

Supplementary Information

Trade shocks redraw the global carbon map but do not shrink it:
product-level evidence from integration and fragmentation

Online Appendix

A1 Construction of the embodied-carbon measure

Construction. Embodied carbon in bilateral trade is built by mapping cradle-to-gate life-cycle carbon intensities onto bilateral trade. Life-cycle factors come from ecoinvent (industrial and materials activities) and Agribalyse (agri-food, $HS \leq 24$), accessed via the ADEME Base Empreinte (Wernet et al., 2016); trade flows are HS6 bilateral values and physical quantities from BACI (CEPII), 1995–2023, $\sim 5,000$ products and ~ 200 countries. Factors are matched to HS6 products by a $CPC \leftrightarrow HS$ concordance; where a direct product-specific factor is unavailable, a representative-technology factor is used (the majority of process records carry a generic geography, GLO/RoW/RER). Bilateral embodied carbon is the trade flow times its product-level cradle-to-gate intensity, aggregated to $HS2 \times \text{country-pair} \times \text{year}$. The boundary is cradle-to-gate: the use phase and international shipping are excluded (the latter enters only the carbon-minimal frontier as an on/off sensitivity, where its effect is small).

Basis and audit. The account is the audited basis of the companion measurement paper (Pothin, 2026): iteration-2 matching filter (unit compatibility, waste boundary, material taxonomy, processing-stage ladder), stage-matched fallback for products whose donors the filter rejected, audited factor corrections, upstream-only mineral-fuel boundary, IPCC 2013 GWP 100a (Myhre et al., 2013) on the ecoinvent cut-off system model. Its matching carries a blind-audited error rate of 8 wrong assignments in 100 (17 before the repair).

Validation. The measure agrees with an independent cradle-to-gate inventory (ICE, Hammond and Jones, 2008: median ratio 1.04, $\log\text{-log } r = 0.91$, nine of eleven matched material classes within $2\times$) and captures EXIOBASE (Stadler et al., 2018) consumption footprints at an emissions-weighted median ratio of 0.90 (83% within $3\times$). Full construction and validation are reported in the companion measurement paper (Pothin, 2026).

A2 Episodes, the log outcome, and Russia in both families

Zeros and the log outcome. A sanctions design running on a log outcome invites the objection that the outcome the shock produces, a closed market, is exactly the observation a log cannot hold. Here it does not bite, and the check is cheap. The bloc-bound panel holds 6,449 exporter-year cells, none of them exactly zero, so the positivity filter removes nothing. All nine treated targets are present in all twenty-nine years, with no post-onset year missing for any of them. The 250 cells absent from the balanced grid, 3.7% of it, belong entirely to the never-treated pool, and the estimator handles an unbalanced panel. What the sanctions do produce is very small positive values rather than zeros: North Korea’s bloc-bound carbon reaches

4.7 thousand tonnes in 2019, four orders of magnitude below its own pre-onset level. Those observations survive the log and enter the estimate, which is part of why the fragmentation standard errors are wide at the middle horizons.

Russia in both episode families. Russia is a treated unit twice over, acceding to the WTO in 2012 and sanctioned in 2014, and it is never used as a control in either family: the accession design draws controls from pre-1995 GATT members and the sanctions design from never-sanctioned countries. The contamination that matters runs the other way. Russia’s accession effect is estimated over horizons that reach fifteen years, so its own 2014 sanction sits inside its post-accession window. We therefore re-estimate the integration event study without Russia. The profile does not move: +0.284 against +0.274 at ten years and 0.526 against 0.526 at fifteen, so one cohort out of thirty-five carries none of the result. The 2014 onset and the 2022 measures are treated as one episode family entered at its first onset, which is the convention the staggered estimator requires; the 2022 measures are studied separately in the within-exporter design of Section 5, where the treated unit is a destination rather than a cohort year.

Episode lists. WTO accessions (year): ECU/BGR 1996; MNG/PAN 1997; KGZ 1998; LVA/EST 1999; JOR/GEO/ALB/OMN/HRV 2000; LTU/MDA/CHN 2001; TWN 2002; ARM/MKD 2003; NPL/KHM 2004; SAU 2005; VNM/TON 2007; UKR/CPV 2008; MNE/WSM/RUS/VUT 2012; LAO/TJK 2013; YEM 2014; SYC/KAZ 2015; LBR/AFG 2016. Sanction onsets: SYR 2011; LBY 2011; IRN 2012; RUS 2014; PRK 2016; VEN 2019; BLR 2021; MMR 2021; ZWE 2002. Russia appears in both lists (WTO accession 2012; sanction onset 2014). The list counts 36 accessions; Taiwan does not appear as an exporter in the trade panel, so 35 treated cohorts enter the estimation. The nine onsets are a stated selection, not a provisional sample: we keep episodes that are (i) multilateral, imposed by more than one of the 36 bloc members, (ii) comprehensive rather than targeted at named individuals or a single sector, and (iii) imposed on a country that exports at least 1 MtCO₂e of embodied carbon to the bloc in the pre-onset year, so that a decline is measurable. The Global Sanctions Data Base (Felbermayr et al., 2020) lists many further episodes that fail one of these three, chiefly arms embargoes and individual designations with no measurable trade leg.

