nature climate change

ARTICLES

https://doi.org/10.1038/s41558-018-0141-x

The carbon footprint of global tourism

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Tourism contributes significantly to global gross domestic product, and is forecast to grow at an annual 4%, thus outpacing many other economic sectors. However, global carbon emissions related to tourism are currently not well quantified. Here, we quantify tourism-related global carbon flows between 160 countries, and their carbon footprints under origin and destination accounting perspectives. We find that, between 2009 and 2013, tourism's global carbon footprint has increased from 3.9 to 4.5 GtCO$_2$e, four times more than previously estimated, accounting for about 8% of global greenhouse gas emissions. Transport, shopping and food are significant contributors. The majority of this footprint is exerted by and in high-income countries. The rapid increase in tourism demand is effectively outstripping the decarbonization of tourism-related technology. We project that, due to its high carbon intensity and continuing growth, tourism will constitute a growing part of the world's greenhouse gas emissions.

Global tourism is a trillion-dollar industry, representing in the order of 7% of global exports and contributing significantly to global gross domestic product (GDP)[1]. International arrivals and tourism receipts have been growing at an annual 3–5%, outpacing the growth of international trade, and in 2016 exceeded 1 billion and US$1.2 trillion, respectively[1,2]. Clearly, economic activity at this scale has a significant impact on the environment[3]. In particular transport, a key ingredient of travel, is an energy- and carbon-intensive commodity, rendering tourism a potentially potent contributor to climate change. The sensitivity and vulnerability of destinations (such as winter- and coastal-recreation locations) to weather and climate change also suggest that, as a result of climate change, the tourism industry will in turn undergo drastic future change and will need to adapt to increasing risk[4]. Given future projections of an unabated 4% growth beyond 2025[1,2], the continuous monitoring and analysis of carbon emissions associated with tourism is becoming more pressing.

By definition, the carbon footprint of tourism should include the carbon emitted directly during tourism activities (for example, combustion of petrol in vehicles) as well as the carbon embodied in the commodities purchased by tourists (for example, food, accommodation, transport, fuel and shopping; Supplementary Section 1). Tourism carbon footprints therefore need to be evaluated using methods that cover the life cycle or supply chain emissions of tourism-related goods and services (Supplementary Section 1). Life-cycle assessment[5–7] and input–output analysis[8–14] have been used to quantify the carbon footprint of specific aspects of tourism operations such as hotels[5], events[6] and transportation infrastructure[7,15], and in particular countries (or regions thereof) such as Spain[5,10,11], the UK[8], Taiwan[9], China[15], Saudi Arabia[6], Brazil[7], Iceland[14], Australia[13] and New Zealand[12].

Previous estimates of global CO$_2$ emissions from selected tourism sectors give values of 1.3 and 1.17 GtCO$_2$ for 2005[16,17] and 1.12 Gt for 2010[18], amounting to about 2.5–3% of global CO$_2$-equivalent (CO$_2$e) emissions. However, these analyses do not cover the supply chains underpinning tourism, and do not therefore represent true carbon footprints. A WTO–UNEP–WMO report[16] states that (p. 134) '[t]aking into account all lifecycle and indirect energy needs related to tourism, it is expected that the sum of emissions would be higher, although there are no specific data for global tourism available'. Similarly, Gössling and Peeters[18] state that (p. 642) "… a more complete analysis of the energy needed to maintain the tourism system would also have to include food and beverages, infrastructure construction and maintenance, as well as retail and services, all of these on the basis of a life cycle perspective accounting for the energy embodied in the goods and services consumed in tourism. However, no database exists for these and the estimate thus must be considered conservative."

This work fills an important knowledge gap by offering a comprehensive calculation of the carbon footprint of global tourism. We source the most detailed compendium of tourism satellite accounts (TSAs) available so far (55 countries with individual TSAs and 105 countries with United Nations World Tourism Organization (UNWTO) data; Supplementary Sections 2.2 and 3.1.2), integrate this into a comprehensive global multi-region input–output (MRIO) database (Supplementary Section 2.5), and use Leontief's standard model (Section 'Input-output analysis') to establish carbon footprint estimates that cover both the direct and indirect, supply chain contributions of tourist activities. In addition, we advance current knowledge by (1) including not only emissions of CO$_2$ but also those of CH$_4$, N$_2$O, hydrofluorocarbons (HFCs), chlorofluorocarbons (CFCs), SF$_6$ and NF$_3$ (Supplementary Section 3.2), (2) presenting an annual carbon footprint time series from 2009 to 2013, (3) analysing drivers of change, (4) providing details about carbon-intensive supply chains, and (5) comparing two accounting perspectives.

The two accounting perspectives mentioned in the final point (5) are residence-based accounting (RBA) and destination-based accounting (DBA). Both perspectives are variants of the well-known consumption-based accounting principle[19]; however, while RBA allocates consumption-based emissions to the tourist's country of residence, DBA allocates them to the tourist's destination country[13]. The two perspectives serve clear and distinct purposes. RBA can shed light on the determinants of travel choices, such as

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travel frequency, distance and transportation modes, reflecting the greenhouse gas (GHG) responsibility borne by travellers. RBA-based emissions therefore match the scope and definition of the conventional carbon footprint. DBA is required to assess options for managing the carbon footprint of tourism operations at the destination, for example by improving the carbon efficiency of local technology, or imposing market-based measures for international aviation[20]. Ultimately, RBA and DBA can be used to evaluate the progress of mitigation strategies proposed by the UNWTO, aiming at changing travel behaviour at departure points and encouraging technology improvement at destinations.

Results

On the back of a growth in tourist expenditure from US\$2.5 trillion in 2009 to US\$4.7 trillion in 2013, the global carbon footprint increased rapidly from 3.9 to 4.5 $GtCO_2e$ during the same period (Supplementary Section 4.1), representing about 8% of global GHG emissions (certain within ±7% at the 95% level of confidence; Supplementary Sections 2.6 and 4.3). Using production layer decomposition (Supplementary Section 4.5), we estimate 2013 direct emissions from tourism operations to be about 2.9 $GtCO_2e$ (exceeding previous estimates[16–18] because of our more complete scope; Supplementary Section 4.4), demonstrating that including all upstream supply chains leads to the addition of at least another 1–2 $GtCO_2e$ that have so far been absent from global tourism studies (Supplementary Sections 4.4 and 4.5).

The United States tops the carbon footprint ranking (Fig. 1, top left) under both DBA (1,060 $MtCO_2e$) and RBA (909 $MtCO_2e$) accounting perspectives, followed by China (528/561 $MtCO_2e$), Germany (305/329 $MtCO_2e$) and India (268/240 $MtCO_2e$). The majority of these carbon footprints are caused by domestic travel. In per capita terms, small-island destinations feature some of the highest destination-based footprints per capita (Fig. 1, top right), mostly due to international visitors. In countries such as the Maldives, Mauritius, Cyprus and the Seychelles, international tourism represents between 30 and 80% of national emissions.

