3. Rodrigues, J., Domingos, T. & Marques, A. *Carbon Responsibility and Embodied Emissions: Theory and Measurement* (Routledge, 2010).
4. Lenzen, M., Murray, J., Sack, F. & Wiedmann, T. *Ecol. Econ.* **61,** 27–42 (2007).
5. Brander, M., Tipper, R., Hutchison, C. & Davis, G. *Consequential and Attributional Approaches to LCA: A Guide to Policy Makers with Specific Reference to Greenhouse Gas LCA of Biofuels* Technical Paper TP-090403-A (Econometrica, 2009).
6. Steininger, K. W., Lininger, C., Meyer, L. H., Muñoz, P. & Schinko, T. *Nature Clim. Change* **6,** 35–41 (2016).

Tiago Domingos[1], Jorge E. Zafrilla[2]* and Luis A. López[2]
[1]Marine, Environment and Technology Centre (MARETEC), Environment and Energy Scientific Area, Department of Mechanical Engineering, Instituto Superior Técnico, Universidade de Lisboa, Portugal. [2]Department of Economic Analysis and Finance, Faculty of Economic and Business Sciences, University of Castilla-La Mancha, Spain.
e-mail: Jorge.Zafrilla@uclm.es

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. ❐

References
1. Domingos, T., Zafrilla, J. E. & López, L. A. *Nature Clim. Change* **6,** 729–730 (2016).
2. Kander, A., Jiborn, M., Moran, D. D. & Wiedmann, T. O. *Nature Clim. Change* **5,** 431–435 (2015).
3. Rodrigues, J., Domingos, T., Giljum, S. & Schneider, F. *Ecol. Econ.* **59,** 256–266 (2006).
4. Rodrigues, J., Domingos, T. & Marques, A. *Carbon Responsibility and Embodied Emission: Theory and Measurement* (Routledge, 2010).

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

Astrid Kander[1]*, Magnus Jiborn[1,2], Daniel D. Moran[3] and Thomas O. Wiedmann[4,5]
[1]Department of Economic History, Lund University, School of Economics and Management, Box 7083, SE-22007 Lund, Sweden. [2]Department of Philosophy, Lund University, Box 192, SE-221 00 Lund, Sweden. [3]Industrial Ecology Program, Department of Energy and Process Technology, Norwegian University of Science and Technology (NNTU) NO-7491 Trondheim, Norway. [4]School of Civil and Environmental Engineering, University New South Wales, Sydney, New South Wales 2052, Australia. [5]ISA, School of Physics A28, University of Sydney, New South Wales 2006, Australia.
e-mail: astrid.kander@ekh.lu.se