Greening Ricardo: Environmental Comparative Advantage and the Environmental Gains From Trade *

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Abstract

We show that climate policy can unlock large environmental gains from trade by inducing economies to specialize according to their environmental comparative advantage. We explore the effects of a carbon tax in a quantitative trade model. In our benchmark, a \$100/tCO_2e carbon tax reduces global greenhouse gas emissions by 44.7%. The environmental gains from trade account for roughly one-third of the abatement from the non-technique margins—scale, industry composition, and international sourcing—with the technique effect the largest margin. This finding holds for a wide range of carbon tax rates and sufficiently broad policy coverage.

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1 Introduction

In this paper, we show that climate policy can unlock large environmental gains from trade by inducing economies to specialize according to their environmental comparative advantage. The main idea is that global greenhouse gas emissions fall when economies specialize in the goods they produce relatively cleanly, just as global real incomes rise when economies specialize in the goods they produce relatively efficiently. While our notion of environmental comparative advantage therefore builds directly on the classic idea of economic comparative advantage, it has so far not been quantified as a distinct margin in global assessments of climate policy.

This matters, since our results provide a strong counterpoint to the common concern that international trade is an obstacle in the fight against climate change. While it is true that international trade causes transport emissions, and that under incomplete climate policy it can contribute to carbon leakage, our analysis shows that it can also be a powerful tool to reduce production emissions, which account for the vast majority of emissions embodied in global production and trade.[1] More broadly, it offers a more inclusive perspective on sustainable development by highlighting that economies do not need to sacrifice the economic gains from trade in the name of climate stewardship but can pursue both objectives concurrently.

We make this point by exploring the effects of a carbon tax in a quantitative trade model of the world economy, with 64 regions and 44 industries linked through trade and input-output relationships. A carbon tax raises the price of every good in line with the emissions embodied in its production, and the world economy adjusts along every margin: production falls, shifts toward cleaner industries and cleaner economies, and becomes cleaner itself as producers change how much energy they use, which fossil fuels they burn, and where they buy them.[2]

[1] Our model includes land, sea, and air transportation as intermediate services. Under our accounting, these transportation sectors—which bundle freight and passenger services—account for 5.2% of baseline global greenhouse gas emissions; the remainder arises at other points of production.

[2] The technique effect in our model captures substitution between energy and non-energy inputs and among fuels. It does not capture endogenous clean innovation or the international diffusion of production

Our benchmark experiment imposes a uniform global carbon tax of \$100 per tCO_2e on all goods in all economies, and we consider a wide range of tax rates and policy coverages around it. The benchmark is equivalent to a global cap-and-trade system that delivers the same permit price and rebates the revenues in the same way. We do not model how greenhouse gas emissions cause climate change or how climate change affects economic activity.[3]

To isolate the environmental gains from trade, we decompose the emissions reduction induced by the carbon price into four effects: a scale effect (the level of global production), a composition effect (reallocation across industries), a green sourcing effect (reallocation across economies within industries), and a technique effect (emissions per unit of output within economy–industry pairs). The scale, composition, and technique effects also operate in a closed economy; green sourcing does not: a closed economy can produce less, shift production across industries, or change production techniques, but it cannot source a given good from a cleaner foreign producer, and the emissions reduction from this trade-specific margin is what we call the environmental gains from trade.

Our main result is that the environmental gains from trade account for roughly one-third of the abatement from the non-technique margins. In our benchmark experiment, the \$100 carbon price reduces global greenhouse gas emissions by 44.7%. The technique effect is the largest single margin, at 57.9%; the remainder reflects the scale, composition, and green sourcing effects, which contribute 6.2%, 22.8%, and 13.1%. Among these three margins—the margins of an accounting with fixed emissions intensities—green sourcing accounts for 31.0%.[4] Environmental comparative advantage is thus a quantitatively important channel through which carbon pricing reduces emissions, alongside the adjustment of production techniques.

technologies.

[3]Well-known examples of integrated assessment models capturing these considerations include Nordhaus (1993), Nordhaus (2018), Golosov et al. (2014), and Boyce (2018).

[4]Varying the substitution elasticities one at a time across their plausible ranges, the technique effect accounts for 52.8–69.7% of total abatement, the green sourcing effect for 10.1–15.0%, and the green sourcing share among the three non-technique margins for 28.9–35.8%. Moving all elasticity families jointly to the corners that minimize and maximize green sourcing widens these ranges to 49.2–75.6%, 6.9–17.8%, and 28.1–36.1%, respectively. The accounting is robust throughout. See Section 4.

Two further findings clarify the role of trade. First, even carbon prices as high as $1,000 per tCO_2e leave world trade relative to world gross production largely unchanged: carbon pricing changes the composition and geography of production, not the degree of trade integration. Second, the green sourcing effect can work in either direction, and its sign depends on who taxes. When a coalition of relatively clean economies prices carbon, production relocates toward unregulated and often more emissions-intensive producers—the effect turns negative, which is conventional carbon leakage; when the taxing coalition includes the browner large producers, the same margin contributes to abatement, and under broad coverage it delivers the environmental gains from trade.

To the best of our knowledge, we provide the first global estimate of the environmental gains from trade driven by environmental comparative advantage. We make this contribution using well-known tools at the intersection of international and environmental economics: a quantitative trade model in the spirit of Caliendo and Parro (2015), extended to allow substitution between energy and non-energy inputs, substitution among fossil fuels, and upward-sloping fossil-energy supply; and a decomposition of emissions changes that builds on the scale-composition-technique tradition dating back to Grossman and Krueger (1991). The novelty of the paper lies not in the individual tools, but in the perspective they allow us to bring to the relationship between trade and climate policy.

Our analysis contributes first to the longstanding literature on trade and the environment, which since Grossman and Krueger (1991) and Copeland and Taylor (2003) has organized changes in pollution into scale, composition, and technique effects. Copeland and Taylor (2005) show theoretically that goods trade can alter both the incidence and the effectiveness of climate policy, while a large subsequent literature studies carbon leakage under incomplete regulation (Felder and Rutherford, 1993; Larch and Wanner, 2017; Kortum and Weisbach, 2021). Empirical decompositions such as Levinson (2009) and Shapiro and Walker (2018) emphasize the quantitative importance of the technique effect, and Baylis et al. (2014) show that leakage itself can be negative. Relative to this tradition, we separate the broad composition margin into reallocation across industries and reallocation across economies within an industry, and quantify the international sourcing margin itself alongside an endogenous technique effect.

The paper also contributes to the growing literature that applies quantitative trade models with input-output linkages to environmental and climate policy, pioneered by Shapiro (2016) and extended to environmental regulation, trade-policy instruments, climate agreements, and multinational production (Duan et al., 2021; Caliendo et al., 2024; Farrokhi and Lashkaripour, 2025; Farrokhi et al., 2025; Garcia-Lembergman et al., 2025a). Where this literature largely studies optimal policy and the welfare consequences of trade and climate policy, we take carbon prices as given and ask through which margins they reduce global emissions. In complementary work, Le Moigne et al. (2026) study the distributional incidence of global carbon pricing; the present paper focuses on the sources of aggregate emissions reductions.

Finally, our environmental-comparative-advantage mechanism is related to research on trade as adaptation to climate change: Costinot et al. (2016) and Gouel and Laborde (2021) show how reallocation guided by comparative advantage can mitigate the economic consequences of climate-induced productivity changes, whereas we study mitigation of emissions in response to carbon pricing. Recent spatial climate models incorporate additional margins such as geography, migration, innovation, and local climate damages (Cruz and Rossi-Hansberg, 2024; Conte et al., 2025); we abstract from these in order to isolate the role of international production reallocation.

The remainder of the paper is organized as follows. Section 2 presents the model and emissions decomposition. Section 3 describes the calibration and data. Section 4 reports the aggregate results, the decomposition, and the experiments with incomplete policy coverage. Section 5 concludes.

2 Model

2.1 Setup

We work with a multi-economy, multi-industry model with roundabout input-output linkages, building on the structure of Armington (1969), which shares the aggregate predictions of Caliendo and Parro (2015), itself built on the Ricardian model of Eaton and Kortum (2002). Production and consumption are organized around a nested treatment of energy that makes economy–industry emissions intensities respond endogenously to carbon pricing.

There are N countries indexed by i (origin) and j (destination) and S industries indexed by s (supplying) and r (demanding). Each country produces a single variety of each industry, and trade is subject to iceberg trade costs $\tau_{isj} \geq 1$ with $\tau_{isi} = 1$. Countries are endowed with an inelastic, internationally immobile supply of labor L_j.

Industries are partitioned into a set of energy industries $\mathcal{E}$ and a set of non-energy industries $\mathcal{N}$. The energy sector comprises five industries: coal, oil, and gas extraction; coke and refined petroleum; and electricity, following the energy-sector architecture of Garcia-Lembergman et al. (2025a). The mining industries $\mathcal{M} \subset \mathcal{E}$—the three fossil fuels—rely on a fixed natural resource and therefore exhibit decreasing returns and upward-sloping supply; all other industries, including refined petroleum and electricity, operate under constant returns. Sections 2.2 and 2.3 develop the demand and production structure; Section 2.4 introduces carbon taxation.

2.2 Demand

Households in each country j have nested CES preferences over the varieties of each industry, the industries within the energy and non-energy sectors, and the two sectors themselves. We describe the three nests from the bottom up.

Varieties within industries. For each industry s and destination j, consumption of the varieties supplied by different origin countries is aggregated into an industry composite

$$Q_{sj} = \left(\sum_{i=1}^{N} a_{isj}^{1/\sigma_s} \, q_{isj}^{(\sigma_s - 1)/\sigma_s} \right)^{\sigma_s/(\sigma_s - 1)},$$

where $\sigma_s > 0$ is the elasticity of substitution across origins within industry s and $a_{isj} > 0$ is a distribution parameter. The associated industry price index is

$$P_{sj} = \left(\sum_{i=1}^{N} a_{isj} \, (p_{isj}^{u})^{1-\sigma_s} \right)^{1/(1-\sigma_s)},$$

with p_{isj}^{u} the user price of origin i's variety in destination j, inclusive of any carbon wedge; Section 2.4 describes how it is determined. Absent carbon taxation, p_{isj}^{u} is simply the producer price grossed up by the iceberg trade cost. Letting $E_{sj} = P_{sj} Q_{sj}$ denote expenditure on industry s in country j, CES demand for each origin's variety is

$$q_{isj} = a_{isj} \, (p_{isj}^{u})^{-\sigma_s} \, P_{sj}^{\sigma_s - 1} \, E_{sj}.$$

Industries within sectors. The industry composites are aggregated into an energy bundle and a non-energy bundle. The energy bundle combines the five energy industries,

$$Q_j^{\mathcal{E}} = \left(\sum_{s \in \mathcal{E}} b_{sj}^{1/\rho_{\mathcal{E}}} \, Q_{sj}^{(\rho_{\mathcal{E}} - 1)/\rho_{\mathcal{E}}} \right)^{\rho_{\mathcal{E}}/(\rho_{\mathcal{E}} - 1)}, \qquad P_j^{\mathcal{E}} = \left(\sum_{s \in \mathcal{E}} b_{sj} \, P_{sj}^{1-\rho_{\mathcal{E}}} \right)^{1/(1-\rho_{\mathcal{E}})},$$

where $\rho_{\mathcal{E}} > 0$ is the elasticity of substitution across energy industries. The non-energy bundle combines the remaining industries,

$$Q_j^{\mathcal{N}} = \left(\sum_{s \in \mathcal{N}} c_{sj}^{1/\rho_{\mathcal{N}}} \, Q_{sj}^{(\rho_{\mathcal{N}} - 1)/\rho_{\mathcal{N}}} \right)^{\rho_{\mathcal{N}}/(\rho_{\mathcal{N}} - 1)}, \qquad P_j^{\mathcal{N}} = \left(\sum_{s \in \mathcal{N}} c_{sj} \, P_{sj}^{1-\rho_{\mathcal{N}}} \right)^{1/(1-\rho_{\mathcal{N}})},$$

with elasticity $\rho_{\mathcal{N}} > 0$. When an elasticity equals one, the corresponding expressions are understood as their Cobb-Douglas limits; our calibration sets $\rho_{\mathcal{N}} = 1$. Writing $E_j^{\mathcal{E}} = P_j^{\mathcal{E}} Q_j^{\mathcal{E}}$ and $E_j^{\mathcal{N}} = P_j^{\mathcal{N}} Q_j^{\mathcal{N}}$ for sector expenditures, industry expenditures within each bundle satisfy

$$E_{sj} = b_{sj}\, P_{sj}^{1-\rho_{\mathcal{E}}}\, (P_j^{\mathcal{E}})^{\rho_{\mathcal{E}}-1}\, E_j^{\mathcal{E}} \quad (s \in \mathcal{E}), \qquad E_{sj} = c_{sj}\, P_{sj}^{1-\rho_{\mathcal{N}}}\, (P_j^{\mathcal{N}})^{\rho_{\mathcal{N}}-1}\, E_j^{\mathcal{N}} \quad (s \in \mathcal{N}).$$

