Embodied carbon emissions in the supply chains of multinational enterprises

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Abstract

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

In 2015, the Paris Agreement set the target of holding this century's global warming well below 2° C above pre-industrial levels. However, the sum of current national pledges and companies' commitments to climate mitigation falls short of meeting the Paris goal[1–3]. Global climate change mitigation calls for more active actions from governments, businesses and investors[4]. Currently, enterprises – particularly MNEs[5–7] – are at the forefront of climate action. For instance, thousands of US businesses have declared that they will continue to support climate action and work towards meeting the terms of the Paris Agreement[8], despite President Trump's announcement that the US will withdraw from the Agreement. Carbon footprint measurement is the first step in reducing carbon emissions[9]. However, the global reach of MNEs makes it more difficult to measure their carbon footprints, especially the carbon footprint of their foreign affiliates, which is also a popular topic of current research[5]. This study attempts to enrich the related literature in the following ways. Here we present a comprehensive study to trace carbon emissions embodied in the supply chains of global MNEs. Existing studies mainly assessed the carbon footprints of MNEs originating in or hosted by a particular country in a certain year, such as China[10–12] or the US[5]. For instance, López et al. (2019)[5] found that in 2009 the carbon footprint of US MNEs' foreign affiliates was greater than that of the territorial emissions of the UK. Different economies around the world may play different roles in global investment networks, which have also been changing over recent years. This study extends the literature by providing time-series and global-level analysis of the carbon footprints of MNEs. We provide two methods, the decomposition method and the hypothetical extraction method (HEM)[13], to calculate the carbon footprints of MNEs and prove that these two methods share the same results[14]. The results of these calculations allow us to illuminate the changing trends in the carbon footprints of MNEs and to identify the global carbon transfer from the sources to the destinations of FDI.

This study proposes an investment-based accounting framework to further motivate MNEs to adopt more ambitious climate actions. To allocate carbon reduction responsibility between producers (the production-based approach)[15] and consumers (the consumption-based approach)[16], a number of studies have carbon flows through commodity trades[17–21]. Carbon transfer through trade means that a country reduces its territorial emissions by importing products from other countries through international trade[18]. However, a country can outsource carbon emissions to other countries through investment as well[22]. Carbon transfer through investment means that a country reduces its territorial emissions by relocating domestic production to other countries through cross-border investment[23]. A comprehensive analysis of carbon transfer through FDI is still lacking. Therefore, we attempt to remap global carbon flows by focusing on the investment channel. MNEs have the power to exercise significant influence over the entire supply chain[24,25]. Some large MNEs play dominant roles in carbon transfer through investment. Therefore, the investment-based accounting framework allocates the carbon footprints of MNEs to the FDI home country[5].

Trends in the carbon footprints of MNEs and driving factors

In 2008, the share of carbon emissions embodied in the supply chains of MNEs' foreign affiliates (also referred to as the carbon footprints of MNEs in this study) to global emissions reached its highest peak, i.e. 22.0% of global CO_2 emissions. A huge volume of global CO_2 emissions is related to the supply chains of MNEs, despite the declining share of MNEs' carbon footprints in global emissions since 2008. In 2016, at the global scale, MNEs' carbon footprints still accounted for 18.7% of global emissions. Clearly, FDI should be a focus of climate change mitigation measures. The volume of investment-related CO_2 is comparable to that of trade-related CO_2 (SI1.1). Based on changing patterns in the carbon footprints of MNEs, we divide the study period into four sub-periods. The carbon footprints of MNEs grew from 5530.8 Mt in 2005 to a preliminary peak of 6419.2 Mt in 2008 (Figure 1). After the financial crisis, the carbon footprints of MNEs increased again and reached the secondary and highest peak of 6677.3 Mt in 2011. After 2011, there was a general declining pattern in the carbon footprints of MNEs, which was down to 6543.4 Mt in 2014 and 6048.9 Mt in 2016, although there were slight increases in 2013 and 2014.

