Flight Quotas Hold the Most Significant Potential for Reducing Carbon Emissions from Academic Travel

Tamara Ben-Ari[1,*], Gaëlle Lefort[2], Jérôme Mariette[3], Olivier Aumont[4], Laurent Jeanneau [5], Alexandre Santerne[6], Aymeric Spiga[7] and Philippe-e Roche[8]

[1] UMR Innovation et transformation des systèmes agricoles et alimentaires, Université de Montpellier, INRAE, CIRAD, Institut Agro, Montpellier, France
[2] CNRS, IFCE, INRAE, Université de Tours, PRC, 37380, Nouzilly, France
[3] Université de Toulouse, INRAE, UR MIAT, F-31320, Castanet-Tolosan, France
[4] IPSL-LOCEAN, IRD/CNRS/MNHN/Sorbonne Université, Paris, France
[5] Univ. Rennes, CNRS, Geosciences Rennes – UMR 6118, 35000 Rennes, France
[6] Aix Marseille Univ, CNRS, CNES, LAM, Marseille, France
[7] Laboratoire de Météorologie Dynamique (LMD/IPSL), Sorbonne Université, CNRS, École Polytechnique, École Normale Supérieure
[8] Univ. Grenoble Alpes, CNRS, Institut NEEL - F-38042 Grenoble, France

E-mail: Mail to : tamara.ben-ari@inrae.fr

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Abstract.

The carbon footprint of academia has become a pressing concern and an emerging research area, with a particular focus on greenhouse gas emissions from research travels. Mitigation strategies often revolve around encouraging virtual communication and adopting more sustainable transportation modes over short distances. However, these approaches are rarely subjected to rigorous quantitative assessments or meaningful comparisons.

This study analyzes a unique database of about 130,000 travel segments by car, train and plane in 159 research units across diverse disciplines and locations in France. We investigate the patterns and associated carbon footprint of these research travels and explore a diversity of mitigation options, including existing institutional guidelines.

Our analysis shows that air travel overwhelmingly outweighs the carbon footprint of research travel, representing more than 96% of greenhouse gas (GHG) emissions. Intercontinental flights are infrequent (less than 10% of all plane trips) but dominate GHG travel emissions, accounting for over 64% of total emissions. In contrast, domestic and continental flights are the most common but their mitigation potential by modal shift to train is limited (*e.g.*, less than 15% for trips under 1,000 km). Similar reductions can be achieved by targeting a small subset of travels, for example by modulating the frequency of conference attendance. The greatest mitigation potential lies in moderating air mileage, for instance by reducing the number of flights. Strategies focusing on electrification or modal shifts for cars are found to have negligible impact.

In the absence of low-carbon alternatives for long-haul flights, we contend that only comprehensive strategies and policies aimed at moderating air travel distance or frequency can achieve a significant reduction in the GHG emissions from academic travel.

1. Introduction

The Intergovernmental Panel on Climate Change has repetitively emphasized that radical and unprecedented changes in society are needed without delay in order to keep global warming to 2°C, and ideally 1.5°C above pre-industrial levels. However, global annual greenhouse gas (GHG) emissions have continued to increase steadily and unabated, reaching approximately 59±6.6 $GtCO_2$-eq in 2019, which is 54% (21 $GtCO_2$-eq) higher than in 1990 IPCC [2023]. While all sectors of the economy are concerned by target mitigation efforts, a mounting body of evidence affirms the obligation of research and higher education institutions to take ownership of this critical topic [Robinson et al., 2015, Knödlseder et al., 2022, Eichhorn et al., 2022, Vidal et al., 2023, El Geneidy et al., 2021, Eriksson et al., 2022]. Given that scientific practices may, to a certain extent, be linked to the credibility of scientific results [Nordhagen et al., 2014, Cologna and Siegrist, 2020], there are concerns regarding the potential impact of the disparity between rhetoric and actions on undermining science-based paradigm shifts in society [Attari et al., 2019, Sparkman and Attari, 2020, Borgermann et al., 2022].

In recent years, a multitude of universities have issued pledges, long-term commitments, and at times travel guidelines aimed at modal shift over short distances, in the context of reducing greenhouse gas emissions and addressing climate-related concerns Eichhorn et al. [2022]. To design and implement robust mitigation strategies, the initial step is to determine the sources and primary drivers of research-related GHG emissions. However, the carbon footprint of scientific activities remains unquantified in the overwhelming majority of cases. If a growing number of studies assess carbon footprints of research-teaching facilities [Lenzen et al., 2010, Larsen et al., 2013, Filimonau et al., 2021], most of these studies are limited to scopes 1 and 2 (*i.e.*, locally produced emissions and indirect emissions related to energy production, respectively) and rarely consider purchases or business travel and commuting, which belongs to scope 3 [Valls-Val and Bovea, 2021, De Paepe et al., 2023, Larsen et al., 2013]. Additionally, these studies are most often conducted at a local scale (*i.e.*, within a university, research unit, department, or a single institution), and the methods used to calculate induced emissions vary in terms of boundaries, tools, or models, making their inter-comparison extremely challenging [Valls-Val and Bovea, 2021, Helmers et al., 2021]. Consequently, making extrapolations or generalizations is difficult, which further complicates the development of effective reduction policies.

Air travel is an important, conspicuous, unequal, and increasingly discussed source of GHG emissions in research and academia Kreil [2021a], Katz-Rosene and Pasek [2023]. A plethora of pledges have emerged within the research community advocating for the reduction of air travel usage (e.g., Fox et al. [2009], Urai and Kelly [2023]). Available published estimates suggest that the carbon footprint of air travel within academia likely greatly exceeds its relative importance compared to the average individual at the national level Wynes et al. [2019], Ciers et al. [2018]. But, a comprehensive large-scale assessment of the weight of academic air-travel and the means to decrease it is still lacking.

In 2020, *GES 1point5*, an online open-source software, was introduced by *Labos 1point5* Ben-Ari [2023] for estimating GHG emissions at the scale of research units [Mariette et al., 2022-09]. Widely adopted in France, *GES 1point5* facilitates the creation of a nationwide database of research carbon assessments. Our study is built upon a subset of this extensive database, featuring over 130,000 verified staff travel records in 159 research units in 2019 across France.

First, we analyse the characteristics and disparities of professional travels and associated carbon footprints across disciplines and locations considering air, train and car travels. Based on this inventory, we explore the potential of a set of GHG emission reduction options spanning from technological or modal shifts to alternative options based on air-travel moderation options. We compare and combine mitigation options to achieve ambitious GHG reductions.

2. Material and Methods

2.1. The GES 1point5 database

GES 1point5 is a free and open-source software designed to assess GHG emissions associated with energy consumption, commuting, purchases, professional travels, refrigerant gases, and digital devices at the research unit level. In France, research units are social structures involving various public and semi-public institutions (including universities), composed of a few dozen to several hundred of personnel working on common topics. In the *GES 1point5* database, the number of staff per research unit exhibits a range from 6 to 688, with an average of 124 staff members per unit (median = 98). When necessary, GHG emissions are normalized to their number of staff members. To assess per-capita quantities, professors and associate professors are assigned a weight of 0.5 to reflect the equal distribution of their working time between teaching and research.

