

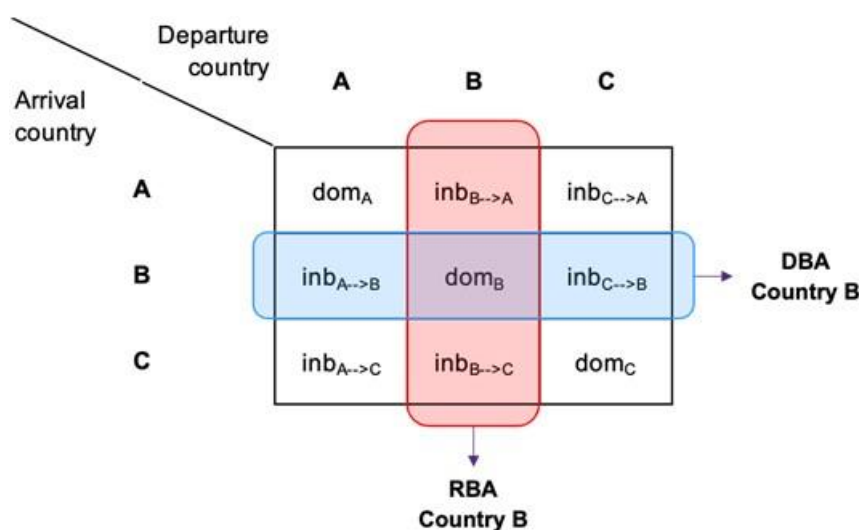
SUPPLEMENTARY INFORMATION – METHOD

Supplementary Method 1. The DBA and RBA accounting methods

We employ two accounting perspectives for assessing carbon footprint: the residence-based accounting (RBA) principle and the destination-based accounting (DBA) principle. Distinguishing between these two perspectives is crucial for assigning carbon responsibility, whether from the viewpoint of origin countries (RBA) or destination countries (DBA). This distinction provides essential information to advise mitigation strategies, addressing both travel behaviours at points of departure and technological improvements at destinations.

The graph below illustrates the distinction between the RBA and DBA perspectives. Assume the rows represent arrival countries and the columns represent departure countries. The RBA emissions is obtained by summing the values across the rows for each column. This means RBA emissions equal the emissions of domestic tourism plus the emissions of outbound tourism. In contrast, the DBA perspective is derived by summing the emissions across the columns for each row. This represents the summation of emissions from domestic tourism and inbound tourism.

For example, the RBA carbon footprint of Country B includes the carbon footprint from domestic tourism activities (dom_B) of Country B, and the carbon footprint associated with residents of Country B traveling abroad to Country A ($inb_{B \rightarrow A}$) and Country C ($inb_{B \rightarrow C}$). The DBA carbon footprint of Country B is the summation of domestic tourism emissions (dom_B) and inbound tourism emissions for tourists from Country A ($inb_{A \rightarrow B}$) and Country C ($inb_{C \rightarrow B}$).



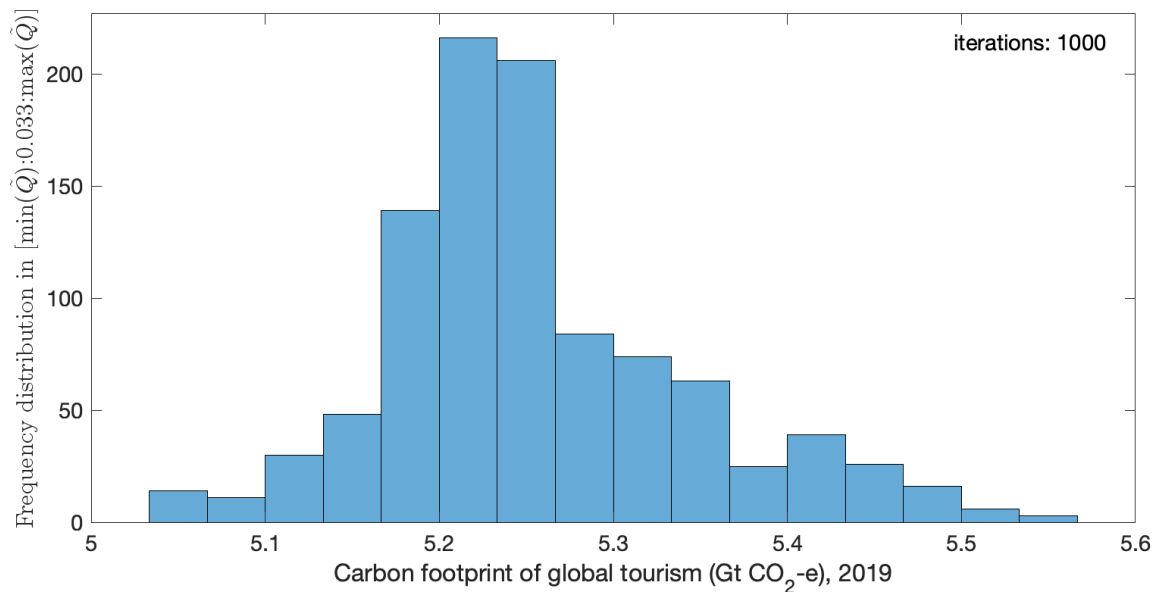
Supplementary Figure 1. The schematic presentation of the DBA and RBA principles

Supplementary Method 2. The Monte Carlo simulation

We conducted an uncertainty analysis using Monte Carlo simulation ¹. A total of 1,000 iterations were performed, resulting in an estimated range for the 2019 tourism carbon footprint of between 5.1 and 5.5 Gt CO₂-e, with 99% confidence.

The procedure for the uncertainty analysis using Monte Carlo simulation is as follows. Firstly, we perturb the MRIO components, which include the intermediate demand T^p , the final demand y^p and the total output x^p , for each iteration. Using standard deviations σ_T and σ_y (sourced from the GLORIA database) and normally distributed random numbers, we generate new Leontief inverses $L^p = (I - T^p \hat{x}^{p-1})^{-1}$ for each iteration.

We also perturb carbon intensity and tourism expenditure. The perturbation of carbon emissions Q^p follows the same procedure as that of the MRIO components, resulting in the new carbon intensity q^p for each iteration. The perturbed tourism expenditure, which serves as a new proxy to allocate tourism expenditure across more detailed sectors, is generated using the new final demand y^p . Finally, the new carbon footprint calculation $\tilde{Q}^p = q^p L^p \hat{y}^p$ was iterated 1,000 times to quantify the uncertainty in the 2019 tourism carbon emissions estimates. The following graph depicts a frequency distribution of the 2019 carbon footprint of global tourism.



Supplementary Figure 2. The distribution of global tourism emissions under Monte-Carlo simulation

Reference:

- 1 Lenzen, M., Wood, R. & Wiedmann, T. Uncertainty Analysis for Multi-Region Input–Output Models – a Case Study of the UK's Carbon Footprint. *Economic Systems Research* **22**, 43-63, doi:10.1080/09535311003661226 (2010).

Supplementary Method 3. Adjustment of per capita outbound tourism emissions

The standard procedure for calculating 'per capita outbound tourism emissions' is to divide the total outbound travel footprint by the population. However, for countries where only a small portion of the population can afford overseas travel, this approach dilutes the 'true' footprint caused by each outbound traveller. To adjust for this, we first calculate the travel propensity ratio (outbound visits/population). If the ratio is greater than 1, no adjustment is made to per capita outbound tourism emissions. If the ratio is less than 1, we divide the per capita footprint by the ratio. For example, China's ratio is 11%. The adjustment raises China's per capita outbound tourism emissions from 0.15 tonnes to 1.41 tonnes.

Supplementary Method 4. Countries in the GLORIA database

The GLORIA classification consists of 164 countries and regions. Within this classification, 160 entities are individual countries, while four are grouped into the Rest of the World (RoW) regions. For countries that do not have a country-specific IO table in the GLORIA, they are assigned with one of the four RoW multipliers.

Supplementary Table 1. List of GLORIA countries.