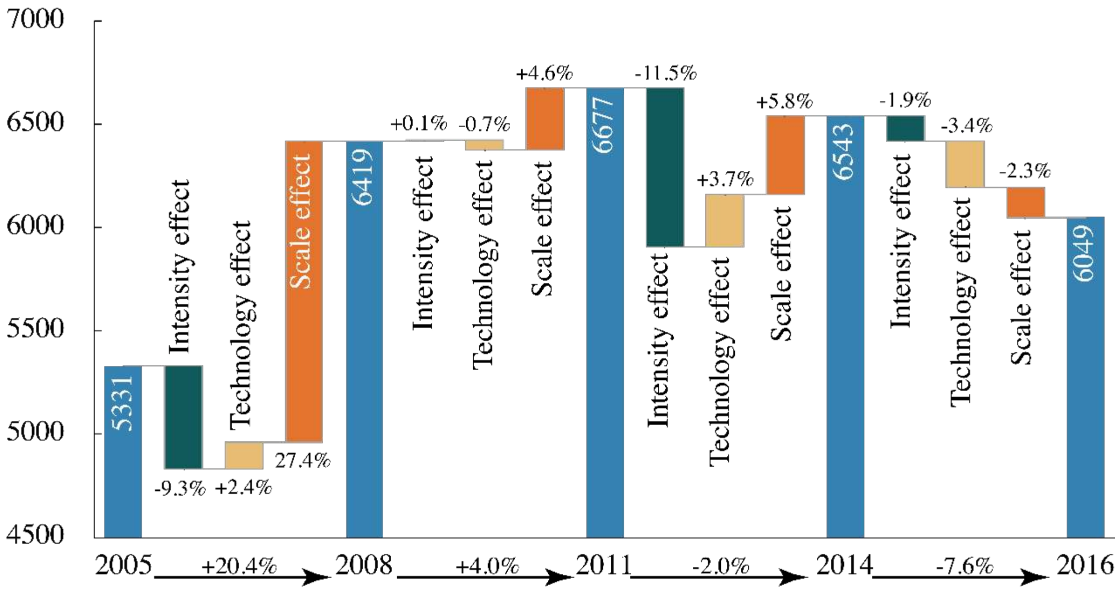

Figure 1. CO_2 emissions embodied in supply chains of MNEs

Over the first sub-period (2005-2008), the CO_2 emissions embodied in the supply chains of MNEs increased by 20.4%. The major contributing factor to this increase was the growth in the outputs of MNEs (scale effect), which would cause MNEs' carbon footprints to increase by 27.4% in the absence of other factors. The decrease in carbon intensity offset MNEs' carbon footprints by -9.3% (intensity effect), and the change in production technology played a relatively modest role (+2.4%, technology effect) (Figure 1). Due to the impact of the financial crisis, the growth rate of MNEs' carbon footprint declined in the second sub-period (2008-2011), during which the MNEs' carbon footprints increased by only 4.0%. The scale effect (+4.6%) was the major contributor, whereas the technology effect decreased the carbon footprints of MNEs by -0.7%. After the peak year in 2011, the declining rates of the carbon footprints of MNEs clearly increased. Over the third (2011-2014) and fourth (2014-2016) sub-periods, the declining rates reached -2.0% and -7.6%, respectively. The decline in carbon intensity was the major driver of the downturn in MNEs' carbon footprint. The global carbon intensity was relatively stable before 2011 whilst decreased sharply after 2011[26,27]. Over the period 2011-2014, both the scale effect (+5.8%) and the technology effect (+3.7%) played a significant role in driving MNEs' carbon footprints. However, the signs of these two effects changed over the last period, as the volume of global FDI shrunk and MNEs began to adopt measures to clean up their supply chains. Over the sub-period 2014-2016, all three effects contributed to the declining carbon footprints of MNEs. The changes in MNEs' output, production technology and carbon intensity would contribute to a decline in their carbon footprints of -2.3%, -3.4% and -1.9%, respectively, with all other factors held constant.