Our analysis focuses on the year 2019, predating the unique pandemic conditions of 2020-2021. It examines travel data from $n = 159$ research units encompassing 19,766 staff members representing 59 diverse disciplines, spanning geography, arts, chemistry, and biology. These disciplines are grouped into three overarching research domains[Hcéres, 2016]: LHS for life and health sciences (including ecology and agronomy; $n = 67$), ST for science and technologies (including environmental sciences; $n = 100$), and HSS for human and social sciences ($n = 27$). Note that

30 research units are affiliated with more than one broad research domain.

2.2. Travel-induced emission

Our database compiles information from 137,081 research trips or single travel segments. Each trip or segment is sanitized to prevent data entry issues, following these guidelines: plane trips with distances below 100 km are excluded, while car and train trips exceeding 2000 km and 4000 km, respectively, are also removed. Among various transportation modes, only "plane," "train," and "car" are considered, as the combined emissions from other transportation modes, including taxi, intercity bus, tram, subway, and ferry, is found to account for less than 2% of total travel-related emissions. When necessary, the domestic travel segments considered for France are limited to mainland France due to the absence of a train alternative in overseas territories .

GES 1point5 travel module requires inputting departure, destination, transport mode and an in France/outside France specification. Orthodromic distance is calculated from geonames database coordinates GeoNames [2023] and corrected to account for the average detour, ×1.3 for cars, ×1.2 for trains [Ballou et al., 2002, Héran, 2009] and +95 km for aircrafts following EN 16258. Henceforth we use *distance* to refer to this corrected distance. Emission factors used in this study are presented in Table 1. According to [Lee et al., 2021], up to two-thirds of the net warming effects of aviation result from non-CO_2 factors, primarily contrails. This study adopts the more conservative official recommendation from ADEME, which employs a Radiative Forcing Index of 2, resulting in non-CO_2 emissions contributing 45% to the overall emission factor for air travel.

2.3. Travel motives

For each travel segment, a motive can be indicated among research management, teaching, seminar, conference, field trip, collaboration and contains overall about 66% missing data. Motives are filled by administration staff which can refer to an "unknown" category for a motive that does not fall in the previously cited categories. In practice, unknown and missing categories are used interchangeably. We focus only on the n = 58 units with at least 80% of informed motives with the hypothesis that these research units performed a careful declaration of travel motives.

Mode	**Description**	Distance (km)	**Emission factor (gCO_2-eq/km)**
plane	Short haul, with contrails	< 1000	258.2
plane	Medium haul, with contrails	1000 - 3500	187.5
plane	Long haul, with contrails	> 3500	152
train	TGV high speed train	> 200	2.3
train	TER regional train	≤ 200	18
train	Mixed train		16
train	International train		37
car	Private car, average fleet, medium engine		215.6

Table 1: Emission factors for each transport mode, extracted from [ADEME, 2020]. The carbon footprint of each travel segment is obtained by multiplying its distance with the corresponding emission factor. Train factors differ between countries. Within France, the *TGV high-speed train* emission factor is used for distances exceeding 200 km and the *intercity train (TER)* factor otherwise. The *international train* emission factor corresponds to travels outside France. When trips involve either a French origin or destination, emissions are determined by the *mixed train* factor. The emission factor for both private and research-unit-owned cars aligns with ADEME category *Private car, average fleet, medium engine.* Car travel may also encompass missions conducted using vehicles owned by research units, evaluated separately in regulatory assessments.

3. Analysis of the carbon footprint of research travels

The *GES 1point5* database lists six major sources of GHG emissions among which research travel accounts for an average of about 25% (median=22, sd=17) of the carbon footprint for the 73 research units that provided a complete assessment for 2019. In 25% (alt.75%) of these research units, professional travels amount to less than 10% (alt. 33%). In only about 11% of these research units is travels predominant (*i.e.*, above 50%) in their total carbon footprint.

3.1. Global picture: a overwhelming contribution of aviation

GHG emissions from the 137,081 travel segments in our database total 26,900 tons CO_2-eq, equivalent to roughly 1.36 tons CO_2-eq per person. Air travel constitutes approximately 83% of the total distance covered, while train and car account for 14% and 3%, respectively (excluding vehicles owned by research units). Even so, air travel contributes to about 95.7% of the overall travel-related GHG emissions, whereas train and car contribute 0.6% and 3.7%, respectively. Even when excluding the impact of contrails on radiative forcing, air travel still contributes to over 90% of all travel emissions. Consequently, this finding suggests that, on average, a simplified greenhouse gas emission assessment for travel can be performed using air travel as a representative proxy for all forms of travel.

3.2. The intersection of transportation modes and distance

Figure 1 displays the distribution of travel frequency (right panel) for each mode of transportation. Boxplots depict the distribution of traveled distances per mode, with key statistics presented in Table 2. The median of the distribution of distances traveled by air is about 1,100 km and about 470 km for trains, with a few one-way trips extending beyond 1,000 km, typically to neighboring European countries. Car travel covers comparatively shorter distances and occurs less frequently with a median value of approximately 115 km. Interestingly the interquartile ranges are nearly adjacent among the three transportation modes (see Table 2), indicating that a quarter of the car and plane trips fall within a distance range where train travel is a common means of transportation. This suggests a potential for mitigation through modal shifts from car to train and from plane to train, which will be assessed in the following section.

The left panel of Fig. 1 displays the corresponding GHG emissions. The predominance of red underscores the overwhelming contribution of GHG emissions from planes compared to cars and trains. Air travel emissions exhibit a nearly bimodal distribution corresponding to flights in France or in close neighbouring countries (first peak around 800km) and intercontinental flights (second peak around 10,000 km). Table. 2 shows that half of train (alternatively car) GHG emissions are concentrated between 1 to 2 kg CO_2-eq (alt. 11 to 48 kg CO_2-eq) per trip). In contrast, plane emissions are notably higher, with median emissions per trip of 235 kg CO_2-eq, and the two distance peaks corresponding to 200 kg CO_2-eq and 1.4 tons

