

Third-country carbon embedded in global trade

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Abstract

International trade records name an exporter and an importer, but the supply chains behind a traded product often draw on production in other countries. Here we quantify third-country carbon: CO₂ emissions generated outside both trade partners, but required by the supply chain that links them. Using the Eora multi-region input-output table, we trace these emissions for 189 economies, 26 sectors and 35,532 directed trade routes from 2000 to 2021. Third-country carbon reached 1.85 Gt CO₂ in 2021, or 27.7% of trade-embodied emissions. After rapid growth from 2000 to 2011, this third-country layer persisted at a high level. It is strongly directional, spread across many trade routes, concentrated in a few upstream production sources and rooted in energy and material sectors. Structural decomposition shows that improvements in carbon coefficients reduced third-country carbon by about 2.0 Gt CO₂ over 2000–2021, whereas trade expansion and production-network restructuring added about 1.85 Gt and 0.91 Gt. These findings shift trade-carbon accounting from endpoint responsibility towards path and source-based responsibility, with implications for carbon border policies, product disclosure and supply-chain decarbonisation.

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22 **Introduction**

23 International trade has reshaped the geography of carbon emissions. By separating final
24 consumption from assembly and upstream production, global value chains redistribute CO₂ emissions
25 across jurisdictions, weakening the link between territorial inventories and the carbon responsibility of
26 consumption^{1–7}. This separation is no longer only an accounting concern. Carbon border policies,
27 product carbon footprints, green procurement rules and corporate supply-chain targets increasingly
28 depend on knowing where emissions are generated within traded production systems, not merely which
29 country appears as the final exporter^{8–12}.

30 The difficulty is that international trade statistics name the exporter and importer in a bilateral
31 transaction, whereas production networks often extend through several countries before that transaction
32 is completed. Work on vertical specialization, global value chains, value-added trade and gross-export
33 decomposition has shown that the country named as the exporter may contribute only part of the value
34 embodied in a traded product, with intermediate inputs and double-counted flows linking many
35 economies before final absorption^{13–20}. Carbon accounting has made parallel progress. Production-based
36 and consumption-based inventories have exposed large emission transfers through trade, and
37 technology-adjusted or protocol-oriented approaches have refined responsibility by considering how
38 emission intensities differ across production locations and how consumption-based accounts should be
39 constructed^{1–7,21–25}. Yet much of this literature still treats the bilateral trade record as the primary object
40 of analysis. It asks how emissions should be allocated between the country that sells and the country that
41 buys, but leaves less visible the production generated along the route by economies that are absent from
42 that bilateral record.

43 This missing production position is the focus of this study. For any directed bilateral route from an
44 exporter to an importer, part of the associated production may occur in countries that are neither the
45 recorded exporter nor the recorded importer. These third countries may supply energy, raw materials,

46 basic materials, intermediate goods or coordination services that make the bilateral trade possible.
47 Previous studies have shown that South-South trade, international sourcing and narrowing emission-
48 intensity gaps have changed the geography and mitigation consequences of trade-embodied emissions²⁶⁻
49 ²⁸. Recent Eora-based evidence on China-U.S. trade also shows that third-country participation can alter
50 country- and sector-level carbon-intensity outcomes, with trade-flow direction shaping the carbon
51 impacts of global value-chain participation²⁹. However, existing work does not isolate, for every directed
52 bilateral corridor, the emissions generated by countries outside both countries named in the trade record.
53 As a result, a substantial share of supply-chain carbon can remain hidden behind bilateral trade labels.

54 This third-country layer matters for climate governance because different trade paths require
55 different decarbonisation targets. Where emissions are generated mainly within the exporting economy,
56 policy attention should fall on the exporter's energy system and industrial processes. Where emissions
57 are split between the visible exporter and upstream suppliers, governance needs to cover both export-
58 side production and third-country inputs. Where the recorded exporter mainly re-exports, assembles or
59 coordinates goods produced elsewhere, policies focused only on that exporter may miss the upstream
60 hubs where most mitigation potential lies. Carbon border adjustment, product disclosure and supply-
61 chain due-diligence measures have already drawn attention to third-country risks, monitoring constraints
62 and unequal exposure among developing trade partners⁸⁻¹⁰. More broadly, recent evidence shows that
63 shocks and policies can travel through production networks and global supply chains beyond the
64 jurisdictions in which they begin³⁰⁻³². A carbon accounting framework that stops at the final exporter
65 may therefore assign responsibility to the wrong place and overlook where emissions can be reduced.

66 Here we define and quantify third-country carbon: CO₂ emissions generated in economies that are
67 neither the exporter named in trade records nor the importer named in trade records along a directed
68 bilateral trade route, but whose production is mobilized within the supply chain serving that route. We
69 use the Eora multi-region input-output table to trace third-country production pathways across 189

70 economies, 26 sectors and 35,532 directed trade corridors from 2000 to 2021. We combine directed path
71 accounting with three network indicators - the third-country share, directional spillover asymmetry and
72 source concentration - and use Shapley-averaged structural decomposition analysis to separate changes
73 in third-country carbon into carbon-coefficient, production-network, trade-path-structure and trade-scale
74 mechanisms.

75 We show that third-country carbon is not a marginal residual of international trade. It reached 1.85
76 Gt CO₂ in 2021, or 27.7% of trade-embodied emissions. After rapid expansion during the 2000s, this
77 layer did not disappear with carbon-efficiency improvements but persisted at a high level, sustained by
78 trade-scale expansion and production-network restructuring. The result shifts the accounting object from
79 the bilateral exporter–importer pair to the full trade path and its upstream production sources, revealing
80 where supply-chain decarbonisation is occurring.

81

82 **Results**

83 **Third-country carbon shifted from expansion to persistence**

84 International production networks increasingly separate the visible label of trade from the
85 geography of production. We define third-country carbon as the CO₂ generated by economies that are
86 neither the exporter named in trade records nor the importer named in trade records along a directed
87 bilateral trade route, but whose production is mobilised within the supply chain serving that route. Using
88 the Eora multi-regional input-output system for 189 economies and 35,532 directed trade routes over
89 2000-2021, we estimate that global third-country carbon reached 1.85 Gt CO₂ in 2021, representing
90 27.7% of all trade-embodied emissions (Fig. 1a,b). More than one quarter of emissions embodied in
91 international trade therefore occurred outside the two economies named in the bilateral trade record.

The time series reveals two regimes. Between 2000 and 2011, third-country carbon increased from about 1.13 to 1.84 Gt CO₂, an absolute rise of 710.1 Mt that coincided with the rapid expansion of global trade and vertically specialised supply chains. After 2011, aggregate growth almost ceased: third-country carbon increased by only 10.2 Mt between 2011 and 2021 and remained close to 1.85 Gt CO₂ (Fig. 1a,c). This plateau, however, does not imply that the third-country layer receded. The network-weighted third-country share remained above one quarter of trade-embodied emissions and reached 27.7% in 2021 (Fig. 1b).

The post-2011 transition is therefore better interpreted as a shift from expansion to structural persistence. Aggregate growth slowed, but the typical trade route remained strongly dependent on third-country production. Third-country carbon changed from a rapidly expanding emission flux into a high-level layer embedded in the organisation of global production.

Third-country carbon is directional

Third-country carbon is not a property of an unordered country pair. It is a property of a directed supply-chain path. A bilateral relationship between economies A and B contains two directed flows, $A \rightarrow B$ and $B \rightarrow A$, which may traverse different production networks, mobilise different third-country suppliers and generate different emission structures. The mean absolute Directional Spillover Asymmetry Index (DSAI) changed only slightly during the expansion decade, rising from 0.471 to 0.478 between 2000 and 2011 (+0.007). It then increased sharply to 0.592 by 2021 (+0.114; Fig. 2a). The volume plateau after 2011 therefore coincided with a marked increase in directional heterogeneity.