Global carbon transfer through FDI

MNEs originate in and are hosted by different countries and regions. Ranked by the carbon footprints of the MNEs hosted by each country, the Chinese mainland was the largest hosting country (1584.5 million tons) in 2016, followed by the EU and the US (**Fig. S3**). Over the study period 2005-2016, the carbon footprints of MNEs hosted by the US and the EU remained relatively stable and even decreased slightly. However, the carbon footprints of MNEs hosted by developing countries, such as the Chinese mainland and India increased sharply, as developing countries have become increasingly attractive FDI destinations[28]. From the perspective of the carbon footprints of MNEs originating in different regions, the EU was the largest originating region of MNEs in 2016 (**Fig. S3**). The carbon footprints originating from the EU totaled at 2151.3 Mt, followed by the US (1259.9 Mt) and Chinese Hong Kong (1074.6 Mt). After 2011, there was a decreasing trend in the volumes of the carbon footprints of MNEs originating from developed countries such as the US (Figure 2). However, there was a significant growth trend in the carbon footprint of MNEs originating from the Chinese mainland. The volume of the carbon footprints of MNEs originating from the Chinese mainland increased from 58.7 Mt in 2005 to 200.5 Mt in 2016.

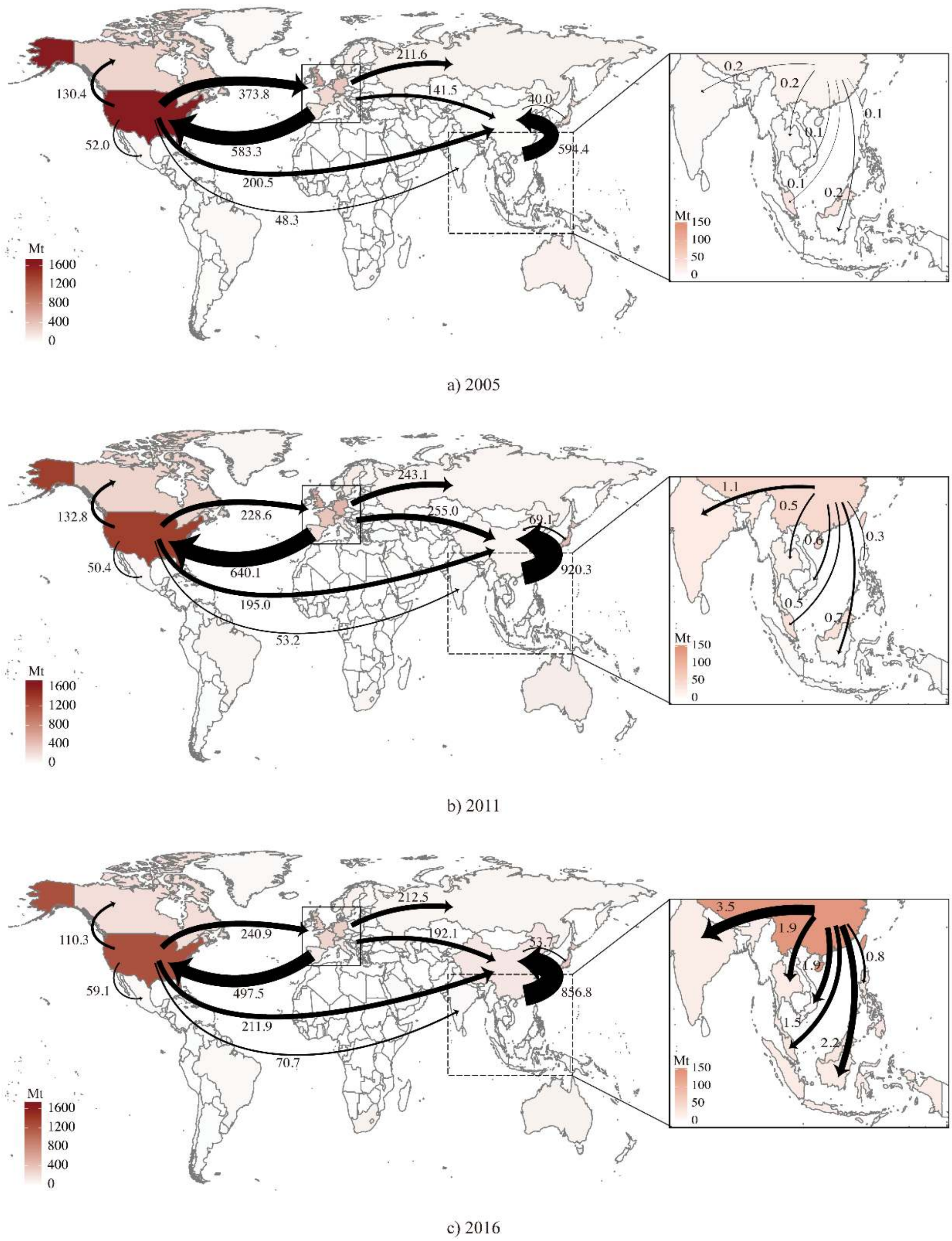

Figure 2. Carbon transfer embodied in global FDI. The color of each country or region represents the gross volume of CO_2 emissions driven by FDI stocks that are sourced from that country or region. The arrows represent the carbon transfer through global FDI. The width of the arrows represents the volume of carbon flows.

The largest carbon transfer through investment is from Chinese Hong Kong to the Chinese mainland, with a volume of 594.4 Mt in 2005, which increased to 856.8 Mt in 2016. Chinese Hong Kong was the leading source of FDI into the Chinese mainland, and more than 60% of the FDI in the Chinese mainland was channeled through Chinese Hong Kong in 2016[29]. The second largest carbon transfer was from the EU to the US, which was the largest FDI recipient[30]. Over the period 2005-2016, there were significant declines in carbon transfer between the US and the EU. However, there were significant increases in carbon transfer from developed countries to developing countries over the study period. For instance, carbon transfer from the US to India increased from 48.3 Mt in 2005, to 53.2 Mt in 2011 and to 70.7 Mt in 2016. The World Investment Report (2019)[28] shows that FDI flows to developing countries have been increasing stably, while