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The carbon footprint of global tourism

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Supplementary Information

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1. Supplementary Methods

Carbon footprint analyses have recently been carried out using a hybrid method[84,85], combining detailed bottom-up process information about the system under study with comprehensive top-down input-output data on the background economy[86,87]. This choice of method holds a number of benefits. Most importantly, it circumvents the problem of systematic truncation errors due to setting of finite system boundaries[88] whilst at the same time guaranteeing complete coverage of upstream supply-chain contributions[89]. Here, "complete coverage" means that all upstream supply-chain contributions such as emissions embodied in anything that a "tourist" as per UNWTO definition (*SI* 2.1) consumes – food, accommodation, transport, fuel, and shopping – are included in the footprint measure. Second, input-output-assisted carbon footprinting is supported by a long history of numerous applications (see for example Hoekstra[90]). Third, international standards on integrated physical and monetary accounting by the United Nations[91,92] mean that input-output-based footprint analyses can be undertaken with consistent scope on a number of complementary indicators, such as energy[93], biodiversity[94], air pollution[95], water[96], land[97], nitrogen[98] and material flow[99]. Finally, a number of very detailed large-scale global multi-region input-output (MRIO) databases have recently become available[100]. As a result, carbon footprint analyses incorporating the global international trade network are now almost routinely carried out[101]. Auxiliary analyses and tools have been developed, touching on issues related to causal driver identification[102-104], aggregation bias[105-108], sensitivity[109] and uncertainty[110], database comparisons[111-114], and corporate reporting[115]. Global carbon footprints have featured prominently in policy and the media[110,116-121] .

One interesting aspect in carbon footprints not only of tourism is what can be described as *additionality*, or *systemic* or *rebound effects*, meaning for example that the carbon footprint of a wind turbine could include a credit for displaced coal or gas, and an addition for the increased need of grid balancing and back-up[122]; or the carbon footprint of a recommended diet could include the carbon footprint of those commodities that are purchased with the money saved (since the recommended diet is generally cheaper)[123]; or the carbon footprint of defense spending could be offset against the carbon footprint of the portfolio that the government funds would alternatively be spent on[124]. In the context of the tourism carbon footprint: if visitors had not embarked on their journey, they would have eaten and travelled at home, giving rise to the question of whether the carbon footprint of tourism should be net of carbon emissions associated with such alternative activities, or in other words, should only comprise *additional* emissions (in the sense of the Clean Development Mechanism[125]). In this work, we do not attempt to quantify additionality, systemics and rebounds, because of a number of reasons. First, footprint or consequential LCA studies that include such rebounds or systemic changes are rare at the national level[122-124], and virtually absent at the global level, because of the inherent difficulty in specifying and estimating the often complex, alternative scenarios that would have occurred in the absence of the activities under investigation. Offsetting food consumption, shopping and travel behavior of tourists against their practices at home, for all individual countries and five years, requires information that is clearly not available. The majority of footprint and LCA studies generally view the so-called functional unit as a clear-cut, distinct entity, including every activity that fell within the scope of the study[87], and without the requirement of capturing wider systemic effects[126]. In the context of tourism this means accepting as a fact that tourists do not eat at home but at their destination, and that the food consumed must be considered as one necessary component for realising – in LCA parlance – the functional unit "visit". Second, past practices aside, we must not simply omit, for example, the food eaten at the tourist destination from the footprint calculation, because the consumption patterns of tourists are found to be different from their lifestyle at home. Visitors tend to use more private transportation than public transportation[127], consume more water[128], and eat more processed food (especially alcoholic drinks and meat products – see also Fig. *SI* 6)[129]. Third, in our case, including food consumption is important in the case of international tourism, because these purchases by visitors increase the carbon footprint of destinations, as opposed to the carbon footprints of the visitors' home country. This matters for international embodied carbon transfers[130].

See separate online-only methods section for details on the methodology used in this article, and also refer to Fig. *SI* 1 below.

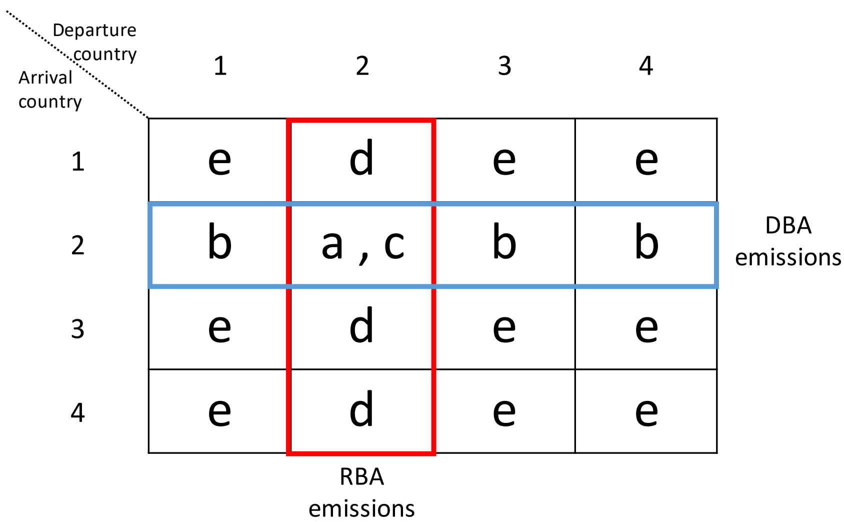

Fig. *SI* 1: Schematic of the tourism expenditure matrix $\tilde{\mathbf{y}}$ for a hypothetical 4-region world, with destinations s in rows and visitor origins t in columns. The RBA perspective $\tilde{Q}^{t}_{\mathrm{RBA}}$ sums over rows for each column (red column), whilst the DBA perspective $\tilde{Q}^{s}_{\mathrm{DBA}}$ sums over columns for each row (blue row). Taking country 2 as an example, segments of $\tilde{\mathbf{y}}$ are labelled a-d to link with data items in the tourism satellite account (TSAs) where a: domestic tourist expenditure in country *i*, b: inbound visitor expenditure in country *i*, c: spending that occurs in the domestic region (country *i*) for residents travelling abroad (such as domestic transportation), and d: residents' outbound spending in foreign countries (country *j*).

2. Supplementary Notes

2.1. The Tourism Satellite Account concept

The Tourism Satellite Account (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[131]. This framework first provides a definition and measurement regarding visitor and their consumption, ensuring a consistent base for individual regions to gauge the scale of tourism activities. Based on the United Nations (UN) and the World Tourism Organization (WTO; hereafter UNWTO), a tourist is defined as "*he/she is taking a trip or a visit to a place outside his/her usual environment for less than a year and for a purpose other than being employed by a resident entity there*" while tourist expenditure as "*the amount paid for the acquisition of consumption goods and services as well as valuables, for own use or to give away, for and during tourism trips*" [132]. In the following we will use the terms "tourist" and "visitor" synonymously.

The compilation of a TSA proceeds by first estimating total visitor expenditure by major items, and then bridging the type of visitor expenditures with the supply of tourism products to indicate the proportion of supply by industries that is contributed by visitors. A ratio between tourism consumption and total value of output of an industry (accommodation, air transportation or entertainment services) is calibrated to portray the significance of tourism to the sales of this specific sector. The sum across tourism sales from sectors that are directly serving visitors then provides an economic estimate that is consistent under the System of National Accounts (SNA). Besides visitor consumption, a broader TSA also measures the contribution to investment in fixed capital by businesses, and quantifies the value provided by certain non-profit organizations and governments to serve visitors[133]. Due to the cost- and labour-intensiveness of data collection, most countries currently focus only on the main core of a TSA, presenting the economic activities associated with direct tourist monetary consumption, without explicitly addressing other components of services associated with vacation accommodation on own account, tourism social transfers in kind, and other imputed consumption types [134]. The coverage of our analysis is therefore limited to carbon emissions associated with annual tourist consumption in cash.

The UNWTO recommends that tourism expenditure is measured and reported by products based on the Central Product Classification (CPC) 5-digit system. While each country is allowed to adjust the CPC based on country-specific context, the most commonly adopted categories are package travel, accommodation, food and beverage, local transport, international transport, transport equipment rental, recreation, shopping and others. Transport sectors can be further segmented by railway, road, water and air depending on data availability.

2.2. Compiling a set of Tourism Satellite Accounts

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[135]. Electronic resources from the UNWTO, OECD, EU, governmental reports, or journal articles were searched in order 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.

The TSA reports collected from individual countries are expressed at a different level of resolution, with various degrees of disaggregation across tourist groups and consumption items. This creates a problem in the process of calibrating the national tourism carbon emissions. We dealt with these data inconsistency problems as follows:

2.2.1. Dealing with a lack of disaggregated information

The first data challenge is the lack of a detailed disaggregation of consumption by visitor types. The UNWTO recommends trip expenditure to be reported by two visitor categories (exemplified for the TSA of country s):

i. Domestic tourism expenditure ($\tilde{y}_{j1}^{ss}$): this includes two sub-categories:
    1) tourism expenditure by resident visitors within the economy of reference for their domestic travel, and
    2) tourism expenditure by residents within the national boundary for their outbound travel. This includes purchases directly associated with the outbound trip (such as suitcases or camera), local transportation to/from the airport, and international airfares paid to national airlines registered in the economy of reference.

ii. Inbound tourism expenditure (an export of country s to residents of countries t; $\tilde{y}_{j1}^{st}$ where $t \neq s$): Tourism expenditure by foreign visitors within the economy of reference. This includes all spending at destination, and international airfares paid to national airlines registered in the economy of reference.

Separating visitor consumption by visitor categories provides advantages for quantifying economic contributions and carbon responsibilities. While domestic tourism expenditure can be seen as a process of income-redistribution, inbound tourism expenditure functions as an export, earning foreign payments and leading to a net increase of GDP. Estimating tourism carbon footprints based on such separated data allows a direct assessment on the trade-off between economic impacts and environmental externalities for developing domestic versus inbound tourism. In addition, differentiating journeys made by residents versus visitor groups from foreign residences is a major prerequisite for assigning carbon responsibility: The residence-based accounting (RBA) principle and the destination-based accounting (DBA) principle both require linking residence information with consumer and producer establishments, respectively. This separation allows tourism carbon emissions to be discussed from the perspectives of origin countries, destination countries, or the rest of world (RoW).

One third of our collected TSA reports document expenditure of categories j from different visitor groups, whilst the remainder just reports one aggregated total. To break down aggregated expenditure into parts for domestic and inbound tourism, we use parameters reported by the World Travel and Tourism Council[136] in their annual economic impact analysis report for more than 100 countries. In these country reports, domestic and foreign tourist expenditure are estimated separately, providing a direct ratio for disaggregation from the TSAs into domestic and international spending, $\tilde{y}_{j1}^{ss}$ and $\tilde{y}_{j1}^{s\cdot}$.

2.2.2. Temporal inconsistencies

The second data challenge is the inconsistency in time: Some countries only possess full TSA data for the early 1990s, while other countries have up-to-date information (to 2015 at the time of writing). To provide a compatible and consistent study basis, we updated the TSA reports of 55 countries into the same study period, 2009~2013. This required country-specific demand indicators to proxy the changes of domestic and inbound tourist consumption over time. Either visitor consumption data or arrival data, from the national tourism offices and WTO, were utilized to update TSA results from the base year to the projected period.

For those 139 countries without a TSA, data on total inbound visitor expenditure were first retrieved from the UNWTO [137]. Supplementing these with parameters that specify percentages of domestic vs. inbound tourism spending (WTTC [136]), we are able to estimate 2009~2013 total visitor expenditure for any given country.

2.3. 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 report one aggregate number without identifying 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 World Tourism Organization[137] 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 $\tilde{y}_{j1}^{st} = w^{st}\left(\tilde{y}_{j1}^{s\cdot}\right)$ 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 authority are manually searched online for important destinations countries across five continents. Secondly, for the remaining missing component, the bilateral travel flow is estimated based on the gravity model assumption[138,139], 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).

2.4. Dealing with international transport

As stipulated by the Kyoto Protocol, emissions from international aviation and shipping (aircraft and shipping bunkers) are excluded from reporting to the United Nations Framework Convention on Climate Change (UNFCCC), because of methodological incompleteness and inconsistencies[140], in particular the difficulty of allocating emissions to either the country of journey origin, destination, or airline / shipping ownership. It was agreed instead to work on reducing emissions from aircraft through the International Civil Aviation Organization and International Maritime Organization, respectively.

Assigning international transport emissions in the context of tourism is an important but a complex issue. Cross-board aviation accounts for as much as 40% of direct tourism carbon emission and, in some instances, is projected to increase to more than 85% of total emissions for certain countries by 2050[141]. Although the importance of international flights is greatly recognized, aviation emissions are handled differently by accounting principles, and by empirical applications. The territorial or Kyoto Protocol perspective would completely ignore emissions associated with international bunkers to be in line with the IPCC suggestions. The DBA approach takes a different perspective by including all the emissions produced by national carriers for its inbound, outbound and stop-over services. The RBA approach, on the other hand, traces the emissions of residents' round-trip flight to a specific country. The RBA output comprises air pollution emitted from domestic and foreign-registered airlines by a share contributed by its own residents. In terms of empirical applications, some may only take into account energy use by national carriers, while others may look into all flights by inbound visitors to the country[142]. No consensus has been reached for dealing with the tourism aviation in the tourism context. Even so, it is stressed that this critical component should be included in the national accounting framework so that adequate tourism carbon efficiency can be established and compared across industries[142-145].

