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International trade undermines national emission reduction targets: New evidence from air pollution

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ABSTRACT

Many developed countries in Annex B of the Kyoto Protocol have been able to report decreasing emissions, and some have officially fulfilled their CO_2 reduction commitments. This is in part because current reporting and regulatory regimes allow these countries to displace emissions intensive production offshore. Using a new highly detailed account of emissions embodied in international trade we investigate this phenomenon of emissions leakage. We independently confirm previous findings that adjusting for trade, developed countries emissions have increased, not decreased. We find that the sectors successfully holding or lowering their domestic emissions are often the same as those increasing their imports of embodied CO_2. We also find that the fastest growing flow paths of embodied CO_2 largely originate outside the Kyoto Annex B signatory nations. Finally, we find that historically the same phenomenon of emissions displacement has already occurred for air pollution, with the result that despite aggressive legislation in major emitters total global air pollution emissions have increased. If regulatory policies do not account for embodied imports, global emissions are likely to rise even if developed countries emitters enforce strong national emissions targets.

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1. Introduction

The shifting of CO_2 emissions from developed to developing countries is a substantial and growing problem. CO_2 leakage was not formally addressed in the initial Kyoto Protocol discussions as it was anticipated to be a minor issue or one to be addressed later (Intergovernmental Panel on Climate Change, 1995). However estimates now indicate that it is not minor, and that up to 30% of global emissions are linked to production for export (Aichele and Felbermayr, 2012; Andrew et al., 2013; Caldeira and Davis, 2011; Chen and Chen, 2011; Hertwich and Peters, 2009; Nakano et al., 2009; Peters and Hertwich, 2008b; Peters et al., 2011a, 2011b). A consumption-based inventory of the UK found that growing consumption in the country was supplied by emissions-intensive imports, not new domestic production. Consequently the UK's total carbon footprint increased 12% between 1992 and 2004, not decreased by 5% as its territorial emissions inventory showed (BBC News, 2008; Wiedmann et al., 2008, 2010). A recent UK study recommended that consumption-based inventories be constructed as a complement to current territorial emissions inventories (Barrett et al., 2013). In China, estimates show that in 2005 nearly 30% of emissions were linked to production for export (Feng et al., 2013; Weber et al., 2008). Since export production has played a major role in its emissions growth (Minx et al., 2011), China has argued that responsibility for emissions should lie not just with the producer but also with the final consumers of goods (BBC News, 2009; Information Office of the State Council of China, 2011; Leggett, 2011). For nearly all large economies the discrepancy between their territorial emissions and their actual carbon footprint is growing.

This study uses a new set of high-resolution global multi-region input–output (MRIO) tables (Lenzen et al., 2012a, 2013b) to investigate flows of embodied CO_2 and air pollution over time. The Eora tables provide high sector detail, cover 187 countries, and offer a true, not interpolated or proxy-estimated, timeseries from 1970 to 2011.

Here we present several findings. First, we are able to independently confirm previous findings that adjusting for trade, developed countries emissions have increased, not decreased. Independent confirmation of this result is important given the prominence of consumption-based accounting in setting national and international GHG reduction targets. Our inventories also consider non-CO_2 GHGs, and we confirm the burden-shifting effect is similar, or stronger, for these gasses. Second, we find that the sectors successfully holding or lowering their domestic emissions are the often the same as those increasing their imports of embodied CO_2. This suggests that it is not cleaner production or

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consumption patterns that are reducing domestic emissions, but simply burden-shifting of the same emissions-intensive activities. Third, we find that 72% of the 200 fastest-growing flows of embodied CO_2 originate outside the Kyoto Annex B signatory nations. These fastest growing flows transport embodied emissions from developing countries both to developed and other developing countries. Finally, we find that historically the same phenomenon of emissions displacement has already occurred for air pollution. The result has been that despite aggressive legislation of SO_2, NO_x and PM_{10} in major emitters, total global air pollution emissions have increased.

2. Materials and methods

All results are based on the Eora environmentally extended multi-region input-output (MRIO) table (Lenzen et al., 2012a, 2013b) and are available online at http://worldmrio.com. Input–output tables have long been used to re-attribute pollution from production to final consumers (Kanemoto et al., 2012; Lenzen et al., 2004; Leontief and Ford, 1971; Peters, 2008; Wiedmann, 2009), including for calculating carbon footprints. Eora is one of a new generation of such systems robust enough for policy use (a survey of current systems is provided by Tukker and Dietzenbacher, 2013 and Wiedmann et al., 2011). Eora advances the state of the art by covering all UNFCCC countries – not just regions or a subset of countries – and provides a consistent, accurately modeled time series from 1970 to 2011, significantly improved detail, non-CO_2 emissions, and confidence estimates for all results. While it has been shown that increasing the resolution of embodied CO_2 models does not alter the basic results (Davis and Caldeira, 2010; Peters et al., 2012), accurate models with complete country coverage are required for policy applications.