Energy versus non-energy. At the top of the nest, the two sector bundles combine into aggregate consumption,

$$U_j = \left[\chi_j^{1/\varepsilon}\, (Q_j^{\mathcal{E}})^{(\varepsilon-1)/\varepsilon} + (1-\chi_j)^{1/\varepsilon}\, (Q_j^{\mathcal{N}})^{(\varepsilon-1)/\varepsilon}\right]^{\varepsilon/(\varepsilon-1)},$$

where $\varepsilon > 0$ is the elasticity of substitution between energy and non-energy and $\chi_j \in (0,1)$ is a distribution parameter. The aggregate consumption price index is

$$P_j = \left[\chi_j\, (P_j^{\mathcal{E}})^{1-\varepsilon} + (1-\chi_j)\, (P_j^{\mathcal{N}})^{1-\varepsilon}\right]^{1/(1-\varepsilon)}.$$

Given total household income I_j (defined in Section 2.5), expenditure on the two bundles is

$$E_j^{\mathcal{E}} = \chi_j \left(\frac{P_j^{\mathcal{E}}}{P_j}\right)^{1-\varepsilon} I_j, \qquad E_j^{\mathcal{N}} = (1-\chi_j) \left(\frac{P_j^{\mathcal{N}}}{P_j}\right)^{1-\varepsilon} I_j.$$

2.3 Production

Firms produce under perfect competition, combining labor and an aggregate intermediate input. The intermediate input is assembled through the same three-level nest as household demand, so that firms, like households, substitute across origins within each industry, across industries within the energy and non-energy sectors, and between the two sectors.

Intermediate inputs. A firm in industry r and country j combines the varieties of each supplying industry into an industry-level input, the industry inputs into energy and non-energy bundles, and the two bundles into an aggregate intermediate X_{rj}. The nest mirrors household demand, with the same elasticities σ_s, $\rho_{\mathcal{E}}$, $\rho_{\mathcal{N}}$, and ε at the corresponding levels, but with firm-specific distribution parameters. At the lowest level,

$$X_{srj} = \left(\sum_{i=1}^{N} {a^x_{isrj}}^{1/\sigma_s} \, x_{isrj}^{(\sigma_s - 1)/\sigma_s} \right)^{\sigma_s/(\sigma_s - 1)}, \qquad P_{srj} = \left(\sum_{i=1}^{N} a^x_{isrj} \, (p^u_{isj})^{1-\sigma_s} \right)^{1/(1-\sigma_s)},$$

where x_{isrj} is the use by industry r in country j of the variety of industry s from origin i, and a^x_{isrj} is a firm-side distribution parameter. The energy and non-energy intermediate bundles and the aggregate intermediate are formed exactly as in household demand, yielding an aggregate intermediate price index P^X_{rj}.[5] The user price p^u_{isj} enters firms' input choices just as it enters household choices.

Non-energy and non-mining energy industries. For non-energy industries $r \in \mathcal{N}$ and for the non-mining energy industries, output combines labor and the aggregate intermediate under constant returns,

$$y_{rj} = A_{rj} \, L_{rj}^{\alpha_{rj}} \, X_{rj}^{1-\alpha_{rj}}, \qquad \alpha_{rj} \in (0, 1),$$

where A_{rj} is productivity and α_{rj} the labor share. Cost minimization gives the unit cost

$$c_{rj} = \frac{1}{A_{rj}} \left(\frac{w_j}{\alpha_{rj}} \right)^{\alpha_{rj}} \left(\frac{P^X_{rj}}{1 - \alpha_{rj}} \right)^{1-\alpha_{rj}},$$

and under perfect competition the untaxed producer price equals unit cost, $p^0_{rj} = c_{rj}$. Because returns are constant, the producer price is independent of the scale of output and supply is perfectly elastic at p^0_{rj}.

[5] The full set of firm-side nesting equations is identical in form to the demand nest of Section 2.2, with x-superscripted distribution parameters; we state them in Appendix A.

Mining industries. For the mining industries $r \in \mathcal{M}$—coal, oil, and gas—production additionally requires a fixed, country-specific natural resource F_{rj},

$$y_{rj} = A_{rj}\, F_{rj}^{\gamma_{rj}}\, L_{rj}^{\alpha_{rj}}\, X_{rj}^{\beta_{rj}}, \qquad \alpha_{rj} + \beta_{rj} + \gamma_{rj} = 1,$$

where γ_{rj} is the share of the fixed resource. Because the resource is fixed in supply, the mining technology has decreasing returns in the variable inputs, labor and intermediates. Conditional on the resource, cost minimization over labor and intermediates yields

$$p^0_{rj} = MC_{rj}(y_{rj}) \propto y_{rj}^{\gamma_{rj}/(1-\gamma_{rj})},$$

so that the untaxed producer price of a fossil fuel increases in the quantity extracted: fossil-fuel supply slopes upward.[6] A share γ_{rj} of mining revenue accrues to the owners of the natural resource as rents, which enter household income in the country where the resource is located. Because supply slopes upward, a carbon price that lowers the demand for fossil fuels reduces their pre-tax price: the fixed factor makes fuel prices, not only quantities, respond to climate policy.

2.4 Carbon taxation

Prices and carbon wedges. We distinguish four prices, which makes the treatment of the carbon tax transparent. The *untaxed producer price* p^0_{is} is determined by technology and input prices alone. If carbon is taxed at the point of production, the *producer-tax-inclusive price* is

$$p^P_{is} \equiv p^0_{is}\big(1 + t^P_{is}\big),$$

where $t^P_{is} \geq 0$ is the ad valorem-equivalent producer-side carbon wedge. After iceberg trade costs, the *delivered price* is $\tilde{p}_{isj} \equiv \tau_{isj}\, p^P_{is}$. If carbon is taxed at the point of use, the *user*

[6] The full marginal-cost expression and the implied supply elasticity are given in Appendix A.

price faced by households and firms in destination j is

$$p^u_{isj} \equiv \tilde{p}_{isj}\big(1 + t^C_{isj}\big),$$

where $t^C_{isj} \geq 0$ is the destination-side carbon wedge. Combining the two wedges gives the general pricing relation

$$p^u_{isj} = \tau_{isj}\, p^0_{is}\big(1 + t^P_{is}\big)\big(1 + t^C_{isj}\big). \tag{1}$$

Households and firms choose among varieties at the user price p^u_{isj}, while the untaxed price p^0_{is} governs the supply side.

Destination- and origin-based schemes. The general pricing relation (1) nests two polar carbon-tax schemes. Under *destination-based* taxation, carbon is priced where a good is used: producer prices are untaxed, $t^P_{is} = 0$, and the user price carries the wedge, $p^u_{isj} = \tau_{isj}\, p^0_{is}(1 + t^C_{isj})$. Under *origin-based* taxation, carbon is priced where a good is produced: the producer price carries the wedge, $p^P_{is} = p^0_{is}(1 + t^P_{is})$, and is passed through to every destination. The formulation also accommodates hybrid schemes such as climate clubs and border adjustments. Because the tax base books each fuel's carbon on the fuel product, an origin-based tax is, for the fuel industries, an extraction-side tax: under uniform global coverage it implements the same allocation as the destination-based benchmark, while under incomplete coverage the two diverge.

The tax base. The tax base is the carbon content of fuels—including the fugitive emissions of their extraction—and the direct emissions of agriculture; no other product carries a direct wedge. A uniform carbon price therefore reaches most of the economy indirectly: taxing the few products that carry carbon raises fuel costs everywhere, and all other products feel the tax through the cost of the fuel embodied in their inputs. Formally, a carbon price of $\tau^{\mathrm{CO_2}}$

dollars per ton translates into product-specific ad valorem wedges

$$t_{isj}^{C} = \tau^{\mathrm{CO_2}} \frac{\tilde{\delta}_{is}}{p_{is}^{0}},$$

where the tax-base intensity $\tilde{\delta}_{is}$ is the carbon booked on the product per unit of output—the physical carbon content of a fuel together with the fugitive emissions of its extraction, the direct emissions of agriculture—and dividing by the producer price expresses the charge per dollar of the product. Because the rate applies to the delivered value, the carbon of units lost to iceberg trade costs is taxed as well: every ton emitted in production is charged $\tau^{\mathrm{CO_2}}$. Through the nested structure of Sections 2.2 and 2.3, the wedge raises the user price of energy varieties relative to non-energy ones and shifts expenditure down the nest: away from the energy bundle at the top, toward cleaner fuels within the energy bundle, and toward cleaner origins within each industry.

Emissions sources. Direct emissions are measured in carbon-dioxide equivalent and arise from three sources. The first is carbon dioxide from the combustion of fossil fuels, which occurs at every stage of production. The second is fugitive emissions from fossil-fuel extraction. The third is direct emissions from agriculture and associated land use. Combustion and fugitive emissions are both attributed to the fossil-fuel products—combustion to the fuels themselves, fugitive emissions to extraction—so that the greenhouse gases associated with a fuel are priced exactly once, when the fuel is purchased, and not again when the goods made with it are sold downstream. The production processes of other industries generate no separately taxed emissions.

Revenue. Carbon-tax revenue is rebated lump-sum to households. Under destination-based taxation, the revenue collected in country j is the carbon charge on its final and intermediate use,

$$T_j^C = \sum_{i,s} t_{isj}^{C}\, \tilde{p}_{isj}\, q_{isj} + \sum_{i,s,r} t_{isj}^{C}\, \tilde{p}_{isj}\, x_{isrj}.$$

Under origin-based taxation, revenue accrues to the producing country instead, $T_j^P = \sum_s t_{js}^P \, p_{js}^0 \, y_{js}$.

Benchmark. In our benchmark scenario, a uniform carbon tax is levied at the point of use on all products in all economies and rebated lump-sum to households in the economy of use, so that $t_{is}^P = 0$ and $p_{isj}^u = \tau_{isj} \, p_{is}^0 (1 + t_{isj}^C)$.[7] Incomplete coverage enters the policy experiments of Section 4, where we also discuss how destination- and origin-based taxation compare.

2.5 Equilibrium

Income. Household income in country j is the sum of labor income, the rents accruing to owners of the fixed natural resource in the country's mining industries, carbon-tax revenue, and an exogenous transfer,

$$I_j = w_j L_j + \sum_{r \in \mathcal{M}} R_{rj}^F + T_j^C + T_j^P + D_j,$$

where w_j is the wage, $R_{rj}^F = \gamma_{rj} \, p_{rj}^0 y_{rj}$ are resource rents, T_j^C and T_j^P are the destination- and origin-based carbon-tax revenues of Section 2.4, and D_j is a transfer that matches the country's aggregate trade imbalance in the data and is held fixed as a share of world income across counterfactuals.[8]

Market clearing. Labor is fully employed, $\sum_r L_{rj} = L_j$. Goods markets clear industry by industry: the output of industry s in country i equals demand from final consumers and

[7] Under uniform global coverage, the point of taxation is immaterial for the allocation: a destination-based (consumer) tax, an origin-based (producer) tax, and a cap-and-trade system delivering the same permit price implement the same allocation whenever the revenue is rebated to the same recipients. The schemes' natural formulations differ in which country's households receive the revenue; this difference affects the allocation only negligibly. We adopt the destination-based formulation because it renders the relative-price effects of the tax most transparent. The equivalence does not extend to incomplete coverage, where the point of taxation matters; we return to this in Section 4.4.

