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# Mapping the Carbon Footprint of Nations

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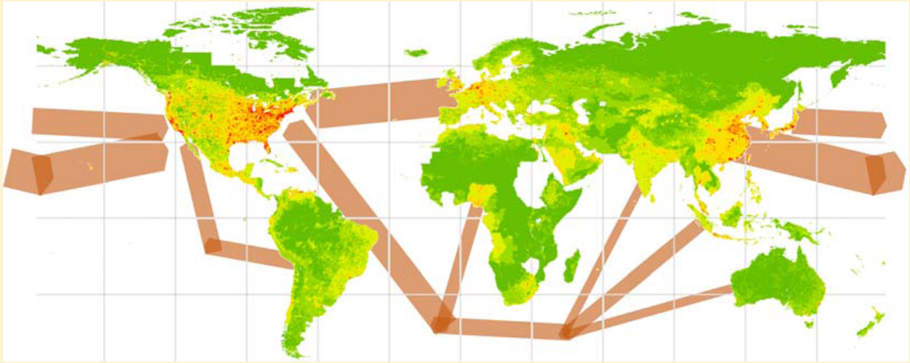
Supporting Information



**ABSTRACT:** Life cycle thinking asks companies and consumers to take responsibility for emissions along their entire supply chain. As the world economy becomes more complex it is increasingly difficult to connect consumers and other downstream users to the origins of their greenhouse gas (GHG) emissions. Given the important role of subnational entities—cities, states, and companies—in GHG abatement efforts, it would be advantageous to better link downstream users to facilities and regulators who control primary emissions. We present a new spatially explicit carbon footprint method for establishing such connections. We find that for most developed countries the carbon footprint has diluted and spread: for example, since 1970 the U.S. carbon footprint has grown 23% territorially, and 38% in consumption-based terms, but nearly 200% in spatial extent (i.e., the minimum area needed to contain 90% of emissions). The rapidly growing carbon footprints of China and India, however, do not show such a spatial expansion of their consumption footprints in spite of their increasing participation in the world economy. In their case, urbanization concentrates domestic pollution and this offsets the increasing importance of imports.

## ■ INTRODUCTION

Greenhouse gas (GHG) emissions are being displaced from developed nations to developing ones through international trade.[1−6] Life-cycle and footprint thinking holds consumers—countries, companies, and individuals—responsible for the impacts their purchases drive, regardless of where those impacts occur.[7,8] Life-cycle assessments and multiregional input-output (MRIO) models have been developed to study the economic and production networks, and associated environmental impacts, that lie upstream of a given purchase. These methods facilitate assessments of the effectiveness of specific climate mitigation measures[9] and to what degree climate policy has reduced global emissions[10,11] but it has not previously been possible for a consumer to locate their carbon footprint spatially.

Carbon footprint analysis has provided important findings that have helped to shape climate policy.[3,4,12] Insights into important consumption categories have contributed to targeting policy making and utilizing product policy and public purchasing guidelines to reduce emissions. The recognition that the share of emissions associated with the production of internationally traded products has grown from 20% in 1990 to nearly 30% in 2010[2,5,13] has triggered a discussion about responsibility for emissions. A substantial share of the rapidly increasing emissions in middle-income countries serves to satisfy the consumption in rich countries, which shows the limited efficacy of domestic climate policies in reducing global pollution. The recognition that an increasing share of energy-intensive products consumed in wealthy countries is produced in emerging economies has supported concerns about carbon leakage, the shifting of emissions from countries with stringent climate policies to countries without such policies. Indeed, an econometric study using MRIO analysis suggests that ca. 40% of the emission reductions achieved by the Kyoto protocol have been obviated by carbon leakage.[10] The analyses suggest a dynamic economic development and reorganization of global production and consumption, which has had and may continue

