Growth in emission transfers via international trade from 1990 to 2008

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Despite the emergence of regional climate policies, growth in global CO_2 emissions has remained strong. From 1990 to 2008 CO_2 emissions in developed countries (defined as countries with emission-reduction commitments in the Kyoto Protocol, Annex B) have stabilized, but emissions in developing countries (non-Annex B) have doubled. Some studies suggest that the stabilization of emissions in developed countries was partially because of growing imports from developing countries. To quantify the growth in emission transfers via international trade, we developed a trade-linked global database for CO_2 emissions covering 113 countries and 57 economic sectors from 1990 to 2008. We find that the emissions from the production of traded goods and services have increased from 4.3 Gt CO_2 in 1990 (20% of global emissions) to 7.8 Gt CO_2 in 2008 (26%). Most developed countries have increased their consumption-based emissions faster than their territorial emissions, and non–energy-intensive manufacturing had a key role in the emission transfers. The net emission transfers via international trade from developing to developed countries increased from 0.4 Gt CO_2 in 1990 to 1.6 Gt CO_2 in 2008, which exceeds the Kyoto Protocol emission reductions. Our results indicate that international trade is a significant factor in explaining the change in emissions in many countries, from both a production and consumption perspective. We suggest that countries monitor emission transfers via international trade, in addition to territorial emissions, to ensure progress toward stabilization of global greenhouse gas emissions.

carbon footprint | carbon leakage | emissions embodied in trade | input-output analysis | emission inventory

Substantial reductions in global emissions are needed to reduce the risk of "dangerous" anthropogenic climate change (1, 2). According to the United Nations Framework Convention on Climate Change (UNFCCC), the level of mitigation for an individual country should be based on "equity and in accordance with their common but differentiated responsibilities and respective capabilities" (2). This concept is implemented in the Kyoto Protocol as a fragmented, two-tier mitigation strategy in which developed countries are given a "quantified emission limitation or reduction commitment" (3) for the period 2008 to 2012, usually relative to the base year 1990. The developing countries do not have emission commitments to allow for the needed economic development. Under the Intergovernmental Panel on Climate Change (IPCC) accounting rules, mitigation only applies to "greenhouse gas emissions and removals taking place within national territory and offshore areas over which the country has jurisdiction" (4). Even though the Kyoto Protocol will soon expire (2012), it is within this context that the UNFCCC, the Kyoto Protocol, and potential future alternatives will be evaluated. In addition, regional climate policies, such as the European Union Emission Trading System, are often based—and hence evaluated—on similar underlying principles.

A challenge with a territorial-based emission accounting system in the context of a fragmented mitigation architecture is that connections between economies are not directly considered. In particular, international trade and investment flows provide a link between production and consumption in different countries. Ignoring these connections might result in a misleading analysis of the underlying driving forces of global, regional, and national emission trends and mitigation policies. In the context of international trade, the development of CO_2 emissions since 1990 can be used to illustrate this point. Global emissions have grown 39% from 1990 to 2008, with accelerated growth in the last decade (5). At the regional level, however, emissions in the group of developed countries (denoted here as Annex B countries in the Kyoto Protocol, with quantified emission limitations) have largely stabilized, but emissions in the group of developing countries have doubled (5). Emission trajectories vary for individual countries, but a general trend is that emissions have increased most in rapidly growing economies (5, 6). From this territorial perspective, developing countries have the largest share of emissions and are allocated most of the emissions growth. However, this viewpoint does not consider the connections between developed and developing countries via international trade.

Some have argued that the divergent emission trends between developed and developing countries are partially the result of a transfer of emissions between countries facilitated via rapidly growing international trade flows (5, 7). Numerous static studies exist for individual countries (8, 9) and a growing number of studies are appearing in time-series, such as China (10, 11) as a net exporter and the United Kingdom (12, 13) and the United States (14) as net importers. Global models have provided more country detail, but lack the ability to consistently track changes over time (15–19). All these studies show a growing importance of international trade in regional emissions trends and indicate strong regional disparities, with most developed countries as net importers of emissions and most developing countries as net exporters. If such studies are found to be robust across more countries and over relevant time periods, then growth in international trade may facilitate emission reductions for net importers (currently developed countries) and emission increases in net exporters (currently developing countries).

