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Drivers of global tourism carbon emissions

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Tourism has a critical role to play in global carbon emissions pathway. This study estimates the global tourism carbon footprint and identifies the key drivers using environmentally extended input-output modelling. The results indicate that global tourism emissions grew 3.5% p.a. between 2009-2019, double that of the worldwide economy, reaching 5.2 Gt CO_2-e or 8.8% of total global GHG emissions in 2019. The primary drivers of emissions growth are slow technology efficiency gains (0.3% p.a.) combined with sustained high growth in tourism demand (3.8% p.a. in constant 2009 prices). Tourism emissions are associated with alarming distributional inequalities. Under both destination- and resident-based accounting, the twenty highest-emitting countries contribute three-quarters of the global footprint. The disparity in per-capita tourism emissions between high- and low-income nations now exceeds two orders of magnitude. National tourism decarbonisation strategies will require demand volume thresholds to be defined to align global tourism with the Paris Agreement.

Travel plays a significant role in contemporary society. Before the COVID-19 pandemic, global tourism contributed US$ 6 trillion in annual economic output and was one of the fastest-growing sectors in the world for ten consecutive years[1–3]. The post-pandemic tourism rebound has been rapid and global tourism is likely to again surpass 20 billion trips in 2024[4]. This sector is pivotal to global emissions trajectories and must be aligned with the Paris Agreement.

UN Tourism (World Tourism Organization) is leading the Glasgow Declaration on Climate Action, in collaboration with the UN Environment Programme, to mobilize tourism stakeholders to support the global goals of cutting emissions in half by 2030 and achieving Net Zero at the latest[5]. The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) aims to reach carbon-neutral growth of international aviation emissions from 2020 onwards[6]. The World Travel and Tourism Council, a representative body for major tourism firms, has put forward a proactive roadmap for private tourism businesses, including accommodation, aviation, cruise, tour operators and travel agents, with the aim to reach net-zero by 2050[7].

Mitigating tourism's carbon footprint however is an imposing task. In 2013, global tourism contributed 8% of global greenhouse gas (GHG) emissions, and its carbon intensity, defined as emissions per dollar sales, was 20% higher than the average for the global economy[8]. Historically, most destinations have demonstrated an inability to decouple growth in tourist demand from increasing tourism emissions[1,9–15].

A rising emissions pathway is determined by multiple factors, such as demand growth and consumption of carbon-intensive tourism products and services. A critical understanding of these drivers is crucial for assessing and informing effective policy responses. Such an analysis requires a comprehensive tourism footprint database to track both the direct and indirect emissions arising from domestic and international travel over an extended timeframe. Lenzen et al.[8] evaluated global tourism emissions over a five-year period (2009–2013) but did not perform a formal analysis to quantify the drivers of emissions growth. National data on the drivers of tourism emissions is now available for individual countries such as Australia, Austria, China, Norway, Portugal, Spain and Iceland[9–12,14,16–18]. However limited insights are available for other countries where substantial variations exist in tourism demand patterns, technology progress and international trade across destinations.

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In this study, we present an analysis of global and national tourism carbon footprints between 2009 and 2020. Using environmentally extended input-output modelling we investigate how tourism emissions increase or decrease in relation to technology and demand drivers, and the similarities or differences within and between countries in terms of tourism emissions. To comprehensively answer these research questions, we identify and analyse five key factors that influence tourism emissions: 1. Technology improvements regarding energy efficiency gains; 2. The supply chain concerning the production structure among suppliers; 3. Population growth relating to changes in the volume of tourists; 4. Tourism consumption for the evolving patterns of tourist expenditure; and 5. The use of private vehicles regarding direct emissions generated by internal combustion vehicles used by tourists.

This study uses tourism expenditure profiles from 175 countries, including the tourism satellite accounts of 62 countries and tourism consumption data of 113 countries, which are combined with multipliers from the GLORIA database to estimate macro-level tourism emissions from 2009-2020[19,20] (see Method). Drawing these sources together allows the development of a comprehensive global database from which tourism carbon footprints can be estimated through input-output analysis. This high-resolution database affords unprecedented analytical depth. Carbon footprints were estimated for inbound, outbound and domestic travel for 175 countries, distinguished by source including those produced by local businesses, foreign producers, international flights, and private vehicle use. Tourism carbon footprints were calculated using both residence-based accounting (RBA) to attribute emissions to the countries of visitor origin and destination-based accounting (DBA) for countries where tourism expenditures takes place[8] (Supplementary Method 1).

Results

Tourism emissions 2009–2020

Tourism has outpaced growth of the global economy, rising from US $3.5 trillion in 2009 to US$6.0 trillion in 2019 (US$5.1 trillion, constant price 2009). This represents an annual expenditure growth rate of 5.5% (3.8%, constant price 2009). This consumption is associated with a tourism carbon footprint of 5.2 Gt CO_2-e in 2019 (5.1–5.5 Gt, 99% likelihood range) (Supplementary Method 2). The breakdown is as follows: direct emissions amounted to 1.8 Gt (52% from aviation, 18% from road transport), indirect emissions were 2.5 Gt (34% from utilities, 14% from petroleum manufacturing), and private vehicle emissions added 0.9 Gt (detailed in SI 1). In total, global tourism in 2019 was responsible for 8.8% of global anthropogenic warming, or 9.9% when excluding LULUCF (Table 1). Substantial non-CO2 radiative forcing effects from air transport was not included in this assessment[21–23].

Between 2009 and 2019, the sector's emissions increased by 1.5 Gt CO_2-e (from 3.7 Gt to 5.2 Gt), which is equivalent to the annual emissions produced by all of Latin America and the Caribbean. The tourism carbon footprint expanded at a rate (3.5% p.a.) twice that of the global economy (1.5% p.a.) during this period, highlighting its status as a sector that is challenging to decarbonize. If the same growth rate is maintained into future years, tourism emissions are expected to double every 20 years.

