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Embodied carbon emissions in the supply chains of multinational enterprises

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3 figures

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29 **Abstract**

30 Enterprises are at the forefront of climate actions and multinational enterprises (MNEs) engage in
31 foreign direct investment (FDI), allowing them significant influence over the entire supply chain.
32 Yet emissions embodied in MNEs international supply chains are poorly known. Here we trace the
33 carbon footprints of MNEs foreign affiliates and show the gross volume of global carbon transfer
34 through investment peaked in 2011, mainly driven by the decline in carbon intensity. Despite
35 declining carbon footprints of developed country-based MNEs, there has been a significant increase
36 in carbon transfer sourced from the Chinese mainland. We propose an investment-based accounting
37 framework to allocate carbon footprints of MNEs to the investing country. Investment-based
38 accounting of emissions could inform targeted and effective climate policies and actions. For
39 instance, some large MNEs play a crucial role in carbon transfer, therefore their originating country
40 should bear more responsibilities of carbon emission reduction as an investor. [143 words]

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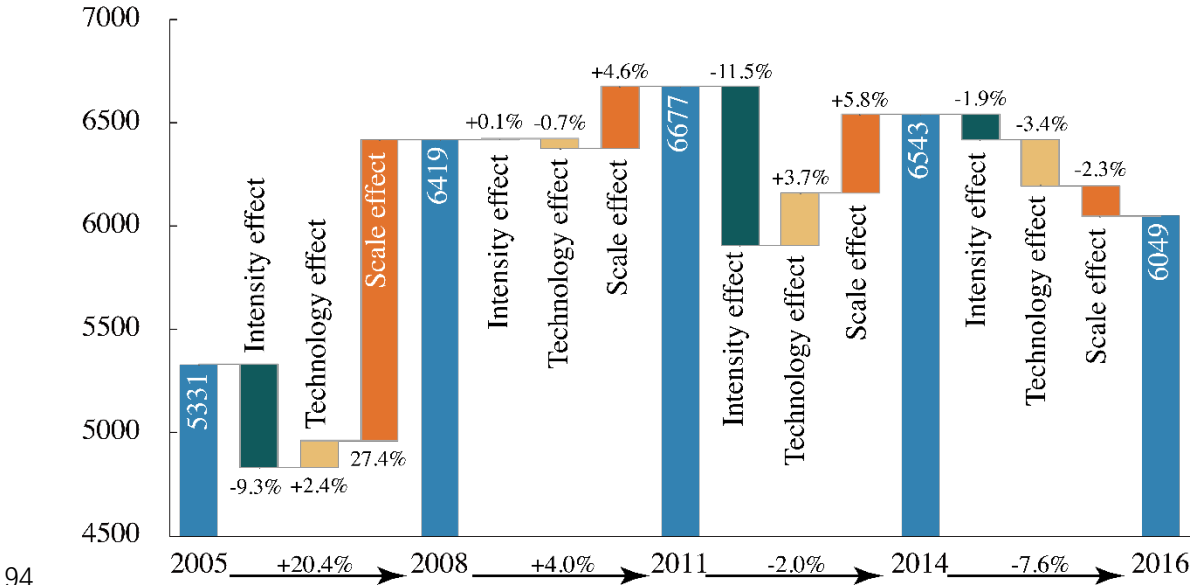
44 In 2015, the Paris Agreement set the target of holding this century's global warming well below 2°
45 C above pre-industrial levels. However, the sum of current national pledges and companies'
46 commitments to climate mitigation falls short of meeting the Paris goal¹⁻³. Global climate change
47 mitigation calls for more active actions from governments, businesses and investors⁴. Currently,
48 enterprises – particularly MNEs⁵⁻⁷ – are at the forefront of climate action. For instance, thousands
49 of US businesses have declared that they will continue to support climate action and work towards
50 meeting the terms of the Paris Agreement⁸, despite President Trump's announcement that the US
51 will withdraw from the Agreement. Carbon footprint measurement is the first step in reducing
52 carbon emissions⁹. However, the global reach of MNEs makes it more difficult to measure their
53 carbon footprints, especially the carbon footprint of their foreign affiliates, which is also a popular
54 topic of current research⁵. This study attempts to enrich the related literature in the following ways.
55 Here we present a comprehensive study to trace carbon emissions embodied in the supply chains of
56 global MNEs. Existing studies mainly assessed the carbon footprints of MNEs originating in or
57 hosted by a particular country in a certain year, such as China¹⁰⁻¹² or the US⁵. For instance, López
58 et al. (2019)⁵ found that in 2009 the carbon footprint of US MNEs' foreign affiliates was greater
59 than that of the territorial emissions of the UK. Different economies around the world may play
60 different roles in global investment networks, which have also been changing over recent years.
61 This study extends the literature by providing time-series and global-level analysis of the carbon
62 footprints of MNEs. We provide two methods, the decomposition method and the hypothetical
63 extraction method (HEM)¹³, to calculate the carbon footprints of MNEs and prove that these two
64 methods share the same results¹⁴. The results of these calculations allow us to illuminate the
65 changing trends in the carbon footprints of MNEs and to identify the global carbon transfer from
66 the sources to the destinations of FDI.

67 This study proposes an investment-based accounting framework to further motivate MNEs to adopt
68 more ambitious climate actions. To allocate carbon reduction responsibility between producers (the
69 production-based approach)¹⁵ and consumers (the consumption-based approach)¹⁶, a number of
70 studies have carbon flows through commodity trades¹⁷⁻²¹. Carbon transfer through trade means that
71 a country reduces its territorial emissions by importing products from other countries through

72 international trade¹⁸. However, a country can outsource carbon emissions to other countries through
 73 investment as well²². Carbon transfer through investment means that a country reduces its territorial
 74 emissions by relocating domestic production to other countries through cross-border investment²³.
 75 A comprehensive analysis of carbon transfer through FDI is still lacking. Therefore, we attempt
 76 to remap global carbon flows by focusing on the investment channel. MNEs have the power to
 77 exercise significant influence over the entire supply chain^{24,25}. Some large MNEs play dominant
 78 roles in carbon transfer through investment. Therefore, the investment-based accounting framework
 79 allocates the carbon footprints of MNEs to the FDI home country⁵.

80 **Trends in the carbon footprints of MNEs and driving factors**

81 In 2008, the share of carbon emissions embodied in the supply chains of MNEs' foreign affiliates
 82 (also referred to as the carbon footprints of MNEs in this study) to global emissions reached its
 83 highest peak, i.e. 22.0% of global CO₂ emissions. A huge volume of global CO₂ emissions is related
 84 to the supply chains of MNEs, despite the declining share of MNEs' carbon footprints in global
 85 emissions since 2008. In 2016, at the global scale, MNEs' carbon footprints still accounted for 18.7%
 86 of global emissions. Clearly, FDI should be a focus of climate change mitigation measures. The
 87 volume of investment-related CO₂ is comparable to that of trade-related CO₂ (SI1.1). Based on
 88 changing patterns in the carbon footprints of MNEs, we divide the study period into four sub-periods.
 89 The carbon footprints of MNEs grew from 5530.8 Mt in 2005 to a preliminary peak of 6419.2 Mt
 90 in 2008 (Figure 1). After the financial crisis, the carbon footprints of MNEs increased again and
 91 reached the secondary and highest peak of 6677.3 Mt in 2011. After 2011, there was a general
 92 declining pattern in the carbon footprints of MNEs, which was down to 6543.4 Mt in 2014 and
 93 6048.9 Mt in 2016, although there were slight increases in 2013 and 2014.