The aims of this study are to quantify the role of international trade in global, regional, and country emission growth and to determine if changes in international trade may have facilitated emission reductions in developed countries. We construct an annual time-series from 1990 to 2008 of CO_2 emission inventories based on consumption by adjusting territorial emission inventories with estimates of the net emission transfers via international trade (20). The net emission transfers represent the CO_2 emissions in each country to produce exported goods and services minus the emissions in other countries to produce imported goods and services, and are sometimes called the "balance of emissions embodied in trade" (21). For the figures and tables, our sign convention is as for an economic balance of trade:

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net exporters are positive (surplus) and net imports are negative (deficit). Throughout the text we explicitly indicate the direction of net emission transfers and report positive values only.

Our analysis is global but disaggregated into 113 regions (including 95 individual countries), each with 57 economic sectors. We use two detailed attribution methods (20) for the years 1997, 2001, and 2004, and develop a method to construct annual estimates from 1990 to 2008 (see *Materials and Methods*). All three methods include the emissions that occur in the supply chain to produce consumed goods and services (22) (e.g., products produced in China but consumed in Europe). The detailed models are more accurate and cover domestic supply chains (15) (emissions embodied in bilateral trade, EEBT) or global supply chains (16, 17) (multiregional input-output, MRIO). We use both methods as they address different perspectives on allocating the emissions from international trade (20). The full-time series from 1990 to 2008 (time-series with trade, TSTRD) is based on gross domestic product (GDP), bilateral trade, and emission statistics from established global datasets and is calibrated to the EEBT method based on the proxy years 1997, 2001, and 2004 (see *Materials and Methods*). Although the proxy years 1997, 2001, and 2004 are more detailed and accurate, the TSTRD method allows the assessment of trends over long time periods and to more recent years. We focus on CO_2 emissions from fossil-fuel combustion, cement production, and gas flaring (23) because of the absence of detailed time-series data on land-use change and other greenhouse gas emissions with the necessary detail.

Results

Global CO_2 emissions from the production of exported products have increased from 4.3 Gt CO_2 in 1990 (20% of global CO_2 emissions) to 7.8 Gt CO_2 in 2008 (26% of global CO_2 emissions) (Table 1). This increase makes CO_2 emissions from the production of exported products similar in magnitude to land-use change-related emissions (5). Moreover, from 1990 to 2008, emissions from the production of exported products grew 4.3% per year, faster than the growth in global population (1.4% per year), CO_2 emissions (2.0% per year), GDP (3.6% per year), but slower than the dollar value of international trade (12% per year) (Fig. 1). Although there has been strong growth in international trade at the aggregated level, the structure of international trade has also changed. Combined with different emission intensities in different regions, the changes in international trade structure and volume indicate large regional shifts in the location of emissions from the production of goods and services and the location of consumption. We analyze these regional shifts using the concept of net emission transfers as defined earlier and discussed in the *Materials and Methods*. First, we consider net emission transfers in the context of developed (Annex B) versus developing (non-Annex B) countries, and then at the regional and country level.

The net emission transfers from non-Annex B to Annex B has grown from 0.4 Gt CO_2 in 1990 to 1.6 Gt CO_2 in 2008 (17% per year average growth) (Fig. 2 and Table 1). Emission transfers from non-Annex B to other non-Annex B countries have grown fastest, followed closely by the emission transfers from non-Annex B to Annex B countries (Fig. 1, Table 1, and *SI Appendix*, Fig. S9). For comparison, if the average emission reduction target for Annex B countries in the Kyoto Protocol (~5% reduction of 1990 emissions) is applied to CO_2 emissions only, representing ~0.7 Gt CO_2 per year, then the net emission transfers from non-Annex B to Annex B countries is 18% higher on average (1990–2008) and 130% higher in 2008. Because estimated Annex B emission reductions from 1990 to 2008 are only ~2%, representing 0.3 Gt CO_2, the net emission transfers from non-Annex B to Annex B countries is 520% higher in 2008. Cumulatively, we find that international trade has relocated 16 Gt CO_2 from Annex B to non-Annex B countries from 1990 to 2008. If historic trends continue linearly (Fig. 2), the net emission transfers from the group of non-Annex B countries to Annex B countries will be around 2.3 Gt CO_2 per year in 2020, representing 16% of Annex B emissions in 1990. This finding is comparable to the most optimistic 2020 emission limitations offered by Annex B countries in the Copenhagen Accord (24).