The MRIO table can be used to estimate consumption-based inventories of CO_2 and other greenhouse gas emissions. Eora covers 15,909 sectors across 187 countries with IO tables modeled for each year and thus offers substantially more breadth, detail, and accuracy than has yet been achieved. The Eora MRIO also incorporates data on trade in services. However these data are often less detailed and thus the MRIO model has higher uncertainty about embodied emissions transfers due to trade in services. Another limitation of the model used in this study is poorer data availability in 1970–1989. The MRIO in those years is built using the 1990 MRIO table as an initial template then using the constrained optimization method described in (Lenzen et al., 2012a) with UNSNA MA and OC data as constraints.

The Leontief demand-pull model used to construct consumption-based inventories is a workhorse model that has been well described since its introduction (Leontief, 1986; Leontief and Ford, 1970). For a detailed explanation of how this model is implemented with the Eora MRIO the reader is referred to previously published descriptions (Lenzen et al., 2012b, 2013a). Briefly, the method proceeds as follows. Territorial environmental emissions F can be decomposed into consumption-based environmental emissions and embodied environmental emissions in export and import for country S using an MRIO table following Kanemoto et al. (2012):

$$\underbrace{F_j^s}_{\text{production}} \quad \sum_r f_i^r \left[\underbrace{\sum_{it} L_{ij}^{rt} y_j^{ts}}_{\text{consumption}} - \overbrace{\underbrace{\sum_{it \neq s} L_{ij}^{rt} y_j^{ts}}_{\text{imports}} + \underbrace{\sum_{it \neq s} L_{ij}^{rs} y_j^{ss}}_{\text{exports}}}^{\text{net trade balance}} \right]$$
$$= \sum_r f_i^r \left[\sum_i L_{ij}^{rs} y_j^{ss} + \sum_{it \neq s} L_{ij}^{rs} y_j^{st} \right] = \sum_r f_i^r \sum_{it} L_{ij}^{rs} y_j^{st}$$

where f is emissions intensity, r is the emitter country, L is the Leontief inverse, y is final demand, and i and j are the sectors of origin and destination. "Consumption" covers consumption-based emissions and "imports" means the embodied emissions in imports, where t is the supplying (most recent seller) region and s is the destination country (region). "Exports" covers embodied emissions in exports where s is the last selling and t is the destination region.

Rather than relying on just one emissions data source Eora provides an timeseries of GHG gas and air pollutant emissions built on multiple data sources including: GHG data from the Emission Database for Global Atmospheric Research (EDGAR), the Carbon Dioxide Information Analysis Center (CDIAC) at Oak Ridge National Laboratory, Eurostat, energy data, linked to CO_2 emissions, from the IEA/OECD, the Energy Information Administration (EIA), the United Nations Statistics Division (UNSD), and Eurostat. All results presented here for CO_2 are exclusive of emissions from land use, land-use change and forestry (LULUCF). It should be noted that Guan et al. (2012) found that official Chinese CO_2 emissions estimates may be unreliable; however to our knowledge no better alternative currently exists. Data on ozone depleting substances (ODS) emissions were sourced from the United Nations Environment Program. The full set of data sources is documented in SI S1.

3. Results and discussion

3.1. Embodied emissions undermine Kyoto targets

Using the Eora MRIO we confirm earlier findings that much of the apparent success in decreasing domestic emissions has been more than offset by an increase in embodied emissions in imports. For the USA, Japan, most EU nations, and the EU-27 as a whole, the amount of CO_2 burden shifting to developing countries exceeds the size of their Kyoto-specified emissions reduction. While territorial emissions in these countries have decreased, their total carbon footprint has increased.

According to the territorial emissions inventory developed (Kyoto Annex B listed) countries reduced emissions by 1.59 Gt and developing countries increased emissions by 13.7 Gt during the period 1990–2011. However, after assigning emissions responsibility to consumers we find that developing countries transfer 2.95 Gt of CO_2 to developed countries thorough international trade in 2011. Under a consumer responsibility principle developed countries have not recorded a decrease from 1990 levels but rather an increase.