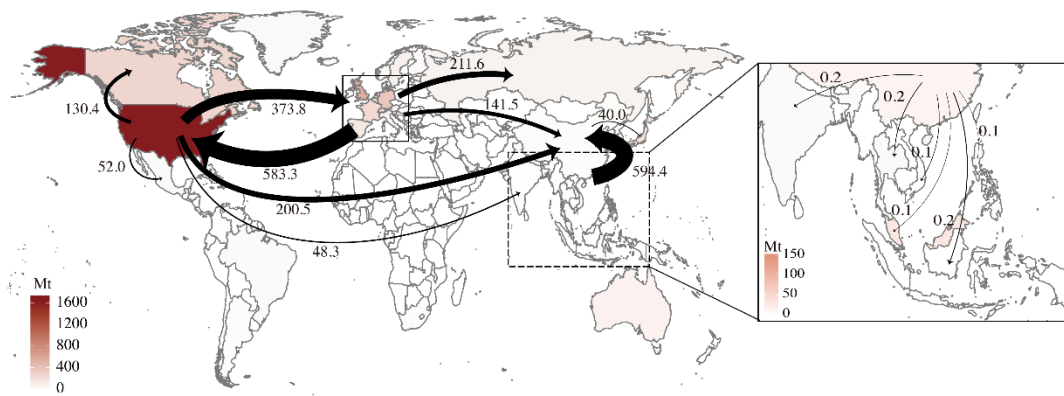
94 **Figure 1. CO₂ emissions embodied in supply chains of MNEs**

96 Over the first sub-period (2005-2008), the CO₂ emissions embodied in the supply chains of MNEs
 97 increased by 20.4%. The major contributing factor to this increase was the growth in the outputs of
 98 MNEs (scale effect), which would cause MNEs' carbon footprints to increase by 27.4% in the
 99 absence of other factors. The decrease in carbon intensity offset MNEs' carbon footprints by -9.3%
 100 (intensity effect), and the change in production technology played a relatively modest role (+2.4%,

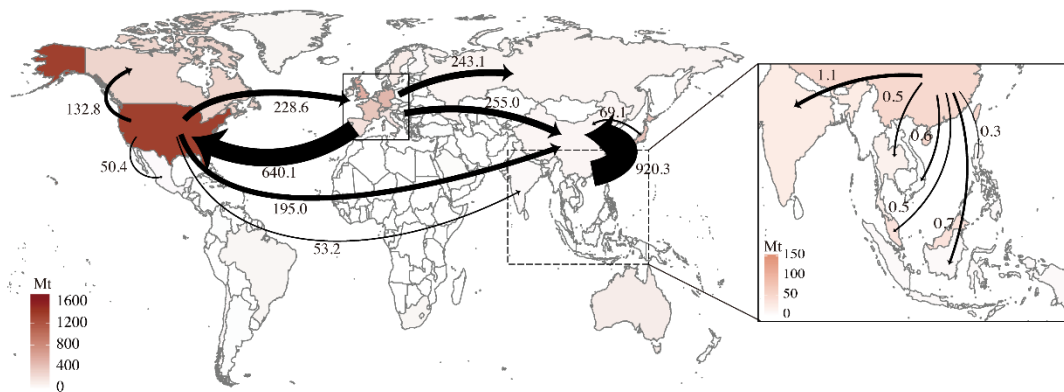
101 technology effect) (Figure 1). Due to the impact of the financial crisis, the growth rate of MNEs'
102 carbon footprint declined in the second sub-period (2008-2011), during which the MNEs' carbon
103 footprints increased by only 4.0%. The scale effect (+4.6%) was the major contributor, whereas the
104 technology effect decreased the carbon footprints of MNEs by -0.7%. After the peak year in 2011,
105 the declining rates of the carbon footprints of MNEs clearly increased. Over the third (2011-2014)
106 and fourth (2014-2016) sub-periods, the declining rates reached -2.0% and -7.6%, respectively. The
107 decline in carbon intensity was the major driver of the downturn in MNEs' carbon footprint. The
108 global carbon intensity was relatively stable before 2011 whilst decreased sharply after 2011^{26,27}.
109 Over the period 2011-2014, both the scale effect (+5.8%) and the technology effect (+3.7%) played
110 a significant role in driving MNEs' carbon footprints. However, the signs of these two effects
111 changed over the last period, as the volume of global FDI shrunk and MNEs began to adopt
112 measures to clean up their supply chains. Over the sub-period 2014-2016, all three effects
113 contributed to the declining carbon footprints of MNEs. The changes in MNEs' output, production
114 technology and carbon intensity would contribute to a decline in their carbon footprints of -2.3%, -
115 3.4% and -1.9%, respectively, with all other factors held constant.

116 **Global carbon transfer through FDI**

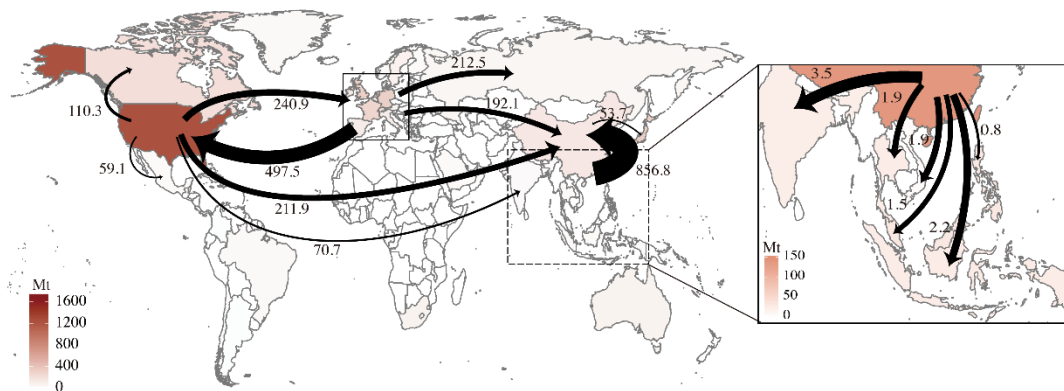
117 MNEs originate in and are hosted by different countries and regions. Ranked by the carbon
118 footprints of the MNEs hosted by each country, the Chinese mainland was the largest hosting
119 country (1584.5 million tons) in 2016, followed by the EU and the US (**Fig. S3**). Over the study
120 period 2005-2016, the carbon footprints of MNEs hosted by the US and the EU remained relatively
121 stable and even decreased slightly. However, the carbon footprints of MNEs hosted by developing
122 countries, such as the Chinese mainland and India increased sharply, as developing countries have
123 become increasingly attractive FDI destinations²⁸. From the perspective of the carbon footprints of
124 MNEs originating in different regions, the EU was the largest originating region of MNEs in 2016
125 (**Fig. S3**). The carbon footprints originating from the EU totaled at 2151.3 Mt, followed by the US
126 (1259.9 Mt) and Chinese Hong Kong (1074.6 Mt). After 2011, there was a decreasing trend in the
127 volumes of the carbon footprints of MNEs originating from developed countries such as the US
128 (Figure 2). However, there was a significant growth trend in the carbon footprint of MNEs
129 originating from the Chinese mainland. The volume of the carbon footprints of MNEs originating
130 from the Chinese mainland increased from 58.7 Mt in 2005 to 200.5 Mt in 2016.



a) 2005



b) 2011



c) 2016

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132 **Figure 2. Carbon transfer embodied in global FDI.** The color of each country or region represents
 133 the gross volume of CO₂ emissions driven by FDI stocks that are sourced from that country or region.
 134 The arrows represent the carbon transfer through global FDI. The width of the arrows represents the
 135 volume of carbon flows.