For the years 1997, 2001, and 2004, we have more detailed and robust datasets that allow comparisons with the time-series method, TSTRD. We find that the more detailed methods increase the estimated net emission transfers from non-Annex B to Annex B countries (Fig. 2), signifying that the TSTRD method produces conservative estimates. For the 3 y where all methods overlap, 24% (TSTRD), 25% (EEBT), and 33% (MRIO) of the growth of non-Annex B emissions can be assigned to Annex B consumption. The results are higher for the MRIO method, because it considers not only the trade activities between two individual countries, but also the trade through multiple countries until the final product is delivered to consumers (16, 20). Comparisons of the TSTRD and EEBT methods with the MRIO method consistently show that including the global supply chain attributes more non-Annex B emissions to Annex B countries compared with methods that do not fully consider the role of emissions-associated imports, which are then used to produce exports (*SI Appendix*). This finding indicates the growing importance of trade between non-Annex B

Table 1. Allocation of global emissions to Annex B and non-Annex B countries separated into domestic and internationally traded components

	Component	1990 (Gt CO_2)	2008 (Gt CO_2)	Growth (%/y)
Annex B				
Domestic	Annex B Domestic (Bdom)	11.3	10.8	−0.3
Trade component	Annex B to Annex B (B2B)	2.1	2.2	0.2
	Annex B to non-Annex B (B2nB)	0.7	0.9	1.8
Production	Annex B production (Bprod = Bdom + B2B + B2nB)	14.2	13.9	−0.1
Consumption	Annex B consumption (Bcons = Bdom + B2B + nB2B)	14.5	15.5	0.3
Non-Annex B				
Domestic	Non-Annex B domestic (nBdom)	6.2	11.7	4.6
Trade component	Non-Annex B to Annex B (nB2B)	1.1	2.6	7.0
	Non-Annex B to non-Annex B (nB2nB)	0.4	2.2	21.5
Production	Non-Annex B production (nBprod = nBdom + nB2B + nB2nB)	7.7	16.4	5.9
Consumption	Non-Annex B consumption (nBcons = nBdom + B2nB + nB2nB)	7.4	14.8	5.3
Trade totals	Traded emissions (B2B + B2nB + nB2B + nB2nB)	4.3	7.8	4.3
	Trade balance (B2nB − nB2B)	−0.4	−1.6	16.9
	Global emissions (Bprod + nBprod = Bcons + nBcon)	21.9	30.3	2.0

Annex B components: Bdom, emission to produce and consume goods and services in Annex B countries; B2B, production in one Annex B country with consumption in another Annex B country; B2nB, production in an Annex B country with consumption in a non-Annex B country. Likewise for non-Annex B countries (nBdom, nB2B, nB2nB). The full time series 1990 to 2008 and results for the detailed methods for 1997, 2001, and 2004 are in the *SI Appendix*, Dataset S1.

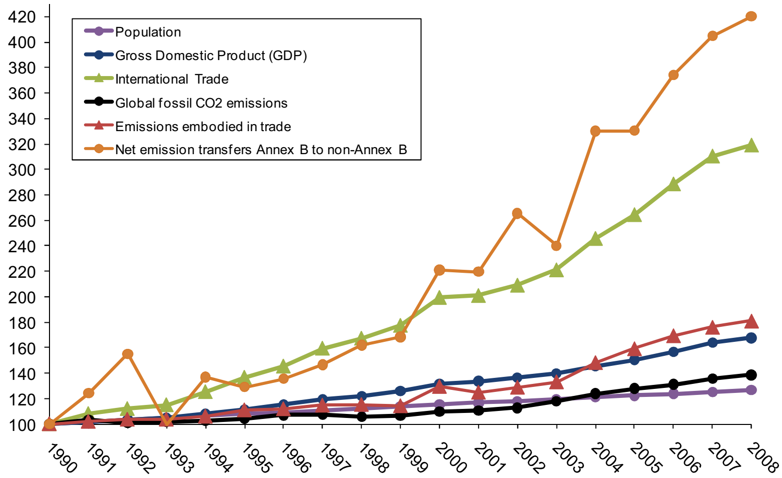

Fig. 1. The development of various global macrovariables indexed to 1990. Source: Population (US Census Bureau), GDP, and international trade in constant prices (United Nations National Account Estimates of Main Aggregates), fossil-fuel and process emissions (Carbon Dioxide Information Analysis Center) (23), emissions embodied in global trade (present study), and the net emission transfers between Annex B and non-Annex B countries (present study).

countries in the production of goods consumed in Annex B countries (25).

