# Carbon Footprint of Nations: A Global, Trade-Linked Analysis

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Processes causing greenhouse gas (GHG) emissions benefit humans by providing consumer goods and services. This benefit, and hence the responsibility for emissions, varies by purpose or consumption category and is unevenly distributed across and within countries. We quantify greenhouse gas emissions associated with the final consumption of goods and services for 73 nations and 14 aggregate world regions. We analyze the contribution of 8 categories: construction, shelter, food, clothing, mobility, manufactured products, services, and trade. National average per capita footprints vary from 1 $tCO_2e$/y in African countries to ~30t/y in Luxembourg and the United States. The expenditure elasticity is 0.57. The cross-national expenditure elasticity for just $CO_2$, 0.81, corresponds remarkably well to the cross-sectional elasticities found within nations, suggesting a global relationship between expenditure and emissions that holds across several orders of magnitude difference. On the global level, 72% of greenhouse gas emissions are related to household consumption, 10% to government consumption, and 18% to investments. Food accounts for 20% of GHG emissions, operation and maintenance of residences is 19%, and mobility is 17%. Food and services are more important in developing countries, while mobility and manufactured goods rise fast with income and dominate in rich countries. The importance of public services and manufactured goods has not yet been sufficiently appreciated in policy. Policy priorities hence depend on development status and country-level characteristics.

## Introduction

The concept of a carbon footprint captures the interest of businesses, consumers, and policy makers alike (*1*). Investors watch the carbon footprint of their portfolios as an indicator of investment risks. Purchasing managers are curious about the carbon footprint of their supply chains, and consumers are increasingly offered carbon-labeled products. Carbon footprints have become popular in spite of the term being a misnomer; it refers to the mass of cumulated $CO_2$ emissions, for example, through a supply chain or through the life-cycle of a product, not some sort of measure of area (*2*). It is most appropriately calculated using life-cycle assessment or input−output analysis (*3, 4*).

Given the interest in the carbon footprint (CF) of products, services, companies, and investment portfolios, there have been surprisingly no consistent comparative studies to understand our collective carbon footprint on a national or global level. What consumption categories cause the CF? How does the contribution of different activities vary across regions and stages of development? Studies on the importance of consumption categories and product groups have been instrumental in focusing Integrated Product Policy on housing, transportation, and food. One study (*5, 6*) is cited prominently in the European Union's (EU) "Sustainable Consumption and Production and Sustainable Industrial Policy Action Plan" (*7*). There is, however, a lack of studies on emerging and developing economies. Cross-national comparisons are hampered by differences in methods and classifications (*8*). In this paper, we present an analysis of the CF of nations using a global multiregional input−output (MRIO) model based on the Global Trade Analysis Project (GTAP) database for the reference year 2001. In our analysis, the carbon footprint is defined as the greenhouse gases (GHGs) $CO_2$, methane, nitrous oxide, and fluoride emitted in the production of goods and services used for final consumption and GHG emissions occurring during the consumption activities themselves, akin to the tier 3 CF in the Greenhouse Gas Protocol (*3*) and the climate footprint in ref *9*. We weight the different GHGs together using 100 year global warming potentials as in the Kyoto Protocol (*10*). We address final consumption by households, governments, and for investments, following the conventions of national accounts. We provide cross-country analysis of the CF of consumption as a function of per capita expenditure and grouped by continent.

The Intergovernmental Panel on Climate Change (IPCC) presents an extensive analysis of the sources of greenhouse gas emissions (*11*). There is no consideration, however, of the ultimate purpose of production activities that cause greenhouse gas emissions. Only the transportation chapter addresses emissions connected to the production of transportation fuels, focusing on well-to-wheel analysis. It ignores, however, the production of the vehicles. As we show in the Supporting Information, the production of motor vehicles alone emitted 800 million metric tons of $CO_2$ equivalent ($MtCO_2e$) in 2001, comparable to aviation. To get a proper picture of the carbon footprint of transportation, one must include the production of the vehicles. Life-cycle assessments show that about half of the GHG emissions of car manufacturing are related to materials (*12*), and because car manufacturing has complex international supply chains, a detailed analysis of the emissions from the production of imported products is essential. Hence, a global trade-linked methodology is necessary to correctly attribute the IPCC emission sources to consumption activities.

Ayres and Kneese (*13*) have pointed out that GHG emissions are an integral part of our system of production and consumption and have provided an overall intellectual framework of addressing this connection. What is now called footprint analysis goes back to the net energy analysis and the concept of "the energy cost of living" developed in the 1970s (*14*). There has been a resurgence of interest in household environmental impacts (*8, 15*) and integrated product policy (*16*), but there have been few studies that quantify the impacts of government services or investments (*17*). The carbon intensity of different economies varies substantially (*11*), but lacking comparable international data,

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most studies apply the "import assumption" of identical carbon intensities of imported and domestic products (*17*). Only recently, multiregional input−output analysis has been applied to better reflect the import intensities (*18*−*21*). Still, these studies focus only on a single country. Although a wide range of studies for individual countries has been published, these studies differ in methodology, so that results are not strictly comparable and a meta-analysis of variations across countries is problematic.

