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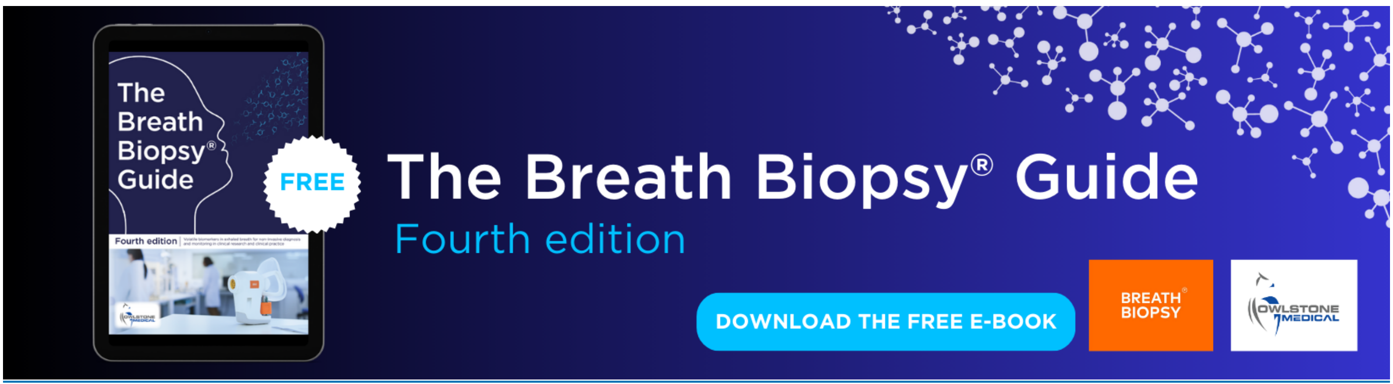

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Flight quotas outperform focused mitigation strategies in reducing the carbon footprint of academic travel

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Abstract

The carbon footprint of academia has become a prominent concern and a burgeoning research area, with a notable focus on greenhouse gas emissions (GHG) from research-related travels. Mitigation strategies often promote alternatives, such as developing virtual communication or adopting sustainable transportation modes for short distances. While more ambitious strategies involving the transformation of research practices are increasingly discussed, these mitigation solutions 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 entities across a wide array of disciplines in France. We investigate the patterns and associated carbon footprint of these research travels and explore a diversity of mitigation options. Our analysis shows that air travel overwhelmingly outweighs the carbon footprint of research travel, representing more than 96% of 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 1000 km). Similar reductions can be achieved by targeting a small subset of travels, for example by modulating the frequency of conference attendance. The greatest and possibly most robust mitigation potential lies in combining modal shift with moderating air mileage (e.g. reducing travelled distance or number of flights). Strategies focusing on electrification or modal shifts for cars, proposed in official guidelines, 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 which include moderating air travel distance or frequency can achieve a robust significant reduction in the GHG emissions from academic travel.

1. Introduction

The Intergovernmental Panel on Climate Change has repeatedly emphasized that radical and unprecedented changes in society are needed without delay in order to limit 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 must cut GHG emissions to comply with national legislative frameworks and nationally determined contributions, 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, El Geneidy *et al* 2021, Eichhorn *et al* 2022, Eriksson *et al* 2022, Vidal *et al* 2023).

Among frequently cited reasons for expecting academia to actively participate in ambitious climate change mitigation efforts are raising concerns about the impacts on the credibility of scientific results of a gap between rhetoric and actions (Nordhagen *et al* 2014, Cologna and Siegrist 2020). A situation which may undermine science-driven paradigm shifts in society (Attari *et al* 2019, Sparkman and Attari 2020, Borgermann *et al* 2022). Another reason pertains to the advantages of embracing the challenge of experimenting with transition dilemmas and controversies (Eichhorn *et al* 2022).

In recent years, the climate transition in universities has manifested through the issuance of net-zero pledges, the establishment of long-term commitments, and the provision of guidelines, such as those addressing plastic usage, energy production on campus or, more recently, travel behaviors. These guidelines or communications are rarely adjoined by an identification of the sources and primary drivers of research-related GHG emissions. In other words, mitigation strategies do not, in the overwhelming majority of cases, rely on a comprehensive and robust quantification of academia's carbon footprint.