International travel footprints. When taking the difference between RBA and DBA footprints, domestic travel cancels out, and the resulting net balance reflects only international travel. This means that the Unites States and India are 'net destinations', and that China and Germany are 'net origins' (Fig. 1, bottom left). On a per capita basis, 'net travellers' such as Canadians, Swiss, Dutch, Danish and Norwegians exert a much higher carbon footprint elsewhere than others in their own country. In contrast, 'net hosts' such as islanders and residents of popular tourist destinations such as Croatia, Greece and Thailand shoulder much higher footprints from their visitors than they exert elsewhere (Fig. 1, bottom right).

Further unravelling footprints into bilateral movements of embodied carbon shows that Canadians and Mexicans travelling to the United States are the two largest individual contributions, making up 2.7% of the global total (Fig. 2). The map of global carbon movements shows that travelling is largely a high-income affair, and as a result carbon embodied in tourism flows mainly between high-income countries acting both as traveller residence and destinations (Fig. 3 and Table 1). About half of the global total footprint was caused by travel between countries with a per capita GDP of more than US\$25,000 (for further details see Supplementary Section 4.1).

Gas species and supply chains. About 72% of the global footprint, or 3.6 $GtCO_2e$, is in the form of CO_2 stemming mostly from the combustion of fuels and land-use changes, with most of the remainder being CH_4 emitted from livestock (enteric fermentation and manure management) and during oil and gas extraction (venting and flaring; Supplementary Section 4.6). Emissions of N_2O and other GHGs were not found to be significant.

The proportion of CO_2 and CH_4 emitted during production is ultimately determined by the basket of commodities purchased for

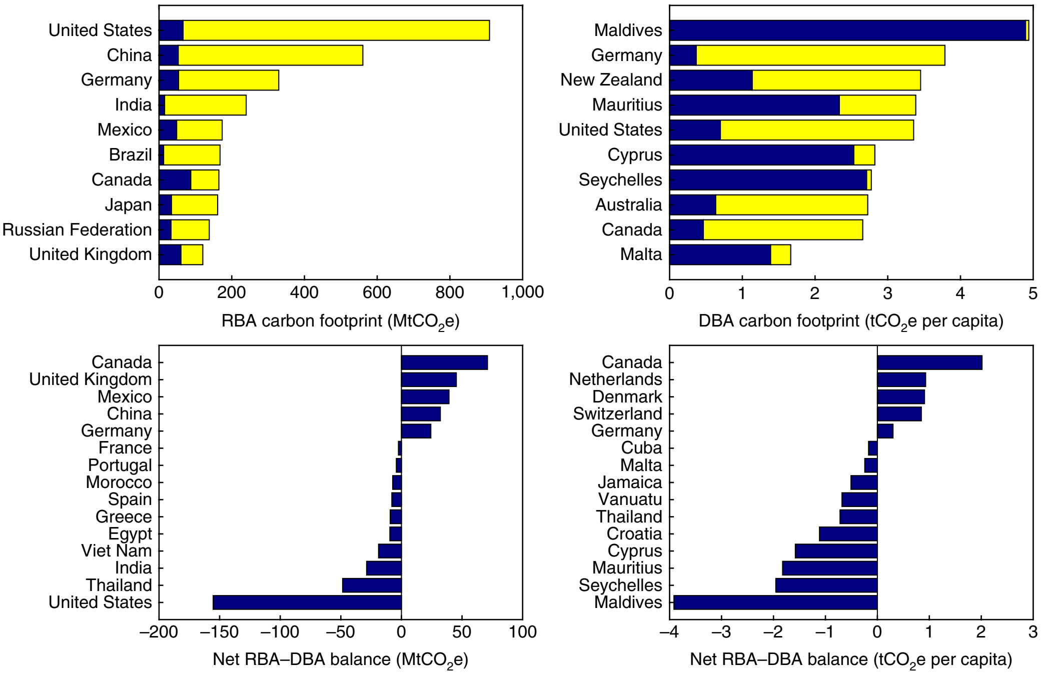

Fig. 1 | Carbon footprint measures of selected top-ranking countries for 2013. Top left, RBA carbon footprint by nationality of visitor. Blue, international travel; yellow, domestic travel. Bottom left, Net RBA–DBA balance. Positive for net origins; negative for net destinations. Top right, Per capita DBA carbon footprint by destination. Blue, international travel; yellow, domestic travel. Bottom right, Per capita net RBA–DBA balance. Positive for net travellers; negative for net hosts.

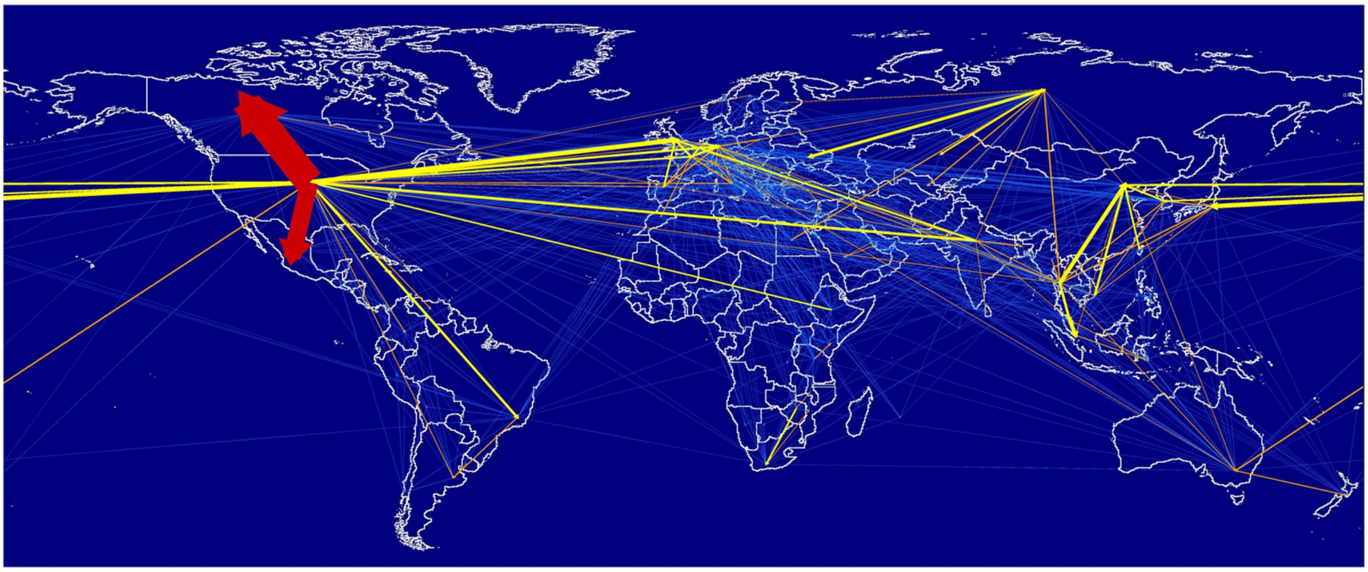

Fig. 2 | Top bilateral embodied carbon movements. In 2013, international travel caused a carbon footprint of about 1 $GtCO_2e$, or 23% of the global carbon footprint of tourism. Arrows point in the direction of embodied carbon flow, which—in accordance with the literature—is the direction of commodity trade, and is opposite to the movement of people. Red arrows: bilateral international movements belonging to the top 10% of the total 1 $GtCO_2e$. Yellow arrows: top 10–30%. Orange arrows: 30–50%. Blue arrows: the remainder.