This paper is to our knowledge the first paper that analyzes and compares the carbon footprint of different countries using a single, trade-linked model of the global economy. The advantage of our approach is that it offers a consistent methodology facilitating comparisons and better estimates of emissions embodied in trade. Previous comparisons across nations had to face the difficulty of divergent methodologies and categorizations (*5, 8*) or apply intensities derived for one country to other countries (*15, 22*). The disadvantage of our approach is the data requirement of a global model and subsequent compromises in data quality and product-level resolution (*23*). Despite this, our study still offers the most consistent global comparison across countries currently available.

## Methods and Data

We use a fully coupled multiregional input−output (MRIO) model (*24*) constructed using the Global Trade Analysis Project (GTAP) database (*25*) supplemented with data on $CO_2$ emissions (*26, 27*) and non-$CO_2$ greenhouse gas emissions (*28, 29*). The fully coupled MRIO model includes all trade linkages between regions. The core of the MRIO model is the MRIO table that shows the requirements of domestic and imported products from each sector in each region. The structure of a fully coupled MRIO model is explained elsewhere (*30*), but the main challenge for MRIO analysis is the construction of the MRIO table and emissions data (*24*).

We have used the GTAP database version 6 as the basis for the MRIO table (*25*). The GTAP database contains the input−output tables (IOT) and bilateral trade statistics for 57 sectors and 87 regions. The GTAP regions cover 72 individual countries and 15 aggregated regions. The aggregated regions represent geographically similar countries where no input−output data was collected, for example, the "rest of Oceania" includes all of the countries in Oceania not including Australia and New Zealand, and the IOT is estimated as a weighted average of Australia and New Zealand (*25*). The GTAP database is balanced, so we did not need to perform additional balancing procedures. The only modification to the GTAP data was to proportionally allocate the bilateral trade data across the interindustry requirements and final consumption of imported products to construct the final MRIO table (*28, 31*).

We supplemented the GTAP IOT and trade data with additional data on the greenhouse gas emission intensity in each sector. The $CO_2$ data was based on the GTAP data set (*27*); however, we overwrote some of the GTAP $CO_2$ data where better data was available and performed several manipulations to improve the accuracy of the data in comparison to national statistics (*24*). Comparisons found this data to be of higher quality than the GTAP $CO_2$ emissions data. Direct emissions of households are derived from fuel use by households, with a default allocation to mobility and shelter. The non-$CO_2$ data set used in this study was constructed for use with the GTAP data (*29*). The only modification was to include non-$CO_2$ GHG emissions from biomass, which are not included in the GTAP data set (*28*). We weighted the GHG together to form $CO_2$ equivalents, using 100 year global warming potentials (*10*). We did not include the sources and sinks of land use, land use change,

**TABLE 1. Volume of GHG Emissions in 2001 as Represented in the Modified GTAP Database**

| gas | emissions [Gt $CO_2$e] |
|---|---|
| $CO_2$ | 24.75 |
| $CH_4$ | 6.13 |
| $N_2O$ | 3.45 |
| F | 0.41 |

and forestry (LULUCF) because of the difficultly in allocating to economic activity. In many countries LULUCF is the dominant source of emissions, thus care should be taken to note that these results only consider the emissions of fossil fuels and process emissions (*44*). The model and data set are fully documented in other publications (*24, 26, 28, 29*).

Although the GTAP database has impressive coverage, care needs to be taken with its consistency and accuracy. Generally, original data are supplied by the members of the GTAP in return for free subscriptions. The data are often from reputable sources such as national statistical offices. Unfortunately, because of the voluntary nature of data submissions, the data are not always the most recently available. Furthermore, once the original data has been received "[GTAP] make[s] further significant adjustments to ensure that the I−O table matches the external macroeconomic, trade, protection, and energy data" (*25*). These adjustments (or calibrations) are made for internal consistency in computable general equilibrium modeling and are of unknown magnitude. However, if we constructed the MRIO table independently, significant manipulations would be required to balance the MRIO table and adjust inconsistent data (*21*). In addition, although GTAP has a lower sector resolution than some studies (*21, 32*), it has considerably more country detail, allowing a more realistic representation of production in other countries. Thus, it is not possible to say in advance if the GTAP data set is more or less accurate than others.

