Re-processing of secondary plastic into new plastic
		Manufacture of rubber and plastic products (25)
		Manufacture of glass and glass products
	Quarrying of stone, sand and clay	Quarrying of stone
		Quarrying of sand and clay
	Recycling	Re-processing of secondary glass into new glass
Manufacturing n.e.s.	Manufacture of motor vehicles and transport eq	Manufacture of motor vehicles, trailers and semi-trailers (34)
		Manufacture of other transport equipment (35)
	Manufacture of office, precision and electronic machinery	Manufacture of office machinery and computers (30)
		Manufacture of electrical machinery and apparatus n.e.c. (31)

		Manufacture of radio, television and communication equipment and apparatus (32)
		Manufacture of medical, precision and optical instruments, watches and clocks (33)
	Manufacture of textiles, leather, wearing	Manufacture of textiles (17)
		Manufacture of wearing apparel; dressing and dyeing of fur (18)
		Tanning and dressing of leather; manufacture of luggage, handbags, saddlery, harness and footwear (19)
	Manufacture of wood, pulp, paper and recorded media	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials (20)
		Re-processing of secondary wood material into new wood material
		Pulp
		Re-processing of secondary paper into new pulp
		Paper
		Publishing, printing and reproduction of recorded media (22)
		Manufacture of furniture; manufacturing n.e.c. (36)
	Processing of Food, beverages and tobacco	Processed rice
		Sugar refining
		Processing of Food products nec
		Manufacture of beverages
		Manufacture of fish products
		Manufacture of tobacco products (16)
	Processing of meat and dairy	Processing of meat cattle
		Processing of meat pigs
		Processing of meat poultry
		Production of meat products nec
		Processing vegetable oils and fats
		Processing of dairy products
		Recycling of waste and scrap
		Recycling of bottles by direct reuse
Services	Air transport	Air transport (62)
	Biogasification and composting	Biogasification of food waste, incl. land application
		Biogasification of paper, incl. land application
		Biogasification of sewage slugde, incl. land application
		Composting of food waste, incl. land application
		Composting of paper and wood, incl. land application
	Construction	Construction (45)
	Electricity	Production of electricity by coal
		Production of electricity by gas
		Production of electricity by nuclear
		Production of electricity by hydro
		Production of electricity by wind
		Production of electricity by petroleum and other oil derivatives

	Production of electricity by biomass and waste
	Production of electricity by solar photovoltaic
	Production of electricity by solar thermal
	Production of electricity by tide, wave, ocean
	Production of electricity by Geothermal
	Production of electricity nec
	Transmission of electricity
	Distribution and trade of electricity
	Manufacture of gas; distribution of gaseous fuels through mains
Financial intermediation and real estate	Financial intermediation, except insurance and pension funding (65)
	Insurance and pension funding, except compulsory social security (66)
	Activities auxiliary to financial intermediation (67)
	Real estate activities (70)
Incineration of waste	Incineration of waste: Food
	Incineration of waste: Paper
	Incineration of waste: Plastic
	Incineration of waste: Metals and Inert materials
	Incineration of waste: Textiles
	Incineration of waste: Wood
	Incineration of waste: Oil/Hazardous waste
Landfill of waste	Landfill of waste: Food
	Landfill of waste: Paper
	Landfill of waste: Plastic
	Landfill of waste: Inert/metal/hazardous
	Landfill of waste: Textiles
	Landfill of waste: Wood
Other service activities	Hotels and restaurants (55)
	Renting of machinery and equipment without operator and of personal and household goods (71)
	Computer and related activities (72)
	Research and development (73)
	Other business activities (74)
	Activities of membership organisation n.e.c. (91)
	Recreational, cultural and sporting activities (92)
	Other service activities (93)
	Private households with employed persons (95)
	Extra-territorial organizations and bodies
Other transport	Transport via railways
	Other land transport
	Transport via pipelines
	Supporting and auxiliary transport activities; activities of travel agencies (63)
Post and telecommunications	Post and telecommunications (64)
Public services, education, health	Public administration and defence; compulsory social security (75)
	Education (80)

		Health and social work (85)
		Re-processing of secondary construction material into aggregates
	Sale, wholesale, commission trade, maintenance, repair	Sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motor cycles parts and accessoiries
		Retail sale of automotive fuel
		Wholesale trade and commission trade, except of motor vehicles and motorcycles (51)
		Retail trade, except of motor vehicles and motorcycles; repair of personal and household goods (52)
	Waste water treatment	Waste water treatment, food
		Waste water treatment, other
	Water supply	Steam and hot water supply
		Collection, purification and distribution of water (41)
	Water transport	Sea and coastal water transport
		Inland water transport