	Country	TSA	WTO/ WTTC	No Data		Country	TSA	WTO/ WTTC	No Data		Country	TSA	WTO/ WTTC	No Data
1	Rest of Americas		1		56	Finland	1			111	Niger		1	
2	Rest of Europe		1		57	France	1			112	Nigeria		1	
3	Rest of Africa		1		58	Gabon			1	113	Nicaragua		1	
4	Rest of Asia-Pacific		1		59	United Kingdom	1			114	Netherlands	1		
5	Afghanistan			1	60	Georgia		1		115	Norway	1		
6	Angola		1		61	Ghana		1		116	Nepal		1	
7	Albania		1		62	Guinea		1		117	New Zealand	1		
8	United Arab Emirates		1		63	Gambia		1		118	Oman		1	
9	Argentina		1		64	Equatorial Guinea			1	119	Pakistan		1	
10	Armenia		1		65	Greece		1		120	Palestine			1
11	Australia	1			66	Guatemala		1		121	Panama		1	
12	Austria	1			67	Honduras	1			122	Peru	1		
13	Azerbaijan		1		68	Hong Kong	1			123	Philippines	1		
14	Burundi		1		69	Croatia	1			124	Papua New Guinea		1	
15	Belgium	1			70	Haiti		1		125	Poland	1		
16	Benin		1		71	Hungary	1			126	North Korea			1
17	Burkina Faso		1		72	Indonesia	1			127	Portugal	1		
18	Bangladesh	1			73	India	1			128	Paraguay		1	
19	Bulgaria	1			74	Ireland	1			129	Qatar		1	
20	Bahrain		1		75	Iran		1		130	Romania	1		
21	Bahamas	1			76	Iraq		1		131	Russia	1		
22	Bosnia and Herzegovina		1		77	Iceland	1			132	Rwanda		1	
23	Belarus		1		78	Israel	1			133	Saudi Arabia	1		
24	Belize		1		79	Italy	1			134	South Sudan			1
25	Bolivia		1		80	Jamaica		1		135	Senegal		1	
26	Brazil	1			81	Jordan	1			136	Singapore	1		
27	Brunei Darussalam		1		82	Japan	1			137	Sierra Leone		1	
28	Bhutan			1	83	Kazakhstan	1			138	El Salvador		1	
29	Botswana		1		84	Kenya		1		139	Somalia			1
30	Central African Republic		1		85	Kyrgyzstan		1		140	Serbia			1
31	Canada	1			86	Cambodia		1		141	North Sudan		1	
32	Switzerland	1			87	South Korea	1			142	Slovakia	1		
33	Chile	1			88	Kuwait		1		143	Slovenia	1		
34	China	1			89	Laos		1		144	Sweden	1		
35	Cote d'Ivoire		1		90	Lebanon		1		145	Syria		1	
36	Cameroon		1		91	Liberia			1	146	Chad			1
37	DR Congo		1		92	Libya		1		147	Togo		1	
38	Congo		1		93	Sri Lanka	1			148	Thailand	1		
39	Colombia	1			94	Lithuania	1			149	Tajikistan		1	
40	Costa Rica		1		95	Luxembourg		1		150	Turkmenistan			1
41	Cuba		1		96	Latvia	1			151	Tunisia		1	
42	Cyprus		1		97	Morocco	1			152	Türkiye	1		
43	Czechia	1			98	Moldova		1		153	Tanzania		1	
44	Germany	1			99	Madagascar		1		154	Uganda		1	
45	Djibouti			1	100	Mexico	1			155	Ukraine		1	
46	DR Yemen (Aden)			1	101	North Macedonia		1		156	Uruguay	1		
47	Denmark	1			102	Mali		1		157	United States of America	1		
48	Dominican Republic		1		103	Malta	1			158	Uzbekistan		1	
49	Algeria		1		104	Myanmar		1		159	Venezuela		1	
50	Ecuador		1		105	Mongolia		1		160	Vietnam	1		
51	Egypt	1			106	Mozambique		1		161	Yemen		1	
52	Eritrea			1	107	Mauritania			1	162	South Africa	1		
53	Spain	1			108	Malawi		1		163	Zambia		1	
54	Estonia	1			109	Malaysia	1			164	Zimbabwe		1	
55	Ethiopia		1		110	Namibia		1						

Supplementary Method 5. Sectors in the GLORIA database

Supplementary Table 2. List of GLORIA sectors.

	Sector Name		Sector Name
1	Growing wheat	61	Printing
2	Growing maize	62	Coke oven products
3	Growing cereals n.e.c	63	Refined petroleum products
4	Growing leguminous crops and oil seeds	64	Nitrogenous fertilizers
5	Growing rice	65	Non-nitrogenous and mixed fertilizers
6	Growing vegetables, roots, tubers	66	Basic petrochemical products
7	Growing sugar beet and cane	67	Basic inorganic chemicals
8	Growing tobacco	68	Basic organic chemicals
9	Growing fibre crops	69	Pharmaceuticals and medicinal products
10	Growing crops n.e.c.	70	Dyes, paints, glues, detergents and other chemical products
11	Growing grapes	71	Rubber products
12	Growing fruits and nuts	72	Plastic products
13	Growing beverage crops (coffee, tea etc)	73	Clay building materials
14	Growing spices, aromatic, drug and pharmaceutical crops	74	Other ceramics n.e.c.
15	Seeds and plant propagation	75	Cement, lime and plaster products
16	Raising of cattle	76	Other non-metallic mineral products n.e.c.
17	Raising of sheep	77	Basic iron and steel
18	Raising of swine/pigs	78	Basic aluminium
19	Raising of poultry	79	Basic Copper
20	Raising of animals n.e.c.; services to agriculture	80	Basic Gold
21	Forestry and logging	81	Basic lead/zinc/silver
22	Fishing	82	Basic nickel
23	Crustaceans and molluscs	83	Basic tin
24	Hard coal	84	Basic non-ferrous metals n.e.c.
25	Lignite and peat	85	Fabricated metal products
26	Petroleum extraction	86	Machinery and equipment
27	Gas extraction	87	Motor vehicles, trailers and semi-trailers
28	Iron ores	88	Other transport equipment
29	Uranium ores	89	Repair and installation of machinery and equipment
30	Aluminium ore	90	Computers; electronic products; optical and precision instruments
31	Copper ores	91	Electrical equipment
32	Gold ores	92	Furniture and other manufacturing n.e.c
33	Lead/zinc/silver ores	93	Electric power generation, transmission and distribution
34	Nickel ores	94	Distribution of gaseous fuels through mains
35	Tin ores	95	Water collection, treatment and supply; sewerage
36	Other non-ferrous ores	96	Waste collection, treatment, and disposal
37	Quarrying of stone, sand and clay	97	Materials recovery
38	Chemical and fertilizer minerals	98	Building construction
39	Extraction of salt	99	Civil engineering construction
40	Mining and quarrying n.e.c.; services to mining	100	Wholesale and retail trade; repair of motor vehicles and motorcycles
41	Beef meat	101	Road transport
42	Sheep meat	102	Rail transport
43	Pork	103	Transport via pipeline
44	Poultry meat	104	Water transport
45	Other meat products	105	Air transport
46	Fish products	106	Services to transport
47	Cereal products	107	Postal and courier services
48	Vegetable products	108	Hospitality
49	Fruit products	109	Publishing
50	Food products and feeds n.e.c.	110	Telecommunications
51	Sugar refining; cocoa, chocolate and confectionery	111	Information services
52	Animal oils and fats	112	Finance and insurance
53	Vegetable oils and fats	113	Property and real estate
54	Dairy products	114	Professional, scientific and technical services
55	Alcoholic and other beverages	115	Administrative services
56	Tobacco products	116	Government; social security; defence; public order
57	Textiles and clothing	117	Education
58	Leather and footwear	118	Human health and social work activities
59	Sawmill products	119	Arts, entertainment and recreation
60	Pulp and paper	120	Other services

Supplementary Method 6. Compilation of tourism expenditure

We compile tourism expenditure data from two primary sources: Tourism Satellite Accounts (TSAs) and aggregated tourism expenditure data. TSAs are critical to this study as they provide a detailed breakdown of tourism expenditure by sector, including accommodation, transportation, food, and other goods and services. TSAs are available for 62 countries, sourced from official government publications (36 countries), international institution reports (22 countries), and academic research papers (4 countries). A list of these 62 countries and their corresponding online sources is provided below.

