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Environmental and social footprints of international trade

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Globalization has led to an increasing geospatial separation of production and consumption, and, as a consequence, to an unprecedented displacement of environmental and social impacts through international trade. A large proportion of total global impacts can be associated with trade, and the trend is rising. Advances in global multi-region input-output models have allowed researchers to draw detailed, international supply-chain connections between harmful production in social and environmental hotspots and affluent consumption in global centres of wealth. The general direction of impact displacement is from developed to developing countries—an increase of health impacts in China from air pollution linked to export production for the United States being one prominent example. The relocation of production across countries counteracts national mitigation policies and may negate ostensible achievements in decoupling impacts from economic growth. A comprehensive implementation of the United Nations Sustainable Development Goals therefore requires the inclusion of footprint indicators to avoid loopholes in national sustainability assessments.

Trade allows nations to benefit economically by exploiting their comparative advantages in producing goods and services. The value of world merchandise exports grew more than 260-fold from 1948 (US$59 billion) to 2016 (US$15,464 billion) and, on average, exports made up 29% of a country's gross domestic product in 2016 (ref. [1]). On the back of trade globalization, wide-ranging and sometimes unforeseen implications for economies, societies and the environment followed. Global supply and production chains have not only fundamentally transformed the way that commodities are produced, exchanged and consumed, they have also changed the location and scale of both environmental and social impacts[2,3].

When production takes place beyond countries' borders, associated impacts are displaced away from the point of consumption. One example is bauxite mined in Australia and processed into raw aluminium in China, which is exported to a German car manufacturer that uses aluminium for the chassis of cars destined for the United States (US) market. Energy used, pollution caused and employment generated by mining in Australia and manufacturing in China and Germany then becomes 'embodied' in the purchase of a car by a US consumer. Even though not traded physically, local energy use, local air pollution and local jobs may become 'embodied in' (associated with) trade. The related field of research is usually referred to as consumption-based accounting (CBA) or 'footprinting'[4–6].

The scale and complexity of international trade is unprecedented[3]. In recent decades, there has been a shift in the geography of global supply chains, first towards China and more recently towards other developing countries of the global south[7,8]. This has been accompanied by a shift of impacts, such as greenhouse gas (GHG) emissions or water use, towards less developed countries[9]. Increased fragmentation of production plays a vital role in the dynamics of trade[10,11]. The average frequency of carbon embodied in traded products crossing borders increased from 1.26 in 1995 to 1.43 in 2008 (ref. [12]).

Between 10% and 70% of total global social and environmental impacts occur somewhere else to the consumption that drives them (Fig. 1, Fig. 2)[3]. The relocation of productive industries to countries with lower income has not only led to a displacement, but often to an overall increase in environmental impacts because production in developing countries tends to be more ecologically intensive[13–15] and less socially regulated[16,17]. Apparent improvements in resource productivity, as well as environmental and working conditions in developed countries, are often dominated by displacements to other countries rather than solely achieved domestically. Consumption-based footprint indicators confirm that—apart from land use—there is no absolute decoupling of environmental impacts from economic growth when global supply chains are accounted for[18–20] and that countries cannot meet social needs for their citizens without transgressing vital, biophysical planetary boundaries[21].

This Review Article focuses on global footprint or trade studies from recent years based on the method of global multi-region input-output (GMRIO) modelling (Box 1).

Advances in analysing the footprints of trade

In recent years, studies involving GMRIO analysis have proliferated, and many of these studies are applications of the footprint concept[22]. Such studies are static, ex-post analyses of international supply-chain networks. At the origin of embodied trade flows are resource use and impacts associated with producing industries. The flows end with households and other final consumers purchasing products for end-use, often in other countries.

Scientific advances in evaluating trade-related impacts have been made in the following four main areas, significantly widening the knowledge base and potential for policy-relevant applications (specific examples are provided in the following sections; see also Tukker et al.[23]).