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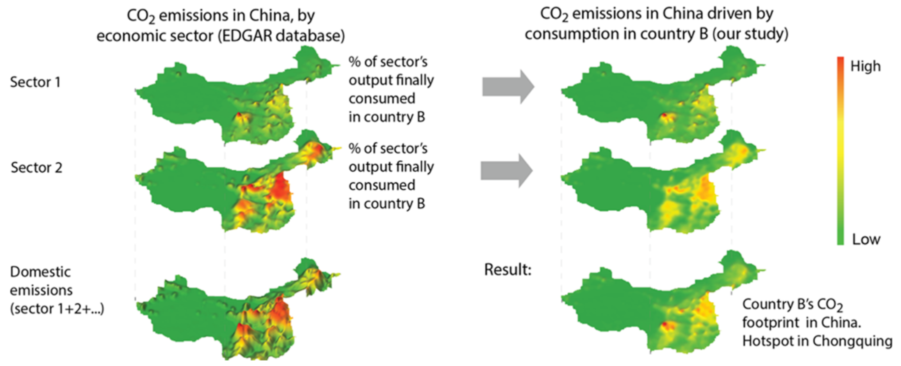

**Figure 1.** Illustration of method. To map country B's carbon footprint within China emissions maps for each sector in China were scaled according to the percentage of each sector's emissions embodied in trade transition destined for B. The GHG emissions hotspots in China differ from B's carbon footprint hotspots in China. The model considers 55 emissions categories spatialized according to 14−16 emissions maps across 187 countries and uses a trade database documenting >5 billion supply chains linking 15 000 industries.

to have a profound influence on greenhouse gas emissions. Yet, the analysis so far has remained at the aggregate level of regions and large countries. While previous findings make it clear that the carbon footprints of high-income countries are increasingly connected to the production in medium-income countries and new emission hotspots have arisen in previously agrarian societies, this development has not yet been mapped out.

Cities and subnational entities such as regions and states are becoming increasingly important actors in climate policy,[14−17] as demonstrated at the climate summit for local leaders as an important feature of the Paris climate summit.[18] Coalitions such as C40 and ICLEI further collaboration among such local entities, learning from each other, and the joint development of methods and standards such as those for measurement and planning.[19] The bottom-up design of the Paris climate agreement, its call for "making financial flows consistent with a pathway towards low GHG emissions" (Article 2.1c) and its emphasis on voluntary cooperation (Article 6) open up the opportunity for projects targeting emission hot-spots. A shared responsibility among consuming and producing regions would provide additional rationale for such focused projects. The new mechanism of *internationally transferred mitigation outcomes*, replacing the clean development mechanism (CDM), may even allow countries to take partial credit for such contributions to reducing their own carbon footprints. A detailed mapping of greenhouse gas emissions and the location of carbon footprints is hence not only valuable for the insight it brings and may find potential uses by the cities and states to target collaboration around climate change mitigation.

Recent developments in spatial modeling and remote sensing have resulted in spatially explicit models of global carbon emissions.[20−23] The EDGAR database[24] provides a set of maps of GHG emissions with relatively good industry resolution making it possible to link the carbon emissions map with global supply chains. Here, we link carbon emissions maps to the Eora MRIO trade database, which connects consumers to ≈15 000 production industries across 187 countries, and generate new spatially explicit maps of carbon footprint hotspots, which we present here. These hotspot maps locate emission hotspots more precisely than previous carbon footprint estimates, which have been limited in resolution to the national or global regional level.

## MATERIALS AND METHODS

The general framework consists of connecting spatially explicit estimates of emissions and economic activities with the economic accounts in a standard multiregional input−output (MRIO) model in order to track embodied GHG emissions to the country of final consumption (Figure 1). The framework extends monetary transaction between sectors and between countries into embodied carbon emission flows. The territorial carbon emissions associated with production ($p$) in country $s$, $F^{(\mathrm{p})s}$, can be decomposed into embodied emissions in consumption, in imports, and in exports:[25]

$$\underbrace{F^{(\mathrm{p})s}}_{\text{production}} = \sum_{ri} f_i^r \Big[ \underbrace{\sum_{tj} L_{ij}^{rt} y_j^{ts}}_{\text{consumption}} - \underbrace{\sum_{t \neq s,j} L_{ij}^{rt} y_j^{ts}}_{\text{imports}} + \underbrace{\sum_{t \neq s,j} L_{ij}^{rs} y_j^{st}}_{\text{exp orts}} \Big]$$

where $f$ is carbon intensity (factor intensity), $L$ is the Leontief inverse,[26] $y$ is final demand, $i$ and $j$ are sector of origin and destination, and $r$ and $s$ are exporting and importing country. $t$ is the country of last sale in the consumption and imports terms and $t$ is the country of final consumption in the exports term.