Supplementary Table 3. List of TSA countries.

	Country	Source	URL
1	Australia	Australian Bureau of Statistics	https://www.abs.gov.au/statistics/economy/national-accounts/australian-national-accounts-tourism-satellite-account/latest-release#main-features
2	Austria	Statistics Austria	https://www.statistik.at/en/statistics/tourism-and-transport/tourism/tourism-satellite-accounts/national-tourism-satellite-accounts
3	Belgium	Tourisme Vlaanderen	https://toerismevlaanderen.be/sites/default/files/assets/documents_KENNIS/onderzoeken/TSA-2016-Executive-summary.pdf
4	Bangladesh	Bangladesh Bureau of Statistics	https://bbs.portal.gov.bd/sites/default/files/files/bbs.portal.gov.bd/page/b343a8b4_956b_45ca_872f_4cf9b2f1a6e0/2021-11-25-09-20-712d6a0fe8d9ed6239e23d39b70c55f7.pdf
5	Bulgaria	OECD	https://www.oecd-ilibrary.org/industry-and-services/oecd-tourism-trends-and-policies-2022_a8dd3019-en
6	Bahamas	Ministry of Tourism	https://www.tourismtoday.com/statistics/satellite-accounts
7	Brazil	Research Paper	https://www.iioa.org/conferences/17th/papers/890206828_090609_165720_CHALLENGESTOTHEDEVELOPMENTOFTOURISMSATELLITEACCOUNTSINBRAZIL.PDF
8	Canada	OECD	https://www.oecd-ilibrary.org/industry-and-services/oecd-tourism-trends-and-policies-2022_a8dd3019-en
9	Switzerland	Federal Statistical Office	https://www.bfs.admin.ch/bfs/en/home/statistics/tourism/surveys/tsa.html
10	Chile	OECD	https://www.oecd-ilibrary.org/industry-and-services/oecd-tourism-trends-and-policies-2022_a8dd3019-en
11	China	Research Paper	https://link.springer.com/chapter/10.1007/978-3-642-38433-2_90
12	Colombia	OECD	https://www.oecd-ilibrary.org/industry-and-services/oecd-tourism-trends-and-policies-2022_a8dd3019-en
13	Czechia	OECD	https://www.oecd-ilibrary.org/industry-and-services/oecd-tourism-trends-and-policies-2022_a8dd3019-en
14	Germany	OECD	https://www.oecd-ilibrary.org/industry-and-services/oecd-tourism-trends-and-policies-2022_a8dd3019-en
15	Denmark	OECD	https://www.oecd-ilibrary.org/industry-and-services/oecd-tourism-trends-and-policies-2022_a8dd3019-en
16	Egypt	OECD Tourism Trends and Policies 2023	https://www.oecd-ilibrary.org/industry-and-services/oecd-tourism-trends-and-policies-2022_a8dd3019-en
17	Spain	INEBase - Instituto Nacional de Estadística (INE)	https://www.ine.es/CDINEbase/consultar.do?mes=&operacion=Cuenta+sat%E9lite+del+turismo+de+Espa%F1a&id_oper=Ir
18	Estonia	OECD	https://www.oecd-ilibrary.org/industry-and-services/oecd-tourism-trends-and-policies-2022_a8dd3019-en

	Country	Source	URL
19	Finland	OECD	https://www.oecd-ilibrary.org/industry-and-services/oecd-tourism-trends-and-policies-2022_a8dd3019-en
20	France	OECD	https://www.oecd-ilibrary.org/industry-and-services/oecd-tourism-trends-and-policies-2022_a8dd3019-en
21	United Kingdom	Office for National Statistics	https://www.ons.gov.uk/economy/nationalaccounts/satelliteaccounts/datasets/uktourismsatelliteaccountssatables
22	Honduras	Instituto Hondureño de Turismo	https://iht.hn/sites/default/files/2022-05/Tourism%20Statistic%20Bulletin%202003-2007.pdf
23	Hong Kong	Census and Statistics Department	https://www.censtatd.gov.hk/en/search.html?prod_type=all
24	Croatia	OECD	https://www.oecd-ilibrary.org/industry-and-services/oecd-tourism-trends-and-policies-2022_a8dd3019-en
25	Hungary	OECD	https://www.oecd-ilibrary.org/industry-and-services/oecd-tourism-trends-and-policies-2022_a8dd3019-en
26	Indonesia	Statistics Indonesia	https://www.bps.go.id/publication/2021/07/06/6f2f99f9fdf5e645773c906b/tourism-satellite-account-indonesia-2016-2019.html
27	India	National Council of Applied Economic Research	https://www.ncaer.org/publication_details.php?PID=304
28	Ireland	OECD	https://www.oecd-ilibrary.org/industry-and-services/oecd-tourism-trends-and-policies-2022_a8dd3019-en
29	Iceland	OECD	https://www.oecd-ilibrary.org/industry-and-services/oecd-tourism-trends-and-policies-2022_a8dd3019-en
30	Israel	OECD	https://www.oecd-ilibrary.org/industry-and-services/oecd-tourism-trends-and-policies-2022_a8dd3019-en
31	Italy	Italian National Institute of Statistics (Istat)	https://www.istat.it/it/files//2018/01/EN_Tourism-satellite-account.pdf
32	Jordan	Acorn Tourism on behalf of USAID	https://www.yumpu.com/en/document/read/8178326/jordan-tourism-satellite-accounts-tables-siyaha
33	Japan	Japan Tourism Agency	https://www.mlit.go.jp/kankocho/en/siryou/toukei/shouhidoukou.html
34	Kazakhstan	Bureau of National Statistics	https://stat.gov.kz/en/industries/labor-and-income/stat-ags/publications/84675/
35	South Korea	Korean Tourism Organization	https://datalab.visitkorea.or.kr/datalab/portal/ts/getKorTursmBalcForm.do#
36	Sri Lanka	Sri Lanka Tourism Development Authority	https://www.sltda.gov.lk/en/statistics
37	Lithuania	Official Statistics Portal	https://osp.stat.gov.lt/statistiniu-rodikliu-analize#/
38	Latvia	OECD	https://www.oecd-ilibrary.org/industry-and-services/oecd-tourism-trends-and-policies-2022_a8dd3019-en
39	Morocco	OECD	https://www.oecd-ilibrary.org/industry-and-services/oecd-tourism-trends-and-policies-2022_a8dd3019-en
40	Mexico	National Institute of Statistics and Geography (INEGI)	https://en.www.inegi.org.mx/programas/turismo/2013/#Open_data