While 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 (Larsen *et al* 2013, Valls-Val and Bovea 2021, De Paepe *et al* 2023). 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 (Helmers *et al* 2021, Valls-Val and Bovea 2021). Consequently, extrapolations or generalizations are difficult, further complicating the development of effective reduction policies.

Among all sources of GHG emissions in research and academia, air travel stands out as conspicuous, unequally distributed, and increasingly debated (Braun and Rödder 2021, Kreil 2021a, Hölbling *et al* 2023, Katz-Rosene and Pasek 2023). A plethora of pledges have emerged within the research community advocating for the reduction of air travel (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 average individual values at the national level (Ciers *et al* 2018, Wynes *et al* 2019). However, a comprehensive large-scale assessment of the carbon weight of academic air-travel and the means to decrease it is still lacking.

In 2020, *GES 1point5* (Mariette *et al* 2022-09), an online open-source software, was introduced by the *Labos 1point5* project (Ben-Ari 2023) for estimating GHG emissions at the scale of research units i.e. entities roughly equivalent to research departments, see methods. 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 for 2019 from 159 research units across France.

First, we analyse the characteristics and disparities of professional travels and associated carbon footprints 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. Research units are entities somewhat equivalent to research departments. They are composed of various types of personnel (i.e. engineers, researchers, professors, doctoral students, administrative staff, etc) employed by universities or various public and semi-public institutions, who also provide base funding. These units typically consist of a few dozen to several hundred individuals working on common topics or research objects. Large research infrastructures are most often shared among research units to spread costs. Research units are directed by one or a collective of scientists for 5 year mandates and are nationally evaluated every 5 years.

In the *GES 1point5* database, the number of staff per research unit ranges from 6 to 688, with an average of 124 staff members per unit (median = 98). To assess per-capita quantities, GHG emissions are normalized to the number of staff members. Professors and associate professors are assigned a weight of 0.5 to reflect the equal distribution of their working time between teaching and research and avoid double

Table 1. Emission factors for each transport mode, extracted from ADEME (2020). Emission factors for the last four entries have been derived from Mariette *et al* (2022-09). 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. Note that each trip is counted one time, regardless of the number of persons in the car.

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

counting emissions attributable to teaching facilities outside research units.

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 different research disciplines, spanning geography, arts, chemistry, physics or 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. Travel segments refer to the journey between point A and point B, which constitutes a one-way trip. A round trip consists of at least two segments (also referred to as 'a mission' in the manuscript). Data cleaning was performed 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 entering departure, destination, transport mode and an in France/outside France specification. Orthodromic distance is calculated from the geonames database coordinates (GeoNames 2023) and corrected to account for average detours, ×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 follows the official recommendation of the French Environment and Energy Management Agency (ADEME), the organization responsible for maintaining the Carbon Footprint Database, which incorporates comprehensive emission factors for various activities. Therefore, we utilize a Radiative Forcing Index of 2, leading to 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 solely on the $n = 58$ units with at least 80% of informed motives, operating under the hypothesis that these research units provided a thorough declaration of travel motives.

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.

Table 2. Statistics of travel distances and GHG emissions.

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

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 GHG emission assessment for academic 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 1100 km and about 470 km for trains, with a few one-way trips extending beyond 1000 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 figure 1 displays the corresponding GHG emissions. The predominance of red underscores the overwhelming contribution of GHG emissions from air travel compared to ground-based travel. Air travel emissions exhibit a nearly bimodal distribution corresponding to flights in France or in close neighbouring countries (first peak around 800 km) 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 CO_2-eq. Continuous lines in figure 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 associated GHG 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 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% of trips and emissions, 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 purpose is accessible via the national *Labos 1point5* 2020 survey (among a sub-sample of 2777 research personnel) conducted for year 2019, see supplement. The survey exhibits coherent declarations 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