consumption. Sectoral breakdown of tourism's carbon footprint at the production and consumption sides are quite different. For example, mining and utilities operate mainly at the production side to produce inputs into the downstream provision of tourism-related goods and services (Fig. 4). Visitors from and in high-income countries demand a high proportion of transport (especially by air), goods (shopping) and hospitality (accommodation and restaurants), reflecting their travel expectations (Fig. 4, top right). Visitors from and in low-income countries consume a high proportion of unprocessed food (listed under 'Ag') and road transport, and little commercial hospitality services (Fig. 4, bottom right), demonstrating that for this income group, travel mostly involves the bare necessities. Such consumer behaviour translates into different upstream emission profiles. While high-income visits are linked with mostly energy-related CO_2 emissions of transport operators (especially by air) and goods manufacturers, low-income visits include a high proportion of CO_2 from road transport, and non-energy CO_2 emissions and CH_4 emissions from farms. In this assessment, the contribution of air travel emissions amounts to 20% (0.9 $GtCO_2e$) of tourism's global carbon footprint (Supplementary Sections 4.4 and 4.6), which is due to our inclusion of (1) food and shopping, (2) upstream supply chains that are relatively insignificant for air travel, and (3) non-CO_2 GHG emissions, rendering food consumption in particular equally carbon-intensive.

These findings need to be qualified. First, we have not included direct non-CO_2 emissions from aviation into our assessment. In particular, contrails and aircraft-induced cloudiness could potentially play a significant role that could well alter air travel's contribution[21]. However, the effects on radiative forcing of short-lived GHGs emitted from subsonic aircraft remains largely unquantified, and we have been made aware of only one carbon footprint study[22] that includes these. Second, it could be argued that food, shopping and ground transport be counted net of what tourists would have eaten, purchased or travelled had they stayed at home. If only additional emissions were counted with reference to a stay-home scenario, air travel may well come out as the dominant emissions component. We do not attempt to quantify additionality for a number of reasons (Supplementary Section 1), but most importantly because food, shopping and transport by international visitors increase the carbon footprint of destinations, as opposed to the carbon footprints of the visitors' home country. These activities matter for international embodied carbon transfers[23].

Drivers and projections. The carbon footprint of global tourism is mainly determined by two factors: demand for and carbon intensity of tourism-related goods and services. The trends of these two factors are known to counteract one another[24]. In the case of tourism, an annual 7% or 5-year 30% increase in tourism-related expenditure during 2009–2013 has cancelled out all carbon intensity reductions (−2.7%/−12.9%), and caused the carbon footprint of global tourism to increase by 3.3% annually or 14% over the period (Supplementary Table 6). Half of the 540 $MtCO_2e$ carbon footprint growth occurred in high-income countries and due to high-income visitors (Supplementary Section 4.7); however, middle-income countries—notably China—recorded the highest growth rate (17.4% per year); Supplementary Section 4.7).

At around 1 $kgCO_2e$ per dollar of final demand (Supplementary Table 6c), the carbon multiplier (Section 'Input-output analysis') of global tourism is higher than those of global manufacturing (0.8 $kgCO_2e$ per US$) and construction (0.7 $kgCO_2e$ per US$), and higher than the global average (0.75 $kgCO_2e$ per US$). Growth in tourism-related expenditure is therefore a stronger accelerator of emissions than growth in manufacturing, construction or services provision.

The International Monetary Fund (IMF) projects the world's average per capita GDP to increase by 4.2% annually, from US$10,750 per year in 2017 to US$13,210 per year in 2022[25], which if true would squarely outpace the 2.2–3.2% average carbon intensity decline projected by the Organisation for Economic Co-operation and Development and the US Energy Information Administration[26,27]. What influence are such developments likely to have on the carbon footprint of global tourism? To obtain an indication of possible future trends we carried out a multiple regression of 2009–2013 per capita carbon footprints (RBA) against three explanatory variables—per capita GDP ('affluence'), carbon intensity ('technology') and time (Supplementary Section 4.8)—and use the regression results to project the global carbon footprint to 2025.

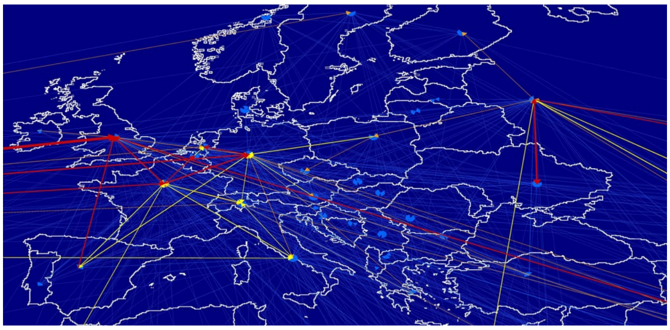

Fig. 3 | Top bilateral embodied carbon movements to and/or from Europe. Arrows point in the direction of embodied carbon flow, which—in accordance with the literature—is the direction of commodity trade, and is opposite to the movement of people. Top flows to and/or from Europe that constitute 30% of the total 1 $GtCO_2e$ are coloured red on the map.

Table 1 | Top 15 global carbon movements and top 15 carbon movements into and/or from Europe

Top 15 global flows	Carbon footprint (Mt)	Top 15 flows into and/or from Europe	Carbon footprint (Mt)
United States → Canada	75	United States → United Kingdom	12
United States → Mexico	47	Russian Federation → Ukraine	7.8
United States → United Kingdom	12	France → Germany	6.2
United States → Japan	12	United States → Germany	6.1
Canada → United States	12	Ukraine → Russian Federation	5.9
Thailand → China	11	France → United Kingdom	5.8
Malaysia → Singapore	10	Spain → United Kingdom	5.3
Russian Federation → Ukraine	7.8	India → United Kingdom	5.2
Mexico → United States	7.3	United States → France	4.8
Thailand → Malaysia	7.0	France → Belgium	4.3
India → United States	7.0	Russian Federation → Kazakhstan	4.3
United States → Brazil	6.6	Germany → Netherlands	4.1
Viet Nam → China	6.3	Thailand → Russian Federation	4.0
United States → China	5.8	France → Italy	3.6
Republic of Korea → China	5.3	Spain → Germany	3.6

Arrows represent flows of carbon; people move in opposite directions.