New indicators. GHG emissions and the use of basic resources, such as land, water and materials, were amongst the first indicators that were assessed from a consumption perspective[19,24–28], sparking political discussions around the responsibility for impacts from consumption. As a result, many more environmental and social impacts

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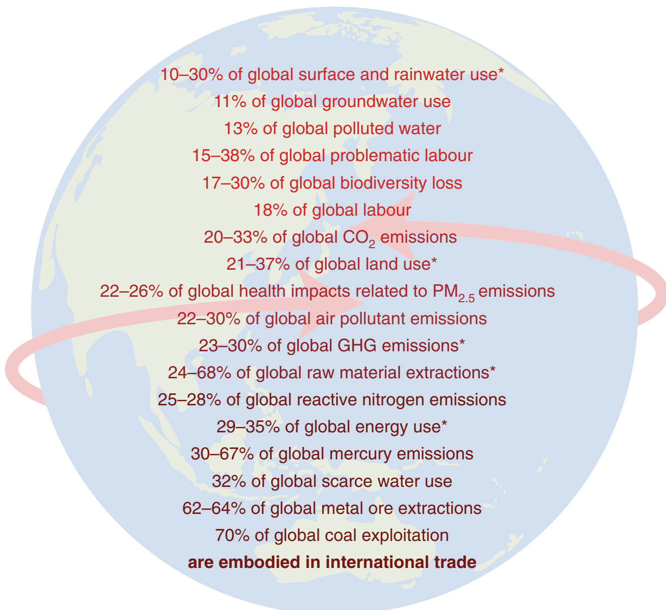

Fig. 1 | Burden shifting. Between 10% and 70% of environmental or social impacts are associated with (embodied in) international trade of goods and services (see Supplementary Information for references and details on method, scope and base year). For comparison, about 23% of global economic output was traded in 2010 (ref. [48]). Asterisks refer to indicators for which the percentages are confirmed to have increased from 1995 to 2011 (ref. [20]).

have been evaluated in the same way in recent years (Fig. 1, Fig. 3), some of them simultaneously in 'nexus' studies[29–31]. Most indicators constitute 'pressure' indicators, but increasingly researchers are trying to quantify the actual 'impact' or even 'damage' that environmental interventions have on earth systems or human health[32].

Modelling impacts. The coupling of physical or chemical process models with GMRIO analysis has enabled the simultaneous capturing of physical movement of pollutants and their virtual transport as commodity embodiments. For example, Oita et al.[33] couple a GMRIO database to a global cycle model for reactive nitrogen formation and emissions in air and water to demonstrate the need for control of nitrogen leakage and demand-side abatement strategies. Similarly, Zhang et al.[34] and Lin et al.[35] employ atmospheric transport modelling to compare impacts from transboundary air pollution and international trade embodiments.

Spatial resolution. A persistent problem associated with input–output data is a lack of spatial resolution of large nations with geographically highly variable natural and economic characteristics. New sub-national input–output databases respond to this need by integrating different regions within a country[36,37]. Yet more comprehensive are so-called multi-scale or nested models[38–40] that combine subnational and international regional trade relationships within one framework.

Collaboration. Growing demands on improving the timeliness, completeness, accuracy and versatility of input–output databases represent a constant challenge for database developers. Collaborative virtual laboratories[41,42] are a conceptually new approach to compiling and using input–output information, replacing institutional ownership with wiki-style platforms, allowing more information and tool sharing, streamlining work flows, and ultimately enhancing research efficiency[43].

New insights from global trade and footprint studies

Providing a consumption perspective exposes problems that were shifted to other countries and opens up the possibility of addressing them with new initiatives and policies.

Air pollution. A case in point is air pollution. It has been shown that over the last 50 years, the footprints of NO_x and SO_2 emissions of developed countries have shifted to developing countries[44] and have also spread over increasingly larger geographical areas than the same footprints of developing countries[45]—just as was the case for CO_2 emissions[44,46]. Thirty per cent of global primary fine particulate matter ($PM_{2.5}$) emissions in 2007 were embodied in trade, mainly in exports from China and India and imports to the US and Europe[47]. This undermines local improvements in air quality that have been achieved in western nations and renders air pollution legislation ineffective at the global scale. Conventions on long-range transboundary air pollution do take into account the physical, intercontinental transport of pollutants but at least in the case of $PM_{2.5}$, primary emissions[47] as well as health impacts[34] induced by trade have been shown to be larger than those caused by atmospheric transport. About 4–8% of air pollutant emissions in China in 2006 were associated with exports of products to the US alone[35]. Some of these emissions were shifted eastwards through atmospheric transport and contributed noticeably to air pollution in western parts of the US.