The distribution of third-country shares in 2021 shows that third-country participation is not restricted to a few exceptional flows. The network-weighted TCS was 27.7%, whereas the unweighted mean reached 40.8% and the median reached 35.2% (Fig. 2b). Large corridors often remain dominated by direct production in the exporter, but the flow-level distribution shows that many smaller and medium-sized routes depend heavily on third-country production sources.

116 Directional contrasts are especially visible in major corridors. MEX→USA induced 42.4 Mt CO₂
117 through third-country platforms, compared with 13.4 Mt in the reverse direction. HKG→USA induced
118 32.2 Mt, whereas USA→HKG induced only 0.9 Mt. CHN→USA generated 22.4 Mt and USA→CHN
119 10.7 Mt; DEU→USA generated 24.2 Mt and USA→DEU 3.6 Mt; SGP→USA generated 16.1 Mt and
120 USA→SGP 1.4 Mt; and KOR→CHN generated 20.1 Mt compared with 3.4 Mt in the reverse direction
121 (Fig. 2c). Third-country carbon is therefore path-dependent: it depends not only on who trades with
122 whom, but on the direction and production network through which trade is organised.

123 **Asian corridors rose in a US- and Europe-facing network**

124 Third-country carbon was not carried by one dominant trade route. In 2021, the top 20 directed
125 corridors accounted for only 19.4% of global third-country carbon (Fig. 3a,c). Even the largest routes
126 therefore explain only part of the hidden layer. Most third-country carbon was spread across many
127 exporter–importer corridors, which means that it cannot be governed by tracking a few headline trade
128 links alone.

129 The corridor map changed over time, but not as a simple shift from Western demand to Asian
130 demand. In 2000, the leading routes were mainly connected to North American and Western European
131 markets, including CAN→USA, DEU→USA, MEX→USA, JPN→USA and several European or
132 transatlantic routes. By 2021, that structure was still clearly present. MEX→USA became the largest
133 corridor, reaching 42.4 Mt CO₂, while HKG→USA, DEU→USA, CHN→USA and CAN→USA also
134 remained among the largest routes. What changed was the growing weight of Asian production and
135 intermediation within this still US- and Europe-facing system. KOR→CHN, DEU→CHN,
136 HKG→CHN, SGP→CHN and SGP→USA moved into the upper ranks, showing that Asian platforms
137 became more important.

138 These large corridors also differ in what they imply for decarbonisation. In HKG→USA and
139 SGP→USA, the exporter named in trade records is mostly a gateway: most embodied emissions are

140 generated elsewhere. In MEX→USA and DEU→USA, third-country inputs are substantial, but the
141 exporter's own production also remains important. In CHN→USA, the third-country share is much
142 lower because much of the production is contained within China's own industrial system, even though
143 the absolute third-country carbon remains sizeable. The same bilateral trade label can therefore represent
144 very different production structures. Policies that stop at the recorded exporter risk missing whether the
145 carbon comes from a gateway, a mixed supply chain or a largely domestic production system.

146 **Many corridors rely on a few upstream production sources**

147 The most consequential feature of third-country carbon is the mismatch between visible trade labels
148 and real production origins. In 2021, China contributed roughly 0.5 Gt CO₂ as a third-country production
149 hub and was by far the largest hidden producer, followed by Russia and India (Fig. 4b,c). The 2021
150 ranking also highlights the roles of the United States, Kazakhstan, Poland, Viet Nam, Japan, Saudi
151 Arabia and Australia among the leading hubs. Bilateral trade labels disperse upstream carbon pressure
152 across many relationships; the production network reconcentrates that pressure in a smaller set of
153 repeatedly used third-country platforms.

154 The hub geography changed in two distinct ways. During 2000-2011, many emerging production
155 sources expanded rapidly relative to their initial size, while China and Russia remained central
156 participants (Fig. 4a,c). During 2011-2021, relative changes became more uneven: several advanced
157 economies declined or stabilised, whereas parts of Southeast Asia, Central Asia and Africa recorded
158 large proportional increases from smaller baselines. The absolute ranking in 2021, however, remained
159 sharply dominated by China, followed by Russia and India. Thus, the geography of change is broad, but
160 the geography of volume is concentrated.

161 **Upstream energy and materials underpin third-country carbon**

162 The sectoral composition of third-country carbon shows that the third-country layer is anchored
163 upstream rather than determined by the appearance of final goods. In 2021, the largest sector was
164 Electricity, Gas and Water, followed by Mining and Quarrying; Petroleum, Chemical and Non-Metallic
165 Mineral Products; Metal Products; Electrical and Machinery; and Financial Intermediation and Business
166 Activities (Fig. 5a,b). The leading sectors are therefore power generation, extractive activity, basic-
167 material processing and the manufacturing and service functions that coordinate complex supply chains.
168 The sectors with the largest increases over 2000-2021 were also upstream. Mining and Quarrying
169 showed the largest increase, at roughly 125-130 Mt CO₂, followed by Petroleum, Chemical and Non-
170 Metallic Mineral Products at about 90 Mt and Electricity, Gas and Water at about 80 Mt (Fig. 5c).
171 Electrical and Machinery, Metal Products and Financial Intermediation and Business Activities also
172 grew substantially. The broad stability of the leading sectors over 22 years suggests an enduring upstream
173 anchoring rather than a short-lived episode of trade relocation.

174 This sectoral evidence reinforces the central result. The apparent clean-up of final exports does not
175 necessarily mean that the full supply chain has decarbonised. A traded product may appear as a high-
176 value, low-emission final good at the export frontier while its third-country carbon footprint remains
177 rooted in electricity generation, mining, petrochemical processing, metallurgy and supply-chain services
178 within hidden hubs. As long as these upstream functions are performed by third-country platforms,
179 visible trade flows can become lighter on paper while carbon remains locked in the concealed production
180 layer.

181 **A stable total masked a changing network**

182 The decomposition explains why third-country carbon barely changed after 2011. During 2000–
183 2011, trade-scale growth and production-network change pushed third-country carbon upward, more
184 than offsetting the large downward effect of carbon-coefficient improvements; the layer increased by

185 710 Mt (Fig. 6a). During 2011–2021, the terms became much smaller and almost cancelled each other:
186 production-network change, carbon coefficients and product composition pushed upward, while the
187 trade-scale effect pushed downward, leaving only a small net increase of about 10 Mt (Fig. 6b,c).
188 Representative corridors show the same tension at the route level. In MEX→USA, CHN→USA,
189 KOR→CHN, DEU→USA and CAN→USA, carbon coefficients reduced third-country carbon, whereas
190 trade scale increased it; the production-network effect varied by corridor, showing that the plateau was
191 produced through different route-level mechanisms rather than one common adjustment (Fig. 6d).

192 The network maps show what changed beneath this stable total. In 2000–2011, large US- and
193 Europe-facing corridors drew heavily on China and Russia as third-country production sources, with
194 many links shown in red or orange, indicating production bundles more carbon-intensive than each
195 source economy’s average export bundle (Fig. 7a). In 2011–2021, the visible corridor side was
196 reshuffled: MEX→USA became the largest route, while CHN→USA, KOR→CHN, HKG→USA,
197 DEU→CHN and SGP→CHN became more prominent. The hidden-source side changed more slowly.
198 China remained the dominant source, Russia weakened and India gained weight. The link color for most
199 countries also shifted towards yellow and orange, suggesting narrower but still persistent carbon-
200 intensity gaps (Fig. 7b). The post-2011 pattern is therefore simple: opposing drivers kept the total almost
201 flat, while the corridors and hidden production sources carrying third-country carbon continued to
202 change.

