CORRESPONDENCE:

Consistency of technology-adjusted consumption-based accounting

To the Editor — The standard accounting method considered for greenhouse gases (for example, in the Kyoto Protocol) is production-based accounting (PBA), where each country is responsible for the emissions occurring in its own territory. However, this conceals the emissions along global supply chains. This criticism has led to the development of consumption-based accounting (CBA), which adds the embodied emissions in imports to a country's emissions, and subtracts the embodied emissions in exports from those emissions.

In a recent article, Kander *et al.*[1] propose an improvement on CBA — called technology-adjusted consumption-based accounting (TCBA) — by considering the technological differences between countries in the production processes of internationally traded goods. TCBA follows the same general calculation principle of CBA. However, there are differences regarding emissions in exports: where CBA does not consider them at all, TCBA considers the difference between a country's actual embodied emissions and the average emissions intensity for the relevant sector in the world market. TCBA considers the same values as CBA regarding embodied emissions in imports.

With TCBA, if a country's exported production is dirtier than the world average, it is still responsible for the part that is above the average, with the remainder transferred to the importing countries. If the country's exported production is cleaner than the world average, not only does it lose responsibility for its exports, it also gets a 'bonus', equal to its 'above average cleanliness'.

Starting from the central principle that "actions that contribute to reduced global emissions should be credited, and actions that increase them should be penalized", Kander and colleagues[1] state three conditions that a national carbon accounting scheme should satisfy: (K1) sensitivity; (K2) monotonicity; and (K3) additivity. These three conditions are a subset of the six conditions introduced in 2006[2] and later reformulated in 2010[3]. The six conditions are: (R1) scale invariance; (R2) normalization (equivalent to K3); (R3) monotonicity (equivalent to K2); (R4) total indirect effects (equivalent to K1); (R5) economic causality; and (R6) symmetry.

Scale invariance requires that if country k is the union of countries k' and k'', then the carbon responsibility of k must equal the sum of the carbon responsibilities of k' and k''. This seems a reasonable property (it was, for example, accepted by Lenzen *et al.*[4] in an analysis of their own indicator), both conceptually and practically. Note also that this is a stronger property than just requiring that the sum of the carbon responsibilities of all countries equal total world emissions (R2/K3).

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In a proposal from Kander and colleagues, the embodied emissions in the exports of k' and k'' to each other are calculated using world average intensities, but the embodied emissions in the imports of k' and k'' (effectively the same trade flows) are calculated using the average emissions intensity of the relevant production sector in the producer country. This means that the sum of the emissions embodied in the exports of k' and k'' to each other is different from the sum of the emissions embodied in the imports of k' and k'' from each other. When considering the TCBA of country k and the union of countries k' and k'', the relevant difference is that exports and imports between k' and k'' are no longer considered. However, since the embodied emissions of these exports are different from the embodied emissions of these imports, their removal means that $TCBA_k \neq TCBA_{k'} + TCBA_{k''}$, and so their proposal violates scale invariance.

In the field of life cycle assessment (conceptually the same framework as the input–output approach used by Kander *et al.*[1]), a relevant distinction is established between 'attributional' and 'consequential' approaches. The former allocates to agents or products the responsibility for the existing production systems. The latter takes into account how the world would be different if agents' actions change, which is highly dependent on model assumptions[5]. PBA and CBA are clearly attributional approaches. TCBA builds on CBA but moves to a consequential approach: how would emissions be different if a country's exports did not exist?

Kander *et al.*[1] assume that if a country opted not to produce and export a certain good, some other country would step in to do that; *a priori* we do not know which country that would be, so it makes sense to assume that the substitution will be provided by the 'average country'. The additional implicit assumption of Kander *et al.*[1] is that, in contrast, an importing country does have the choice of choosing from where its substituting imports come from.