136 The largest carbon transfer through investment is from Chinese Hong Kong to the Chinese mainland,
 137 with a volume of 594.4 Mt in 2005, which increased to 856.8 Mt in 2016. Chinese Hong Kong was
 138 the leading source of FDI into the Chinese mainland, and more than 60% of the FDI in the Chinese
 139 mainland was channeled through Chinese Hong Kong in 2016²⁹. The second largest carbon transfer
 140 was from the EU to the US, which was the largest FDI recipient³⁰. Over the period 2005-2016, there
 141 were significant declines in carbon transfer between the US and the EU. However, there were
 142 significant increases in carbon transfer from developed countries to developing countries over the

143 study period. For instance, carbon transfer from the US to India increased from 48.3 Mt in 2005, to
144 53.2 Mt in 2011 and to 70.7 Mt in 2016. The World Investment Report (2019)²⁸ shows that FDI
145 flows to developing countries have been increasing stably, while developed countries are becoming
146 less attractive to global investment. In recent years, developed countries as well as some developing
147 countries, such as China, have been increasing their investment in emerging economies³¹. China has
148 established the Asian Infrastructure Investment Bank and the Silk Road Fund to strengthen
149 investment in developing countries along the land and sea Silk Roads. Over the study period, there
150 was a significant growth trend in carbon transfer from China to India and Southeast Asian countries.
151 The volume of carbon transfer from China to the five studied Southeast Asian countries (Vietnam,
152 Indonesia, Philippines, Thailand, and Malaysia) increased by ten times, from 0.7 Mt CO₂ emissions
153 in 2005 to 8.2 Mt CO₂ emissions in 2016. With the rise of South-South trade³² and FDI flows, the
154 volume of carbon transfer between developing countries will increase rapidly in the future and
155 should be a major focus of policy makers.

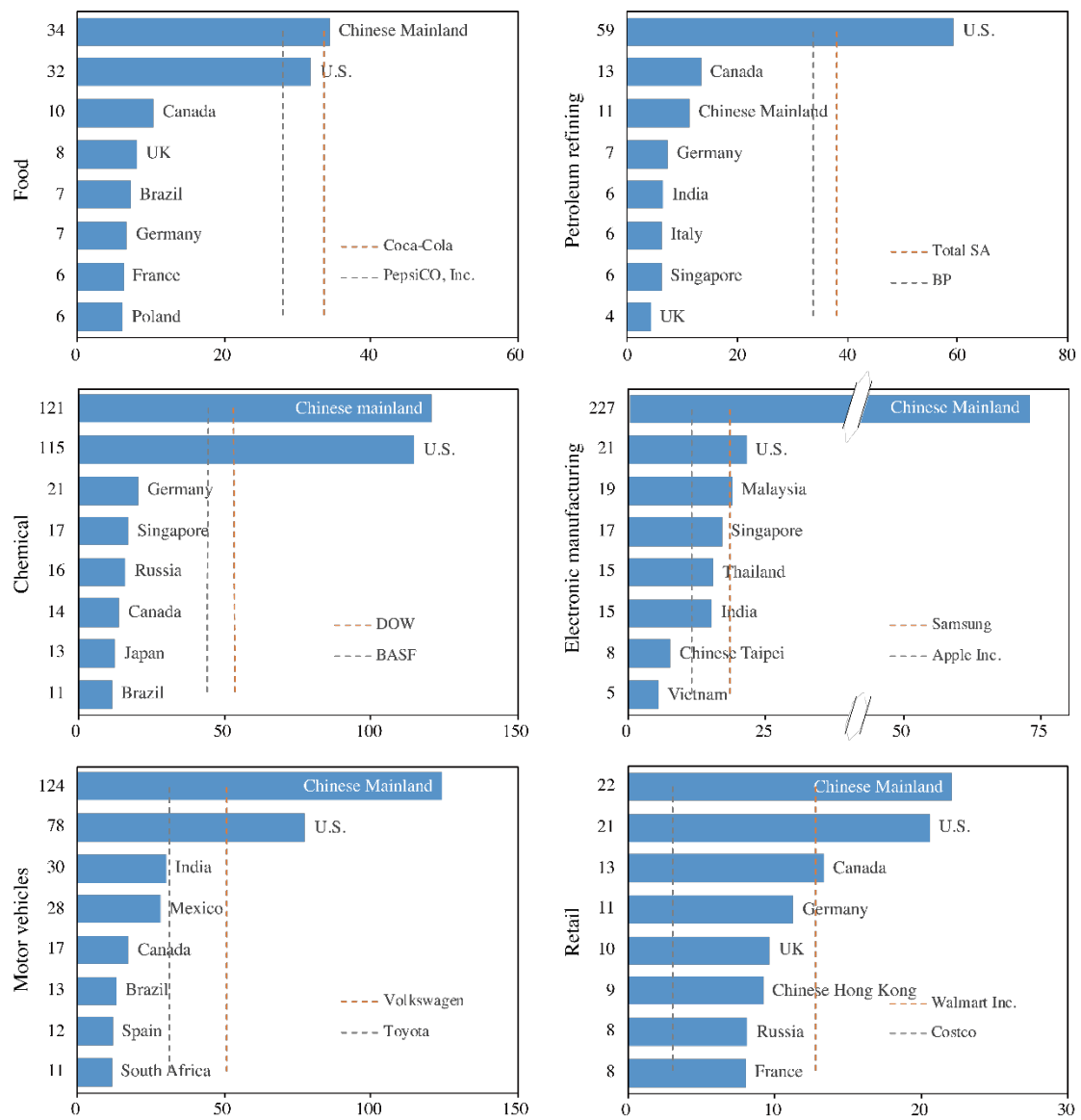
156 A region may outsource carbon emissions to other regions through investment. We analyze the
157 impact of FDI on the distribution of global emissions by the difference in the carbon footprints of
158 MNEs under investment-based and production-based accounting approaches. Under the investment-
159 based accounting approach, the carbon footprints of MNEs are allocated to the investing country.
160 Under the production-based accounting approach, a region should be responsible for its territorial
161 emissions. We found that the volume of the carbon footprints of MNEs invested by developed
162 countries was greater than the volume of their territorial emissions induced by foreign-owned
163 enterprises, whilst the opposite findings for developing countries (**Fig. S4**). This result is consistent
164 with previous studies that showed developed countries outsource embodied CO₂ emissions to
165 developing countries^{16,18–20}. Chinese Hong Kong has the largest net negative balance of embodied
166 emissions in the supply chains of MNEs (-1031.1 Mt), followed by the EU (-931.8 Mt) and the US
167 (-295.1 Mt). The Chinese mainland has the largest net positive balance of carbon emissions related
168 to FDI. The Chinese mainland's territorial emissions induced by foreign-owned enterprises in 2016
169 reached 1811.0 Mt. However, the Chinese mainland's investment in foreign countries in 2016
170 resulted in only 138.7 Mt CO₂ emissions. The foreign-owned firms' production activities lead to a
171 greater burden on the host country to reduce the related emissions relative to the economic gains
172 that they bring to the host country (**SI1.5**). Policy makers should encourage FDI flows in industries
173 with high value-added and low carbon intensity.

174 **Large MNEs play an important role in curbing carbon transfer**

175 Significant sector heterogeneity exists in the volume of the carbon footprints of MNEs. Various
176 countries and enterprises also play different roles in international markets at the sectoral level. **Fig.**
177 **3** shows the volume of the carbon footprints of MNEs for six different sectors. The blue bars
178 represent the top eight carbon footprints (in terms of volume) of sectoral MNEs hosted by different
179 regions. For each subfigure, we use two lines to indicate the volume of carbon emissions embodied
180 in the supply chains of two selected large or representative MNEs. Taking the retail sector as an
181 example, we select Walmart Inc., which is the world's largest retailer and operates over 11,500 stores
182 in 28 countries.