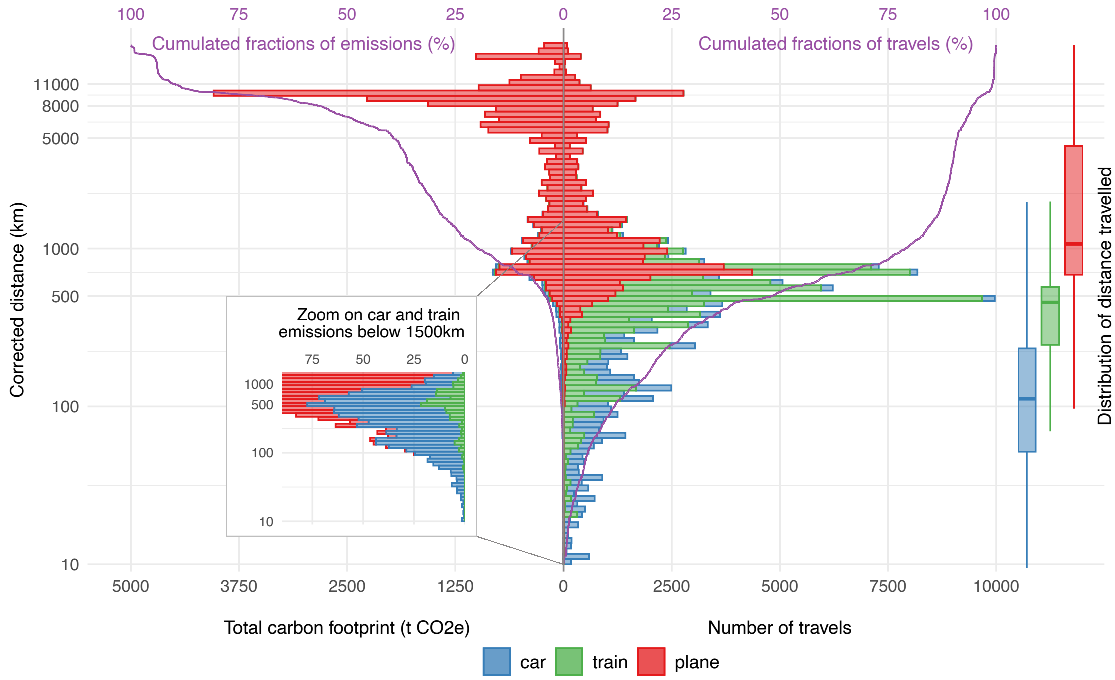

Figure 1: Histograms of travel distances (right) and associated GHG emissions (left) for car (blue), train (green) and plane (red) travels from 137,081 academic travels in 159 research units in France in 2019. Boxplots whiskers extends to $\pm 1.5\times$ the inter-quartile range) independently for each travel modality. The insert is a zoom of the distributions of GHG emissions for cars and trains below 1500 km. Cumulative percentage of the number of trips and GHG emissions are presented as bold purple continuous lines.

CO_2-eq. Continuous lines in Fig. 1 illustrate that intercontinental flights, typically over 3700 km (alt. 5000 km) amount to about 10% (alt. 9%) of the number of travels but contribute to as much as 64% (alt. 61%) of their emissions.

3.3. Research travels motives

We analyze a sub-sample of 58 research units that submitted assessments in which at least 80% of motives are informed (see methods). Adding up all distances and modes of transport, conferences represent a substantial and dominant share of the

Mode	Trip distance (in km)			
	mean	median	lower quartile	upper quartile
car	185	116	54	240
train	443	467	253	584
plane	2961	1091	699	4513
Mode	**GHG emissions (in kg CO_2-eq)**			
	mean	median	lower quartile	upper quartile
car	37	24	11	48
train	3	2	1	2
plane	499	235	181	685

Table 2: Statistics of travel distances and GHG emissions.

motives in our sub-sample (i.e, 28.5% of travels) or 38% of total travel-related GHG emissions. Collaborations represent about 18% of the trips and 19% of total GHG emissions and field studies amount to 8 and 8.5% respectively. Seminars (i.e., oral presentations in other research units) account for about 6% of the total motives in our sub-sample or 4% of total GHG emissions. Trips undertaken for research management purposes amount to 9% of trips but 3.5% of total GHG emissions and teaching about 3% of trips and GHG emissions. An independent assessment of travel motives is accessible via the national *Labos 1point5* survey (among a subsample of 2777 research personnel, see supplement) conducted in 2020 for year 2019. The survey exhibits coherent results with conferences representing about 40% of travel purposes, visits (or collaboration) 15%, fieldwork 8% and teaching 7%.

All transport modes considered, conferences and collaborations are associated with the largest total averaged round trip travelled distances in our database (about 1695 km for both), followed by teaching (about 1480 km), field work (1345 km), seminars (985 km) and research administration (below 665 km). Yet, average air-travel distances per motive in the database are the largest for field work with about 4765 km, about 3700 km for teaching, about 3060 km for conference attendance and about 1915 km for research administration. Comparatively, the *Labos 1point5* survey data shows an average plane round trip distance of 5200 km for field studies, 3600 km for teaching and about 3400 km for conference attendance. Research management/administration items total about 1960 km on average which is also consistent with our analysis.

As illustrated in Fig. 2, the relative distribution of motives versus travel distance does not show any marked dependence with the distances, with the exception of field studies, somewhat more prevalent above 3000 km, and travels for management and administration, more prevalent under 1000 km. Conferences, followed by collaborations, are the dominant motives of travel across 8 representative distances bins. However, the 3000-5000 km bin which roughly corresponds to North Africa and the Balkans, Central Asia and Eastern Russia, exhibits a dip in the density of travels (see Fig. 1).

3.4. Differences across research domains

Our database informs a list of 59 research disciplines, aggregated into three large research domains. We focus on the 129 research units who are affiliated with only one of the three broad domains considered here. Among these, the relative share of each large domain is unequal with science and technologies (ST, n=75 research units) followed by life and environmental sciences (LHS, n=39) and human and social sciences (HSS, n=15). The average distance per trip is approximately 2880 km in ST, 3100 km in LHS and 3000 km for HSS. These research domains exhibit very similar distances distributions which does not justify to segregate plane travelling patterns per discipline, nor to correct our dataset for representativeness bias of the different research domains.

3.5. Disparity of air travel carbon footprints between research units

Fig.3 shows ordered research units with bar width dependent on units sizes, and one colour for each broad research domain to illustrate the between-domains size distribution of units. Units are ordered according to increasing fraction of total per-capita GHG emissions from plane travel. For each domain, Lorenz curves are plotted to illustrate disparity of emissions among research units. Within few percents due to finite-size effect, Fig.3 for example shows that 50% of total GHG are emitted by about 25% of total ST staff working in the most emitting research unit (about 19% and 27% in LHS and HSS respectively). We also estimate that, on average, the 10% of staff working in top-emitting units generate 2.5 times more emissions than if emissions were evenly distributed across all research unit (3.2 times in LHS and 2.3 and 2.4 for ST et HSS respectively).