	Country	Source	URL
41	Malta	National Statistics Office	https://nso.gov.mt/en/publications/Publications_by_Unit/Documents/A1_National_Accounts/TSA_2010.pdf
42	Malaysia	Department of Statistics	https://www.dosm.gov.my/v1/index.php?r=column/cthemByCat&cat=111&bul_id=SXp2ZUF0TGx2OTU0YXo2YXZ1QUYdz09&menu_id=TE5CRUZCblh4ZTZMODZlbnk2aWRRQT09
43	Netherlands	CBS Statsline	https://opendata.cbs.nl/#/CBS/en/dataset/84285ENG/table?ts=1655640992473
44	Norway	Statistics Norway	https://www.ssb.no/en/statbank/table/10638/
45	New Zealand	Statistics New Zealand	https://infoshare.stats.govt.nz/SelectVariables.aspx?pxID=7e787911-4aa0-4136-bcd3-4773267d9d7b
46	Peru	Ministry of Foreign Trade and Tourism	https://www.gob.pe/institucion/mincetur/informes-publicaciones/22168-peru-cuenta-satelite-de-turismo
47	Philippines	Department of Tourism	http://www.tourism.gov.ph/tourism_dem_sup_pub.aspx
48	Poland	OECD	https://www.oecd-ilibrary.org/industry-and-services/oecd-tourism-trends-and-policies-2022_a8dd3019-en
49	Portugal	Statistics Portugal	https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine_cnacionais2010&contexto=cs&selTab=tab4&perfil=220677460&INST=220617355
50	Romania	OECD	https://www.oecd-ilibrary.org/industry-and-services/oecd-tourism-trends-and-policies-2022_a8dd3019-en
51	Russia	Research Paper	https://www.ncbi.nlm.nih.gov/pmc/articles/PMC10072802/pdf/11507_2023_Article_7369.pdf
52	Saudi Arabia	Ministry of Tourism	https://mt.gov.sa/tic/dashboard/tourism-demand
53	Singapore	Singapore Tourism Board	https://stan.stb.gov.sg/content/stan/en/tourism-statistics.html
54	Slovakia	OECD	https://www.oecd-ilibrary.org/industry-and-services/oecd-tourism-trends-and-policies-2022_a8dd3019-en
55	Slovenia	Statistical Office of the Republic of Slovenia (SURS)	https://pxweb.stat.si/SiStatData/pxweb/en/Data/Data/0380805S
56	Sweden	Swedish Agency for Economic and Regional Growth	https://tillvaxtverket.se/statistik/turism/turismrakenskaperna.html
57	Thailand	Ministry of Sports and Tourism	https://www.mots.go.th/news/category/520
58	Turkiye	Turkish Statistical Institute	https://data.tuik.gov.tr/Bulten/Index?p=Tourism-Satellite-Account-2019-2022-53813&dil=2#:~:text=TRKSTAT%20Corporate&text=Tourism%20satellite%20account%20is%20an,information%20at%20the%20international%20level
59	Uruguay	Ministry of Tourism	https://www.gub.uy/ministerio-turismo/
60	United States of America	Bureau of Economic Analysis	https://www.bea.gov/tourism-satellite-accounts-data-sheets
61	Vietnam	Ministry of Culture, Sports and Tourism	https://vietnamtourism.gov.vn/post/42838
62	South Africa	Statistics South Africa	https://www.statssa.gov.za/?page_id=1854&PPN=Report-04-05-07&SCH=73010

Countries publish TSA data using different sector classifications. This inconsistency necessitates the adoption of a compatible sectoral division to facilitate cross-country comparisons. In this study, we use 39 sectors as a standard format to compile and organize the TSA information. This ensures the comparability of TSA data and facilitates mapping with the GLORIA database in the next step. The details of the 39 TSA sectors are presented below.

Supplementary Table 4. List of TSA sectors.

	Sector Code	Sector Name
1	A	Accommodation, food, and beverage serving services
2	Aa	Accommodation services
3	Aa1	Hotels and similar (include motel)
4	Aa2	Imputed and actual rent on vacation homes
5	Aa3	Meals from accommodation
6	Ab	Food and beverage serving services
7	B	Transportation services
8	Ba	Passenger transport services
9	Ba1	Road transportation
10	Ba11	Railways passenger transport
11	Ba12	On-road passenger transport
12	Ba2	Air transportation
13	Ba3	Water transportation
14	Bb	Fuel and other automotive products
15	Bb1	Fuel (petrol, diesel)
16	Bb2	Other automotive products
17	Bc	Transport equipment rental services
18	Bd	Repair and maintenance
19	Be	Passenger transport supporting services
20	C	Travel agency and tour operator services
21	D	Recreational, cultural, and sporting services
22	E	Other tourism goods and services
23	Ea	Miscellaneous tourism services
24	Ea1	Education services
25	Ea2	Convention fees
26	Ea3	Medical services
27	Ea4	Financial and insurance services
28	Ea5	Postal and communication services
29	Ea6	Others
30	Eb	Other goods (shopping)
31	Eb1	Cosmetics & skin care / perfume
32	Eb2	Electrical / photographic goods
33	Eb3	Foodstuff, alcohol, and tobacco
34	Eb4	Garments / fabric and leather / synthetic goods
35	Eb5	Jewellery and watch
36	Eb6	Medicine / chines herbs
37	Eb7	Souvenirs / handicrafts and gifts
38	Eb8	Other items
39	TT	TOTAL

For countries without TSAs, we derive tourism expenditure data from two alternative sources: the United Nations World Tourism Organization (UNWTO) for inbound tourism expenditure, and the World Travel and Tourism Council (WTTC) for domestic expenditure. These sources provide tourism expenditure data for 113 countries. Overall, our study covers a total of 175 countries: 62 countries that report TSAs, and 113 countries for which we have tourism expenditure data.

Disaggregate tourism expenditure based on the GLORIA sectors

TSA data and tourism expenditure data are reported in different sectors than those found in the GLORIA database. To facilitate the mapping of tourism expenditure to GLORIA sectors, we first need to disaggregate the tourism expenditure and then match it with the relevant sectors in the GLORIA model.

Disaggregating tourism expenditure allows us to capture the nuances of spending behavior, which are crucial for understanding the distribution of tourism-related expenditures across different sectors. This disaggregation process relies on final demand data from the GLORIA model. GLORIA's final demand includes household final consumption, non-profit institutions serving households, government final consumption, gross fixed capital formation, changes in inventories, and acquisitions less disposals of valuables. We select the first three categories as proxies because they most closely reflect the distribution of household spending and are directly relevant to tourism-related activities. This selection also ensures that the allocation of tourism expenditure aligns with how households typically distribute their spending across various sectors. For simplicity, we refer to these categories—household final consumption, non-profit institutions serving households, and government final consumption—as “household consumption”.

Different final demand data is used to disaggregate domestic tourism expenditure and inbound tourism expenditure, respectively. For domestic tourism expenditure, we rely on domestic household consumption within the GLORIA final demand matrix, which allows us to reflect the spending behavior of residents within their own country.

However, disaggregating inbound tourism expenditure requires a broader and more sophisticated proxy to capture the diverse spending patterns of foreign tourists in the domestic economy. Unlike domestic tourism, inbound tourism involves spending by individuals from various countries, whose consumption preferences may differ from those of local residents. To address this complexity, we integrate domestic household consumption with the consumption patterns of overseas households, as provided in the GLORIA final demand matrix. This approach ensures that the disaggregation of inbound tourism expenditure reflects the globalized nature of tourism, where the spending habits of international visitors differ from those of local residents.

The disaggregation of TSA data and its mapping to the GLORIA sectors is performed using eq. 1. TSAs typically categorize expenditure into several clusters that correspond to specific sectors, enabling further disaggregation within each cluster if their TSA data do not report detail break-down. For instance, if a country's TSA only reports one aggregated transport expenditure figure, we use the proportions of road, rail, water, and air transport in that country's household consumption as proxies for disaggregation.

$$e_{c,i} = e_{c,j} C h_{c,i} \quad (\text{eq.1})$$

Where:

- $e_{c,i}$ = Vector of disaggregated tourism expenditure in country c within selected GLORIA sector i
- $e_{c,j}$ = Vector of tourism expenditure in country c within TSA sector j
- C = Concordance matrix from TSA sectors j to GLORIA sectors i

$h_{c,i}$ = Vector of household consumption in country c within selected GLORIA sector i

A concordance matrix, C , is created to map TSA spending to their corresponding sectors within the GLORIA framework, ensuring consistency and comparability across data from different countries. The concordance between TSA and GLORIA sectors is developed based on semantic similarity and sectoral relevance, as detailed in Supplementary Table 5.

For countries that do not have TSAs and only provide a single aggregated internal tourism expenditure figure, we cannot rely solely on household consumption patterns from GLORIA. Household consumption distribution may be skewed towards certain sectors; for instance, spending on education is significantly high in daily household activities but not in tourism expenditure. To address this, we take an additional step by dividing total tourism expenditure into two clusters: one for accommodation and transportation, and another for food and other goods and services. This two-cluster approach (eq. 2) allows for greater accuracy in distributing tourism expenditure according to a nation's spending characteristics. The proportions for each cluster are derived from the global average tourism consumption patterns of countries with TSAs.

$$e_{c,i} = (e_c \bar{e}_j) C h_{c,i} \quad (\text{eq.2})$$

Where:

e_c = Total tourism expenditure in country c

$\bar{e}_j$ = Vector of average global tourism expenditure within two-cluster sector j

Supplementary Table 5. Concordance from TSA sectors to GLORIA sectors.