[8] Holding the transfers fixed in nominal levels would make counterfactual outcomes depend on the choice of numeraire; scaling them with world income keeps all reported objects invariant to it.

from firms in all destinations, inclusive of iceberg losses,

$$y_{is} = \sum_j \tau_{isj}\, q_{isj} + \sum_j \sum_r \tau_{isj}\, x_{isrj}.$$

Equilibrium. Given carbon wedges, trade costs, endowments, and the transfers $\{D_j\}$, an equilibrium is a set of wages, prices, and quantities such that households maximize utility, firms minimize cost and price at marginal cost, and the labor and goods markets clear in every country. We solve the model in exact hat algebra, expressing the equilibrium in proportional changes relative to the observed equilibrium so that the counterfactual depends only on benchmark expenditure shares, the elasticities, and the resource share γ_{rj}, without requiring unobserved productivity or preference levels. The full system of equilibrium conditions in changes, and the recursive procedure that recovers all prices and quantities from a small set of jointly determined objects, are given in Appendix A.

2.6 Emissions and the environmental gains from trade

Emissions accounting. Decomposing the change in emissions into economic margins requires first locating emissions at particular producers. We attribute each ton of greenhouse gas to the producer that physically emits it: coal, oil, and gas are burned by their purchaser; purchasers of refined petroleum burn the carbon passed through by the origin refinery, net of the refinery's own use; and fugitive and agricultural emissions arise in extraction and in agriculture and land use.[9]

Formally, let δ_{is} denote direct emissions per unit of output of industry s in country i

[9] We keep a share $f^{own} = 0.09$ of the fuel entering refining on the refining industry itself, anchored on conventional combustion accounts, and pass the remainder through to purchasers of refined petroleum in proportion to their purchases.

under this convention, measured in carbon-dioxide equivalent.[10] Emissions are

$$\text{GHG} = \sum_i \sum_s \delta_{is}\, y_{is}. \tag{2}$$

Because fuel sold to final demand—primarily refined petroleum—leaves the producer base, equation (2) covers 86.8% of baseline emissions; total emissions GHG^{tot} include the remainder. The headline reduction of Section 4.1 is computed on GHG^{tot} and does not depend on the attribution convention; the decomposition applies to equation (2).

A producer's emissions intensity moves with its inputs: δ_{is} falls as the firm uses less fuel per unit of output, shifts toward cleaner fuels, and buys its fuels from cleaner origins, while the fugitive and agricultural components are fixed per unit of output. Carbon pricing therefore lowers δ_{is} endogenously.

The four-effect decomposition. To isolate the environmental gains from trade, we totally differentiate equation (2). Let $y_s = \sum_i y_{is}$ be world output of industry s, $y = \sum_s y_s$ total world output, and let ϕ_{is} and ϕ_s denote the shares of producer (i, s) and of industry s in world emissions. The change in emissions then decomposes into four effects,

$$d \ln \text{GHG} = \underbrace{d \ln y}_{\text{scale (SC)}} + \underbrace{\sum_s \phi_s \, d \ln \tfrac{y_s}{y}}_{\text{composition (CO)}} + \underbrace{\sum_i \sum_s \phi_{is} \, d \ln \tfrac{y_{is}}{y_s}}_{\text{green sourcing (GS)}} + \underbrace{\sum_i \sum_s \phi_{is} \, d \ln \delta_{is}}_{\text{technique (TE)}}. \tag{3}$$

This is the central equation of the paper: it reflects the four channels through which carbon taxes reduce emissions in our model. First, they reduce the level of world output by moving the economy away from the output-maximizing laissez-faire equilibrium—the *scale effect*.[11] Second, they reallocate production toward greener industries by making browner

[10] This decomposition intensity differs by construction from the tax-base intensity $\tilde{\delta}_{is}$ of Section 2.4: the tax books a fuel's carbon on the fuel product itself, whereas the decomposition locates it at the producer that burns the fuel.

[11] In a neoclassical trade model like ours, the laissez-faire equilibrium maximizes world output valued at its own prices. This would differ in a model with climate damages, where the laissez-faire equilibrium would itself be distorted.

products relatively more expensive for final and intermediate consumers—the *composition effect*. Third, they reallocate production toward greener economies within industries by making products from browner economies relatively more expensive—the *green sourcing effect*. Fourth, they induce producers to lower their emissions intensities—by using less fuel per unit of output, shifting toward cleaner fuel mixes, and sourcing each fuel from cleaner origins—the *technique effect*. The scale, composition, and technique effects also operate in a closed economy; the green sourcing effect requires international trade, and the emissions reduction it delivers is what we call the environmental gains from trade.

Decomposing the technique effect further. Because the model has no abatement technology, a producer's emissions intensity moves only with its fuel inputs. The technique term of equation (3) can therefore be decomposed one level further, along the same margins that organize equation (3) itself: producers can use less fuel per unit of output, shift toward cleaner fuel mixes, and source each fuel from cleaner origins. Appendix A.4 constructs this decomposition, weighting each margin by the share of world emissions it carries; we denote the resulting components $\mathrm{SC}^{\mathrm{TE}}$, $\mathrm{CO}^{\mathrm{TE}}$, and $\mathrm{GS}^{\mathrm{TE}}$ after the output-level margins they mirror. Adding each component to its output-level counterpart then yields a coarser classification of equation (3),

$$d \ln \mathrm{GHG} = \underbrace{\left(\mathrm{SC} + \mathrm{SC}^{\mathrm{TE}}\right)}_{\text{augmented scale}} + \underbrace{\left(\mathrm{CO} + \mathrm{CO}^{\mathrm{TE}}\right)}_{\text{augmented composition}} + \underbrace{\left(\mathrm{GS} + \mathrm{GS}^{\mathrm{TE}}\right)}_{\text{augmented green sourcing}}, \tag{4}$$

with an augmented scale, composition, and green sourcing effect. The appendix details the construction and the sense in which the technique effect ultimately reduces to scale and substitution. We use equation (3) for all headline results and revisit this refinement in Section 4.2.

2.7 A Ricardian illustration

The environmental gains from trade are easiest to see in a stripped-down version of the model. Consider two countries, Green and Brown, and two industries, Clean and Dirty, in a simple 2×2 Ricardian setting. Suppose Green has lower emissions intensities in both industries—an environmental absolute advantage in each—and that its intensity advantage is more pronounced in Clean, giving it an environmental comparative advantage there. Suppose production is diversified in the benchmark.[12]

A uniform carbon tax raises the relative cost of emissions-intensive production. Because Green is cleaner in both industries, the tax makes it more competitive in both relative to Brown; because its advantage is larger in Clean, the competitiveness gain is larger there. Labor-market clearing then requires Green's wage to rise relative to Brown's, which offsets its absolute advantage and restores Brown's competitiveness in Dirty. The result is specialization according to environmental comparative advantage: Green expands in Clean and Brown expands in Dirty.

At first glance the second reallocation looks troubling—dirty production concentrates in the browner country. But it is the flip side of clean production concentrating in the much greener one: because Green's intensity advantage is proportionally larger in Clean than in Dirty, the emissions saved by moving Clean production to Green typically exceed the emissions added by moving Dirty production to Brown. Global emissions fall on net. Comparative, not absolute, advantage governs the outcome. This is the green sourcing effect in its simplest form; under narrow policy coverage the same margin can turn negative, which is the carbon leakage we return to in Section 4.4.

[12]This is a knife-edge case in the textbook 2×2 model; with differentiated varieties, as in our quantitative model, diversification is generic.

3 Calibration

3.1 Data

Data on trade flows for both intermediate and final goods are sourced from the OECD Inter-Country Input-Output (ICIO) tables (OECD, 2023). These tables cover the entire world economy, broken down into 45 industries and 67 economies, including an aggregate Rest of the World, from 1995 to 2018. We calibrate the model to the 2018 data and use the entire panel when estimating the trade elasticities (Section 3.3). Because the ICIO records the mining of energy products as a single industry, we split it into coal, oil, and gas extraction using the gross-output shares of the corresponding Exiobase fuel products (Stadler et al., 2018); together with the aggregation of smaller economies into the rest-of-world composite and the consolidation of three further ICIO industries (mining support services, motor vehicles with other transport equipment, and other services with household activities), this yields the model's 64 regions and 44 industries.

Greenhouse gas emissions are measured in carbon-dioxide equivalent and constructed source by source, under the attribution convention of Section 2.6. Combustion emissions are built from the fuel quantities implied by input-output purchases and fuel prices: emissions factors for coal, oil, and gas of 3.81, 2.94, and 2.06 tCO_2 per ton of oil equivalent—the U.S. Energy Information Administration (EIA) factors, as compiled by Garcia-Lembergman et al. (2025b)—are converted into emissions per dollar of fuel using country-specific fuel prices derived from International Energy Agency (IEA) data (IEA, 2023). Direct emissions from agriculture and land use come from the Emissions Totals of FAOSTAT, the statistical database of the UN Food and Agriculture Organization (FAO, 2023), using the 'Agricultural Land' categories and excluding on-farm energy use to avoid double counting with fuel combustion. FAOSTAT converts non-CO_2 gases at the 100-year global warming potentials of the IPCC's Fifth Assessment Report (AR5), whereas the EDGAR series below uses Fourth Assessment (AR4) values; we retain each source's native convention, which affects total baseline emissions by less than 2.5%. Fugitive emissions from fossil-fuel extraction come from the European Commission's Emissions Database for Global Atmospheric Research (EDGAR; European Commission, 2023), IPCC inventory category 1.B, allocated to the three fuel-extraction industries in proportion to output, with non-CO_2 gases converted to CO_2 equivalents at the 100-year global warming potentials of the IPCC's Fourth Assessment Report (AR4). The construction of both non-combustion series follows Le Moigne et al. (2026). We do not separately measure industrial-process or waste emissions.

Finally, the OECD's Trade in Embodied CO_2 dataset (OECD, 2021), which records combustion by burning industry under conventional inventory accounting, plays three auxiliary roles. It isolates the agriculture and land-use component: the FAOSTAT series enters our data through an account augmented with agriculture, and differencing the augmented and unaugmented accounts recovers it. It anchors the refining own-use share f^{own} of Section 2 as the ratio of its refining combustion to the carbon booked at refining under first-purchaser attribution. And it provides the conventional-inventory benchmark against which the attribution conventions of Section 4.2 can be read. Appendix E details each source's native attribution and its transformation into the model's objects.

3.2 Calibration

The energy-nest parameters follow the estimates of Garcia-Lembergman et al. (2025a): the elasticity of substitution between energy and non-energy inputs is $\varepsilon = 0.45$ and the elasticity across energy industries is $\rho_{\mathcal{E}} = 0.45$. Within the non-energy bundle we set $\rho_{\mathcal{N}} = 1$, the Cobb-Douglas case (Garcia-Lembergman et al., 2025a; Krusell and Smith, 2022). The revenue share of the fixed natural resource in the mining industries, γ_{rj}, is set to a common value of 0.25, the share Garcia-Lembergman et al. (2025b) estimate from the pooled supply curves of the three fuels. Through the mining technology of Section 2.3, this share pins the supply elasticity of each fossil fuel at $(1 - \gamma_{rj})/\gamma_{rj} = 3$.

The remaining production parameters are recovered from the input-output data. For each mining industry, the intermediate-input share β_{rj} is measured directly from the use table and the labor share is the residual $\alpha_{rj} = 1 - \gamma_{rj} - \beta_{rj}$; for all other industries the labor share is one minus the intermediate share. The refining own-use share $f^{own} = 0.09$ is anchored on the conventional combustion accounts of Section 3.1, as described in Section 2.6.

The robustness exercises of Section 4.2 vary each elasticity family over the range supported by the literature. The trade elasticities are scaled up and down by a common factor so that their output-weighted mean spans 2.5–5.1 (Bajzik et al., 2020). The energy/non-energy elasticity ε varies over 0.1–0.9, the within-energy elasticity $\rho_{\mathcal{E}}$ over 0.45–2 (Stern, 2012), and the non-energy elasticity $\rho_{\mathcal{N}}$ over 0.2–2 (Atalay, 2017; Peter and Ruane, forthcoming).

3.3 Estimation

We estimate the trade elasticities σ_s using the standard methodology of Caliendo and Parro (2015), which identifies them from the impact of import tariffs on trade flows in a fixed-effects model; we use all available years of our dataset. Estimating a single elasticity per industry is consistent with the model, in which households and firms share substitution elasticities at each nest. Elasticities that are not estimated with statistical significance—notably in the service sectors, which lack tariff variation—are replaced with the mean of the retained estimates. The estimates have a simple mean of 3.52 and an output-weighted mean of 3.61, ranging from 0.65 for coal extraction to 5.86 for basic metals. The below-unity elasticity for coal implies that a carbon tax reallocates coal purchases across origins only weakly. The full set of estimates is reported in Appendix F.[13]

3.4 Solution and decomposition method

To take the model to the data, we use the Dekle et al. (2007) exact hat algebra: expressing the equilibrium conditions in changes relative to the baseline eliminates the need to esti-

[13] We have also experimented using the alternative methodology of Fontagné et al. (2022) and found that our main results were robust to this variation.

mate the preference and productivity shifters and the iceberg trade costs, and matches the observed global pattern of production and international trade by construction. To solve for a counterfactual equilibrium given a schedule of carbon taxes, we solve jointly for the wage changes, the intermediate-input price indices, and the outputs of the mining industries; all remaining prices and quantities follow recursively, as discussed in Section 2.5 and detailed in Appendix A.3. We normalize world labor income to its baseline value; all reported objects are invariant to this normalization.