developed countries are becoming less attractive to global investment. In recent years, developed countries as well as some developing countries, such as China, have been increasing their investment in emerging economies[31]. China has established the Asian Infrastructure Investment Bank and the Silk Road Fund to strengthen investment in developing countries along the land and sea Silk Roads. Over the study period, there was a significant growth trend in carbon transfer from China to India and Southeast Asian countries. The volume of carbon transfer from China to the five studied Southeast Asian countries (Vietnam, Indonesia, Philippines, Thailand, and Malaysia) increased by ten times, from 0.7 Mt CO_2 emissions in 2005 to 8.2 Mt CO_2 emissions in 2016. With the rise of South-South trade[32] and FDI flows, the volume of carbon transfer between developing countries will increase rapidly in the future and should be a major focus of policy makers.

A region may outsource carbon emissions to other regions through investment. We analyze the impact of FDI on the distribution of global emissions by the difference in the carbon footprints of MNEs under investment-based and production-based accounting approaches. Under the investment-based accounting approach, the carbon footprints of MNEs are allocated to the investing country. Under the production-based accounting approach, a region should be responsible for its territorial emissions. We found that the volume of the carbon footprints of MNEs invested by developed countries was greater than the volume of their territorial emissions induced by foreign-owned enterprises, whilst the opposite findings for developing countries (**Fig. S4**). This result is consistent with previous studies that showed developed countries outsource embodied CO_2 emissions to developing countries[16,18–20]. Chinese Hong Kong has the largest net negative balance of embodied emissions in the supply chains of MNEs (-1031.1 Mt), followed by the EU (-931.8 Mt) and the US (-295.1 Mt). The Chinese mainland has the largest net positive balance of carbon emissions related to FDI. The Chinese mainland's territorial emissions induced by foreign-owned enterprises in 2016 reached 1811.0 Mt. However, the Chinese mainland's investment in foreign countries in 2016 resulted in only 138.7 Mt CO_2 emissions. The foreign-owned firms' production activities lead to a greater burden on the host country to reduce the related emissions relative to the economic gains that they bring to the host country **(SI1.5)**. Policy makers should encourage FDI flows in industries with high value-added and low carbon intensity.