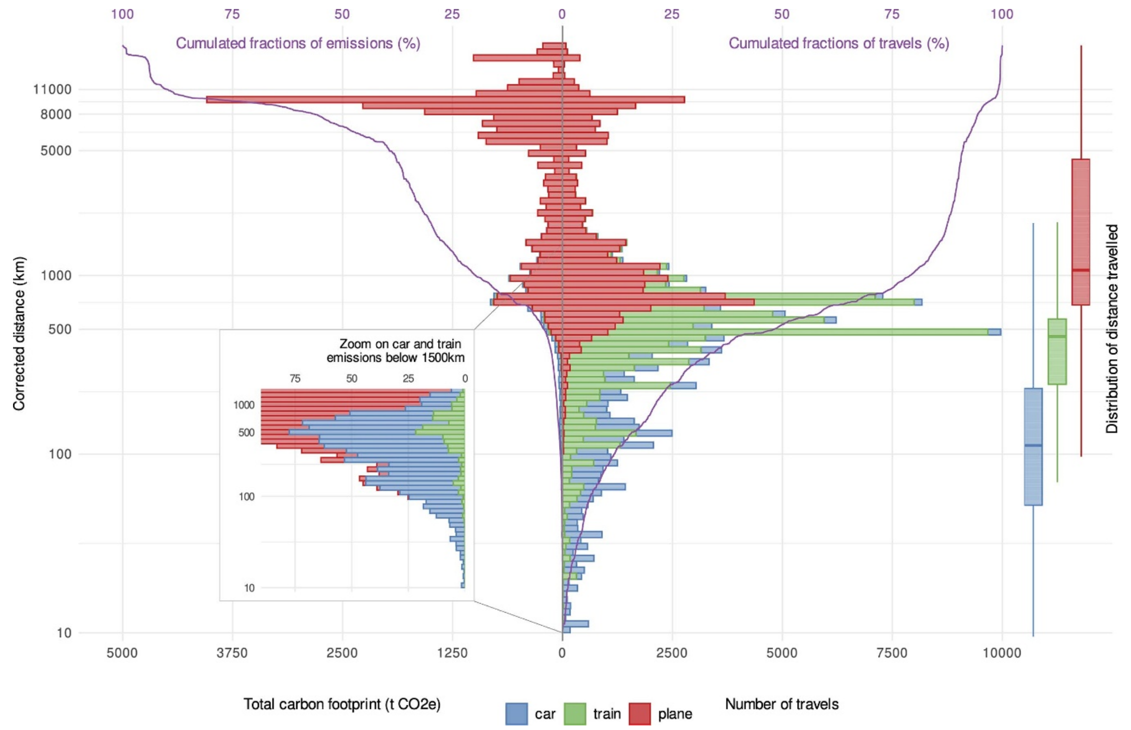

Figure 1. Histograms of travel distances (right) and associated GHG emissions (left) for car (blue), train (green) and plane (red) travels from 137 081 academic travels in 159 research units in France in 2019. Boxplots whiskers extends to $\pm1.5\times$ the inter-quartile range) independently for each 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.

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. Travelling for research management/administration corresponds to about 1960 km on average in the survey, which is also consistent with our analysis.

As illustrated in figure 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 figure 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. The relative distribution of research units across the three broad domains is not uniform. The majority of research units are affiliated with the broad research domain referred to as science and technologies (ST, $n = 75$ research units), followed by life and health sciences, which include ecology and agronomy (LHS, $n = 39$), and human and social sciences (HSS, $n = 15$).

The average distance per trip (alternatively, average number of trips per capita) is approximately 2880 km (alt. 7.4) in ST, 3100 km (alt. 6) in LHS and 3000 km (alt. 8.4) for HSS. These research domains also 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. Note however that due to small number of research units in HSS, estimated average distances and number of trips are more uncertain than in the two other broad domains.