The health impacts of aerosols are immense and trade plays an important role in displacing these impacts. Twenty-six per cent of global human health impacts[48] and 22% of global premature deaths[34] related to $PM_{2.5}$ pollution are embodied in trade (Supplementary Table 1). Fifty-seven per cent of the global PM-related disease burden is carried by China and India alone[49]. These health impact studies are not directly comparable, however, since Liang et al.[48] use a simple estimate of population exposure to primary $PM_{2.5}$ emissions based on intake fractions and Xiao et al.[49] use occupational exposure to airborne particulates, both of which are arguably less accurate than the chemical transport modelling employed by Zhang et al.[34].

China has both the highest production- and consumption-based emissions of primary carbonaceous aerosols, and 111,000 premature deaths in East Asia can be related to China's consumption-based emissions[50]. China's global exports, on the other hand, were responsible for 157,000 deaths or 12% of the total mortality in China attributable to $PM_{2.5}$ pollution in 2007 (ref. [51]).

Lin et al.[52] evaluated the global radiative forcing of aerosol pollution from a consumption perspective by coupling chemical atmospheric transport and climate modelling with GMRIO-based trade analysis. The short atmospheric lifetimes of aerosols mean that radiative forcing is much more localized than is the case for GHG emissions. It was shown that consumption in western Europe and North America in 2007 contributed significantly to both cooling (through primary organic and secondary inorganic aerosols) and heating (through black carbon) over East Asia, where most emissions occurred[52]. As is the case for $PM_{2.5}$ emissions, shifting trade patterns have a stronger influence on the location of impacts from aerosol emissions than atmospheric transport alone. These findings are highly relevant for global environmental policy, which has so far insufficiently addressed the trade-related increase of many aerosol emissions and their impacts in Eastern Asia.

Biodiversity and land use. Whilst the direct trade of endangered plant and animal species has been recognized by the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) since 1975 (ref. [53]), it was only in recent years that researchers have started to link final consumption to the loss of biodiversity at a global level. GMRIO modelling was used for the first time in 2012 to evaluate the number of threats to endangered species embodied in international supply chains of commodities

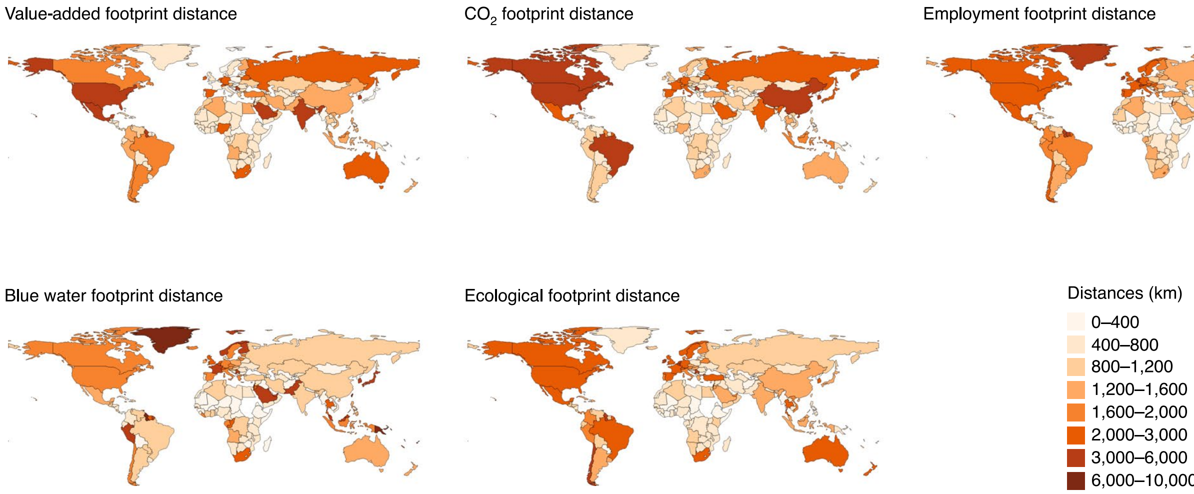

Fig. 2 | Average physical distances of national footprints in kilometres in 2010. Consumption in both developed and BRIC countries (Brazil, Russia, India and China) creates more distant footprints for CO_2 than is the case for water use or land use (ecological footprint distance). In Europe in particular, value added of consumption is closer to the own country compared to environmental impacts. Developed countries also outsource employment related to their consumption further afield than developing countries. Figure derived from ref. [113].