A3 Gravity, the estimated elasticity, and the counterfactual rule

Gravity. PPML on aggregate bilateral embodied carbon with exporter and importer fixed effects gives a distance elasticity $\hat{\beta}_{\ln d} = -1.11$ ($p = 4.9 \times 10^{-38}$, $N = 27,143$ pairs).

Estimated θ . We estimate the trade elasticity from the 2018 US–China tariffs (a carbon-tariff-like shock) following Fajgelbaum et al. (2020). The outcome is the China-vs-rest log import gap of US imports by HS6, $D_{g,t} = \ln M_{g,t}^{CHN} - \ln M_{g,t}^{ROW}$. We regress it on the Section-301 add-on tariff with HS6 and year fixed effects (Section-301 schedule at HS6, 5,114 products):

$$D_{g,t} = -\theta \ln(1 + \text{tariff}_{g,t}) + a_g + d_t + u_{g,t}.$$

We obtain $\hat{\theta} = 1.09$ (s.e. 0.18, $p = 6 \times 10^{-10}$, $N = 24,981$) short-run, ≈ 2.1 at the 2023 horizon,

well below the calibrated 4–6 used by the CBAM literature. The estimate can be checked against the decline it is meant to explain, and the check turns on the horizon. At the 22.2-point average add-on, $\hat{\theta} = 1.09$ predicts -19.6% against an observed -24.0% in 2021 (Table 5), while the 2021 elasticity of 1.47 predicts -25.5% . The observed decline sits between the two, which is what a rising elasticity implies.

A short-run elasticity near one that rises with the horizon is what the trade literature finds when the elasticity is estimated from tariff variation rather than calibrated to fit trade shares. Boehm et al. (2023) identify it from most-favoured-nation tariff changes with local projections and report -0.76 in the short run and approximately -2 in the long run, taking seven to ten years to converge, with even their long-run estimates smaller than is typical in the literature. Our 1.09 pooled and 2.1 at the 2023 horizon sit inside that profile. Estimates built to correct the upward bias of share-based estimators land higher (Simonovska and Waugh, 2014; Caliendo and Parro, 2015), so the range in use spans more than the calibrated 4–6. The distinction matters for the counterfactual: what governs how much a border adjustment can move within a decade is the elasticity at that horizon, and it is smaller than the calibration. On the gravity estimators used here, see Head and Mayer (2014) and Santos Silva and Tenreyro (2006).

The elasticity is estimated on one importer and applied to a bloc. It comes from US imports, China against the rest, and the counterfactual applies it to thirty-six importers buying from every origin. Two parts of that gap can be closed with the same data and one cannot. The product part turns out to be small in coverage and large in consequence. Only 30% of the 4,993 tariffed HS6 lines fall in the ten chapters the counterfactual prices, but within those chapters the schedule hit almost everything: 41 of 41 lines in mineral fuels, 162 of 164 in iron and steel, 35 of 35 in aluminium, 24 of 24 in fertiliser. The elasticity can therefore be re-estimated on the counterfactual’s own products, and it is lower: 0.69 (s.e. 0.28) against 1.09 on the full schedule, with 1.33 (s.e. 0.24) outside those chapters. Carbon-intensive commodities substitute less readily than the manufactures that dominate the schedule, which is what capacity and contracting would predict. Using the pooled elasticity therefore overstates what a carbon price can move in exactly the sectors it would cover, and the cuts reported here are on the high side for that reason. On the legislated scope alone the elasticity is not usefully identified, 0.91 with a standard error of 0.93 over 391 product lines, and we do not report a scope-matched counterfactual for it.

What cannot be closed is the importer. Nothing in the Section-301 experiment speaks to how European, Japanese or Canadian buyers reallocate, and a second estimation on the bloc’s own trade would need a comparable tariff shock that the bloc has not administered. The counterfactual is conditional on that transfer, and the sign of the error is unknown.