3.5. Disparity of air travel carbon footprints between research units

Figure 3 shows ordered research units with bar width dependent on units sizes, and one colour for each broad research domain to highlight the between-domains size distribution of units. Units are ordered according to increasing fraction of total per-capita

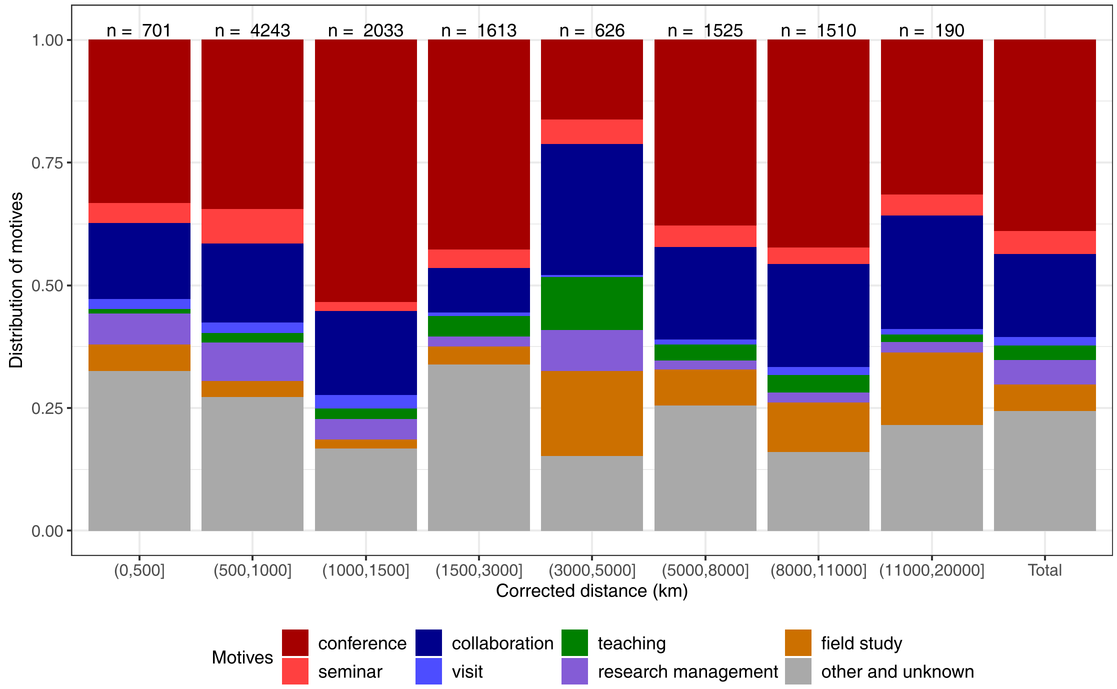

Figure 2. Breakdown of plane travel motives in distance bins distributed between 0 and 11 000 km (in $n = 58$ research units). Distance bins are constructed to reflect intercontinental distances: approximately 1000 km corresponds to distances within France or close neighbouring countries, below 5000 km includes Europe, North America, and Western Asia, 5000–8000 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 proportion of motives over all distances.

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, figure 3 for example shows that 50% of total GHG are emitted by about 28% of total ST staff working in the most emitting research unit and about 19% and 25% 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).

The Gini index is a widely applied indicator of the levels and spread of income disparity (Dorfman 1979), with values close to about 0.3 in France. The GINI index indicates a deviation from a theoretical uniform distribution. The closer to 1, the higher the level of inequality, and the closer to 0, the higher the level of equality (GINI = 0, see figure 3 dotted line). We estimate its value for each broad research domain to capture between-units emissions heterogeneity. We find that the GINI index for travel-induced GHG emissions, computed across research units is 0.36, 0.46 and 0.40 in ST, LHS and HSS respectively. Comparatively, a similar analysis was performed between labs at university level in Switzerland and found a GINI coefficient of 0.607 (Ciers *et al* 2018). At individual level, an estimation of heterogeneity in air travel use in England found values close to 0.75 (Büchs and Mattioli 2021). In the academic context, (Berné *et al* 2022) reported a GINI index of 0.5 for GHG air-travel emissions in France, lower than Switzerland's 0.722 (Ciers *et al* (2018)), partly because of the use of business class in the Swiss academic sector. Note that larger values are expected at individual levels since disparities are partly smoothed out by the aggregation at unit scale.