When the reported territorial emissions are adjusted for net emission transfers, a consumption-based emission inventory is obtained (analogous to a carbon footprint for CO_2 only) (20, 26) (*SI Appendix*, Figs. S10 and S11). For individual countries, a shift to consumption-based emissions often changes the emission ranking of countries. For example, China is the largest emitter of CO_2 emissions with a territorial-based inventory, with the United States second, but with a consumption-based inventory the United States is first and China second (*SI Appendix*, Fig. S11). Most developed countries increase their ranking with a consumption-based inventory (*SI Appendix*, Dataset S1). Globally, all territorial emission growth has taken place in the group of non-Annex B countries, despite variations in individual Annex B and non-Annex B countries (5). However, the difference between Annex B consumption-based emissions and territorial emissions is growing over time (Fig. 2 and *SI Appendix*, Fig. S10). In terms of consumption-based inventories, 11% of the growth in global CO_2 emissions can be attributed to Annex B consumption (instead of a 3% reduction for territorial). Thus, a significant share of the growth in Annex B consumption since 1990 is reported in the emission statistics of non-Annex B countries. This share would be further increased if a share of capital formation was allocated to exports instead of considering capital as domestic consumption only (27, 28).

Within the group of Annex B nations, territorial emission reductions and changes in net emission transfers with non-Annex B countries have varied. Fig. 3 compares the change in net emission transfers for selected countries with the estimated change in territorial emissions from 1990 to 2008 and the Kyoto Protocol reduction commitments. In all cases shown, net emission transfers have grown over time, despite variations in the change in territorial emissions. The United States has increased emissions 17%, despite a pledge to reduce emissions by 7% (3), yet at the same time the change in emission transfers have additionally supported increased consumption in the United States. Similarly, with a 6% reduction in territorial emissions, Europe is close to meeting its Kyoto Protocol target of an ~8% reduction (3); however, the additional net emission transfers from non-Annex B countries are larger than these reductions. The remainder of the non-Annex B countries have had a substantial reduction in territorial emissions (−16%), primarily because of the collapse of the Russian Federation and Ukraine in the early 1990s. However, even in this case, the net emission transfers with non-Annex B countries have increased over time. Collectively, the net CO_2 emission reduction of ~2% (0.3 Gt CO_2) in Annex B countries from 1990 to 2008 is much smaller than the additional net emission transfer of 1.2 Gt CO_2 from non-Annex B to Annex B countries (equivalent to subtracting the net emission transfers in 2008 from 1990 in Fig. 2).

Fig. 4 shows the total emission transfers for six aggregated regions (exports and imports shown separately in *SI Appendix*, Figs. S4 and S5) for both Annex B and non-Annex B countries. The net emission transfers via international trade are shown between each region with all other regions (black line) and the net emission transfers between the United States, Europe, and the rest of Annex B with the non-Annex B countries (dotted black line). Consistent with other studies, we find particularly rapid growth in Chinese exported emissions (10, 11). Our results show that Chinese emissions accounted for 55% of the growth in global

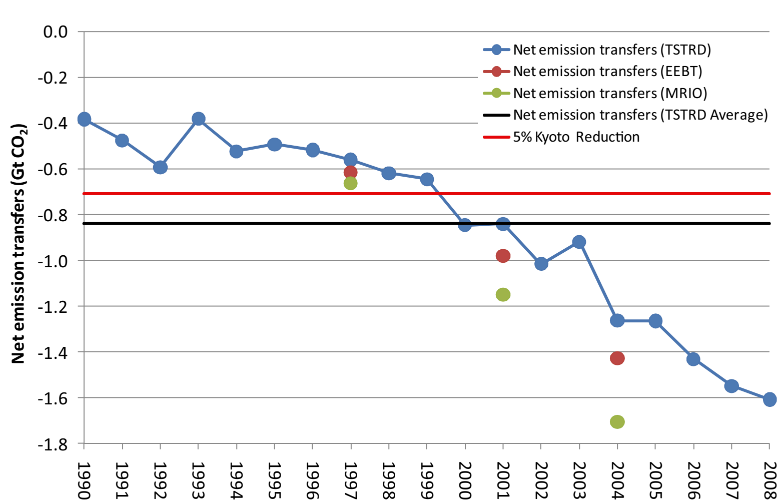

Fig. 2. The net emission transfers between non-Annex B and Annex B countries using the TSTRD, EEBT, and MRIO methods. The change in the net emission transfers over time are compared with the Kyoto Protocol emission reduction target of ~5% relative to 1990 (red line) and the average net emission transfer from 1990 to 2008 (black line). The EEBT and MRIO methods give a larger net emission transfer from non-Annex B to Annex B countries, signifying that the TSTRD method is conservative. The MRIO is larger than the EEBT method as the MRIO considers global supply chains (see text).