Because the decomposition of equation (3) is exact only for infinitesimal changes, we compute it as a line integral along a path that divides the carbon-tax change into one hundred steps, weighting each increment with log-mean (LMDI) weights; the reported contributions are shares of the finite change in emissions, expressed relative to baseline emissions, rather than log points. Output aggregates are measured in values rather than quantities: we deflate observed values by the model's price changes and aggregate the resulting constant-baseline-price outputs, so that the shares entering the decomposition are value shares.[14]

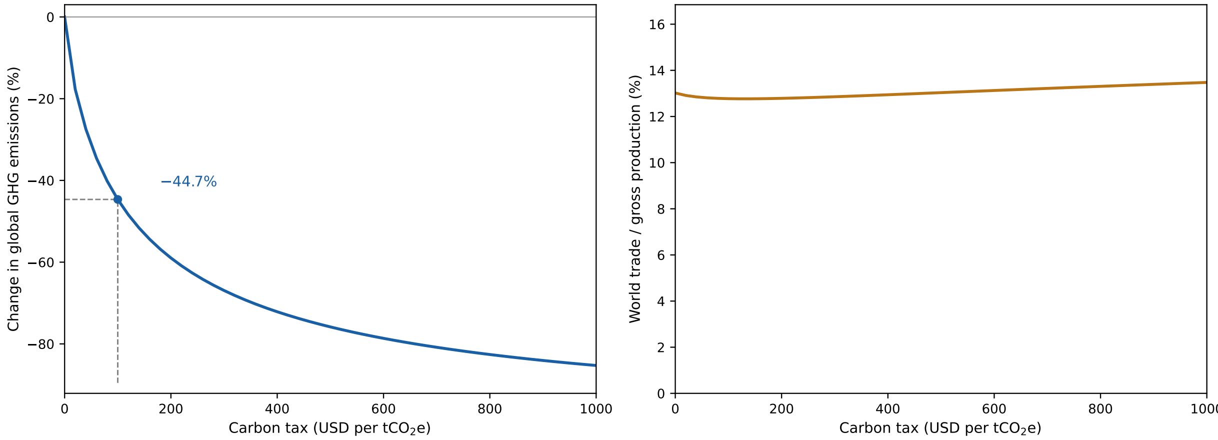
4 Results

4.1 Aggregate effects of carbon taxes

Greenhouse gas emissions are strongly decreasing in the carbon tax, with the global emissions reduction reaching 44.7% at our benchmark carbon tax of \$100/tCO_2e. Figure 1 summarizes the aggregate effects of carbon taxes, relative to a no-carbon-tax benchmark in 2018: the left panel shows the proportional change in global greenhouse gas emissions for carbon taxes up to \$1,000/tCO_2e. Emissions continue to fall as the tax rises, reaching a reduction of 85.3% at \$1,000. The reduction is computed on total emissions and is independent of the attribution

[14] World output y and sectoral outputs y_s are thus sums of economy–industry outputs valued at baseline prices, with $d\ln y_s = \sum_i \frac{v_{is}}{v_s}\, d\ln y_{is}$ and $d\ln y = \sum_s \frac{v_s}{v}\, d\ln y_s$, where v denotes baseline values. Any approximation error from using value shares cancels in the aggregate: the scale, composition, and green sourcing terms of equation (3) jointly reduce to $\sum_i \sum_s \phi_{is}\, d\ln y_{is}$, which is measured without error, since $\sum_s \phi_s = 1$ and $\sum_i \sum_s \phi_{is} = \sum_s \phi_s$.

Figure 1: Aggregate effects of carbon taxes



Note: The left panel shows the proportional change in global greenhouse gas emissions, and the right panel world trade as a share of gross production, for carbon taxes up to \$1,000/tCO_2e.

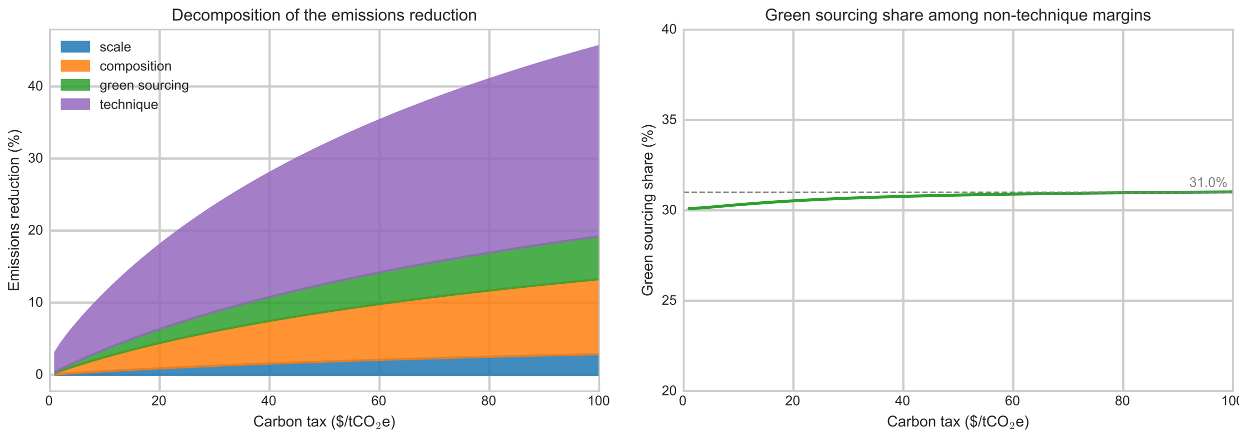
convention of Section 4.2. The right panel depicts world trade as a share of gross production for carbon taxes up to \$1,000/tCO_2e. The trade share barely moves: it is 13.0% without a carbon tax, 12.8% at \$100, and 13.5% at \$1,000. A carbon tax is not a retreat from trade integration.

4.2 Environmental gains from trade

Figure 2 decomposes the emissions reduction of the \$100 carbon tax following equation (3): the technique effect accounts for 57.9% of the reduction, the composition effect for 22.8%, the green sourcing effect for 13.1%, and the scale effect for 6.2%. The shares refer to the reduction in the covered producer base of equation (2). The technique effect is thus the largest single margin: with emissions intensities responding endogenously to fuel prices, most of the abatement comes from producers using less and cleaner fuel.

The environmental gains from trade are the green sourcing effect. Setting the technique effect aside—the margin invisible to an analysis with fixed emissions intensities—we renormalize over the remaining three: scale, composition, and green sourcing account for 14.8%, 54.1%, and 31.0%. Roughly one-third of the non-technique abatement arises because production moves to cleaner economies within industries. This is the headline statistic of the

Figure 2: Decomposition of emissions reductions



Note: The left panel shows the four-effect decomposition of the emissions change for carbon taxes up to \$100/tCO_2e. The right panel shows the green sourcing share among the non-technique margins over the same range, with a reference line at 31.0%. Unlike Figure 1, the horizontal axis ends at \$100: the decomposition is computed along the canonical tax path. The decomposition applies to the covered producer base of equation (2) in Section 2.6.

paper.

The green sourcing share among the non-technique margins is remarkably stable. The right panel of Figure 2 shows it across tax levels: at positive taxes up to \$100, it stays within 30.1–31.0%; Appendix D reports five points on the tax path. The composition of the reduction does shift with the tax: the technique share falls from 68.9% at \$10 to 57.9% at \$100, as fuel substitution—strong even at low taxes—is joined by reallocation that builds as the tax deepens.

Table 1 examines the robustness of the decomposition to the substitution elasticities. The stability of the headline statistic has a simple source: green sourcing feeds on the within-industry, cross-producer dispersion in emissions intensities, which is a feature of the calibrated data rather than of any single parameter. Varying the elasticities rescales the overall response to the tax and shifts the split between technique and the other margins; it does not remove that dispersion. The share rises with the trade elasticities, which govern how strongly expenditure reallocates across origins when relative prices move, and falls with the energy/non-energy elasticity, which shifts abatement toward a demand-side energy margin that green sourcing does not feed; the corner exercises bound the joint effect (per-corner

Table 1: Robustness of the decomposition to substitution elasticities

	Benchmark	One-at-a-time range	Joint-corner range
Technique effect	57.9%	52.8–69.7%	49.2–75.6%
Green sourcing (full decomposition)	13.1%	10.1–15.0%	6.9–17.8%
Green sourcing (share of non-technique margins)	31.0%	28.9–35.8%	28.1–36.1%

Note: One-at-a-time ranges vary each elasticity family separately across its plausible range. Joint-corner ranges vary all families jointly to the green-minimizing and green-maximizing corners.

Table 2: The decomposition under the two attribution conventions

	Pass-through (benchmark)	First purchaser
Green sourcing (full decomposition)	13.1%	15.7%
Technique effect	57.9%	50.7%
Green sourcing (share of non-technique margins)	31.0%	31.8%

Note: Pass-through (benchmark): the attribution convention of Section 2.6, which passes the carbon of refined products through to the industries that burn them. First purchaser: combustion booked at the first purchaser of each raw fuel. Appendix B reports the full comparison.

settings in Appendix D). Even at the green-minimizing corner, green sourcing remains above one-quarter of the non-technique abatement (28.1%), and the technique effect remains the largest margin throughout. What would remove the result is thus not a parameter within its plausible range but the elimination of the dispersion on which the margin operates.

The split between technique and the remaining margins also depends on where combustion is booked. Our benchmark passes the carbon of refined products through to the industries that burn them rather than booking it at the first purchaser of the raw fuel (Section 2.6). Table 2 shows that this choice shifts the technique share but leaves the green sourcing share among the non-technique margins essentially unchanged: the booking point relabels where reductions are recorded, not whether reallocation toward cleaner producers occurs. Appendix B reports the full comparison.

The technique effect itself decomposes along the fuel margins of equation (5) in Appendix A.4: fuel use per unit of output accounts for 54.0% of the overall reduction, a cleaner mix across fuels for 1.5%, and the reallocation of fuel purchases toward cleaner refiners for 2.3%,[15] which together make up the technique effect's 57.9%. Roughly a quarter of

[15] The magnitude of this component is subject to a data limitation in five origins' input-output fuel records; its sign and order of magnitude are robust. Details in Appendix C.

the intensity component reflects upstream refinery technique passed through to fuel buyers; Appendix C reports the full split. Collected into the augmented margins of equation (4), augmented scale accounts for 60.2% of the reduction, augmented composition for 24.3%, and augmented green sourcing for 15.5%; Appendix A.5 details the reconciliation. Under this finest classification, green sourcing is the sole trade-specific channel, and the technique effect enlarges rather than absorbs it.

4.3 Environmental comparative advantage

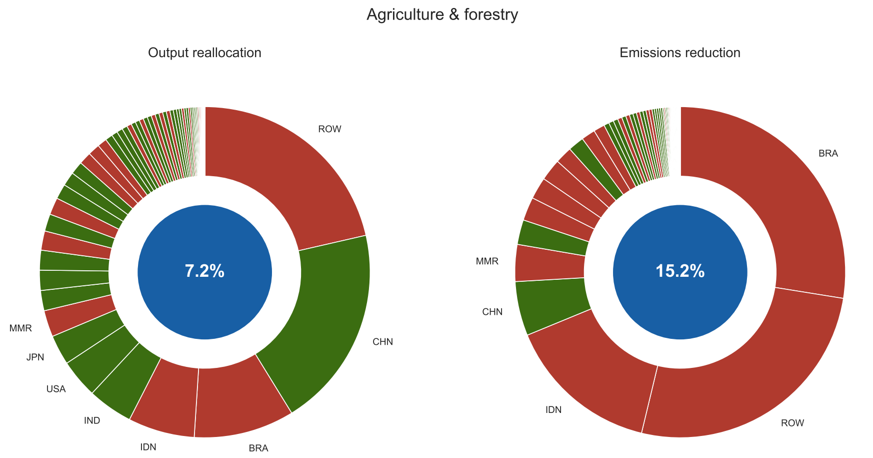
Figure 3 shows the green sourcing effect at work in two sectors: agriculture and forestry, the largest source of direct non-combustion emissions, and basic metals, a heavily traded, emissions-intensive manufacturing sector. In each panel, the left circle shows output changes as shares of the sector's baseline world output and the right circle the associated emissions changes as shares of its baseline world emissions. The ratio of an economy's emissions change to its output change is thus a measure of its emissions intensity relative to the sector's world average—its relative intensity.