such as coffee, tea, sugar, fish, textiles and manufactured items[54]. In developing countries, a large part (35–60%) of domestic species threats are linked to production for export. Developed economies, on the other hand, are mostly net importers of biodiversity impacts: more than 50% of their biodiversity footprint is exerted outside of their territorial boundaries, mostly in developing countries. Recent studies focused on projected extinctions of endemic species[55] and on biodiversity loss related to land use and GHG emissions[56].

Conclusions depend on how exactly the impact on biodiversity is measured[57]. In contrast to previous studies that used pressures on biodiversity measured in threatened species counts[54], the countryside species–area relationship[55] and mean species abundance[56], Verones et al.[58] used a life-cycle impact assessment method to model the actual damage to species richness as a consequence of the impact from pollutant and GHG emissions and use of land and water. The resulting ‘biodiversity impact footprint’ takes into account species vulnerability and potential extinction. Using this impact-focused measure showed that wealthy countries exert most of their biodiversity impact in higher-income countries and not in developing countries, as was shown to be the case when using the pressure-based indicators of previous studies[54–56]. This contrast was explained with a higher level of endemism and species richness in some high-income countries compared to low-income countries[58].

In contrast to global warming and air pollution, biodiversity impacts are even more specific to the location where they occur and to the commodities that are implied in exerting biodiversity pressures. The spatial resolution of biodiversity footprints has recently been increased by combining a GMRIO model with high-resolution maps that show the location of threats to species[59]. This points to specific global hotspots of biodiversity effects—for example, US consumption is shown to exert threats to marine species in Southeast Asia and to terrestrial biodiversity in southern Brazil (due to extensive agriculture and grazing there), whereas consumption in the European Union (EU) has a hotspot of threats to marine species around islands in the Indian Ocean. Currently, however, GMRIO models are not capable of tracing trade flows within a nation. This means that a subnational region’s trade flows with other global regions—and therefore its region-specific impacts—are merged with national trade flows at international level. For an optimally resolved GMRIO model that connects consumption and effects of production anywhere, resolution must therefore be increased and linked at three levels: the spatial level of impacts[58], the product and sector level[60], and the level of subnational-to-international trade[38–40].

All biodiversity footprint studies confirm that food consumption (intensified by trade) is the ultimate and most important driver of biodiversity loss globally. Land use causes twice as much biodiversity loss as GHG emissions[56]. More than 50% of the EU’s total

Box 1 | GMRIO analysis—an analytical technique from the discipline of economics, conceived in the 1930s by Nobel Prize Laureate Wassily Leontief[115]

GMRIO analysis is based on statistical data, published by statistical agencies around the world and governed by international standards[116]. Whilst national agencies issue data for a single country, databases with a global coverage have been rapidly developing on the back of advances in computational capabilities[117]. Five GMRIO databases are now routinely used in footprint and trade-related studies[43,117] (Fig. 4). Differences between footprints derived from these have been the subject of recent inquiry[118], attributing divergences mainly to the physical satellites rather than the economic GMRIO transactions[119,120]. An intuitive reference for the magnitude of inter-database differences can be obtained from a cross-entropy analysis[114] (Fig. 4). GMRIO-based footprints can usually be estimated with an uncertainty of less than 30% (ref. [121]).

Already in the 1970s, Leontief had envisaged the application of input–output analysis to environmental and social issues[122,123] and the development of a global information system for policy decisions[124,125]. Environmental input–output applications experienced their first rise with energy analyses performed during the 1970 oil shocks[126], and the term ‘embodied energy’ was coined[127]. With the growing importance of human-caused climate change, ‘embodied emissions’ followed suit[128]. Later, input–output techniques were successfully integrated into life-cycle assessments[129] and environmental footprinting[27]. Today, environmental and economic accounts are seamlessly integrated into one coherent framework under the UN System of Environmental-Economic Accounting[130].