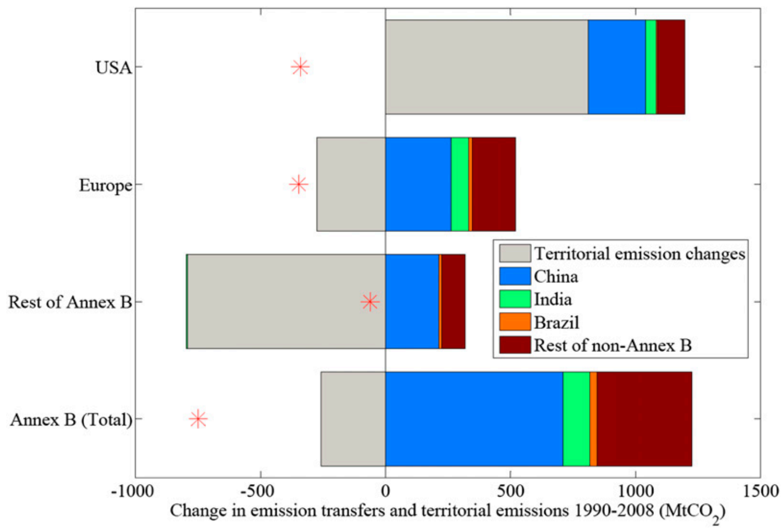

Fig. 3. The net change in territorial emissions (1990–2008) together with the change in the net emission transfer between each country and non-Annex B countries (1990–2008). The red stars represent pledged emission reduction commitments in the Kyoto Protocol. Emission transfers between Annex B countries have been removed, as these emissions are already covered in the Kyoto Protocol. Europe represents the Annex B EU27 countries plus Croatia, Iceland, Liechtenstein, Norway, and Switzerland.

CO_2 emissions from 1990 to 2008 and the production of Chinese exports accounted for 18% of the growth in global CO_2 emissions. Furthermore, the production of Chinese exports later exported to Annex B countries accounted for 75% of the growth in Annex B consumption-based emissions. We also identify large growth in the emissions from the production of exports in other non-Annex B countries and, as with China, a considerable share of the growth is toward other non-Annex B countries. The United States has shown rapid growth in imported emissions, largely because of China and other developing nations (14). Because of the collapse of the former Soviet Union, Europe had a drop in net emission transfers with the rest of the world in the mid 1990s, despite strong growth from 1990 to 2008 in emission transfers with non-Annex B countries (as for the United States). The remainder of the Annex B countries have had strong growth in imported products, despite including net exporters such as Australia, Ukraine, and the Russian Federation, with net importers, such as Japan. *SI Appendix*, Dataset S1 has detailed results for 95 individual countries from 1990 to 2008.

In terms of sector contributions, 40% of the emissions from the production of traded products at the global level are because of energy-intensive industries (cement, steel, pulp and paper, and so forth) and this has been stable from 1990 to 2008 (*SI Appendix*, Fig. S6). Non–energy-intensive manufacturing (textiles, electronics, furniture, cars, and so forth) accounts for a growing and substantial share at 30% of global exported emissions in 2008, rising from 24% in 1990 (*SI Appendix*, Fig. S6). There has been a strong growth in the export of both energy-intensive and non–energy-intensive products from non-Annex B to Annex-B countries (*SI Appendix*, Fig. S7), accounting for most of the change in emission transfers from 1990 to 2008 (Fig. 5). International trade in non–energy-intensive manufactured products dominates the net emission transfers (accounting for 41% of the growth), despite the policy focus on energy-intensive manufacturing. In the early 1990s, Annex B countries were small net exporters of emissions from energy-intensive manufacturing, but because of strong growth in imports (accounting for 35% of the growth) they are now substantial net importers.