We found that the per capita carbon footprint increases strongly with increasing affluence (wealthier people travel more), decreases weakly with improving technology (saving energy means emitting less), and that time has no significant bearing (Supplementary Sections 4.8.3 and 4.8.4).

Although a positive relationship between footprint and affluence can be expected[28–30]—after all, wealth determines the ability to travel—the relative weakness of the connection between footprint and technology seems surprising at first. If under any accounting perspective technology had a significant influence on carbon footprints, the latter should saturate towards higher per capita GDP where the carbon intensity is low[29] (Fig. 5, right panel). However, we do not observe such a saturation in the RBA perspective, where carbon footprints increase as travellers' per capita GDP increases (Fig. 5, left panel). At affluence levels beyond US$40,000 per capita the GDP relationship becomes so strong that a 10% increase in wealth brings about a carbon footprint increase of up to 13% (Supplementary Section 4.8.3). Expressed in economics parlance, the GDP elasticity of the carbon footprint is higher than 1, reflecting that tourism is a luxury good the consumption of which (1) is largely enjoyed by the wealthy segment of the global population and (2) does not appear to satiate as incomes grow (Supplementary Section 4.8.3).

Above-unity elasticities are reported in previous work on international tourism demand[31–33] and on Brazilian households[34], whose propensity to consume fuel for mobility increased more than proportionally with income as Brazil went through a rapid socio-economic development phase. A similar process may be at work here, as wealthy citizens in emerging economies such as Brazil, Russia, India, China and Mexico—who are among those nationalities recording the strongest growth in RBA-based footprints (Supplementary Fig. 5)—find new opportunities for enhancing quality of life and expressing socio-economic status. These aspirations motivate desires to visit countries that offer exotic experiences combined with luxury and comfort, leading people to use aviation to travel further (especially internationally)[35,36]. Previous work confirms this view in that travel distance and transportation modes were found to be the most critical factors in determining the magnitude of direct tourism emissions[37–40].

Our finding provides both an explanation for the rapid growth of the carbon footprint of global tourism, and an indication of the growth it is likely to experience over the next five years. Extrapolating our 2009–2013 multiple regression (Supplementary Section 4.8; DBA and RBA perspectives yield similar results) to 2025, we estimate that under very optimistic assumptions (2% p.a. per capita GDP increase and −4% p.a. technology-driven carbon intensity decline[41,42], the latter brought about by unprecedented afforestation), the carbon footprint of global tourism can be limited to about 5 $GtCO_2e$ (Supplementary Fig. 13). In contrast, business as usual (4.2% p.a. per capita GDP increase and −2.7% p.a. carbon intensity decline) would probably continue the current 3% annual growth pattern, and lead to tourism-related emissions of 6.5 $GtCO_2e$.

Conclusions

Travel is highly income-elastic and carbon-intensive. As global economic development progresses, especially among high-income countries and regions experiencing rapid economic growth, consumers' demand for travel has grown much faster than their consumption of other products and services. Driven by the desire for exotic travel experiences and an increasing reliance on aviation and luxury amenities, affluence has turned tourism into a carbon-intensive consumption category. Global demand for tourism is outstripping the decarbonization of tourism operations, and, as a result, is accelerating global carbon emissions. At the same time, at least 15% of global tourism-related emissions are currently under no binding reduction target as emissions of international aviation and bunker shipping are excluded from the Paris Agreement. In addition, the United States, the most significant source of tourism emissions, does not support the Agreement.

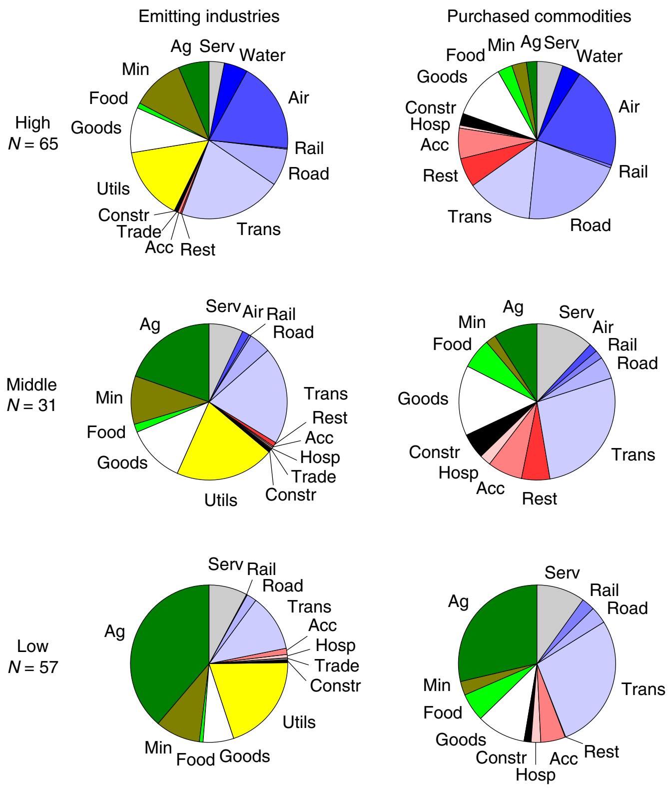

Fig. 4 | Breakdown of the tourism carbon footprint into purchased commodities and emitting industries, and into high-, middle- and low-income countries. 'Purchased commodities' represent the consumers' end-of-the-supply-chain network, 'emitting industries' the producers' end. Due to the many input–output tables of low-income countries not distinguishing modes, 'Trans' represents unspecified transport, which includes air transport. The three per capita GDP brackets are L (<US$3,000), M (US$3,000–US$10,000) and H (>US$10,000), and *N* represents the number of countries in the income group. 2013 tourist volumes from the three groups are 53.9 million (L), 281.5 million (M) and 656.7 million (H). For further details and an explanation of sector abbreviations see Supplementary Section 3.3.

There exists a popular mindset assuming that 'tourism is a low-impact and non-consumptive development option'[43]. This belief has compelled countries to pursue rapid and large-scale tourism development projects, in some cases attempting to double visitor volume over a short time period[44–46]. We have shown that such a pursuit of economic growth comes with a significant carbon burden, as tourism is significantly more carbon-intensive than other potential areas of economic development. Developing tourism has therefore been—at least on average—not instrumental in reducing national greenhouse inventories. This finding should be considered in future deliberations on national development strategies and policies. In particular, the results of this study could serve to inform the work of the UNWTO (which advocates further tourism growth, even in already highly developed tourism economies) and the World Travel and Tourism Council (WTTC) in creating awareness of the carbon burden faced by tourism-stressed areas.