The Kyoto Protocol Annex B signatories agreed to reduce emissions a total of 0.76 Gt (5.2%) from 1990 levels. The EU as a group has nearly succeeded in meeting its target (due both to intentional action and to economic recession) and Russia and the former Soviet states have reduced emissions even beyond their Kyoto targets. However despite these successful reductions, in 2011 1.67 Gt of CO_2 was embodied in net imports to developed countries. In many countries the magnitude of emissions transfers is on par with that of the original reduction target (Fig. 1). The United Kingdom and Poland are perhaps the most striking cases for how outsourcing emissions-intensive production has helped countries meet their targets. Both countries report reductions that exceed their Kyoto targets, however once emissions embodied in their imports are included, they no longer achieve these targets. Similar outsourcing can be observed also for countries that either have failed to meet their targets, such as the USA and Japan, or that have met their Kyoto targets even including emissions embodied in imports, such as Russia. Remarkably, in all cases, changes in emissions embodied in imports are comparable to, or larger than, changes in domestic emissions.

Non-CO_2 GHG emissions comprise 18% of total developed countries' GHG emissions yet comparatively little analysis has been presented on embodied flows of these gasses. An early study by Subak (1995) estimated international flows of CH_4, and Nijdam et al.

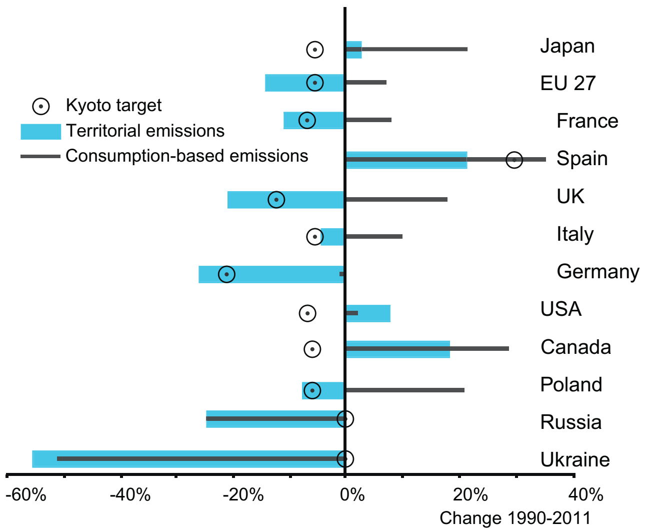

Fig. 1. Kyoto Protocol emissions targets (circles), territorial emissions (gray bars) with which progress is measured, and consumption-based emissions (black bars). Many major emitters appear to be progressing toward their Kyoto targets yet their actual carbon footprints are increasing.

(2005) calculated CO_2, CH_4, and other air pollutions embodied in international trade, but these studies did not use the more accurate global MRIO-based methods used today. Hertwich and Peters (2009) estimated CH_4 and N_2O embodied in international trade using an MRIO model but did not conduct a timeseries analysis. By constructing a time series consumption-based inventory of non-CO_2 GHGs (CH_4, N_2O, HFC-125, HFC-134a, HFC-143a, HFC-152a, HFC-227ea, HFC-23, HFC-236fa, HFC-245fa, HFC-32, HFC-365mfc, HFC-43-10-mee, C_2F_6, C_3F_8, C_4F_{10}, C_5F_{12}, C_6F_{14}, C_7F_{16}, CF_4, c-C_4F_8, SF_6) it can be see that, like CO_2, developed countries have shifted their non-CO_2 GHG emissions to developing countries. Our findings indicate that burden-shifting occurs even more strongly for non-CO_2 GHG's than for CO_2.

Fig. 2 shows this for CH_4 and N_2O emissions. The non-CO_2 emissions not only follow the CO_2 emissions trend but have more embodied emissions flowing from developing to developing countries. In 2008, 32% of the CH_4 footprint (consumption-based inventory) of developed countries came from net imports; for CO_2 that figure was just 15%.

3.2. Burden-shifting occurs in specific sectors

Examining the sectors importing/exporting embodied emissions reveals that increased embodied emissions in net imports arrive in the same sectors that are achieving domestic reductions in developed countries. For example in the UK the Electricity, Gas, and Water sector has achieved a 16% reduction in domestic CO_2 emissions (through a combination of changing demand and increasing efficiency) since 1990, yet embodied CO_2 emissions in imports in that sector rose 208% over the same period. The result is that while territorial CO_2 emissions in that sector dropped, its total carbon footprint rose 10%. As seen in Fig. 3 the composition of domestic reduction is closely matched, or exceeded, by increased embodied CO_2 in imports. This implies that rather than actually reducing their carbon footprint, for these sectors it has grown and moved abroad. This pattern is observed in many Annex B countries individually and for the Annex B countries collectively.