Large MNEs play an important role in curbing carbon transfer

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

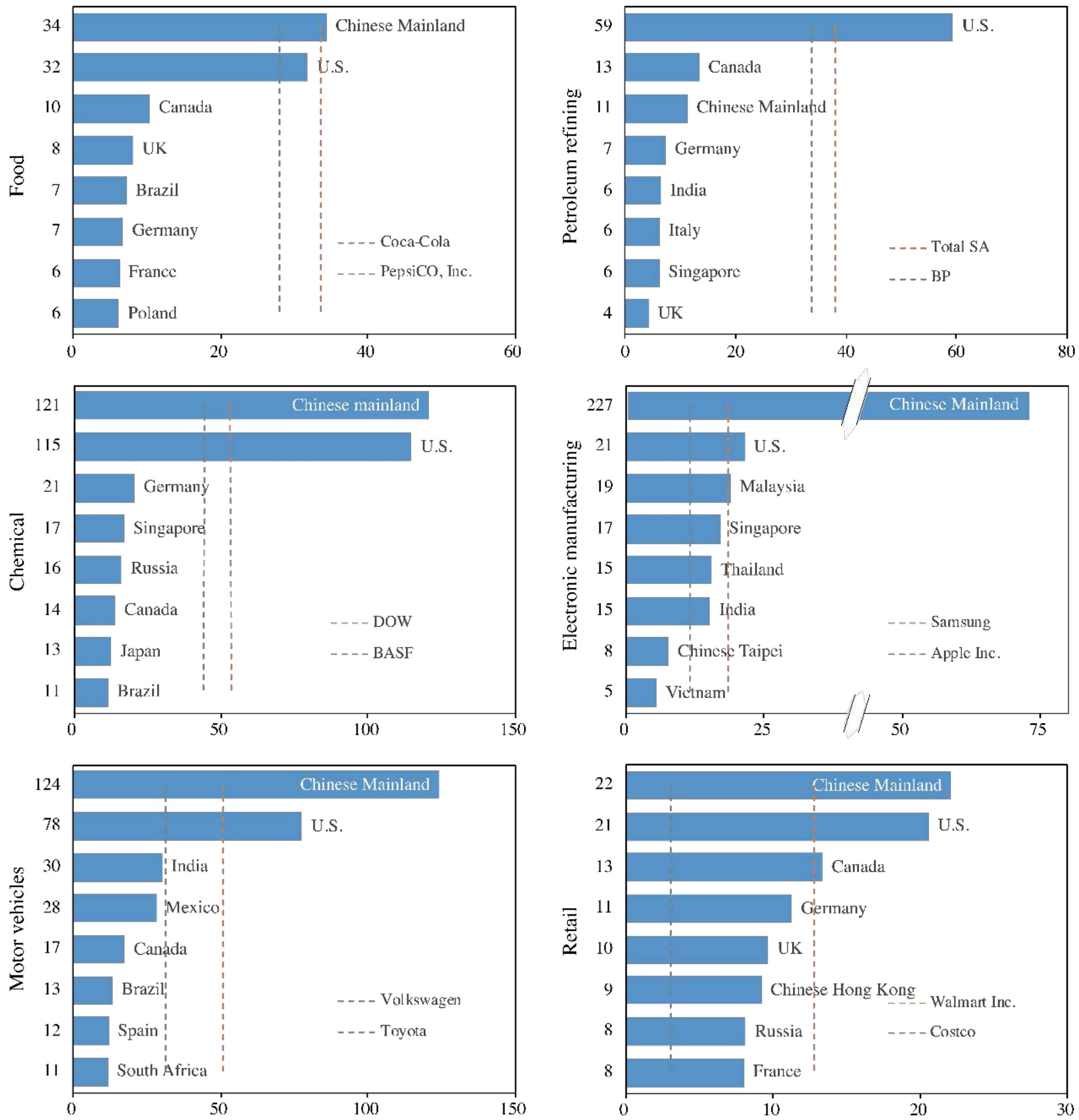

Figure 3. Carbon footprint of MNEs at the sectoral level in 2016 (million tons). The blue bars represent the carbon emissions embodied in the supply chains of sectoral MNEs in a certain country. The lines represent the carbon emissions embodied in the supply chains of large MNEs' foreign affiliates.