In agriculture and forestry (panel a), reallocating 7.2% of world output across economies reduces sectoral emissions by 15.2%. Brazil and Indonesia, with relative intensities of 4.2 and 3.5, lose 1.4% and 0.9% of world output share, while China, the largest gainer, expands by 2.8% at a relative intensity of only 0.4.

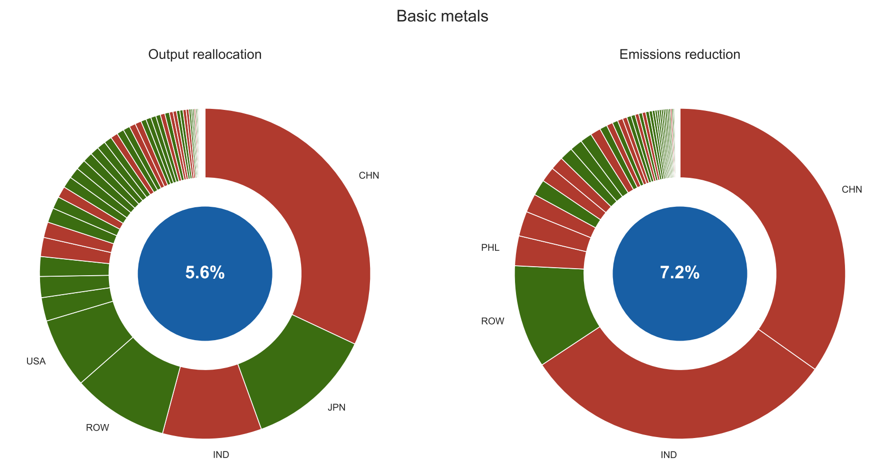
In basic metals (panel b), a reallocation of 5.6% of world output reduces sectoral emissions by 7.2%. China, the largest loser, cedes 3.6% of world output at a relative intensity of 1.2, India loses 1.1% at 3.5, and the United States, among the largest gainers, expands by 0.8% at 0.25.

In both sectors, the economies that lose market share have systematically higher relative intensities than those that gain it—the essence of specialization according to environmental comparative advantage. The comparison across panels shows that the mechanism is comparative rather than absolute: China is the largest gainer in agriculture, where its intensity lies

Figure 3: Environmental comparative advantage in selected sectors



(a) Agriculture & forestry sector

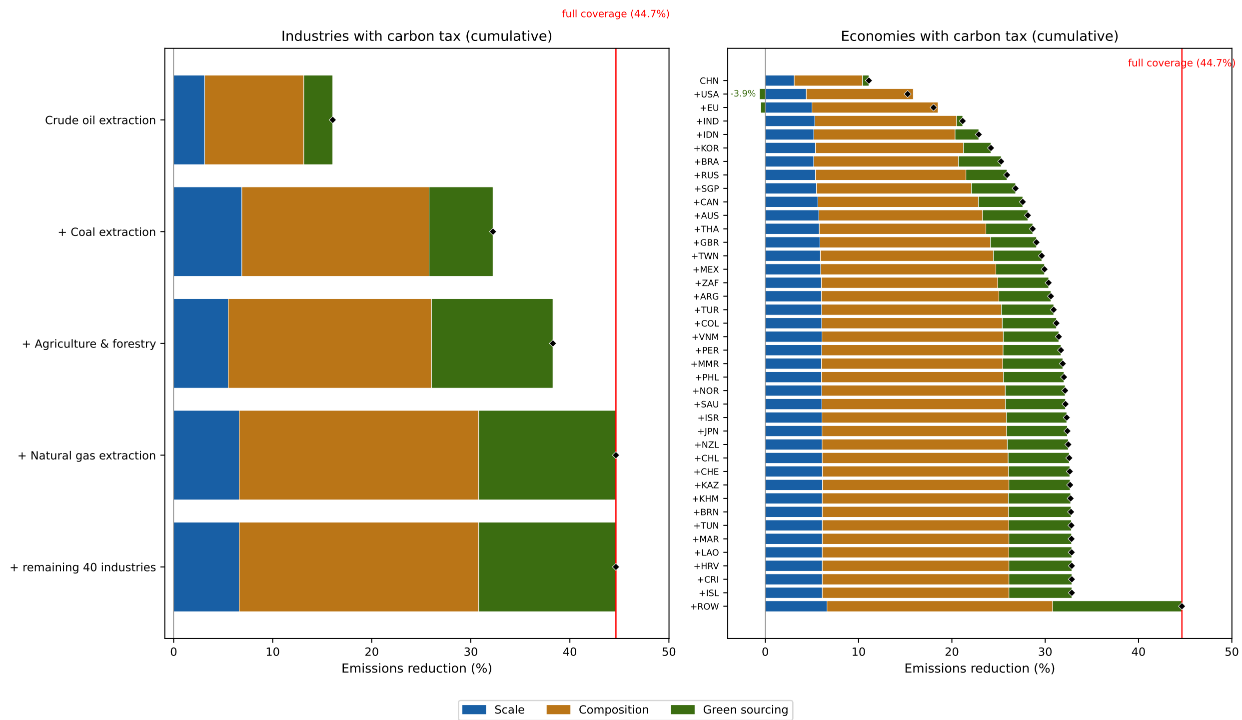


(b) Basic metals sector

Note: Each panel shows the reallocation of production across economies under the $100 carbon tax. Left circles: output gains (green) and losses (red) in percent of the sector's baseline world output, summing to zero; the blue center gives the share of world output reallocated. Right circles: the associated emissions increases (green) and reductions (red) in percent of the sector's baseline world emissions; the blue center gives the net sectoral emissions reduction. A data limitation affecting Japan's measured intensity in the basic metals panel is discussed in Appendix C.

far below the world average, and the largest loser in basic metals, where it lies above. The same economy contributes to global abatement by expanding in its relatively clean sectors and contracting in its relatively dirty ones.

Figure 4: Incomplete tax coverage



Note: Each bar reports the global emissions reduction from a \$100/tCO_2e carbon tax applied to a subset of industries (left) or economies (right), with subsets added cumulatively from top to bottom—industries in descending order of production emissions under the tax base, economies in descending order of the emissions their coverage adds under the destination-based tax, with the residual Rest-of-the-World aggregate last. Bars are split into the three non-technique margins—scale, composition, and green sourcing—scaled by the total reduction; segments to the left of the zero line indicate negative contributions—the green segment left of zero under narrow coalitions is carbon leakage; diamonds mark the net reduction, and the most negative green sourcing share is labeled. The red line marks the full-coverage reduction of 44.7%. The left panel names the industries up to saturation and collapses the remaining 40.

4.4 Incomplete tax coverage

Figure 4 shows the emissions reduction from a \$100/tCO_2e carbon tax applied to a subset of industries (left panel) or economies (right panel), with subsets added cumulatively. Industries enter in descending order of production emissions under the tax base; economies enter in descending order of the emissions their coverage adds under the destination-based tax, with the residual Rest-of-the-World aggregate last.

The industry panel shows immediate saturation. Taxing crude oil alone cuts global emissions by 16.1%; adding coal brings the reduction to 32.2%, agriculture and forestry to

38.3%, and natural gas to 44.7%—the full-coverage reduction. The remaining 40 industries add nothing. The economics is that the four are the primary-emission industries: the input-output system passes the fuel wedge into every downstream cost, so statutory coverage can be tiny while economic coverage is complete. This is the administrative logic of upstream carbon taxation.

The economy panel has no saturation analogue: the reduction builds with the taxing coalition. China alone delivers an 11.1% reduction; adding the United States and the European Union raises it to 18.0%; the ten largest covered emitters together reach 27.6%; and the 39 individually distinguished economies deliver 32.9%, with the residual rest-of-world aggregate completing the 44.7%.

Incomplete coverage determines the sign of the green sourcing margin, and the sign depends on who taxes. With China taxing alone, the share among the non-technique margins is +6.2%: reallocation away from the world's largest emitter is, on net, reallocation toward cleaner producers, so the margin contributes to abatement even without broad coverage. Adding the United States and the European Union turns the share negative (−3.9% and −2.7%): production now also relocates away from relatively clean economies toward the untaxed remainder, which raises emissions—this is carbon leakage. Once India joins, the share turns positive and rises toward the full-coverage 31.0%. Leakage and the environmental gains from trade are thus the same margin under different coverage, its sign governed by the environmental comparative advantage of the taxing coalition relative to the rest—and the answer to the leakage concern remains broader coverage, not less trade.

The configuration underlying the border-adjustment debate—the European Union taxing alone—is not a step on this path, and we report it as a separate experiment. The European Union alone delivers a 2.5% reduction with a green sourcing share among the non-technique margins of −10.9% (the sign and pattern are convention-independent; Appendix B). This is leakage at its starkest: a coalition of relatively clean producers taxing alone, so that reallocation runs strongly toward browner untaxed economies. We do not model the border adjustment itself; our experiment prices the carbon burned within the Union and quantifies the leakage that a border adjustment is designed to curb.

The EU case also answers whether these results depend on taxing purchasers rather than extraction. Under uniform global coverage the two schemes implement the same allocation (Section 2.4);[16] under EU-only coverage they diverge sharply: an origin-based tax reaches only the carbon embodied in the Union's own extraction and agriculture, delivering a 0.6% reduction with a green sourcing share of −48.1%. The environmental gains from trade are thus not an artifact of taxing purchasers rather than producers. For a fuel-importing coalition, however, the choice matters greatly: the destination-based instrument is by far the stronger one.

5 Conclusion

In this paper, we show that climate policy can unlock large environmental gains from trade by inducing economies to specialize according to their environmental comparative advantage. We make this point by exploring the effects of a carbon tax in a quantitative trade model. In our benchmark, green sourcing—the reallocation of production toward cleaner economies within industries—accounts for roughly one-third of the abatement from the non-technique margins, alongside a technique effect that is the largest single margin.

We identify two particularly promising avenues for future research. First, it would be valuable to explore a version of the model with heterogeneous firms. We hypothesize that this would reveal additional environmental gains from trade, resulting from the reallocation of resources from browner firms to greener firms within industries. Second, our technique effect captures substitution between energy and non-energy inputs and among fuels; it does not capture endogenous clean innovation or the international diffusion of production technologies.

[16] The same qualification applies to the cap-and-trade equivalence of Section 2.4: under partial coverage, a climate-club cap of the same aggregate stringency implements the same allocation as a club tax at the permit price the cap induces, differing only in how that wedge is determined. The coverage experiments therefore speak to both instruments.

Extending the model along these lines would connect the environmental gains from trade to the dynamics of green technology.

A Model appendix

This appendix states the full nested demand and production systems deferred from Section 2.2 and Section 2.3, derives the mining cost structure and the implied fuel-supply elasticity, and defines the equilibrium in levels and in changes together with the recursive solution procedure and the recovery of all benchmark objects from the input-output data. It then derives the emissions decomposition of equations (3), (4), and (5), including the attribution convention used in the measurement.

Throughout, countries are indexed by $i, j \in \{1, \ldots, N\}$ and industries by $s, r \in \{1, \ldots, S\}$. Industries are partitioned into the energy set $\mathcal{E}$ and the non-energy set $\mathcal{N}$; the mining industries $\mathcal{M} \subset \mathcal{E}$ are coal, oil, and gas extraction, and we denote the refined-petroleum industry by $\mathrm{rp} \in \mathcal{E} \setminus \mathcal{M}$. The fixed factor is specific to the mining industries: refined petroleum and electricity are constant-returns members of the energy bundle.