The scope of the national tourism carbon footprint calibrated in this study is based on visitor expenditure reported in the TSA, which documents all tourism economic activities within the national boundary, including national registered carriers (both aviation and marine transportation). In this approach, emissions are only attributable to the tourism sector of a country when the transaction creates an economic significance at the geographic territory. National carriers are included as their sales are documented in the Systems of National Account, and their energy use is allocated for the proportion contributed by inbound and outbound visitors arriving to and departing from the country. Internationally-registered carriers are assumed to leave no economic contribution and their emissions are excluded. The underlying logic for such a treatment is that the economic benefits of those transactions accrue to the destinations so that the host nation bears the responsibility to mitigate and control the national carriers' emissions[143,146,147].

The United Nation's System of Environmental-Economic Accounting (SEEA [91]) differs somewhat from UNFCCC guidelines. The German Federal Statistical Office[148] writes: "*The Environmental-Economic Accounting concept is more comprehensive than the IPCC concept: In addition to the emissions according to the IPCC it includes the emissions arising from […] international aviation and shipping. […] The delimitations made in the Environmental-Economic Accounting are geared to the definitions and delimitations of the economic performance parameters used in the national accounts. According to the international system of national accounts (SNA 2008), the measurement of activities refers to the economic units (residents) in an economic area. This means that the calculation of energy consumption and CO2 emissions in Environmental-Economic Accounting is also based on the residence concept.*" This perspective implies that for the purposes of a carbon footprint, emissions from international travel are always allocated to the country of residence of the entity carrying out the economic activity, ie the visitor. As with any other commodity, such emissions are calculated based on

- expenditure of households on international transport $\tilde{y}^{st}_{\text{air transport,1}}$ as recorded in the final demand matrix, based on national input-output tables for expenditures on resident transport establishments, and based on statistics on trade in services [149,150] for expenditures on non-resident transport establishments; and
- on the emissions intensities of the air transport sectors $q^{s}_{\text{air transport}}$ in the resident and non-resident economies, based on various data sources (see Section 2 in [151]).

For example, the direct CO_2 emissions associated with a German citizen flying on a UAE-based airline from Cyprus to Malta are part of Germany's carbon footprint, and are calculated as $q^{\text{UAE}}_{\text{air transport}} \times \tilde{y}^{\text{UAE,Germany}}_{\text{air transport,1}}$. Here the producer, emitter and final seller is $r = s =$ UAE, and the consumer $t =$ Germany. The direct CO_2 emissions associated with an Australian citizen flying on an Australian airline from Fiji to Kiribati are part of Australia's carbon footprint, and are calculated as $q^{\text{Australia}}_{\text{air transport}} \times \tilde{y}^{\text{Australia,Australia}}_{\text{air transport,1}}$.[1]

These examples show that the TSA and input-output accounting principles care only about the residence of the producing establishment, and that CO_2 emissions are allocated irrespective of country of origin and destination. Having said this, and given that most

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[1] The input-output calculus also covers indirect emissions arising from air travel. To stick with one of the examples: the total CO_2 emissions associated with a German citizen flying on a UAE-based airline from Cyprus to Malta are part of Germany's carbon footprint, and are calculated as $\sum_{r,i} q^{r}_{i} L^{r,\text{UAE}}_{i,\text{air transport}} \times \tilde{y}^{\text{UAE,Germany}}_{\text{air transport,1}}$. This footprint component originates in a multitude of countries r and sectors i, depending on the supply-chain network underlying the UAE air transport sector. This footprint may include contributions such as the 3rd-order supply chain $q^{\text{Canada}}_{\text{non-ferrous metal}} A^{\text{Canada,USA}}_{\text{non-ferrous metal,aircraft}} A^{\text{USA,UAE}}_{\text{aircraft,air transport}} \times \tilde{y}^{\text{UAE,Germany}}_{\text{air transport,1}}$ describing emissions by Canadian manufacturers of non-ferrous metal exported to the USA for making aircraft, which in turn are exported to the UAE for providing air transport to the German passenger.

airlines operate flights to and from their resident country, in most cases at least one of origin or destination country is likely to coincide with the residence of the transport establishment.

2.5. 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, UK[152], Taiwan[143], Australia[142], Spain[153], and Switzerland[154]. 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 an economic significance at the geographic territory.

Technically, TSA data enter Leontief's model as final demand[2] $\tilde{\mathbf{y}}$, where the 39 classifications of the original TSAs (Tab. *SI* 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.

[2] According to the UNWTO, travel for business purposes is to be included in the official TSAs. The treatment of business trip expenses for input-output analysis is different across studies. Some authors argue that it should be treated as an intermediate input, not as final demand – see 134 Libreros, M., Massieu, A. & Meis, S. Progress in Tourism Satellite Account Implementation and Development. *Journal of Travel Research* **45**, 83-91, doi:10.1177/0047287506289517 (2006). However, in our global study this approach is impossible to implement, since there exists no information on the sectoral identity of the businesses in questions, let alone of which downstream sectors their business-travel carbon emissions would have to be passed on to under consumption-based accounting (CBA). Data availability aside, allocating business travel to final demand is unlikely to introduce a significant error, since a) private travel constitutes the clear majority of travel activities, and b) there is no double-counting problem since we do not compare the carbon footprint of tourism with the carbon footprint of commodities purchased from business-travelling establishments. Finally, from a conceptual perspective, including business travel into intermediate demand is undesirable since it would lead to significantly underestimating the global carbon footprint of tourism as defined by the UNWTO, since then the carbon emissions from business travel would become embodied in consumer goods and services that are unrelated to tourism activities, and hence missed.

Tab. *SI* 1: 39-product group classification in the Tourism Satellite Accounts (TSAs)

A	Accommodation, food and beverage serving services
Aa	Accommodation services
Aa1	Hotels and similar (include motel)
Aa2	Imputed and actual rent on vacation homes
Aa3	Meals from accommodation
Ab	Food and beverage serving services
B	Transportation services
Ba	Passenger transport services
Ba1	Road transportation
Ba11	Railways passenger transport
Ba12	On-road passenger transport
Ba2	Air transportation
Ba3	Water transportation
Bb	Fuel and Other Automotive Products
Bb1	Fuel (petrol, diesel)
Bb2	Other Automotive Products
Bc	Transport equipment rental services
Bd	Repair and maintenance
Be	Passenger transport supporting services
C	Travel agency and tour operator services
D	Recreational, cultural and sporting services
E	Other tourism goods and services
Ea	Miscellaneous tourism services
Ea1	Education services
Ea2	Convention fees
Ea3	Medical services
Ea4	Financial and insurance services
Ea5	Postal and Communication Services
Ea6	Others
Eb	Other goods (shopping)
Eb1	Cosmetics & Skin Care / Perfume
Eb2	Electrical / Photographic Goods
Eb3	Foodstuff, Alcohol and Tobacco
Eb4	Garments / Fabric and Leather / Synthetic Goods
Eb5	Jewellery and Watch
Eb6	Medicine / Chines Herbs
Eb7	Souvenirs / Handicrafts and Gifts
Eb8	Other Items
TT	TOTAL

Final demand in turn drives economic output $\tilde{\mathbf{x}} = (\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1})^{-1}\tilde{\mathbf{y}}\mathbf{1}^{\mathbf{y}}$, which then causes the carbon footprint of tourism, $\tilde{Q} = \mathbf{q}\tilde{\mathbf{x}}$.[3] Here, $\mathbf{T}$ is an $N\times N$ MRIO matrix listing international trade transactions (so-called intermediate demand) between countries, and $\mathbf{y}$ is 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 $\mathbf{x} = \mathbf{T}\mathbf{1}^{\mathbf{T}} + \mathbf{y}\mathbf{1}^{\mathbf{y}}$, with $\mathbf{1}^{\mathbf{T}} = \underbrace{\{1,1,\dots,1\}'}_{N\text{ elements}}$ and $\mathbf{1}^{\mathbf{y}} = \underbrace{\{1,1,\dots,1\}'}_{M\text{ elements}}$ being suitable summation operators, and with the $'$ symbol denoting vector transposition. This accounting identity can be transformed into the fundamental input-output equation $\mathbf{x} = (\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1})^{-1}\mathbf{y}\mathbf{1}^{\mathbf{y}}$, where $\mathbf{I}$ is an $N\times N$ identity matrix. This equation represents Leontief's demand-pull model of the economy[155], 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[156]. The matrix $(\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1})^{-1}$ is Leontief's inverse.

Writing out the tensor products in this aggregate relationship for the scalar $\tilde{Q}$ allows unraveling carbon footprints into supplying and demanding regions, commodities and

[3] The $\sim$ symbol denotes a particular final demand stressor $\tilde{\mathbf{y}}$ for the Leontief model. This stressor does not normally satisfy the national accounting identity.

agents.[157] The most general breakdown of the carbon footprint in an MRIO setting is achieved by an element-wise product $\mathbf{q}\#\mathbf{L}\#\tilde{\mathbf{y}}$, or $\tilde{Q}_{ijk}^{rst} = q_i^r L_{ij}^{rs} \tilde{y}_{jk}^{st}$, where $\mathbf{L} = (\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1})^{-1}$ is the Leontief inverse, and where *r* counts regions of production and therefore emissions, *s* regions of final sale (eg 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 etc), and *k* the consuming agents (practically only households, *k*=1).

2.6. Uncertainty

Data quality and detail in the Tourism Satellite Accounts (TSAs) varies between countries, which is reflected in the different levels of the classification descriptors in Tab. *SI* 1 Some countries specify detailed types of tourist expenditures, but others just report sub-totals and/or totals. Lack of detail will have a particular influence on the carbon footprint of TSA classes E (Other tourism goods and services), Ea (Miscellaneous tourism services), Eb (Other goods – shopping), and TT (Total), because these classes are very broad and could potentially include a wide and varying mix of products with different emissions characteristics. We deal with this circumstance by including in our TSA-to-MRIO bridging concordance **C**, all possible goods and services that tourists could buy (most manufactured goods and commercial services, but no mining products, basic chemicals and metals, construction services, pipeline transport, and so on). We determine the mix of products bought at any particular tourist destination by distributing the sub-total or total expenditure on TSA classes E, Ea, Eb and TT across MRIO classes according to total sales of the destination country. For example, if sales of electronic goods are generally high in Japan, we assume that they are equally high in tourist's consumption basket. Obviously, if electronic goods were hardly sold in, say Gambia, then the expenditure of tourists to Gambia would not include them. Of course, this assumption carries a degree of uncertainty, since there may not be a proportionality between national sales and tourist consumption.

Further sources of stochastic uncertainty exist within the measurement of primary data such as **Q** and **T** (see Methods Section).[158]

In order to assess the influence of allocation and parametrical uncertainty on our carbon footprint results, we carry out a detailed uncertainty analysis, using error propagation.[159,160] The calculation of carbon footprints based on input-output analysis involves a matrix inversion ($\mathbf{L} = (\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1})^{-1}$), and as a consequence analytical error propagation is not possible.[161] Input-output researchers have gotten around this difficulty by resorting to Monte-Carlo approaches.[158,162-164] Here, uncertainty is propagated using standard deviations[110] $\sigma_{\mathbf{Q}}, \sigma_{\mathbf{T}}$ and $\sigma_{\mathbf{y}}$ (sourced from the same MRIO database, Eora[165,166] , as constructed in the Global MRIO Virtual Laboratory[167]) for perturbing the basic data items **Q**, **T** and **y**, then 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. More specifically, we generate normally distributed random numbers $\nu \in \mathcal{N}(0|1)$ and use these perturb the basic footprint equation $\tilde{Q} = \mathbf{Q}\hat{\mathbf{x}}^{-1}(\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1})\tilde{\mathbf{y}}$ to[168]

$$\tilde{Q}^{\mathrm{p}} = \mathbf{Q}^{\mathrm{p}}\widehat{\mathbf{x}^{\mathrm{p}}}^{-1}\left(\mathbf{I} - \mathbf{T}^{\mathrm{p}}\widehat{\mathbf{x}^{\mathrm{p}}}^{-1}\right)\tilde{\mathbf{y}}^{\mathrm{p}}\,, \qquad (SI\ 2.1)$$

where $\mathbf{x}^{\mathrm{p}} = \mathbf{T}^{\mathrm{p}}\mathbf{1}^{N} + \mathbf{y}^{\mathrm{p}}$, and where the logarithmic perturbations

$$\mathbf{Q}^{\mathrm{p}} = 10^{\log_{10}\mathbf{Q}+\nu\sigma_{\log_{10}\mathbf{Q}}} \text{ and } \mathbf{T}^{\mathrm{p}} = 10^{\log_{10}\mathbf{T}+\nu\sigma_{\log_{10}\mathbf{T}}} \qquad (SI\ 2.2)$$

ensure that neither $\mathbf{Q}^{\mathrm{p}}$ nor $\mathbf{T}^{\mathrm{p}}$ will ever become negative.[168] Here, the standard deviation of logarithms can be approximated by[110]

$$\sigma_{\log_{10}x} \approx \log_{10}(x+\sigma_x) - \log_{10}(x) = \log_{10}\left(\frac{x+\sigma_x}{x}\right). \qquad (SI\ 2.3)$$

The perturbation of the tourist demand stressor $\tilde{\mathbf{y}}$ to $\tilde{\mathbf{y}}^{\mathrm{p}}$ proceeds in a slightly different way. As discussed above, the uncertainty in $\tilde{\mathbf{y}}$ is more on of allocation, not of measurement. As such, we perturb the bridging procedure $\tilde{\mathbf{y}} = \mathbf{C} \times \mathbf{TSA}$ that translates from the 39 categories in the TSAs (Tab. *SI* 1) into the MRIO classification. More specifically, for MRIO region *r* we have $\tilde{y}_i^r = \sum_j C_{ij}^r \times TSA_j$, with the concordance bridge matrix $\mathbf{C}$ being normalized as $\sum_i C_{ij}^r = 1 \forall r,j$. Our approach to determining allocation uncertainty is to perturb the concordance matrix as ${C^{\mathrm{p}}}_{ij}^r = C_{ij}^r\zeta_{ij}^r / \sum_i C_{ij}^r\zeta_{ij}^r$, where the $\zeta_{ij}^r \in \mathcal{U}(1-\bar{\zeta}|1+\bar{\zeta})$ are uniformly distributed between $1-\bar{\zeta}$ and $1+\bar{\zeta}$. In our work, we use $\bar{\zeta} = 0.9$, which we think is a rather extreme way of simulating mis-allocation. To give a simple example, this procedure could mean that the initial allocation of, say 10% of TSA class shopping (Eb in Tab. *SI* 1) to MRIO class electronics and 10% to MRIO class clothing, can be perturbed to 1% electronics and 19% clothing. The perturbed tourist demand stressor is then $\tilde{\mathbf{y}}^{\mathrm{p}} = \mathbf{C}^{\mathrm{p}} \times \mathbf{TSA}$.