Residence- and destination-based accounting perspectives amply demonstrate the unequal distribution of tourism impacts across citizens of traveller and host nations. In particular, island destinations face an enormous additional carbon burden as they host a significant number of inbound tourists[47]. These islands benefit substantially from the incomes from tourists, so their governments face a challenge of how to impose national mitigation strategies without reducing tourism income[9]. Switching from high-volume to high-revenue marketing[39] and developing local income streams[48] can assist in decoupling income and local emissions. Because of many islands' remoteness, international air travel will remain a critical component in the DBA carbon footprint[36,39,49,50]. The issue is complex, but channelling financial and technical assistance from major and wealthy tourism departure countries to disadvantaged island destinations could provide avenues for better preparing island nations for the future[51].

Recognizing the global significance of tourism-related emissions, the UNWTO proposed two mitigation strategies: (1) to encourage travellers to choose short-haul destinations with an increased use of public transportation and less aviation; and (2) to provide market-based incentives for tourism operators to improve their energy and carbon efficiency[16]. Our findings provide proof that so far these mitigation strategies have yielded limited success. Neither responsible travel behaviour nor technological improvements have been

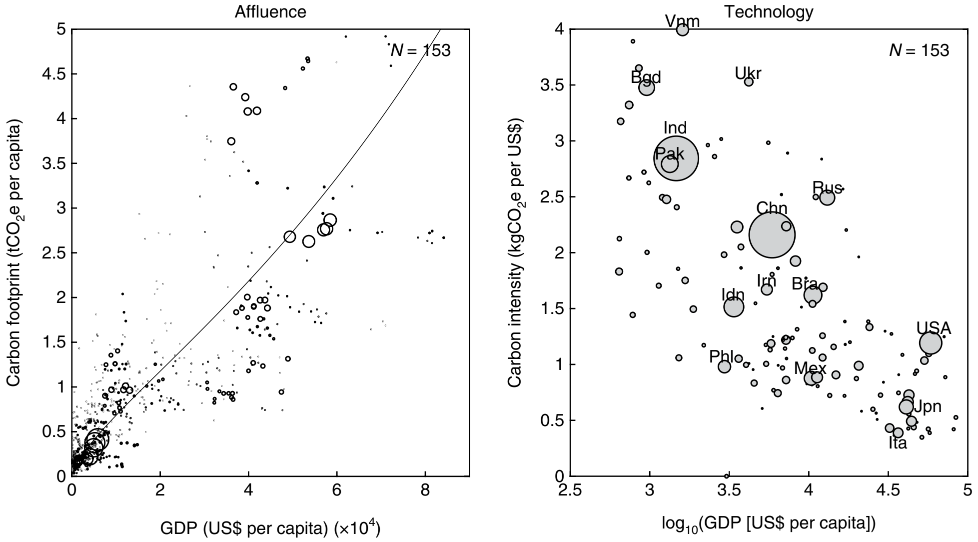

Fig. 5 | Affluence and technology as drivers of the carbon footprint of global tourism for the RBA perspective. Left, Affluence is measured as per capita GDP (including regression curve from Supplementary Section 4.8.3). Right, Technology is measured as carbon intensity. Circle size represents population, and *N* represents the number of countries in the sample.

able to rein in the increase of tourism's carbon footprint. Carbon taxes or carbon trading schemes (especially for aviation services) may be required to curtail unchecked future growth in tourism-related emissions[20].

Received: 5 December 2017; Accepted: 20 March 2018;

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Acknowledgements

This work was financially supported by the Australian Research Council through its Discovery Projects DP0985522 and DP130101293, the National eResearch Collaboration Tools and Resources project (NeCTAR) through its Industrial Ecology Virtual Laboratory, and the Taiwan Ministry of Science and Technology (no. 105-2410-H-006-055-MY3). The authors thank S. Juraszek for expertly managing the Global IELab's advanced computation requirements, and C. Jarabak for help with collecting data.

Author contributions

Y.-Y.S. and M.L. conceived and designed the experiments. M.L., Y.-Y.S., F.F., Y.-P.T., A.G. and A.M. performed the experiments. F.F., Y.-P.T., M.L. and Y.-Y.S. analysed the data. Y.-P.T., A.G., Y.-Y.S. and M.L. contributed materials/analysis tools. M.L., Y.-Y.S. and A.M. wrote the paper.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information is available for this paper at https://doi.org/10.1038/s41558-018-0141-x.

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Methods

Summary. We combine detailed TSAs[52] with a detailed global MRIO and GHG emissions database of $N = 14{,}838$ country/industry sector pairs[53,54] covering the 2009–2013 period (Supplementary Section 2). We subject this system to Leontief's demand–pull formalism[55] (Section 'Input-output theory'), matching previous high-level research that applies MRIO techniques to carbon and nitrogen emissions, groundwater depletion, biodiversity threats, aerosol forcing and health impacts from air pollution[19,56–62]. More specifically, we convert TSA data into an $N \times 1$ matrix $\tilde{\mathbf{y}}$ acting as the final demand block of the MRIO system[63], and determine carbon footprints of tourism $\tilde{Q}$ through Leontief's fundamental input–output equation $\tilde{\mathbf{Q}} = \mathbf{q}\left(\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1}\right)^{-1}\tilde{\mathbf{y}}$, where $\mathbf{q}$ is a $1 \times N$ matrix of carbon emissions intensities (in kgCO$_2$e per US\$), $\mathbf{I}$ is an $N \times N$ identity matrix, $\mathbf{T}$ is an $N \times N$ MRIO matrix listing international trade transactions between countries, where $\mathbf{x} = \mathbf{T}1^{\mathrm{T}} + \mathbf{y}1^{\mathrm{y}}$ is total economic output, with $\mathbf{1}^{\mathrm{T}} = \underbrace{\{1, 1, \ldots, 1\}}_{N\mathrm{elements}}$ and $\mathbf{1}^{\mathrm{y}} = \underbrace{\{1, 1, \ldots, 1\}}_{M\mathrm{elements}}$ being suitable summation operators, and where $\mathbf{y}$ is an $N \times M$ matrix of final demand by M global agents (households, governments, the capital sector, stocks) of N products. We slice the resulting tensor $\tilde{Q}_{ij}^{rst}$ to generate carbon footprints for two perspectives of consumption-based accounting: (1) RBA ($\tilde{Q}_{\mathrm{RBA},j}^{t} = \tilde{Q}_{.j1}^{..t}$) and (2) DBA ($\tilde{Q}_{\mathrm{DBA},j}^{s} = \tilde{Q}_{.j1}^{.s.}$), as well as for (3) production-based accounting ($\tilde{Q}_{\mathrm{PBA},j}^{t} = \tilde{Q}_{i.1}^{r..}$). We use these tensor representations to reveal the global footprint's detailed country and commodity content (Input–output theory section), and to prepare a global map of embodied carbon flows. We employ production layer decomposition $\tilde{\mathbf{Q}} = \mathbf{q}(\mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \ldots)\tilde{\mathbf{y}}\mathbf{1}^{\mathrm{y}}$ to unravel the aggregate carbon footprint into contributions from various layers of the supply chain network (Section 'Production layer decomposition'). We use multiple regression to investigate trends and drivers of the global tourism carbon footprint over time (Section 'Multiple regression').