## Results

The total emissions analyzed are 24.7 Gt of $CO_2$ and 9.5 Gt $CO_2$ equivalent of non-$CO_2$ greenhouse gases, as listed in Table 1. These values represent the emissions data constructed for the GTAP database and, therefore, approximate but do not agree exactly with other emission statistics. The average per capita footprint varies from just over 1 t per person per year (py) for several African countries and Bangladesh to 28 t/py for the United States and 33 t/py for Luxemburg (Table 2). A number of countries of interest for footprint analysis are unfortunately not represented as individual countries in the GTAP database such as the entire Middle East, except for Turkey, and a disproportionately large number of poor countries in Africa, Southeast Asia, and Latin America.

The footprint is strongly correlated with per capita consumption expenditure (Figure 1). Elasticities were derived using a regression of log-transformed data, measuring the slope in Figure 1. The pattern shown in Figure 1 indicates that $CO_2$ increases strongly with expenditure, with an elasticity $\varepsilon = 0.81$ ($r^2 = 0.88$), while other greenhouse gases increase less, $\varepsilon = 0.32$ ($r^2 = 0.63$). In fact, methane- and nitrous oxide-related food production tend to be more important than fossil $CO_2$ for expenditures to \$1000/year. For all GHGs, $\varepsilon = 0.57$ ($r^2 = 0.88$). This means that as nations become wealthier the CF increases by 57% for each doubling of consumption. Because the elasticity is less than 1, the carbon intensity of consumption deceases with rising expenditure. For the variation of the "energy cost of living" within countries, $\varepsilon \sim 0.8$ is quite common (*8, 14, 33*), but the