203

204 Discussion

205 Decarbonisation of global trade is often evaluated through two questions: whether production is
206 becoming less carbon intensive, and whether emissions are being shifted between producer and
207 consumer countries. This study shows that a third question is equally important: where, within the trade

208 path, emissions are generated. Third-country carbon reveals a form of supply-chain dependence in which
209 the production required for a bilateral trade flow occurs partly in economies absent from the trade label
210 itself. This matters because improvements in carbon intensity can reduce emissions per unit of
211 production without resolving the accounting boundary that assigns responsibility mainly to the visible
212 exporter and final importer. The implication is that trade-related carbon responsibility is not only a
213 producer-consumer problem, but also a path-position problem.

214 These findings extend trade-carbon accounting from a producer–consumer dyad to a triadic account
215 of exporter, importer and third-country production. Carbon accounting for trade has often been framed
216 around a producer-consumer dyad: where emissions are produced, where goods are consumed and how
217 responsibility should be assigned between the two. Technology-adjusted and consumption-based
218 approaches have refined this dyad by considering differences in carbon intensity, final demand and the
219 construction of consumption-based accounts^{21–25}. Third-country carbon introduces a triadic structure:
220 the exporter, the importer and the third-country production network mobilised between them. This
221 structure matters because the same bilateral trade label can hide very different production geographies,
222 and the same third-country production source can support many seemingly unrelated bilateral flows.

223 This perspective changes how progress in trade-related decarbonisation should be interpreted.
224 Lower emission intensities and narrower gaps between developed and developing economies can reduce
225 carbon-leakage pressure through trade^{28,29}. Yet these improvements do not necessarily change where
226 supply-chain production takes place. A trade flow can become less carbon-intensive while still
227 depending on upstream production in economies outside the exporter-importer pair. Our findings
228 therefore point to a distinction between carbon-performance improvement and network reorganisation.
229 The former reduces emissions per unit of production; the latter determines whether trade remains
230 dependent on third-country production sources. Decarbonising global trade requires progress on both
231 dimensions.

232 The policy implication is that endpoint-based governance can misidentify the decarbonisation
233 target. In direct-production corridors, the main lever is the exporter's energy and industrial system. In
234 hybrid corridors, local production and third-country inputs must be governed together. In re-export
235 platform corridors, the exporter named in trade records may be primarily a trade intermediary, while the
236 decisive mitigation leverage lies in upstream production hubs. Carbon border adjustments, product
237 carbon footprints, green procurement standards and supply-chain due diligence schemes will be less
238 effective if they stop at the final exporter and do not identify third-country production sources.

239 This point is particularly important for border carbon policies. Research on carbon border
240 adjustment has highlighted third-country risks, monitoring and reporting capacity, the exposure of
241 developing trade partners, carbon leakage and alternative tariff designs as central concerns for policy
242 fairness and effectiveness^{8–10,50–54}. Our results suggest an additional design requirement. Policies should
243 not only evaluate the average carbon intensity of the exporting economy; they should also identify
244 whether the exported product is a direct-production, hybrid or re-export platform flow, and whether its
245 embodied carbon is concentrated in a small number of third-country production source.

246 The concentration of third-country production sources creates both vulnerability and opportunity.
247 Because a small set of countries is repeatedly embedded across many trade routes, local energy
248 transitions, industrial policies or supply shocks can propagate through global value chains. Similar
249 amplification mechanisms have been observed in production-network shocks, climate-related supply-
250 chain losses and the mesoscale structure of carbon trading networks, where network position and
251 institutional frictions shape system-wide outcomes^{30–32,55}. The same concentration also creates high-
252 leverage mitigation opportunities. Deep decarbonisation of electricity, mining, petrochemical and metal
253 production in major third countries would not only reduce territorial emissions; it would also lower the
254 embodied carbon of thousands of downstream trade routes.

255 The sectoral results make clear that third-country carbon is not primarily a question of final
256 assembly or the visible identity of the traded product. It is an energy and materials problem. Earlier
257 studies of international sourcing, South-South trade and emission-intensity convergence showed that
258 changes in procurement and supply-chain organisation can redistribute emissions through electricity,
259 mineral products, chemicals, metals and machinery sectors^{26–28}. This interpretation is also consistent
260 with work showing that deep decarbonisation requires low-carbon energy systems, industrial
261 transformation and material-efficiency strategies^{56–58}. Our results show that the third-country layer is
262 anchored in the same upstream systems. A supply chain can appear cleaner at the final export stage while
263 remaining carbon-intensive in the hidden production stages that supply power, raw materials, basic
264 materials and coordination services.

265 These findings also sharpen the equity problem in trade-related climate policy. Third-country
266 production sources often carry upstream emissions pressure on behalf of global consumption networks,
267 but their finance, technology and monitoring capacities may not match their functional role in those
268 networks. Assigning responsibility only to the exporter named in trade records can obscure the true
269 production source, whereas assigning responsibility only to the third countries can ignore final demand
270 and the firms that organise the supply chain. A more balanced approach would combine product-level
271 disclosure of third-country production sources with technology transfer, low-carbon infrastructure
272 finance and monitoring, reporting and verification support for hubs that have both high third-country
273 carbon contributions and strong transition constraints.

274 Several limitations should be kept in view. First, the analysis is based on the Eora MRIO
275 framework. Eora offers broad country coverage and is well suited to identifying global third-country
276 pathways, but MRIO databases differ in sector classification, trade balancing, price treatment and
277 environmental extensions^{33,37–41}. Core indicators should therefore be tested against EXIOBASE, WIOD,
278 OECD-ICIO or hybrid physical-monetary datasets. Second, MRIO resolution cannot identify firms,

279 facilities, specific products or actual logistics routes. Third-country carbon should be interpreted as a
 280 production-network accounting source, not as shipment-level customs tracing. Third, SDA attributes
 281 historical changes to modelled structural mechanisms, but it is not a causal experiment and remains
 282 sensitive to decomposition form and model specification^{43–49}. Finally, the present analysis focuses on
 283 CO₂ and does not include non-CO₂ greenhouse gases, land-use change, price responses, substitution
 284 behaviour or future supply-chain restructuring.

285 Future work can advance this framework in three directions. First, MRIO path accounting should
 286 be linked with customs microdata, firm supply-chain disclosures, product-level life-cycle inventories
 287 and facility emissions databases to improve the verifiability of third-country production sources. Second,
 288 third-country carbon indicators can be embedded in dynamic trade and scenario models to evaluate how
 289 border carbon adjustment, re-export regulation, supply-chain regionalisation and upstream energy
 290 transitions would reshape the third-country layer. Third, the framework should be extended from CO₂
 291 to multiple environmental and social pressures, identifying hidden hubs that jointly carry carbon, water,
 292 land, air-pollution, biodiversity, material and capital-stock risks^{59–61}. Third-country carbon is not a
 293 marginal accounting residual in global trade. It is a structural test of whether supply-chain
 294 decarbonisation is truly occurring. Climate governance must therefore move beyond endpoint
 295 responsibility towards path-based and source-based responsibility.