Tourism is carbon intensive. Every dollar earned in tourism generates 1.02 kg of GHG emissions in 2019 (SI 2). This is approximately 4 times higher than the service sector (0.24 kg/$), and 30% higher than the global economy (0.77 kg/$). From a sectoral perspective, most net emissions were generated by air transport (0.27 Gt) and utilities (0.26 Gt). Travellers' use of private vehicles also contributed substantially, with combustion engines estimated to produce net emissions of 0.29 Gt and petrol production resulting in 0.13 Gt.

The COVID-19 pandemic is the only event that drastically reduced tourism's carbon footprint, producing a smaller environmental impact than the base year 2009 (Table 1). In 2020, limitations in international travel and reductions in domestic tourism led to a decline in global tourism emissions from 5.2 Gt in 2019 to 2.2 Gt in one year. The sector's carbon intensity improved from 1.02 to 0.85 kg CO_2-e per US$ (constant price 2009). The decline in emissions is a result of foregone consumption of US$ 3.1 trillion (US$2.5 trillion, constant price 2009) and the concomitant reduction in air travel and private vehicle use. Expenditure associated with these two components decreased by 50% within one year. The net decline of 3.0 Gt CO_2-e in tourism carbon footprints represents two thirds of total global carbon emissions reduction in the first year of the COVID-19 pandemic[15]. The pandemic provides a living experiment of the significance of tourism as a driver of growth in global emissions.

Tourism carbon emissions vary considerably by country. RBA analysis reveals that visitors from the United States produced 1.0 Gt CO_2-e, accounting for 19% of the total global tourism footprint in 2019. In that year three countries, the United States, China (0.8 Gt CO_2-e, or 15%) and India (0.3 Gt CO_2-e, or 6%), produced 39% of global tourism CO_2-e. The top twenty countries, predominantly highly developed countries with large populations, contributed 3.9 Gt CO_2-e in total, or three quarters of the total tourism footprint (Fig. 1, left). A substantial inequality in emissions contributions by countries is observed (SI 3-5). DBA analysis again highlights the significance of the United States (19%), China (15%) and India (6%), while several Middle East countries including Saudi Arabia, and the United Arab Emirates, have emerged in the twenty highest emitting countries due to substantial increases in inbound tourism over the past decade (Fig. 1, right).

Drivers of tourism emissions: technology vs consumption

Using structural decomposition analysis (see Method), the net increase of 1.5 Gt CO_2-e tourism emissions between 2009 and 2019 can be broken down into five components. At the global level, growth in tourism consumption is the largest factor driving tourism emissions. The amount of money spent on accommodation, gastronomy and transport has constantly increased over time[24]. Per capita tourism expenditure increased from US$536 per capita in 2009 to US$672 in 2019 (constant price 2009), and this caused tourism emissions to rise by 1.4 Gt CO_2-e (Fig. 2).

Table 1 | Expenditure, carbon footprint and carbon intensity of global tourism, 2009–2020

	2009	2013	2019	2020	Annual % change (2009–2019)
Tourism expenditure (US$ trillion)	3.5	4.8	6.0	2.9	5.5%
Tourism expenditure, constant price 2009 (US$ trillion)	3.5	4.3	5.1	2.6	3.8%
Tourism carbon footprint (Gt CO_2-e)	3.7	4.4	5.2	2.2	3.5%
Total global GHG/GHG without LUC* (Gt CO_2-e)	50.9/45.0	55.5/49.9	59.1/52.4	54.5/50.8	1.5%
Tourism shares in global GHG	7.3%	8.0%	8.8%	4.1%	
Tourism shares in global GHG without LUC	8.2%	8.9%	9.9%	4.4%	
Emissions per dollar spending, constant price 2009 (kg/US$)	1.05	1.04	1.02	0.85	-0.3%

*Source: United Nations Environment Programme[58]United Nations Environment Programme[59]United Nations Environment Programme[60]

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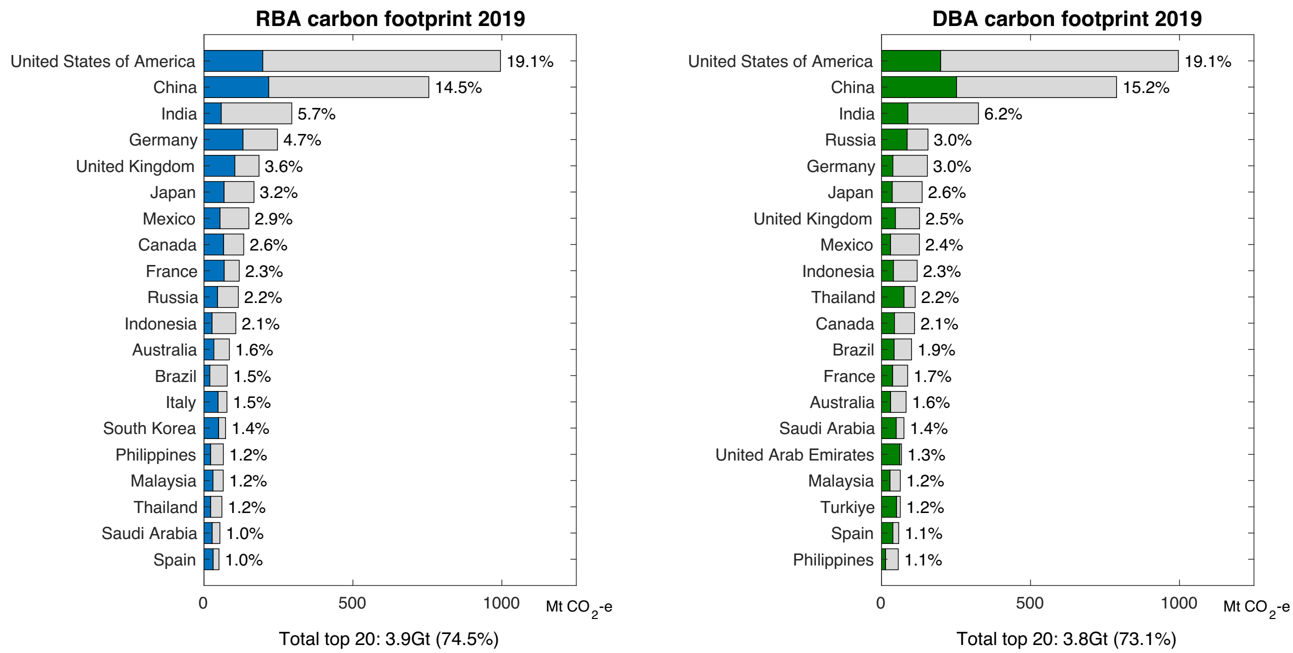