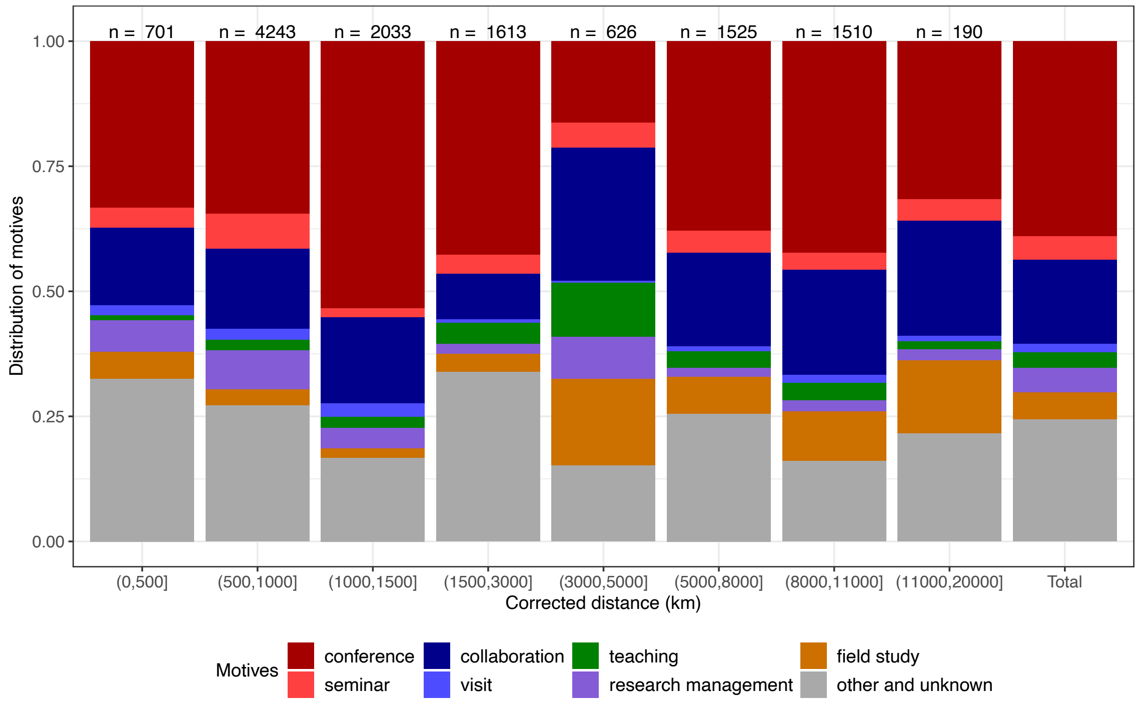

Figure 2: Breakdown of plane travel motives in distance bins distributed between 0 and 11,000 km (in n = 58 research units). Distance bins are constructed to reflect intercontinental distances: approximately 1,000 km corresponds to distances within France or close neighbouring countries, below 5,000 km includes Europe, North America, and Western Asia, 5,000-8,000 km covers South America, Eastern Asia, and the southern part of Africa, and distances from Paris above 11,000 km include the southern part of South America and Oceania. The number of trips in each bin is indicated at the top of the bars. The right-most bar corresponds to the sum of the motives over all distances.

The Gini index is a widely applied indicator of the levels and spread of income disparity Dorfman [1979]. It indicates a deviation from a theoretical uniform distribution in which the per-capita emissions of each research unit are equal (GINI = 0, see Fig. 3 dotted line). Here, the GINI index is 0.36, 0.46 and 0.40 for plane travel only in ST, LHS and HSS respectively. Comparatively, a similar analysis performed from the *Labos 1point5* survey shows a between-individual GINI index for

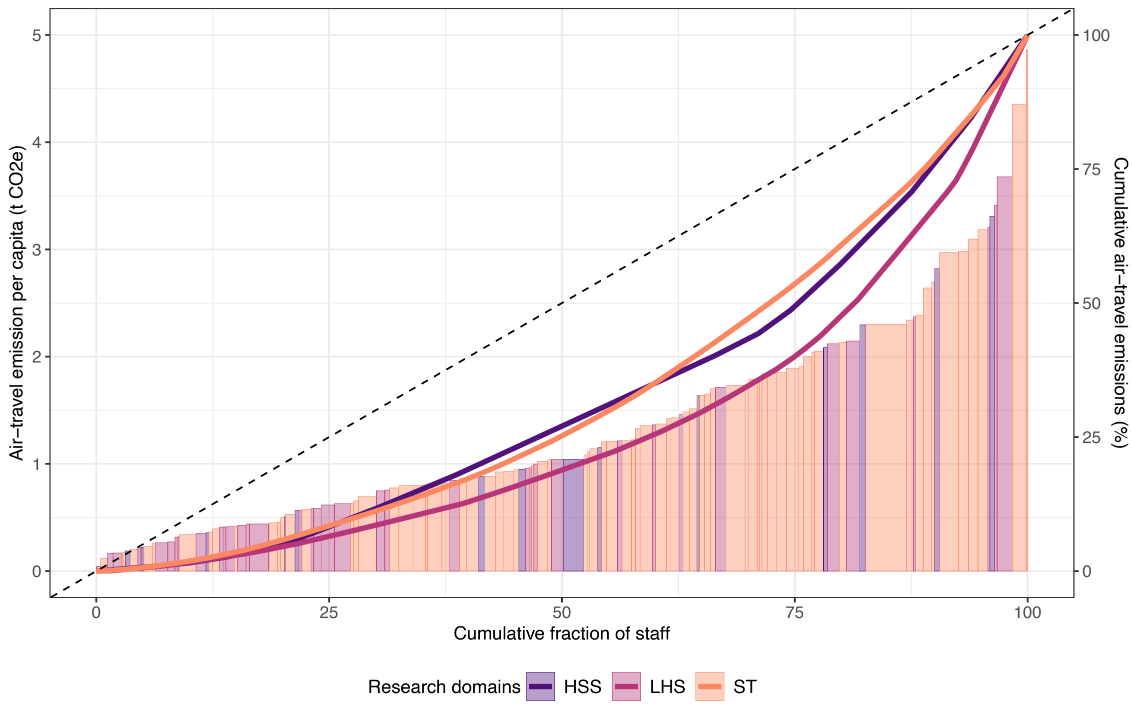

Figure 3: Lorenz curve of cumulative air travel emissions and staff for the three broad research domains. Normalized research units are organized for increasing proportion per-capita GHG emissions. Bars size correspond to the size of research units. The three curves correspond to values in each broad research domain. Dotted line indicate strict equality.

plane travel of 0.5 in Berné et al. [2022]. A value larger than ours is expected since individual disparities are partly smoothed out by the aggregation at unit scale.

4. Mitigation options

This section evaluates the mitigation potential of a series of options. We preferentially explore modal shifts from plane to train and plane travel restrictions, but also address technological shift for fleet vehicles owned by research units. In practice, the implementation of these options involves reassigning a transportation mode to existing trips (modal shift) and/or masking trips (moderation option). We then reassess the total emissions while assuming that the rest of the dataset remains unchanged. The masked trips are randomly selected until the moderation target is achieved, and this process is repeated 1000 times to ensure statistical convergence."

4.1. Modal shift from plane to train

On average, domestic flights cover a distance of 390 km and amount to 4.3% of total travel distances. A complete shift to train for all domestic routes, neglecting from now on the contribution of routes without rail possibility, would reduce travel GHG footprint by 7.6% (or per research unit, a median reduction 4.5%, with an interquartile range of [2.0% - 8.6%]). Interestingly, three routes in continental France concentrate about 36% of air travel domestic emissions (see Fig. 4), highlighting the need from national mitigation policies to address the peculiarities of the air-routes intensively used by academic staff.