**TABLE 2. Per Capita GHG Footprint of Nations in 2001**

| country | footprint [$tCO_2e/p$] | domestic share | population (million) | construction[a] | shelter[a] | food[a] | clothing[a] | manufactured products[a] | mobility[a] | service[a] | trade[a] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Albania | 2.5 | 61% | 3.4 | 9% | 13% | 35% | 3% | 6% | 17% | 10% | 8% |
| Argentina | 6.5 | 88% | 37.5 | 4% | 12% | 39% | 3% | 6% | 18% | 12% | 6% |
| Australia | 20.6 | 82% | 19.4 | 9% | 21% | 16% | 2% | 8% | 16% | 16% | 11% |
| Austria | 13.8 | 48% | 8.1 | 7% | 17% | 12% | 3% | 15% | 28% | 16% | 5% |
| Bangladesh | 1.1 | 86% | 132.1 | 7% | 13% | 55% | 3% | 4% | 6% | 11% | 0% |
| Belgium | 16.5 | 46% | 10.3 | 8% | 17% | 14% | 5% | 19% | 25% | 14% | 3% |
| Botswana | 5.1 | 54% | 1.6 | 10% | 8% | 31% | 1% | 11% | 11% | 26% | 2% |
| Brazil | 4.1 | 88% | 172.3 | 6% | 5% | 43% | 2% | 7% | 19% | 15% | 4% |
| Bulgaria | 6.1 | 81% | 8.1 | 7% | 32% | 14% | 1% | 4% | 10% | 28% | 7% |
| Canada | 19.6 | 75% | 31.2 | 8% | 18% | 8% | 2% | 9% | 30% | 18% | 6% |
| Chile | 4.9 | 73% | 15.4 | 8% | 11% | 26% | 6% | 10% | 27% | 12% | 5% |
| China | 3.1 | 94% | 1269.9 | 25% | 12% | 27% | 3% | 10% | 8% | 15% | 2% |
| Colombia | 3.4 | 89% | 43.0 | 5% | 7% | 45% | 2% | 5% | 15% | 16% | 5% |
| Croatia | 6.9 | 66% | 4.4 | 4% | 28% | 20% | 2% | 15% | 21% | 11% | 2% |
| Cyprus | 15.9 | 46% | 0.8 | 17% | 13% | 16% | 5% | 12% | 21% | 10% | 7% |
| Czech Republic | 10.8 | 75% | 10.2 | 2% | 34% | 15% | 2% | 11% | 13% | 22% | 3% |
| Denmark | 15.2 | 68% | 5.3 | 11% | 24% | 12% | 4% | 10% | 34% | 18% | 5% |
| Estonia | 12.4 | 78% | 1.4 | 5% | 49% | 9% | 1% | 9% | 15% | 18% | 1% |
| Finland | 18.0 | 67% | 5.2 | 8% | 24% | 12% | 2% | 13% | 18% | 16% | 9% |
| France | 13.1 | 64% | 59.5 | 8% | 19% | 16% | 3% | 16% | 19% | 16% | 4% |
| Germany | 15.1 | 63% | 82.0 | 8% | 22% | 13% | 4% | 11% | 22% | 17% | 5% |
| Greece | 13.7 | 65% | 10.6 | 14% | 16% | 19% | 3% | 10% | 18% | 15% | 5% |
| Hong Kong | 29.0 | 17% | 7.2 | 13% | 8% | 7% | 28% | 20% | 11% | 9% | 7% |
| Hungary | 9.5 | 76% | 10.0 | 6% | 35% | 14% | 1% | 9% | 14% | 19% | 6% |
| India | 1.8 | 95% | 1032.1 | 8% | 14% | 41% | 3% | 9% | 12% | 10% | 3% |
| Indonesia | 1.9 | 89% | 213.3 | 8% | 20% | 28% | 1% | 4% | 22% | 16% | 1% |
| Ireland | 16.0 | 56% | 3.8 | 9% | 15% | 20% | 3% | 7% | 23% | 17% | 8% |
| Italy | 11.7 | 62% | 57.5 | 9% | 16% | 14% | 4% | 15% | 20% | 16% | 6% |
| Japan | 13.8 | 68% | 126.8 | 14% | 12% | 11% | 4% | 15% | 22% | 18% | 8% |
| Korea | 9.2 | 75% | 47.6 | 11% | 15% | 12% | 3% | 12% | 32% | 19% | 7% |
| Latvia | 6.7 | 58% | 2.4 | 8% | 23% | 18% | 2% | 12% | 21% | 18% | 7% |
| Lithuania | 5.9 | 59% | 3.7 | 7% | 21% | 20% | 2% | 11% | 19% | 17% | 9% |
| Luxembourg | 33.8 | 56% | 0.4 | 10% | 14% | 11% | 2% | 17% | 51% | 11% | 3% |
| Madagascar | 1.5 | 90% | 16.0 | 3% | 7% | 59% | 2% | 1% | 5% | 22% | 0% |
| Malawi | 0.7 | 83% | 11.3 | 1% | 15% | 26% | 1% | 8% | 6% | 41% | 3% |
| Malaysia | 4.2 | 81% | 23.7 | 9% | 17% | 12% | 1% | 13% | 31% | 25% | 2% |
| Malta | 13.0 | 35% | 0.4 | 2% | 24% | 12% | 2% | 17% | 19% | 21% | 3% |
| Mexico | 5.6 | 77% | 100.9 | 9% | 12% | 18% | 3% | 11% | 29% | 14% | 4% |
| Morocco | 1.9 | 73% | 29.2 | 15% | 12% | 22% | 1% | 8% | 12% | 29% | 2% |
| Mozambique | 1.1 | 86% | 18.0 | 6% | 11% | 46% | 1% | 2% | 5% | 28% | 2% |
| Netherlands | 16.7 | 53% | 16.0 | 8% | 18% | 12% | 3% | 14% | 21% | 23% | 7% |
| New Zealand | 11.4 | 69% | 3.8 | 7% | 15% | 19% | 3% | 10% | 21% | 16% | 14% |
| Norway | 14.9 | 44% | 4.5 | 6% | 7% | 15% | 3% | 14% | 28% | 21% | 6% |
| Peru | 2.6 | 83% | 26.1 | 7% | 7% | 37% | 4% | 6% | 20% | 13% | 6% |
| Philippines | 1.9 | 76% | 79.9 | 8% | 13% | 36% | 1% | 5% | 17% | 17% | 4% |
| Poland | 8.7 | 87% | 38.7 | 6% | 31% | 18% | 1% | 10% | 16% | 13% | 8% |
| Portugal | 10.8 | 60% | 10.0 | 18% | 9% | 20% | 4% | 12% | 15% | 19% | 4% |
| Romania | 5.2 | 84% | 22.3 | 7% | 33% | 17% | 1% | 11% | 17% | 15% | 2% |
| Russian Federation | 10.1 | 92% | 145.7 | 9% | 40% | 15% | 1% | 3% | 16% | 17% | 1% |
| Singapore | 24.1 | 36% | 3.3 | 9% | 11% | 8% | 2% | 24% | 28% | 21% | 11% |
| Slovakia | 8.0 | 68% | 5.4 | 11% | 28% | 18% | 2% | 12% | 15% | 19% | 3% |
| Slovenia | 11.9 | 64% | 2.0 | 13% | 15% | 15% | 2% | 10% | 26% | 20% | 4% |
| South Africa | 6.0 | 90% | 43.4 | 5% | 21% | 21% | 2% | 10% | 17% | 15% | 9% |
| Spain | 10.9 | 65% | 39.4 | 14% | 14% | 17% | 3% | 12% | 21% | 12% | 10% |
| Sri Lanka | 1.4 | 67% | 19.4 | 8% | 12% | 27% | 3% | 8% | 20% | 19% | 4% |
| Sweden | 10.5 | 54% | 8.9 | 9% | 12% | 16% | 3% | 12% | 29% | 23% | 6% |
| Switzerland | 18.4 | 36% | 7.2 | 6% | 19% | 11% | 3% | 15% | 26% | 13% | 6% |
| Taiwan | 11.3 | 68% | 22.3 | 10% | 17% | 14% | 2% | 16% | 21% | 15% | 7% |
| Tanzania | 1.2 | 90% | 34.5 | 1% | 22% | 45% | 2% | 3% | 5% | 21% | 2% |
| Thailand | 3.2 | 78% | 62.8 | 11% | 12% | 21% | 4% | 8% | 25% | 17% | 2% |
| Tunisia | 3.0 | 68% | 9.7 | 11% | 15% | 21% | 4% | 12% | 21% | 14% | 4% |
| Turkey | 4.6 | 82% | 66.2 | 9% | 15% | 27% | 3% | 10% | 24% | 9% | 5% |
| Uganda | 1.1 | 91% | 22.6 | 4% | 9% | 61% | 0% | 1% | 6% | 16% | 3% |
| United Kingdom | 15.4 | 62% | 59.3 | 7% | 21% | 14% | 3% | 15% | 22% | 10% | 11% |
| United States | 28.6 | 82% | 277.5 | 7% | 25% | 8% | 3% | 12% | 21% | 16% | 8% |
| Uruguay | 6.8 | 77% | 3.4 | 5% | 3% | 59% | 3% | 6% | 12% | 9% | 3% |
| Venezuela | 8.1 | 88% | 24.7 | 7% | 10% | 20% | 3% | 11% | 32% | 11% | 7% |
| Vietnam | 1.7 | 80% | 79.5 | 20% | 15% | 40% | 1% | 6% | 8% | 12% | 1% |
| Zambia | 2.1 | 88% | 10.3 | 2% | 5% | 67% | 1% | 3% | 5% | 18% | 1% |
| Zimbabwe | 2.0 | 79% | 12.3 | 3% | 20% | 38% | 3% | 6% | 12% | 16% | 4% |