Whilst Rose and Miernyk[131] provide an account of the first 50 years in the history of input–output analysis, Dietzenbacher et al.[132] venture into its future prospects.

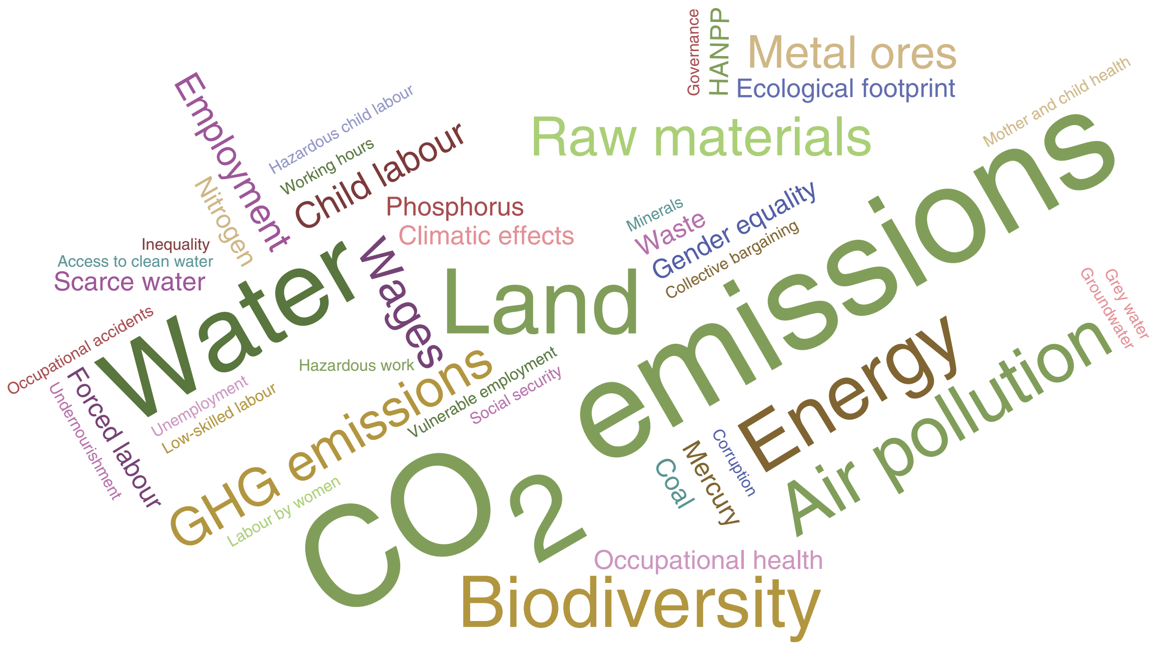

Fig. 3 | Semi-quantitative visualization of the identity and frequency of environmental and social indicators used in footprint or trade studies. Word size is proportional to the square root of the number of keywords attributed to publications between 2010 and 2017, as listed in the first column of Supplementary Table 1. HANPP, human appropriation of net primary production. Figure produced using https://www.jasondavies.com/wordcloud.

consumption of cropland, grazing land and forestland in 2007 took place in other countries[61]. However, the ranking of land-use footprints changes if the availability of land and the scarcity of water is taken into account (with India and Indonesia ranking higher)[62].

Water. Affluence is a main driver of trade-embodied ('virtual') water consumption across the world[63]. A number of GMRIO-based studies have applied the water footprint concept to account for the volume of virtual water traded[64–66] (Supplementary Table 1). It has been criticized, however, that simple accounting of water-use volumes provides insufficient and potentially misleading information, since the impacts of water use vary spatially and temporally[67]. Not only do the sources of water need to be considered, but in particular the availability (or scarcity) of water at local scale, which is also where water-related problems can be addressed most appropriately[68].