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186 **Figure 3. Carbon footprint of MNEs at the sectoral level in 2016 (million tons).** The blue bars
 187 represent the carbon emissions embodied in the supply chains of sectoral MNEs in a certain country.
 188 The lines represent the carbon emissions embodied in the supply chains of large MNEs' foreign
 189 affiliates.

190 For MNEs in the petroleum-refining sector, the US was the largest host country by volume of
 191 embodied emissions, and the Chinese mainland was the largest host country for the other five sectors.
 192 The US and the Chinese mainland were the top two largest host regions of FDI inflows³⁰. The
 193 Chinese mainland's foreign-owned enterprises tend to have carbon-intensive supply chains mainly
 194 due to its coal-based energy mix. The other significant host countries in **Fig. 3** are mainly major
 195 developed countries, such as Canada, Germany and the UK, and large developing countries, such
 196 as Brazil, India, and Russia. The electronic sector (**Fig. 3**, row 2, right) has a greater degree of
 197 concentration in the MNEs' carbon footprints. In 2016, the volume of carbon footprints of Chinese
 198 mainland's foreign-owned electronic enterprises reached 226.7 Mt, which is significantly greater
 199 than that of other regions. Several Southeast Asian countries, which also have lower labor costs,
 200 are also listed among the top eight host countries of electronics MNEs based on the volume of carbon

201 footprints.

202 The total volume of the carbon footprints of the foreign affiliates of the Coca-Cola Company, an
203 American multinational enterprise, was almost equal to the volume of CO₂ emissions embodied in
204 the Chinese mainland's foreign-owned enterprises (**Fig. 3**, row 1, left). For the petroleum refining
205 sector (**Fig. 3**, row 1, right), Total SA and BP, which are multinational chemical companies
206 headquartered in France and the UK, respectively, had a greater responsibility for the carbon
207 emissions induced by the foreign affiliates of petroleum-refining MNEs than did most host countries,
208 except the US. For the chemical sector (**Fig. 3**, row 2, left), Dow Chemical Company and BASF,
209 which are multinational chemical companies headquartered in the US and Germany, respectively,
210 were the third and fourth most responsible agents for carbon emissions induced by chemical MNEs'
211 foreign affiliates, respectively, following the Chinese mainland and the US. Large MNEs also play
212 dominant roles in the electronic manufacturing sector (**Fig. 3**, row 2, right), motor vehicles sector
213 (**Fig. 3**, row 3, left), and retail sector (**Fig. 3**, row 3, right). Although these large MNEs may generate
214 a lower volume of CO₂ emissions per unit sales than the average sectoral level, for example, Apple
215 Inc., their climate actions still represent crucial supplements to carbon control measures adopted by
216 different countries or regions. Their climate actions can not only push their upstream suppliers to
217 reduce emissions but also encourage other companies to adopt climate actions.

218 These selected MNEs have played active roles in fighting climate change. For instance, Apple Inc.,
219 which is the world's largest technology company by revenue, launched Apple's Supplier Clean
220 Energy Program in 2015. Walmart Inc. has launched Project Gigaton to reduce the carbon emissions
221 of Walmart Inc. and its upstream suppliers by one billion tons over the period 2015-2030. The MNEs'
222 carbon footprints or carbon intensity have decreased significantly over the past few years. For
223 instance, in 2017, Coca-Cola reduced the volume of its carbon footprint by 19% against the 2010
224 baseline. International cooperation in fighting climate change is creating new opportunities for the
225 development of MNEs. However, MNEs are also facing great uncertainty in climate policies, green
226 technology, investment profitability, and so on³³. MNEs tend to be cautious in their climate activities.
227 For instance, Toyota produces hybrid cars, rather than fuel cell vehicles, as a bridging strategy as it
228 moves towards offering more environmentally friendly vehicles. In addition, more than half of the
229 companies with quantified carbon reduction targets have set only short-term targets (**SI3.5**)³. MNEs
230 should adopt more ambitious climate actions to reduce the carbon emissions induced by their
231 international investments.

232 **Discussion**

233 The temporal, spatial and sectoral characteristics of MNEs' carbon footprints are presented above.
234 International FDI flows have recently taken on some new characteristics. The volume of global FDI
235 is shrinking, declining by 23%³⁰ in 2017 and 13%²⁸ in 2018. The process of deglobalization may
236 reduce the carbon footprints of MNEs in the next few years. However, there is a stable increase in
237 FDI flows to developing countries²⁸, and there is an increase in South-South FDI between
238 developing countries³². In recent years, an increasing number of companies that sourced from
239 developing countries have become MNEs with a greater pace of internalization³⁴. Compared with
240 traditional MNEs, which must bear sunk costs to rebuild their supply chains, new MNEs based in
241 developing countries³¹ enjoy a second mover advantage in that they can build clean supply chains
242 from the inception. This study analyzed the carbon footprints of only twelve selected large MNEs

243 in six sectors. As an increasing number of MNEs have begun to measure and report their greenhouse
244 gas emissions in recent years, future studies should provide a more detailed ranking of MNEs in
245 terms of their carbon footprints.

246 A region can outsource CO₂ emissions to other regions through both trade and investment, which
247 are both crucial channels of carbon transfer. This study maps the global carbon transfer, shifting the
248 focus from trade flows to FDI flows. The recent strengthening of the trade-investment nexus³⁵⁻³⁷
249 has made global carbon transfer more complicated (SI1.4). A clearer picture of global carbon
250 transfer through trade and FDI can guide policy makers to adopt more targeted measures to address
251 carbon leakage. For instance, Borghesi et al., (2020)³⁸ noted that unilateral climate policies may
252 promote the production of the existing foreign subsidiaries of MNEs, especially in trade-intensive
253 sectors. Majority of existing studies focuses on the economic impacts^{39,40} of the trade-investment
254 nexus. Future studies are expected to provide a more in-depth analysis of the links between trade-
255 related and investment-related carbon transfer. In addition, MNEs play a crucial role in the trade-
256 investment nexus. For instance, the production of foreign-owned enterprises relies on imported
257 intermediate products. Meanwhile, a greater share of the products of foreign-owned enterprises will
258 be exported to the global market. MNEs should play a more leading role in fighting carbon leakage.

259 This study proposes an investment-based accounting approach to allocate the carbon footprints of
260 MNEs to the investing country. The investment-based accounting approach, which allocates the
261 outward responsibility of MNEs to the FDI home country, shifts the focus of policy makers from
262 producers and consumers¹⁶ to investors⁵. This is because MNEs have the power to exercise
263 significant influence over the entire supply chain due to their massive scale and global reach^{24,25}
264 (please see SI1.3 for a comparison of different accounting approaches). The investment-based
265 approach can be used to address the carbon leakage that occurs through investment channels⁴¹ and
266 to reduce international investment in regions with a greater carbon intensity. Developing countries,
267 which are playing an increasingly important role in the fight against climate change, must adopt
268 more active climate actions to attract international investment. The results of this study can also be
269 used in international climate change negotiations to determine the regional carbon reduction
270 responsibilities. Notably, the control power of MNEs may fade with the increase in the border-
271 crossing frequency associated with carbon footprints^{42,43}. In addition, different types of FDI and
272 headquarters have different types of control power over their foreign affiliates. Future studies can
273 take these factors into account and explore mechanisms to share emissions responsibilities between
274 FDI-sourcing and FDI-hosting countries⁴⁴.