Input–output theory. Let $\mathbf{T}$ be an $N \times N$ MRIO matrix listing international trade transactions (so-called intermediate demand) between countries, and let $\mathbf{y}$ be an $N \times M$ matrix of final demand by M global agents (households, governments, the capital sector, stocks) of N products. Both matrices are expressed in units of money. The sum of intermediate and final demand equals total economic output $\mathbf{x} = \mathbf{T}1^{\mathrm{T}} + \mathbf{y}1^{\mathrm{y}}$. This accounting identity can be transformed into the fundamental input–output equation $\mathbf{x} = \left(\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1}\right)^{-1}\mathbf{y}\mathbf{1}^{\mathrm{y}}$, where $\mathbf{I}$ is an $N \times N$ identity matrix. This equation represents Leontief's demand–pull model of the economy[64], where the provision of final demand $\mathbf{y}$ requires—directly and indirectly via international trade routes throughout a global supply chain network—total output $\mathbf{x}$ to be produced[65]. The matrix $\left(\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1}\right)^{-1}$ is Leontief's inverse.

The integration of the monetary input–output calculus with CO$_2$ emissions data is straightforward. Let $\mathbf{Q}$ be a $1 \times N$ matrix listing CO$_2$ emissions (in units of tonnes) by country and industry sector. Let $\mathbf{q} = \mathbf{Q}\hat{\mathbf{x}}^{-1}$ be a $1 \times N$ matrix of carbon emissions intensity (in tonnes per monetary unit) by country and industry sector. Then $\mathbf{q}\mathbf{x} = \mathbf{Q}\hat{\mathbf{x}}^{-1}\left(\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1}\right)^{-1}\mathbf{y}\mathbf{1}^{\mathrm{y}}$ is called the global carbon footprint. The elements of the $1 \times N$ vector $\mathbf{m} = \mathbf{Q}\hat{\mathbf{x}}^{-1}\left(\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1}\right)^{-1}$ are called emissions multipliers, because they characterize the CO$_2$ emissions embodied in a unit of final demand, rather than the coefficients $\mathbf{q}$ that describe CO$_2$ emissions per unit of industrial output. Thus, input–output analysis provides the so-called producer perspective ($\mathbf{qx}$) and consumer perspective ($\mathbf{my}$) of global CO$_2$ emissions[66]. Note here that $\mathbf{Q}$, and therefore also $\mathbf{q}$, do not distinguish between tourism-related and non-tourism-related activities, because such detail is not available in the data. This means that all tourism-specific activities are treated within the broader industry: For example, a coach transporting tourists is assumed to have the same fuel-use and embodied-emissions characteristics as a coach transporting school children.

MRIO analysis of tourism expenditures. MRIO analysis is a straightforward extension of conventional (single-region) input–output analysis[55]. MRIO databases feature a number of regions and/or countries, with each country's economy represented by a number of economic sectors[67]. As a result, final demand is a four-dimensional tensor with elements y_{ik}^{rs}, where the index r counts regions of final sale, s regions of final demand, i the commodities consumed, and k the consuming agents (households, and so on). In fact, in an MRIO context, $\mathbf{x}$, $\mathbf{T}$ and $\mathbf{y}$ are all four-dimensional tensors.

Expenditures on tourism enter Leontief's model as final demand $\tilde{\mathbf{y}}$, which in turn drives economic output $\tilde{\mathbf{x}} = \left(\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1}\right)^{-1}\tilde{\mathbf{y}}\mathbf{1}^{\mathrm{y}}$, which then causes the carbon footprint of tourism, $\tilde{Q} = \mathbf{q}\tilde{\mathbf{x}}$. (The ~ symbol denotes a particular final demand stressor for the Leontief model. This stressor does not normally satisfy the national accounting identity.)Writing out the tensor products in this aggregate relationship for the scalar $\tilde{Q}$ allows unravelling carbon footprints into supplying and demanding regions, commodities and agents[68]. The most general breakdown of the carbon footprint in an MRIO setting is achieved by an element-wise product $\mathbf{q} \circ \mathbf{L} \circ \tilde{\mathbf{y}}$, or $\tilde{Q}_{ijk}^{rst} = q_i^{r} L_{ij}^{rs} \tilde{y}_{jk}^{st}$, where $\mathbf{L} = \left(\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1}\right)^{-1}$ is the Leontief inverse, and where r counts regions of production and therefore emissions, s regions of final sale (for example, of airfares and food services, often the tourist destinations), t the regions of final demand (the residence of the visitors), i the commodities produced during emission, j the commodities consumed (airfares, hotels, and so on), and k the consuming agents (practically only households, $k = 1$).

The tensor $\tilde{Q}_{ij1}^{rst}$ can now be sliced in various ways, using tensor contraction (denoted by a dot '.'), to provide various types of information. For example, $\tilde{Q}_{.j1}^{.st} =: \sum_{r,i} q_i^{r} L_{ij}^{rs} \tilde{y}_{j1}^{st}$ sums over emitting entities and shows the final-commodity content and regions of visitor residence (t) and location of final sale (s). Another option is $\tilde{Q}_{i.1}^{r.t} =: \sum_{s,j} q_i^{r} L_{ij}^{rs} \tilde{y}_{j1}^{st}$, showing the carbon footprint by region and industry of emission, and region of visitor residence. $\tilde{Q}_{..1}^{r.t} =: \sum_{i,s,j} q_i^{r} L_{ij}^{rs} \tilde{y}_{j1}^{st}$ and $\tilde{Q}_{..1}^{.st} =: \sum_{r,i,j} q_i^{r} L_{ij}^{rs} \tilde{y}_{j1}^{st}$ simply map bilateral embodied CO$_2$ flows[68]. The terms $\tilde{Q}_{..1}^{.st}$ link locations of final sale and residence, and might therefore more or less resemble actual visitor movements. In contrast, the $\tilde{Q}_{..1}^{r.t}$ link visitor residence with country of emission, and thus provide a measure of the ultimate regional spread of a country's carbon footprint of tourism.

In our work, we use two particular ways of slicing $\tilde{\mathbf{Q}}$: RBA and DBA. Both perspectives are variants of the well-known consumption-based accounting principle[19]; however, while RBA allocates consumption-based emissions to the country of the visitor residence, DBA allocates them to the country of the tourist destination.