Fig. 1 | Tourism carbon footprints according to residence-based accounting (RBA) and destination-based accounting (DBA). RBA measures emissions resulting from residents' domestic and outbound travel, while DBA measures emissions from domestic and inbound tourism activities occurring within a country. The domestic travel footprint is represented in grey, the inbound tourism footprint in green, and the outbound tourism footprint in blue.

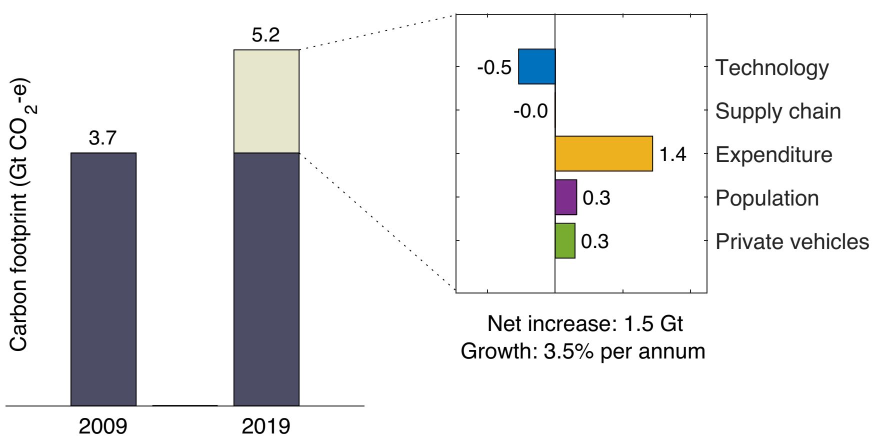

Fig. 2 | Decomposition result of the tourism carbon footprints, 2009-2019. Tourism carbon footprints increased from 3.7 GtCO_2-e to 5.2 Gt from 2009 to 2019. The net changes, 1.5 Gt CO_2-e, were broken down into five components to highlight relative contribution of individual factors.

Global population growth from 6.9 billion to 7.8 billion over the decade is an important factor behind changes in tourism consumption that is responsible for 0.3 Gt CO_2-e. As people travel more frequently, the use of private internal combustion vehicles by tourists accounted for 0.3 Gt CO_2-e whereas two thirds of the increase in emissions resulted from domestic travel.

Technology improvements simultaneously led to a decline in emissions of 0.5 Gt CO_2-e. Emissions intensities, defined as emissions per dollar economic output, improved by 0.3% per annum over the period 2009–2019 (Table 1). In comparison, tourism expenditure growth was 3.8% per year, confirming that emissions intensity improvements were heavily outweighed by consumption growth. These findings are corroborated by airlines, cruise lines and hotel chains that report efficiency gains of 1–2.6% per annum, and sales increases of 3–7%[25].

Overall, production factors (technology and the supply chain) only offset around 25% of the tourism emissions growth that was driven by consumption factors (expenditure per capita, population and private car use). The global tourism carbon footprint has expanded at approximately two-thirds of the speed of tourism consumption in nominal price.

Drivers of tourism emissions: top countries

The net increase in tourism emissions is unevenly distributed, with growth in domestic travel in three countries—the USA, China, and India —contributing most to the absolute rise in emissions (Fig. 3). China's domestic tourism expenditure expanded by 17% per annum over the past decade and pushed global emissions up by 0.4 Gt CO_2-e, followed by domestic tourism in the USA (0.2 Gt) and India (0.1 Gt). A noteworthy rise in emissions was also caused by outbound travel from China (0.1 Gt).

Assessing relative emissions over economic status reveals that middle-income countries, were drivers of the growth trajectory in outbound tourism, with emissions increasing by more than 57% from

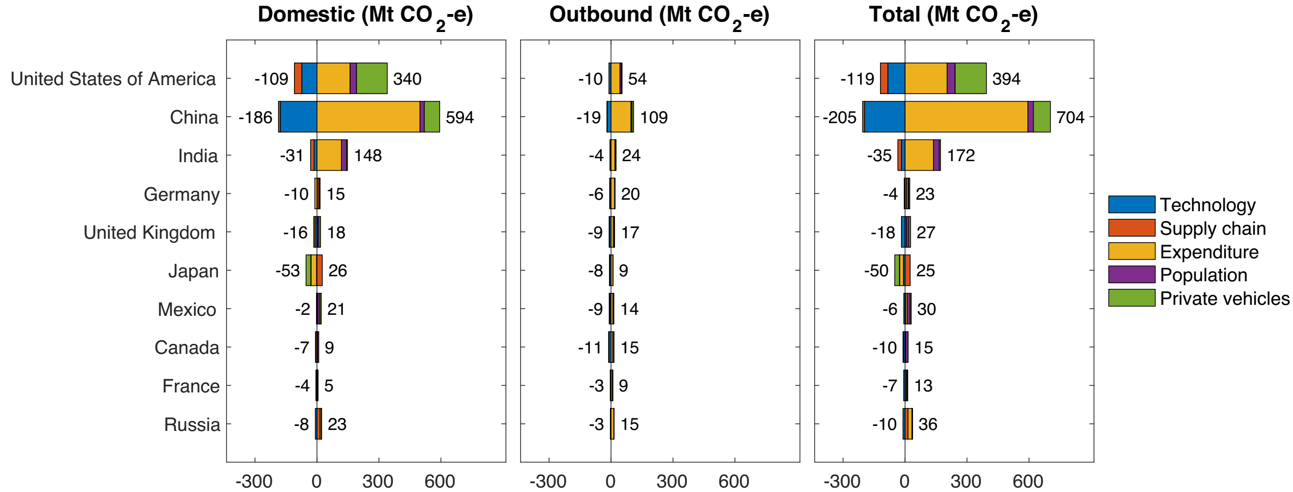

Fig. 3 | Decomposition result for the top 10 RBA countries, 2009–2019. Changes in tourism carbon footprints can be attributed to production factors: technology (blue) and supply chain (red) and consumer factors: per capita expenditure (yellow), population (purple), and private vehicle use (green). Negative values indicate the extent to which emissions are reduced through a particular factor, ceteris paribus. Conversely, positive values demonstrate how that particular factor contributes to an increase in emissions.