[a] Contribution of different consumption categories.

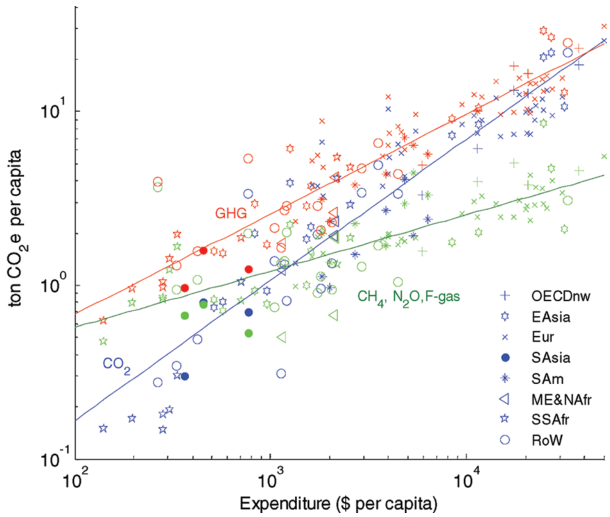


**FIGURE 1. Per capital greenhouse gas emissions due to the consumption in different countries as a function of consumption volume, base year 2001. Blue indicates $CO_2$, green other GHGs, and red total GHGs measured in GWP-100. The regions are: OECD new world, East Asia, Europe, South Asia, South America, Middle East and North Africa, Sub-Saharan Africa, and Rest-of-World.**

relationship is not always straightforward and $\varepsilon$ tends to be larger for developing countries (*33*). It is, hence, the inclusion of non-$CO_2$ greenhouse gases that provides for a flatter increase.

Figure 2 provides an overview of the consumption categories and final uses responsible for these emissions. On the global level, 72% are related to household consumption, 10% to government consumption (compared to a 16% share in global GDP), and 18% to investments (compared to a 21% share in global GDP). Nutrition is the most important consumption category, with food accounting for nearly 20% of the GHG emissions. Because we include the supply chain in our analysis, methane and nitrous oxides from agricultural production play a significant role. "Shelter", the operation and maintenance of residences, causes 19% of the emissions, most of it related to the direct energy consumption by the buildings. Unlike the convention in household environmental impact studies (*8*), the sectoral detail in the GTAP data did not allow us to allocate furniture or cleaning products to the category of shelter; they are rather grouped under manufactured products. The construction of buildings is mostly allocated to investments, together with the construction of infrastructure. Construction accounts for 10% of the CF globally. Mobility for private households accounts for 17% of the emissions. Almost half of this is caused by fuel combustion by private motorists. Other important contributors are the production of motor vehicles and the purchase of air and land transport services. Freight transportation is allocated to consumed products and not private mobility. Services apart from wholesale and retail trade margins account for a total of 16%, where "public administration, defense, health, and education" is by far the most important with 11%. Trade margins account for 5.5% and represent the accumulated emissions from distribution between the producer and final consumer. Manufactured products cause a total of 13% of the CF, whereas clothing represents 2.8%, machinery and equipment account for 5%, followed by the household consumption of chemical products and the consumption of electronic equipment.

