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National greenhouse-gas accounting for effective climate policy on international trade

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National greenhouse-gas accounting should reflect how countries' policies and behaviours affect global emissions. Actions that contribute to reduced global emissions should be credited, and actions that increase them should be penalized. This is essential if accounting is to serve as accurate guidance for climate policy. Yet this principle is not satisfied by the two most common accounting methods. Production-based accounting used under the Kyoto Protocol does not account for carbon leakage—the phenomenon of countries reducing their domestic emissions by shifting carbon-intensive production abroad[1]. Consumption-based accounting[2,3] (also called carbon footprinting) does not credit countries for cleaning up their export industries, and it also punishes some types of trade that could contribute to more carbon efficient production worldwide. We propose an improvement to consumption-based carbon accounting that takes technology differences in export sectors into account and thereby tends to more correctly reflect how national policy changes affect total global emissions. We also present empirical results showing how this new measure redraws the global emissions map.

There are three important conditions that a national carbon accounting scheme ideally should satisfy to provide useful and reliable feedback for global and national climate policy.

First, it should be responsive to factors that nations can influence, for example the level and composition of their consumption, and their domestic carbon efficiency (sensitivity). Second, countries should not be able to reduce their national carbon footprints in ways that contribute to increased global carbon emissions (monotonicity). Third, the sum of national emissions for all countries should equal total global emissions (additivity). For a further elaboration of these conditions see Supplementary Section 1.

An accounting method that does not satisfy Sensitivity will leave some relevant and manageable sources of emissions out of its scope. A method that does not satisfy Monotonicity may sometimes yield misleading feedback on the effects of national policies: a country that tries to contribute to global climate targets by reducing its own carbon emissions may inadvertently contribute to increased emissions globally. Finally, a method that does not respect Additivity is inadequate as a baseline for allocating responsibilities for emission reductions because it cannot guarantee that global reduction targets are reached even if all countries meet their individual targets.

Neither production-based accounting (PBA) nor consumption-based accounting (CBA) satisfies the first two conditions. The problems with PBA have been widely recognized[2,3] but the problems with CBA are less frequently noted[4,5]. One weakness of CBA is that it is not responsive to changes in the carbon efficiency of export sectors, because all export-linked emissions are passed on to final consumers.

A second weakness is that CBA fails to encourage certain kinds of specialization and trade that might contribute to a more carbon efficient use of global production resources. This argument is analogous to classical economic arguments about the possibility of welfare gains through trade between parties with different comparative advantages. Even if a country has more carbon efficient production than its trading partners in all production sectors, it might be possible to achieve welfare gains in terms of reduced global carbon emissions by exploiting differences in sectoral carbon efficiency through international trade.

Under CBA, however, countries with more carbon efficient production technologies than their trading partners can be punished for participating in such trade—in the sense of having higher national emissions—even if the overall result is a reduction of global emissions. This argument is supported by an example and formal proof in Supplementary Section 2.

Unlike classical comparative advantages, which are defined in terms of production factor costs that are covered by the parties to a transaction, comparative advantages are in this case related to an external cost—physical carbon emissions—and hence do not provide direct economic incentives. For this reason, it is essential that differences in production technologies between countries are recognized in carbon accounting, so that policies can be designed to support carbon-efficient trade patterns.

Because traded goods account for about one quarter of global CO_2 emissions, counterproductive policy implications in this area may affect a substantial fraction of total emissions.

When it comes to the first of these weaknesses, proponents of CBA have suggested regulating export-linked emissions indirectly by using border tax adjustments (BTAs; ref. 6). BTAs have been discussed at least since the early 1990s (ref. 7), but the idea remains controversial and unimplemented[8–11]. Here, it is sufficient to note that, although CBA supports some policy options available to import countries, which might in turn create indirect economic incentives to exporters, it does not provide direct feedback to export countries on the carbon efficiency of their export industries. Thereby, some potentially effective policy options are left out of focus.