the base year in 2009 (SI 6). In comparison, high-income and low-income countries experienced 27% and 38% increases, respectively, in emissions over the past decade.

Tourism emissions in all countries have been mitigated to varying degrees by technology innovation, most notably China (−0.2 Gt) and the USA (−0.1 Gt). China demonstrated a higher-than-average efficiency improvement, shifting their RBA tourism emissions intensity from 1.36 kg CO2-e /$US to 0.91 kg CO2-e /$US (constant price 2009), or a 4.0% improvement rate per annum. However, efficiency gains were insufficient to offset total emissions growth driven by increasing demand for most countries.

Overall, the global tourism emissions trajectory is dominated by the United States, China, and India, primarily due to population size combined with the strong growth in travel demand observed over the period 2009–2019. Together, these three countries were responsible for 0.9 Gt CO_2-e of the net emissions growth, or 60% of the global total increase in tourism emissions across the study period.

Drivers of tourism emissions: inequality within and between countries

Economic prosperity determines if and how people travel. The global average per-capita carbon footprint of tourism in 2019 was 0.68 t CO_2-e. The top ten countries with the highest per-capita RBA emissions are highly-developed economies, all with a per-capita GDP exceeding US$ 25,000 (SI 5). Citizens in these countries produced more than 3.1 t CO_2-e per capita in tourism-related emissions, primarily as a result of outbound travel. In contrast, the bottom ten countries with the lowest per-capita tourism footprints are low-income economies. There is effectively no outbound travel from these countries, with average tourism carbon footprints of 0.02 t CO_2-e per capita. The difference between countries that travel the most and least is more than 100-fold.

Further analysis indicates that outbound tourism emissions are influenced by income. Using the World Bank's income classification system, we found that high-income countries (GNI > US$12,375) have an outbound travel footprint of 1.52 t CO2-e per capita, while low-income countries (GNI < US$1,025) bear only 0.04 t CO2-e per capita. Income per capita is a key predictor of international travel emissions (adjusted $r^2 = 0.881$, Fig. 4, left), however wealth distribution within the population is also very relevant. For instance, China recorded 0.16 billion outbound trips in 2019, which means that at most 10% of its 1.4 billion population travelled internationally. In low-income countries, this rate is even smaller, at around 3% of the population. Hence, computations of average per-capita carbon footprints by country obscure the disproportionate consumption of tourism and production of high-growth tourism emissions by the wealthiest citizens[26]. Outbound tourist emissions therefore need to be adjusted to more accurately reflect only those who consume international trips, using travel propensity.

After adjusting for international travel propensity (see Supplementary Method 3), the results indicate that emissions per outbound visit are not significantly influenced by income status (adjusted $r^2 = 0.003$, of Fig. 4, right). On average, per-capita outbound travel emissions from high, medium, and low-income countries are 1.7 t CO_2-e, 1.4 t CO_2-e, and 1.5 t CO_2-e, respectively. This suggests that cohorts who can afford international travel produce similar emissions per year per person, regardless of their country's economic status.

Global analysis reveals a large disparity in per-capita tourism carbon footprints, both between and within countries (Fig. 4 and SI 7). The differences between countries are largely attributed to varying levels of affluence. In contrast, within less developed and developing countries, disparities are primarily a result of income inequality, with a very small minority of high income individuals engaging in carbon-intensive international trips while the majorities in these populations generate minimal emissions due to limited opportunities for domestic or international travel.

Discussion

Our analysis reveals that compared to the 2013 baseline established by Lenzen et al.[8], the tourism industry has made very little progress in reducing emissions. While technology and supply chain efficiencies improved from 2009 to 2019, those carbon efficiency gains have lagged far behind other sectors[27]. With rapid expansion in travel demand, the growth rate of tourism carbon emissions has been twice that of the global economy, and the sector now accounts for 8.8% of the world's greenhouse gas emissions.

The COVID-19 pandemic offered a brief respite in tourism's climate impact. The swift resurgence in global tourism demand[4] signals a return to the high emissions levels of 2019. We anticipate annual increases in emissions of 3–4% following current trends. This pattern presents an insurmountable challenge for the tourism sector in