While MRIO databases do not currently offer detailed tracking of flows at the subnational level, that is, which goods come from which cities (though this is changing[27−30]), emissions maps exist differentiated by sector (IPCC emissions categories), and it is known how the sector mix contributes to the trade shares of goods and services exported for final consumption in other countries. Figure 1 provides an illustration of the method.

In this study the Eora MRIO embodied emissions framework,[31] covering $r$ = 187 countries and 15,984 industries and the EDGAR[24] greenhouse gas emissions database and industry-specific emission maps were used. For each country and each GHG (in this study, $CO_2$, $CH_4$, and $N_2O$), the EDGAR database provides the emissions volumes, $d$, split into 57 IPCC emissions categories (see Table S1 in the Supporting Information), a raster map $R$ providing the spatial distribution pattern of each emission for each of $h$ = 14 to 16 industries. The emissions categories and distribution maps correspond to economic sectors in the MRIO. The EDGAR emissions maps are provided at 0.1° resolution, with grid cells ≈10 $\mathrm{km}^2$ at the equator.

The number of sectors defined in EDGAR is generally less than the number of products individuated by the Eora MRIO. In this case the detailed daughter industries from the MRIO are

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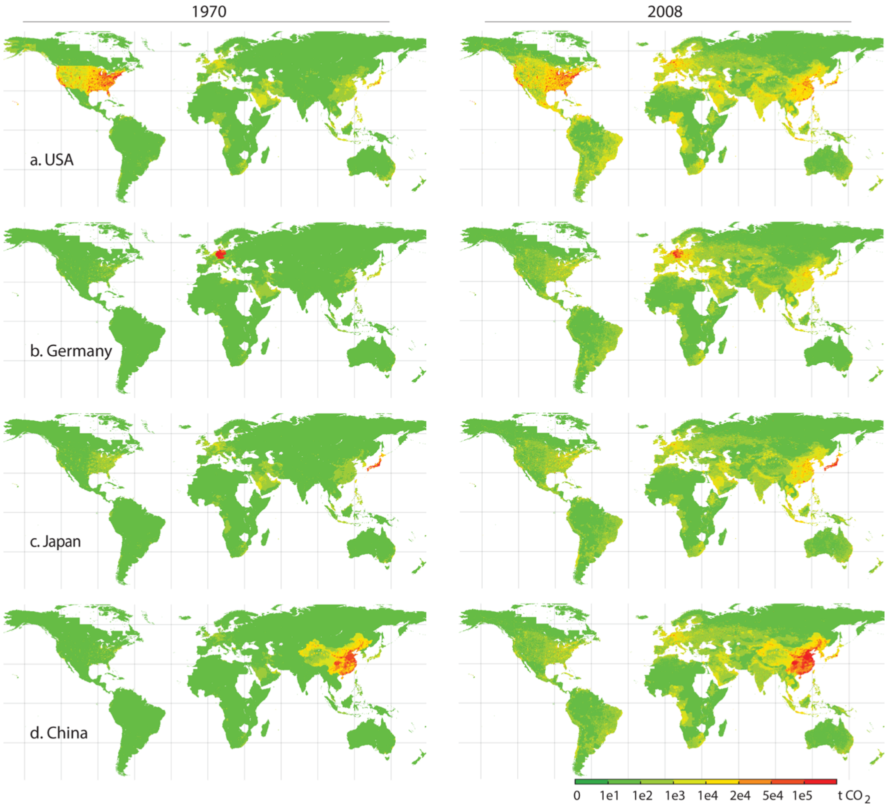

**Figure 2.** Shift and growth in carbon footprint hotspots between 1970 and 2008 for the United States (a), Germany (b), Japan (c), and China (d).