Emissions shifting manifests in several ways: new and existing emitters can relocate, a company can choose a different supplier to fulfill an order, or a decrease in domestic emissions can be more than compensated for by increased imports, as happens for example when an economy shifts from an industrial base to an information economy that increases physical imports to compensate for declining domestic production. The microeconomic decisions underlying emissions shifting are complex and energy and pollution costs are only some of the variables in businesses' decision-making. These decisions will also vary by type of industry. The embodied CO_2 used to manufacture a television or truck can easily be emitted abroad, but it is more difficult to relocate the GHG emissions needed to light a home or fuel a car. Yet whatever the precise mechanics of emissions shifting (explored by Arto and Dietzenbacher, 2012), the problem is growing.

It is desirable to know which particular inter-country flows and supply chains are involved in burden-shifting. Mapping the top-growing bilateral flows of embodied CO_2 emissions into and out of the USA (Fig. 4) by trade partner clearly shows a modest rise in American exports to developed countries but a large rise in imports from developing countries, particularly China and India. Embodied CO_2 flows out of China, India, Canada, Korea, Mexico, Qatar, Saudi Arabia, Indonesia, and Malaysia, and others, have grown sharply since 1990. Increases in embodied exports from the US (most substantially to China, Mexico, UK, Russia, Poland, Singapore) have been smaller. The result is a net increase in embodied imports into the US.

Flow maps such as Fig. 4 are useful for visualizing flows to or from individual countries. Fig. 5 uses the Circos data visualization tool (Krzywinski et al., 2009) to find the top 20 fastest growing inter-country flows China is a major origin point of embodied emissions flows. In addition to China's contribution to emission shifting it is possible to observe some new trends. Increases in emissions in the Russian ores and minerals sectors have been driven by higher consumption in Europe. Despite considerable economic growth during the period Australia, India, and Other Asia

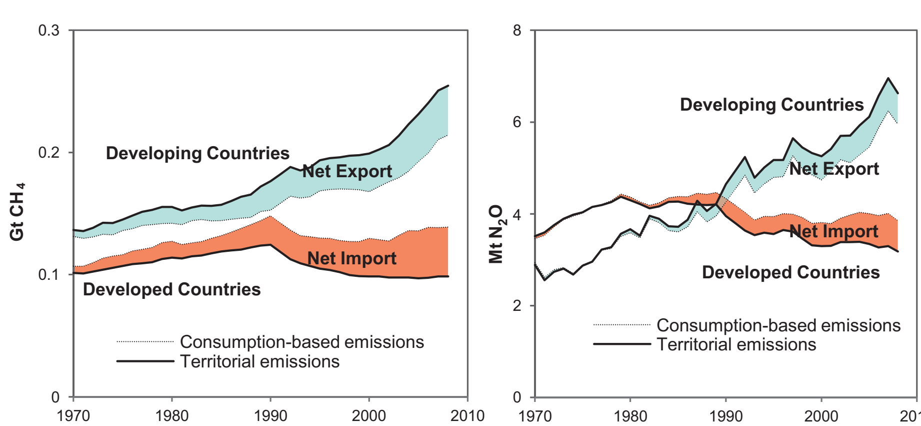

Fig. 2. (a) CH_4 emissions and transfers from developing to developed countries, 1970–2008. (b) N_2O emissions and transfers from developing to developed countries, 1970–2008.

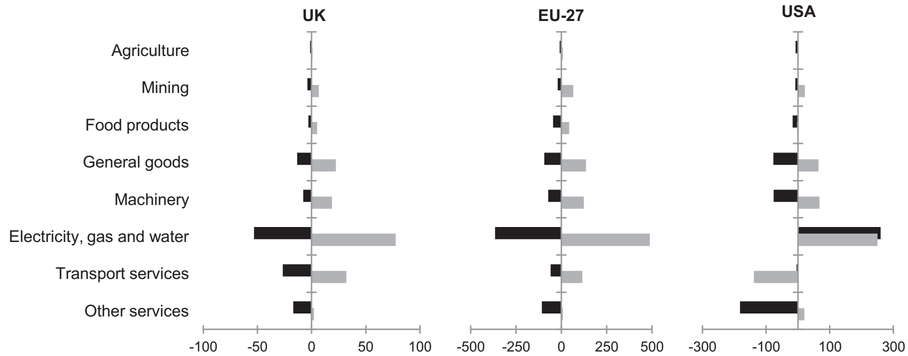

Fig. 3. Domestic CO_2 emissions reductions (black bars) have a similar composition to the makeup of increased embodied net imports (gray bars) (in Kt CO_2). Rather than achieving reductions, for these sectors their carbon footprint has actually grown and shifted abroad. This pattern holds for most Annex B countries including the UK and the EU27 as a whole.