Specifically,

$$\tilde{Q}_{\mathrm{RBA},j}^{t} = \tilde{Q}_{.j1}^{..t} \mathrm{and} \tilde{Q}_{\mathrm{RBA},i}^{t} = \tilde{Q}_{i.1}^{..t} \tag{1}$$

are residence-based carbon footprints of visitors from countries t, broken down either by commodities j purchased by the visitor, or by emitting industries i. Similarly,

$$\tilde{Q}_{\mathrm{DBA},j}^{s} = \tilde{Q}_{.j1}^{.s.} \mathrm{and} \tilde{Q}_{\mathrm{DBA},i}^{s} = \tilde{Q}_{i.1}^{.s.} \tag{2}$$

are destination-based carbon footprints of tourism operations in countries s, broken down either by commodities j sold to the visitor, or by emitting industries i.

Calculating $\tilde{Q}_{\mathrm{RBA}}^{t}$ and $\tilde{Q}_{\mathrm{DBA}}^{s}$ involves slicing the stressor $\tilde{y}_{j1}^{st}$ in two different ways (Supplementary Fig. 1), so that

$$\tilde{y}_{\mathrm{RBA},j}^{t} = \tilde{y}_{j1}^{.t} \mathrm{and} \tilde{y}_{\mathrm{DBA},j}^{t} = \tilde{y}_{j1}^{s.} \tag{3}$$

Production layer decomposition. A further option for carbon footprint analysis is production layer decomposition. Utilizing the series expansion of the Leontief inverse[69] $\mathbf{L} = \left(\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1}\right)^{-1} =: (\mathbf{I} - \mathbf{A})^{-1} = \sum_{n=0}^{\infty} \mathbf{A}^n = \mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \ldots$, where $\mathbf{A} = \mathbf{T}\hat{\mathbf{x}}^{-1}$ is the input coefficients matrix. The terms $\mathbf{A}^n$ correspond to contributions from supply chains of nth order, that is with n nodes. The sum of all contributions from supply chains of nth order is called the nth production layer.

For example, total output $\tilde{\mathbf{x}} = \left(\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1}\right)^{-1}\tilde{\mathbf{y}}\mathbf{1}^{\mathrm{y}}$ can be unravelled as $\tilde{\mathbf{x}} = (\mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \ldots)\tilde{\mathbf{y}}\mathbf{1}^{\mathrm{y}}$. The first production layer $\mathbf{A}\tilde{\mathbf{y}}\mathbf{1}^{\mathrm{y}}$ contains production inputs of the direct suppliers to final demand, the second layer $\mathbf{A}^2\tilde{\mathbf{y}}\mathbf{1}^{\mathrm{y}}$ production inputs of the suppliers of the direct suppliers to final demand, the third layer $\mathbf{A}^3\tilde{\mathbf{y}}\mathbf{1}^{\mathrm{y}}$ production inputs of the suppliers of the suppliers of the direct suppliers to final demand, and so on. In carbon terms, a production layer decomposition reads $\tilde{Q} = \mathbf{q}(\mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \ldots)\tilde{\mathbf{y}}\mathbf{1}^{\mathrm{y}}$, with 0th-order terms being $\mathbf{q}\tilde{\mathbf{y}}\mathbf{1}^{\mathrm{y}}$, 1st-order terms $\mathbf{q}\mathbf{A}\tilde{\mathbf{y}}\mathbf{1}^{\mathrm{y}}$, 2nd-order terms $\mathbf{q}\mathbf{A}^2\tilde{\mathbf{y}}\mathbf{1}^{\mathrm{y}}$, and so on.

Separating the 0th-order term and the remainder of the expansion, and considering that $\mathbf{A} + \mathbf{A}^2 + \ldots = \mathbf{A}(\mathbf{I} + \mathbf{A} + \ldots) = \mathbf{AL}$, carbon footprints can be split into a sum of direct and indirect effects: $\tilde{Q}_{ij1}^{rst} = q_i^{r}\tilde{y}_{i1}^{rt} + q_i^{r}(\mathbf{AL})_{ij}^{rs}\tilde{y}_{j1}^{st}$. The term $q_i^{r}\tilde{y}_{i1}^{rt}$ holds what consumers usually associate with their carbon responsibility when travelling, including, for example, the emissions from the plane they board.

Input–output data. The quantities $\mathbf{Q}$, $\mathbf{T}$ and $\mathbf{x}$, and therefore also $\mathbf{q}$, $\mathbf{A}$ and $\mathbf{L}$, are computed using the Eora global MRIO database[53,54], as constructed in the Global MRIO Virtual Laboratory[70]. The final demand stressor $\tilde{y}_{j1}^{st}$ needs to be specified by purchased commodity j, country of visitor residence s, and tourist destination t. This information is sourced primarily from TSA reports published by individual countries. Where TSA reports are not available, a visitor expenditure total for individual countries reported by UNWTO is adopted. See Section 'TSAs, data processing and uncertainty' for a detailed description of the tourism data compilation process.

Multiple regression. Multiple regression can be used to reveal drivers of the carbon footprint F by optimizing the parameters p_j of functions $f_j(x_{ji}, p_j)$ of explanatory variables $x_j(i)$, so that $g(F_i) = p_0 + \sum_j f_j(x_{ji}, p_j) + \varepsilon_i$, where g is a function, p_0 is the regression intercept, and where ε_i are called residuals of observations i. To estimate the regression equation for $g(F_i)$, we use the ordinary least squares method in which parameters p_j are adjusted so that the sum of squared residuals $\mathrm{SSE} = \sum_i \varepsilon_i^2$ is minimized.

In our work, we follow earlier studies[28,29], and formulate a multiplicative relationship for per capita carbon footprints F as

$$F = k x^{\eta_x} \mathrm{e}^{\varrho_q q} \mathrm{e}^{\varrho_t t} \tag{4}$$

where the explanatory variables are (1) per capita GDP x, carbon intensity of production q, and time t. Equation (4) is parameterized by a regression constant k, and so-called elasticities η and ρ. To transform this equation into additive form for multiple regression we take natural logarithms

$$\ln(F) = \ln(k) + \eta_x \ln(x) + \varrho_q q + \varrho_t t \tag{5}$$

Here it can be seen that $\ln(k)$ is the regression intercept. Calculating derivatives of F in equation (4) yields for example

$$\frac{\partial F}{\partial x} = k\eta_x x^{\eta_x - 1} \mathrm{e}^{\varrho_q q} \mathrm{e}^{\varrho_t t} = \eta_x \frac{F}{x} \Leftrightarrow \eta_x = \frac{\partial F / F}{\partial x / x} \tag{6}$$

This relationship shows that the parameter η_x describes the relative change in carbon footprint F as a result of a relative change in GDP x. Similarly,

$$\frac{\partial F}{\partial q} = \varrho_q F \Leftrightarrow \varrho_q = \frac{\partial F / F}{\partial q} \text{ and } \frac{\partial F}{\partial t} = \varrho_t F \Leftrightarrow \varrho_t = \frac{\partial F / F}{\partial t} \tag{7}$$

describes the relative change in carbon footprint F as a result of a unit change (one kgCO$_2$e per US$ and one year) in carbon intensity and time.