We propose a new method for carbon accounting—technology-adjusted CBA (TCBA)—that addresses the issue of carbon intensity in exports. Like conventional carbon footprints, technology-adjusted footprints incorporate emissions embodied in trade, but also adjust for differences in carbon efficiency in export sectors of different countries.

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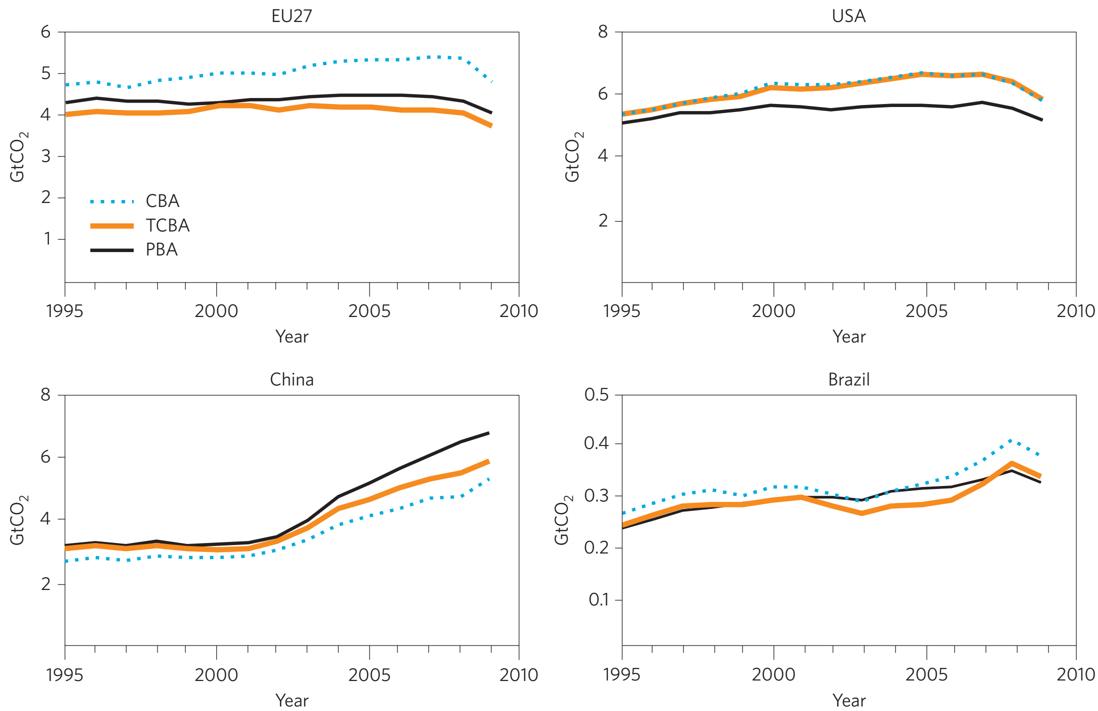

Figure 1 | TCBA of the EU27, China and Brazil compared with PBA and CBA. Complete results are available in Supplementary Section 5. The legend applies to all panels.