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277 **References**

- 278 1. Peters, G. P., Andrew, R. M., Solomon, S. & Friedlingstein, P. Measuring a fair and ambitious
279 climate agreement using cumulative emissions. *Environ. Res. Lett.* **10**, 105004 (2015).
- 280 2. King, L. C. & Bergh, J. C. van den. Normalisation of Paris agreement NDCs to enhance
281 transparency and ambition. *Environ. Res. Lett.* **14**, 084008 (2019).
- 282 3. Kuramochi, T. *et al.* Global climate action from cities, regions and businesses: Impact of
283 individual actors and cooperative initiatives on global and national emissions. (2019).
- 284 4. UN Framework Convention on Climate Change. *UN Climate Change Annual Report*. New

- 285 *Scientist* (2018). doi:10.1016/s0262-4079(19)31788-9
- 286 5. López, L.-A., Cadarso, M.-Á., Zafrilla, J. & Arce, G. The carbon footprint of the US
287 multinationals' foreign affiliates. *Nat. Commun.* **10**, 1672 (2019).
- 288 6. Comyns, B. Climate change reporting and multinational companies: Insights from institutional
289 theory and international business. *Account. Forum* **42**, 65–77 (2018).
- 290 7. Kolk, J. E. M. & Pinkse, J. M. Multinationals' Political Activities on Climate Change. *Bus.*
291 *Soc.* **46**, 201–228 (2007).
- 292 8. We Are Still In. Available at: <https://www.wearestillin.com/signatories>.
- 293 9. Shan, Y. *et al.* China CO₂ emission accounts 1997–2015. *Sci. Data* **5**, 1–14 (2018).
- 294 10. Dietzenbacher, E., Pei, J. & Yang, C. Trade, production fragmentation, and China's carbon
295 dioxide emissions. *J. Environ. Econ. Manage.* **64**, 88–101 (2012).
- 296 11. Liu, Y. *et al.* 'Made in China': A reevaluation of embodied CO₂ emissions in Chinese exports
297 using firm heterogeneity information. *Appl. Energy* **184**, 1106–1113 (2016).
- 298 12. Jiang, X., Guan, D., Zhang, J., Zhu, K. & Green, C. Firm ownership, China's export related
299 emissions, and the responsibility issue. *Energy Econ.* **51**, 466–474 (2015).
- 300 13. Paelinck, J., De Caemel, J. & Degueldre, J. Analyse quantitative de certaines phénomènes du
301 développement régional polarisé: Essai de simulation statique d'itératives de propagation.
302 *Problèmes Convers. économique Anal. théoriques études appliquées* **7**, 341–387 (1965).
- 303 14. Los, B., Timmer, M. P. & De Vries, G. J. Tracing value-added and double counting in gross
304 exports: Comment. *Am. Econ. Rev.* **106**, 1958–1966 (2016).
- 305 15. Liu, Z. *et al.* Reduced carbon emission estimates from fossil fuel combustion and cement
306 production in China. *Nature* **524**, 335–338 (2015).
- 307 16. Peters, G. P. From production-based to consumption-based national emission inventories. *Ecol.*
308 *Econ.* **65**, 13–23 (2008).
- 309 17. Peters, G. P. & Hertwich, E. G. CO₂ Embodied in International Trade with Implications for
310 Global Climate Policy. *Environ. Sci. Technol.* **42**, 1401–1407 (2008).
- 311 18. Peters, G. P., Minx, J. C., Weber, C. L. & Edenhofer, O. Growth in emission transfers via
312 international trade from 1990 to 2008. *Proc. Natl. Acad. Sci. U. S. A.* **108**, 8903–8908 (2011).
- 313 19. Davis, S. J. & Caldeira, K. Consumption-based accounting of CO₂ emissions. *Proc. Natl.*
314 *Acad. Sci. U. S. A.* **107**, 5687–5692 (2010).
- 315 20. Davis, S. J., Peters, G. P. & Caldeira, K. The supply chain of CO₂ emissions. *Proc. Natl. Acad.*
316 *Sci. U. S. A.* **108**, 18554–18559 (2011).
- 317 21. Liu, Z. *et al.* Targeted opportunities to address the climate–trade dilemma in China. *Nat. Clim.*
318 *Chang.* **145**, 143–145 (2015).
- 319 22. Koch, N. & Basse, H. Does the EU Emissions Trading System induce investment leakage?
320 Evidence from German multinational firms. *Energy Econ.* **81**, 479–492 (2019).
- 321 23. Hanna, R. US Environmental Regulation and FDI: Evidence from a Panel of US-Based
322 Multinational Firms. *Am. Econ. J. Appl. Econ.* **2**, 158–189 (2010).
- 323 24. Pinkse, J. & Kolk, A. Challenges and trade-offs in corporate innovation for climate change.
324 *Bus. Strateg. Environ.* **19**, 261–272 (2010).
- 325 25. Cravens, K. S. Examining the role of transfer pricing as a strategy for multinational firms. *Int.*
326 *Bus. Rev.* **6**, 127–145 (1997).
- 327 26. Jackson, R. B. *et al.* Reaching peak emissions. *Nat. Clim. Chang.* **6**, 7–10 (2016).
- 328 27. Enerdata. *Global Energy Statistical Yearbook 2019*. (2019).

- 329 28. United Nations. *World investment report 2019*. (2019).
330 29. National Bureau of Statistics of China. *China statistical Yearbook*. (China Statistics Press,
331 2018).
332 30. United Nations. *World investment report 2018*. (2018).
333 31. Wells, L. T. *Third World Multinationals: The Rise of Foreign Investment from Developing*
334 *Countries*. (The MIT Press, 1983).
335 32. Meng, J. *et al.* The rise of South-South trade and its effect on global CO2 emissions. *Nat.*
336 *Commun.* **9**, 1–7 (2018).
337 33. Kolk, A. & Pinkse, J. A perspective on multinational enterprises and climate change: Learning
338 from ‘an inconvenient truth’? *J. Int. Bus. Stud.* **39**, 1359–1378 (2008).
339 34. García-Canal, E. & Guillén, M. F. *The Rise of the New Multinationals (Aritical from the book*
340 *Third World Multinationals: The Rise of Foreign Investment from Developing Countries)*.
341 (2003).
342 35. Mundell, R. A. International Trade and Factor Mobility. *Am. Econ. Rev.* **47**, 321–335 (1957).
343 36. Daniels, J. P. & von der Ruhr, M. Transportation Costs and US Manufacturing FDI. *Rev. Int.*
344 *Econ.* **22**, 299–309 (2014).
345 37. UNCTAD. *World Investment Report 2002: Transnational Corporations and Exports*
346 *Competitiveness*. (2002). doi:10.1177/0015732515040106
347 38. Borghesi, S., Franco, C. & Marin, G. Outward Foreign Direct Investment Patterns of Italian
348 Firms in the European Union’s Emission Trading Scheme. *Scand. J. Econ.* **122**, 219–256
349 (2020).
350 39. Chow, P. C. Y. The effect of outward foreign direct investment on home country’s export: A
351 case study on Taiwan, 1989–2006. *J. Int. Trade Econ. Dev.* **21**, 725–754 (2011).
352 40. Urata, S. Emergence of an FDI-trade nexus and economic growth in East Asia. in *Rethinking*
353 *the East Asian Miracle* (eds. Stiglitz, J. E. & Yusuf, S.) 409–459 (Oxford University Press,
354 2001).
355 41. Zhang, Z. Competitiveness and Leakage Concerns and Border Carbon Adjustments. *Int. Rev.*
356 *Environ. Resour. Econ.* **6**, 225–287 (2012).
357 42. Zhang, Z., Zhang, Z. & Zhu, K. Allocating carbon responsibility: The role of spatial production
358 fragmentation. *Energy Econ.* 104491 (2019). doi:10.1016/j.eneco.2019.104491
359 43. Zhang, Z., Zhu, K. & Hewings, G. J. D. The effects of border-crossing frequencies associated
360 with carbon footprints on border carbon adjustments. *Energy Econ.* **65**, 105–114 (2017).
361 44. Lenzen, M., Murray, J., Sack, F. & Wiedmann, T. Shared producer and consumer
362 responsibility - Theory and practice. *Ecol. Econ.* **61**, 27–42 (2007).
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376

377 **Author contributions**

378 D.G., H.D., and Z.Z. designed the research. Z.Z. and K.Z. determined the calculation method. Z.Z.
379 J.M., H.Z., and R.W. carried out the calculation and analysis. Z.Z. and D.G. wrote the manuscript,
380 and all authors contributed to this manuscript.