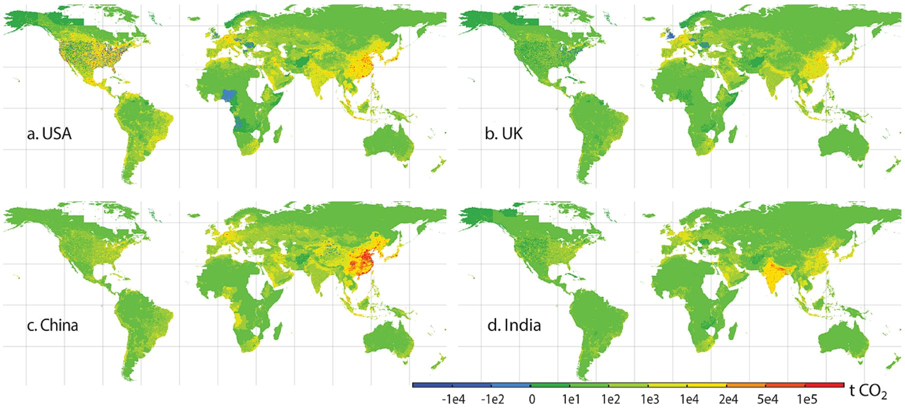

**Figure 3.** Changes in the carbon footprint of United States (a), UK (b), China (c), and India (d) from 1990 to 2008.

mapped using the sector's share of total emissions ($d$) from the parent sector and the spatial distribution of the parent sector in EDGAR. It may be hoped that in the future the sectoral resolution of the emissions data and maps will improve. The accuracy of the results is also constrained by the reliability of the MRIO used (though it has been shown that all current MRIO databases are broadly consistent[32]), as well as by the reliability of the emissions maps themselves.

Formally, the emission hotspots $H$ driven by imports ($m$) into country $s$ are estimated as

$$H_{(\mathrm{m})s} = \sum_{hr} R_h^r \frac{\sum_i f_{hi}^r \sum_{jt\neq s} L_{ij}^{rt} y_j^{ts}}{\sum_i d_{hi}^r}$$

The figures presented in this paper are the GHG emission hotspots driven by total consumption ($c$) of country $s$:

$$H^{(\mathrm{c})s} = \sum_{hr} R_h^r \frac{\sum_i f_{hi}^r \sum_{jt} L_{ij}^{rt} y_j^{ts}}{\sum_i d_{hi}^r}$$

Since both the embodied emissions term ($fLy$) and emission maps term ($R$) are in absolute values, the embodied emissions term $fLy$ is normalized by total emissions $d$ so that the result is in absolute values. A walkthrough of the spatial footprint method is provided in Excel format in the Supporting Information.

## FINDINGS

Carbon footprint hotspot maps identify where around the world the emissions associated with a given consumption bundle occur. For each of the greenhouse gases the core data set provides 187 maps—one per consuming nation—showing the magnitude and spatial location(s) of that nation's carbon footprint on each of its trading partners. Emissions hotspots move over time, both as locations increase or decrease their GHG emissions and as trade and production networks change. These movements occur both inter- and intranationally.[2,33] Comparing the carbon footprint hotspot maps for 1980 and 2007 reveals that the US footprint has expanded most significantly in Asia, with additional hotspots emerging in the Middle East, coastal Algeria, Pretoria/eastern South Africa, Northern India, Tokyo, and Nagoya, in addition to the expected growth in Europe, China, and Southeast Asia (Figure 2a). Japan's footprint has risen in Asia, Europe, and in the U.S. with notable growth hotspots in Casablanca, Doha, Tehran, and Moscow (Figure 2c). Similar worldwide growth is seen for China and Germany (Figure 2b, d).