Taking into account water scarcity leads to a significant change in the trade balance of global virtual water flows[69], with countries ranking higher in the list of net importers if their virtual water comes from water-scarce regions. Water availability is location-specific, and tracing the EU's water footprint back to water extraction in about 11,000 watersheds worldwide[70] shows that almost 80% of the EU's water-scarcity-weighted water consumption occurs outside of EU borders, with the largest pressure exerted in the Indus Delta.

Water scarcity is not only caused by limited availability, but also by pollution of water. A study on the water footprint related to nitrogen pollution in 14 global regions[71] found that EU and the US outsourced the largest amount of polluted water to other regions. The effects of trade on global groundwater resources was recently studied by combining data on non-renewable groundwater abstraction for cropland irrigation with bilateral, physical trade data for food products[72]. In 2010, three countries alone—Pakistan, the US and India—exported 67% of trade-embodied groundwater (17.2 $km^3\ yr^{-1}$). This is 7.1% of the total global groundwater extraction for food production (241 $km^3\ yr^{-1}$)[72]. As a consequence, aquifers in these and neighbouring countries are overexploited, leading to problems such as land subsidence and seawater intrusion.

Resources and nexus studies. Combining consumption-based trade-flow analysis with network analysis provides additional information on international dependencies and the security of resource supplies. It could be shown, for example, that the US, China and Germany are key economies that strongly determine the amount of embodied energy supplied to other countries[73]. Changes to energy use in these countries have wide-ranging ripple effects around large parts of the world. The extent of global fragmentation is also reflected in the fact that 85% of globally traded embodied energy use can be attributed to intermediate production, while only 15% is embodied in final consumption[74].

The benefits of CBA have also been demonstrated for the indicator of resource productivity. Using the material footprint to measure raw material consumption showed that most developed countries did not improve their resource productivity in the late twentieth and early twenty-first century[19], see also ref. [75]. This was in contrast to previous assessments that used less-complete metrics than the material footprint[26].

The use of different resources is often linked and interdependent (for example, water is needed to produce energy and vice versa), prompting researchers to study the nature and strength of such resource nexuses from a global trade and consumption perspective. Interlinkages between water, energy and land seem particularly strong and complex from a consumption perspective[29]. A strong link of embodied freshwater and agricultural land use is confirmed for major importers of these two resource embodiments[31]. In the case of freshwater use embodied in global energy demand, a significant nexus was found with the consumption of petroleum across countries, but much less so with gas and electricity[30].

Translating volumes of resources or materials embodied in trade into actual impacts or damage is a long-awaited milestone in footprint modelling. Concepts that include the scarcity and depletion of resources have been proposed[76]. Implementation of scarcity weighting of metal ore consumption[62] showed that metal ore footprint rankings increased for the US and the Asia-Pacific region due to intensive extraction rates for copper ores in both regions, and iron ore in the Asia-Pacific region. Using life-cycle impact assessment methodology,

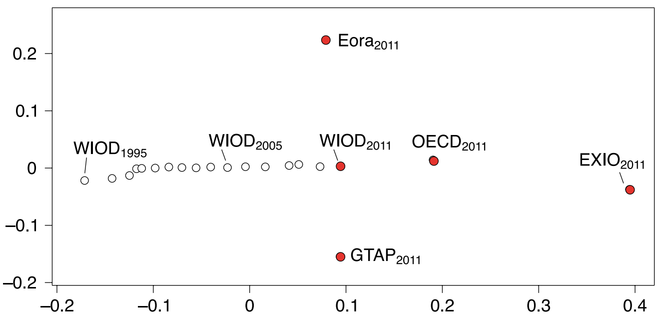

Fig. 4 | Closeness of commonly used GMRIO matrices measured in unitless cross-entropy distances and depicted on a two-dimensional plane using multidimensional scaling. Two sets of information are shown. First, the chain of World Input–Output Database (WIOD) GMRIO year-on-year matrix distances (represented by open circles) provides a visual reference for inter-year differences of the global economic structure. Second, red dots show the differences between 2011 GMRIO databases from various sources. Compared against the WIOD time chain, inter-database differences can be as large as ten years' worth of economic change. EXIO, Exiobase; GTAP, Global Trade Analysis Project. Figure adapted from ref. [114], Taylor & Francis.