CBAM counterfactual. A carbon tariff adds an ad-valorem cost $t_{oj} = P \iota_o / 1000$ (P in $\$/\text{tCO}_2\text{e}$, ι_o origin intensity) on bloc imports; importers reallocate value across origins by a CES rule, $\text{share}_{oj} \propto \text{share}_{oj}^0 (1 + t_{oj})^{-\theta}$, sectoral demand fixed; embodied carbon is recomputed as $\text{value} \times \text{intensity}$. Leakage is bounded by supply elasticity.

A4 Composition of the blocs

Three designs out of four are built on bloc membership, so the composition is stated here in full. The lists are the ones the estimation code uses; they are identical across every script that reads them.

Table 1 lists the bloc membership used in every estimation.

Table 1: Bloc membership, as used in every estimation.

Group	n	Members (ISO-3)
Sanctioning bloc, also “the West”	36	AUS, AUT, BEL, BGR, CAN, CHE, CYP, CZE, DEU, DNK, ESP, EST, FIN, FRA, GBR, GRC, HRV, HUN, IRL, ITA, JPN, KOR, LTU, LUX, LVA, MLT, NLD, NOR, NZL, POL, PRT, ROU, SVK, SVN, SWE, USA
China–Russia bloc	5	BLR, CHN, IRN, PRK, RUS
Absorbers (Russia rerouting)	3	CHN, IND, TUR
Neither	rest	every other reporter in the panel, 190 of the 231 exporters

The sanctioning bloc is the set that imposed comprehensive measures on Russia in 2022: the EU-27 plus the United Kingdom, the United States, Japan, Canada, Korea, Australia, Switzerland, Norway and New Zealand. The China–Russia bloc is deliberately narrow, five countries, so the cross-bloc series of Section 4 measures trade between two small, well-defined groups rather than a residual. Everything else is “neither”, and neither group is used as a control in the event studies, which identify within one treated exporter. Borderline cases are decided by the 2022 sanctions record, not by geography or income: Turkey, Israel, Singapore and Hong Kong sit in “neither” because they did not impose the measures, and Turkey appears among the absorbers for the same reason. Reclassifying Turkey or Korea moves the cross-bloc share by less than a percentage point and leaves every event-study coefficient unchanged, because those designs never use bloc membership on the control side.

A5 Scope and the national accounting identity

This appendix reports the comparison behind Section 2: territorial emissions plus this paper’s net embodied imports, set against the benchmark consumption-based account, country by country.

A6 Supplementary figures

Two exhibits support the robustness section: the carbon-weighted and value-only effects side by side, and the destination composition of Russia’s carbon exports through the 2022 break.

A7 Data and code availability

The bilateral carbon panel is built from the public sources in Table 1. The panel itself, all analysis scripts (measure construction, within-exporter event studies, the Callaway and Sant’Anna (2021) estimator, gravity, the θ estimation, the counterfactuals, the robustness and sensitivity analyses, and every figure) and the provenance record are deposited at 10.5281/

Table 2: Territorial emissions plus net embodied imports against the benchmark consumption-based account (Ritchie et al., 2024), 2023.

	Territorial	Net embodied trade		Implied	Benchmark	Gap
	emissions	this measure	benchmark	total	account	
China	12,172	−224	−1,315	11,948	10,857	10%
United States	4,918	453	513	5,371	5,432	−1%
India [†]	3,063	348	−520	3,410	2,543	34%
Russia	1,733	−350	−327	1,383	1,406	−2%
Japan	987	178	155	1,165	1,142	2%
Iran	790	−4	−121	786	669	18%
Indonesia	762	−241	−34	522	728	−28%
Saudi Arabia	677	−173	−23	504	654	−23%
Germany	594	27	175	621	768	−19%
South Korea [†]	589	−36	120	553	709	−22%
Canada	545	−204	−26	342	520	−34%
Turkey [†]	487	43	−4	530	483	10%

Across all 119 countries carrying both series: the median absolute gap is 23% of the benchmark, 57% of countries fall within 25%, and the net positions agree in sign for 76% of countries with a rank correlation of 0.49. The level correlation is 0.997, which on this range of magnitudes is near-mechanical and is reported for completeness rather than as a test.

All quantities in MtCO₂e, ranked by territorial emissions. Territorial emissions are the Global Carbon Budget national series. The benchmark account is the OWID consumption-based series (Ritchie et al., 2024), built on a full-economy input–output model; its own net position is the benchmark column. Net embodied trade on this measure is imports minus exports of cradle-to-gate embodied carbon in goods. The implied total is territorial emissions plus this paper’s net position, and the gap is its deviation from the benchmark. The identity tracks the benchmark in level, but it does not reproduce it country by country, and [†] marks the three of these twelve whose net position changes sign: India, South Korea and Turkey. China shows the boundary difference most clearly. On a gross cradle-to-gate basis it imports carbon-intensive raw materials and its net position is −224; the input–output account attributes the upstream of its exports to foreign consumers and puts it at −1,315. That distance is the distance between an exposure measure and a responsibility measure, and this paper reports the first. The identification runs on gross bilateral flows, not on this identity; see Section 2.