381

382 **Competing financial interests**

383 The authors declare no competing financial interests.

384

385 **Methods**

386 **Carbon footprints of MNEs' foreign affiliates**

387 It is well recognized that MNEs are important agents in the fight against climate change⁵⁻⁷. MNEs
388 have massive scale and global reach, and different entities around the world can influence each
389 other's climate change mitigation activities⁴⁵. In addition, climate change mitigation relies on
390 technological innovations⁴⁶, and MNEs have the capacity to pursue clean technology research and
391 development (R&D) and to dominate the demonstration and diffusion of new technologies^{47,48}. In
392 2018, the top 100 MNEs accounted for more than one-third of business-funded R&D worldwide²⁸.
393 What, then, are the characteristics of embodied carbon emissions in the supply chains of MNEs? To
394 inform targeted climate policies and actions, this study traces embodied carbon emissions in the
395 supply chains of MNEs and maps the global carbon transfer through FDI.

396 The input-output model⁴⁹ is widely employed to trace the carbon footprints of different economic
397 activities⁵⁰⁻⁵⁴. However, we cannot calculate the CO₂ emissions embodied in MNEs' outputs that
398 are used as intermediate inputs by simply multiplying the Leontief inverse matrix with the gross
399 intermediate inputs⁵⁵. López et al. (2019)⁵ calculate the carbon footprints of MNEs' foreign affiliates
400 by multiplying the final demand matrix with an emission multiplier matrix and an index that
401 measures the sectoral presence of MNEs in each country. However, multinational enterprises can be
402 involved in the entire supply chain and are not necessarily directly related to the final production
403 stages. In addition, domestic-owned and foreign-owned firms may have different production
404 technologies.

405 The literature on embodied value added has proposed two methods to go beyond the traditional
406 Leontief model. The first method is based on a decomposition of the traditional Leontief model^{55,56}.
407 Los et al. (2016)¹⁴ noted that this method is too complex and proposed a more straightforward and
408 intuitive method based on "hypothetical extraction". These two methods share the same results¹⁴
409 (**SI2.1**). Here, we present how to calculate the carbon footprints of multinational enterprises based
410 only on the decomposition method; the hypothetical extraction method is presented in Supporting
411 Information **SI2**.

412 We suppose the world is composed of m regions, and that each region has n sectors. The
413 production of each sector is divided into two parts: the production of domestic-owned firms (D)
414 and the production of foreign-owned firms (F). The final demand matrix is

$$415 \quad \mathbf{Y} = \begin{bmatrix} \mathbf{y}_{11}^D & \mathbf{y}_{12}^D & \cdots & \mathbf{y}_{1m}^D \\ \mathbf{y}_{11}^F & \mathbf{y}_{12}^F & \cdots & \mathbf{y}_{1m}^F \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{y}_{m1}^D & \mathbf{y}_{m2}^D & \cdots & \mathbf{y}_{mm}^D \\ \mathbf{y}_{m1}^F & \mathbf{y}_{m2}^F & \cdots & \mathbf{y}_{mm}^F \end{bmatrix}, \text{ and the intermediate input matrix is } \mathbf{A} = \begin{bmatrix} \mathbf{A}_{11}^{DD} & \mathbf{A}_{11}^{DF} & \cdots & \mathbf{A}_{1m}^{DD} & \mathbf{A}_{1m}^{DF} \\ \mathbf{A}_{11}^{FD} & \mathbf{A}_{11}^{FF} & \cdots & \mathbf{A}_{1m}^{FD} & \mathbf{A}_{1m}^{FF} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \mathbf{A}_{m1}^{DD} & \mathbf{A}_{m1}^{DF} & \cdots & \mathbf{A}_{mm}^{DD} & \mathbf{A}_{mm}^{DF} \\ \mathbf{A}_{m1}^{FD} & \mathbf{A}_{m1}^{FF} & \cdots & \mathbf{A}_{mm}^{FD} & \mathbf{A}_{mm}^{FF} \end{bmatrix}.$$

416 Taking \mathbf{A}_{1m}^{DF} as an example, it represents the direct requirements for the products of
 417 domestic-owned firms in region 1 per unit of output of foreign-owned firms in region
 418 m . The Leontief model implies that

$$419 \quad \mathbf{X} = (\mathbf{I} - \mathbf{A})^{-1} \mathbf{Y} \quad (1)$$

420 where \mathbf{X} is the output matrix. Define \mathbf{E} as the carbon intensity matrix, which is a diagonalized
 421 matrix. The carbon emissions induced by final demand can be expressed as

$$422 \quad \mathbf{C} = \mathbf{E}(\mathbf{I} - \mathbf{A})^{-1} \mathbf{Y} \quad (2)$$

423 Summing the matrix \mathbf{C} by rows (columns), we obtain the production-based (consumption-based)
 424 emissions of each country. We define \mathbf{Y}_r^F as the final demand matrix of products from foreign-
 425 owned firms in country r ($r=1,2,\dots,m$) and \mathbf{A}_r^F as the intermediate demand ratio matrix of
 426 products from foreign-owned firms in country r . Taking country 1 as an example,

$$427 \quad \mathbf{Y}_1^F = \begin{bmatrix} 0 & 0 & \cdots & 0 \\ \mathbf{y}_{11}^F & \mathbf{y}_{12}^F & \cdots & \mathbf{y}_{1m}^F \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 \end{bmatrix}, \quad \mathbf{Y}_1^{F*} = \mathbf{Y} - \mathbf{Y}_1^F, \quad \mathbf{A}_1^F = \begin{bmatrix} 0 & 0 & \cdots & 0 & 0 \\ \mathbf{A}_{11}^{FD} & \mathbf{A}_{11}^{FF} & \cdots & \mathbf{A}_{1m}^{FD} & \mathbf{A}_{1m}^{FF} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & 0 & 0 \\ 0 & 0 & \cdots & 0 & 0 \end{bmatrix}, \quad \mathbf{A}_1^{F*} = \mathbf{A} - \mathbf{A}_1^F,$$

428 and $\mathbf{I} - \mathbf{A} = \mathbf{I} - \mathbf{A}_r^{F*} - \mathbf{A}_r^F$. Then, we obtain

$$429 \quad \mathbf{C} = \mathbf{E}(\mathbf{I} - \mathbf{A}_r^{F*} - \mathbf{A}_r^F)^{-1} \mathbf{Y}_r^{F*} + \mathbf{E}(\mathbf{I} - \mathbf{A})^{-1} \mathbf{Y}_r^F \quad (3)$$