Visible patterns in the international movement of carbon footprint hotspots include the carbon leakage phenomenon:[5,34] developed countries reducing their carbon emissions within their territorial area but increasing their footprint in foreign countries. This effect is particularly strong for the UK (Figure 3b) where emissions are decreasing domestically but increasing globally, in line with previous analysis. Hotspots for the UK's carbon footprint are located in The Netherlands, Cologne, Brussels, and Milan in Europe, in coastal China and the greater Beijing/Hebei province, and in Bangkok and Kuala Lumpur. Hotspots have waned within the UK and in Bucharest and southern and western Romania, throughout the Czech Republic, in Oslo, a handful of cities in Hungary, Slovakia, and Poland, and widely across cities in the U.S. Northeast. The leakage phenomenon is also apparent in other European countries like Germany (map in Supporting Information). For most developing countries such as China and India (Figure 3c, d), emissions growth occurs both territorially and globally. For India no lessening of emissions hotspots is observed.

Carbon footprint hotpot maps also show shifts in hotspot locations within countries. Taking the U.S. as an example, total territorial emissions have risen since 1970, but emissions have increased in some regions and decreased in others (Figure 3a). Emissions decreased in the Pacific Northwest, along the Rockies, and in the northeastern states, but new hotspots have arisen in central and southern California, Florida, and Texas, among others. In China the situation is mostly one of increasing emissions, though interestingly focused emissions footprint reduction hotspots can be seen across several cities in the Northwest provinces (Figure 3c).

Visualizing carbon footprint hotpots over time shows that the footprints of most developed countries have spread significantly into new countries. The spatial growth of these footprints is noteworthy because the footprints are growing in area more quickly than in volume, meaning a dilution process is occurring. For example, the U.S. carbon footprint roughly doubled in area between 1970 and 2008 (with the minimum land area required to contain 90% of emissions growing from 0.628% of global land area in 1970 to 1.573% in 2008), whereas the country's $CO_2$ emissions increased by just 23% and footprint increased by just 38% during that time. The UK emitted 99.235% of its carbon footprint on 1% of the global land area in 1970, but by 2008 its footprint had spread such that 1% of global and area held just 88.5% of its footprint (Figure 4a). India, in contrast, has experienced roughly 700% growth in its carbon footprint since 1970 but the spatial extent of that footprint changed relatively little by 2008 (Figure 4b). In China, the footprint has increased 340%, but the share of its emissions that can be contained in 1% of global land area has increased from 70 to 88%. The divergence in the developments of the U.S. and UK vs India and China presents an interesting puzzle. The increasing land area covered by emissions from industrialized countries is consistent with the increasing interconnections of the global economy and the general growth in international trade. Such developments, however, apply even stronger to emerging economies, but there we rather observe a concentration. We suggest that such a concentration may be the result of the growth of emissions in urban centers and a relative decline in importance of rural areas. A close examination of Figure 3a indeed shows also for the U.S. a decline of emissions in some areas of the U.S., which is more than offset by the increase in emissions outside. With the rapid rise in emissions in India and China, absolute decreases in emissions per pixel are less likely. These observations suggest that the spatial extent of the carbon footprint is shaped by two competing developments, an increasingly global organization of production and therefore densification of the global population. While in high-income countries, the influence of globalization is stronger, in emerging economies, the influence of urbanization prevails, given that these countries undergo rapid urbanization and become the centers of energy-intensive production.

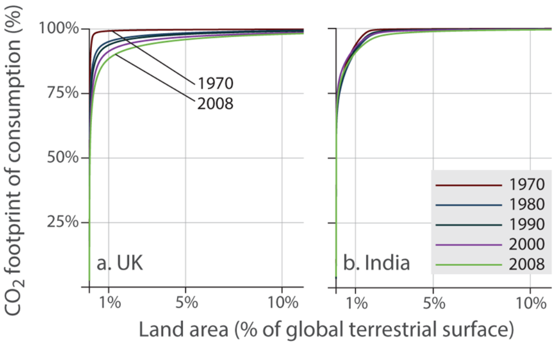

**Figure 4.** Spatial spread of carbon footprint from 1970 to 2008 for UK (a) and India (b), showing the minimum percentage of total global land area (horizontal axis) required to hold the carbon footprint emissions (vertical axis). For developed countries the footprints are growing and spreading in area, implying a dilution process, whereas for developing countries their footprints are generally growing in volume but not area, implying densification of emissions.