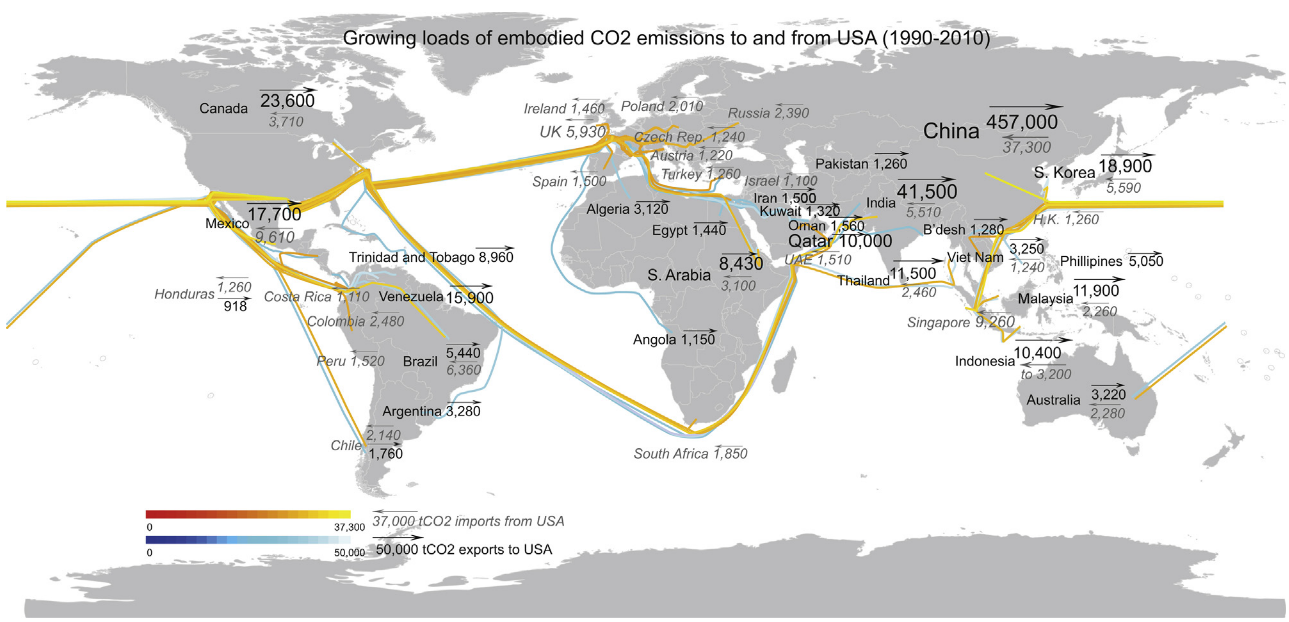

Fig. 4. Largest growing flows of embodied CO_2 to (rightward arrows) and from (leftward arrows) the USA (absolute growth 1990–2010, in tons of CO_2).

do not originate any major growing flows. China is not just an exporter but also drives CO_2 emissions from energy production elsewhere in Asia and Oceania. This flow is likely to continue to grow because of other Asian countries' economic growth. Overall, the electricity, gas, and water sector is the dominant sector associated with territorial emissions growth and tertiary services sectors the main sectors driving this increase.

Using the methods of Structural Path Analysis (SPA) (Defourny and Thorbecke, 1984; Lenzen, 2003; Peters and Hertwich, 2006) it is possible to enumerate and rank the individual supply chains through which displaced emissions flow to consumers in developed countries. This analysis is done using an aggregated version of Eora in which every country uses a common 26-sector classification so that all individual supply chains are comparable, Grouping the top international supply chains experiencing the biggest growth in embodied emissions since 1990 by origin and destination it may be seen that 72% of the 200 fastest-growing paths originate outside the Annex B signatories (Table 1). Embodied emissions originating in Annex B countries fall within the jurisdiction of the Kyoto Protocol. Yet just 28% of the 200 fastest-growing flows originate there. Of the 200 top fastest-growing flows, 144 originate outside Annex B countries and thus fall outside the jurisdiction of the Kyoto Protocol. If the same Kyoto signatories set targets using consumption-based emissions in addition to territorial emissions, the jurisdiction of the protocol would improve from covering 28% of the fastest-growing flows to covering 80% of the fastest-growing flows.