Table A5 – Reconstructed mapping between Shapiro's sectors and EXIOBASE sectors

Five main sectors	Shapiro's sectors	EXIOBASE sectors
Agriculture	Agriculture, Hunting, Forestry, and Fishing	Cultivation of paddy rice
		Cultivation of wheat
		Cultivation of cereal grains nec
		Cultivation of vegetables, fruit, nuts
		Cultivation of oil seeds
		Cultivation of sugar cane, sugar beet
		Cultivation of plant-based fibers
		Cultivation of crops nec
		Cattle farming
		Pigs farming
		Poultry farming
		Meat animals nec
		Animal products nec
		Raw milk
		Wool, silk-worm cocoons
		Manure treatment (conventional), storage and land application
		Manure treatment (biogas), storage and land application
		Forestry, logging and related service activities (02)
		Fishing, operating of fish hatcheries and fish farms; service activities incidental to fishing (05)
Fossil Extraction	Coal and Peat Extraction and Related	Mining of coal and lignite; extraction of peat (10)
	Natural Gas Extraction and Related	Extraction of natural gas and services related to natural gas extraction, excluding surveying
	Petroleum Extraction and Related	Extraction of crude petroleum and services related to crude oil extraction, excluding surveying

Brown Industries	Basic Metals and Fabricated Metal	Manufacture of basic iron and steel and of ferro-alloys and first products thereof
		Re-processing of secondary steel into new steel
		Precious metals production
		Re-processing of secondary preciuos metals into new preciuos metals
		Aluminium production
		Re-processing of secondary aluminium into new aluminium
		Lead, zinc and tin production
		Re-processing of secondary lead into new lead, zinc and tin
		Copper production
		Re-processing of secondary copper into new copper
		Other non-ferrous metal production
		Re-processing of secondary other non-ferrous metals into new other non-ferrous metals
		Casting of metals
		Manufacture of fabricated metal products, except machinery and equipment (28)
	Chemicals, Fertilizer, and Basic Plastics	Plastics, basic
		Re-processing of secondary plastic into new plastic
		N-fertiliser
		P- and other fertiliser
	Coke, Refined Petroleum, and Nuclear Fuel	Extraction, liquefaction, and regasification of other petroleum and gaseous materials
		Manufacture of coke oven products
		Petroleum Refinery
		Processing of nuclear fuel
	Glass, Cement, Other Non-Metallic Minerals	Manufacture of rubber and plastic products (25)
		Manufacture of glass and glass products
		Re-processing of secondary glass into new glass
		Manufacture of ceramic goods
		Manufacture of bricks, tiles and construction products, in baked clay
		Manufacture of cement, lime and plaster
		Re-processing of ash into clinker
		Manufacture of other non-metallic mineral products n.e.c.
	Machinery N.E.C.	Manufacture of machinery and equipment n.e.c. (29)
	Other Mining	Mining of uranium and thorium ores (12)
		Mining of iron ores
		Mining of copper ores and concentrates
		Mining of nickel ores and concentrates
		Mining of aluminium ores and concentrates
		Mining of precious metal ores and concentrates
		Mining of lead, zinc and tin ores and concentrates
		Mining of other non-ferrous metal ores and concentrates
		Quarrying of stone
		Quarrying of sand and clay

		Mining of chemical and fertilizer minerals, production of salt, other mining and quarrying n.e.c.
	Rubber and Plastic Products	Chemicals nec
Manufacturing n.e.s.	Electrical and Optical Equipment	Manufacture of office machinery and computers (30)
		Manufacture of electrical machinery and apparatus n.e.c. (31)
		Manufacture of radio, television and communication equipment and apparatus (32)
		Manufacture of medical, precision and optical instruments, watches and clocks (33)
	Food, Beverages, and Tobacco	Processing of meat cattle
		Processing of meat pigs
		Processing of meat poultry
		Production of meat products nec
		Processing vegetable oils and fats
		Processing of dairy products
		Processed rice
		Sugar refining
		Processing of Food products nec
		Manufacture of beverages
		Manufacture of fish products
		Manufacture of tobacco products (16)
	Manufacturing, N.E.C., Recycling	Manufacture of furniture; manufacturing n.e.c. (36)
		Recycling of waste and scrap
		Recycling of bottles by direct reuse
	Pulp and Paper	Pulp
		Re-processing of secondary paper into new pulp
		Paper
		Publishing, printing and reproduction of recorded media (22)
	Textiles, Textile Products, and Leather	Manufacture of textiles (17)
		Manufacture of wearing apparel; dressing and dyeing of fur (18)
		Tanning and dressing of leather; manufacture of luggage, handbags, saddlery, harness and footwear (19)
	Transport Equipment	Manufacture of motor vehicles, trailers and semi-trailers (34)
		Manufacture of other transport equipment (35)
	Wood; Wood and Cork Products	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials (20)
		Re-processing of secondary wood material into new wood material
Services	Electricity Generation	Production of electricity by coal
		Production of electricity by gas
		Production of electricity by nuclear
		Production of electricity by hydro