Finally, in our Monte-Carlo analysis, perturbations as in equation *SI* 2.1 are repeated *P* times, and outcomes $\tilde{Q}^{(p=1,\dots,P)}$ collected. Finally, a normal distribution is fitted to a frequency plot of the $\tilde{Q}^{(p)}$, and the standard deviation $\sigma_{\tilde{Q}}$ derived from the fit. In order to obtain an accurate estimate of $\sigma_{\tilde{Q}}$, *P* needs to be large enough for the frequency plot of the $\tilde{Q}^{(p)}$ to be smooth. In this work, $P = 10^4$.

3. Supplementary Data

3.1. Countries in our analysis and UN ISO-3 acronyms[4] used

Tab. *SI* 2: Country names and ISO-3 codes.

Country name	ISO-3 acronym
Afghanistan	Afg
Albania	Alb
Algeria	Dza
Angola	Ago
Argentina	Arg
Armenia	Arm
Australia	Aus
Austria	Aut
Azerbaijan	Aze
Bahrain	Bhr
Bangladesh	Bgd
Barbados	Brb
Belgium	Bel
Belize	Blz
Benin	Ben
Bolivia	Bol
Bosnia and Herzegovina	Bih
Botswana	Bwa
Brazil	Bra
Brunei Darussalam	Brn
Bulgaria	Bgr
Burkina Faso	Bfa
Burundi	Bdi
Cambodia	Khm
Cameroon	Cmr
Canada	Can
Cabo Verde	Cpv
Central African Republic	Caf
Chile	Chl
China	Chn
Colombia	Col
Congo	Cog
Costa Rica	Cri
Croatia	Hrv
Cuba	Cub
Cyprus	Cyp
Czech Republic	Cze
Côte d'Ivoire	Civ
D.R. of the Congo	Cod
Denmark	Dnk
Dominican Republic	Dom
Ecuador	Ecu
Egypt	Egy
El Salvador	Slv
Eritrea	Eri
Ethiopia	Eth
Fiji	Fji
Finland	Fin
France	Fra
French Polynesia	Pyf
Gambia	Gmb
Georgia	Geo
Germany	Deu
Ghana	Gha
Greece	Grc
Guatemala	Gtm
Guinea	Gin
Haiti	Hti
Honduras	Hnd
Hungary	Hun
India	Ind
Indonesia	Idn
Iran	Irn
Iraq	Irq
Ireland	Irl
Israel	Isr
Italy	Ita
Jamaica	Jam
Japan	Jpn
Jordan	Jor
Kazakhstan	Kaz
Kenya	Ken
Kuwait	Kwt
Kyrgyzstan	Kgz
Lao PDR	Lao
Latvia	Lva
Lebanon	Lbn
Liberia	Lbr
Libya	Lby
Lithuania	Ltu
Madagascar	Mdg
Malawi	Mwi
Malaysia	Mys
Maldives	Mdv
Mali	Mli
Malta	Mlt
Mauritius	Mus
Mexico	Mex
Mongolia	Mng
Morocco	Mar
Mozambique	Moz
Myanmar	Mmr
Namibia	Nam
Nepal	Npl
Netherlands	Nld
New Caledonia	Ncl
New Zealand	Nzl
Nicaragua	Nic
Niger	Ner
Nigeria	Nga
Norway	Nor
Oman	Omn
Pakistan	Pak
Panama	Pan
Papua New Guinea	Png
Paraguay	Pry
Peru	Per
Philippines	Phl
Poland	Pol
Portugal	Prt
Qatar	Qat
Republic of Korea	Kor
Romania	Rou
Russian Federation	Rus
Rwanda	Rwa
Samoa	Wsm
Saudi Arabia	Sau
Senegal	Sen
Serbia	Srb
Seychelles	Syc
Sierra Leone	Sle
Singapore	Sgp
Slovakia	Svk
Slovenia	Svn
South Africa	Zaf
Spain	Esp
Sri Lanka	Lka
Suriname	Sur
Sweden	Swe
Switzerland	Che
Syrian Arab Republic	Syr
Taiwan	Twn
Tajikistan	Tjk
Thailand	Tha
Macedonia	Mkd
Togo	Tgo
Trinidad and Tobago	Tto
Tunisia	Tun
Turkey	Tur
Uganda	Uga
Ukraine	Ukr
United Arab Emirates	Are
United Kingdom	Gbr
Tanzania	Tza
United States of America	Usa
Uruguay	Ury
Uzbekistan	Uzb
Vanuatu	Vut
Venezuela	Ven
Viet Nam	Vnm
Yemen	Yem
Zambia	Zmb
Zimbabwe	Zwe

[4] https://unstats.un.org/unsd/tradekb/Knowledgebase/50347/Country-Code.

3.1.1. List of member countries in the five annual per-capita GDP groups

Tab. *SI* 3a: Countries in the five annual per-capita GDP groups (supporting Figs. *SI* 2-4).

Class	Low	Low-middle	Middle	Middle-high	High
Income bracket (US$/cap)	<$1k	$1k-$4k	$4k-$8k	$8k-$25k	>$25k
Population (mill)	788.7	2523	1853	916.9	942.1
Countries	Afghanistan	Armenia	Albania	Argentina	Australia
	Bangladesh	Bolivia	Algeria	Bahrain	Austria
	Benin	Cambodia	Angola	Barbados	Belgium
	Burkina Faso	Cameroon	Azerbaijan	Botswana	Brunei
	Burundi	Congo	Belize	Brazil	Canada
	Central African Republic	Côte d'Ivoire	Bosnia and Herzegovina	Chile	Cyprus
	DR Congo	Egypt	Bulgaria	Costa Rica	Denmark
	Eritrea	Ghana	Cabo Verde	Croatia	Finland
	Ethiopia	Guatemala	China	Czech Republic	France
	Gambia	Honduras	Colombia	Hungary	French Polynesia
	Guinea	India	Cuba	Kazakhstan	Germany
	Haiti	Indonesia	Dominican Republic	Latvia	Greece
	Kenya	Kyrgyzstan	Ecuador	Lebanon	Ireland
	Liberia	Lao PDR	El Salvador	Lithuania	Israel
	Madagascar	Mongolia	Fiji	Malaysia	Italy
	Malawi	Morocco	Georgia	Maldives	Japan
	Mali	Nicaragua	Iran	Malta	Kuwait
	Mozambique	Nigeria	Iraq	Mauritius	Netherlands
	Myanmar	Pakistan	Jamaica	Mexico	New Caledonia
	Nepal	Papua NG	Jordan	Oman	New Zealand
	Niger	Philippines	Libya	Panama	Norway
	Rwanda	Senegal	Namibia	Poland	Qatar
	Sierra Leone	Sri Lanka	Paraguay	Portugal	Singapore
	Tajikistan	Syria	Peru	South Korea	Slovenia
	Togo	Ukraine	Samoa	Romania	Spain
	Uganda	Uzbekistan	Serbia	Russia	Sweden
	Tanzania	Viet Nam	South Africa	Saudi Arabia	Switzerland
	Zimbabwe	Yemen	Thailand	Seychelles	UAE
		Zambia	Macedonia	Slovakia	UK
			Tunisia	Suriname	USA
			Vanuatu	Taiwan	
				Trinidad & Tobago	
				Turkey	
				Uruguay	
				Venezuela	

Tab. *SI* 3b: Travelers in the three annual per-capita GDP groups.

Class	Low	Low	Middle	Middle	High	High
Bracket (US$/cap)	<2.9k	<2.9k	$ 2.9k -10.9k	$ 2.9k -10.9k	$1000k	$1000k
Population (mill)	2829	2829	2785	2785	1405	1405
Travelers	Afghanistan	Malawi	Albania	Jordan	Australia	New Caledonia
	Bangladesh	Mali	Algeria	Kazakhstan	Austria	New Zealand
	Benin	Mozambique	Angola	Lebanon	Bahrain	Norway
	Bolivia	Myanmar	Argentina	Libya	Barbados	Oman
	Burkina Faso	Nepal	Armenia	Malaysia	Belgium	Poland
	Burundi	Nicaragua	Azerbaijan	Maldives	Brunei Darussalam	Portugal
	Cambodia	Niger	Belize	Mexico	Canada	Qatar
	Cameroon	Nigeria	Bosnia and Herzegovina	Mongolia	Chile	Republic of Korea
	Central African Republic	Pakistan	Botswana	Morocco	Croatia	Russian Federation
	Congo	Papua New Guinea	Brazil	Namibia	Cyprus	Saudi Arabia
	Côte dIvoire	Philippines	Bulgaria	Panama	Czech Republic	Seychelles
	D.R. of the Congo	Rwanda	Cabo Verde	Paraguay	Denmark	Singapore
	Eritrea	Senegal	China	Peru	Finland	Slovakia
	Ethiopia	Sierra Leone	Colombia	Romania	France	Slovenia
	Gambia	Tajikistan	Costa Rica	Samoa	French Polynesia	Spain
	Ghana	Togo	Cuba	Serbia	Germany	Sweden
	Guinea	Uganda	Dominican Republic	South Africa	Greece	Switzerland
	Haiti	United Republic of Tanzania: Mainland	Ecuador	Sri Lanka	Hungary	Taiwan
	Honduras	Uzbekistan	Egypt	Suriname	Ireland	Trinidad and Tobago
	India	Viet Nam	El Salvador	Syrian Arab Republic	Israel	Turkey
	Kenya	Yemen	Fiji	Thailand	Italy	United Arab Emirates
	Kyrgyzstan	Zambia	Georgia	The former Yugoslav Republic of Macedonia	Japan	United Kingdom
	Lao Peoples Democratic Republic	Zimbabwe	Guatemala	Tunisia	Kuwait	United States
	Liberia		Indonesia	Ukraine	Latvia	Uruguay
	Madagascar		Iran (Islamic Republic of)	Vanuatu	Lithuania	Venezuela (Bolivarian Republic of)
			Iraq		Malta	
			Jamaica		Mauritius	
					Netherlands	

3.1.2. List of countries for which detailed national TSAs were sourced

Australia
Austria
Brazil
Bulgaria
Canada
Chile
China
Colombia
Croatia
Cyprus
Czech Republic
Denmark
Ecuador
Egypt
Estonia
Finland
France
Germany
Honduras
Hong Kong
Hungary
Iceland
India
Indonesia
Ireland
Israel
Italy
Japan
Korea
Latvia
Lithuania
Macao
Malaysia
Mexico
Morocco
Netherlands
New Zealand
Norway
Oman
Peru
Philippines
Poland
Portugal
Romania
Singapore
Slovak
Slovenia
South Africa
Spain
Sri Lanka
Sweden
Switzerland
Taiwan
United Kingdom
United States

3.2. Greenhouse gases included, and their Global Warming Potentials

The Global Warming Potentials (GWP) allow for a comparison of the global warming impacts of different gases. Carbon dioxide is used as a reference point for the calculation of GWP of different gases. By definition, carbon dioxide has a GWP of 1. The GWPs are calculated for a specific time period, typically 100 years[169]. Gases with a large GWP have a high warming potential, i.e. for a given amount of mass nitrous oxide traps more energy than methane. Hydrofluorocarbons, chloroflurocarbons, sulfur hexafluoride and nitrogen trifluoride are considered high GWP gases because they trap considerably more heat than carbon dioxide.

Tab. *SI* 4: Greenhouse gases and their Global Warming Potentials.

Species	Chemical formula	Global Warming Potential
Carbon dioxide	CO_2	1
Methane	CH_4	25
Nitrous oxide	N_2O	298
Hydrofluorocarbons	HFC	3772
Chlorofluorocarbon	CFC	8925
Sulfur hexafluoride	SF_6	22800
Nitrogen trifluoride	NF_3	17200

Sub-sonic aviation is responsible for the emission of a range of short-lived greenhouse gases that are not listed in Tab. *SI* 4. These include[170] NO_x responsible for the formation of tropospheric O_3 with a positive radiative forcing (RF; warming) and for the destruction of ambient CH_4 with a negative RF (cooling); sulphate particles from sulphur in the fuel (negative RF); soot particles (positive RF); contrails in the wake of an aircraft (positive RF); cloud formation (positive RF). Except for CO_2 emissions from the combustion of aircraft fuel, all other effects on global temperature increases are very poorly understood, highly uncertain, and lacking globally comprehensive databases across individual countries and multiple years. In addition, possibly except for aircraft-induced cloudiness and contrails, the effects of these short-lived greenhouse gases, in terms of a number of specifically developed emission metrics[171], are likely to be smaller than those of fuel-borne CO_2. This is particularly true when applying a 50-year time horizon that matches contemporary policy targets.

3.3. Commodity acronyms used in Sections 4.2 and 4.5.

Tab. *SI* 5: Commodity acronyms and full sector names.