China dominates this list with 25 of the top 200 fastest-growing sectors emitting CO_2 for production bound for developed countries' consumers. In that country and others, coal and oil production, electricity generation, and transportation sectors are

Table 1
Direction of fastest-growing flows of embodied CO_2 since 1990 from SPA results. 72% of the 200 fastest-growing flows originate outside Kyoto Annex B countries.

Flow direction	Percentage of the 200 fastest-growing flows of embodied CO_2
Developed countries → Developed countries	20%
Developed countries → Developing countries	8%
Developing countries → Developed countries	52%
Developing countries → Developing countries	21%

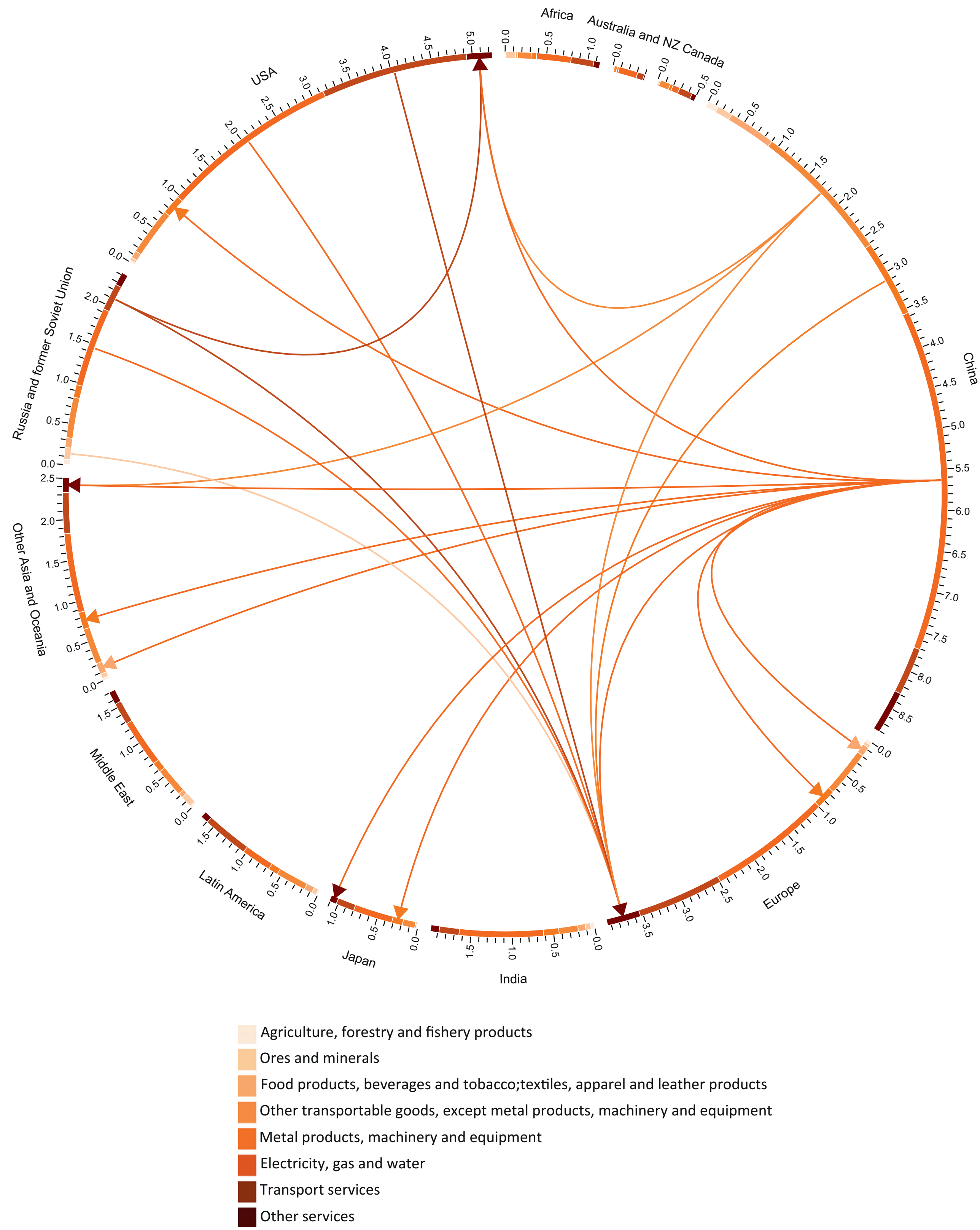

Fig. 5. The top 20 fastest-growing inter-country CO_2 emission transfers since 1990. Arrows show embodied CO_2 flows from production sectors to final consumption sectors. Arrowhead color corresponds to final consumption sector; line color corresponds to the production sector. Each country/region arc width corresponds to its consumption-based emissions in 2011 (in Gt CO_2).