A.1 Demand and production nests

Households. For each industry s and destination j, varieties are aggregated across origins with elasticity σ_s,

$$Q_{sj} = \left(\sum_{i=1}^{N} a_{isj}^{1/\sigma_s} \, q_{isj}^{(\sigma_s - 1)/\sigma_s} \right)^{\sigma_s/(\sigma_s - 1)}, \qquad P_{sj} = \left(\sum_{i=1}^{N} a_{isj} \, (p_{isj}^{u})^{1-\sigma_s} \right)^{1/(1-\sigma_s)},$$

with CES demand $q_{isj} = a_{isj} (p_{isj}^{u})^{-\sigma_s} P_{sj}^{\sigma_s - 1} E_{sj}$, where $E_{sj} = P_{sj} Q_{sj}$. The industry composites aggregate into the energy and non-energy bundles with elasticities $\rho_{\mathcal{E}}$ and $\rho_{\mathcal{N}}$,

$$Q_j^{\mathcal{E}} = \left(\sum_{s \in \mathcal{E}} b_{sj}^{1/\rho_{\mathcal{E}}} Q_{sj}^{(\rho_{\mathcal{E}} - 1)/\rho_{\mathcal{E}}} \right)^{\rho_{\mathcal{E}}/(\rho_{\mathcal{E}} - 1)}, \qquad Q_j^{\mathcal{N}} = \left(\sum_{s \in \mathcal{N}} c_{sj}^{1/\rho_{\mathcal{N}}} Q_{sj}^{(\rho_{\mathcal{N}} - 1)/\rho_{\mathcal{N}}} \right)^{\rho_{\mathcal{N}}/(\rho_{\mathcal{N}} - 1)},$$

with price indices $P_j^{\mathcal{E}}$ and $P_j^{\mathcal{N}}$ of the standard CES form and industry expenditures

$$E_{sj} = b_{sj} P_{sj}^{1-\rho_{\mathcal{E}}} (P_j^{\mathcal{E}})^{\rho_{\mathcal{E}} - 1} E_j^{\mathcal{E}} \quad (s \in \mathcal{E}), \qquad E_{sj} = c_{sj} P_{sj}^{1-\rho_{\mathcal{N}}} (P_j^{\mathcal{N}})^{\rho_{\mathcal{N}} - 1} E_j^{\mathcal{N}} \quad (s \in \mathcal{N}).$$

At the top, the two bundles combine with elasticity ε into aggregate consumption with price index P_j, and expenditure on the bundles is

$$E_j^{\mathcal{E}} = \chi_j \left(\frac{P_j^{\mathcal{E}}}{P_j} \right)^{1-\varepsilon} I_j, \qquad E_j^{\mathcal{N}} = (1-\chi_j) \left(\frac{P_j^{\mathcal{N}}}{P_j} \right)^{1-\varepsilon} I_j.$$

Firms. The firm-side nest is identical in form at every level, with firm-specific distribution parameters. A firm in industry r and country j aggregates input varieties with the same σ_s,

$$X_{srj} = \left(\sum_{i=1}^{N} (a_{isrj}^{x})^{1/\sigma_s} \, x_{isrj}^{(\sigma_s-1)/\sigma_s} \right)^{\sigma_s/(\sigma_s-1)}, \qquad P_{srj} = \left(\sum_{i=1}^{N} a_{isrj}^{x} \, (p_{isj}^{u})^{1-\sigma_s} \right)^{1/(1-\sigma_s)},$$

with input demand $x_{isrj} = a_{isrj}^{x} (p_{isj}^{u})^{-\sigma_s} P_{srj}^{\sigma_s - 1} M_{srj}$ and $M_{srj} = P_{srj} X_{srj}$. Input industries aggregate into energy and non-energy input bundles $X_{rj}^{\mathcal{E}}$ and $X_{rj}^{\mathcal{N}}$ with elasticities $\rho_{\mathcal{E}}$ and $\rho_{\mathcal{N}}$ and price indices $P_{rj}^{X\mathcal{E}}$ and $P_{rj}^{X\mathcal{N}}$, and input-industry expenditures satisfy

$$M_{srj} = b_{srj}^{x} P_{srj}^{1-\rho_{\mathcal{E}}} (P_{rj}^{X\mathcal{E}})^{\rho_{\mathcal{E}}-1} M_{rj}^{X\mathcal{E}} \quad (s \in \mathcal{E}), \qquad M_{srj} = c_{srj}^{x} P_{srj}^{1-\rho_{\mathcal{N}}} (P_{rj}^{X\mathcal{N}})^{\rho_{\mathcal{N}}-1} M_{rj}^{X\mathcal{N}} \quad (s \in \mathcal{N}),$$

where $M_{rj}^{X\mathcal{E}}$ and $M_{rj}^{X\mathcal{N}}$ denote spending on the two bundles. The bundles combine with elasticity ε into the aggregate intermediate X_{rj} with price index

$$P_{rj}^{X} = \left[\chi_{rj}^{x} \, (P_{rj}^{X\mathcal{E}})^{1-\varepsilon} + (1-\chi_{rj}^{x}) \, (P_{rj}^{X\mathcal{N}})^{1-\varepsilon} \right]^{1/(1-\varepsilon)},$$

and spending on the bundles is

$$M_{rj}^{X\mathcal{E}} = \chi_{rj}^{x} \left(\frac{P_{rj}^{X\mathcal{E}}}{P_{rj}^{X}} \right)^{1-\varepsilon} M_{rj}^{X}, \qquad M_{rj}^{X\mathcal{N}} = (1-\chi_{rj}^{x}) \left(\frac{P_{rj}^{X\mathcal{N}}}{P_{rj}^{X}} \right)^{1-\varepsilon} M_{rj}^{X},$$

where $M_{rj}^{X} = P_{rj}^{X} X_{rj}$ is total intermediate spending.

A.2 Mining technology and fuel supply

For mining industries $r \in \mathcal{M}$, production requires the fixed, country-specific resource F_{rj},

$$y_{rj} = A_{rj}\, F_{rj}^{\gamma_{rj}}\, L_{rj}^{\alpha_{rj}}\, X_{rj}^{\beta_{rj}}, \qquad \alpha_{rj} + \beta_{rj} + \gamma_{rj} = 1.$$

Define $\tilde{\alpha}_{rj} \equiv \alpha_{rj}/(1-\gamma_{rj})$ and $\tilde{\beta}_{rj} \equiv \beta_{rj}/(1-\gamma_{rj})$, so that $\tilde{\alpha}_{rj} + \tilde{\beta}_{rj} = 1$. Conditional on the resource, minimizing variable cost over labor and intermediates yields

$$VC_{rj}(y_{rj}) = \frac{1}{A_{rj}^{1/(1-\gamma_{rj})}\, F_{rj}^{\gamma_{rj}/(1-\gamma_{rj})}} \left(\frac{w_j}{\tilde{\alpha}_{rj}}\right)^{\tilde{\alpha}_{rj}} \left(\frac{P_{rj}^X}{\tilde{\beta}_{rj}}\right)^{\tilde{\beta}_{rj}} y_{rj}^{1/(1-\gamma_{rj})},$$

and marginal cost

$$MC_{rj}(y_{rj}) = \frac{1}{1-\gamma_{rj}} \frac{1}{A_{rj}^{1/(1-\gamma_{rj})}\, F_{rj}^{\gamma_{rj}/(1-\gamma_{rj})}} \left(\frac{w_j}{\tilde{\alpha}_{rj}}\right)^{\tilde{\alpha}_{rj}} \left(\frac{P_{rj}^X}{\tilde{\beta}_{rj}}\right)^{\tilde{\beta}_{rj}} y_{rj}^{\gamma_{rj}/(1-\gamma_{rj})}.$$

Under perfect competition, $p_{rj}^0 = MC_{rj}(y_{rj})$, so the price elasticity of fossil-fuel supply with respect to p_{rj}^0, holding input prices fixed, is $(1-\gamma_{rj})/\gamma_{rj} = 3$ at the calibrated $\gamma_{rj} = 0.25$. Factor payments are $w_j L_{rj} = \alpha_{rj} Y_{rj}^0$, $M_{rj}^X = \beta_{rj} Y_{rj}^0$, and resource rents $R_{rj}^F = \gamma_{rj} Y_{rj}^0$, where $Y_{rj}^0 = p_{rj}^0 y_{rj}$. Non-mining industries, including refined petroleum and electricity, have $\gamma_{rj} = 0$: their producer price equals unit cost and supply is perfectly elastic.

A.3 Equilibrium and exact hat algebra

Equilibrium in levels. Given carbon wedges, an equilibrium is a wage vector $\{w_j\}$, intermediate price indices $\{P_{rj}^X\}$, and mining outputs $\{y_{rj}\}_{r\in\mathcal{M}}$ such that (i) P_{rj}^X is consistent with the firm-side nest evaluated at the implied user prices; (ii) labor markets clear, $\sum_r L_{rj} = L_j$; and (iii) goods markets clear for every mining industry,

$$y_{is} = \sum_j \tau_{isj}\, q_{isj} + \sum_j \sum_r \tau_{isj}\, x_{isrj}, \qquad s \in \mathcal{M}.$$

All remaining objects follow recursively: producer prices from unit costs (constant-returns industries) and marginal costs (mining), user prices from the pricing chain (1), price indices and expenditures down the two nests, quantities from CES demands, and income from

$$I_j = w_j L_j + \sum_{r \in \mathcal{M}} R^F_{rj} + T^C_j + T^P_j + D_j.$$

Constant-returns goods markets clear automatically by zero profits and demand consistency; only the mining industries, whose supply slopes upward, require explicit quantity-clearing conditions.

Equilibrium in changes. For any variable x, let $\hat{x} = x'/x$ denote its proportional change between the baseline and the counterfactual. The economy and industry indices appear in both orders, inherited from the corresponding main-text sections—the pricing chain and market clearing write the economy first (p^0_{is}, y_{is}), the production-side derivations the industry first (p^0_{rj}, y_{rj})—with the letters disambiguating: i and j always denote economies, r and s industries. Defining the gross wedges $\tau^P_{is} \equiv 1+t^P_{is}$ and $\tau^C_{isj} \equiv 1+t^C_{isj}$ from the pricing relation (1), the carbon-policy shifters are their proportional changes,

$$\hat{\tau}^P_{is} = \frac{1+t^{P\prime}_{is}}{1+t^P_{is}}, \qquad \hat{\tau}^C_{isj} = \frac{1+t^{C\prime}_{isj}}{1+t^C_{isj}}, \qquad \hat{p}^P_{is} = \hat{p}^0_{is}\,\hat{\tau}^P_{is}, \qquad \hat{p}^u_{isj} = \hat{p}^P_{is}\,\hat{\tau}^C_{isj}.$$

An equilibrium in changes is a set $\{\hat{w}_j\}$, $\{\hat{P}^X_{rj}\}$, $\{\hat{y}_{rj}\}_{r\in\mathcal{M}}$ satisfying the hat analogues of (i)–(iii), with producer-price hats

$$\hat{p}^0_{rj} = \hat{w}_j^{\alpha_{rj}} (\hat{P}^X_{rj})^{1-\alpha_{rj}} \quad (r \notin \mathcal{M}), \qquad \hat{p}^0_{rj} = \hat{w}_j^{\tilde{\alpha}_{rj}} (\hat{P}^X_{rj})^{\tilde{\beta}_{rj}}\, \hat{y}_{rj}^{\gamma_{rj}/(1-\gamma_{rj})} \quad (r \in \mathcal{M}),$$

and all remaining hats recovered recursively from the CES system evaluated at benchmark value shares. The trade imbalances D_j are held fixed as a share of world income, and hence constant under the normalization below. Because they and the tax wedges enter income in levels, the income identity is evaluated in levels,

$$\hat{I}_j I_j = \hat{w}_j w_j L_j + \sum_{r \in \mathcal{M}} \hat{p}^0_{rj} \hat{y}_{rj} R^F_{rj} + T^{P\prime}_j + T^{C\prime}_j + D_j,$$

with counterfactual revenues built from the counterfactual wedges and flows. We normalize world labor income to its baseline value; all reported objects are invariant to this normalization.

Recovery of benchmark objects. Every benchmark share required by the hat system is a value share observable in the input-output data: bilateral final-expenditure and intermediate-input flows deliver the origin shares within each industry and the industry shares within each bundle; gross industry revenue at producer prices is recovered from sales net of the destination wedge; and the goods-market weights are the corresponding revenue shares. For the mining industries, the intermediate share β_{rj} is measured from the use table, γ_{rj} is set externally, and $\alpha_{rj} = 1 - \gamma_{rj} - \beta_{rj}$; for all other industries the labor share is one minus the intermediate share. No quantity data are required.