430 Since $\mathbf{I} = (\mathbf{I} - \mathbf{A}_r^{F*})^{-1}(\mathbf{I} - \mathbf{A}_r^{F*})$ and $\mathbf{I} = (\mathbf{I} - \mathbf{A}_r^{F*} - \mathbf{A}_r^F)^{-1}(\mathbf{I} - \mathbf{A}_r^{F*} - \mathbf{A}_r^F)$, we obtain
 431 $(\mathbf{I} - \mathbf{A}_r^{F*} - \mathbf{A}_r^F)^{-1} = (\mathbf{I} - \mathbf{A}_r^{F*})^{-1}(\mathbf{I} - \mathbf{A}_r^{F*} - \mathbf{A}_r^F + \mathbf{A}_r^F)(\mathbf{I} - \mathbf{A}_r^{F*} - \mathbf{A}_r^F)^{-1} = (\mathbf{I} - \mathbf{A}_r^{F*})^{-1} + (\mathbf{I} - \mathbf{A}_r^{F*})^{-1} \mathbf{A}_r^F (\mathbf{I} - \mathbf{A})^{-1}$
 432 . Inserting this equation into equation (3), we obtain

$$433 \quad \mathbf{C} = \underbrace{\mathbf{E}(\mathbf{I} - \mathbf{A}_r^{F*})^{-1} \mathbf{Y}_r^{F*}}_{(4.1)} + \underbrace{\mathbf{E}(\mathbf{I} - \mathbf{A}_r^{F*})^{-1} \mathbf{A}_r^F (\mathbf{I} - \mathbf{A})^{-1} \mathbf{Y}_r^{F*}}_{(4.2)} + \underbrace{\mathbf{E}(\mathbf{I} - \mathbf{A})^{-1} \mathbf{Y}_r^F}_{(4.3)} \quad (4)$$

434 Term 4.1 represents the CO₂ emissions that are not related to the MNEs' production activities in
 435 country r . Term 4.2 represents the CO₂ emissions embodied in MNEs' output in country r that
 436 are used as intermediate inputs. Term 4.3 represents the CO₂ emissions embodied in MNEs' output
 437 in country r that are used to satisfy final demand. Based on equation (4), the carbon footprints of
 438 the MNEs hosted by country r are

$$439 \quad \mathbf{C}_r^{host} = \mathbf{E}(\mathbf{I} - \mathbf{A}_r^{F*})^{-1} \mathbf{A}_r^F (\mathbf{I} - \mathbf{A})^{-1} \mathbf{Y}_r^{F*} + \mathbf{E}(\mathbf{I} - \mathbf{A})^{-1} \mathbf{Y}_r^F \quad (5)$$

440 Based on $\mathbf{I} = (\mathbf{I} - \mathbf{A}_r^{F*})^{-1}(\mathbf{I} - \mathbf{A}_r^{F*})$, we obtain

$$\begin{aligned}
\mathbf{C}_r^{host} &= \mathbf{E}(\mathbf{I} - \mathbf{A}_r^{F*})^{-1} \mathbf{A}_r^F (\mathbf{I} - \mathbf{A})^{-1} \mathbf{Y}_r^{F*} + \mathbf{E}(\mathbf{I} - \mathbf{A}_r^{F*})^{-1} (\mathbf{I} - \mathbf{A}_r^{F*} - \mathbf{A}_r^F + \mathbf{A}_r^F) (\mathbf{I} - \mathbf{A})^{-1} \mathbf{Y}_r^F \\
&= \mathbf{E}(\mathbf{I} - \mathbf{A}_r^{F*})^{-1} \mathbf{A}_r^F (\mathbf{I} - \mathbf{A})^{-1} \mathbf{Y}_r^{F*} + \mathbf{E}(\mathbf{I} - \mathbf{A}_r^{F*})^{-1} (\mathbf{I} - \mathbf{A}_r^{F*} - \mathbf{A}_r^F) (\mathbf{I} - \mathbf{A})^{-1} \mathbf{Y}_r^F \\
&\quad + \mathbf{E}(\mathbf{I} - \mathbf{A}_r^{F*})^{-1} \mathbf{A}_r^F (\mathbf{I} - \mathbf{A})^{-1} \mathbf{Y}_r^F \\
&= \mathbf{E}(\mathbf{I} - \mathbf{A}_r^{F*})^{-1} \mathbf{A}_r^F (\mathbf{I} - \mathbf{A})^{-1} \mathbf{Y}_r^{F*} + \mathbf{E}(\mathbf{I} - \mathbf{A}_r^{F*})^{-1} \mathbf{Y}_r^F + \mathbf{E}(\mathbf{I} - \mathbf{A}_r^{F*})^{-1} \mathbf{A}_r^F (\mathbf{I} - \mathbf{A})^{-1} \mathbf{Y}_r^F
\end{aligned} \tag{6}$$

442 We define $\mathbf{Z}_r^F = \mathbf{A}_r^F \mathbf{X}$ as the MNEs' output in country r that are used as intermediate inputs.
443 Based on $\mathbf{Y} = \mathbf{Y}_r^{F*} + \mathbf{Y}_r^F$ and $\mathbf{A} = \mathbf{A}_r^{F*} + \mathbf{A}_r^F$, we have

$$\begin{aligned}
\mathbf{C}_r^{host} &= \mathbf{E}(\mathbf{I} - \mathbf{A}_r^{F*})^{-1} \mathbf{A}_r^F (\mathbf{I} - \mathbf{A})^{-1} \mathbf{Y} + \mathbf{E}(\mathbf{I} - \mathbf{A}_r^{F*})^{-1} \mathbf{Y}_r^F \\
&= \mathbf{E}(\mathbf{I} - \mathbf{A}_r^{F*})^{-1} \mathbf{Z}_r^F + \mathbf{E}(\mathbf{I} - \mathbf{A}_r^{F*})^{-1} \mathbf{Y}_r^F \\
&= \mathbf{E}(\mathbf{I} - \mathbf{A}_r^{F*})^{-1} (\mathbf{Z}_r^F + \mathbf{Y}_r^F) \\
&= \mathbf{E}(\mathbf{I} - \mathbf{A} + \mathbf{A}_r^F)^{-1} (\mathbf{Z}_r^F + \mathbf{Y}_r^F)
\end{aligned} \tag{7}$$

445 We define $\mathbf{B}_r^F = (\mathbf{I} - \mathbf{A} + \mathbf{A}_r^F)^{-1}$ as the gross output of each sector required to produce per unit of
446 output of the MNEs hosted by country r and $\mathbf{O}_r^F = \mathbf{Z}_r^F + \mathbf{Y}_r^F$ as the output of the MNEs in country
447 r . Then, the carbon footprints of the MNEs hosted by country r ($r=1,2,\dots,m$) are

448 $\mathbf{C}_r^{host} = \mathbf{E} \mathbf{B}_r^F \mathbf{O}_r^F$. The change in the carbon footprints of MNEs hosted by country r over a period
449 is

$$\Delta \mathbf{C}_r^{host} = \mathbf{C}_{r,t}^{host} - \mathbf{C}_{r,0}^{host} = \mathbf{E}_t \mathbf{B}_{r,t}^F \mathbf{O}_{r,t}^F - \mathbf{E}_0 \mathbf{B}_{r,0}^F \mathbf{O}_{r,0}^F \tag{8}$$

451 This study first deflates the input-output tables to the constant price and then adopts structural
452 decomposition analysis (SDA) to analyze the driving factors of the carbon footprints of the MNEs
453 hosted by each country. There are different decomposition approaches⁵⁷, and this study adopts the
454 two polar decomposition approach^{32,58-60}, the average of which can be viewed as an approximation
455 of the average of all equivalent decompositions⁶¹. The change in the carbon footprints of MNEs can
456 be expressed as

$$\Delta \mathbf{C}_r^{host} = \frac{1}{2} (\Delta \mathbf{E} \mathbf{B}_{r,t}^F \mathbf{O}_{r,t}^F + \Delta \mathbf{E} \mathbf{B}_{r,0}^F \mathbf{O}_{r,0}^F) + \frac{1}{2} (\mathbf{E}_0 \Delta \mathbf{B}_{r,t}^F \mathbf{O}_{r,t}^F + \mathbf{E}_t \Delta \mathbf{B}_{r,0}^F \mathbf{O}_{r,0}^F) + \frac{1}{2} (\mathbf{E}_0 \mathbf{B}_{r,0}^F \Delta \mathbf{O}_r^F + \mathbf{E}_t \mathbf{B}_{r,t}^F \Delta \mathbf{O}_r^F) \tag{9}$$

458 The three parts in equation (9) represent the carbon intensity effect, production structure effect, and
459 scale effect.