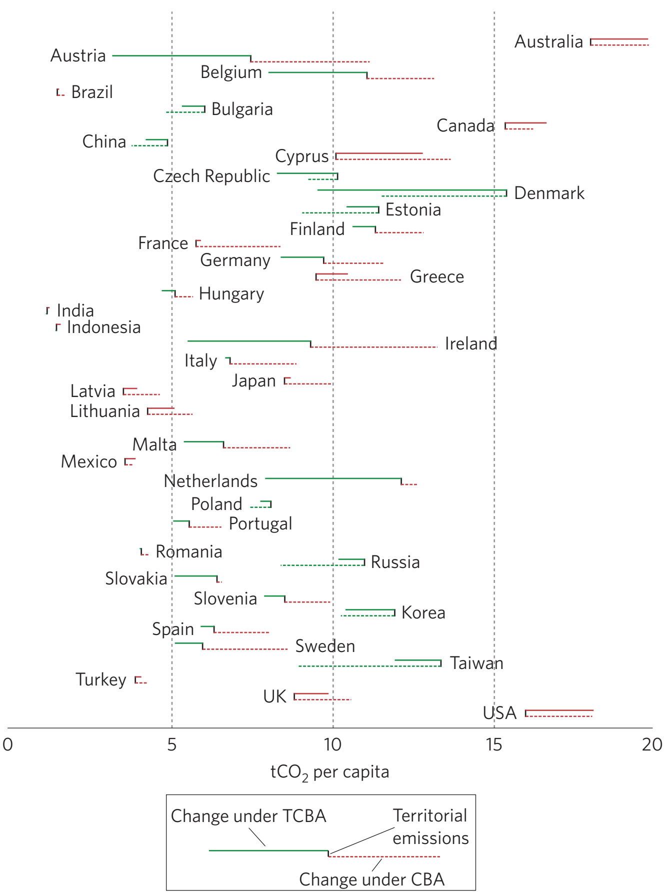

Figure 2 | Change from territorial to CBA and TCBA accounting for 2009. For many countries, TCBA accounting suggests different abatement responsibility (carbon footprint) than do CBA or PBA.

CBA is calculated by adding embodied emissions in imports to production emissions and subtracting embodied emissions in exports—in both cases using the average emissions intensity of the relevant production sector in the producer country.

TCBA applies a similar formula, with a twist: export-related emissions are subtracted based on the average carbon intensity for the relevant sector on the world market, rather than the domestic average. The reasoning is this: if carbon footprints are to reflect the effects of a country's export on global emissions, we must consider not only how a certain exported commodity was actually produced, but also what alternative production it replaces.

Because we here compare, *ex ante*, the current state of affairs with a potential change—we consider what would be the case if a certain commodity were not to be exported from the country in question—we normally do not know exactly which alternative supplier would provide the substitute.

Given this lack of knowledge, we suggest that the most plausible, and least demanding, assumption is that a similar good would have been produced at the average emissions intensity on the world market for the relevant sector.

Because the global sum of all imports, given the actual emissions intensities of producers, equals the global sum of all exports, given the world market average emissions intensities for each sector, TCBA will satisfy Additivity.

On the assumption that the expected effect of a marginal change in a country's export can be calculated by comparing it against the world market average emissions intensity for the relevant sector, TCBA would also satisfy the first two conditions. A proof is provided in Supplementary Section 3.

Note that the world market average in this calculation includes the export of the country under study. The reason for doing this (rather than taking just the average of all other countries) is that it is a simple way of ensuring that it satisfies Additivity. As a consequence, however, TCBA will to some extent underestimate the effects on global emissions of technology differences between countries in their export industries, and it will therefore not fully satisfy Monotonicity.

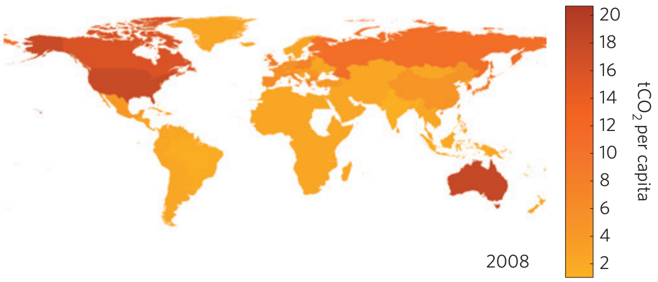

Figure 3 | World map of per-capita emissions responsibility using TCBA.

TCBA is designed to account for the effects of small, marginal changes, but is less suitable for tracing the effects of large-scale changes in exports with dynamic impacts especially for larger exporters.

Still, TCBA does constitute a clear improvement of consumption-based carbon accounting in this respect, because standard CBA ignores technology differences in export completely.

We used a global multi-regional input–output table to compute the TCBA for 40 countries. Comparing the results against those of PBA and CBA, it is found that TCBA changes the levels and trends of many regions of the world, but not in a way that systematically benefits either developed or developing regions (Fig. 1).