The alternative assumption we introduce here is to consider that countries' imports should be replaced by world averages (hence also changing their responsibility). From the consequential point of view, and in the absence of extra empirical information, both would be equally plausible assumptions. Moreover, in the real world any responsibility criterion implemented will have blind spots according to Steininger and colleagues[6]. However, although Kander and colleagues[1] assumption violates the scale invariance property, what we are proposing does not and should be preferred if scale invariance is to be considered an important property of national carbon accounting schemes. ❐

References
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Reply to 'Consistency of technology-adjusted consumption-based accounting'

Kander *et al.* reply — Domingos *et al.*[1] point out that the technology-adjusted consumption-based accounting (TCBA) principle that we proposed in a recent Letter[2] does not satisfy a condition called scale invariance[3,4]. This is correct.

Scale invariance means that, for any union of countries, the sum of carbon responsibility for all countries in the union should equal the carbon responsibility of the union if treated as a country. TCBA fails to satisfy this requirement as it treats emissions in imports and exports differently. Emissions embodied in imports are added to a country's carbon inventory based on the emissions intensities in the actual producer countries, but emissions in exports are subtracted based on the average emissions intensities for the relevant product groups on the world market.

For the entire world, export emissions equals import emissions, so the additivity condition is satisfied, that is, the sum of national emissions equals global emissions. But for smaller groups of countries, for instance the EU, results will differ depending on whether trade between group members is regarded as foreign or domestic. Thus, under TCBA, the sum of carbon responsibility for all EU member states, for example, will not equal the carbon responsibility of the EU treated as one country. To avoid this Domingos *et al.*[1] suggest that carbon emissions embodied in imports should also be calculated based on world-average emissions intensities.

We agree with Domingos *et al.*[1] that scale invariance is a desirable property, and we are therefore grateful to the authors for bringing this issue to light, and find their proposed solution a valuable contribution. We considered a similar option when writing the original Letter, but dismissed it for three reasons: first, the motivation for replacing domestic emissions intensities with world market averages when calculating export-related emissions was to better reflect how a country's exports affect global emissions. As we argue in the Letter[2], one must consider "not only how a certain exported commodity was actually produced, but also what alternative production it replaces". Without being able to know which alternative producer would step in to fill a gap in supply, we suggest that the most plausible assumption is that the alternative supplier will have the world average emissions intensity. We found no corresponding independent motivation for replacing actual emissions intensities with world market averages on the import side.

Second, if consumers (including governments) are thought to be able to choose their suppliers — and thereby influence production patterns — there might be good reason to hold countries accountable for the actual emissions intensities of their imports. Third, we wanted the new measure to be as similar as possible to standard consumption-based accounting, in order to make our point that adjusting for technology differences in the export sectors can make a large difference.

The question, then, is how important scale invariance is. One important objective of national carbon accounting is to inform countries about how policies and behavioural patterns on a national level affect global carbon emissions. For this purpose, it is essential that countries are held responsible for factors they can control, and that their carbon accounts correctly reflect how their actions affect global emissions. For this purpose scale invariance is not vital. To the extent that consumers can influence production patterns through their choice of supplier, accounting properly for this factor seems more important than preserving scale invariance.

However, another way of using national carbon accounting is to compare the level of responsibility among countries. Here, scale invariance seems quite important: the carbon responsibility of Europeans in comparison with Americans, for example, should not depend on whether accounting is done at the state or federal level.

One interesting question is whether a shift to world market average emissions intensities on the import side would make a difference to the overall results. To investigate this we recalculated emissions for the 40 countries that were presented in the Letter, using world averages for imports as well as exports.

Full results are presented in the Supplementary Information, but it is worth noting here that there is hardly any difference for the US, China and Brazil. For the EU 27, emissions after 2002 are slightly higher compared to the results in the Letter, whereas for Australia and Japan they are lower. The reason is probably that a large part of European trade is with other European countries, with actual emissions intensities below world average, whereas a large part of Australian and Japanese foreign trade is with Asian countries, with actual emissions intensities above world average. ❐

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Additional information
Supplementary information is available in the online version of the paper.

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