TSA Sector Code	TSA Sector Name	GLORIA Sector Number	GLORIA Sector Name
A Aa Aa1 Aa2 Aa3 Ab	Accommodation, food, and beverage serving services Accommodation services Hotels and similar (include motel) Imputed and actual rent on vacation homes Meals from accommodation Food and beverage serving services	108	Hospitality
B Ba Ba1	Transportation services Passenger transport services Road transportation		
Ba11	Railways passenger transport	102	Rail transport
Ba12	On-road passenger transport	101	Road transport
Ba2	Air transportation	105	Air transport
Ba3	Water transportation	104	Water transport
Bb Bb1 Bb2	Fuel and other automotive products Fuel (petrol, diesel) Other automotive products	63	Refined petroleum products
Bc Bd Be C	Transport equipment rental services Repair and maintenance Passenger transport supporting services Travel agency and tour operator services	106	Services to transport
D Ea2	Recreational, cultural, and sporting services Convention fees	119	Arts, entertainment and recreation
E Ea	Other tourism goods and services Miscellaneous tourism services		
Ea1 Ea6 Ea3	Education services Others Medical services	120 118	Other services Human health and social work activities
Ea4	Financial and insurance services	112	Finance and insurance
Ea5	Postal and communication services	107 110	Postal and courier services Telecommunications
Eb	Other goods (shopping)	100	Wholesale and retail trade
Eb1 Eb6	Cosmetics & skin care / perfume Medicine / chines herbs	69	Pharmaceuticals and medicinal products
Eb2	Electrical / photographic goods	90	Computers; electronic products; optical and precision instruments
Eb3	Foodstuff, alcohol, and tobacco	41 42 43 44 45 46 47 48 49 54 55 56	Beef meat Sheep meat Pork Poultry meat Other meat products Fish products Cereal products Vegetable products Fruit products Dairy products Alcoholic and other beverages Tobacco products
Eb4	Garments / fabric and leather / synthetic goods	57 58	Textiles and clothing Leather and footwear
Eb5 Eb7 Eb8	Jewellery and watch Souvenirs / handicrafts and gifts Other items	92	Furniture and other manufacturing n.e.c

Of the 175 countries included in this study, 144 are directly matched with country-specific multipliers provided by the GLORIA model. The remaining 31 countries, for which country-specific multipliers are unavailable, are grouped into four broader regions: Rest of Americas, Rest of Europe, Rest of Africa, and Rest of Asia-Pacific. Refer to the table below for classifications.

Supplementary Table 6. List of countries in the observation.

	GLORIA					Total
	Country coefficient	Rest of Americas ¹⁾	Rest of Europe ²⁾	Rest of Africa ³⁾	Rest of Asia-Pacific ⁴⁾	
Tourism data	144	16	1	7	7	175
TSA	62					62
UNWTO/WTTC	82	16	1	7	7	113

- 1) Rest of Americas: Aruba, Antigua and Barbuda, Bermuda, Barbados, Curaçao, Cayman Islands, Dominica, Grenada, Guyana, St. Kitts and Nevis, St. Lucia, Puerto Rico, Suriname, Trinidad and Tobago, St. Vincent and the Grenadines, Virgin Islands (U.S.)
- 2) Rest of Europe: Montenegro
- 3) Rest of Africa: Comoros, Cabo Verde, Lesotho, Mauritius, Sao Tome and Principe, Swaziland, Seychelles
- 4) Rest of Asia-Pacific: Fiji, Kiribati, Macao SAR, Maldives, Solomon Islands, Taiwan, Vanuatu

Supplementary Method 7. Greenhouse gas emissions and GWP

Supplementary Table 7. List of GHG emissions and its respective Global Warming Potential (GWP).

	Gas	GWP		Gas	GWP		Gas	GWP
1	C2F6	11,100	11	HCFC-141b	782	21	HFC-236fa	8,060
2	C3F8	8,900	12	HCFC-142b	1,980	22	HFC-245fa	858
3	C4F10	9,200	13	HFC-125	3,170	23	HFC-32	677
4	C5F12	8,550	14	HFC-134a	1,300	24	HFC-365mfc	804
5	C6F14	7,910	15	HFC-134	1,120	25	HFC-41	116
6	C7F16	7,910	16	HFC-143a	4,800	26	HFC-43-10-mee	1,640
7	c-C4F8	9,540	17	HFC-143	328	27	N2O	265
8	CF4	6,630	18	HFC-152a	138	28	NF3	16,100
9	CH4	28	19	HFC-227ea	3,350	29	SF6	23,500
10	CO2	1	20	HFC-23	12,400			

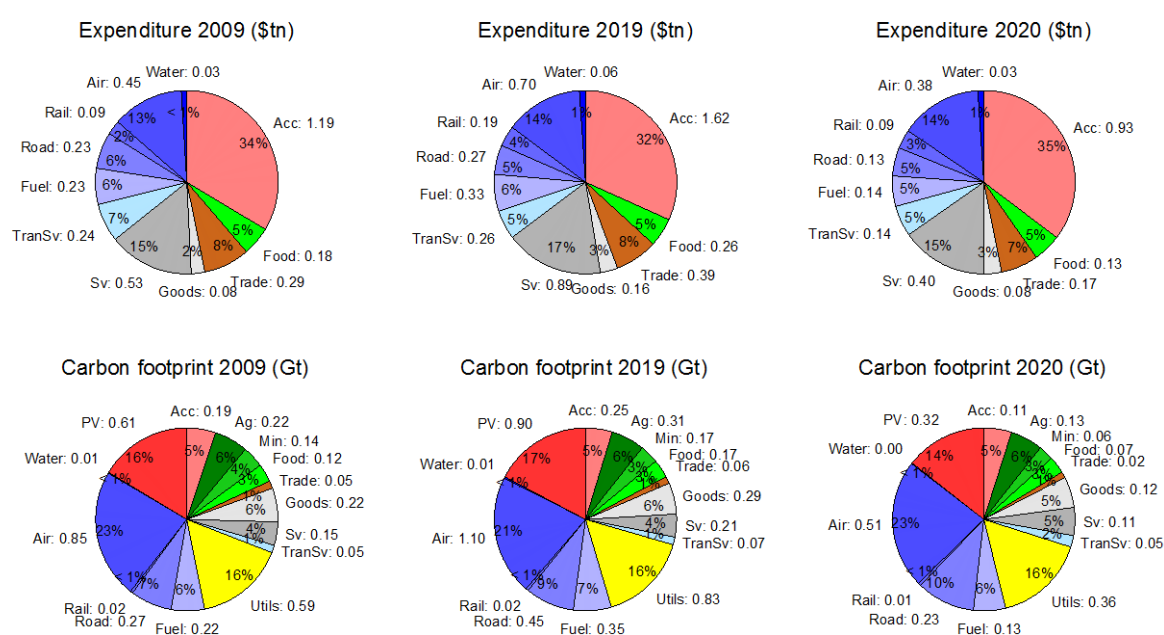
The 100-year time horizons GWP values were retrieved from the IPCC Sixth Assessment Report (AR6), <https://www.ipcc.ch/assessment-report/ar6/>, accessed on 14th December 2023.

SUPPLEMENTARY INFORMATION - RESULT

Supplementary Information 1. Tourism expenditure and carbon footprint by sectors

Globally, tourism expenditure follows an interesting pattern: one-third is spent on accommodation, one-third on transportation (including fuel, road, rail, air, water, and transport services), and the remaining one-third on other goods and services. This spending pattern remained stable from 2009 to 2020.

However, a different picture emerges when examining the carbon footprint by sector. Accommodation accounts for only 5% of the overall carbon footprint, whereas transportation, due to its high carbon intensity, is responsible for over 55%. Sectors such as agriculture, mining, and utilities, which do not directly receive tourism expenditure, still contribute approximately 25% of the total carbon footprint due to supply chain effects.