For Europe, previous interpretations of consumption-based carbon footprints have suggested that Europe's compliance with Kyoto targets is mainly due to displacement of emissions[1]. TCBA suggests a different interpretation. Under TCBA, the European carbon footprint is below PBA, indicating that at least some of the observed difference between its CBA and PBA is due to differences in carbon efficiency between Europe and its trading partners, rather than outsourcing of emissions.

In contrast to Europe, the USA's profile as a net importer of embodied emissions is confirmed by our results. Hence, whereas trends in the USA and EU27 look very similar under both PBA and CBA, the underlying stories are completely different according to TCBA: the EU has improved its domestic carbon efficiency faster than the world as a whole, whereas the US has not.

It should be noted that this interpretation is to some extent limited by the sectorial resolution of the available data. There is a possibility that part of the result can be explained by structural shifts within the same export sector, rather than by technological improvements. Only more detailed sector data in the global trade models would allow us to fully settle this issue. This so-called 'aggregation problem' is further discussed in the Methods.

For China, a country that would be advantaged by CBA accounting, emissions under TCBA are significantly lower than under PBA, but higher than under CBA. With TCBA, China is still credited for its large exports of embodied carbon (recall that more than a quarter and up to one third of China's total emissions arise from the production of exports[12–14]) but is also held responsible for improving its carbon efficiency. This feature of the TBCA results aligns conveniently with current Chinese pledges that focus should not be on absolute emissions cuts but on improving carbon efficiency.

For Brazil, another rapidly growing economy, emissions have increased since 1995 by all three accounts. However, whereas the conventional carbon footprint suggests net displacement to other parts of the world, this is much less pronounced when the country's low carbon energy system, with much renewable ethanol, is taken into account via TCBA. For some years, Brazil's TCBA is even lower than its PBA.

The overall results (Fig. 2) show that, for several countries, the technology-adjusted carbon footprint is substantially smaller than the traditional footprint.

The global map of carbon footprints changes significantly when technology differences in exports are taken into account (Fig. 3). With TCBA, Australia, the USA and Canada remain high emitters (>16 t CO_2/cap), whereas India, Indonesia and Brazil remain low emitters (<2 t CO_2/cap). However, many countries in Europe change from high to medium emitters, whereas China, Mexico and Russia change from low to medium emitters. Several European countries—Sweden, France, Ireland and Austria—are large net importers of embodied carbon emissions according to CBA, but are instead net exporters when the carbon footprint is adjusted for technology differences in exports. China and Russia remain net exporters with TCBA, although less so than with CBA.

TCBA also differs significantly from PBA. Figure 4 illustrates the change in emissions responsibility between PBA and CBA (Fig. 4a) and between PBA and TCBA (Fig. 4b).

Conclusions

Technology-adjusted carbon footprints throw new light on the so-called displacement hypothesis and improve our understanding of the impact of international trade on global emissions.

By accounting for technological differences in production for export TCBA will support a wider range of policy options, available to consumers as well as producers, and also better align incentives with available policy options at a national level, than conventional consumption-based footprints.

All methods have their limitations, however, as TCBA, CBA and PBA do not reflect all kinds of indirect and dynamic climate policy effects. Indirect effects—for example, positive stimulus on other countries' climate policies—will not be accounted for.

Another limitation with both CBA and TCBA is that all responsibility for consumption is allocated to consumers, even in cases where producers clearly influence it through marketing or innovations. TCBA assumes that export countries are held responsible for the technology in their exports but not for consumption that is induced by such export. If a country has contributed to lower global emissions by an innovation that also triggers a change in world demand for this clean product—and thereby also in the country's export—this contribution may not always be reflected correctly by TCBA.