the large primary emitters accounting for most of the emissions shifting. Other sectors actively contributing to emissions shifting include the Chinese steel smelting, processing, and motor vehicle manufacturing industries (increased 2.5, 6.5, and 7.7 Mt), chemicals industries in Indonesia, Malaysia, South Korea, and India (increased 0.9, 1.1, 1.6, and 4.1 Mt), production of cement, electronics, paper, food, fertilizer, and plastics from Thailand, Malaysia, Indonesia, and India, and petroleum exports from Iran

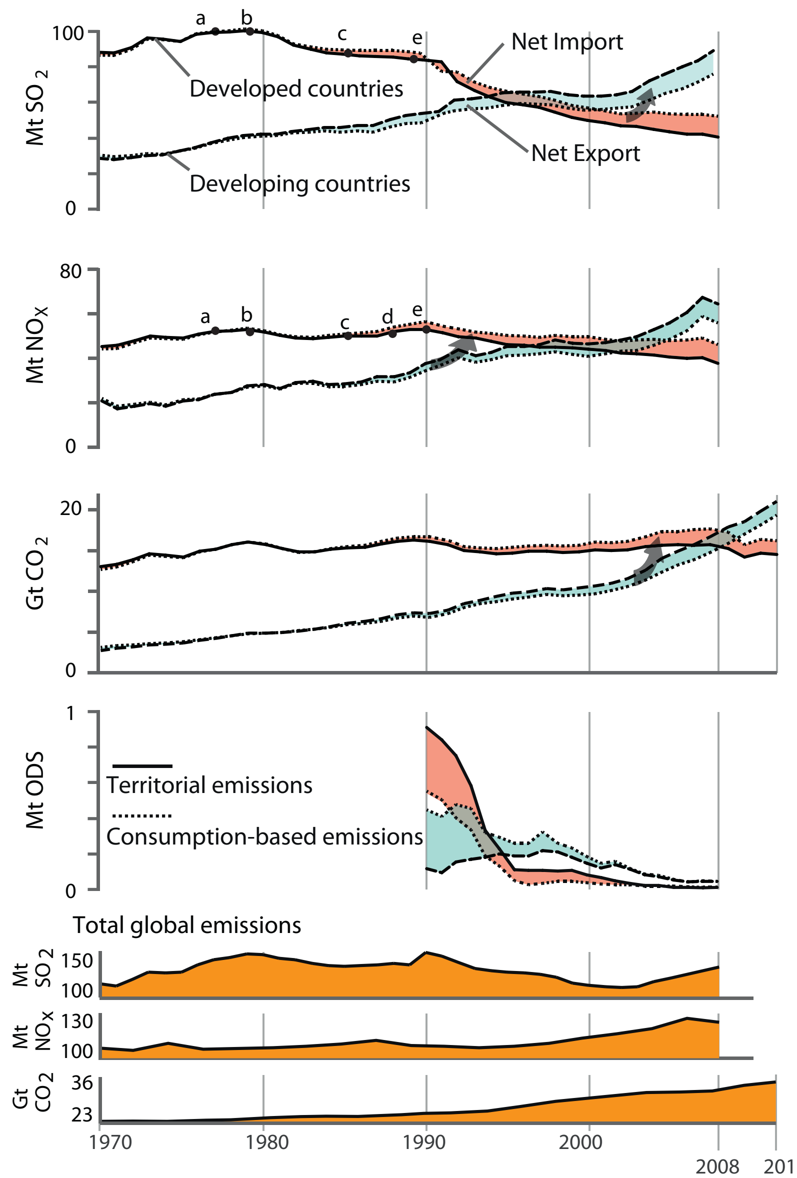

Fig. 6. Territorial and consumption-based SO_2, NO_x, CO_2, and ODS emissions. Despite considerable regulation in the large developed economies, global emissions have increased. This increase is in part to due to shifting of embodied pollution in trade (shaded area). Major US and EU air quality regulations are annotated: (a) US Clean Air Act (CAA) 1977 Amendments (b) 1979 European Convention on Long-Range Transboundary Air Pollution (c) 1985 Helsinki Protocol (d) 1988 Sophia Protocol (e) CAA 1990 Amendments.