Figure 4 explores the GHG mitigation potential of a complete modal shift from plane to train under arbitrary travel distances. By compiling data from the national rail service, we estimate the theoretical effective train speed between major cities, including connections, to be 150 km/h ± 60 km/h. Approximate trip duration are indicated as areas to take into account the uncertainty involved in estimating the duration of travel segments. Figure 4 for example shows that a modal shift under 1000 km or 1500 km (Western Europe) which can be covered in less than 8 to 10h is found to lower the carbon footprint of research-related travels by at most 18% or 21%. Reductions in GHG emissions fall to 12% for a modal shift of less than 6 hours travel time and to less than 8% for a simple ban on domestic flights.

French public service guidelines recommend that all trips that can be completed in less than 2h30 should be undertaken by train. This limit is extended to 4h in research institutional guidelines MESR Ministry [2022]. We estimate that this equates to a reduction of about 0.2% and 3% in total emissions induced by air travel respectively.

4.2. Mitigation potential of car fleet technological shifts

Proposed policies from several research institutions focus on switching vehicles fleet owned by research units to electric or hybrid vehicles. GHG emissions from vehicles are equivalent to about 2.1% of total travel-related GHG emissions in the *GES 1point5* database. Switching a national fleet of vehicles to hybrid car would spare about 14.4% of total vehicles GHG emissions (incl. fabrication) compared with the

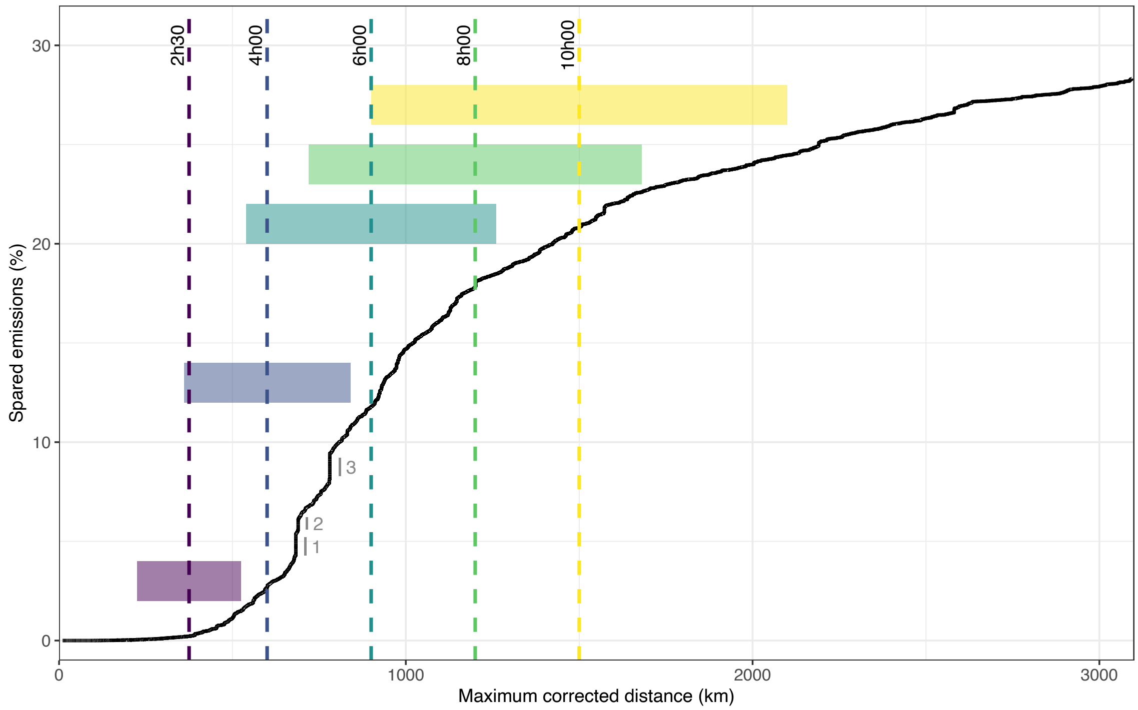

Figure 4: Mitigation potential of modal shift from plane to train as a function of distance. Vertical lines correspond to median time travel by train and rectangles express the uncertainty related to train speed, with 150 km/h ± 60 km/h. The three numbers indicate key routes in France with 1: Paris-Toulouse, 2. Paris-Montpellier and 3. Paris-Nice, contributing respectively to 14%, 7% and 16% of total domestic GHG emission from air travel.

current situation and 49.2% for electric cars. This amounts to 0.3% and 1.1% of total travel-related GHG emissions respectively.

4.3. Moderation options

We compare the mitigation potential of a series of moderation or sufficiency options which can be defined as a set of measures aiming at reducing demand. Here, this translates into avoided travels as opposed to modal shifts in which travelling is taking place but with a more carbon-efficient mode of transport. We first evaluate three implementations of limitations on air travel distance or air mileage quotas keeping all research motives unchanged.

First, if the total flown distance of each research unit decreases by 10% (alt. 25%), the corresponding GHG emissions decrease by 10% (alt. 24%). All research units are impacted.

Second, we apply a cap on flown distances fixed at the per-capita median value of all units, around 5780 km/person/year. The corresponding average GHG footprint decrease is 38% and half of the research units are impacted.

Third, we explore three implementations of a quota on the number of conference and seminar attendance. A 20% reduction of air travel to conferences, would decrease travel-related GHG emissions of about 8%. Halving conference attendance would reduce total GHG emissions by a median of 19%, or by 21% if seminars are halved too. As an indication, a full hybrid mode for all conferences and seminars would equate to a decrease of about 41 % of yearly travel-induced GHG emissions. If all research units limit their conference attendance to the median value across research units (corresponding to about 1 conference every 3 years per person), about 13% of travel induced GHG emissions can be spared. As a comparison, shifting all air travel for research administration to virtual meetings would cut down travel-related GHG emissions by about 3%.

Finally, Air mileage quota involving a halving of distance travelled by plane in each research unit or a per-capita distance limitation close to the between-units median have the potential to reduce GHG emissions by about 40%.

5. Discussion

Mitigation options, and their combination, can be ranked according to their estimated potential relative to total travel carbon emissions. Figure 5 explores the mitigation potential of a range of options focusing on modal shift to train and flight moderation. Moderation options are explored keeping the research-unit distance distribution unchanged (the percentage of reduction is specified in the left of the figure) or by changing distance patterns (the maximum allowable distance or trip occurrence is then specified).

This calls for a few observations. First, in light of the European Community's goal to cut its carbon emissions by 55% in less than a decade to meet the Paris Climate Agreement, it is interesting to combine mitigation options to achieve a halving of travel GHG emissions. Moderation of air-travel can reach or surpass a 50% reduction of emissions by halving the number of flights or the overall distance travelled, or by setting quotas at a below-median distance (*i.e.*, less than 5,800 km) or at a below-median number of average yearly per capita plane trips (*i.e.*, less than 1), all travel motives combined.