Discussion

Our analysis shows that a significant and growing share of global emissions are from the production of internationally traded goods and services. Although this finding may follow directly from increases in international trade itself, it could have unintended

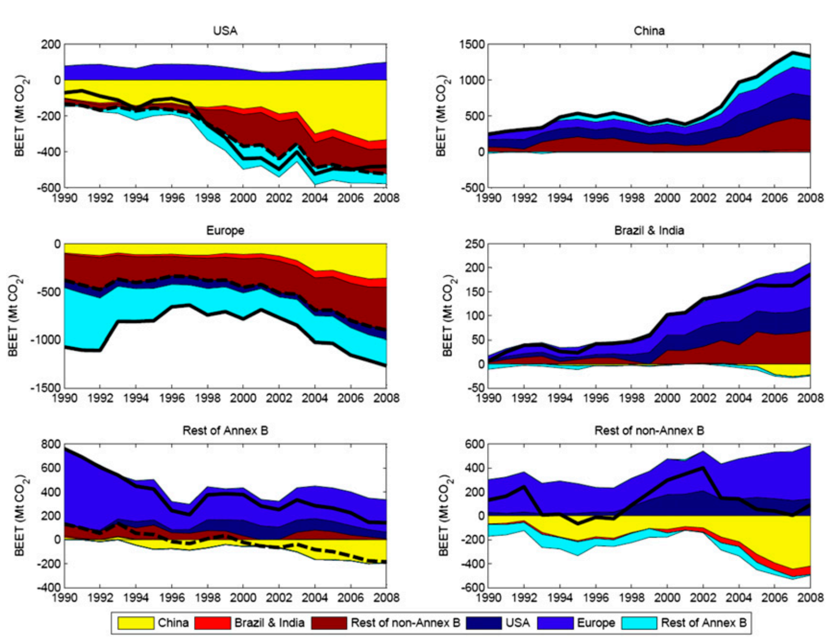

Fig. 4. The development of the net emission transfer via international trade between Annex B and non-Annex B countries for six aggregated regions from 1990 to 2008 using the TSTRD method. Net emission transfers represent the emissions from the production of exports (*SI Appendix*, Fig. S4) minus the emissions in other countries from the production of imports (*SI Appendix*, Fig. S5). The colored areas are the emission transfers for each region, the solid black line is the net emission transfers for each region with the rest of the world, and the dashed black line is the net emission transfers for the Annex B with non-Annex B countries (comparable with Fig. 2).

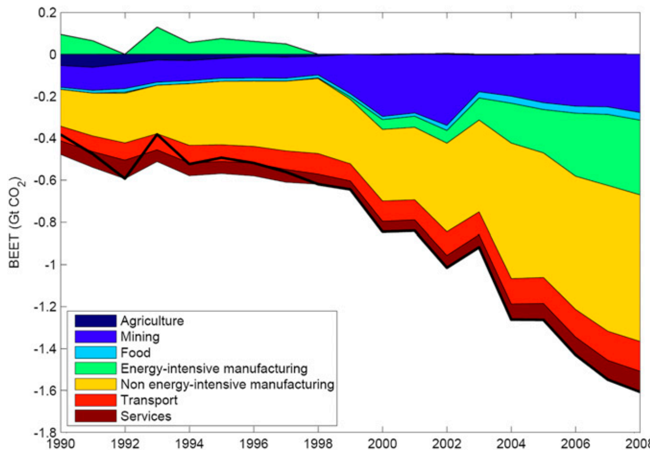

Fig. 5. The development of the net emission transfer via international trade between Annex B and non-Annex B countries for seven aggregated sectors from 1990 to 2008 using the TSTRD method. Net emission transfers represent the emissions from the production of exports minus the emissions in other countries from the production of imports (*SI Appendix*, Fig. S7). The solid black line is the net emission transfers for Annex B and non-Annex B countries (compare with Fig. 2) and the colored areas are the balance for each sector.

consequences for climate policy, as it leads to a spatial disconnect between the point of consumption and the emissions in production. Under the IPCC accounting rules of only reporting territorial emissions, many developed countries have reported stabilized emissions. However, our results show that the global emissions associated with consumption in many developed countries have increased with a large share of the emissions originating in developing countries. This finding may benefit economic growth in developing countries, but the increased emissions could also make future mitigation more costly in the developing countries. In addition, we find that the emission transfers via international trade often exceed the emission reductions in the developed countries. Consequently, increased consumption in the Annex B countries has caused an increase in global emissions contrary to the territorial emission statistics reported to the UNFCCC.