A.4 Emissions accounting and the decomposition

The four effects. Let δ_{is} denote direct emissions per unit of output and y_{is} real output, so that $\text{GHG} = \sum_i \sum_s \delta_{is} y_{is}$. Writing $y_s = \sum_i y_{is}$, $y = \sum_s y_s$, $\Gamma_s = y_s/y$, and $\Gamma_{is} = y_{is}/y_s$, output factorizes as $y_{is} = \Gamma_{is}\Gamma_s y$. Total differentiation and division by total emissions give

$$d \ln \text{GHG} = d \ln y + \sum_s \phi_s \, d \ln \Gamma_s + \sum_i \sum_s \phi_{is} \, d \ln \Gamma_{is} + \sum_i \sum_s \phi_{is} \, d \ln \delta_{is},$$

where ϕ_{is} and ϕ_s are emissions weights. This is equation (3). In the computation, the four terms are accumulated along a one-hundred-step tax path with log-mean (LMDI) weights, so that they sum to the total change in emissions at machine precision.

Attribution. The measured intensity δ_{is} attributes combustion to the industries that burn fuel. Directly purchased coal, oil, and gas are burned by their purchaser. The exception is the raw fuel entering the refined-petroleum industry, which is transformed rather than burned, apart from the own-use share f^{own}. The carbon content of refiner j's raw-fuel purchases that is not used by the refinery itself passes through to purchasers of refined petroleum at the origin-specific rate

$$e_j = (1 - f^{own})\, C_j / y_{j,\mathrm{rp}},$$

where C_j is the carbon content of refiner j's raw-fuel intake and $y_{j,\mathrm{rp}}$ its real output; refined petroleum sold to final demand exits the producer base. Fuels form two groups g: the raw fuels $\mathcal{M}$ and refined petroleum, with $\mathcal{F} = \mathcal{M} \cup \{\mathrm{rp}\}$ and t indexing the individual fuels in these sets. The buyer-level carbon atoms are therefore

$$b^t_{jis} = \kappa_t\, x_{jtis} \;\; (t \in \mathcal{M}), \qquad b^{\mathrm{rp}}_{jis} = e_j\, x_{j,\mathrm{rp},is},$$

where x_{jtis} denotes physical purchases of raw fuel t by industry s in country i from origin j, κ_t the fixed physical carbon content of raw fuel t, $x_{j,\mathrm{rp},is}$ the corresponding real purchases of refined petroleum, and the raw-fuel atoms of the refining industry itself are scaled by f^{own}. The fuel-level weights are these atoms normalized by total emissions, $\varphi = b/\mathrm{GHG}$; throughout, the fuel or fuel group appears as a superscript, the origin, where tracked, as the leading subscript, and a weight with an index omitted sums over it: $\varphi^t_{jis} = b^t_{jis}/\mathrm{GHG}$, $\varphi^t_{is} = \sum_j \varphi^t_{jis}$, and $\varphi^g_{is} = \sum_{t \in g} \varphi^t_{is}$. Within each fuel group, purchases per unit of output factor into total fuel use per unit of output, the mix across fuels, and the origin mix within each fuel, $x/y = f \cdot \eta \cdot \pi$: f^g_{is} is producer (i,s)'s group-g fuel purchases per unit of output, η_{tis} the share of raw fuel $t \in \mathcal{M}$ within the group's purchases, and $\pi_{j|tis}$ the share of origin j in the producer's purchases of fuel t. For the raw-fuel group, purchases across the heterogeneous fuels are aggregated in physical energy units (tons of oil equivalent), so the group intensity $f^{\mathcal{M}}_{is}$ is fuel use per unit of output and the mix shares η_{tis} are energy shares; the fixed carbon contents κ_t enter only through the emission atoms $b^t_{jis} = \kappa_t\, x_{jtis}$ and hence the weights $\varphi = b/\text{GHG}$, not the factors f, η, π themselves. With these weights and factors the technique term decomposes as

$$\begin{aligned}\text{TE} \equiv \sum_{i,s} \phi_{is}\, d\ln\delta_{is} = \underbrace{\sum_{g}\sum_{i,s} \varphi^g_{is}\, d\ln f^g_{is} + \sum_{j,i,s} \varphi^{\text{rp}}_{jis}\, d\ln e_j}_{\text{fuel intensity (SC}^{\text{TE}})} + \underbrace{\sum_{t\in\mathcal{M}}\sum_{i,s} \varphi^t_{is}\, d\ln\eta_{tis}}_{\text{fuel composition (CO}^{\text{TE}})} \\ + \underbrace{\sum_{t\in\mathcal{F}}\sum_{j,i,s} \varphi^t_{jis}\, d\ln\pi_{j|tis}}_{\text{fuel sourcing (GS}^{\text{TE}})}\,. \end{aligned} \tag{5}$$

The agricultural and fugitive component of δ_{is}—the only non-combustion emissions in the data—is fixed per unit of output.

The four-term technique split. Substituting the factorization $x/y = f \cdot \eta \cdot \pi$ into the technique term yields the four computed components of equation (5): fuel intensity ($d\ln f$, for raw fuels and refined petroleum), fuel composition ($d\ln\eta$, across the raw fuels), fuel sourcing ($d\ln\pi$), and the upstream technique component ($d\ln e_j$, which varies only for refined petroleum). The equation displays three braces because the upstream component is folded into its fuel-intensity term: SC^{TE} is the sum of the producers' own intensity terms and this upstream component, while Appendix C reports the four components separately. For the raw fuels the sourcing term is exactly zero: with origin-invariant κ_t, the atoms within a fuel are proportional to the origin shares, so

$$\sum_j b\, d\ln\pi_j \;\propto\; \sum_j d\pi_j \;=\; 0.$$

For refined petroleum, e_j varies across origin refineries, so reallocating purchases across refiners carries a nonzero sourcing term. The upstream term $\sum L(b^{\text{rp}})\, d\ln e_j$, where $L(\cdot)$ denotes the log-mean (LMDI) weight of the corresponding atom, captures upstream refiners' own technique; it has no raw-fuel counterpart because the κ_t are fixed physical constants.

In the computation, the point weights φ of equation (5) are replaced by these log-mean counterparts, accumulated along the same tax path as the four effects. Their sum reconciles with the technique term of equation (3) up to the standard LMDI aggregation error, which is five orders of magnitude below the reported digits. Because e_j moves with refiner j's fuel use per unit of output, fuel mix, and fuel origins, the upstream component decomposes once more into the same three margins, with the refinery-level sourcing term again exactly zero. The recursion terminates there—refineries purchase only raw fuels—so, absent abatement technology, every margin of abatement in the model reduces to scale and substitution.

A.5 The augmented decomposition

Collecting terms maps the technique components onto the three reallocation margins as in equation (4): the fuel-intensity term $\mathrm{SC}^{\mathrm{TE}}$, which includes the upstream technique component, joins the output scale effect SC (augmented scale); the fuel-composition component $\mathrm{CO}^{\mathrm{TE}}$ joins the output composition effect CO (augmented composition); and the fuel-sourcing component $\mathrm{GS}^{\mathrm{TE}}$ joins the output green sourcing effect GS (augmented green sourcing). At the benchmark, the reported shares satisfy this mapping: augmented scale $60.2\% = 6.2\% + 54.0\%$ (output scale, fuel intensity), augmented composition $24.3\% = 22.8\% + 1.5\%$, and augmented green sourcing $15.5\% = 13.1\% + 2.3\%$, up to rounding.

B Alternative attribution conventions

The tax wedge books each fuel's carbon at the fuel product, so the instrument is unaffected by how the measurement locates reductions; the decomposition requires a choice. Attributing combustion to the first purchaser of each raw fuel books the carbon of crude oil, coal, and gas largely at the refining industry, which transforms rather than burns most of it; passing it through refined products attributes combustion to the industries that burn the fuel. Table 3 reports the decomposition under both conventions for the benchmark and all one-at-a-time elasticity configurations, together with the EU-only leakage experiment. The technique-versus-reallocation split shifts with the booking point; the green sourcing share among the non-technique margins is essentially invariant to it.

Table 3: Attribution comparison across configurations (shares in percent)

	First purchaser					Pass-through (benchmark)				
Configuration	Scale	Comp.	Green	Tech.	WR green	Scale	Comp.	Green	Tech.	WR green
Baseline	6.3	27.3	15.7	50.7	31.8	6.2	22.8	13.1	57.9	31.0
$\rho_{\mathcal{E}}$=1	5.2	23.5	14.1	57.2	32.9	5.2	19.7	11.7	63.5	32.0
$\rho_{\mathcal{E}}$=2	3.9	19.8	12.2	64.1	34.1	3.9	16.3	10.1	69.7	33.4
$\rho_{\mathcal{N}}$=0.2	6.6	23.6	14.5	55.3	32.5	6.6	18.3	11.5	63.6	31.6
$\rho_{\mathcal{N}}$=2	6.1	30.6	16.7	46.6	31.2	6.0	26.8	14.4	52.8	30.5
ε=0.1	8.2	22.8	17.8	51.2	36.4	8.1	21.4	14.8	55.7	33.5
ε=0.9	4.8	30.6	14.0	50.6	28.3	4.8	23.7	11.6	59.9	28.9
σ uniform_4	6.0	25.8	15.2	53.0	32.4	5.9	21.9	12.5	59.7	31.1
σ rescaled_to_4	5.8	25.0	15.1	54.1	33.0	5.7	21.5	12.0	60.8	30.7
σ fgo	5.7	24.9	18.4	51.0	37.4	5.7	21.2	15.0	58.2	35.8
EU-only leakage (WR green; full decomp.)			−18.0; −6.4					−10.9; −4.4		

Note: First purchaser: combustion booked to the first purchaser of each raw fuel. Pass-through: the benchmark convention of Section 2. WR green is the green sourcing share among the three non-technique margins. The EU-only row reports that share and the total-base green sourcing share in the EU-only coverage experiment of Section 4.4.

C The technique effect in detail

Table 4 reports the full component split of the technique effect under equation (5) for all configurations, separating the raw-fuel and refined-petroleum intensity margins and the raw-fuel sourcing term. In the grouping of the main text, the fuel-intensity term is the sum of the raw-intensity, refined-intensity, and upstream-technique columns; the fuel-sourcing term is the refined-sourcing column plus the raw-sourcing residual.

Five origins—Japan, Brazil, Switzerland, Kazakhstan, and Saudi Arabia—have defective raw-fuel records in the input-output data: their recorded fuel purchases are implausibly small relative to their refining output, Japan by roughly two orders of magnitude. Because these records also enter the measured intensities of the affected origins' downstream industries, Japan's relative intensity in the basic metals panel of Figure 3 is understated for the same reason. These cells carry about 2% of the carbon passed through refined petroleum, and their direct contribution to the refined-petroleum sourcing term is about 6% at the recorded

Table 4: Technique-effect components (shares of the total reduction, percent)

Configuration	Raw intensity	Refined intensity	Fuel mix	Raw sourcing (residual)	Refined sourcing	Upstream	Technique
Baseline	34.9	5.9	1.5	0.0	2.3	13.1	57.9
$\rho_{\mathcal{E}}$=1	40.2	4.9	2.0	0.0	2.1	14.3	63.5
$\rho_{\mathcal{E}}$=2	46.2	3.9	2.3	0.0	1.8	15.4	69.7
$\rho_{\mathcal{N}}$=0.2	38.4	6.5	1.7	0.0	2.6	14.4	63.6
$\rho_{\mathcal{N}}$=2	31.9	5.3	1.4	0.0	2.1	12.0	52.8
ε=0.1	34.0	3.3	1.7	0.0	2.8	13.8	55.7
ε=0.9	35.8	8.0	1.4	0.0	1.9	12.7	59.9
σ uniform_4	36.1	5.4	1.0	0.5	2.4	14.2	59.7
σ rescaled_to_4	36.7	5.1	0.7	0.7	2.7	14.9	60.8
σ fgo	34.8	5.2	1.1	0.4	3.1	13.6	58.2

Note: Raw and refined intensity are the fuel-per-unit-output margins of the two fuel groups; the upstream column is the refiners' technique passed through to fuel buyers (the upstream technique component). Components sum to the technique share up to LMDI aggregation error (below 10^{-4} of the total in every configuration). The raw-sourcing column reports the finite-grid integration residual of an analytically zero term; it is larger under the alternate trade-elasticity vectors and shrinks with grid refinement.

weights. Their main effect is on the measured magnitude of that term: replacing the five origins' passed-through factors with the output-weighted world mean moves the benchmark refined-petroleum sourcing component from -5.0×10^8 to -2.8×10^8 tCO_2e, a range of roughly $\pm 45\%$. The sign and order of magnitude of the component are robust; its share of the total reduction is 2.3% at the recorded weights.