The historical shifting of SO_2 and NO_x-intensive production to countries with weaker regulation suggests that CO_2-intensive production may similarly relocate to avoid regulation. If CO_2 emissions follow the same precedent set by air pollution emissions, it could mean global emissions continue to grow even if developed countries successfully reduce their emissions.

to India, from Qatar and Saudi Arabia to the USA, from Libya to Italy and Spain, and from Algeria to France.

Further detailed results are available in Supplementary Information (SI) S2. Skelton et al. (2011) have advanced similar visualization work using a Sankey diagram and Structural Path Analysis to help users locate CO_2-intensive segments of value chains.

3.3. CO_2 follows fleeting air pollution

The phenomenon of emissions shifting has already occurred with NO_x, SO_2 and PM_{10} emissions. Polluting production increasingly occurs in countries with less stringent regulation. For air pollution the result has been that despite effective regulation and technical measures (i.e. scrubbers and low-sulphur fuels) in major emitters, total global emissions have increased. A long-term time series of the air pollution footprint of nations (Fig. 6) shows that SO_2 emissions in developed nations remained at fairly constant levels until about 1980, followed by a continuous decrease throughout the following 30 years (punctuated mainly by the 1985 Helsinki Protocol and the 1990 amendments to the US Clean Air Act). All of the European SO_2 policies annotated in Fig. 6 attempted to address transboundary pollution, though not embodied pollution within or from outside Europe. Since 1990 total SO_2 emissions in developing countries have risen 32 Mt, with 8 Mt of that increase emitted for the production of goods bound for consumers in developed countries. A similar pattern can be observed for emissions of NO_x (Fig. 6). Accounting for net imports, developed countries would not have recorded a 23% NO_x reduction since 1990 but would have more or less remained at 1990 emissions levels. It must be noted that while higher pollutant emissions are generally deleterious, depending on local situations the same emission load could result a heavier or lighter societal impact. The relationship between emission and impact is complex and deserving of further study.

In contrast, the efficacy of the Montreal Protocol is clearly visible (Fig. 6). Ratified in stages between 1987 and 1993 by 190 countries, the ban on emissions on ozone-depleting substances (ODS) and the import of products containing ODS left no safe haven to which polluters could flee. Admittedly the small volume and ready availability of substitutes made ODS a relatively easy pollutant to control, yet still the Protocol's efficacy is notable.

4. Conclusion

Burden-shifting, originally anticipated to be a minor phenomenon, has turned out to be an important dynamic shaping global GHG emissions patterns. Using a high-resolution MRIO timeseries account of the global economy we are able to confirm earlier findings that burden-shifting is a growing problem. The efficacy of previous air pollution regulation has been undermined by burden-shifting. If GHG emissions and regulation follow this precedent there is a real risk that unless major economies recognize their imported carbon footprint even strong regulation on domestic emissions in major economies may not be effective in reducing total global emissions.The Kyoto Protocol only regulates territorial emissions. We are not the first to propose to regulate imports and/or consumption-based emissions instead (Lenzen et al., 2012b; Munksgaard and Pedersen, 2001; Peters and Hertwich, 2008a; Steckel et al., 2010). The Montreal Protocol, the Convention on International Trade in Endangered Species and the Basel Convention are all environmental regimes that attempt to mitigate the shifting of environmental impacts by regulating both domestic activity and imports. Potential policy solutions include a carbon border tax adjustment (Atkinson et al., 2011; Helm et al., 2012; Hepburn, 2007; Ismer and Neuhoff, 2007; Ghosh et al., 2012; Wiedmann and Barrett, 2013), expansion of the Clean Development Mechanism (which allocates emissions abatement dollars to the most cost-efficient reduction opportunities), and setting reduction targets using consumption-based accounts. We conclude that burden-shifting is a real problem, with the fastest-growing flows of embodied emissions originating outside the jurisdiction of the Kyoto Protocol and we raise the concern that international trade can undermine pollution national emissions reduction targets.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gloenvcha.2013.09.008.

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