Supplementary Figure 3. Tourism expenditure and carbon footprint by sectors, 2009, 2019 and 2020

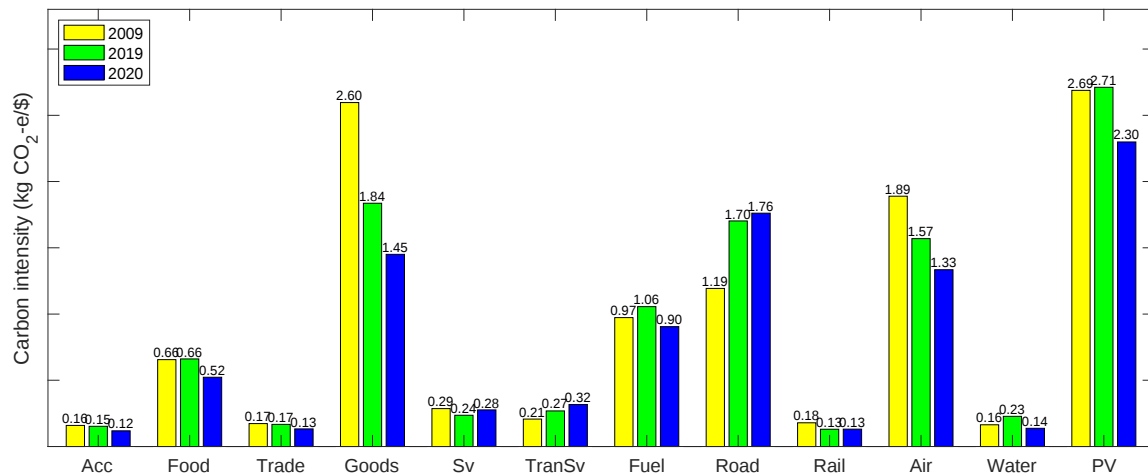
In 2019, direct tourism emissions from the sector amounted to 1.8 Gt, with air transport accounting for 52%, followed by road transport at 18%. The supply chain effect contributed an additional 2.5 Gt of emissions, primarily from utilities (34%) and petrochemical manufacturing (14%). Including private vehicle emissions (0.9 Gt), total tourism-related emissions were 5.2 Gt in 2019. The top three sources were aviation (21%), private vehicles (17%), and utilities (16%). See the table below.

Supplementary Table 8. Tourism direct and indirect carbon emissions, 2019

Sector	Acronym	Direct emissions 2019 (Mt)	Indirect emissions 2019 (Mt)	Total tourism emissions 2019 (Mt)
Agriculture	Ag	0	309	309
Mining	Min	0	172	172
Food	Food	85	85	170
Goods	Goods	30	259	289
Utilities	Utils	0	830	830
Trade	Trade	29	35	64
Services	Sv	100	109	209
Accommodation	Acc	235	11	246
Fuel	Fuel	0	350	350
Road transport	Road	330	121	451
Rail transport	Rail	16	8	24
Air transport	Air	954	148	1,102
Water transport	Water	9	3	13
<u>Transport services</u>	<u>TranSv</u>	<u>43</u>	<u>27</u>	<u>71</u>
Subtotal		1,834	2,466	4,299
Private vehicles	PV	899	0	899
Total	Tot	2,733	2,466	5,198

Supplementary Information 2. Carbon intensity by sectors

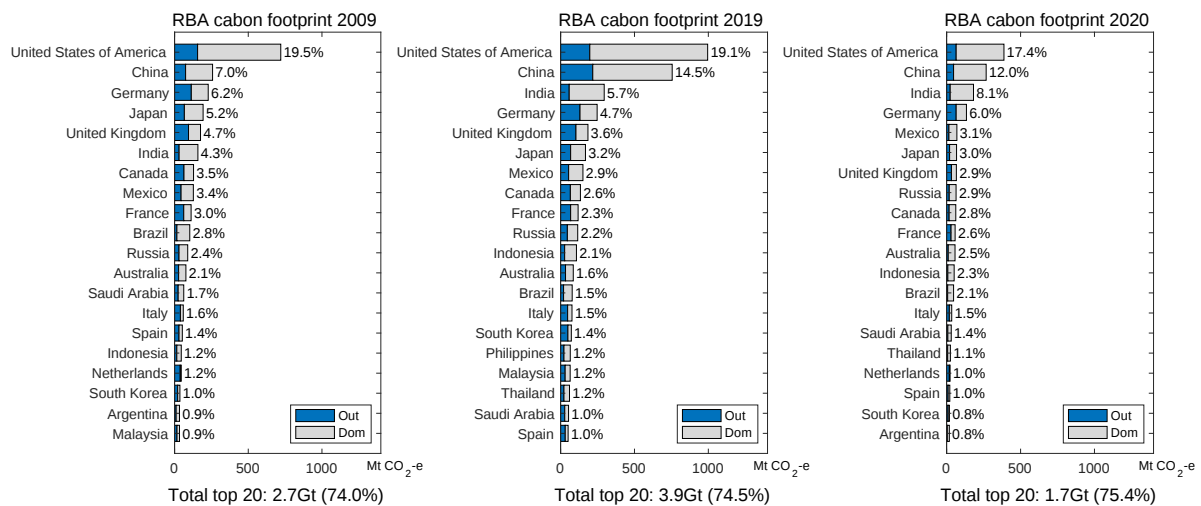
Using the 2009 constant prices, the carbon intensity (kg/US\$) of accommodation, trade, goods and services shows a decreasing pattern between 2009-2019. However, the carbon intensity of transportation sector generally exhibits an increasing trend, with the exceptions of rail and air transport. In 2009, goods accounted for the highest carbon intensity, while the use of private vehicles (PV) exhibited the highest carbon intensity among all sectors in 2019 and 2020. This shift underscores the growing environmental impact of transportation and highlights the need for targeted mitigation strategies in this sector.



Supplementary Figure 4. Carbon intensity (kg/\$) in constant price by sectors, 2009, 2019 and 2020

Supplementary Information 3. The resident-based accounting emissions for top 20 countries

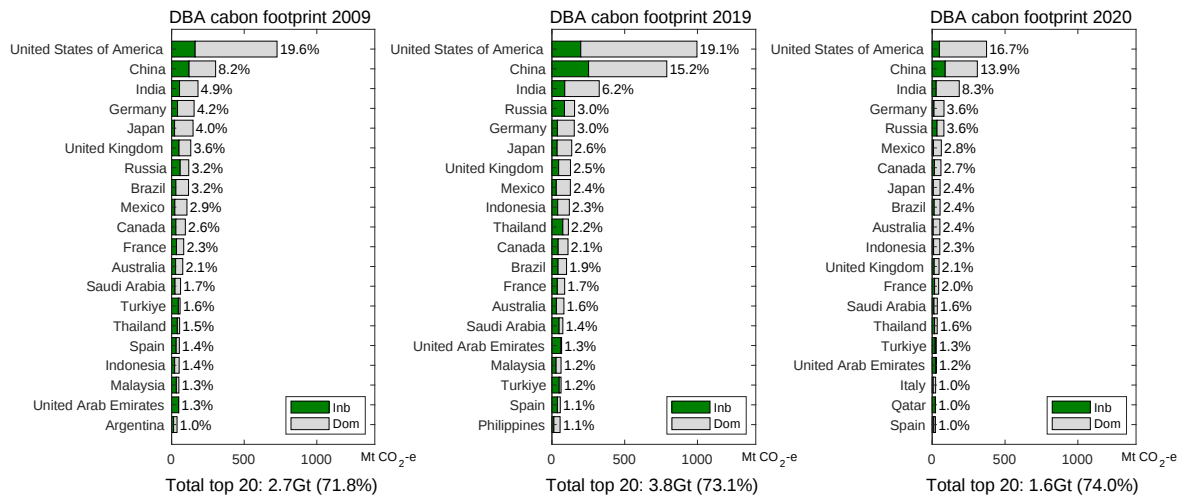
The resident-based accounting (RBA) carbon footprint of the top 20 countries accounts for nearly three-quarters of the total tourism carbon footprint in 2009, 2019, and 2020. This concentration highlights the disproportionate impact of a few major countries on global tourism emissions. The USA consistently holds the top position, followed by China in second place. Notably, China's tourism carbon footprint doubled from 2009 to 2019, reflecting the rapid growth of its tourism sector and the associated environmental challenges.