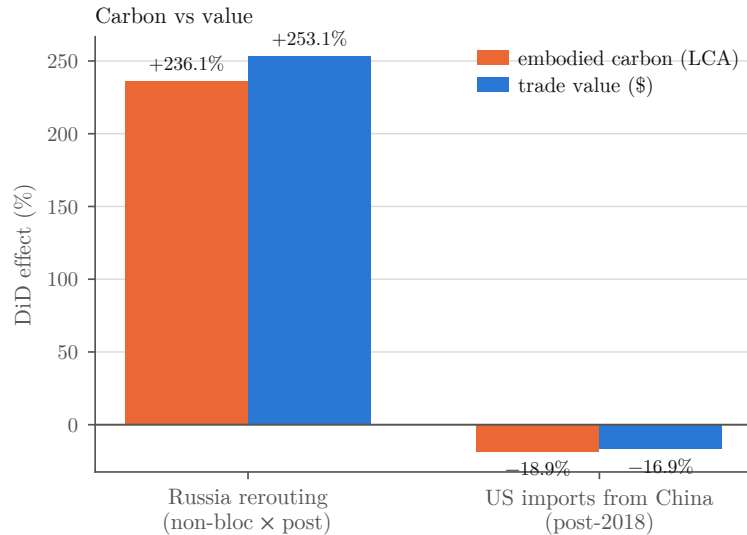


Fig. 1 Carbon-weighted vs value-only DiD effects; near-identical magnitudes (cf. Table 12).

Notes. PPML difference-in-differences on the same shocks, once weighting flows by carbon and once by value; the two agree to 2.0 percentage points for China and 17.0 for Russia. *Source:* author’s calculations on the audited product-level embodied-carbon account (BACI (Gaulier and Zignago, 2010) × ecoinvent (Wernet et al., 2016) and Agribalyse (ADEME, 2023) cradle-to-gate factors, IPCC 2013 GWP 100a); see Table 12 for the coefficients and the inference each row rests on.

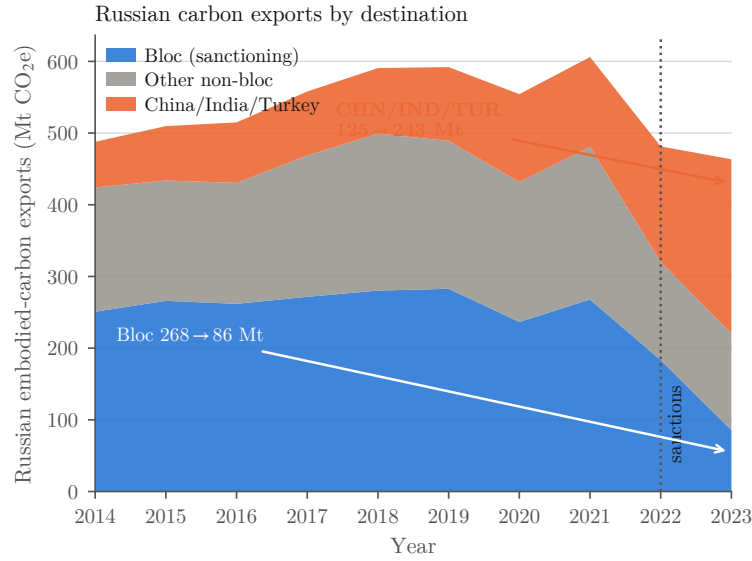


Fig. 2 Russia’s embodied-carbon exports by destination, 2014–2023 (stacked): the bloc collapses (268→86 Mt) while China/India/Turkey rise (125→243 Mt). Time-series companion to the flow map. *Notes.* Stacked embodied-carbon exports by destination group. The series are ordered as in the legend and carry a hatch so the groups separate in greyscale. *Source:* author’s calculations on the audited product-level embodied-carbon account (BACI (Gaulier and Zignago, 2010) × ecoinvent (Wernet et al., 2016) and Agribalyse (ADEME, 2023) cradle-to-gate factors, IPCC 2013 GWP 100a); totals over all destinations in each group.

zenodo.21889661, a concept identifier that resolves to the latest version. Every table in the paper is produced by the deposited code from a logged run. Life-cycle factors are accessed through the ADEME Base Empreinte and trade data from BACI (CEPII); neither is redistributed there, and the Global Sanctions Data Base requires a non-commercial request to its maintainers.

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