460 Based on equation (5), we can allocate the carbon footprints of MNEs' foreign affiliates to the
461 country of production and the country of consumption. However, in this study, we are interested in
462 the carbon reduction responsibility of the FDI home country. In the input-output table, the firms
463 owned by different countries are not distinguished. For instance, the US and the UK may both invest
464 in firms in the chemical industry in China. To deal with this problem, we use the bilateral FDI stock
465 at the sectoral level as the factor to disaggregate MNEs' carbon footprints. Applying the
466 decomposition method at the sectoral level, we can obtain the carbon footprints ($\mathbf{C}_{r,i}^{host}$) of the MNEs
467 hosted by country r in sector i ($i=1,2,\dots,n$). The bilateral FDI stock from country s to country
468 r in sector i is ($t_{sr,i}$). Then, the carbon footprints of MNEs originating from different regions can
469 be obtained by

470

$$C_s^{home} = \sum_{r,i} \frac{t_{sr,i}}{\sum_k t_{kr,i}} C_{r,i}^{host} \quad (10)$$

471 This study mainly focuses on the carbon footprints of MNEs, which are defined as firms that engage
 472 in FDI and own or control value-adding activities in more than one country⁶². Therefore, we think
 473 that the FDI is the closest indicator for estimating the production of MNEs' foreign affiliates.
 474 However, one limitation of using FDI as the indicator is that firms' carbon emissions in a year are
 475 related not only to the FDI in that year but also to the FDI in the previous years. To deal with this
 476 problem, we use the stock of FDI as the indicator rather than the flow or income of FDI in a specific
 477 period⁶³. The advantage of using the FDI stock as an indicator is that it captures the accumulated
 478 investment. The drawback of using the FDI stock as an indicator is that it fails to reflect the different
 479 production technologies of firms owned by different countries. For instance, Bloom et al., (2012)
 480 noted that US MNEs obtain higher productivity from their information technologies capital than
 481 European MNEs⁶⁴. It is difficult to solve this problem by choosing an alternative indicator because
 482 the sector homogeneity assumption of the input-output model determines that we have to assume
 483 that foreign-owned firms in an industry have the same production technology and carbon intensity.
 484 Therefore, the FDI stock matrix is a suitable indicator for this study

485

486 Data & code availability statement

487 Data availability

488 This study uses a newly published time-series inter-regional input-output table⁶⁵ that is constructed
 489 by the Organization for Economic Co-operation and Development (OECD) and captures firm
 490 heterogeneity for sixty regions (<http://www.oecd.org/sti/ind/analytical-AMNE-database.htm>). The
 491 other data adopted by this study are bilateral FDI stock data from the OECD ([https://www.oecd-](https://www.oecd-ilibrary.org/finance-and-investment)
 492 [ilibrary.org/finance-and-investment](https://www.oecd-ilibrary.org/finance-and-investment)) and the United Nations
 493 (<https://unctad.org/en/Pages/DIAE/FDI%20Statistics/FDI-Statistics-Bilateral.aspx>)^{65,66}, sectoral
 494 CO₂ emissions data from the International Energy Agency ([https://www.iea.org/data-and-](https://www.iea.org/data-and-statistics)
 495 [statistics](https://www.iea.org/data-and-statistics))⁶⁷, and emissions data of selected MNEs from their sustainability reports (SI3). Those data
 496 can be freely downloaded as public data. We also provide a detailed explanation on these data in
 497 Supporting Information.

498

499 Code availability

500 The code of the method is available at Mendeley Data for academic use.

501

502 References

- 503 45. OECD. *OECD Guidelines for Multinational Enterprises 2011 Edition. OECD Guidelines for*
 504 *Multinational Enterprises 2011 Edition (Chinese version)* (2011).
 505 doi:10.1787/9789264204881-zh
- 506 46. IPCC. *Summary for Policymakers. In: Global warming of 1.5°C.* (2018).
- 507 47. Narula, R. & Zanfei, A. *Globalization of Innovation : The Role of Multinational Enterprises.*
 508 (Oxford University Press, 2006).
- 509 48. McKinsey Global Institute. *Growth and competitiveness in the United States : The role of its*
 510 *multinational companies.* (2010).

- 511 49. Leontief, W. W. *Structure of the American Economy, 1919–1929*. (Harvard University Press,
512 1941).
- 513 50. Wiedmann, T. & Lenzen, M. Environmental and social footprints of international trade. *Nat.*
514 *Geosci.* **11**, 314–321 (2018).
- 515 51. Xiao, Y. *et al.* The Corruption Footprints of Nations. *Journal of Industrial Ecology* (2017).
516 doi:10.1111/jiec.12537
- 517 52. Wiedenhofer, D. *et al.* Unequal household carbon footprints in China. *Nat. Clim. Chang.* **1**,
518 (2016).
- 519 53. Zhang, Z., Zhu, K. & Hewings, G. J. D. The effects of border-crossing frequencies associated
520 with carbon footprints on border carbon adjustments. *Energy Econ.* **65**, 105–114 (2017).
- 521 54. Hertwich, E. G. & Peters, G. P. Carbon footprint of nations: A global, trade-linked analysis.
522 *Environ. Sci. Technol.* **43**, 6414–6420 (2009).
- 523 55. Wang, Z., Wei, S.-J. & Zhu, K. Quantifying international production sharing at the bilateral
524 and sector levels. *Work. Pap. Sources*
525 http://scholar.harvard.edu/files/jorgenson/files/zhi_wang_wwz-mar-7-2014.pdf (2015).
526 doi:10.3386/w19677
- 527 56. Koopman, R., Wang, Z. & Wei, S.-J. Tracing value added and double counting in gross
528 exports. *Am. Econ. Rev.* **104**, 0–41 (2014).
- 529 57. Zhang, Z., Zhu, K. & Hewings, G. J. D. A multi-regional input – output analysis of the
530 pollution haven hypothesis from the perspective of global production fragmentation. *Energy*
531 *Econ.* **64**, 13–23 (2017).
- 532 58. Chen, Q., Dietzenbacher, E. & Los, B. Structural decomposition analyses: the differences
533 between applying the semi-closed and the open input-output model. *Environ. Plan. A* **47**,
534 1713–1735 (2015).
- 535 59. Meng, B. *et al.* Spatial spillover effects in determining China’s regional CO2 emissions
536 growth: 2007–2010. *Energy Econ.* (2017).
- 537 60. Mi, Z. *et al.* Chinese CO2 emission flows have reversed since the global financial crisis. *Nat.*
538 *Commun.* **8**, 1712 (2017).
- 539 61. Dietzenbacher, E. & Los, B. Structural Decomposition Techniques: Sense and Sensitivity.
540 *Econ. Syst. Res.* **10**, 307–324 (1998).
- 541 62. Dunning, J. H. & Lundan, S. M. *Multinational Enterprises and the Global Economy*. (Edward
542 Elgar Publishing, 2008).
- 543 63. OECD. *Measuring International Investment by Multinational Enterprises: Implementation of*
544 *the OECD’s Benchmark Definition of Foreign Direct Investment, 4th edition*. (2015).
- 545 64. Bloom, N., Sadun, R. & Van Reenen, J. Americans do IT better: US multinationals and the
546 productivity miracle. *Am. Econ. Rev.* **102**, 167–201 (2012).
- 547 65. Cadestin, C. *et al.* *Multinational enterprises and global value chains : the OECD analytical*
548 *AMNE database*. OECD Publishing, Paris (2018).
- 549 66. United Nations Conference on Trade and Development. *Bilateral FDI Statistics*. (2014).
- 550 67. International Energy Agency. *CO2 Emissions from Fuel Combustion 2018*. (2018).
- 551