Second, keeping air-travel mileage or number of long-haul trips at per-unit median level can achieve close to 50% reduction if combined with a minimum allowable distance travelled by plane above 1,500 km (or 10h of train on average). Reductions of about 20% in air-travel mileage or number of (long-haul) flights are capped under a 35% reduction, including when combined with the most drastic modal shift options. The most stringent conference moderation options with modal shift hardly reaches this level of reduction.

Third, current official guidelines for reducing emissions through a set focused actions in France (as presented for example in MESR Ministry [2022]) show a disconnect between stated ambitions and proposed pathways. The options under consideration target (i) a modal shift when there are 4h train alternatives to air travel, and (ii) restricting car use for distances below 300 km. The combination of these options is here estimated to decrease carbon emissions from academic travel by about 2.2%.

Numerous European universities have issued (often non-binding) guidelines on air travel frequency reduction to raise awareness on the impacts of frequent air travel and encourage its limitationEichhorn et al. [2022], Schmidt [2022], Kreil [2021b]. These include for example reducing travel emissions (*e.g.*, by 20%, 25% or 60% by the year 2025 at the KTH in Sweden, in Cambridge University and at SLU in Sweden, respectively) and modal shift from plane to train based on distance thresholds (*e.g.*, 500, 700 km or 1000 km at the Universities of Groningen, Utrecht and at the HNEE in Berlin), or based on duration thresholds (*e.g.*, 6, 8, 9 and 10 hours at Universities of Gent, Leiden, Groningen and Lausanne, respectively). Note that, to the best of our knowledge, none of these guidelines have relied on thorough assessments of their mitigation potential.

Our results suggest that shifting from plane to train for journeys up to 10h (or 1500 km) which are among the most ambitious reduction plans currently experimented by a handful of universities, are capped at about 20% reduction in travel-induced GHG emissions. A dense ground transport network connects Western European countries suggesting that these findings are representative of many European countries, despite variations in travel-related emission factors. Still, significant benefits can be obtained making it a valuable complementary goal. These include decreasing the ecological impact of airportsGreer et al. [2020], reducing health risks associated with noise exposure(Sainz Pardo and Rajé [2022]) and participating to a shift in the air travel academic culture. A modal shift policy can also promote the efficiency of a flight number quota policy, as discussed below.

Translating mitigation options into a travel policy is not straightforward. Examples within the *Labos 1point5* initiative show that distance quotas policies can imply delicate collective assignments of priorities between travels, considering *e.g.* time spent on-site or the travelling motive. Policies based on flight number quotas are technically simpler to implement, however their performance in reducing emission is contingent upon an effective reduction in the number of long haul flights, and not only short and medium haul ones. To warrant and promote the efficiency of flight-number-quota policies, they can be combined with a (prior) modal shift policy limiting the number of short-distance flights. This effect is expected to be more pronounced than in Figure 5, which is computed with an idealized random reduction of flights. Thus, despite their limited efficiencies, modal shift policies can remain useful to complement a flight-number-quota policy.

Yet, a key finding is the limited relative effectiveness of narrowly scoped mitigation policies that do not comprehensively address the cumulative air travel distance, mostly originating from long-haul flights. Here, we find that travels beyond 3,700 km contribute to 64% of all travel emissions or 66% of air travel emissions. In support, travels from the University of Lausanne also exhibit a bi-modal distribution versus distance with the less frequent trips beyond 3,700 km amounting for 84% of air travel emissionsCiers et al. [2018]. In online data from the University of Edinburgh, travels beyond 3,700,km, though a minority, account for 68% of all travel emissions in 2018-2019 University of Edinburgh [2023].

Prior to the 2020-21 COVID pandemic, hybrid or remote modes of communication and collaboration were largely marginal in academia, but their acceptability has significantly increased, paving the way for a generalization of such solutions. A fraction of air travels are, at least theoretically, substitutable by online virtual or remote exchanges. This typically concerns attendance to conferences Skiles et al. [2022], Klöwer et al. [2020]. It should be noted that if online conferences do have an environmental impact, it has been estimated to be close to negligible with respect to that of an in-person conference (*e.g.*, Tao et al. [2021] Burtscher et al. [2020]). Based on our data, we show that a conference attendance quota fixed at the

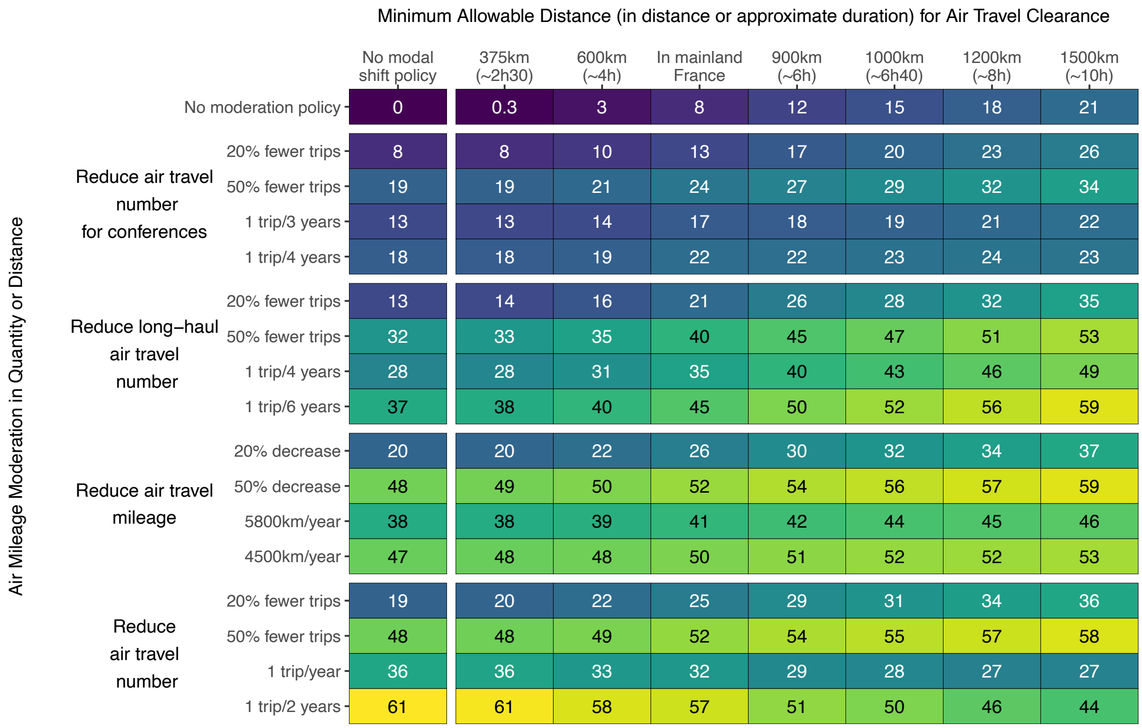

Figure 5: Percentage of total (plane, train, car) travel-induced GHG reductions from single or combined options. Colors represent the intensity in GHG mitigation potential with yellow options offering the greatest potential. Each column corresponds to a specific modal shift policy, characterized by a threshold distance (and average travel time), below which a complete shift from plane to train is assumed.Modal shift options are always applied first. Each line corresponds to a specific air travel moderation policy applied at research unit scale. Moderation options are expressed in missions (equivalent to a round trip) and modal shift are considered per segment (equivalent to a one way trip). Options which correspond to actual per-capita per-year research unit median are presented at the third modality in each moderation option (*i.e.*, 1 conference every 3 yrs, 1 trip every 4 years, 5,800 km and 1 trip per yr).

median per unit attendance reached a potential of about 14% which is roughly equal to a minimum allowable distance for air travel clearance of 1,000 km (*i.e.*, equivalent to a ban of air travel in France and neighbouring countries).