Sector acronyms	Sector names	Notes
Ag	Agriculture	
Min	Mining	- The general classes 'Hospitality' and 'Transport' are due to data that do not allow distinguishing hotels and restaurants, and transport modes, respectively.
Food	Food	
Good	Goods	
Utils	Utilities	- 'Transport' is mostly road transport based on modal data by the WTO.
Constr	Construction	
Trade	Trade	
Hosp	Hospitality	- 'Goods' and 'Services' are goods and services other than those covered by the other categories, restricted to those items that visitors typically buy (that is excluding construction materials, livestock, electricity etc).
Acc	Accommodation	
Rest	Restaurants	
Trans	Transport	
Road	Road Transport	
Rail	Rail Transport	
Air	Air Transport	- "Agriculture" includes hunting and fishing, and "Utilities" include electricity, gas and water.
Water	Water Transport	
Serv	Services	

4. Supplementary Results

In the following, we will use the term "carbon footprint" to mean the footprint of global tourism in units of CO_2 equivalents (CO_2-e), even though this measure includes greenhouse gases such as N_2O that do not contain carbon. Greenhouse gases included in our analysis are listed in Section 3.2.

4.1. Global tourism carbon footprint estimates for 2009-2013

On the back of a growth in tourist expenditure from 2.5 $tr in 2009 to 4.7 $tr in 2013, the global carbon footprint increased rapidly from 3.9 Gt CO_2-e to 4.4 Gt CO_2-e during the same period. More than half of this carbon footprint was caused in high-income country destinations (DBA perspective; left column in Fig. *SI* 2), and by visitors from high-income countries (RBA perspective; right column in Fig. *SI* 2).

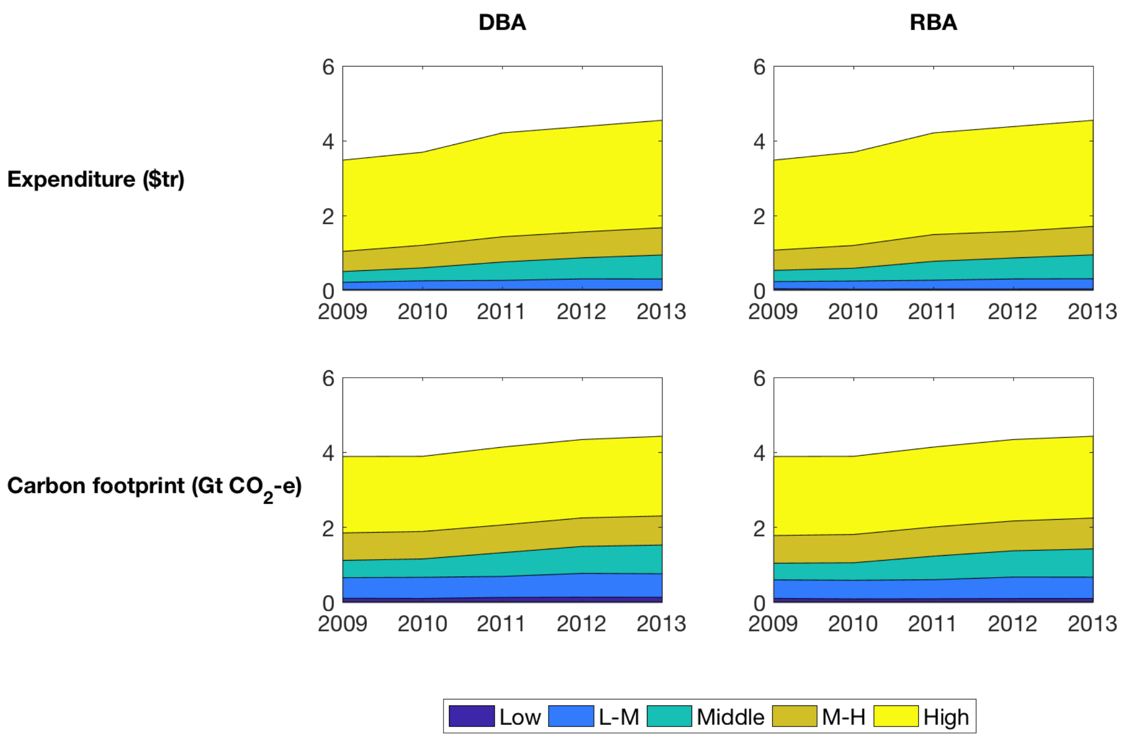

Fig. *SI* 2: Evolution of the expenditure and carbon footprint of global tourism between 2009 and 2013, clockwise from top right: $\tilde{y}^{:t}_{.1}$, $\tilde{Q}^{::t}_{..1}$, $\tilde{Q}^{.s:}_{..1}$, $\tilde{y}^{s:}_{.1}$. Coloured bands represent five income groups containing approximately 35 countries each (see membership in *SI* 3.1.1), starting from low-income (L; purple) to high-income (H; yellow).

Note: The five annual per-capita GDP brackets are L <$1k, L-M $1k-$4k, M $4k-$8k, M-H $8k-$25k, H >$25k. Average annual growth rates in the income bands are 2.4% (L), 9.3% (L-M), 23.9% (M), 7.1% (M-H) and 3.4% (H).

We present per-capita results in addition to totals, in order to show a) who – as a host – suffers a large burden from tourism, and b) who exerts the pressure that leads to these burdens. In this context we use the terms "net travelers" and "net hosts".

A per-capita-based view of the global carbon footprint of tourism (Fig. *SI* 3) confirms the trends in totals. Driven by increasing levels of expenditure, high-income-country per-capita carbon footprints surpass 2 tonnes, more than 10 times higher than those for low-income countries. Again, there is no clear distinction between the DBA and RBA accounting perspectives: per-capita carbon footprints are high in high-income destinations (bottom left) as well as for high-income visitors (bottom right).

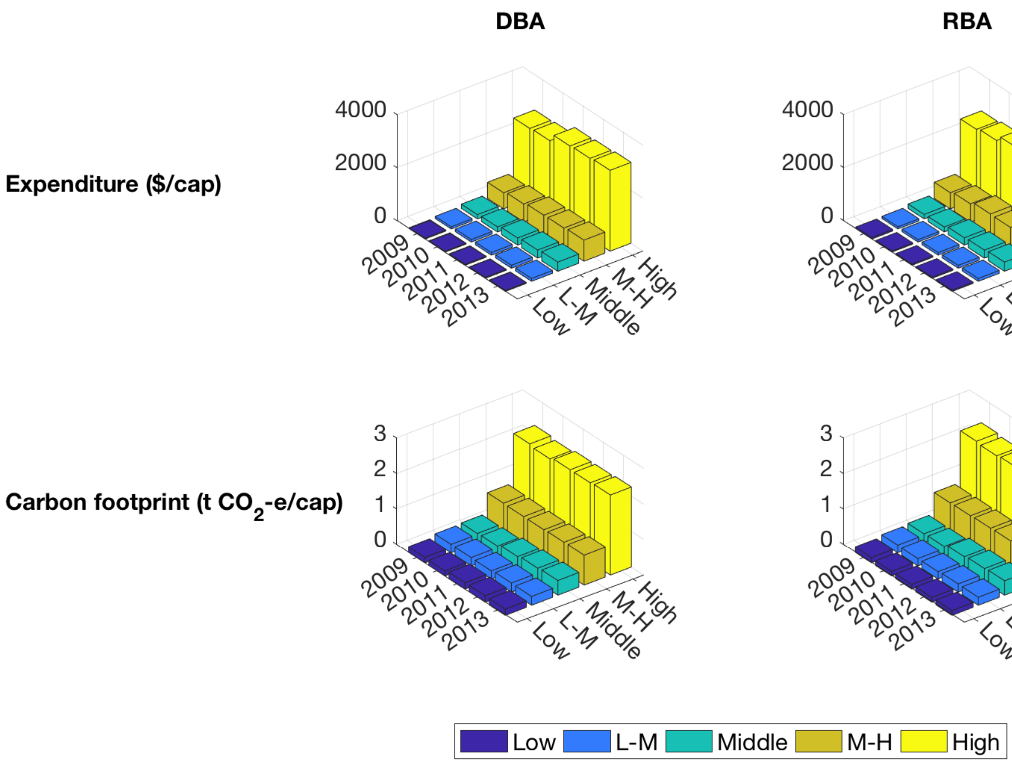

Fig. *SI* 3: Evolution of the per-capita expenditure and carbon footprint of global tourism between 2009 and 2013, clockwise from top right: $\tilde{y}^{\cdot t}_{\cdot 1}$, $\tilde{Q}^{\cdot\cdot t}_{\cdot\cdot 1}$, $\tilde{Q}^{\cdot s \cdot}_{\cdot\cdot 1}$, $\tilde{y}^{s \cdot}_{\cdot 1}$. Coloured bands represent five income groups containing approximately 35 countries each (see membership in *SI* 3.1.1), starting from low-income (L; purple) to high-income (H; yellow).

Note: The five annual per-capita GDP brackets are L <$1k, L-M $1k-$4k, M $4k-$8k, M-H $8k-$25k, H >$25k. Average annual growth rates in the income bands are 0.4% (L), 7.6% (L-M), 22.6% (M), 6.2% (M-H) and 2.9% (H). These growth rates are lower than those of the totals in Fig. SI 2, because they are net of population growth.

The overall difference between DBA and RBA accounting perspectives is small because – simply speaking – tourism is high-income business. By far the largest volume of visitor movements (almost 40% of total) occurs amongst high-income countries (Fig. *SI* 4), meaning that both destinations (DBA) as well as visitors (RBA) feature similar footprint characteristics.

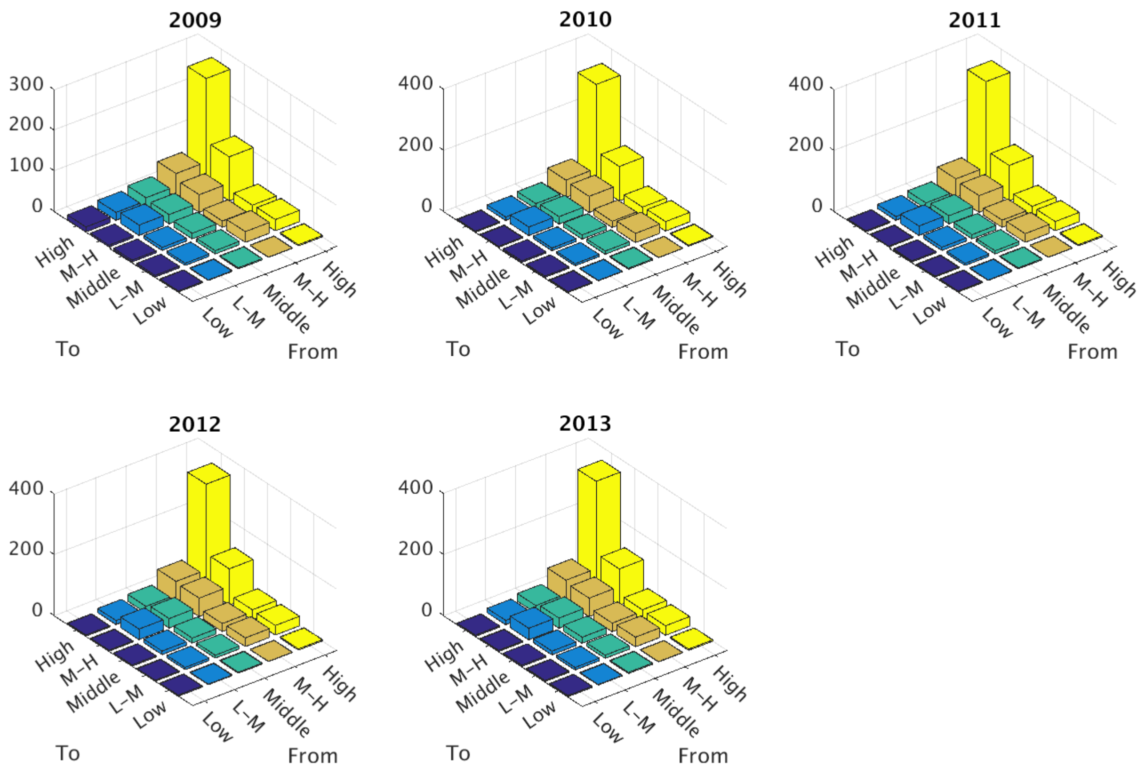

Fig. *SI* 4: International visitor movements (in millions) within and between five income groups containing approximately 35 countries each (see membership in *SI* 3.1.1), starting from low-income (purple) to high-income (yellow).
Note: The five annual per-capita GDP brackets are L <$1k, L-M $1k-$4k, M $4k-$8k, M-H $8k-$25k, H >$25k.

Whilst at the global level, DBA and RBA yield almost identical results, this is not the case for each country (Fig. *SI* 5). For example, under DBA the USA has a tourism carbon footprint of about 900 Mt CO_2-e, whilst under RBA, US visitors are responsible for 770 Mt CO_2-e, characterising the US as a “net tourist destination”. The same holds for popular tourist destinations such as Thailand, Vietnam, Egypt, Greece, Spain, Morocco, Croatia and Mauritius. On the other hand, Canada, the UK, China, Japan, Germany, the Netherlands and Switzerland have a higher carbon footprint under RBA than under DBA, characterising them as “net traveller origins”.