D The decomposition across tax levels

Table 5 reports the four-effect decomposition and the shares among the non-technique margins at five points on the tax path. The technique share falls as the tax rises, while the green sourcing share among the non-technique margins varies by less than one percentage point.

Table 5: The decomposition across tax levels (shares in percent)

	Full decomposition				Share of non-technique margins		
Carbon tax	Scale	Comp.	Green	Tech.	Scale	Comp.	Green
$10	4.2	17.4	9.4	68.9	13.7	56.0	30.3
$25	5.1	20.1	11.1	63.6	14.0	55.3	30.6
$50	5.7	21.6	12.2	60.6	14.4	54.7	30.8
$75	6.0	22.3	12.7	59.0	14.7	54.4	31.0
$100	6.2	22.8	13.1	57.9	14.8	54.1	31.0

The joint-corner ranges of Table 1 rest on four elasticity corners: all elasticity families are moved together to the combinations that minimize and maximize green sourcing, with the trade elasticities at either end of their plausible range. Table 6 reports the parameter settings and the resulting shares at the \$100 tax.

Table 6: The decomposition at the joint elasticity corners (\$100 tax)

	$\rho_{\mathcal{E}}$	$\rho_{\mathcal{N}}$	ε	σ_s scale	Technique	Green (total)	Green (within)
Green-maximizing, low σ_s	0.45	2.0	0.1	×0.69	51.0%	14.9%	30.3%
Green-maximizing, high σ_s	0.45	2.0	0.1	×1.41	49.2%	17.8%	35.1%
Green-minimizing, low σ_s	2.0	0.2	0.9	×0.69	75.6%	6.9%	28.1%
Green-minimizing, high σ_s	2.0	0.2	0.9	×1.41	73.2%	9.7%	36.1%

Note: The σ_s scale factor rescales the estimated trade elasticities of Appendix F. Technique and green (total) are shares of the total reduction in the full decomposition; green (within) is the green sourcing share among the three non-technique margins. That share peaks at the green-minimizing corner with high trade elasticities, where the large technique effect shrinks the non-technique base.

E Data provenance

Table 7 lists each data source, the attribution convention native to it, the variables we use, the transformation applied, and the role the resulting object plays in the model.

Table 7: Data sources and their transformation into model objects

Source	Native attribution	Variable used	Transformation	Role in the model
OECD ICIO (2018)	production and use flows at basic prices	bilateral final and intermediate flows, output, value added	aggregated to 64 regions and 44 industries	trade and input-output structure; all benchmark shares
Exiobase fuel split	gross output by product	coal, oil, and gas components of energy mining	splits the ICIO energy-mining industry into three extraction industries	the mining industries $\mathcal{M}$
OECD TECO2	combustion by burning industry (inventory)	industry CO_2 from fuel combustion	with-agriculture minus without-agriculture difference; refining combustion share	agricultural component; f^{own} anchor; attribution benchmark
FAOSTAT	emissions by agricultural activity (CO_2e)	'Agricultural Land' categories, including land-use CO_2 sources	on-farm energy use excluded; assigned to industry 01T02 per unit of output (Le Moigne et al., 2026)	agriculture and land-use part of the fixed component of δ_{is}
EDGAR	emissions by source category	fugitive emissions from fuel extraction (IPCC 1.B)	non-CO_2 gases at AR4 100-year GWP; allocated across 05T06.1–.3 in proportion to output (Le Moigne et al., 2026)	fugitive part of the fixed component of δ_{is}
IEA fuel prices	price per ton of oil equivalent, by country	country-level fuel prices	converts physical factors into per-dollar wedges	tax wedge; physical fuel quantities
EIA emissions factors	tCO_2e per ton of oil equivalent, by fuel	3.81, 2.94, 2.06 for coal, oil, gas	applied directly	carbon content of fuels

F Estimated trade elasticities

Table 8 reports the estimated trade elasticities σ_s by industry; the estimation methodology is described in Section 3.3.

Table 8: Estimated trade elasticities by industry

Code	Industry	σ_s
01T02	Agriculture, forestry	4.95
03	Fishing and aquaculture	2.58
05T06.1	Coal extraction	0.65
05T06.2	Oil extraction	3.26
05T06.3	Gas extraction	1.09
07T08	Mining, non-energy products	3.29
10T12	Food, beverages, tobacco	4.05
13T15	Textiles, apparel, leather	5.17
16	Wood products	5.02
17T18	Paper and printing	4.54
19	Coke, refined petroleum	3.61
20	Chemicals	3.77
21	Pharmaceuticals	4.10
22	Rubber and plastics	4.17
23	Other non-metallic minerals	3.68
24	Basic metals	5.86
25	Fabricated metal products	4.87
26	Computer, electronic, optical	2.19
27	Electrical equipment	3.24
28	Machinery n.e.c.	2.91
29T30	Motor vehicles, transport equipment	3.49
31T33	Other manufacturing, repair	4.90

Code	Industry	σ_s
35	Electricity, gas, steam	3.78
36T39	Water supply, waste	1.91
41T43	Construction	3.49
45T47	Wholesale and retail trade	3.49
49	Land transport	3.49
50	Water transport	3.49
51	Air transport	3.49
52	Warehousing, transport support	3.49
53	Postal and courier	3.49
55T56	Accommodation, food services	3.49
58T60	Publishing, audiovisual, broadcasting	4.03
61	Telecommunications	3.49
62T63	IT and information services	3.49
64T66	Finance and insurance	3.49
68	Real estate	3.49
69T75	Professional, scientific, technical	3.76
77T82	Administrative, support services	2.46
84	Public administration	3.49
85	Education	2.80
86T88	Health and social work	3.49
90T93	Arts, entertainment, recreation	2.29
94T98	Other services, households	3.49

References

Armington, P. S. (1969). A Theory of Demand for Products Distinguished by Place of Production (Une theorie de la demande de produits differencies d'apres leur origine) (Una teoria de la demanda de productos distinguiendolos segun el lugar de produccion), *Staff Papers - International Monetary Fund* **16**(1): 159.

Atalay, E. (2017). How important are sectoral shocks?, *American Economic Journal: Macroeconomics* **9**(4): 254–280.

Bajzik, J., Havránek, T., Iršová, Z. and Schwarz, J. (2020). Estimating the Armington elasticity: The importance of study design and publication bias, *Journal of International Economics* **127**: 103383.

Baylis, K., Fullerton, D. and Karney, D. H. (2014). Negative Leakage, *Journal of the Association of Environmental and Resource Economists* **1**(1/2): 51–73.

Boyce, J. K. (2018). Carbon pricing: effectiveness and equity, *Ecological Economics* **150**: 52–61.

Caliendo, L., Dolabella, M., Moreira, M., Murillo, M. and Parro, F. (2024). Voluntary Emission Restraints in Developing Economies: The Role of Trade Policy, *Technical Report w32459*, National Bureau of Economic Research, Cambridge, MA.

Caliendo, L. and Parro, F. (2015). Estimates of the trade and welfare effects of nafta, *The Review of Economic Studies* **82**(1 (290)): 1–44.

Conte, B., Desmet, K. and Rossi-Hansberg, E. (2025). On the Geographic Implications of Carbon Taxes, *Forthcoming in The Economic Journal* .

Copeland, B. R. and Taylor, M. S. (2003). *Trade and the Environment: Theory and Evidence*, stu - student edition edn, Princeton University Press.

Copeland, B. R. and Taylor, M. S. (2005). Free trade and global warming: a trade theory view of the Kyoto protocol, *Journal of Environmental Economics and Management* **49**(2): 205–234.

Costinot, A., Donaldson, D. and Smith, C. (2016). Evolving Comparative Advantage and the Impact of Climate Change in Agricultural Markets: Evidence from 1.7 Million Fields around the World, *Journal of Political Economy* **124**(1): 205–248.

Cruz, J.-L. and Rossi-Hansberg, E. (2024). The Economic Geography of Global Warming, *Review of Economic Studies* **91**(2): 899–939.

Dekle, R., Eaton, J. and Kortum, S. (2007). Unbalanced trade, *American Economic Review* **97**(2): 351–355.

Duan, Y., Ji, T., Lu, Y. and Wang, S. (2021). Environmental Regulations and International Trade: A Quantitative Economic Analysis of World Pollution Emissions, *Journal of Public Economics* **203**: 104521.

Eaton, J. and Kortum, S. (2002). Technology, geography, and trade, *Econometrica* **70**(5): 1741–1779.

European Commission, J. (2023). Emission database for global atmospheric research (edgar). Joint Research Centre (JRC)/Netherlands Environmental Assessment Agency (PBL), release version 4.tox2 global gridmaps.

FAO (2023). Faostat emissions totals. License: CC BY-NC-SA 3.0 IGO. Accessed: April 15, 2024.

Farrokhi, F. and Lashkaripour, A. (2025). Can trade policy mitigate climate change, *Econometrica* **93**(5): 1561–1599.

Farrokhi, F., Lashkaripour, A. and Taheri, H. (2025). A Framework for Integrating Climate Goals into Trade Agreements, *Working Paper* .

Felder, S. and Rutherford, T. F. (1993). Unilateral co2 reductions and carbon leakage: The consequences of international trade in oil and basic materials, *Journal of Environmental Economics and Management* **25**(2): 162–176.

Fontagné, L., Guimbard, H. and Orefice, G. (2022). Tariff-based product-level trade elasticities, *Journal of International Economics* **137**: 103593.

Garcia-Lembergman, E., Ramondo, N., Rodrıguez-Clare, A. and Shapiro, J. S. (2025a). The Carbon Footprint of Multinational Production, *Working Paper* .

Garcia-Lembergman, E., Ramondo, N., Rodrıguez-Clare, A. and Shapiro, J. S. (2025b). Carbon Taxes in the Global Economy: A Quantitative Analysis, *Working Paper* .

Golosov, M., Hassler, J., Krusell, P. and Tsyvinski, A. (2014). Optimal taxes on fossil fuel in general equilibrium, *Econometrica* **82**(1): 41–88.

Gouel, C. and Laborde, D. (2021). The crucial role of domestic and international market-mediated adaptation to climate change, *Journal of Environmental Economics and Management* **106**: 102408.

Grossman, G. M. and Krueger, A. B. (1991). Environmental impacts of a North American free trade agreement, *NBER Working Papers 3914*, National Bureau of Economic Research, Inc.

IEA (2023). Energy prices. IEA, Paris (database).

Kortum, S. and Weisbach, D. (2021). Optimal unilateral carbon policy, *SSRN Electronic Journal* .

Krusell, P. and Smith, Anthony A, J. (2022). Climate change around the world, *Working Paper 30338*, National Bureau of Economic Research.

Larch, M. and Wanner, J. (2017). Carbon tariffs: An analysis of the trade, welfare, and emission effects, *Journal of International Economics* **109**: 195–213.

Le Moigne, M., Lepot, S., Ritel, M. and Simon, D. (2026). The distributional effects of carbon pricing across countries, *Journal of International Economics* **160**: 104228.

Levinson, A. (2009). Technology, International Trade, and Pollution from US Manufacturing, *American Economic Review* **99**(5): 2177–2192.

Nordhaus, W. (2018). Projections and uncertainties about climate change in an era of minimal climate policies, *American economic journal: economic policy* **10**(3): 333–360.

Nordhaus, W. D. (1993). Optimal greenhouse-gas reductions and tax policy in the" dice" model, *The American Economic Review* **83**(2): 313–317.

OECD (2021). Trade in embodied co2 (teco2) database. Accessed: April 15, 2024.

OECD (2023). Oecd inter-country input-output database. Accessed: April 15, 2024.

Peter, A. and Ruane, C. (forthcoming). Intermediate input substitutability, *Econometrica* .

Shapiro, J. S. (2016). Trade costs, co2, and the environment, *American Economic Journal: Economic Policy* **8**(4): 220–254.

Shapiro, J. S. and Walker, R. (2018). Why Is Pollution from U.S. Manufacturing Declining? The Roles of Environmental Regulation, Productivity, and Trade, *American Economic Review* **108**(12): 3814–3854.

Stadler, K., Wood, R., Bulavskaya, T., Södersten, C.-J., Simas, M. et al. (2018). EXIOBASE 3: Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables, *Journal of Industrial Ecology* **22**(3): 502–515.

Stern, D. I. (2012). Interfuel substitution: A meta-analysis, *Journal of Economic Surveys* **26**(2): 307–331.