Our analysis indicates that the emission transfers reflect macroeconomic imbalances of the world economy, which are caused by a multitude of socioeconomic drivers and policies. Although growth and structural changes in international trade are important, our analysis does not determine what factors cause these changes. Apportioning changes in emission transfers to specific policies requires additional modeling. Based on existing general computable equilibrium studies of (strong) carbon leakage, it is likely that existing national or regional climate policies themselves—such as the European Emission Trading Scheme—have had a minimal effect on international trade (29, 30). If these modeling studies are robust, they suggest that other economic and policy factors have determined past production decisions (and hence emission transfers), which is also consistent with the broader literature on this topic (31–36). Based on this theory, the likely cause of the large emission transfers we report here are preexisting policies and socioeconomic factors that are unrelated to climate policy itself. As an example, we find that both the United States and European Union have had a large increase in net emission transfers, but only the European Union has a broad-based climate policy. Net emission transfers, which are independent of the policy and socioeconomic drivers, are often called weak carbon leakage (as opposed to strong carbon leakage) (15, 16, 37, 38), although others have used demand-driven displacements (as opposed to policy-induced displacement) (39).

Given that emission transfers via international trade are a significant and growing share of country, regional, and global emissions, we suggest that policies that affect international trade should not be continually separated from climate policy, particularly in the context of a fragmented mitigation architecture (as in the Kyoto Protocol). Our results do not directly imply that a fragmented mitigation architecture is not effective at reducing global emissions, but they do suggest caution is required if there is rapid and differential growth in emission transfers as we report here. Even if these emissions have not been induced by climate policies, careful analysis may be required to determine if changes in international trade might influence the mitigation costs and strategies when a fragmented mitigation architecture is in place.

Although there may be many mechanisms to address emission transfers via international trade in climate policy, as a first step we suggest that Annex B and other key countries regularly compile emission statistics for international trade and consumption-based inventories (7, 20, 26) overseen and monitored, as for existing territorial emission statistics (e.g., IPCC and UNFCCC). In early stages, reporting may be limited in country and temporal coverage, but as data and methods improve reporting can become more regular and widespread. The method we use here allows updated and regular monitoring to track recent trends, and can be followed up with more detailed and accurate studies as new data are released. Although some argue that the calculation of consumption-based emissions is too difficult and uncertain at the national level, evidence suggests otherwise. The data and methods have existed for decades (8, 9, 22, 26, 40) and are the foundation of the System of National Accounts compiled by most countries. Even though uncertainty is higher for consumption-based emissions compared with territorial emissions (41), the absolute values and trends are robust across data, methods, and independent studies (8, 9). Although we believe that territorial emission statistics should still remain central to climate policy, our results show a need for a regular monitoring, verification, and reporting of emission transfers via international trade.

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Materials and Methods

For a given country, r, our analysis follows trends in territorial-based emissions (production, P^r) and consumption-based emissions, C^r. The territorial emission inventories cover CO_2 emissions from fossil-fuel combustion, cement production, and gas flaring (23). We do not include emissions from land-use change, as the data are not available in the necessary detail, although this is an area of current research. We define the difference between the territorial- and consumption-based emissions a "net emission transfer," $T^r = P^r - C^r$. The net emission transfer can be expressed equivalently in terms of "emission transfers," $T^r = E^r - M^r$, where E^r are the emissions in r to produce exports and M^r are the emissions outside of r to produce imports (20, 38). The emission transfers (or embodied emissions) are not a physical part of the exports but, rather, are emitted in the production of the exports. If T^r is negative then r is a net importer of embodied emissions, and if positive then r is a net exporter. To facilitate a comparison of how P^r and C^r change over time, we analyze the net emission transfers, T^r. If T^r becomes increasingly negative, then C^r grows faster than P^r; if T^r becomes increasingly positive, then P^r grows faster than C^r. We often reference the net emission transfers to 1990, $\Delta T^r(t) = T^r(t) - T^r(1990) = [P^r(t) - C^r(t)] - [P^r(1990) - C^r(1990)] = [P^r(t) - P^r(1990)] - [C^r(t) - C^r(1990)] = \Delta P^r(t) - \Delta C^r(t) = \Delta E^r(t) - \Delta M^r(t)$. Thus, if $\Delta T^r(t)$ is negative, then C^r (or M^r) has grown more than P^r (or E^r) relative to 1990. We also compare emission transfers between developed and developing countries only, $T^{rs} = E^{rs} - M^{rs}$, where r may represent an Annex B country and s a non-Annex B country.