For MNEs in the petroleum-refining sector, the US was the largest host country by volume of embodied emissions, and the Chinese mainland was the largest host country for the other five sectors. The US and the Chinese mainland were the top two largest host regions of FDI inflows[30]. The Chinese mainland's foreign-owned enterprises tend to have carbon-intensive supply chains mainly due to its coal-based energy mix. The other significant host countries in **Fig. 3** are mainly major developed countries, such as Canada, Germany and the UK, and large developing countries, such as Brazil, India, and Russia. The electronic sector (**Fig. 3**, row 2, right) has a greater degree of concentration in the MNEs' carbon footprints. In 2016, the volume of carbon footprints of Chinese mainland's foreign-owned electronic enterprises reached 226.7 Mt, which is significantly greater than that of other regions. Several Southeast Asian countries, which also have lower labor costs, are also listed among the top eight host countries of electronics MNEs based on the volume of carbon footprints.

The total volume of the carbon footprints of the foreign affiliates of the Coca-Cola Company, an American multinational enterprise, was almost equal to the volume of CO_2 emissions embodied in the Chinese mainland's foreign-owned enterprises (**Fig. 3**, row 1, left). For the petroleum refining sector (**Fig. 3**, row 1, right), Total SA and BP, which are multinational chemical companies headquartered in France and the UK, respectively, had a greater responsibility for the carbon emissions induced by the foreign affiliates of petroleum-refining MNEs than did most host countries, except the US. For the chemical sector (**Fig. 3**, row 2, left), Dow Chemical Company and BASF, which are multinational chemical companies headquartered in the US and Germany, respectively, were the third and fourth most responsible agents for carbon emissions induced by chemical MNEs' foreign affiliates, respectively, following the Chinese mainland and the US. Large MNEs also play dominant roles in the electronic manufacturing sector (**Fig. 3**, row 2, right), motor vehicles sector (**Fig. 3**, row 3, left), and retail sector (**Fig. 3**, row 3, right). Although these large MNEs may generate a lower volume of CO_2 emissions per unit sales than the average sectoral level, for example, Apple Inc., their climate actions still represent crucial supplements to carbon control measures adopted by different countries or regions. Their climate actions can not only push their upstream suppliers to reduce emissions but also encourage other companies to adopt climate actions.

These selected MNEs have played active roles in fighting climate change. For instance, Apple Inc., which is the world's largest technology company by revenue, launched Apple's Supplier Clean Energy Program in 2015. Walmart Inc. has launched Project Gigaton to reduce the carbon emissions of Walmart Inc. and its upstream suppliers by one billion tons over the period 2015-2030. The MNEs' carbon footprints or carbon intensity have decreased significantly over the past few years. For instance, in 2017, Coca-Cola reduced the volume of its carbon footprint by 19% against the 2010 baseline. International cooperation in fighting climate change is creating new opportunities for the development of MNEs. However, MNEs are also facing great uncertainty in climate policies, green technology, investment profitability, and so on[33]. MNEs tend to be cautious in their climate activities. For instance, Toyota produces hybrid cars, rather than fuel cell vehicles, as a bridging strategy as it moves towards offering more environmentally friendly vehicles. In addition, more than half of the companies with quantified carbon reduction targets have set only short-term targets **(SI3.5)**[3]. MNEs should adopt more ambitious climate actions to reduce the carbon emissions induced by their international investments.

Discussion

The temporal, spatial and sectoral characteristics of MNEs' carbon footprints are presented above. International FDI flows have recently taken on some new characteristics. The volume of global FDI is shrinking, declining by 23%[30] in 2017 and 13%[28] in 2018. The process of deglobalization may reduce the carbon footprints of MNEs in the next few years. However, there is a stable increase in FDI flows to developing countries[28], and there is an increase in South-South FDI between developing countries[32]. In recent years, an increasing number of companies that sourced from developing countries have become MNEs with a greater pace of internalization[34]. Compared with traditional MNEs, which must bear sunk costs to rebuild their supply chains, new MNEs based in developing countries[31] enjoy a second mover advantage in that they can build clean supply chains from the inception. This study analyzed the carbon footprints of only twelve selected large MNEs in six sectors. As an increasing number of MNEs have begun to measure and report their greenhouse gas emissions in recent years, future studies should provide a more detailed ranking of MNEs in terms of their carbon footprints.