Steinmann et al.[32] calculated the human health and biodiversity damage caused by the demand for 976 products. They found that damage footprints correlate well with simpler, volume-based resource footprints: fossil-fuel use in the case of human health damage, and fossil fuel and land use in the case of biodiversity damage.

Employment and social impacts. International trade also has profound impacts on social changes in all countries, with differences in wage costs arguably being a driver for rapid globalization. A consumption perspective on social indicators helps to unravel trade-implicated inequality and questions of (corporate) social responsibility.

Studies on employment embodied in international trade[77–80] confirm that wealthy countries outsource labour— mostly low-skilled—to developing countries, similar to the displacement of environmental impacts. Incidentally, labour-exporting countries—mostly in Africa and Asia[78,79]—often exhibit low energy productivities, which means that outsourcing of production leads to increased energy use and GHG emissions, offsetting any mitigation achievements in developed countries[77].

Attention is shifting towards an evaluation of the quality of labour and (associated) social risk[81], including aspects such as forced, hazardous or child labour[78]. Almost 1 million children in India in 2011/2012 worked for exports alone[82]. Per 100,000 workers in and along all global supply chains, there were 12 fatal and 4,800 non-fatal occupational health and safety incidents in 2010, which led to the loss of US$2 million and 27,000 working days, globally[16]. Similarly, many developed countries exhibit a large inequality footprint because their imports stem from production with highly unequal wages. Of the 70 million worker-years embodied in the US annual labour footprint, 40 million come from countries with high inequality, such as Brazil, the Philippines, Mexico or China[80].

Consumption-based accounting of social issues, such as gender equality, mother and child health, governance and access to clean water[83] or corruption[17], reveals how trade is implicated in large disparities of social impacts between developed and developing countries, informing policies and strategies needed to implement the United Nations Sustainable Development Goals (UN SDGs)[83].

Trade footprints and policy

The shift in perspective provided by global footprint studies has led to many new and different insights, implying the need for a shift in policy responses. Outsourced environmental and social impacts escape domestic regulation[84,85], prompting suggestions to 'bring back in' displaced impacts through actions and policies informed by CBA.

The most advanced discussion evolves around the usefulness of carbon footprints in climate policy, documented in the Intergovernmental Panel on Climate Change (IPCC)'s Fifth Assessment Report (AR5) on the mitigation of climate change[86]. Besides their ability to monitor carbon leakage[84], footprints inform about international supply security and dependency[73,84], and arguably provide a more equitable and just picture of global environmental and social impacts[87,88].

Grasso[89] argues that—provided democracy and institutions of sufficient quality—CBA can in principle be politically both feasible and effective. Jakob and Marschinski[90], however, caution against the use of CBA-based net CO_2 transfer estimates for the design of climate policies, because CBA cannot inform decision-makers of the likely consequences of trade restrictions. Afionis et al.[87] conclude that, given its technical and practical complexity, inherent assumptions and limitations and the necessity of increased international political collaboration to render it effective, CBA in its current form will probably not be firmly implemented in national policy making. The removal of CBA from the AR5's Summary for Policymakers may be a reflection of this.

A probable outcome is increased use of footprint indicators and consumption-based models to inform decision making, evidenced by reporting initiatives such as the UK's national carbon footprint[88], triple-bottom-line reporting in Australia[91], resource and water footprint estimates for European countries[67,70,92], carbon and material footprints for Organisation for Economic Co-operation and Development (OECD) countries[93,94], and material footprint indicators published by the UN Environment Programme (UNEP)[95] and used in the SDGs[96]. While such information does not necessarily translate into specific policies, there is evidence that it helps to shape fundamental programmes—for example, the UK's Industrial Strategy and Waste and Resources Strategy[97], EU policies on resource efficiency and security[70,92], and the 'green economy' and 'green growth' concepts supported by the UNEP and OECD[92].

Suggestions for specific policy initiatives to influence global impacts related to trade and consumption[87,97] include adjustments of border taxes or tariffs[98,99]; widening of technical standards[87]; transfer of technology, know-how and practices of management and enforcement[100]; resource efficiency initiatives[101]; or interventions aimed at curbing consumption[85,87,88]. Consumption-related impact reporting has already proven successful in consumer- and product-labelling campaigns, including campaigns for ending child labour, avoiding dolphin by-catch, or promoting fair trade.