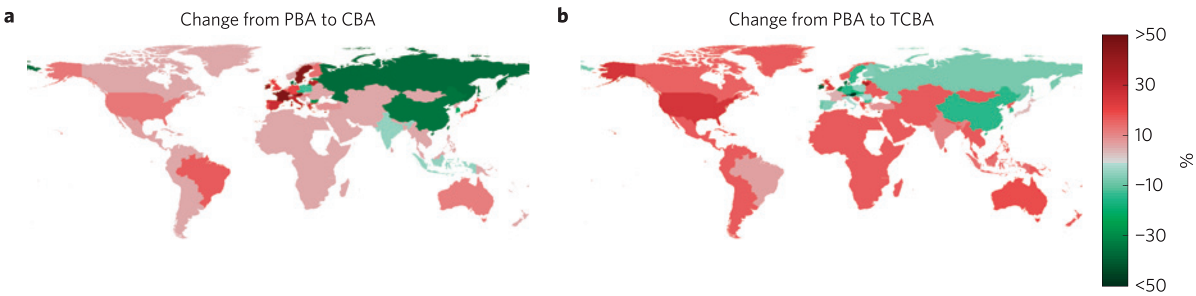

Figure 4 | Emissions responsibilities change considerably between PBA, CBA and TCBA.

Table 1 | A summary of differences in outcome between the methods for three regions.

Ordinal ranking	Representative country/region
CBA > PBA > TCBA	EU
CBA ≈ TCBA > PBA	USA
PBA > TCBA > CBA	China

Typical relationships of CBA, PBA and TCBA and some representative regions.

A third limitation is that TCBA may to some extent underestimate the effects of technology differences in export between countries, and hence does not fully satisfy Monotonicity. Still, even with these limitations, TCBA does offer clear advantages compared to standard CBA in accounting for the effects on global emissions of international trade.

Complementing conventional national carbon inventories with carbon footprinting according to TCBA would therefore provide useful information on the expected effects of national decisions on global emissions. Together with additional information about demand and supply elasticities, it may assist national decision makers in choosing efficient policies to contribute to global climate goals.

Methods

The calculations in this study were executed using the World Input–Output Database (WIOD; ref. 15), one of a new generation[16] of global multi-region input–output (MRIO) databases that document trade flows between countries. WIOD was chosen over the other available MRIO databases (specifically, over Eora[17]) because of its homogeneous sector classification, which allows industries in different countries to be directly compared. For the purposes of this initial analysis WIOD offers reasonable resolution (35 sectors per country), country coverage (40 countries responsible for >97% of global GDP), and temporal coverage (1995–2010).

The accuracy of CBA and TCBA accounting is constrained by the level of sectoral resolution available in MRIO tables because sector-average carbon intensities are applied to a potentially diverse set of products within that sector. This may introduce an unintended bias in the balances of embodied emissions if a country's import and export mix of products within one sector differs significantly in terms of carbon intensity. This 'aggregation' problem is well known in input–output analysis[18], is generally accepted to introduce manageable uncertainty, and can be addressed by increasing the number of sectors in the model[19,20] as done, for example, in the Eora[21] and EXIOPOL (ref. 22) projects. To give one concrete example of how product-level heterogeneity can affect results, consider a country which exclusively exports pharmaceutical products which it is able to produce with low carbon emissions. In the MRIO tables pharmaceutical products are included within a broader chemicals sector. This country will receive 'bonuses' in relation to the world average for the total chemical sector (because its export mix is so clean), yet if the MRIO tables had distinguished pharmaceutical products from chemicals more generally, these bonuses would be fewer. The inverse may occur too: a country could export a specific product which is significantly more carbon intensive than is its parent sector as a whole. The question whether TCBA is more susceptible to aggregation error than CBA would merit further empirical analysis which was beyond the scope of this Letter.

Whilst the results presented here demonstrate the principal validity, applicability and relevance of the TCBA method with the 35-sector WIOD model we would recommend more detailed analyses before implementing specific policies in practice.