A region can outsource CO_2 emissions to other regions through both trade and investment, which are both crucial channels of carbon transfer. This study maps the global carbon transfer, shifting the focus from trade flows to FDI flows. The recent strengthening of the trade-investment nexus[35–37] has made global carbon transfer more complicated (**SI1.4**). A clearer picture of global carbon transfer through trade and FDI can guide policy makers to adopt more targeted measures to address carbon leakage. For instance, Borghesi et al., (2020)[38] noted that unilateral climate policies may promote the production of the existing foreign subsidiaries of MNEs, especially in trade-intensive sectors. Majority of existing studies focuses on the economic impacts[39,40] of the trade-investment nexus. Future studies are expected to provide a more in-depth analysis of the links between trade-related and investment-related carbon transfer. In addition, MNEs play a crucial role in the trade-investment nexus. For instance, the production of foreign-owned enterprises relies on imported intermediate products. Meanwhile, a greater share of the products of foreign-owned enterprises will be exported to the global market. MNEs should play a more leading role in fighting carbon leakage.

This study proposes an investment-based accounting approach to allocate the carbon footprints of MNEs to the investing country. The investment-based accounting approach, which allocates the outward responsibility of MNEs to the FDI home country, shifts the focus of policy makers from producers and consumers[16] to investors[5]. This is because MNEs have the power to exercise significant influence over the entire supply chain due to their massive scale and global reach[24,25] (please see SI1.3 for a comparison of different accounting approaches). The investment-based approach can be used to address the carbon leakage that occurs through investment channels[41] and to reduce international investment in regions with a greater carbon intensity. Developing countries, which are playing an increasingly important role in the fight against climate change, must adopt more active climate actions to attract international investment. The results of this study can also be used in international climate change negotiations to determine the regional carbon reduction responsibilities. Notably, the control power of MNEs may fade with the increase in the border-crossing frequency associated with carbon footprints[42,43]. In addition, different types of FDI and headquarters have different types of control power over their foreign affiliates. Future studies can take these factors into account and explore mechanisms to share emissions responsibilities between FDI-sourcing and FDI-hosting countries[44].

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Author contributions

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

Competing financial interests

The authors declare no competing financial interests.

Methods

Carbon footprints of MNEs' foreign affiliates

It is well recognized that MNEs are important agents in the fight against climate change[5–7]. MNEs have massive scale and global reach, and different entities around the world can influence each other's climate change mitigation activities[45]. In addition, climate change mitigation relies on technological innovations[46], and MNEs have the capacity to pursue clean technology research and development (R&D) and to dominate the demonstration and diffusion of new technologies[47,48]. In 2018, the top 100 MNEs accounted for more than one-third of business-funded R&D worldwide[28]. What, then, are the characteristics of embodied carbon emissions in the supply chains of MNEs? To inform targeted climate policies and actions, this study traces embodied carbon emissions in the supply chains of MNEs and maps the global carbon transfer through FDI.

The input-output model[49] is widely employed to trace the carbon footprints of different economic activities[50–54]. However, we cannot calculate the CO_2 emissions embodied in MNEs' outputs that are used as intermediate inputs by simply multiplying the Leontief inverse matrix with the gross intermediate inputs[55]. López et al. (2019)[5] calculate the carbon footprints of MNEs' foreign affiliates by multiplying the final demand matrix with an emission multiplier matrix and an index that measures the sectoral presence of MNEs in each country. However, multinational enterprises can be involved in the entire supply chain and are not necessarily directly related to the final production stages. In addition, domestic-owned and foreign-owned firms may have different production technologies.