A fraction of plane travel may be more difficult to substitute by other means of transportation or virtual platforms. This mostly concerns long distance field trips. Our database suggests that they represent about 8% of all known travel motives above 1,500 km or 7% of the total carbon footprint of air travel. Discussions within the *Labos 1point5* initiative suggests that field trips often are at the heart of mitigation discussions and one of the feared consequence of reduced access to air travel. While decreasing academic flying related to conferences and networking is an intensive topic of research, questioning of the rationale for fieldwork and the development of reduction strategies are almost absent from academic work Guasco [2022]. The grey literature highlights the emergence of this question and provides examples (1, 2) of how delegation to local staff and the use of new technologies can reduce the carbon footprint of fieldwork. However more research is necessary on this specific aspect of academic flying to understand the constraints in data acquisition and possible substitution by wider use and sharing of existing data.

The array of reasons as to why academics and researcher fly is wide and diverse Bjørkdahl et al. [2022], Tseng et al. [2022]. On an individual level, scientific and personal motivations or career advancement play a key role Kreil [2021a], Eichhorn et al. [2022]. By producing norms, policies and incentives, scientific institutions also generate situations in which individual scientists are trapped between environmental attitudes and everyday practices. This contradictory situation is sometimes referred to as the "knowledge-action gap" Kroesen [2013]. Therefore, the normative context set by institutions in which research is conducted should not be neglected Hopkins et al. [2016], Reyes-García et al. [2022]. For instance, the quest for "scientific visibility" aiming to fit the standards of success as set by policymakers appears to shape practices in favour of more flying Berné et al. [2022].

It is important to note however that ambitious mitigation targets on air travel, although necessary, are insufficient to align research with the objectives of the Paris Agreement since travels amount to approximately 25% of total GHG emissions at the scale of research units. Purchases are often a more important component of research footprint De Paepe et al. [2023] and research infrastructures even more so, specifically in disciplines with very large investments such as experimental physics or astrophysics Knödlseder et al. [2022]. This article focuses on GHG emissions, but it is worth noting that the footprint of any given activity is broader than its impact on the climate. Other essential dimensions include biodiversity loss, pollution, water usage, land utilization, and resource usage in general.

Here, we provide the results of a nation-wide database and show that the limits encountered by moderation policies that do not target air travel distance and frequency. Collective data-informed decisions on the reduction of intercontinental plane use can help bridge this paradox and help avoid relying on the future use of carbon offsetting or expose these institutions to carbon liability.

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Supplementary material - Flight Quotas Hold the Most Significant Potential for Reducing Carbon Emissions from Academic Travel

The present manuscript is a non-peer reviewed preprint submitted to EarthArXiv. The preprint was submitted to Environmental Research Letters (IOP) for peer review.

1. Supplementary Material and methods

1.1. The GES 1point5 database

GES 1point5 is an online open source software which provides a GHG footprint estimation calculator at the scale of research units in France [Mariette et al., 2022-09]. To date, about 830 research units have used GES 1point5 to estimate, at varying levels of completeness, their carbon footprint for at least one calendar year. They have generated over 1600 assessments for years ranging from 2019 to 2022, with 2 research units going back as far as 2010 Ben-Ari [2023]. In 2019, France counted over 1579 public or semi-public research units overall with at least two associated research institutions, also called mixed research units [MESR Ministry, 2020]. Because this number perhaps underestimates the total number of research units, we estimate that the *GES 1Point5* database aggregates between one third and half of all research units in France.

In this analysis, in compliance with *GES 1point5* data policy, we only consider assessments that have been verified and submitted. The submission procedure requires the user to validate each assessment for each source independently and confirm its use for research purposes. The database analysed here hence focuses on 159 research units with a submitted and verified assessment for year 2019. We analyse here 137,081 research trips (or 73,825 total missions with a mission defined as a round trip) carried out in 2019 in 159 research units. Note that some research trips are one way, explaining the disconnect between mission and trip numbers. Note that connecting flights are not informed.

The research units considered in our analysis cover 59 disciplines aggregated into three broad research domains[Hcéres, 2016]. When research units are affiliated to a variety of sub-domains and disciplines, they are asked to report a percentage for each discipline according to its prevalence among staff members. When focusing on travel patterns per broad research domain, we take into account the 129 research units that only report one broad research domain. Note that the between-domain distribution somewhat over-represents environmental sciences and under-represents humanities compared to their actual weight in the French research system. This can be attributed to a larger engagement at individual and research unit scale in disciplines that deal closely with the impacts of climate change on socio-ecosystems, as verified in the *Labos 1point5* survey (see below).

GES 1point5 emission factors are associated with uncertainties, also taken from the same official database [ADEME, 2020]. Uncertainty are generally informed as percentages of emission factors values and include uncertainty in the evaluation of the physical or monetary-based CO_2-emissions but also usage (such as public transport occupancy rate or car speed). These are very often estimated from expert knowledge (com. pers ADEME). Note also that, due to a lack of detailed data, we do not differentiate between ticket classes in plane trips, although business or first-class tickets are rarely used within the French research system.

1.2. National Survey data

We compare our results to those obtained by a nation-wide *Labos 1point5* survey using random sampling, independently conducted between June and December 2020 and sent by email to 30 000 research personnel (regardless of their status or discipline) drawn randomly from a national staff directory. The survey database comprises 6724 answers from scientists and staff from all research disciplines in France. Here, we specifically focus on the 2777 respondents who provided their number of return flights and their discipline, statuses and travel motives. A description of the content of the survey can be found here Blanchard et al. [2022] and the data are available upon request here Bouchet-Valat et al. [2022].