296

297 **Methods**

298 **Multi-regional Input-Output Framework**

299 We represented the world economy in year τ as a multi-regional input-output system with G
 300 countries and N sectors per country. In the empirical implementation, $G = 189$ and $N = 26$, giving $K =$
 301 GN country-sector nodes. Country indices are denoted by $s, r, t, g \in \mathcal{G}$ and sector indices by $i, \phi \in \mathcal{N}$.

302 Vectors are columns unless transposed. Unless a temporal comparison is being made, the year index is
 303 suppressed below and all matrices and vectors refer to the same year. The operator $\hat{z}$ forms a diagonal
 304 matrix from vector z ; $\mathbf{1}$ denotes a conformable vector of ones; and $\chi_g \in \{0,1\}^K$ selects the country-sector
 305 nodes located in country g ^{33–41}.

306 Let Z denote the global intermediate-input matrix, x the gross-output vector and f aggregate final
 307 demand. The technical-coefficient matrix is constructed by normalizing each column of Z by the gross
 308 output of the purchasing sector:

$$\begin{aligned}
 309 \quad & A = Z\hat{x}^{-1} \\
 310 \quad & x = Ax + f \\
 & L = (I - A)^{-1} \\
 & x = Lf
 \end{aligned} \tag{1}$$

311 The block $L^s = L[:, I_s]$ denotes the columns of the global Leontief inverse associated with the N
 312 sectors of exporter s . For each directed corridor $s \rightarrow r$, the validated Wang-Wei-Zhu right-side vector
 313 y_{sr} contains the final-demand and intermediate-embedding components needed to reproduce the
 314 forward-pair carbon total^{13,17,19,20}. The induced global production vector is

$$x_{sr}^{\text{ind}} = L^s y_{sr} \tag{2}$$

315 This directed formulation is evaluated for all ordered country pairs, excluding self-flows.

316 **Third-Country Carbon in Directed Trade**

317 Sectoral direct emission rates are obtained from the environmental satellite account as

$$e_i^g = \frac{\text{CO}_{2i}^g}{x_i^g} \tag{3}$$

318 where CO_{2i}^g is direct carbon dioxide emissions and x_i^g is gross output. Let v_i^g denote the value-added
 319 rate. Direct rates enter the forward carbonization step through $k_i^g = \sum_{\ell \in I_g} e_\ell^g L_{\ell i}^{gg}$, where I_g is the country-

320 sector index set of g and L^{gg} is the within-country block of the global Leontief inverse retained in the
 321 forward carbonization step. The effective coefficient is $h_i^g = v_i^g k_i^g$, and $\hat{h} = \text{diag}(h)$. Thus e is the direct
 322 source term used to construct h , while $\hat{h}$ is the diagonal effective coefficient applied in equations (4)-
 323 (6).

$$E_{sr}^{\text{tot}} = 1^T \hat{h} L^s y_{sr} \quad (4)$$

$$m_{sr} = \sum_{g \in \mathcal{G}, g \neq s, r} \chi_g \quad (5)$$

$$E_{sr}^{\text{TC}} = m_{sr}^T \hat{h} L^s y_{sr} \quad (6)$$

324 Equation (6) is the operational accounting identity used throughout the analysis. It is equivalent to
 325 retaining from the bilateral value-added decomposition only components generated outside the exporter
 326 and importer, then carbonizing those components with country-sector coefficients.

327 **Carbon-Intensity Gap Relative to Country-Specific Export Benchmarks**

328 Let $o_{t,sr}^i$ denote the sector- i value-added component generated by third country t and embodied in
 329 corridor $s \rightarrow r$. Let κ_t^i denote carbon per unit value added, and VAX_t^i value added from country-sector
 330 (t, i) embodied in world exports. The country-level gap is

$$\sigma_{t,sr} = \frac{\sum_i \kappa_t^i o_{t,sr}^i}{\sum_i o_{t,sr}^i} - \frac{\sum_i \kappa_t^i \text{VAX}_t^i}{\sum_i \text{VAX}_t^i}, \quad t \in \mathcal{G}, t \neq s, r \quad (7)$$

331 A positive $\sigma_{t,sr}$ means that country t participates in the focal corridor through a more carbon-intensive
 332 value-added bundle than its own average export bundle.

333 All monetary values used in equation (7) are converted to 2010 US dollars before intensity measures
 334 are constructed, using exchange-rate and GDP-deflator series from the World Bank World Development
 335 Indicators⁴².

336 Third-Country Share and Directional Asymmetry

$$\text{TCS}_{sr} = \frac{E_{sr}^{\text{TC}}}{E_{sr}^{\text{tot}}} \quad (8)$$

$$\text{TCS}^{\text{network}} = \frac{\sum_{s \in \mathcal{G}} \sum_{r \in \mathcal{G}, r \neq s} E_{sr}^{\text{TC}}}{\sum_{s \in \mathcal{G}} \sum_{r \in \mathcal{G}, r \neq s} E_{sr}^{\text{tot}}} \quad (9)$$

$$\text{DSAI}_{sr} = \frac{E_{sr}^{\text{TC}} - E_{rs}^{\text{TC}}}{E_{sr}^{\text{TC}} + E_{rs}^{\text{TC}}} \quad (10)$$

337 Aggregate claims use the network-weighted TCS. Flow-level TCS and DSAI are interpreted only
 338 when the relevant denominator is positive and the resulting value lies in the admissible interval. A
 339 positive DSAI indicates that the $s \rightarrow r$ direction induces more third-country carbon than the reverse
 340 direction. Near-zero denominators and sign-related balancing entries are retained as diagnostics.

341 Structural Decomposition Analysis

342 The right-side vector is separated into product composition and scale:

$$\begin{aligned} V_{sr\tau} &= 1^T y_{sr\tau} \\ p_{sr\tau} &= \frac{y_{sr\tau}}{V_{sr\tau}} \end{aligned} \quad (11)$$

$$S_{sr\tau} \equiv E_{sr\tau}^{\text{TC}} = m_{sr}^T \hat{h}_\tau L_\tau^S p_{sr\tau} V_{sr\tau} \quad (12)$$

$$S_{sr\tau} = S_{sr}(h_\tau, L_\tau^S, p_{sr\tau}, V_{sr\tau}) \quad (13)$$

$$\Delta S_{sr} = S_{sr1} - S_{sr0} = \Delta S_h + \Delta S_L + \Delta S_p + \Delta S_V \quad (14)$$

343 The four flow-level factors are the effective carbon coefficient, the Leontief production network, product
 344 composition and trade scale.

345 Following standard permutation-averaged SDA practice^{43–49}, let Ω be the set of n factors. Let $S(Q)$
 346 denote the state in which factors in subset $Q \subseteq \Omega$ take end-year values and all remaining factors take

base-year values. Let n_Q denote the number of factors in Q . The Shapley-averaged contribution of factor j is

$$\Delta S_j = \sum_{Q \subseteq \Omega, j \notin Q} \omega_Q [S(Q \cup \{j\}) - S(Q)] \quad (15)$$

$$\omega_Q = \frac{n_Q! (n - n_Q - 1)!}{n!} \quad (16)$$

This is equivalent to averaging over all $n!$ replacement orders. The implementation caches each subset state, requiring only 2^n unique state evaluations. Decomposition closure is checked by verifying that the sum of factor effects equals the endpoint change to numerical precision.