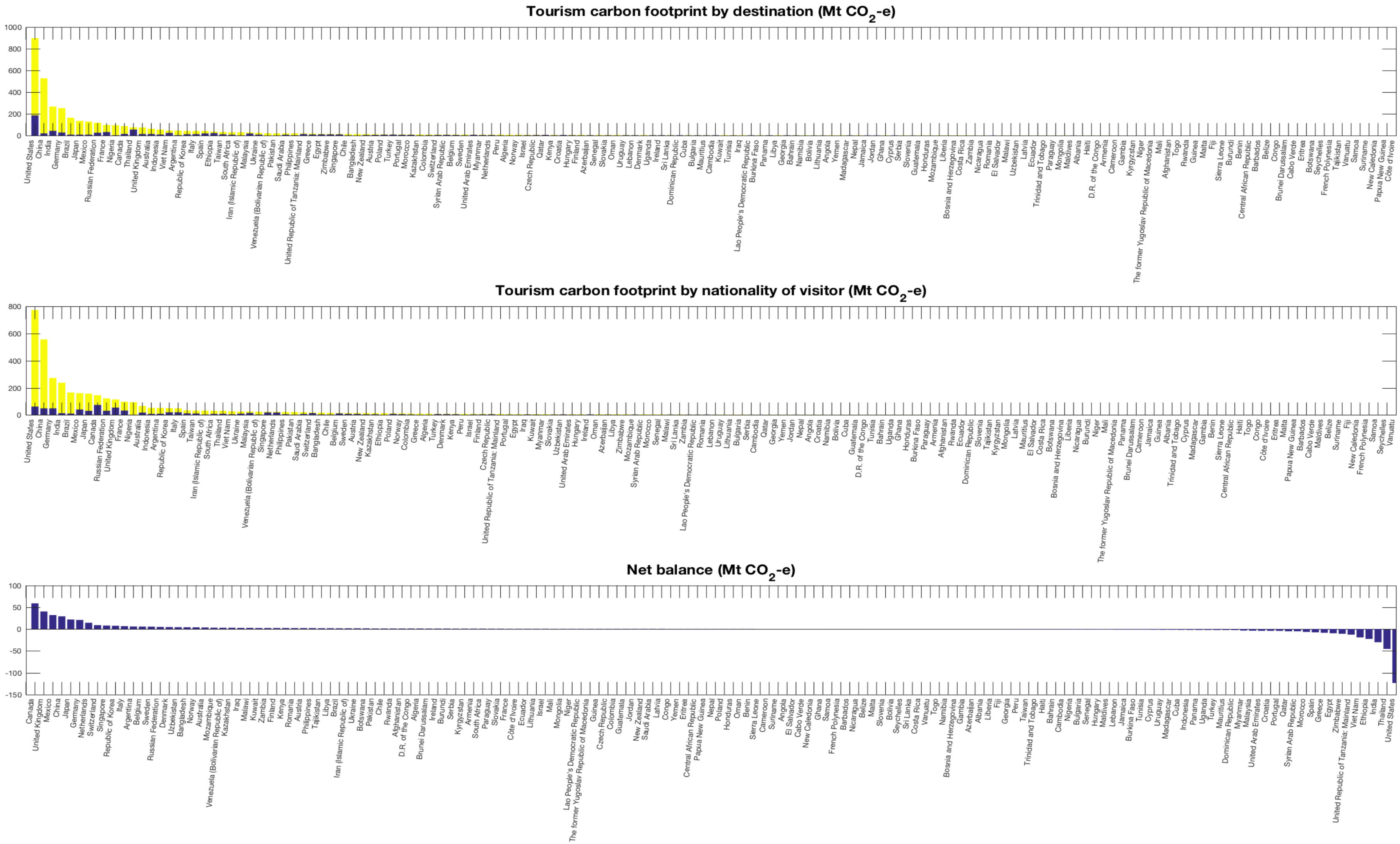

Fig. *SI* 5: Global tourism carbon footprint by destination (DBA, $\tilde{Q}^{\cdot s \cdot}_{\cdot\cdot 1}$) and visitor nationality (RBA, $\tilde{Q}^{\cdot\cdot t}_{\cdot\cdot 1}$), and the net trade balance $\tilde{Q}^{\cdot r \cdot}_{\cdot\cdot 1} - \tilde{Q}^{\cdot\cdot r}_{\cdot\cdot 1}$. Each bar distinguishes domestic travel (yellow) and international travel (blue).

4.2. Important commodities in the global tourism carbon footprint

Whether visitors are from high-income or low-income countries determines their spending pattern and therefore their carbon footprint (left column in Fig. *SI* 6): Whilst high-income visitors spend relatively more money on air travel and shop more for goods, low-income visitors buy more unprocessed food (shown under "Ag") and spend less money on hospitality.

Whether tourism occurs in high-income or low-income destinations determines visitors' spending pattern and therefore their carbon footprint as well (centre column in Fig. *SI* 6): Whilst high-income destinations are often reached by air travel and include high-end accommodation, restaurants and goods shopping in the visitor's experience, low-income destinations rely more on road transport, and feature food provision through retail rather than restaurants.

High-, middle- and low-income country all include industries that are situated at the origins of supply chains, where greenhouse gas emissions take place (right column in Fig. *SI* 6): Whilst tourism supply chains ending in high-income countries are often associated with airlines and other transport establishments combusting petroleum-based fuels, tourism supply chains ending in low-income countries often involve agriculture emitting through animals' enteric fermentation and land use changes. All producer locations include utilities with emissions mainly from coal- and gas-fired power plants, and mining operations emitting through fuel combustion as well as venting and flaring.

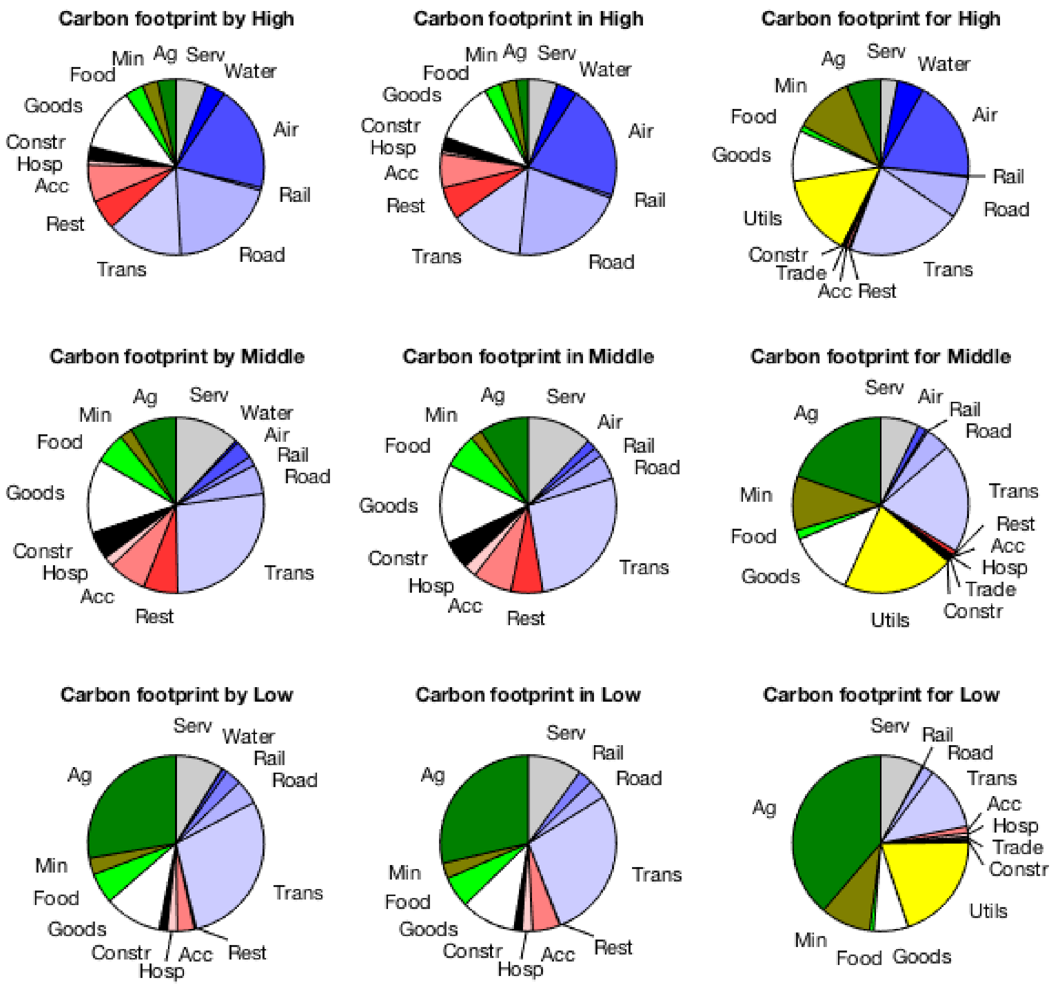

Fig. *SI* 6: Commodity content of carbon footprints of tourism, for high-, middle- and low-income countries (rows), and for visitors (left column, $\tilde{Q}^{\cdot\cdot t}_{\cdot j1}$), destinations (centre column, $\tilde{Q}^{\cdot s \cdot}_{\cdot j1}$) and emitters (right column, $\tilde{Q}^{r\cdot\cdot}_{i\cdot 1}$). For explanations of commodity acronyms see Section 3.3). Note: The three annual per-capita GDP brackets are L <\$3k, M \$3k-\$10k, H >\$10k.

Tab. *SI* 6: Expenditure, carbon footprint and carbon multiplier of various commodities for years 2009-2013.

Tab. *SI* 6a Expenditure

Expenditure on various commodities ($bn)					
Commodities	**2009**	**2010**	**2011**	**2012**	**2013**
Agriculture	81.9 (2.35%)	93.4 (2.53%)	106 (2.53%)	115 (2.62%)	122 (2.68%)
Mining	54.8 (1.57%)	61.8 (1.67%)	75.5 (1.79%)	83 (1.9%)	85.4 (1.88%)
Food	121 (3.47%)	134 (3.63%)	149 (3.53%)	158 (3.61%)	166 (3.66%)
Goods	552 (15.8%)	572 (15.5%)	654 (15.5%)	676 (15.4%)	699 (15.4%)
Utilities	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Construction	151 (4.34%)	161 (4.36%)	181 (4.3%)	192 (4.38%)	203 (4.47%)
Trade	0.927 (0.0266%)	0.921 (0.0249%)	0.992 (0.0236%)	0.874 (0.02%)	0.916 (0.0202%)
Hospitality unspecified	87.1 (2.5%)	98.3 (2.66%)	99.7 (2.37%)	110 (2.5%)	112 (2.45%)
Accommodation	546 (15.7%)	558 (15.1%)	629 (14.9%)	630 (14.4%)	640 (14.1%)
Food & beverage serving	394 (11.3%)	419 (11.4%)	470 (11.2%)	492 (11.2%)	517 (11.4%)
Transport unspecified	368 (10.6%)	400 (10.8%)	473 (11.2%)	493 (11.3%)	512 (11.3%)
Road transport	118 (3.39%)	128 (3.46%)	161 (3.82%)	168 (3.83%)	170 (3.73%)
Rail transport	51.8 (1.49%)	55.8 (1.51%)	65.6 (1.56%)	70.4 (1.61%)	69.8 (1.54%)
Air transport	317 (9.11%)	346 (9.36%)	386 (9.17%)	398 (9.08%)	403 (8.86%)
Water transport	24.9 (0.717%)	26.5 (0.718%)	28.1 (0.666%)	29.2 (0.668%)	30.4 (0.67%)
Services	613 (17.6%)	638 (17.3%)	730 (17.3%)	763 (17.4%)	816 (18%)

Tab. *SI* 6b Carbon footprint

Carbon footprint by purchased commodity (Mt CO_2-e)					
Commodities	**2009**	**2010**	**2011**	**2012**	**2013**
Agriculture	315 (8.1%)	302 (7.75%)	318 (7.68%)	342 (7.88%)	353 (7.96%)
Mining	115 (2.95%)	112 (2.87%)	116 (2.81%)	122 (2.82%)	121 (2.73%)
Food	173 (4.44%)	173 (4.44%)	175 (4.23%)	187 (4.32%)	194 (4.38%)
Goods	482 (12.4%)	481 (12.3%)	501 (12.1%)	525 (12.1%)	534 (12%)
Utilities	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Construction	113 (2.9%)	114 (2.93%)	123 (2.97%)	133 (3.05%)	139 (3.13%)
Trade	0.206 (0.0053%)	0.201 (0.00515%)	0.194 (0.00469%)	0.172 (0.00396%)	0.166 (0.00374%)
Hospitality unspecified	60.1 (1.54%)	59.8 (1.54%)	54.5 (1.32%)	60.9 (1.4%)	58.1 (1.31%)
Accommodation	282 (7.24%)	268 (6.88%)	273 (6.59%)	277 (6.39%)	282 (6.37%)
Food & beverage serving	187 (4.81%)	193 (4.95%)	208 (5.02%)	218 (5.02%)	227 (5.11%)
Transport unspecified	763 (19.6%)	766 (19.7%)	814 (19.7%)	862 (19.8%)	871 (19.7%)
Road transport	459 (11.8%)	471 (12.1%)	565 (13.7%)	593 (13.7%)	602 (13.6%)
Rail transport	37.5 (0.963%)	40.1 (1.03%)	46.4 (1.12%)	51.8 (1.19%)	54.6 (1.23%)
Air transport	523 (13.5%)	531 (13.6%)	534 (12.9%)	536 (12.4%)	547 (12.4%)
Water transport	104 (2.68%)	102 (2.62%)	94.5 (2.28%)	95.5 (2.2%)	97.9 (2.21%)
Services	276 (7.1%)	282 (7.25%)	318 (7.68%)	339 (7.81%)	350 (7.91%)

Tab. *SI* 6c Carbon multiplier (derived from the Eora MRIO database, see Section *SI* 1)

Carbon multiplier by purchased commodity (kg CO_2-e/$ final demand)					
Commodities	**2009**	**2010**	**2011**	**2012**	**2013**
Agriculture	3.85	3.23	2.99	2.98	2.89
Mining	2.09	1.81	1.54	1.47	1.42
Food	1.43	1.29	1.18	1.19	1.17
Goods	0.874	0.84	0.765	0.776	0.764
Utilities	n.a.	n.a.	n.a.	n.a.	n.a.
Construction	0.745	0.709	0.679	0.692	0.683
Trade	0.222	0.218	0.196	0.197	0.181
Hospitality unspecified	0.69	0.608	0.547	0.556	0.521
Accommodation	0.516	0.481	0.434	0.44	0.441
Food & beverage serving	0.475	0.46	0.442	0.443	0.438
Transport unspecified	2.08	1.92	1.72	1.75	1.7
Road transport	3.89	3.69	3.51	3.53	3.55
Rail transport	0.723	0.719	0.707	0.736	0.782
Air transport	1.65	1.53	1.38	1.35	1.36
Water transport	4.19	3.85	3.37	3.27	3.21
Services	0.451	0.443	0.436	0.444	0.429
Total tourism	1.12	1.05	0.984	0.992	0.975
Global average	0.801	0.772	0.721	0.716	0.715

Tab. *SI* 6c lists only an aggregation of carbon multipliers from the Eora MRIO database[165,166]. This database distinguished multipliers of almost 15,000 country-sector pairs. Tab. *SI* 6c compares the tourism industry against other industries. The comparison is between entire sectors, ie tourism is compared against construction in general, not just tourism-related construction.