Supplementary Figure 5. Tourism carbon footprint for top 20 countries from the Residence-Based Account (RBA) perspective.

Supplementary Information 4. The destination-based accounting emissions for top 20 countries

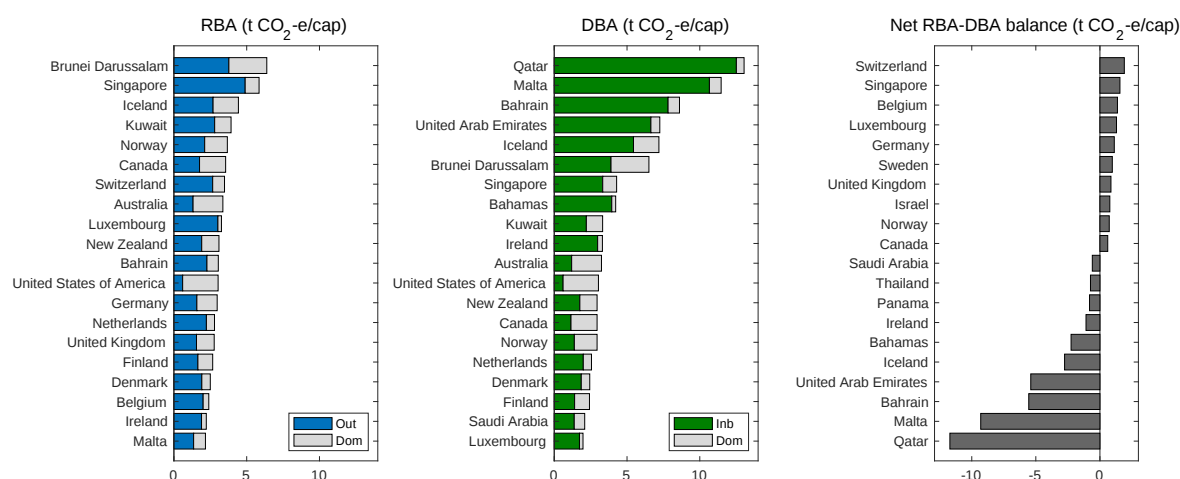
Similar to the RBA perspective, the top 20 countries in the DBA perspective account for nearly three-quarters of the total tourism carbon footprint in 2009, 2019, and 2020. The USA, China, and India have consistently occupied the top three positions during these periods. The high concentration of tourism-related emissions in a few countries highlights the need for targeted policy interventions and sustainability initiatives in these regions. Addressing the carbon emissions of these key destination countries is crucial for making significant progress in reducing the overall environmental impact of global tourism.



Supplementary Figure 6. Tourism carbon footprint for top 20 countries from the Destination-Based Account (DBA) perspective.

Supplementary Information 5. Tourism carbon footprint per capita from top 20 countries

In 2019, Brunei Darussalam, Singapore, Iceland, and Kuwait led in per capita carbon footprint from the RBA perspective, primarily due to their extensive outbound travel. From the DBA perspective, Qatar, Malta, Bahrain, the United Arab Emirates, and Iceland ranked highest in terms of per capita carbon footprint, driven by significant inbound travel volumes. The net balance between RBA and DBA reveals that Switzerland, Singapore, Belgium, Luxembourg, and Germany had a positive net balance, indicating that their outbound emissions from residents exceeded the inbound emissions generated by incoming visitors. Conversely, Qatar, Malta, Bahrain, the United Arab Emirates, and Iceland exhibited a negative net balance, with inbound emissions from foreign visitors surpassing the outbound emissions from residents' travel.



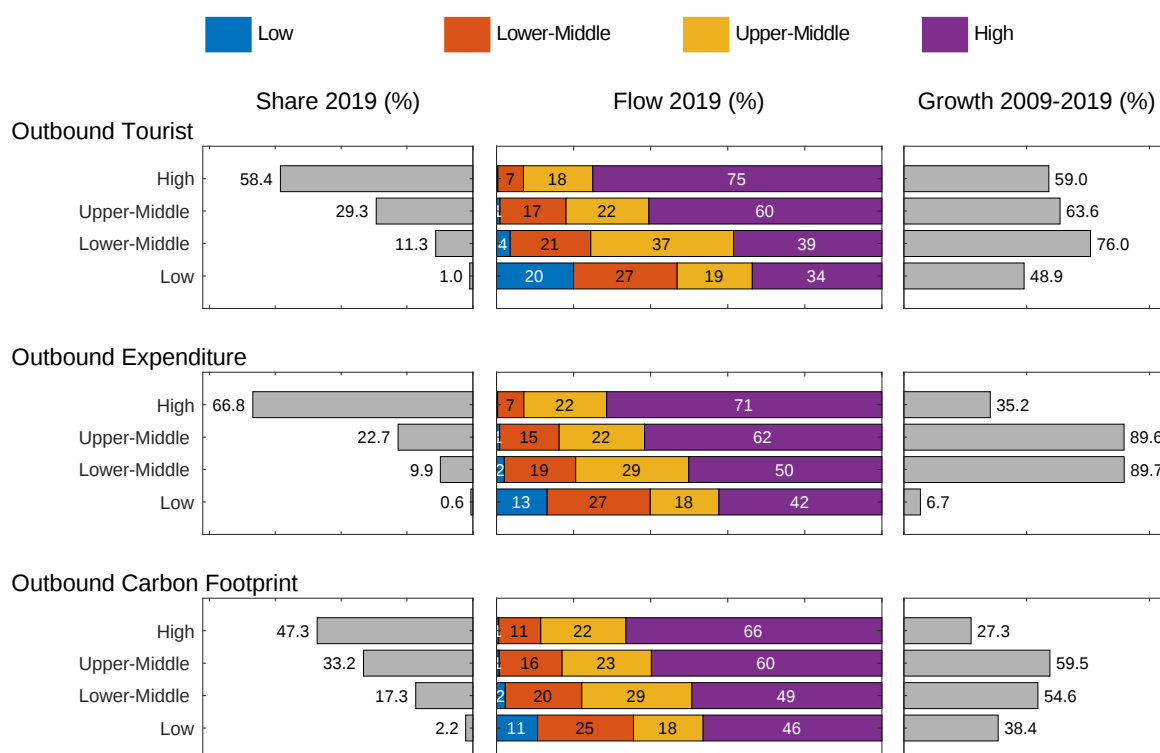
Supplementary Figure 7. Per capita tourism carbon footprint and net RBA-DBA balance.

Supplementary Information 6. Outbound travel by country's income status

In 2019, outbound tourism was dominated by high-income countries, which accounted for 58.4% of all outbound tourists, followed by upper-middle-income countries (29.3%), lower-middle-income countries (11.3%), and low-income countries (1.0%). This trend was also reflected in outbound expenditures and carbon footprints. Most visitors from high-income countries preferred traveling to high-income destinations rather than middle- or low-income destinations.

In terms of growth between 2009 and 2019, there was a remarkable surge in outbound tourists from upper-middle and lower-middle-income countries. Outbound tourists from these two income groups grew by 63.6% and 76.0%, respectively, outpacing the growth of high-income countries (59.0%). This growth pattern extended to outbound expenditures and carbon footprints, with the same groups experiencing the highest growth among all income groups. This suggests that, in the future, the share of outbound tourists, expenditures, and carbon footprints may be largely driven by travellers from upper- and lower-middle-income countries.

The growth in carbon footprints across all income groups, which is lower than the growth in expenditures, indicates improved carbon efficiency across all income groups. Moreover, analysing expenditure and carbon footprints by income group allows for the calculation of carbon intensity. We found that tourism carbon intensity decreases as income rises, with low-income (1.43), lower-middle (1.40), upper-middle (1.02), and high-income countries (0.93) following this trend.