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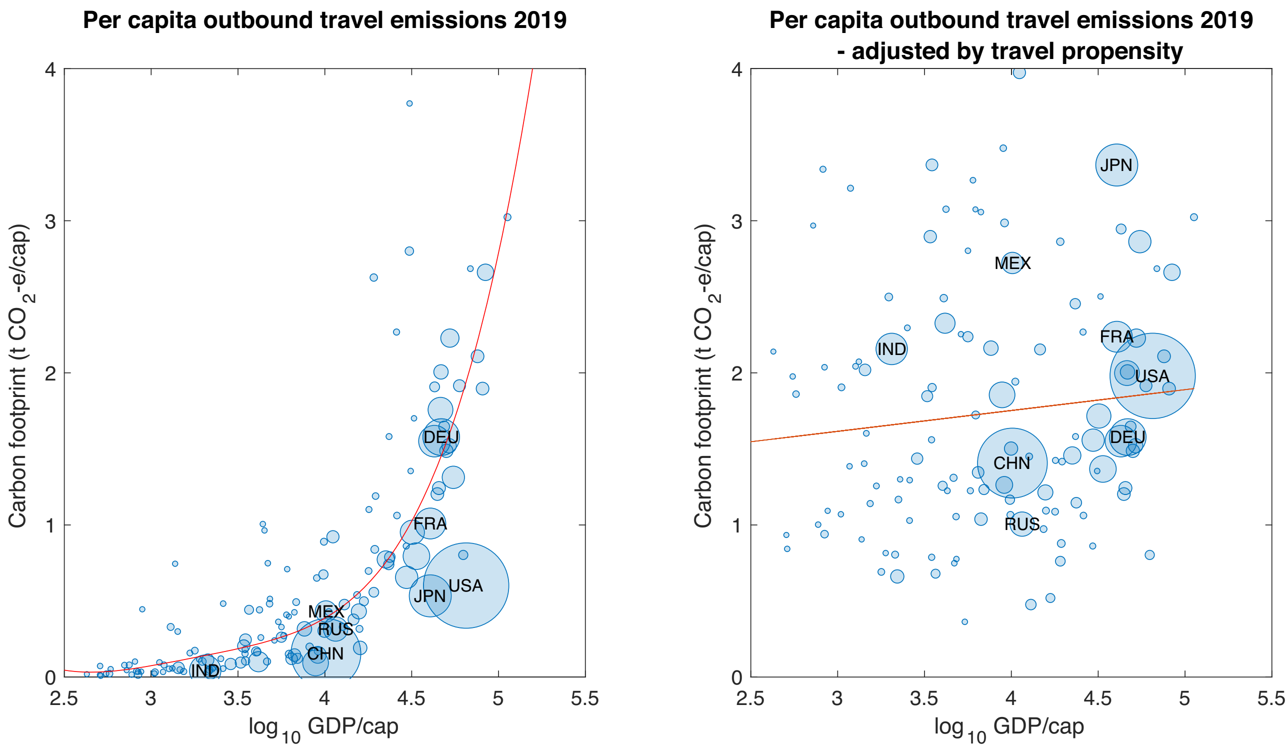

Fig. 4 | Distribution of per-capita outbound travel emissions (left) and the adjusted per capita outbound travel emissions by GDP (right), 2019. Average per-capita outbound travel emissions are strongly correlated with per-capita GDP. However, once adjusted for the proportion of the population able to afford international travel, per-capita outbound travel emissions show no differences across income levels of countries. The bubbles represent the size of each country's GDP.

aligning with the target of limiting global warming to +1.5 °C as outlined in the Paris Agreement. To meet this goal, the sector's 5.2 Gt of CO_2-e emissions would need to be reduced by more than 10% annually to year 2050.

Rapid demand growth and slow technology efficiency gains are the fundamental drivers of high growth in tourism carbon emissions. Demand for tourism is driven by multiple factors, most notably rising income levels especially among the emerging economic powerhouses of China and India. High growth tourism carbon emissions are also driven by countries that view tourism as an economic engine and aggressively pursue national tourism economic growth strategies[28–30].

Accelerating tourism demand growth clearly presents an impossible emissions challenge in the absence of much greater technology and supply chain efficiencies. This echoes the degrowth research findings that technology improvements that could cancel out demand growth would be extremely unrealistic[31]. Defining 'tourism volume thresholds' to manage demand growth is ultimately required to curb rising tourism emissions.

A simple universal reduction of tourism volume across countries (e.g., all countries reduce their tourism demand by 5%) however is not an ideal approach as this procedure does not represent a fair and just mitigation approach. The IPCC[32] suggests that a "fair contribution" in emissions mitigation needs to acknowledge four components: equality, responsibility, capability, and cost-effectiveness. Based on this, we support the view that tourism demand volume controls must consider historical and cumulative tourism emissions, while also being cognizant of the varied financial and technical capacities of individual countries to mitigate, and responsibilities to support low-income and small island economies.

These strategies are most urgent in the case of the world's twenty highest-emitting tourism destinations, especially the United States, China, and India. These countries have developed large domestic and inbound tourism markets with high demand growth over differing timeframes. Our scenario analysis indicates that if the top 20 destinations had reduced their tourism growth rate by 1% per annum from 2009 to 2019 (from 5.9% to 4.9% annual growth in current prices), they could have achieved a reduction of 0.38 Gt CO2-e emissions in 2019. This alone would have represented a 7% reduction of global tourism emissions.

Our findings indicate that aviation, utilities, and private internal combustion vehicle use are major hotspots of high growth tourism emissions. The International Energy Agency (IEA) has evaluated the corresponding alternatives to mitigate emissions for these three areas. The IEA describes a fully decarbonized electricity grid as 'moving in a positive direction but requiring more effort', and the transition to electric vehicles as 'on track' in progress toward the 2050 Net Zero Emissions goal[33]. This offers some reason for optimism that tourism emissions growth from utilities and private vehicle use can be mitigated over the course of future years.

By contrast, air transport remains the Achilles heel of global tourism emissions. Critical barriers in management, technology and fuel transition, finance, and governance continue to make progress on aviation emissions mitigation 'substantially insufficient' in terms of 2030 and 2050 emissions trajectories based on the IEA assessment[33]. Limiting continued growth in demand for air transportation, especially in long-haul international travel, would achieve outcomes that are climatically and socially desirable. Targeted measures such as CO_2 taxes, carbon budgets, and alternative fuel obligations must be urgently considered in an effort to rein in future air travel emissions[34].

Carbon inequality is an inescapable and increasingly entrenched feature of global tourism. Substantial disparities exist in total tourism carbon footprints between countries, and in per-capita tourism carbon footprints within countries. These inequalities need to be considered within the principle of 'common but differentiated responsibilities'[35] to assign mitigation responsibilities to both

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countries and individuals. The inequality in carbon emissions from travel stems from the gap between those who can and those who cannot afford international travel. Focusing on limiting continuing growth in international air travel rather than domestic tourism would offer a more socially equitable approach to addressing this challenge.