4.3. Uncertainty

The results from 42,000 Monte-Carlo runs yield that global tourism's carbon footprint in 2013 lies

- between 4.2 and 4.8 Gt CO_2-e at the 95.5%-level of confidence, and
- between 4.1 and 4.9 Gt CO_2-e at the 99.7%-level of confidence.

These estimates include parametrical uncertainty of the entire MRIO database, and allocation uncertainty caused during the bridging between unknown TSA consumption categories and MRIO sectors (see Section *SI* 2.6).

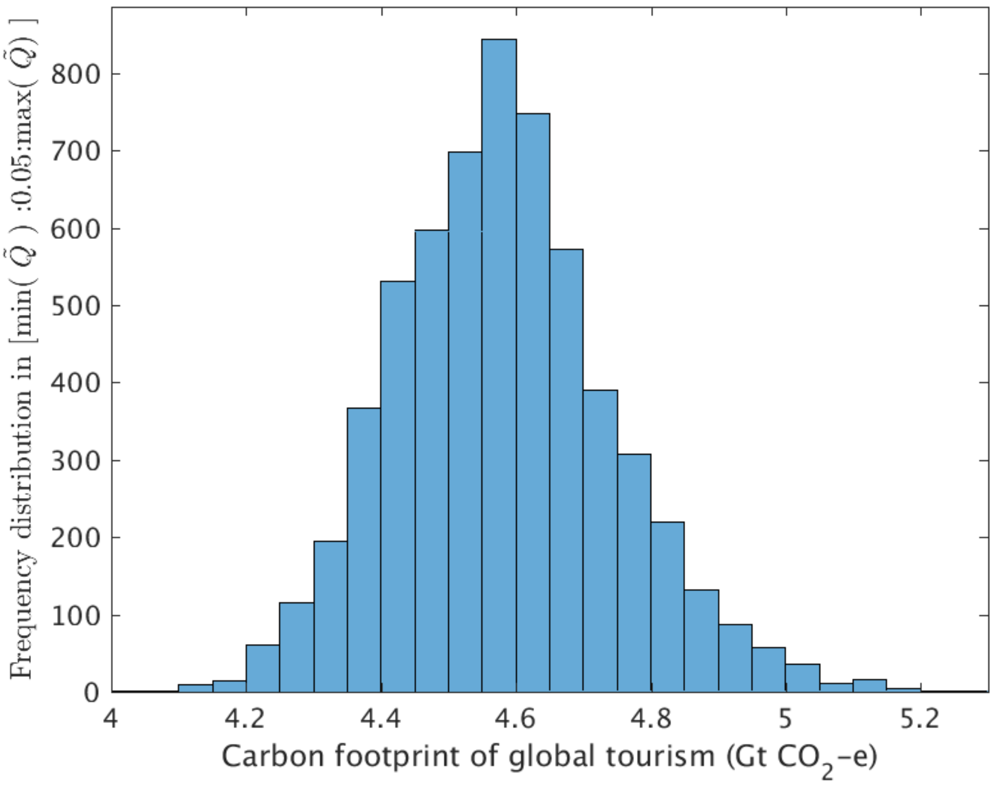

Fig. *SI* 7: Frequency distribution of the carbon footprint of global tourism.

We find that the contributions of commodity groups as distinguished in Section *SI* 4.2 are certain (95.5% level of confidence, or the 2σ band) to within ±10% to ±30%, but that the total carbon footprint is certain (95.5% level of confidence) to within about ±7.1% (Tab. *SI* 7).

These results can be understood as follows. The contributions of the shopping and food categories vary within about ±10% from their unperturbed value even though the TSA-to-MRIO allocation is perturbed by up to ±90%. This is because the perturbation is stochastic, and an increase in a particular tourist spending category for one country may cancel out by a decrease in the same tourist spending category for another country. This is a typical feature of error propagation[168], where the relative standard deviations of aggregate measures stay relatively low because the standard deviations of their components (factors, summands) partially cancel out. The same holds for the total carbon footprint, where the relative standard deviation is lower than that of any consumption category. Once again, the stochastic errors of contributing components partially cancel out.

Tab. *SI* 7: As in Tab *SI* 6b, carbon footprint by purchased commodity (Mt CO_2-e), but including 2σ standard deviation estimates.

Consumption category	Carbon footprint (Mt CO_2-e)	2σ Standard (Mt CO_2-e)	deviation (%)
Agriculture	353	109	30.4
Mining	121	33.8	27.4
Food	194	27.2	13.3
Goods	534	44.5	8.0
Construction	139	27.9	17.1
Hospitality unspecified	58	6.8	11.3
Accommodation	282	27.2	9.5
Food & beverage serving	227	28.2	11.6
Transport unspecified	871	128	14.2
Road transport	602	49.1	8.1
Rail transport	55	11.9	20.4
Air transport	547	178	32.3
Water transport	98	48.6	49.5
Services	351	43.7	11.7
Total	4,430	324	7.1

4.4. Comparison with prior work

We are able to compare our results to prior work that covers either the world or an entire country[142,153,172-175]. Considering the differences in base years, scope, data sources, and methods employed, the results are in reasonable agreement even at the sectoral level of detail. We choose 2010 as the basis for the comparison because the TSA data coverage is slightly better than for 2009.

Note that the way relative contributions (percentages within totals, or contributions to GDP[176]) are calculated varies from report to report. Notably, two reference points are important: 1) whether direct, indirect and induced effects are included, and 2) whether only CO_2 or also non-CO_2 greenhouse gases (CO_2-equivalents) are included. i) In the UNWTO-UNEP_WMO's report only direct CO_2 emissions are addressed, without including indirect, upstream (footprint) supply-chain contributions, and without considering other types of GHG gases. For example, when translating percentages to refer to the same CO_2-e emission definition, the UNWTO's result only corresponds to 2.8% of the global base, half of the originally quoted value (Tab. *SI* 8). ii) The WTTC study[176] arrives at the 10% tourism contribution (year 2016) to GDP by including direct, indirect and induced economic effects. The latter include the effects of households' earning-spending-earning cycles, and multipliers obtained from such so-called type-II calculations are usually much higher than those of the more common (type-I) calculations[177,178] that include direct and indirect contributions. iii) Our study is of type I (including direct and indirect effects). We did not opt for a type-II approach, because such calculations usually require information on value added and final demand to be distinguished by income class, to ensure that the earning-spending cycles are appropriately represented[179,180]. Comprehensive income-class detail on value added and final demand is not available at the global level.

The different approaches mean that percentage estimates as originally quoted are not directly comparable between the UNWTO-UNEP-WMO, the WTTC, and our study.

Tab. *SI* 8: Comparison of direct emissions in our study against other estimates of global tourism CO_2 emissions.

No	Sources	Scope 1	Scope 2	Scope 3	Base year	Direct emissions	% of direct air emissions	Contribution to global CO_2 emissions	Contribution to global CO_2-e emissions
1	Our estimates	Direct + indirect emissions	Transport, food, shopping, lodging, activities and others	CO_2, CH_4, N_2O, HFCs, CFCs, SF_6 and NF_3	2013	2.92 Gt CO_2e	> 459 Mt CO_2-e (16%)*	8.1%	5.3%
2	WTO-UNEP[173]	Direct emissions	accommodation, transport, activities	CO_2	2005	1.30 Gt CO_2	520 Mt CO_2 (40%)	4.9%	2.8%
3	Gössling & Peeters[174]	Direct emissions	accommodation, transport, activities	CO_2	2010	1.12 Gt CO_2	NA	NA	NA
4	Peeters & Dubois[175]	Direct emissions	accommodation, transport, activities	CO_2	2005	1.17 Gt CO_2	503 Mt CO_2 (43%)	4.4%	2.5%

* Estimates differ because of two reasons: 1) some air transport emissions are included in the unspecified ‘Transport’ category, this is because despite the TSAs distinguishing transport modes, some countries’ input-output databases do not; and 2) we include methane and nitrous oxide emissions that make food footprints more important. Nevertheless, our total air transport emissions estimate (> 459 Mt CO_2-e) is close to that from previous studies (500-520 Mt CO_2-e).

Tab. *SI* 9: Comparison of the global carbon footprint $\tilde{Q}^{\cdot s \cdot}_{\cdot j1}$ by selling sector, between this work and UNWTO, UNEP & WMO[172]. UNWTO, UNEP & WMO[172] includes direct and some lower-order emissions only.

	Carbon emissions (Mt CO_2-e)	
Commodity	UNWTO, UNEP & WMO [172]	this work 2010
Agriculture		302
Mining		112
Food		173
Goods		481
Utilities		0
Construction		114
Trade		0.201
Hospitality unspecified		59.8
Accommodation	274	268
Food & beverage serving		193
Transport unspecified	465	766
Road transport		471
Rail transport		40.1
Air transport	515	531
Water transport		102
Services	48	282
TOTAL	1303	3895

Tab. *SI* 10: Comparison of Spain's tourism carbon footprints $\tilde{Q}^{r}_{i.\ddot{1}}$ by emitting sector, between this work and Cadarso *et al*[153]. Cadarso *et al*'s assessment is for 2007 and excludes goods.

	Carbon emissions (Mt CO_2)	
	Cadarso *et al* [153]	this work
Commodity	2007	2010
Agriculture	4.10	5.83
Mining	2.52	8.52
Food	1.04	0.80
Goods		7.32
Utilities	9.86	8.54
Construction		
Trade		
Hospitality unspecified	0.22	0.75
Accommodation		
Food & beverage serving		
Transport unspecified	10.47	10.53
Road transport		
Rail transport		
Air transport		
Water transport	0.69	0.66
Services	1.13	1.20
TOTAL	30.03	44.16

Tab. *SI* 11: Comparison of Australia's tourism carbon footprints $\tilde{Q}^{r}_{i.\bar{1}}$ by emitting sector, between this work and Dwyer *et al*[142]. Dwyer *et al*'s assessment is for 2004.

Commodity	Carbon emissions (Mt CO_2) Dwyer *et al* [142] 2004	this work 2010
Agriculture	5.76	13.34
Mining	0.76	0.63
Food	0.30	0.79
Goods	4.11	5.96
Utilities	7.57	11.10
Construction		0.26
Trade	0.28	0.11
Hospitality unspecified		0.01
Accommodation	0.97	0.17
Food & beverage serving		0.01
Transport unspecified	7.08	13.92
Road transport	0.27	0.86
Rail transport		0.03
Air transport		
Water transport		0.32
Services	0.35	0.60
TOTAL	27.45	48.09

4.5. Production Layer Decomposition

A production layer decomposition (PLD) unravels the contributions to footprints from different upstream layers of the supply-chain system. Visitor expenditures have an economic footprint in that visitor demand requires various upstream producers to provide inputs that are ultimately need to supply the commodities that visitors purchase.

Global visitor expenditure on tourism activities was about 4.8 $tr in 2013 (layer 0, left panel in Fig. *SI* 8), with goods, hospitality, transport and services being the main commodities purchased. Further upstream, these commodities required inputs from agriculture, mining, wholesale and retail trade, construction and utilities (water, gas and electricity). Total economic output ultimately needed to satisfy 4.7 $tr of tourism demand was about 14 $tr (layer 15, left panel in Fig. *SI* 8).

Similarly, we estimate that the 2013 carbon footprint of tourism operators directly supplying tourists amounted to about 2.9 Gt CO_2-e (counting production layers 0 and layer 1 as an upper limit, right panel in Fig. *SI* 8), which exceeds prior estimates by the WTO[172] (see Tab. *SI* 9) and by Gössling *et al*[174]. Including all upstream supply-chain contributions, the total carbon footprint was 4.5 Gt CO_2-e (layer 15, right panel in Fig. *SI* 8). Road and air transport and utilities, in particular electricity, feature prominently upstream, because of their high carbon intensity. In contrast, general services and hospitality are less important because of their relatively low carbon intensities.

These results prove how important it is to include input-output analysis into the methods applied for enumerating the carbon footprint of tourism. Without using input-output analysis, it is impossible to capture higher-order supply-chain contributions, simply because there are too many supply chains to be followed up manually[89,181]. In an input-output system where each producer requires inputs from, say, 100 suppliers, the 1st production layer includes 100 supply chains, the 2nd layer 100^2 = 10,000, the 3rd layer 100^3 = 1 million, and the 4th layer 100^4 = 100 million supply chains. Such extensive networks are impossible to evaluate using conventional bottom-up process-type Life-Cycle Assessment methods[88].