The CF by consumption category in Figure 3 confirms the general pattern that food is of dominant importance for poor countries, while mobility becomes more important for rich countries (*8*). Looking in more detail on a country-by-country breakdown (Table 2 and Figure 3), we find many general features emerge. The CF of food generally falls in a narrow band between 0.4 and 4 $tCO_2e$/py. We are not very confident about the lower boundary because of the difficulties of accounting for subsistence agriculture and the difficult emission measurements for $CH_4$ and $N_2O$. Elasticity for food has the lowest $r^2$, probably reflecting geographical conditions affecting diets and production methods (Table 3). The CF of shelter is to a significant degree driven by climate and energy for heating and cooling. Countries in cold climates generally have a larger fraction of their footprint connected to shelter such as 40% in Russia. Countries in warm climates have significant footprints from shelter only if they have achieved a certain level of wealth such as Spain or Greece. The spread is wider here, from 0.1 t/py (Africa) to 7 t/py (United States). Mobility is strongly correlated with expenditure, from 0.05 (Africa) to 6 t/c (United States). In rich countries, mobility rivals shelter in importance, and on average, it is more important.

The share of manufacturing in the overall CF is around 10−15% for most OECD countries, around 10% for emerging countries, and distinctly lower for poor countries. The service sector is almost linearly related to expenditure. It contributes 10−20% to the total CF. Much of this is related to public services, education, and health. The relatively even share across nations is actually surprising because the share of services in total employment and GDP is often taken as an indicator for the level of development. For many economies, the contribution of construction is around 10%. The high levels in China (25%) and Vietnam (20%) reflect a general trend of large investments as countries develop (*34*).

An uncertainty analysis of the presented results would require a wide range of uncertainty information on the input data and substantial computational power. There is only one available MRIO study quantifying the uncertainty in the CF of a country using the Monte Carlo analysis (*35*). This study and other information on the uncertainty of input parameters (*17, 36*−*39*) was used to provide a rough estimate of the uncertainty in the results, which is indicated in Table 4. We can see high uncertainties in the CF of individual goods but surprisingly low uncertainties in the CF of nations (*35*). This has two reasons. First, the national carbon footprint is the sum of many small contributions that are not correlated and, following the law of large numbers, the relative uncertainty in sum is smaller than the uncertainty in the components. Second, the sum of total household consumption or total output of specific sectors is usually much better known than the composition of the consumption or destination of the output. Such constraints on the distribution of individual data points are not always represented in the modeling. In our judgment, the uncertainty in emissions of different industry sectors and the uncertainty of the input−output and trade calculations have an about equal contribution to the uncertainty in CF results. Further discussion on the uncertainties is found in the Supporting Information.

## Discussion

This study confirms the conclusions of earlier studies on the importance of consumption categories for the overall household environmental impact (*5, 6, 8*). Indirect impacts in the supply chain are more important than direct impacts in the household. Shelter (including its construction), food, and mobility are the most important consumption categories. Figure 3 and the regression lines for consumption categories shown in Figure 4, however, indicate there is a substantial degree of structural change in consumption patterns with rising income. Food and, surprisingly, services are relatively more important at low income. The variation in GHG emissions for food consumption across countries is not as