Sustained high growth emissions undermine the future viability of global tourism. Destinations are witnessing the accelerating impact of climate change which is altering patterns of tourism demand. Reduced snow volume at ski resorts, increasing fire risks and heatwave exposure are vivid examples of these climate impacts[36,37]. Global destinations face varying levels of climate change vulnerability. Africa, the Middle East, South Asia, and Small Island Developing States are among the most affected, with projections indicating tourism demand will be negatively influenced due to climate change[38,39]. Overall, tourism emissions that are primarily driven by high-income countries contribute to suppressing tourism demand for destinations in more vulnerable poorer regions. With the intensified effects of climate change expected in the coming decades, further study is needed to understand the extent to which regional tourism demand will be impacted by changing seasonality and weather patterns. Such information is crucial for addressing the many inequality issues that may arise in climate justice discussion.

Global tourism governance bodies including the UN Tourism and the World Travel and Tourism Council, have long based their climate ambitions on technology efficiency gains and infrastructure improvements[1,5,7]. Our findings provide concrete evidence that focusing alone on technology and efficiency gains is insufficient for achieving net-zero milestones. Strong measures to reduce travel demand are urgently required. The urgency of such measures is particularly acute among high-emitting countries and in relation to long-haul air travel. The definition and implementation of tourism volume thresholds will be inevitable under the current emissions trajectory if tourism is to be aligned with global net-zero goals.

Methods

Input-output analysis

We employ the input-output technique[40] to estimate tourism carbon footprints $\widetilde{Q}$. The input-output framework allows for the estimation of direct and indirect emissions generated through the interdependencies of the tourism sector. Tourism expenditure $\widetilde{y}$ serves to represent the economic contribution of the tourism sectors to the national economy. It is integrated into Leontief's model $L=(I-A)^{-1}$ as the final demand[19], where I is the identity matrix and A the interdependency coefficient. The calculation of carbon footprints is facilitated by employing country-specific carbon emission intensities $q=Qx^{-1}$, where Q represents $CO_2{}^{-e}$ emissions by country and industry sector, and x denotes industrial output. The formula to calculate the carbon footprints is therefore $\widetilde{Q}=qL\widetilde{y}$.

To conduct a comprehensive assessment of the tourism carbon footprints from 2009 to 2020, we utilize a global multi-region input-output (MRIO) model, or the so-called GLORIA environmentally-extended database[20]. The GLORIA database encompasses 160 countries and 4 rest-of-the-world regions, with each country's economy represented by 120 economic sectors (Supplementary Method 4 and 5). This extensive coverage enables the estimation of carbon footprints up to 19,680 sectors, providing a detailed understanding of the carbon footprints associated with various tourism-related activities.

We gain deeper insights into the dynamics of global tourism markets by analysing carbon footprints from both the visitors' residence perspective known as residence-based accounting (RBA) and the tourist destination perspective known as destination-based accounting (DBA)[8]. Using both RBA and DBA (Supplementary Method 1), we are able to discern to whom the carbon footprints in the tourism sector belong. The RBA approach attributes consumption-based emissions to the country of the visitors' residence (encompassing emissions from both domestic and outbound tourism), while the DBA approach assigns these emissions to the host country (covering emissions from both domestic and inbound tourism).

Structural Decomposition Analysis

Building upon the input-output framework, our study further explores the factors driving the increase in global tourism carbon footprints from 2009 to 2019, using structural decomposition analysis (SDA)[41,42]. In this analysis, we first focus on four key determinants: technology improvement D_{tech}, the supply chain D_{scha}, tourism consumption D_{cons}, and population growth D_{pop}. To integrate the population effect P into SDA, tourism expenditure has to be transformed into per capita values $\widetilde{y}_{pc}=\widetilde{y}P^{-1}$.

Additionally, we incorporate the carbon footprints from the use of private vehicle (f) as an extra factor due to its computation being conducted outside the input-output model. Let $\triangle$ represent the change values from 2009 to 2019, then the increase of the carbon footprints from the use of private vehicle is denoted as $\triangle f = f_{2019} - f_{2009}$. The drivers of tourism carbon footprints are $\triangle\widetilde{Q}=D_{tech}+D_{scha}+D_{cons}+D_{pop}+\triangle f$, with each factor's SDA formula as follow:

Technology improvement:

$$\begin{aligned}D_{tech}=\triangle qL\widetilde{y}_{pc}P+\frac{1}{2}\left(\triangle q\triangle L\widetilde{y}_{pc}P+\triangle qL\triangle\widetilde{y}_{pc}P+\triangle qL\widetilde{y}_{pc}\triangle P\right)\\+\frac{1}{3}\left(\triangle q\triangle L\triangle\widetilde{y}_{pc}P+\triangle q\triangle L\widetilde{y}_{pc}\triangle P+\triangle qL\triangle\widetilde{y}_{pc}\triangle P\right)\\+\frac{1}{4}\left(\triangle q\triangle L\triangle\widetilde{y}_{pc}\triangle P\right)\end{aligned}\tag{1}$$

The supply chain:

$$\begin{aligned}D_{scha}=q\triangle L\widetilde{y}_{pc}P+\frac{1}{2}\left(\triangle q\triangle L\widetilde{y}_{pc}P+q\triangle L\triangle\widetilde{y}_{pc}P+q\triangle L\widetilde{y}_{pc}\triangle P\right)\\+\frac{1}{3}\left(\triangle q\triangle L\triangle\widetilde{y}_{pc}P+\triangle q\triangle L\widetilde{y}_{pc}\triangle P+q\triangle L\triangle\widetilde{y}_{pc}\triangle P\right)\\+\frac{1}{4}\left(\triangle q\triangle L\triangle\widetilde{y}_{pc}\triangle P\right)\end{aligned}\tag{2}$$