	Production of electricity by wind
	Production of electricity by petroleum and other oil derivatives
	Production of electricity by biomass and waste
	Production of electricity by solar photovoltaic
	Production of electricity by solar thermal
	Production of electricity by tide, wave, ocean
	Production of electricity by Geothermal
	Production of electricity nec
	Transmission of electricity
	Distribution and trade of electricity
Land, pipeline, air, and sea transportation	Transport via railways
	Other land transport
	Transport via pipelines
	Sea and coastal water transport
	Inland water transport
	Air transport (62)
	Supporting and auxiliary transport activities; activities of travel agencies (63)
Services and all other industries	Manufacture of gas; distribution of gaseous fuels through mains
	Steam and hot water supply
	Collection, purification and distribution of water (41)
	Construction (45)
	Re-processing of secondary construction material into aggregates
	Sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motor cycles parts and accessoiries
	Retail sale of automotive fuel
	Wholesale trade and commission trade, except of motor vehicles and motorcycles (51)
	Retail trade, except of motor vehicles and motorcycles; repair of personal and household goods (52)
	Hotels and restaurants (55)
	Post and telecommunications (64)
	Financial intermediation, except insurance and pension funding (65)
	Insurance and pension funding, except compulsory social security (66)
	Activities auxiliary to financial intermediation (67)
	Real estate activities (70)
	Renting of machinery and equipment without operator and of personal and household goods (71)
	Computer and related activities (72)
	Research and development (73)
	Other business activities (74)
	Public administration and defence; compulsory social security (75)
	Education (80)
	Health and social work (85)

	Incineration of waste: Food
	Incineration of waste: Paper
	Incineration of waste: Plastic
	Incineration of waste: Metals and Inert materials
	Incineration of waste: Textiles
	Incineration of waste: Wood
	Incineration of waste: Oil/Hazardous waste
	Biogasification of food waste, incl. land application
	Biogasification of paper, incl. land application
	Biogasification of sewage slugde, incl. land application
	Composting of food waste, incl. land application
	Composting of paper and wood, incl. land application
	Waste water treatment, food
	Waste water treatment, other
	Landfill of waste: Food
	Landfill of waste: Paper
	Landfill of waste: Plastic
	Landfill of waste: Inert/metal/hazardous
	Landfill of waste: Textiles
	Landfill of waste: Wood
	Activities of membership organisation n.e.c. (91)
	Recreational, cultural and sporting activities (92)
	Other service activities (93)
	Private households with employed persons (95)
	Extra-territorial organizations and bodies

Table A6 – Mapping between model's regions and EXIOBASE's regions

Our regions		Shapiro's regions	
Aggregated	EXIOBASE	Aggregated	EXIOBASE
Australia	Australia	China	China
Belgium, Netherlands, and Luxembourg	Belgium	Eastern Europe	Bulgaria
	Luxembourg		Czech Republic
	Netherlands		Estonia
Brazil	Brazil		Hungary
Canada	Canada		Lithuania
China	China		Latvia
Eastern EU countries in OECD data	Czech Republic		Poland
	Estonia		Romania
	Hungary		Russia
	Lithuania		Slovenia
	Latvia		Slovakia
	Poland	Indian Ocean	Indonesia
	Slovenia		India
	Slovakia	Latin America	Brazil
France	France		Mexico
Germany	Germany	North America	Canada
India	India		United States
Indonesia	Indonesia	Northern Europe	Denmark
Italy	Italy		Finland
Japan	Japan		United Kingdom
Mexico	Mexico		Ireland
Non EU European countries	Switzerland		Norway
	Turkey		Sweden
Nordic countries in the EU	Denmark	Pacific Ocean	Australia
	Finland		Japan
	Sweden		South Korea
Norway	Norway		Taiwan
Other EU countries in OECD data	Austria	Rest of the World	Switzerland
	Cyprus		Croatia
	Greece		Rest of Asia and Pacific
	Ireland		Rest of Europe
	Portugal		Rest of Africa
Other EU countries not in OECD data	Bulgaria		Rest of America
	Croatia		Rest of Middle East
	Malta		South Africa
	Romania	Southern Europe	Cyprus
Rest of the World	Rest of Asia and Pacific		Spain
	Rest of Europe		Greece
	Rest of Africa		Italy
	Rest of America		Malta
	Rest of Middle East		Portugal
	South Africa		Turkey
	Taiwan	Western Europe	Austria
Russia	Russia		Belgium
South Korea	South Korea		Germany
Spain	Spain		France
United Kingdom	United Kingdom		Luxembourg
United States	United States		Netherlands