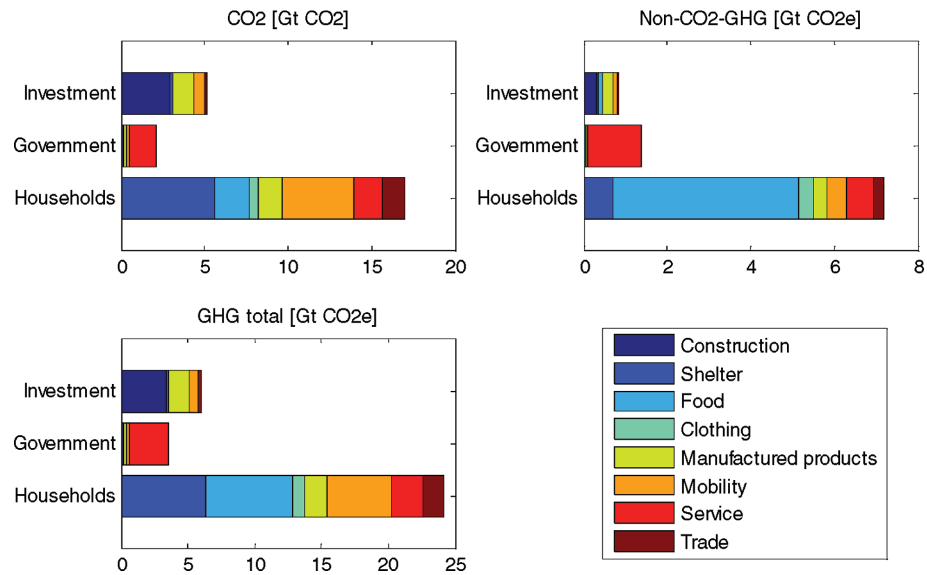


**FIGURE 2. Global $CO_2$ and non-$CO_2$ greenhouse gas footprint for different consumption categories and users.**

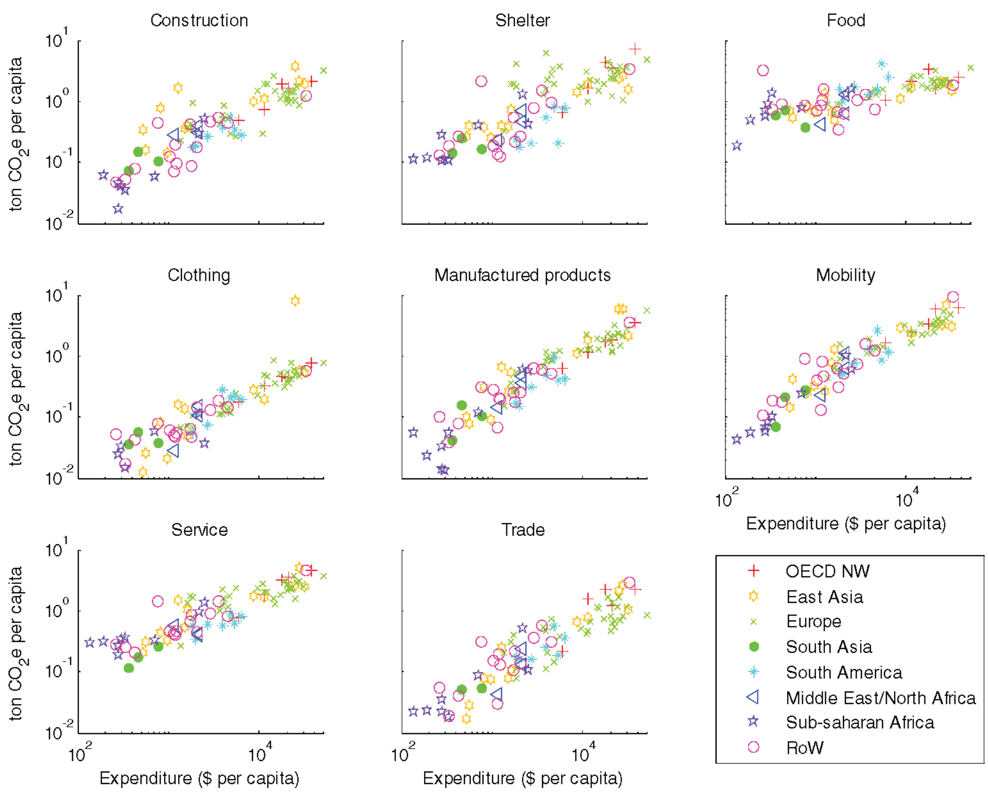


**FIGURE 3. Carbon footprint (ton $CO_2$ equivalent per capita in 2001) of different consumption categories in 87 countries and regions as a function of expenditure measured in United States dollars per capita.**

well explained by expenditure differences and should be investigated further. The large share of public services also warrants further investigation. In GTAP, "public administration, defense, health, and education" are a single sector but country-level studies would offer more detail. In China, for example, public administration accounts for about half of the total public services CF, while education accounts for 20% and health for 10%. There is a wide range of inputs to public administration, with electricity contributing the most at 18%. Our results confirm that services are more important than initially believed, consistent with other analysis (*40*).

At high expenditure, mobility and the consumption of manufactured goods cause the largest GHG emissions. We expect the importance of these categories to increase with further increases in income as consumers purchase more luxury items relative to necessities. Manufactured goods are also the category where international trade is most important and issues of carbon leakage need to be addressed (*26*). Mobility is an area where even advanced technologies may be insufficient to reduce GHG emissions to sustainable levels, so that limiting demand and modals shifts are unavoidable. The category of shelter can also be important in high-income countries but can be reduced more easily through passive house technology (*41*).

Statistical analysis indicates that the CF per unit expenditure is lower in rich countries than in poor countries. CF elasticity with increasing expenditure levels corresponds surprisingly well with observations of reduced energy and

**TABLE 3. Monetary and Carbon Footprint Elasticity of Consumption Categories[a]**

| consumption category | expenditure elasticity $\varepsilon$ | expenditure elasticity $r^2$ | GHG elasticity $\varepsilon$ | GHG elasticity $r^2$ | GHG emissions (t/py) at various expenditure levels $300/py | $4000/py | $50000/py |
|---|---|---|---|---|---|---|---|
| construction | 0.99 | 0.93 | 0.74 | 0.76 | 0.07 | 0.45 | 2.9 |
| shelter | 0.97 | 0.90 | 0.65 | 0.67 | 0.17 | 0.92 | 4.8 |
| food | 0.64 | 0.92 | 0.29 | 0.54 | 0.61 | 1.3 | 2.6 |
| clothing | 0.91 | 0.89 | 0.79 | 0.84 | 0.02 | 0.15 | 1.1 |
| manufactured products | 1.09 | 0.96 | 0.88 | 0.88 | 0.06 | 0.55 | 5.0 |
| mobility | 1.07 | 0.96 | 0.83 | 0.90 | 0.12 | 1.06 | 8.7 |
| service | 1.16 | 0.98 | 0.55 | 0.79 | 0.25 | 1.04 | 4.1 |
| trade | 0.99 | 0.93 | 0.88 | 0.77 | 0.03 | 0.26 | 2.5 |
| total | | | | | 1.3 | 5.7 | 32 |