Tourism consumption:

$$\begin{aligned}D_{cons}=qL\triangle\widetilde{y}_{pc}P+\frac{1}{2}\left(\triangle qL\triangle\widetilde{y}_{pc}P+q\triangle L\triangle\widetilde{y}_{pc}P+qL\triangle\widetilde{y}_{pc}\triangle P\right)\\+\frac{1}{3}\left(\triangle q\triangle L\triangle\widetilde{y}_{pc}P+\triangle qL\triangle\widetilde{y}_{pc}\triangle P+q\triangle L\triangle\widetilde{y}_{pc}\triangle P\right)\\+\frac{1}{4}\left(\triangle q\triangle L\triangle\widetilde{y}_{pc}\triangle P\right)\end{aligned}\tag{3}$$

Population growth:

$$\begin{aligned}D_{pop}=qL\widetilde{y}_{pc}\triangle P+\frac{1}{2}\left(\triangle qL\widetilde{y}_{pc}\triangle P+q\triangle L\widetilde{y}_{pc}\triangle P+qL\triangle\widetilde{y}_{pc}\triangle P\right)\\+\frac{1}{3}\left(\triangle q\triangle L\widetilde{y}_{pc}\triangle P+\triangle qL\triangle\widetilde{y}_{pc}\triangle P+q\triangle L\triangle\widetilde{y}_{pc}\triangle P\right)\\+\frac{1}{4}\left(\triangle q\triangle L\triangle\widetilde{y}_{pc}\triangle P\right)\end{aligned}\tag{4}$$

Tourism expenditure

Tourism Satellite Account (TSA) is the primary data source to capture tourism-related expenditure, which specifies all expenditure relating to domestic and inbound trips spent on businesses registered within

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the territory[43]. TSAs are only available for 62 countries, and the data is re-categorized based on the Tourism Satellite Account 39 sectors classification system (Supplementary Method 6).

For the 113 countries that do not report TSA, we resort to alternative sources. Inbound tourism expenditure data is obtained from the UN Tourism (World Tourism Organization), and domestic tourism expenditure data is sourced from the World Travel and Tourism Council (WTTC). These sources are used to compile the total tourism expenditure, referred to as internal tourism expenditure, for each country.

The aggregated internal tourism expenditure data must be allocated to different tourism sub-sectors. To disaggregate tourism expenditure into sectors for each countries, the following procedure is used. We first choose 31 goods and services in the GLORIA that tourists may purchase. *Domestic* household and government consumption data across 31 goods and services is then used to disaggregate domestic tourism expenditure into sectors. *Total* household and government consumption (domestic + exports) is chosen to disaggregate inbound tourism expenditure—this proxy considers export values consumed by overseas households, in this case, inbound tourists. This approach provides valuable insights into the interaction between tourism spending and various sectors of domestic economies, as well as international consumption patterns. The procedure also captures the dynamics of a country's economic conditions, including large-scale downturns such as those experienced during the COVID-19 pandemic. For more information on the estimation process and equation, please see Supplementary Method 6.

To account for inflation over time, constant-price tourism expenditure (base year 2009) for the period 2009–2020 was calculated by first converting local currencies to US dollars and then adjusting for inflation using the USA Consumer Price Index across 44 categories, obtained from the US Bureau of Labor Statistics[44].

This "convert-first, then deflate" approach is preferred by most researchers[45]. The main condition for adopting this procedure is that the sectoral output composition between countries should be similar[46]. Tourism satisfies this condition as its production of tourism services mainly consists of transportation, accommodation, food, recreational activities, and retailing. Every destination uses these components and similar production structure to construct "tourism".

From a feasibility perspective, this approach is further supported by the availability of high-quality currency converters and deflators. Exchange rates against a common currency (the U.S. dollar) are available for all countries from 2009 to 2020. The availability of the U.S. Consumer Price Index across 44 categories, including those specific to food away from home, motor fuel, and transport services, allows for sector-specific adjustments. This helps minimize the noise that would occur from applying a single consumer price index across all expenditures. We did not employ the 'deflate-first, then convert' procedure because several countries lack consumer price index data from the World Bank database. The literature suggests that similar results are achieved whether the 'convert-first, then deflate' or 'deflate-first, then convert' approach is used[47].

Tourist flow

The Tourism Satellite Account and international tourism expenditure provide detailed spending patterns for domestic and inbound tourism in a given country. However, they do not account for outbound tourism spending. To estimate how much residents spend abroad per country, we rely on international bilateral travel flows. These flows facilitate the allocation of international tourism spending to each destination from their respective origins, and vice versa (inbound spending from country A to country B = outbound spending from country B to country A). By mapping out bilateral travel patterns and expenditures for each origin-destination pair, we can estimate outbound tourism spending per country.

The UNWTO data provides bilateral travel volume between countries. In instances where tourist flow information is absent from the UNWTO dataset (around 30% of the bilateral travel data), we resort to a modelling approach, namely the gravity model[48]. This model considers factors that influence tourist movements, including the population size of both the visitor and the destination countries, and the physical distance between countries. The complete picture of tourist flows subsequently determines how each country is responsible for consuming inbound and outbound tourism.

Emissions

We include 29 types of emissions, ranging from carbon dioxide (CO_2) to sulfur hexafluoride (SF_6) obtained from the GLORIA database to capture detailed information about greenhouse gases (GHG) emissions (Supplementary Method 7). This inclusion allows us to capture all potential air pollutant emissions, including those from fuel combustion, industrial processes, residential activities, as well as emissions from animals and land use. We then utilize the 100-year time horizons Global Warming Potentials (GWP) provided by the Intergovernmental Panel on Climate Change[49] (IPCC) to standardize the impact of different gases relative to CO_2, forming carbon dioxide equivalent (CO_2-e).

Both aviation and fuel-based private vehicle use are major contributors to the overall tourism carbon footprints. To ensure robustness in our analysis, we conduct calculations of these two components using additional data. We utilize the database from ForwardKeys to estimate air transport carbon emissions for individual countries. ForwardKeys monthly CO_2 calculations draw inspiration from the ICAO methodology, analysing CO_2 emissions on a per-route and per-aircraft basis. It first considers aircraft fuel consumption and flight distance while excluding the CO_2 component that are related to freight. Passenger service aviation emissions are then allocated to countries where airlines register. This allocation process aligns with the United Nations' 'System of Economic and Environmental Accounting (SEEA)' and the World Tourism Organization's 'Measuring the Sustainability of Tourism (MST)' framework[50–52]. We then calculate aviation emissions related to tourism based on the proportion of air transport used for tourism purposes and fed this information to GLORIA to calculate indirect emissions in the supply chain (e.g., truffle in France to be air transported to restaurants in Australia). For estimating emissions from private vehicle use, we use specific fuel prices for 144 countries and the emission factor (CO_2 per litre) to convert visitor expenditures on gasoline into carbon emissions.