The reported long-period factor attribution is chained over the two observed phases, 2000-2011 and 2011-2021. For each factor j , the cumulative contribution is

$$\begin{aligned} \Delta S_j^{\text{chain}}(2000, 2021) &= \Delta S_j^{2000 \rightarrow 2011} + \Delta S_j^{2011 \rightarrow 2021} \\ \Delta S^{\text{chain}}(2000, 2021) &= \sum_{j \in \Omega} \Delta S_j^{\text{chain}}(2000, 2021) \end{aligned} \quad (17)$$

This chained implementation preserves additivity between the two historical phases and defines the reported long-period factor allocation.

Data and Validation

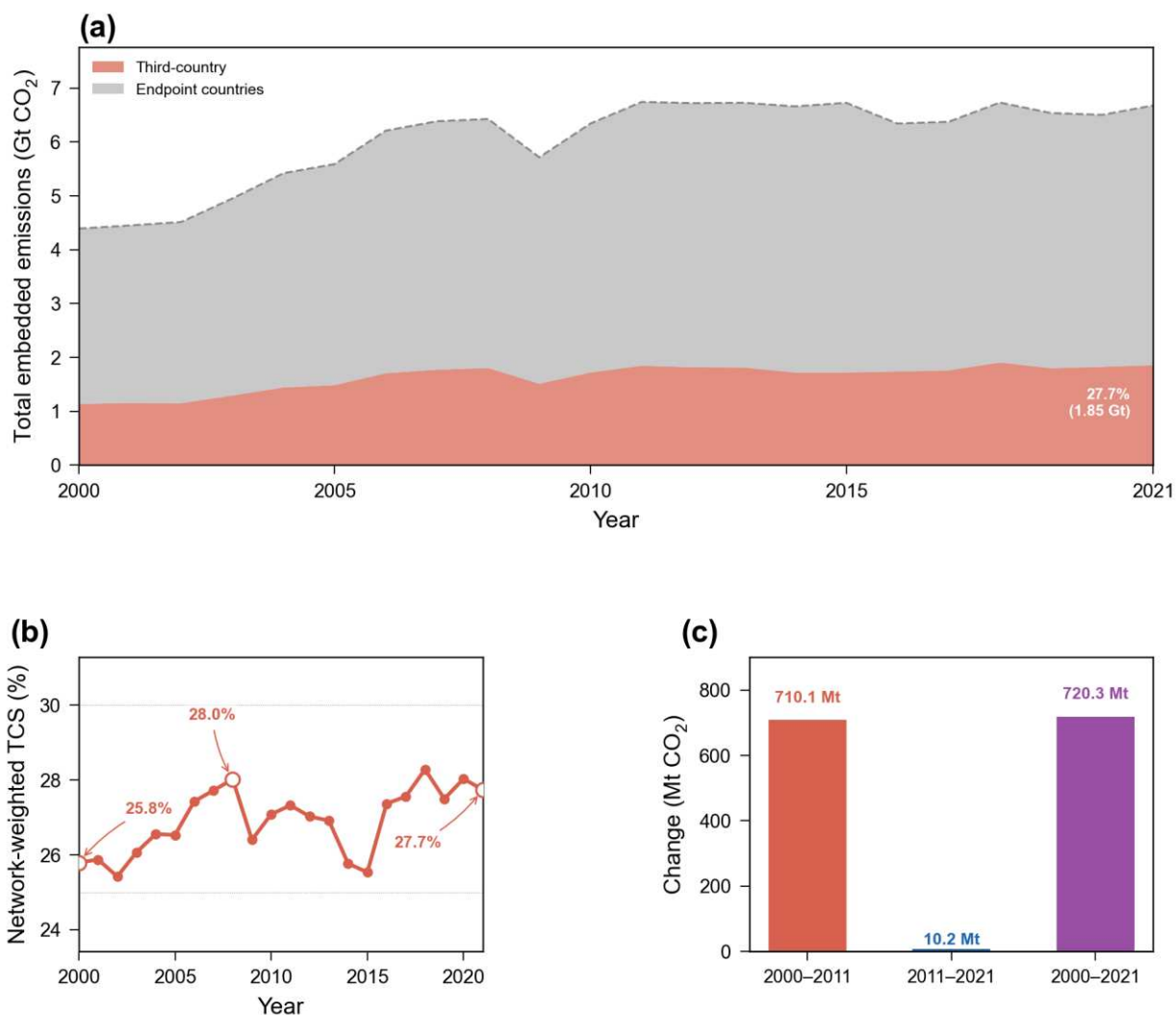
The empirical analysis uses the Eora26 MRIO database and environmental satellite accounts for 2000-2021.³³ After retaining countries with a complete analytical panel, the dataset contains 189 countries and 26 sectors. Excluding self-flows gives 35,532 directed bilateral corridors per year.

All monetary values used in carbon-intensity comparisons are expressed in 2010 US dollars. Current-price values were converted using exchange-rate and GDP-deflator series from the World Bank World Development Indicators⁴². Carbon quantities are reported as tonnes or megatonnes of CO₂, depending on aggregation level.

364 We also computed a conventional emissions embodied in trade (EET) diagnostic from the same
 365 Eora tables as a consistency check. This diagnostic solves the standard final-demand MRIO problem and
 366 reproduces early literature benchmarks: 5.14 Gt CO₂ in 2001 and 6.24 Gt CO₂ in 2004¹⁻². This check
 367 indirectly demonstrates the stability of the cross-database calculation.