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

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

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

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

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

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

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

Summing the matrix $\mathbf{C}$ by rows (columns), we obtain the production-based (consumption-based) emissions of each country. We define $\mathbf{Y}_r^F$ as the final demand matrix of products from foreign-owned firms in country $r\left(r=1,2,\cdots,m\right)$ and $\mathbf{A}_r^F$ as the intermediate demand ratio matrix of products from foreign-owned firms in country r. Taking country 1 as an example, $\mathbf{Y}_1^F=\begin{bmatrix} 0 & 0 & \cdots & 0 \\ \mathbf{y}_{11}^{F} & \mathbf{y}_{12}^{F} & \cdots & \mathbf{y}_{1m}^{F} \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 \end{bmatrix}$, $\mathbf{Y}_1^{F*}=\mathbf{Y}-\mathbf{Y}_1^F$, $\mathbf{A}_1^F=\begin{bmatrix} 0 & 0 & \cdots & 0 & 0 \\ \mathbf{A}_{11}^{FD} & \mathbf{A}_{11}^{FF} & \cdots & \mathbf{A}_{1m}^{FD} & \mathbf{A}_{1m}^{FF} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & 0 & 0 \\ 0 & 0 & \cdots & 0 & 0 \end{bmatrix}$, $\mathbf{A}_1^{F*}=\mathbf{A}-\mathbf{A}_1^F$, and $\mathbf{I}-\mathbf{A}=\mathbf{I}-\mathbf{A}_r^{F*}-\mathbf{A}_r^F$. Then, we obtain

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

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

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

Term 4.1 represents the CO_2 emissions that are not related to the MNEs' production activities in country r. Term 4.2 represents the CO_2 emissions embodied in MNEs' output in country r that are used as intermediate inputs. Term 4.3 represents the CO_2 emissions embodied in MNEs' output in country r that are used to satisfy final demand. Based on equation (4), the carbon footprints of the MNEs hosted by country r are

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

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

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

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. 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

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

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 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 r. Then, the carbon footprints of the MNEs hosted by country $r\left(r = 1,2,\cdots,m\right)$ are $\mathbf{C}_r^{host} = \mathbf{E}\mathbf{B}_r^F\mathbf{O}_r^F$. The change in the carbon footprints of MNEs hosted by country r over a period is

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

This study first deflates the input-output tables to the constant price and then adopts structural decomposition analysis (SDA) to analyze the driving factors of the carbon footprints of the MNEs hosed by each country. There are different decomposition approaches[57], and this study adopts the two polar decomposition approach[32,58–60], the average of which can be viewed as an approximation of the average of all equivalent decompositions[61]. The change in the carbon footprints of MNEs can be expressed as

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

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

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

$$\mathbf{C}_s^{home} = \sum_{r,i} \frac{t_{sr,i}}{\sum_k t_{kr,i}} \mathbf{C}_{r,i}^{host} \tag{10}$$

This study mainly focuses on the carbon footprints of MNEs, which are defined as firms that engage in FDI and own or control value-adding activities in more than one country[62]. Therefore, we think that the FDI is the closest indicator for estimating the production of MNEs' foreign affiliates. However, one limitation of using FDI as the indicator is that firms' carbon emissions in a year are related not only to the FDI in that year but also to the FDI in the previous years. To deal with this problem, we use the stock of FDI as the indicator rather than the flow or income of FDI in a specific period[63]. The advantage of using the FDI stock as an indicator is that it captures the accumulated investment. The drawback of using the FDI stock as an indicator is that it fails to reflect the different production technologies of firms owned by different countries. For instance, Bloom et al., (2012) noted that US MNEs obtain higher productivity from their information technologies capital than European MNEs[64]. It is difficult to solve this problem by choosing an alternative indicator because the sector homogeneity assumption of the input-output model determines that we have to assume that foreign-owned firms in an industry have the same production technology and carbon intensity. Therefore, the FDI stock matrix is a suitable indicator for this study

Data & code availability statement

Data availability

This study uses a newly published time-series inter-regional input-output table[65] that is constructed by the Organization for Economic Co-operation and Development (OECD) and captures firm heterogeneity for sixty regions（http://www.oecd.org/sti/ind/analytical-AMNE-database.htm）. The other data adopted by this study are bilateral FDI stock data from the OECD (https://www.oecd-ilibrary.org/finance-and-investment) and the United Nations (https://unctad.org/en/Pages/DIAE/FDI%20Statistics/FDI-Statistics-Bilateral.aspx)[65,66], sectoral CO_2 emissions data from the International Energy Agency (https://www.iea.org/data-and-statistics)[67], and emissions data of selected MNEs from their sustainability reports (**SI3**). Those data can be freely downloaded as public data. We also provide a detailed explanation on these data in Supporting Information.

Code availability

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

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