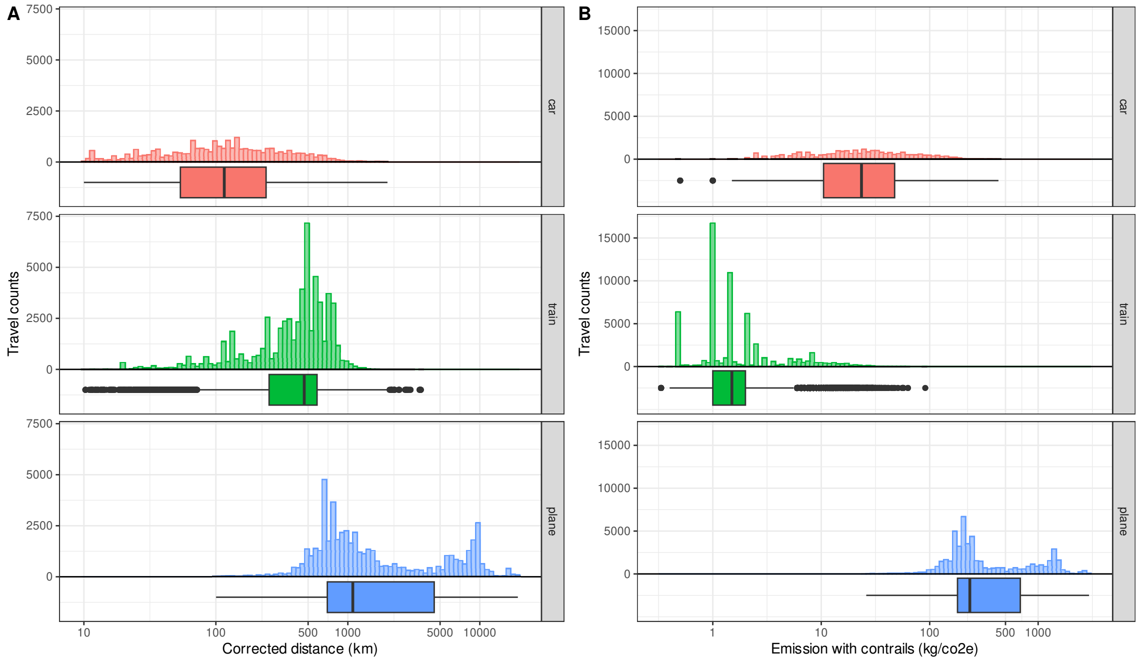

Figure 1: Histograms of log of distances (left) and log of associated GHG emissions (right) for car (red), train (green) and plane (blue) travels for 137,081 academic travels in 159 research units in France. In each subplot, data are presented both as histograms (top) and boxplots (bottom, whiskers extends to ±1.5× the inter-quartile range) independently for each travel modality.

2. Supplement figures

Figure 1 details the distance (km) and associated emission (kg CO_2-eq) distributions for travel by car, train and air. The distances shown are adjusted geodesic distances (*i.e.*, between the location of departure and the location of arrival) to take into account the detours associated with the different modes of transportation. Note that the use of a logarithmic scale on the x-axis is chosen to help highlight the wide range of relevant distances, but the areas beneath the distribution curves of each transport mode are no longer proportional to a relative contribution.

To visualize the contribution of each distance traveled to cumulated CO_2 emissions, we show the relation between log bins of distances travelled, CO_2 emissions and the relative cumulated CO_2 emissions (see Figure 2). The left axis corresponding

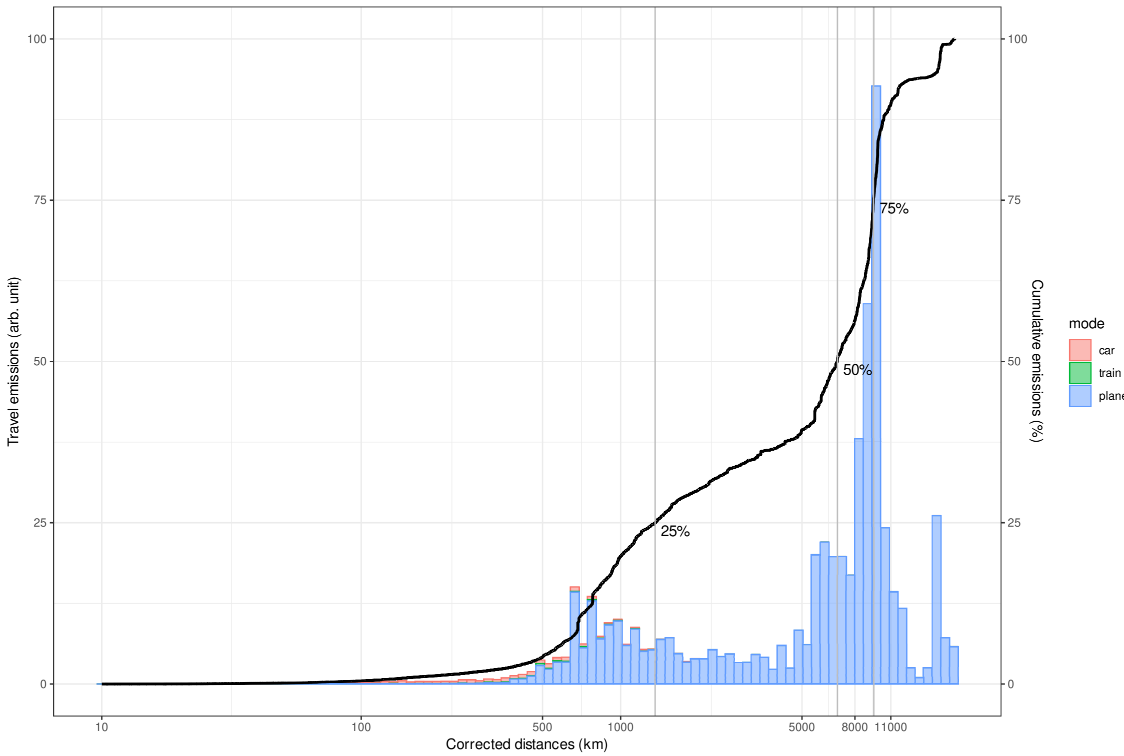

Figure 2: GHG emissions as a function of bins of distances in km travelled by plane. The left y-axis is constructed such that the surface of the bars are proportional to corresponding CO_2-eq emissions, despite the logarithmic scale of the x-axis. The cumulated CO_2-eq emissions of plane travels is represented as a continuous black line (right y-axis). Vertical grey lines are indicated to delineate the fraction of travels with 25, 50 and 75% of cumulative travel emissions (1358, 6850 and 9460 km respectively). In this representation, CO_2-eq emissions from train and car are accounted for using stacked bars, but appear negligible.

to travel emissions is normalized such that the surface associated with each bin is proportional to the corresponding CO_2-eq emissions. While the most frequently travelled distance translates into the largest share of CO_2-eq emissions for car and train (with about 33.5 and 45% of total CO_2-eq emissions for these modes respectively), the situation is different for air travel.

Figure 2 shows that air trips below 1000 km - which is the most frequent travelled distance (see **??**) - amount to only about 15% of the total carbon footprint of air travel (*i.e.*, including car and train GHG emissions). Plane trips shorter than 5,000 km, or around 76% of trips, correspond to only 37% of cumulated CO_2-eq emissions. The majority of GHG emissions from plane travels in academic research are concentrated beyond 5,000 km (*i.e.*, in long-haul intercontinental flights). The cumulative CO_2-eq emissions show that the largest contribution to total CO_2-eq emissions from air travel (*i.e.*, 51%) is between 5,000 and 11,000 km with a peak between 8000 and 11000 km. This has strong implications for the mitigation strategies outlined in the main manuscript.

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