368

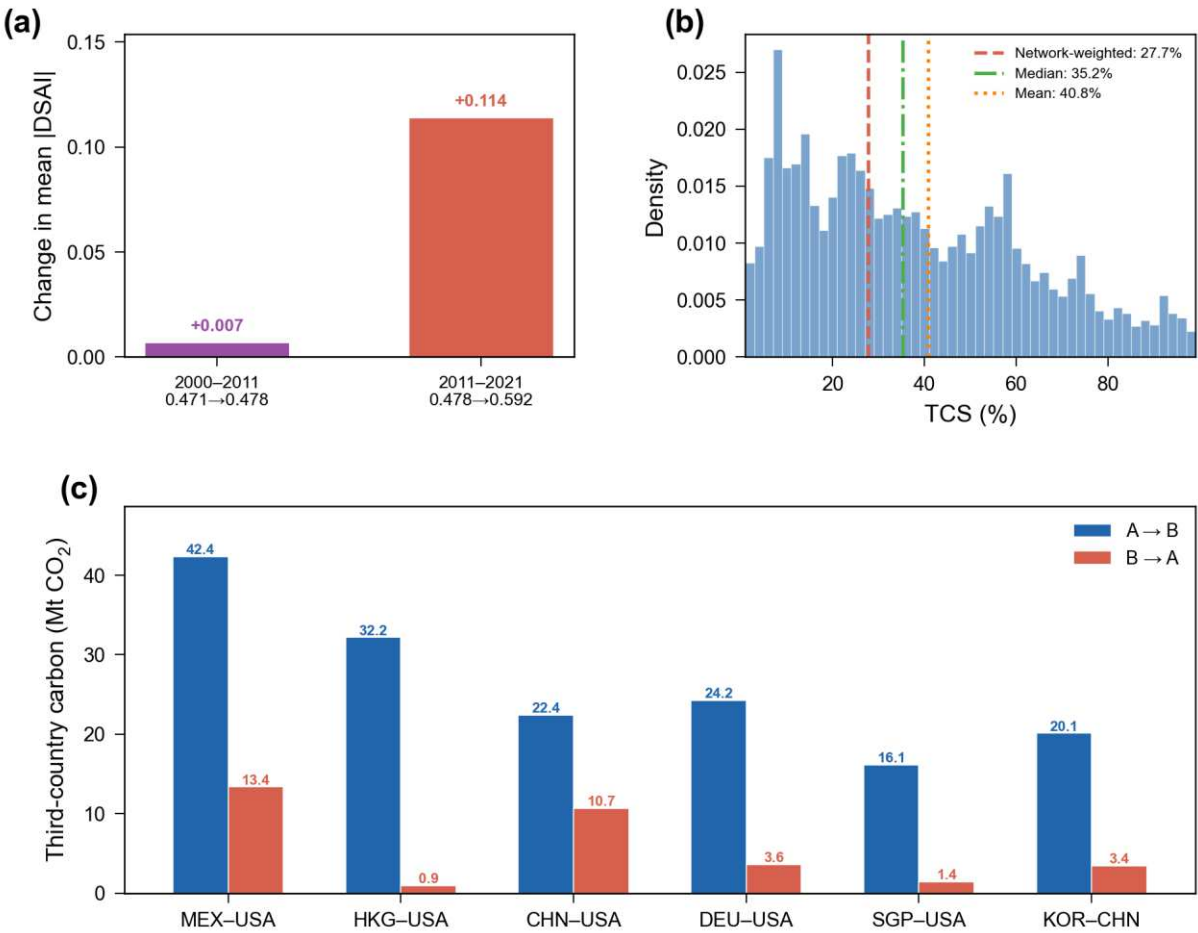
369 **Figure legends**



370

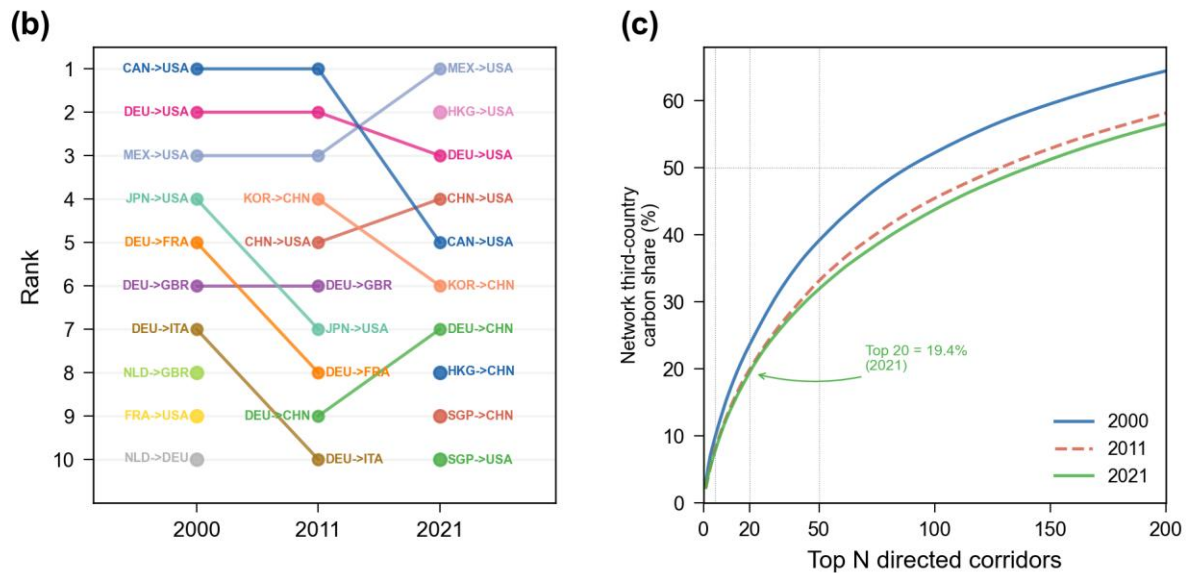
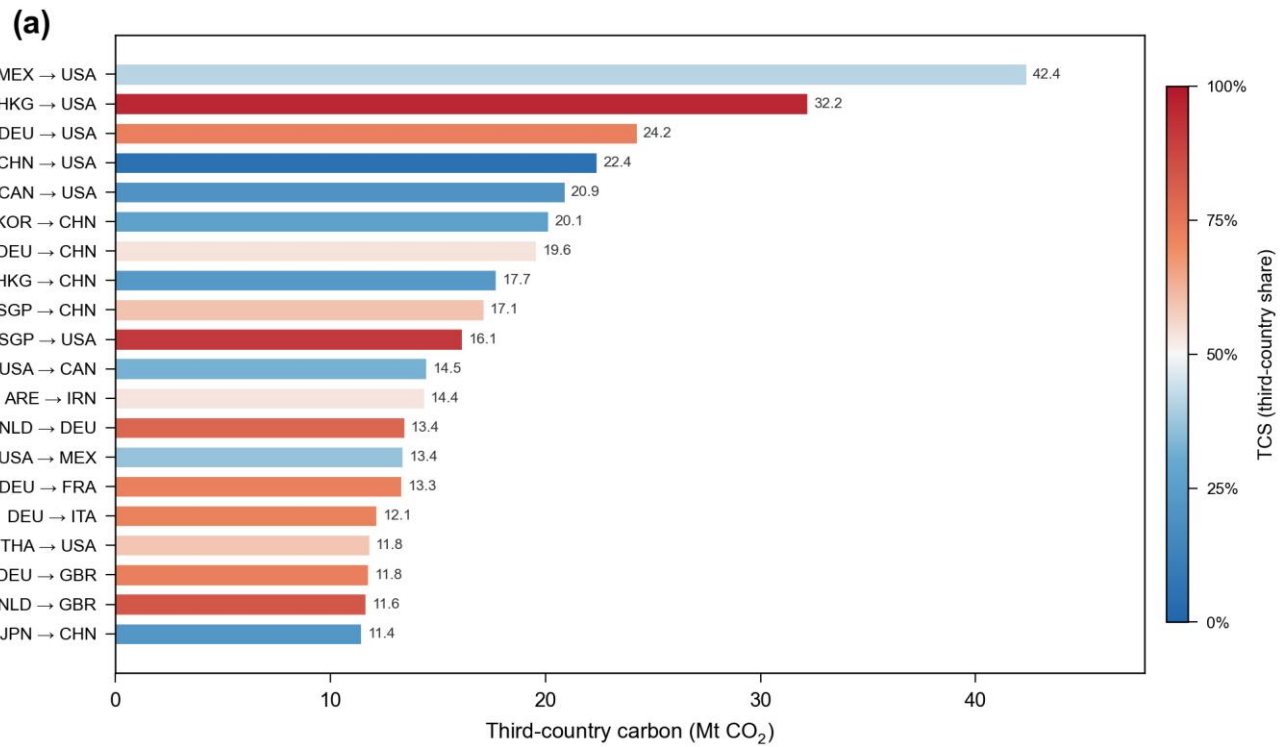
371 **Fig. 1** | Third-country carbon in directed global trade. (a), Corridor-based trade-chain embedded CO₂ emissions
 372 across all directed bilateral corridors, decomposed into third-country emissions and emissions generated in the

373 two endpoint economies. (b), Network-weighted third-country share (TCS) time series. (c), Period changes in
 374 third-country carbon for 2000-2011, 2011-2021 and 2000-2021.