Consumption-based accounting (CBA) results were calculated in the normal manner using a Leontief demand-pull model[23–25]. In this model emissions in producer countries are reallocated to final consumers by following products through multiple trade and transformation steps. A summary of differences between PBA, CBA and TCBA for some typical countries is given in Table 1. In the Leontief model the CBA emissions account can be calculated as in equation (1):

$$\mathrm{CBA}^s = \sum_i f_i^s + \overbrace{\underbrace{\sum_{i,r\neq s} q_i^r \# x_i^{rs}}_{\text{imports}} - \underbrace{\sum_{i,r\neq s} q_i^s \# x_i^{sr}}_{\text{exports}}}^{\text{net trade balance}} \quad (1)$$

where f denotes direct emissions, q is an emissions multiplier # denotes elementwise multiplication, and x_i^{sr} is the output from production sector i in country s that is produced for final consumption in country r. The distribution of total output from each sector over final consumers is given by equation (2):

$$x_i^{sr} = \sum_{j,t} L_{ij}^{st} y_j^{tr} \quad (2)$$

Here y is a collection of final demand bundles and L is the classical Leontief inverse, $L = (I - Z\hat{k}^{-1})^{-1}$, where I is the identity matrix, Z is a multi-region input–output table documenting economic flows between countries and sectors, $\hat{k}$ is the diagonal of k, and k_i records gross output of sector i. The emissions multiplier q is calculated by simply dividing direct emissions with total output—allocated amongst all final consumers—for the relevant sector:

$$q_i^s = \frac{f_i^s}{\sum_r x_i^{sr}} = \frac{f_i^s}{\sum_{j,t} L_{ij}^{st} y_j^{tr}}$$

To calculate TCBA we begin as before by adding emissions embodied in imports to territorial emissions. But then, when subtracting export-related emissions, instead of using the domestic emissions multiplier q_i^s of the exporter, we use a weighted world market average emissions multiplier $\dot{q}_i$ for each sector i. World market average is defined as the average emissions multiplier in the part of production that, directly or indirectly, is exported for foreign final consumption. This multiplier is calculated as:

$$\dot{q}_i = \frac{\sum_{s,r\neq s} q_i^s \# x_i^{sr}}{\sum_{s,r\neq s} x_i^{sr}}$$

Although it would be preferable to divide emissions linked to export production from those linked to production for domestic use, current emissions and economic databases, and thus current CBA accounts, do not make such a distinction.

However, the shares of production output that is consumed domestically (x_i^{ss}) versus abroad (x_i^{sr}) vary between countries. Hence it is important to distinguish between world market average emissions intensities based on traded goods and world averages based on total global output.

Thus the TCBA inventory for country s is given by equation (3):

$$\mathrm{TCBA}^s = \sum_i f_i^s + \overbrace{\underbrace{\sum_{i,r\neq s} q_i^r \# x_i^{rs}}_{\text{imports}} - \underbrace{\sum_{i,r\neq s} \dot{q}_i \# x_i^{sr}}_{\text{exports}}}^{\text{net trade balance}} \quad (3)$$

The calculation, and results, are also provided in spreadsheet form in the Supplementary Information.

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References

1. Peters, G. P., Minx, J. C., Weber, C. L. & Edenhofer, O. Growth in emission transfers via international trade from 1990 to 2008. *Proc. Natl Acad. Sci. USA* **108,** 8903–8908 (2011).
2. Peters, G. P. & Hertwich, E. G. Post-Kyoto greenhouse gas inventories: Production versus consumption. *Climatic Change* **86,** 51–66 (2008).
3. Davis, S. J. & Caldeira, K. Consumption-based accounting of CO_2 emissions. *Proc. Natl Acad. Sci. USA* **107,** 5687–5692 (2010).
4. Steininger, K. *et al.* Justice and cost effectiveness of consumption-based versus production-based approaches in the case of unilateral climate policies. *Glob. Environ. Change* **24,** 75–87 (2014).
5. Jakob, M. & Marschinski, R. Interpreting trade-related CO_2 emission transfers. *Nature Clim. Change* **3,** 19–23 (2013).
6. Zhou, X., Yano, T. & Kojima, S. Proposal for a national inventory adjustment for trade in the presence of border carbon adjustment: Assessing carbon tax policy in Japan. *Energy Policy* **63,** 1098–1110 (2013).
7. Wyckoff, A. W. & Roop, J. M. The embodiment of carbon in imports of manufactured products: Implications for international agreements on greenhouse gas emissions. *Energy Policy* **22,** 187 (1994).
8. Böhringer, C., Balistreri, E. J. & Rutherford, T. F. The role of border carbon adjustment in unilateral climate policy: Overview of an energy modeling forum study (EMF 29). *Energy Econom.* **34** (Supplement 2), S97–S110 (2012).
9. McAusland, C. & Najjar, N. Carbon Footprint Taxes. *Environ. Resour. Econ.* 1–34 (2014).
10. Helm, D., Hepburn, C. & Ruta, G. Trade, climate change, and the political game theory of border carbon adjustments. *Oxford Rev. Econ. Policy* **28,** 368–394 (2012).