We use three different methods to construct the consumption-based emission inventories, C^r, for CO_2 by adjusting established territorial emission inventories with estimates of emission transfers via international trade. We use two detailed attribution methods for the years 1997, 2001, and 2004, and develop a method to construct annual estimates from 1990 to 2008. All three attribution methods include the emissions that occur in the supply chain to produce consumed goods and services (e.g., products produced in China, but consumed in Europe). Allocation along the supply chain is based on a well-established method, environmentally extended input-output analysis (22), but applied for multiple regions (20). The first method, EEBT, enumerates the domestic supply chain and considers total bilateral exports (15, 20). We repeat our earlier analysis using 2001 data (15) to additionally cover 1997 and 2004 using different releases of the Global Trade Analysis Project (GTAP) database (42). The second method, MRIO analysis, further disaggregates the EEBT method into globally connected supply chains by treating final consumption as exogenous and international trade for intermediate consumption as endogenous (16, 17, 20). The MRIO and EEBT methods give the same global emissions, but distinct regional emissions because of the different allocation of intermediate consumption (20). We present the results from both approaches as they provide different perspectives of how to allocate the emissions from international trade to countries (*SI Appendix* and ref. 20). As for the EEBT method, we repeat our earlier MRIO analysis using 2001 data (17) to additionally cover 1997 and 2004 using different releases of the GTAP databases (42). We scale the GTAP CO_2 data to match our territorial emission database (23) and further overwrite the emissions in some countries using more accurate data wherever possible (*SI Appendix*). Details on the particular method and data used in this article can be found in our previous work (15, 17, 20, 43) and *SI Appendix*.

Because it is resource-intensive to construct detailed datasets on an annual basis (42), in this article we develop a method for annual estimates of the emissions embodied in international trade and consumption-based emission inventories from 1990 to 2008 using more aggregated information (time-series with trade). The TSTRD method is based on widely available GDP, bilateral trade, and emission statistics from established global datasets and is calibrated to the simpler and more related EEBT method. We use a two-step process. Our estimates start with GDP data by final expenditure from the United Nations Statistic Division (UNSD) National Accounts Main Aggregates Database and territorial emission estimates (23). We use the GDP data to construct a one-sector input-output table analogous to the EEBT method. It is not possible to use the GDP data directly as it does not represent the supply chain nor the different emission intensities in different economic sectors. We use the EEBT method in 1997, 2001, and 2004 as proxies to estimate the industry consumption of imports and the supply-chain emission in each country and each sector, and apply it to the TSTRD method: 1990 to 1998 (1997 EEBT estimates), 1999 to 2002 (2001 EEBT estimates), and 2003 to 2008 (2004 EEBT estimates). Our results are not significantly affected by using different base years as the proxy for the other years. The TSTRD method is calibrated to the EEBT method in common years 1997, 2001, and 2004. In some countries there are small differences in estimates from EEBT and TSTRD because of different GDP data in GTAP and UNSD. The second and final step of the TSTRD method is to distribute the estimated emissions from the production of exports to receiving countries. We do this distribution after weighting the harmonized GTAP time-series trade data (42) with sector and region emission intensities from the EEBT method: 1990 to 1998 (1997 EEBT estimates), 1999 to 2002 (2001 EEBT estimates), and 2003 to 2008 (2004 EEBT estimates). We performed a variety of comparisons of the EEBT and TSTRD methods and found the results to be consistent with available evidence. Details on the method and method comparisons can be found in the *SI Appendix* and *SI Appendix*, Dataset SI.

Our analysis has uncertainties in both the input data and model calculations (*SI Appendix*). The territorial emission estimates are the most certain (23) and uncertainty increases as we disaggregate the results into regions and sectors (41). Because of averaging of errors, uncertainty decreases as we again aggregate the results (41). Despite large potential uncertainties, there is not a strong tradition of performing uncertainty analysis in input-output analysis because of the relative lack of information on uncertainty distributions (44). Instead, we do a model comparison across a variety of independent studies and find sufficient agreement to support our findings (*SI Appendix*).

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