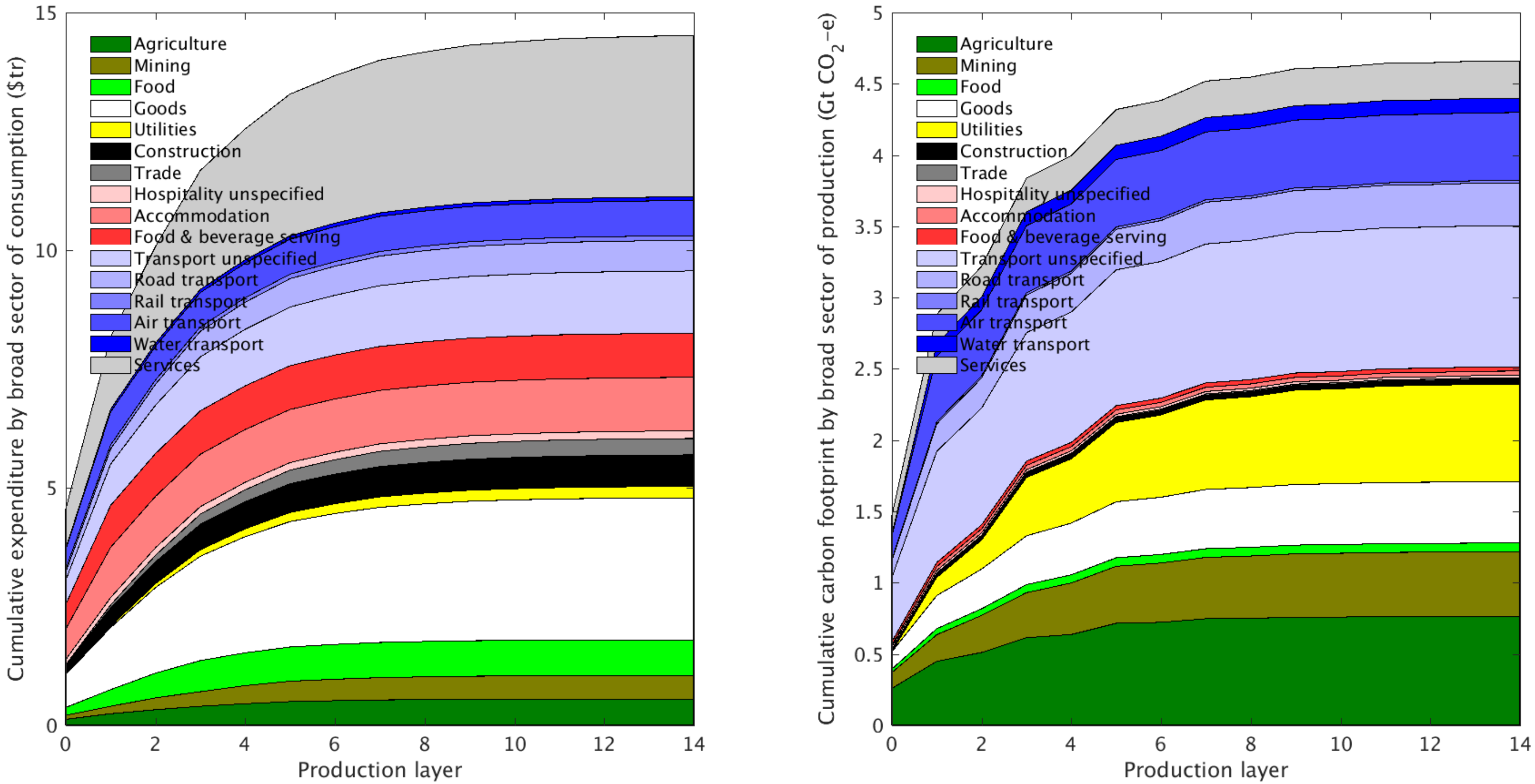

Fig. *SI* 8: Cumulative Production Layer Decompositions. Left panel: PLD of the economic output required to satisfy tourist demand $\tilde{\mathbf{x}} = (\mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \cdots)\tilde{\mathbf{y}}\mathbf{1}^{\mathbf{y}}$. Right panel: PLD of the of the global tourism carbon footprint $\tilde{Q} = \mathbf{q}(\mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \cdots)\tilde{\mathbf{y}}\mathbf{1}^{\mathbf{y}}$. For more details on the PLD method see separate online-only methods section, and for explanations of commodities see Section 3.3).

4.6. The global tourism greenhouse gas footprint

Industry sectors differ with respect to their emissions profile across various greenhouse gases. CO_2 is associated mainly with fuel combustion and land use changes, and therefore important for transport and energy conversion. CH_4 is emitted from animals (enteric fermentation and manure) and during oil and gas extraction (venting and flaring), and is therefore important for agriculture and mining. Emissions of N_2O and other greenhouse gases (see *SI* 3.2) occur in agriculture as well during industrial processes; in terms of equivalent CO_2 emissions they are less important. Whilst we needed to exclude short-lived greenhouse gases from aviation, aviation-induced clouding and contrails could however play a significant role (*SI* 3.2).

The total global tourism carbon footprint of 4.5 Gt CO_2-e consists mainly of 3.2 Gt CO_2-e in from of CO_2 emissions for moving planes and road vehicles, electricity for running hotels and restaurants, and from the combustion of various fuels required to manufacture consumer goods purchased by tourists (Fig. *SI* 9). 0.7 Gt CO_2-e in from of CH_4 are emitted mainly from farms in the supply-chain network of food processing and retail, from oil and gas rigs extracting feedstock that is transformed into refined fuels used in just about any sector of the economy, and directly from various manufacturing sectors producing consumer goods.

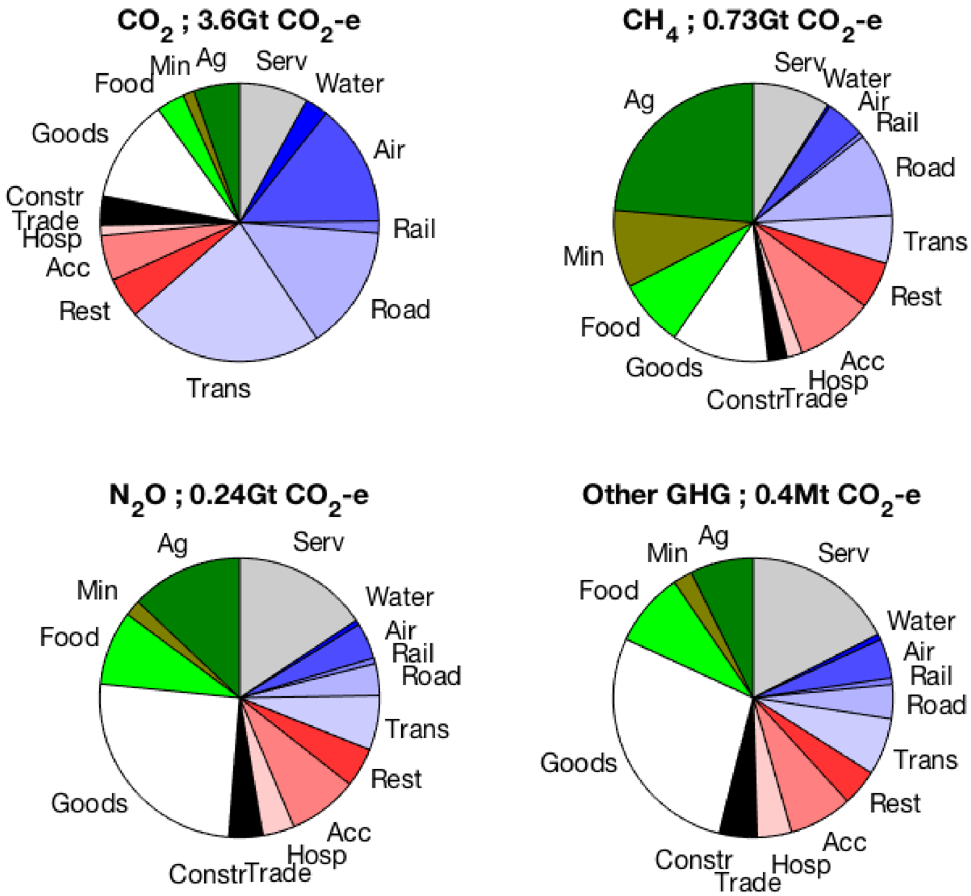

Fig. *SI* 9: Global tourism carbon footprint for CO_2, CH_4, N_2O and other greenhouse gases (GHG, see Section 3.2), for the year 2013.

4.7. Growth in the global tourism carbon footprint

Half of the total 2009-2013 carbon footprint growth of 1.1 Gt CO_2-e occurred in high-income countries and due to high-income visitors, with the remainder recorded for middle-income countries (Fig. *SI* 10), notably China (see Section 3.1.1). Middle-income countries recorded the highest growth rate of the tourism carbon footprint (22.6% p.a.).

RBA allows examining changes in visitors' carbon footprint. Chinese visitors alone contributed to an average annual increase in the global tourism carbon footprint of 75 Mt CO_2-e, followed by the United States (25 Mt CO_2-e), India (19 Mt CO_2-e) and Canada (12 Mt CO_2-e).

DBA enables monitoring changes in the carbon footprint of destinations. Small-island destinations with low populations are especially vulnerable to high and increasing tourist load [182,183], and this is reflected in the Maldives, the Seychelles, Mauritius, Trinidad and Tobago, Malta, Vanuatu, Fiji, Samoa, French Polynesia and Cabo Verde occupying top-ranking positions in terms of the per-capita increase in the tourism carbon footprint within their territory. For every inhabitant of Maldives, tourism has brought significant income, but also an annual carbon footprint increase of nearly 300 kg.

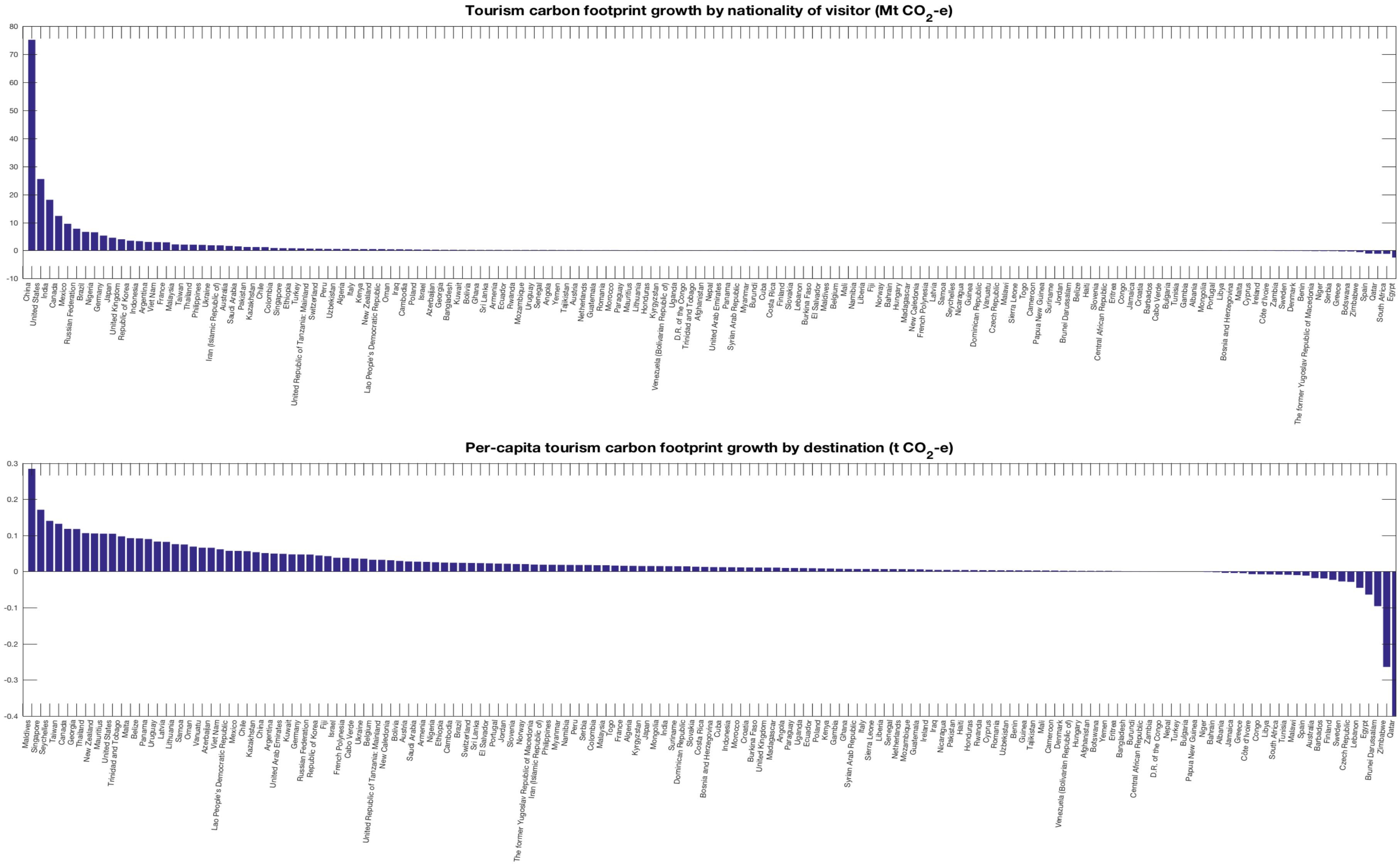

Fig. *SI* 10: Growth in the tourism carbon footprint by visitor nationality (RBA, $\tilde{Q}^{\cdot\cdot t}_{\cdot\cdot 1}$), and destination (DBA, $\tilde{Q}^{\cdot s\cdot}_{\cdot\cdot 1}$).

4.8. Using multiple regression to investigate possible drivers of tourism carbon footprints

Multiple regression can be used to reveal drivers of the carbon footprint F. In our work, we follow Wier *at al*[184] and Lenzen *et al*[185] and formulate a multiplicative relationship for per-capita carbon footprints as $F = k\ x^{\eta_{x,0}+\theta x}\ \mathrm{e}^{\varrho_q q}\ \mathrm{e}^{\varrho_t t}$.