Carbon hotspot maps of individual GHGs linked to specific industries can also be mapped. Methane ($CH_4$) emissions arise predominantly from agriculture activities and natural gas use, thus both the distribution of emissions and the embodied international flows differ from those of $CO_2$. Since abatement strategies for $CH_4$ are also different from those for $CO_2$, it is useful to map $CH_4$ footprint hotspots separately. The US $CO_2$ emissions footprint (Figure 2a) is strongly localized in Europe and China, however, the U.S. $CH_4$ footprint is prominent in Canada, Central and Latin America, Africa, India, and Australia/New Zealand, with notable foreign growing hotspots including the Dominican Republic, Guatemala, and El Salvador, northern India, and along the Australian east coast (Figure 5). This reflects the global distribution of agricultural vs industrial production consumed by the U.S.

## ■ DISCUSSION

Reducing GHG emissions is a global challenge and will require involvement from emitters, manufacturers, and consumers, cooperating across borders. The footprint or life-cycle perspective helps parties other than primary emitters to

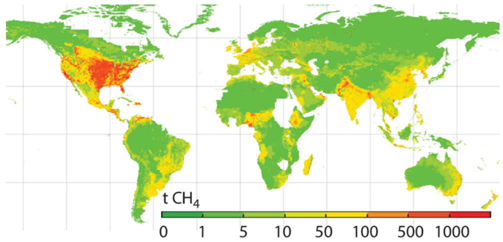

**Figure 5.** U.S. $CH_4$ footprint in 2008. Compared with the $CO_2$ footprint (Figure 2a), $CH_4$ emissions are notably higher in Africa, Latin America, and Australia/New Zealand.

become involved in reducing indirect emissions. Carbon footprint maps provide one more source of data that can be used to inform action. While carbon footprints for developed countries are growing in magnitude and spreading spatially, using hotspot analysis to identify key emissions hotspots could be one tool to help in abatement efforts. The maps illustrate different linkages.

For the United States, we see the importance of oil imports for the overall carbon footprint. The importance of Nigeria and Angola increased markedly from 1970 (Figure 2a), but experienced a decline in the period 1990−2008. In that later period, the importance of Alberta, Venezuela, and Iraq increased, a development that is also underlined by the $CH_4$ footprint in Figure 5. The map locates emissions caused by the supply of oil in the supplying regions and the use in the consuming countries; both suggest that in order to reduce footprints, oil consumption needs to be reduced. However, upstream emissions of different barrels of oil are not equal and shifting supply away from tar sands and heavy oils can indeed reduce overall emissions.[35] Second, the developments in Japan, the UK and China underline the importance of the rise of China as a global manufacturing power and the overarching importance of the trade in manufactured goods in explaining the spatial expansion of the carbon footprints.

Spatially explicit footprint analysis is at an early stage. Both emission maps and MRIO model have uncertainty. Oita et al.,[36] for example, estimate the error of nitrogen footprint. In the future work it will be necessary to integrate uncertainty analysis with emission maps and MRIO model, but this is a difficult task and outside of the present paper's scope.

Spatial emissions hotspot maps can facilitate concrete actions by identifying hotspots in developing nations that would offer high marginal returns on abatement investment. We note recent work by Chen, Wiedmann, and colleagues to spatialize the carbon footprints for certain supply chains and cities.[37,38] Traditional carbon footprints are traced via supply chains. Hotspot maps provide a new, different, perspective. Using a hotspot map a company, individual, or government can find the actual locations where their supply chain emissions occur, thus creating new opportunities to participate in reducing the emissions at that place.

## ■ ASSOCIATED CONTENT

### Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.6b03227.

Additional information as noted in the text (PDF) (XLSX)
Maps (ZIP)

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### Notes

The authors declare no competing financial interest.

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