[a] These values are a function of total per capita consumption expenditure and emission levels at three expenditure levels calculated by regression.

**TABLE 4. Sources of Parameter Uncertainty in the Calculation of Carbon Footprints and Resulting Relative Mean Error[a]**

| uncertain parameters | further specification | relative mean error |
|---|---|---|
| emissions coefficients | $CO_2$ OECD | 5−10% (*37, 45*) |
| | $CO_2$ non-OECD | 10−20% (*37, 38*) |
| | $CH_4$ | 30−50% (*36*) |
| | $N_2O$ | 35−230% (*36*) |
| input−output coefficients | small inputs have a much larger uncertainty than large inputs | 1−50% (*17, 35, 39*) |
| trade inputs | uncertainty in trade volumes | 10% |
| | uncertainty about country of origin | 20% |
| consumption | what is really bought | 10% |
| uncertainty in results | | |
| CF of goods | for the national consumption of a good | 50−200% (*35*) |
| CF of consumption categories | | 10−40% |
| CF of countries | | 5−15% (*35, 46*) |

[a] Values are based on our judgment and supported by the literature where indicated.

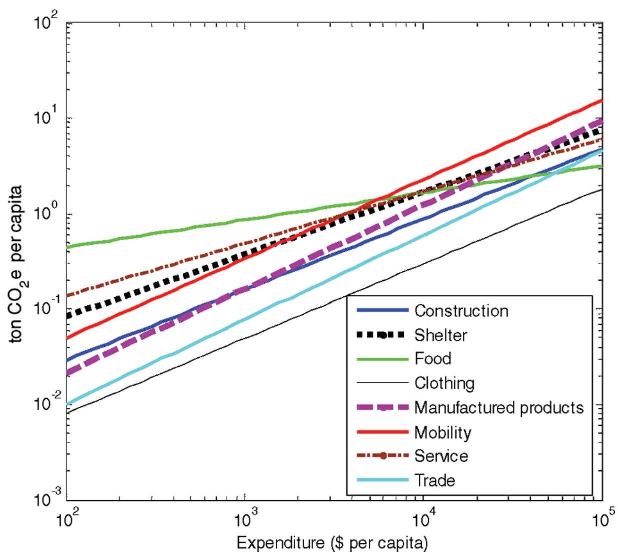


**FIGURE 4. Regression lines for the carbon footprint of different consumption categories as a function of expenditure level.**

carbon intensity with economic growth in longitudinal studies (*42, 43*), which suggests that with economic growth, countries move from left to right in Figure 4. An interesting question is whether the lowering of carbon intensity is due to better technology, structural change in what is consumed, or lower prices for necessities in poorer countries. Does wealth lead to improved quality of products purchased (or other nonmaterial attributes such as design or product differentiation), more efficient production processes, or a shift toward services with an increase in manufactured imports? These questions have significant implications for future mitigation strategies, and cross-sectional analysis may help answer them. We suggest that future analysis should focus on physical quantities and quality descriptors of what is consumed to remove potential biases in the use of monetary data. In addition, longitudinal studies are needed to assess how the global production system and, hence, emissions change with increasing income as individual countries develop.

Another motivation for this study is to provide a different perspective on the drivers for GHG emissions at the global level. The current focus on the emission sources is useful for compiling statistics and understanding the global carbon cycle but is insufficient to design mitigation policy (*44*). The IPCC emission inventories do not reveal any information about what causes emissions; they only reveal that the emissions occur. Studies such as this one are an attempt to reallocate standard emission inventories to consumption activities that are more relevant for policy makers (*31*). Although international climate agreements may still be based around the standard IPCC emission inventory methods, the design of mitigation policy must consider the underlying drivers for emissions. Ultimately, our daily consumption and production decisions drive global emissions.

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## Supporting Information Available

Discussion of sources and effects of uncertainty, information on the continental distribution of emissions, versions of Figure 3 for separating $CO_2$ from the other GHGs, and a different view of Figure 4. In addition, a table shows the CF of purchases on the IO-sector level. Further country-level information is available at http://carbonfootprintofnations.com. This material is available free of charge via the Internet at http://pubs.acs.org.

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