11. Springmann, M. Integrating emissions transfers into policy-making. *Nature Clim. Change* **4,** 177–181 (2014).
12. Yunfeng, Y. & Laike, Y. China's foreign trade and climate change: A case study of CO_2 emissions. *Energy Policy* **38,** 350–356 (2010).
13. Weber, C. L., Peters, G. P., Guan, D. & Hubacek, K. The contribution of Chinese exports to climate change. *Energy Policy* **36,** 3572–3577 (2008).
14. Liu, Y., Jayanthakumaran, K. & Neri, F. Who is responsible for the CO_2 emissions that China produces? *Energy Policy* **62,** 1412–1419 (2013).
15. Dietzenbacher, E., Los, B., Stehrer, R., Timmer, M. & de Vries, G. The construction of world input–output tables in the WIOD project. *Econ. Syst. Res.* **25,** 71–98 (2013).
16. Tukker, A. & Dietzenbacher, E. Global multiregional input–output frameworks: An introduction and outlook. *Econ. Syst. Res.* **25,** 1–19 (2013).
17. Lenzen, M., Kanemoto, K., Moran, D. & Geschke, A. Mapping the structure of the world economy. *Environ. Sci. Technol.* **46,** 8374–8381 (2012).
18. Lenzen, M. Aggregation versus disaggregation in input–output analysis of the environment. *Econ. Syst. Res.* **23,** 73–89 (2011).
19. Alexeeva-Talebi, V., Böhringer, C., Löschel, A. & Voigt, S. The value-added of sectoral disaggregation: Implications on competitive consequences of climate change policies. *Energy Econom.* **34** (Supplement 2), S127–S142 (2012).
20. Caron, J. Estimating carbon leakage and the efficiency of border adjustments in general equilibrium—Does sectoral aggregation matter? *Energy Econom.* **34** (Supplement 2), S111–S126 (2012).
21. Lenzen, M., Moran, D., Kanemoto, K. & Geschke, A. Building eora: A global multi-region input–output database at high country and sector resolution. *Econ. Syst. Res.* **25,** 20–49 (2013).
22. Tukker, A. *et al.* EXIOPOL—Development and illustrative analyses of a detailed global MR EE SUT/IOT. *Econ. Syst. Res.* **25,** 50–70 (2013).
23. Kanemoto, K., Lenzen, M., Peters, G. P., Moran, D. D. & Geschke, A. Frameworks for comparing emissions associated with production, consumption, and international trade. *Environ. Sci. Technol.* **46,** 172–179 (2012).
24. Hertwich, E. G. & Peters, G. P. Carbon footprint of nations: A global, trade-linked analysis. *Environ. Sci. Technol.* **43,** 6414–6420 (2009).
25. Leontief, W. Structure of the world economy: Outline of a simple input–output formulation. *Am. Econ. Rev.* **64,** 823–834 (1974).

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Author contributions

A.K., M.J. and D.D.M. designed the methodology and T.O.W. contributed to background and analysis. All authors contributed to writing the paper.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to A.K.

Competing financial interests

The authors declare no competing financial interests.