Preliminary findings showed that using equation (4) as the basis for regressing tourism carbon footprints indicated that there is no uniform relationship across the entire international per capita GDP range, and that the regression form must allow for a GDP elasticity of the carbon footprint that varies with per capita GDP:

$$\eta_x = \eta_{x,0} + \theta x \tag{8}$$

where θ describes the change in the elasticity η_x as a result of change in per capita GDP. Inserting equation (8) into equation (4) yields the linear regression form

$$\ln(F) = \ln(k) + \eta_x \ln(x) + \theta x \ln(x) + \varrho_q q + \varrho_t t \tag{9}$$

Differentiating

$$\begin{aligned}
\frac{\partial F}{\partial x} &= \frac{\partial (k x^{\eta_{x,0}+\theta x} \mathrm{e}^{\varrho_q q} \mathrm{e}^{\varrho_t t})}{\partial x} \\
&= k \mathrm{e}^{\varrho_q q} \mathrm{e}^{\varrho_t t} \frac{\partial (x^{\eta_{x,0}}\ x^{\theta x})}{\partial x} \\
&= k \mathrm{e}^{\varrho_q q} \mathrm{e}^{\varrho_t t} \left[x^{\theta x} \frac{\partial (x^{\eta_{x,0}})}{\partial x} + x^{\eta_{x,0}} \frac{\partial (x^{\theta x})}{\partial x} \right] \\
&= k \mathrm{e}^{\varrho_q q} \mathrm{e}^{\varrho_t t} [x^{\theta x} \eta_{x,0} x^{\eta_{x,0}-1} + x^{\eta_{x,0}}\ \theta x^{\theta x} (\ln(x) + 1)] \\
&= \eta_{x,0} \frac{F}{x} + F\theta (\ln(x) + 1) \\
&= \frac{F}{x} (\eta_{x,0} + \theta x (\ln(x) + 1))
\end{aligned} \tag{10}$$

yields a modified expression for the GDP elasticity of the carbon footprint

$$\frac{\partial F / F}{\partial x / x} = \eta_{x,0} + \theta x (\ln(x) + 1) \tag{11}$$

TSAs, data processing and uncertainty. *Compiling a set of TSAs.* The TSA concept was proposed by the United Nations and other multi-lateral organizations in 1993 to provide a comprehensive and consistent evaluation framework for documenting the economic contribution of tourism consumption to a national economy[71]. To compile a global visitor expenditure database, our search for the individual TSA reports starts with a list from the UNWTO, identifying around 60 countries that in 2010 had produced or were currently developing a TSA exercise[72]. Electronic resources from the UNWTO, OECD, EU, governmental reports or journal articles were searched to locate national TSA consumption data. Finally, we identified 55 full TSA reports from major tourism countries, covering around 88% (2009–87.2%, 2010–88.3%, 2011–88.3%, 2012–88.1%, 2013–88.1%) of the global tourism consumption. For further details see Supplementary Section 2.

Estimate inbound visitor consumption by country of departure. After compiling a global longitudinal visitor expenditure database, the next step is to establish the origin–destination (O–D) pattern for inbound travel. Inbound tourism expenditure reported by the standard TSA only reports one aggregate number without identifying the point of origin (departure country) of foreigners or their associated spending. To estimate inbound spending to destination s from individual countries t, we use origin- and destination-specific data from the UNWTO[73] containing 'arrivals of non-resident visitors at national borders by country of residence' as a proxy to allow us to estimate normalized weights w^{st} for allocating the inbound tourism expenditure $\tilde{y}_{j1}^{st} = w^{st}(\tilde{y}_{j1}^{s.})$ across countries of residence t of inbound visitors. While UNWTO data are complete for about 80% total visitor movements (2009–79.8%, 2010–94.5%, 2011–95.6%, 2012–95.8%, 2013–95.6%), additional steps are taken to estimate the bilateral travel flows. First, official inbound/outbound data published by individual tourism authorities are manually searched online for important destination countries across five continents. Second, for the remaining missing component, the bilateral travel flow is estimated based on the gravity model assumption[74,75], which allocates the undistributed inbound visits to the remaining departure countries in a direct proportion to the gross national GDP of the visitor's country (approximating purchasing power for tourism activities), and in inverse proportion to the distance between two countries (approximating cost of journey).

Integrating TSA and MRIO data. A TSA captures economic transactions within the national boundary for visitors taking trips within, towards or from the country of reference. It does not reflect economic activities at foreign destinations from outbound travel nor airfares paid to foreign-based airlines. TSAs have been used before as the basis for consumption-based accounting (CBA) and for establishing input–output-based tourism carbon footprints, for example for Wales, the UK[8], Taiwan[9], Australia[13], Spain and Switzerland[22]. Integrating a TSA into the final-demand block of an MRIO database offers several advantages. First, the TSA conceptual framework and data compliance are comprehensive and consistent across nations, allowing inter-country comparisons on tourism economic significance, GHG emissions, and tourism eco-efficiency. Second, both the TSA and MRIO databases comply with the system of national accounts, allowing individual destinations to benchmark their tourism development against other sectors in the economy in terms of both economic and environmental performance. Third, adopting the TSA concept offers a straightforward treatment of the international aviation issue. Aviation emissions are only attributable to the tourism sector of a country when the transaction of the air transportation creates economic significance at the geographic territory.

Technically, TSA data enter Leontief's model as final demand $\tilde{\mathbf{y}}$, where the 39 classifications of the original TSAs (Supplementary Table 1) and the MRIO database are bridged using concordance matrices. A concordance matrix $\mathbf{C}$ shows an entry $C_{ij} = 1$ where TSA class i corresponds to MRIO class j, and 0 elsewhere.

Uncertainty. To assess the influence of allocation and parametrical uncertainty on our carbon footprint results, we carry out a detailed uncertainty analysis using error propagation[76,77]. The calculation of carbon footprints based on input–output analysis involves a matrix inversion, and as a consequence analytical error propagation is not possible[78]. Input–output researchers have overcome this difficulty by resorting to Monte Carlo approaches[79–82]. Here, uncertainty is propagated using standard deviations[83] (sourced from the same MRIO database, Eora[53,54], as constructed in the Global MRIO Virtual Laboratory[70]) for perturbing the basic data items Q, T and $\mathbf{y}$, calculating perturbed carbon footprints and then gathering these for a large number of perturbation runs. Standard deviations of derived carbon footprint measures are then taken from the statistical distribution of the perturbations. For further technical details, and details on our uncertainty calculus, see Supplementary Section 4.3.

Data availability. The data that support the findings of this study are available from the corresponding author upon request.

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