Supplementary Figure 8. Share (left graphs) and flow (middle graphs) of outbound tourists, expenditure, and carbon footprint by income class in 2019. Note: The right graphs display their growth rate from 2009 to 2019.

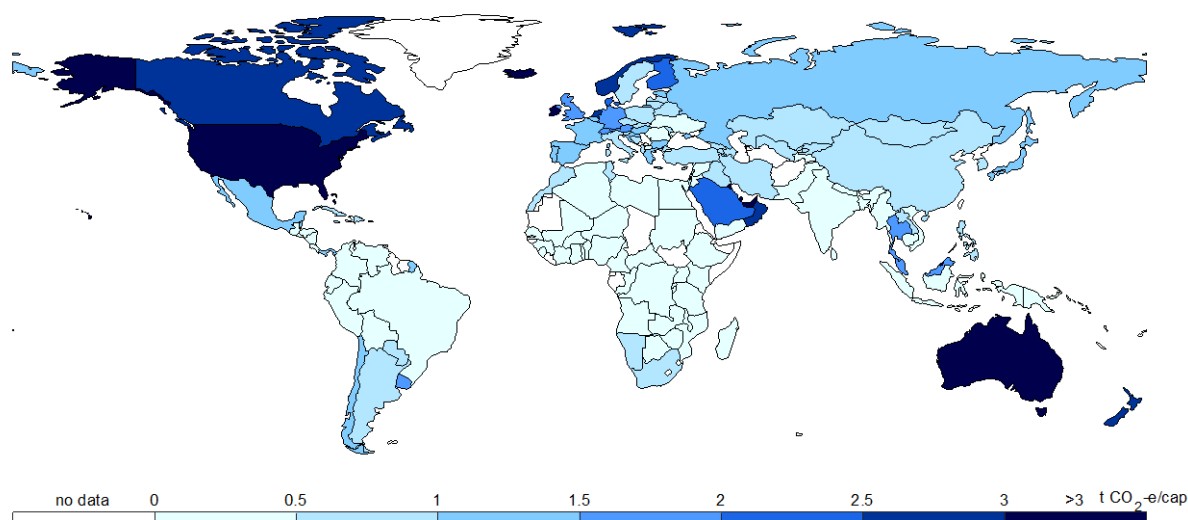
Supplementary Information 7. Tourism carbon footprint per capita globally

Per capita carbon footprint by country shows the distribution of the footprint without being influenced by population size. The following three maps illustrate the tourism footprint by resident-based accounting (RBA), destination-based accounting (DBA), and the net balance between them.

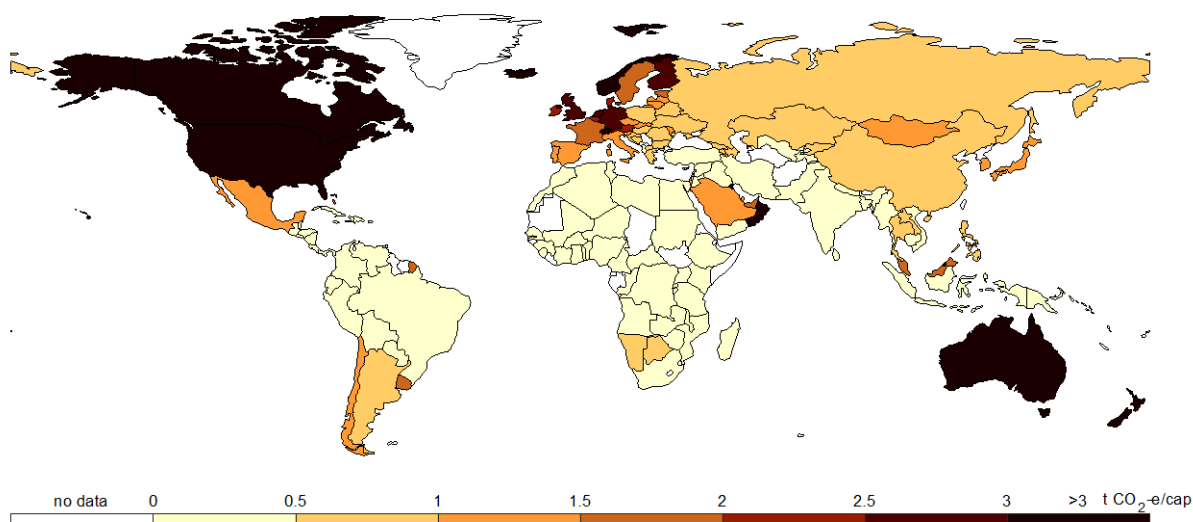
In 2019, developed nations dominated the RBA per capita carbon footprint landscape, with 22 countries exceeding 2.0 t CO₂-e/cap. The top countries included Singapore, Switzerland, Canada, the USA, the Netherlands, Belgium, New Zealand, Norway, Finland, the UK, Australia, and Germany. This confirms the pattern that travel is a luxury good, extensively consumed by residents of very high-income countries.

For the DBA per capita footprint, 20 countries exceeded 2.0 t CO₂-e/cap due to high levels of inbound and domestic tourism activities. These countries are generally popular tourist destinations with a significant share of international tourists. This group includes small popular nations like Brunei Darussalam, Iceland, and Malta, as well as Middle Eastern nations such as Kuwait, Bahrain, Saudi Arabia, and the United Arab Emirates.

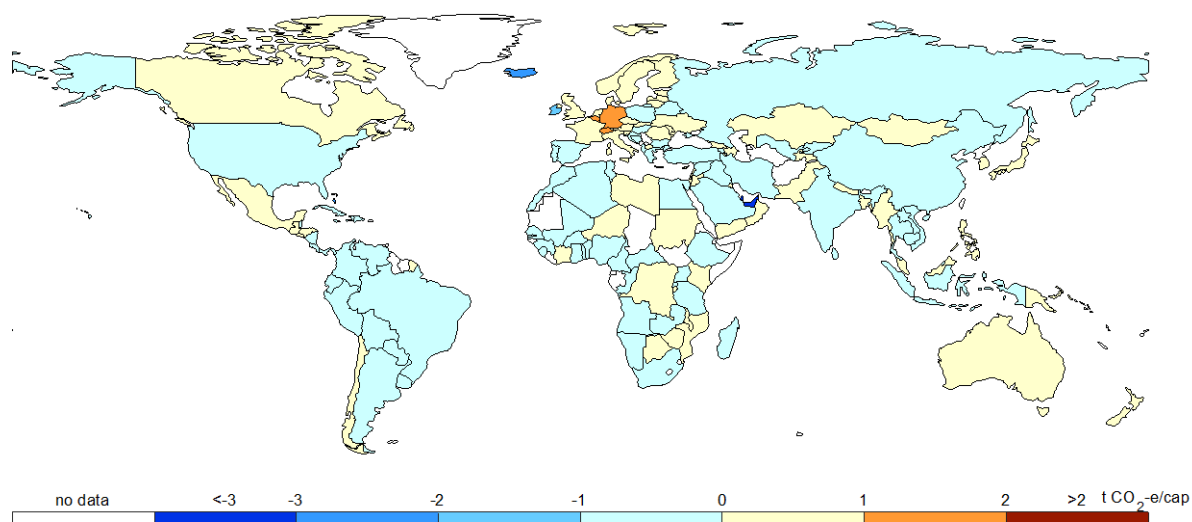
In 2019, around 60% of countries had a negative net RBA-DBA balance (inbound carbon footprint exceeding outbound carbon footprint), while 40% had a positive balance (outbound carbon footprint exceeding inbound carbon footprint). This indicates that most countries are net destinations, receiving a larger volume of inbound tourism than their residents' outbound travel, while relatively fewer countries are net origins, driving international travel with a higher demand for outbound travel.



Supplementary Map 1. Global map of per capita tourism carbon footprint from the DBA perspective, 2019.



Supplementary Map 2. Global map of per capita tourism carbon footprint in 2019 from the RBA perspective, 2019.



Supplementary Map 3. Global map of net per capita RBA-DBA balance, 2019.