It has been argued[85] that footprint indicators will be indispensable for consistent implementation of the SDGs. The 17 goals can be broadly categorized into 12 social goals, 4 environmental goals, and 1 related to implementation. The 'safe and just space' (SJS) framework developed by Raworth extends the biophysical planetary boundaries derived from earth science principles[102], with social and economic benchmarks derived from the main social objectives articulated under the UN SDG process[103]. These 'social thresholds' should not be undercut if a sustainable society is to be maintained. Defining both planetary and social boundaries in this way maps out the operating space for humanity that is both environmentally safe and socially just.

Using 7 environmental footprints and 11 social indicators, O'Neill et al.[21] assessed the performance of individual countries with respect to the SJS framework, finding that no country meets basic social needs without transgressing biophysical boundaries. Even though this study does not enumerate social indicators from a footprint (CBA) perspective, other studies have demonstrated that this can be done (for example, see refs [77–83]). These footprint indicators can help countries to achieve social goals in other countries.

While the material footprint is the only consumption-based indicator that is explicitly listed as an SDG indicator—under 8.4.1 (SDG 8 on sustainable economic growth) and 12.2.1 (SDG 12 on sustainable consumption and production)—other global footprint indicators might be equally useful in areas related to resource use (SDGs 6, 7, 14, 15), inequality (SDGs 1, 4, 5, 7, 10, 16) and international cooperation (SDGs 2, 7, 13, 14, 15, 17). Input–output models are particularly relevant for SDG12 (ref. [104]). In general, GMRIO databases are well suited for tracking progress on SDGs because of their ability to bridge economic, social and physical dimensions that can be quantified under a global scope. Well-established standards on input–output accounting ensure that this scope is identical for all dimensions, and therefore that comparisons of progress between countries, between SDGs and over time are valid. However, a comprehensive synthesis study including global results for GMRIO satellite variables that can act as meaningful proxies for individual goals is yet outstanding. Depending on the availability of appropriate data, footprint indicators can also be employed at city level, thus helping with the implementation of city-related SDGs (for example, SDG target 11.6).

In the case of resource use, supra-national governance for sustainable resource management could be strengthened by a regular reporting mechanism on global resource use and footprints of countries[85], for example, overseen by the UNEP International Resource Panel[105]. Similarly, the IPCC could govern a CBA scheme parallel to the reporting of territorial emissions under the UN Framework Convention on Climate Change. The International Energy Agency could include embodied energy when considering energy security[73]. The required GMRIO data and methods could be supported by agencies such as the UN Statistical Division, Eurostat or OECD directorates[106]. Most importantly, footprint indicators encourage international collaboration between governments, financial institutions, companies, trade organizations, trade unions, non-governmental organizations and others[83], based on an understanding of shared responsibility.

To enhance the policy relevance of footprint accounting, several improvements and future research avenues should be pursued[88,106–108]:

- Model improvements related to spatial and sectoral resolution, the number and quality of indicators, and faster updating. Further research is required to assess the influence of capital investments in footprint results[15,109].
- Further inter-model comparisons (for example, as in Fig. 4) and harmonization of GMRIO compilation to reduce uncertainty.
- Coupling with integrated assessment models[110], taking into account the local context of scarcity, risk or vulnerability.
- Nexus and trade-off studies, including human–nature interactions across ecological, social and economic systems[111], and for specific issues such as food, groundwater depletion or deforestation[107].
- Footprint-based research with policy orientation. This should include the generation of socio-economic and environmental system scenarios and an assessment of economic outcomes of policy options.
- Separate research efforts (not within the scope of this Review Article) that evolve around the question of whether and how trade activities increase or decrease environmental burdens[112]. There is a clear need to link such research to footprint studies to gain further insights.

Ultimately, both sides of the coin—production and consumption—need to be addressed when trying to meet one of humanity's biggest challenges: keeping its impact on Earth's resources within planetary boundaries[4].

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T.W. and M.L. wrote the paper. T.W. analysed data to create Figs. 1–3.

Competing interests

The authors declare no competing interests.

Additional information

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