Uncertainties

Two levels of uncertainty arise from modelling global tourism carbon emissions. The first is based on the assumptions used in the MRIO model. This model assumes that emissions coefficients and production structures are stable for a given year, leading to constant multipliers[40]. In other words, economies of scale, short-run price effects, and supply constraints do not affect production coefficients. Under these assumptions, tourism expenditure and emissions are presumed to have a linear relationship. However, this may not accurately reflect the operation of some tourism subsectors, which often experience strong seasonality, price fluctuations, and varying utilization rates[53,54].

The second source of uncertainty arises from the data and parameters adopted in the model. The GLORIA database Release 057 serves as the source of GHG emissions data for this study. This data aligns with the EDGAR 7.0 dataset, which provides GHG emissions data updated only through 2019. Consequently, GHG emissions data beyond 2019 are estimated values[55]. This may introduce uncertainty into the 2020 tourism emissions results.

In addition, GLORIA's updated emissions satellite uses two emissions data sources: the EDGAR database (emissions by activities) and the OECD/Eurostat databases (emissions by industries). Proxies and assumptions were employed to derive the activity-by-industry emissions estimates needed by GLORIA. While the adjustment procedures provide reliable estimates for most sectors, road transport remains ambiguous. The current method can only divide road transport emissions into private vehicles (allocated to households) and allocate the remainder to road transport, postal, and courier services, but not to other sectors[55].

Data quality is crucial for global tourism emissions modelling, with tourism expenditure and input-output tables being the key parameters. We introduce a three-grade system of "very good," "good," and "fair" to represent the reliability of parameters and emissions results in our study.

"Very good" applies to countries that produce their own tourism satellite accounts and national input-output tables. Tourism satellite accounts provide detailed spending breakdowns by sector, allowing for an accurate match of consumption (tourism expenditure) to the MRIO sectors. Additionally, having a national input-output table ensures that local economic information is directly embedded into GLORIA, accurately representing the economic structure of an economy, which is essential for deriving emissions multipliers.

The second grade, "good," includes countries where either the official tourism satellite account or the national input-output table is missing. In such cases, a disaggregation procedure is required to develop a comprehensive tourism spending profile, or trade data is used to estimate the economic multipliers of a given economy.

"Fair" applies to countries lacking both official tourism satellite accounts and input-output tables. In these instances, a higher level of uncertainty in the results is expected, as these two key parameters are based on estimation.

Our model currently includes 62 countries with TSA and IO tables, classified as 'very good,' covering 92% of global tourism expenditure (see Supplementary Method 6). The 'good' group comprises 81 countries, while the 'fair' group includes 32 countries—most of which are small countries with a limited scale of tourism activities.

Modelling aviation emissions remains a key challenge in mapping out the global tourism carbon footprint. This study relies on ForwardKeys data to assign passenger emissions (based on a weight-per-passenger estimation, including luggage) to individual countries using CO_2 emissions on a per-route and per-aircraft basis. Our analysis shows that tourism air transport contributed 1.1 Gt CO2 in 2019, including direct emission (passenger transport, 0.96 Gt) and indirect emissions (freight transport due to supply chain activities, 0.14 Gt). While our results on aviation are slightly larger than existing references[56,57], it is unclear what is summarized under "aviation" and whether freight aviation emissions are included in these reports.

Overall, the high coverage rate of 92% global tourism expenditure data based on 62 TSA data in the model enables us to model global tourism emissions with a high level of reliability. A Monte Carlo simulation indicated that tourism carbon emissions in 2019 were between 5.1 and 5.5 Gt CO2-e, with a 99% likelihood range (Supplementary Method 2).

Reporting summary
Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability
We utilized the GLORIA (Global Resource Input-Output Assessment) database Release 057, developed by the University of Sydney through the Industrial Ecology Virtual Laboratory (IELab) infrastructure. The GLORIA database provides a global Multi-Region Input-Output (MRIO) model and carbon emissions data, accessible at https://ielab.info/labs/ielab-gloria. We gathered tourism expenditure information from 62 country-specific Tourism Satellite Accounts (TSAs) published in official government sources, reports or journal articles (See Supplementary Method 6 for the full list). Aggregated inbound and/or outbound tourism expenditure, as well as tourist flow data, were sourced from the UN Tourism (World Tourism Organization) library https://www.e-unwto.org/toc/unwtotfb/current. In addition, domestic tourism expenditure was obtained from the World Travel and Tourism Council (WTTC) Economic Impact Research publication https://wttc.org/research/economic-impact, accessed on 11 April 2023. Carbon emissions data for the aviation industry were obtained from ForwardKeys (https://forwardkeys.com), and Global Warming Potential (GWP) values were retrieved from the IPCC Sixth Assessment Report (AR6), available on https://zenodo.org/records/6483002. The fuel prices were sourced from the International Energy Agency, available at https://www.iea.org/data-and-statistics/data-product/energy-prices. The data points to plot Figs. 1–4 in the main text, along with the decomposition results by country, are provided in the Supplementary Information Source Data file. Source data are provided with this paper.

Code availability
The MATLAB code used to calculate tourism carbon footprints are available via https://github.com/GlobalCarbon/2024_Tourism.

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Author contributions

Y.-Y.S., F.F., and M.L. conceived and designed the study. M.L., Y.-Y.S., and F.F. contributed materials/analysis tools. F.F. and Y-Y.S. analysed the data. Y.-Y.S., F.F., S.G., J.H., and M.L. wrote the paper.

Competing interests

The authors declare no competing interests.

Additional information

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