4.8.1. Regression coefficients

Before carrying out our regression analysis, we test all variables for multicollinearity (Tab. *SI* 12). None of the explanatory variables are highly correlated, so we did not exclude any of them in our regression.

Tab. *SI* 12: Pairwise linear correlation coefficients between all variables.
CF = carbon footprint, GDP = Gross Domestic Product.

	DBA Per-capita CF	Per-capita GDP	Carbon intensity	Time
DBA Per-capita CF		0.63	-0.17	-1.11×10^{-4}
Per-capita GDP	0.63		-0.29	0.04
Carbon intensity	-0.17	-0.29		-0.006
Time	-1.11×10^{-4}	0.04	-0.006	

Our multiple regression of tourism carbon footprints across 162 countries and 5 years yields the following results (Tabs. *SI* 13 and *SI* 14):

Tab. *SI* 13: Regression results for the destination-based accounting (DBA) perspective (goodness of fit $R^2 = 0.74$).
*** = statistically significant at the 99%-level of confidence, ** = @ 95% level, * = @ 90%-level.

	Regression parameter	Standard deviation (%)	*t* statistics	Significance
Hosts' pc GDP *x*	$\eta_{x,0} = 0.78$	0.098	10.2	***
	$\theta = 6.17\times10^{-8}$	6.61	0.15	
Carbon intensity *q*	$\varrho_q = 0.30$	0.16	6.1	***
Time *t*	$\varrho_t = -6.5\times10^{-3}$	6.03	0.17	
Constant *k*	$k = 4.06\times10^{-4}$	0.08	11.82	***

Tab. *SI* 14: Regression results for the residence-based accounting (RBA) perspective (goodness of fit $R^2 = 0.80$).
*** = statistically significant at the 99%-level of confidence, ** = @ 95%-level, * = @ 90%-level.

	Regression parameter	Standard deviation (%)	*t* statistics	Significance
Travelers' pc GDP *x*	$\eta_{x,0} = 0.69$	0.095	10.48	***
	$\theta = 6.09\times10^{-7}$	0.58	1.73	*
Carbon intensity *q*	$\varrho_q = 0.21$	0.21	4.84	***
Time *t*	$\varrho_t = -8.3\times10^{-3}$	4.07	0.25	
Constant *k*	$k = 9.23\times10^{-4}$	0.08	12.24	***

4.8.2. Range of per-capita tourism carbon footprints under DBA and RBA

The range of per-capita tourism carbon footprints is different under DBA (≈0 to 4 t CO_2-e/cap) and RBA (≈0 to 5 t CO_2-e/cap) accounting. How can we understand this difference? Imagine a 2-billion-people world with one part being wealthy frequent travelers from uninteresting countries, and the other being poor and populous but popular tourist destination. Per-capita footprints under DBA will be low for the wealthy group (because not many tourist go there) and low for the poor group (because of their high population). Per-capita footprints under RBA will be high for the wealthy group (because they travel a lot) but again low for the poor group (because they do not travel a lot).

4.8.3. Per-capita GDP elasticities of the tourism carbon footprint

The GDP-elasticity of the carbon footprint is in both accounting perspectives highly significant and positive. These results agree well with prior work on nations[184,185] and cities[186], where expenditure elasticities between 0.5 and 0.9 were reported for many nations.

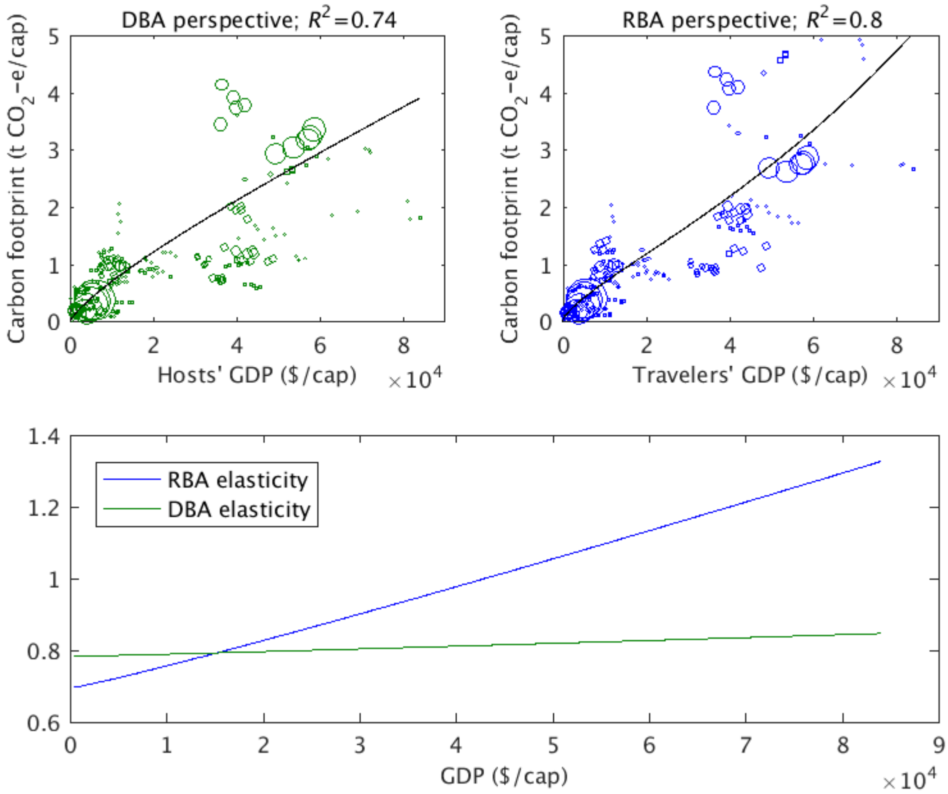

Fig. *SI* 11: Regressions and elasticity functions for the multiple regression of tourism carbon footprints according to the DBA perspective (green) and RBA perspective (blue). Circle size in upper panels represents population.

For RBA, the variation θ of the elasticity with affluence (measured as per-capita GDP) is also significant and positive, meaning that the GDP-elasticity of the carbon footprint increases with increasing affluence (from 0.7 to 1.3). Along with the higher goodness of fit of the RBA-based regression (R^2 = 0.80 instead of DBA's R^2 = 0.72), this shows that per-capita GDP is a stronger driver in the RBA perspective than in the TSA perspective (Tabs. *SI* 13 and *SI* 14, and Fig. *SI* 11). This is to be expected, because per-capita GDP at the tourist destination does not necessarily translate into tourism carbon footprints, simply because luxury resorts may exist in poor countries. In contrast, per-capita GDP at the visitor home does translate into tourism carbon footprints, as wealth determines the ability to travel.

The fact that in the RBA perspective, the GDP-elasticity increases with affluence is a noteworthy result, since for the higher per-capita ranges (> $40,000 per annum) this elasticity becomes larger than 1, meaning that, for example, if per-capita GDP increased by 10%, the per-capita tourism carbon footprint would increase by more than 10%. This effect is due to tourism being a luxury good the consumption of which a) is largely restricted to the wealthy segment of the global population, and b) does not appear to satiate towards higher incomes. Above-unity elasticities are documented in prior work on Brazilian households by Cohen[187], who found that their propensity to consume fuel for mobility increased more than proportionally with income as Brazil went through a rapid development phase.

4.8.4. Remaining regression coefficients

A sea-change decrease in the carbon intensity of production by 100 g CO_2-e/$ causes carbon footprints to decrease by 3.0% (DBA) and 2.1% (RBA) respectively, reflecting that more carbon-efficient technology has a beneficial effect. Carbon intensity has a stronger influence on carbon footprints under the DBA perspective, because it relates to the destinations where visitors consume, as opposed to their home country (MRIO perspective).

The reason for the carbon intensity effect on tourism carbon footprint being relatively weak is the dominance of the affluence effect (Section 4.8.3). As countries become wealthier, their carbon intensity decreases (Fig. *SI* 12). However, affluence growth outpaces technology improvements in driving up emissions, leading the carbon footprint to increase whilst their technology becomes more carbon efficient. This becomes evident when carrying out a single regression with the carbon intensity term, that is $F = k\ \mathrm{e}^{\varrho_q q}$. This form yields a negative coefficient for the elasticity ϱ_q, suggesting that the footprint increases with decreases carbon intensity (compare also with the negative correlation coefficient in Tab. *SI* 12). Of course, this counterintuitive behaviour comes about because of the missing affluence term $x^{\eta_{x,0}+\theta x}$; once this is included the role of the carbon intensity in the regression diminishes. These counteracting effects are well demonstrated and explained in Structural Decomposition Analyses (SDAs) of global greenhouse gas emissions[103,104].

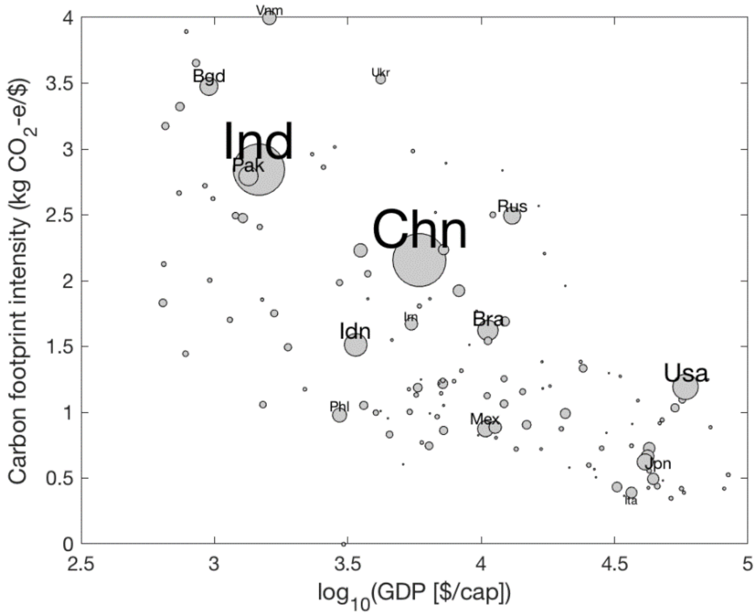

Fig. *SI* 12: Carbon footprint intensity ($\tilde{Q}^{\cdot s \cdot}_{\cdot\cdot 1}/\tilde{y}^{s \cdot}_{\cdot 1}$, in units of kg CO_2-e/$) as a function of per-capita GDP. Circle size represents population. As countries become wealthier the carbon intensity of their tourism operations decreases.

Time as such does not have a significant influence, showing that the increase in the global tourism carbon footprint is not primarily a matter of changing circumstances (beyond affluence and technology, for example social norms).

4.8.5. Visualisation of regression results

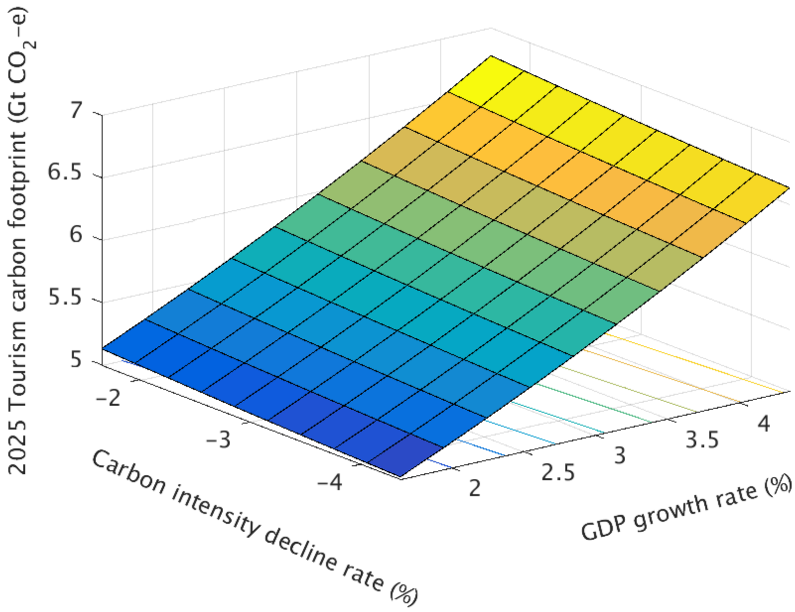

Fig. *SI* 13: Projections of the 2025 global tourism carbon footprint (based on DBA and RBA multiple regressions).

5. Supplementary Discussion

The principle of “common but differentiated responsibility” is embraced by the Paris Agreement, acknowledging the individual responsibility and capacity of carbon mitigation in light of national circumstances[188]. This study provides the first comprehensive tourism-related emission pattern globally, and future research can leverage this result to discuss the design and implications of abatement policies by complying with the aforementioned principle. Related issues include the attribution of carbon responsibility between major departure countries versus small island destination countries; the impact of mitigation on “net destinations” and “net origins” from economic and environmental perspectives; and the discussion of climate justice: “who can travel, for how long, using which transport mode, why, and how comfortably (p.1041)”. [189]

Human decision-making is a cognitive process resulting in the selection of a belief or a course of action among several alternatives. Results of this study pinpoint the carbon intensive nature of tourism, and thus serve as a foundation for possible changes of current mindset among consumers, firms and policy makers. A future research on the relationship between information dissemination and behavior changes toward more sustainable travel patterns and production technology would confirm whether footprint information can effectively change our course of actions, at least on travel.

Our research also serves as a starting point to further theoretical developments. Due to the lack of empirical data, the environmental and economic trade-off of tourism services have thus far remained an untouched field. By filling this information gap, our results enable further discussion on tourism Environmental Kuznets Curve or the tourism Pollution Haven Theory, which has the potential to advance our understanding on 1) whether tourism development can improve/deteriorate national emissions efficiency over time, 2) the comparative advantages of individual countries on developing tourism against other potential alternatives, and 3) the net-effect of tourism emissions transfer with respect to different abatement regulation.

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