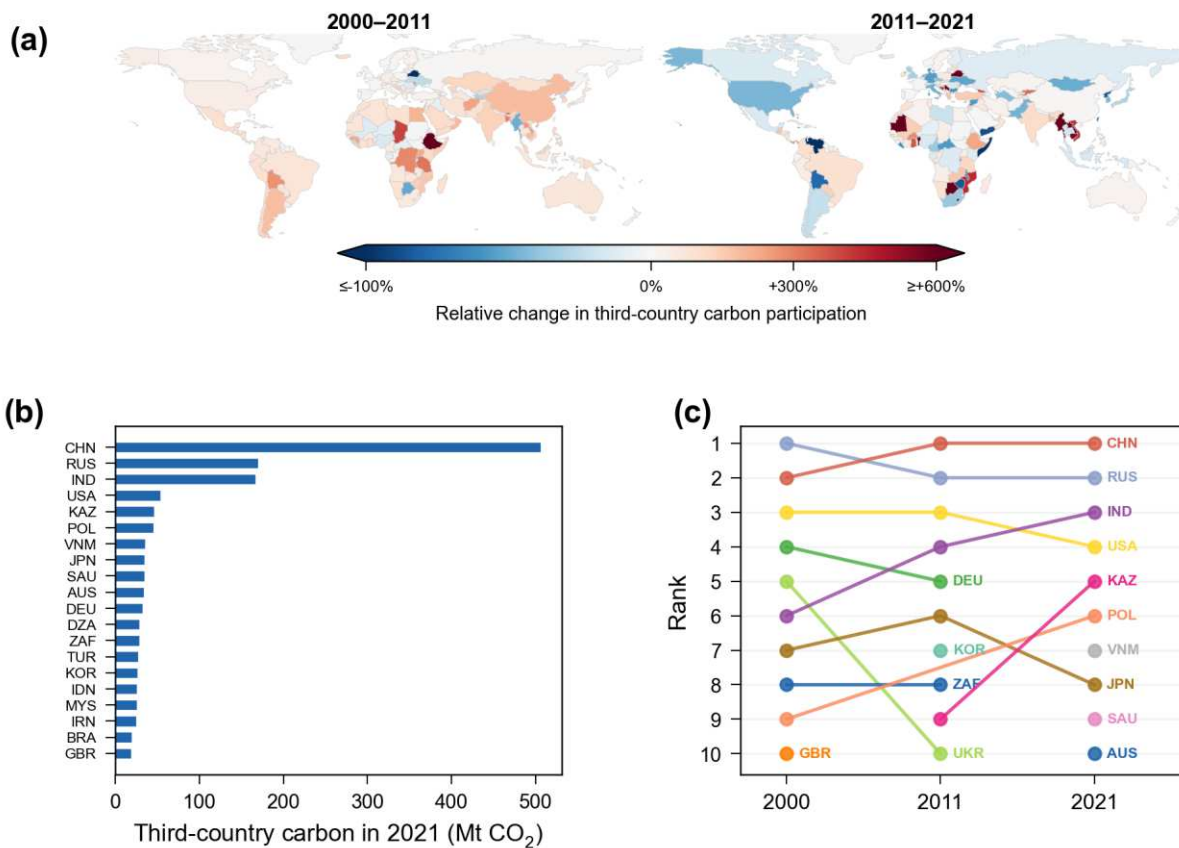
375

376 **Fig. 2** | Directional asymmetry of third-country carbon. (a), Period changes in mean absolute DSAI for
 377 2000-2011 and 2011-2021. (b), Distribution of TCS across directed flows in 2021, with network-
 378 weighted, median and mean markers. (c), Paired comparisons of forward and reverse corridors for
 379 representative high-emission country pairs.



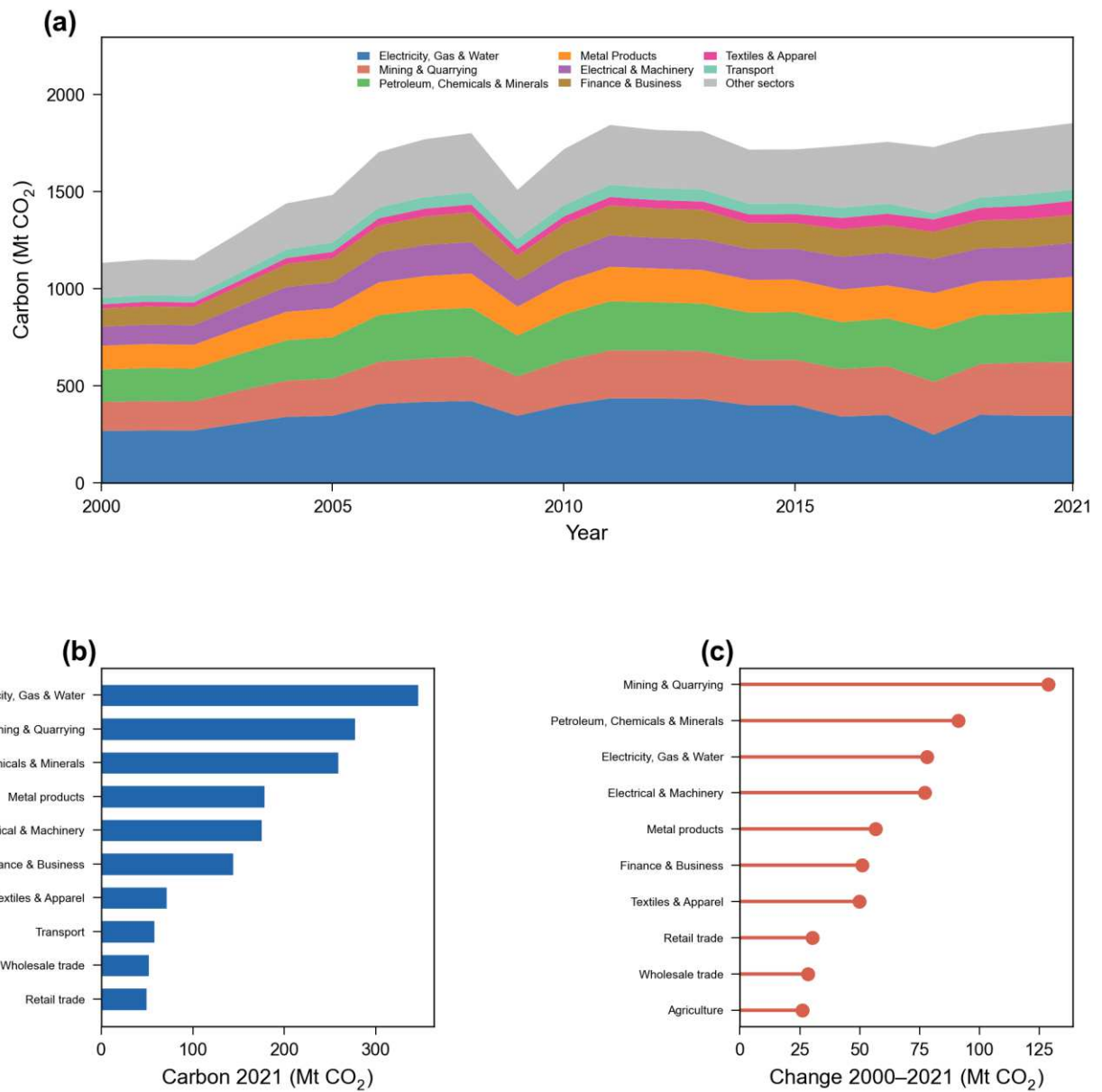
380

381 **Fig. 3** | Shifting backbone of high-emission corridors. (a), Top 20 directed third-country carbon corridors
 382 in 2021, with bar colour indicating TCS. (b), Rank shifts of leading corridors across 2000, 2011 and
 383 2021. (c), Cumulative contribution of the top N directed corridors to total third-country carbon.



384

385 **Fig. 4** | Major third-country production sources behind bilateral trade records. (a), Relative changes in
 386 third-country carbon by production source for 2000–2011 and 2011–2021. (b), Top third-country
 387 production sources ranked by carbon contribution in 2021. (c), Rank shifts of leading production sources
 388 across 2000, 2011 and 2021.



389

390 **Fig. 5** | Sectoral origins of third-country carbon. (a), Time series of leading sectoral contributions. (b),
 391 Top sectors by third-country carbon in 2021. (c), Sectors with the largest changes over 2000-2021.

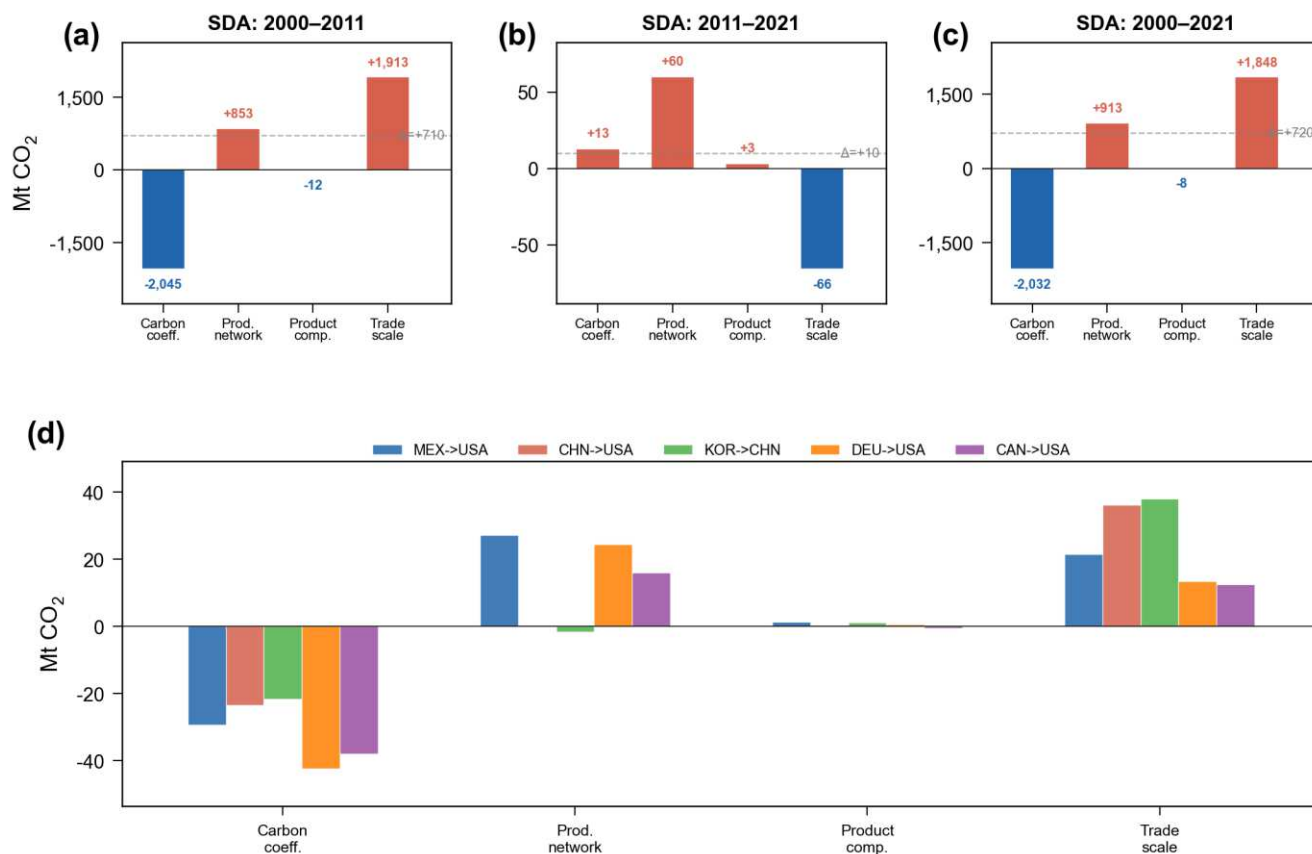


Fig. 6 | Structural drivers of third-country carbon change. a-c, Four-mechanism structural decomposition analysis for 2000-2011 (a), 2011-2021 (b) and the chained 2000-2021 attribution (c). Bars show the contributions of the effective carbon coefficient, production network, product composition and trade scale; dashed lines indicate the net period change. (d), Representative trade flow SDA over 2000-2021 for MEX→USA, CHN→USA, KOR→CHN, DEU→USA and CAN→USA.

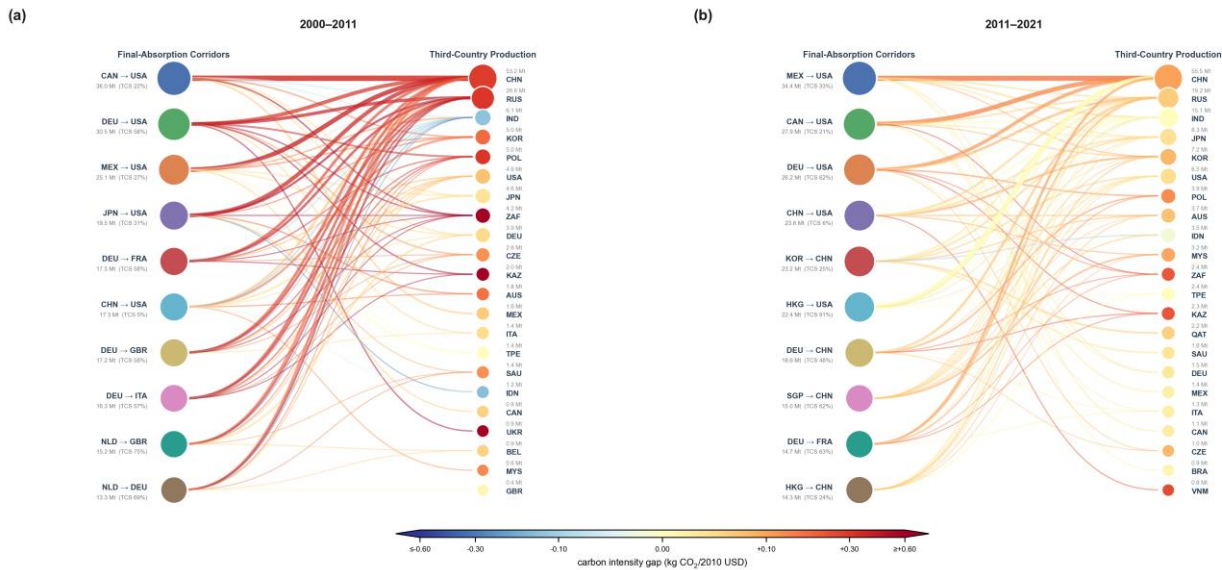


Fig. 7 | Period-mean networks linking trade corridors to third-country production sources. (a), Final-absorption corridors and third-country production hubs averaged over 2000-2011. (b), Corresponding network averaged over 2011-2021. Left nodes represent bilateral trade corridors and right nodes represent third-country production sources. Left nodes represent exporter–importer corridors named in trade records; right nodes represent third-country production sources. Link widths indicate source-level carbon contributions.

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529 **Supplementary Information**

530 In this study, we interpret the h term primarily as an effective carbon-coefficient effect: although h is
531 constructed as the product of the forward carbon factor and the value-added rate, the nested
532 decomposition shows that changes in the forward carbon factor account for 96.6% of the absolute
533 chained (h)-effect over 2000–2021, while the value-added-rate component contributes only 3.4%.