4. Mitigation options

This section evaluates the mitigation potential of various options, primarily examining modal shifts from air travel to train travel and the moderation of air travel. 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. Additionally, we address technological shifts for fleet vehicles owned by research units while disregarding technological shifts in aviation. Indeed, technological shifts capable of rapidly and efficiently decarbonizing air travel are highly uncertain and likely unfeasible by 2030. In contrast, some technological shifts for cars are already available on

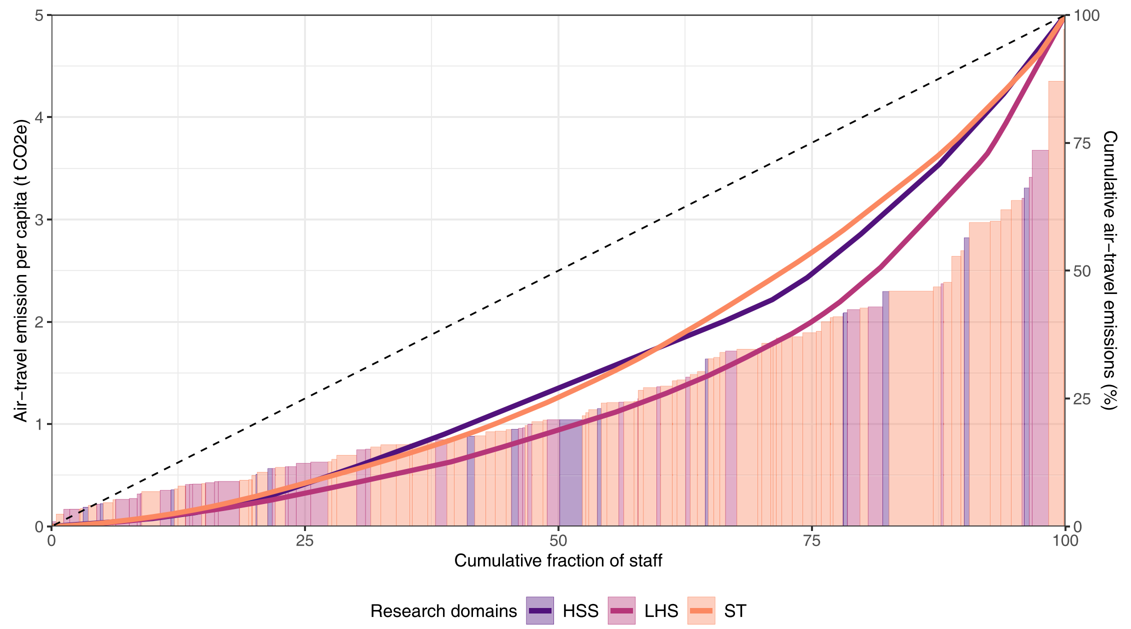

Figure 3. Lorenz curve of cumulative air travel GHG emissions for the three broad research domains. Normalized research units are organized for increasing proportion per-capita GHG emissions. Bars width correspond to the size of research units. The three curves correspond to values in each broad research domain. The dotted line represents an hypothetical situation in which all laboratories have the same per-capita emission.

the market, and their use is encouraged by official eco-guidelines.

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 travelled 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 inter-quartile range of [2.0%–8.6%]). Interestingly, three routes in continental France concentrate about 36% of air travel domestic emissions (see figure 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 in France and neighbouring countries. By compiling data from the national rail service, we estimate the theoretical effective train speed between major cities, including connections, to be $150\,\mathrm{km\,h^{-1}} \pm 60\,\mathrm{km\,h^{-1}}$. 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 10 h 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 h travel time and to less than 8% for a simple ban on domestic flights. Note that a May 2023 law enforced a ban on three short distance domestic lines in France (i.e. achievable within a 2 h train ride).

French public service guidelines recommended that all trips that can be completed in less than 2 h30 should be undertaken by train. This limit is extended to 4 h 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 current situation and 49.2% for electric cars. This amounts to 0.3% and 1.1% of total travel-related GHG emissions respectively. We limit our examination of technological changes to the sector of car travel, intentionally excluding aviation (see supplement).

4.3. Moderation options

We compare the mitigation potential of a series of moderation options which can be defined as a set of measures aiming at reducing demand. Here, this translates into avoided travels as opposed to modal

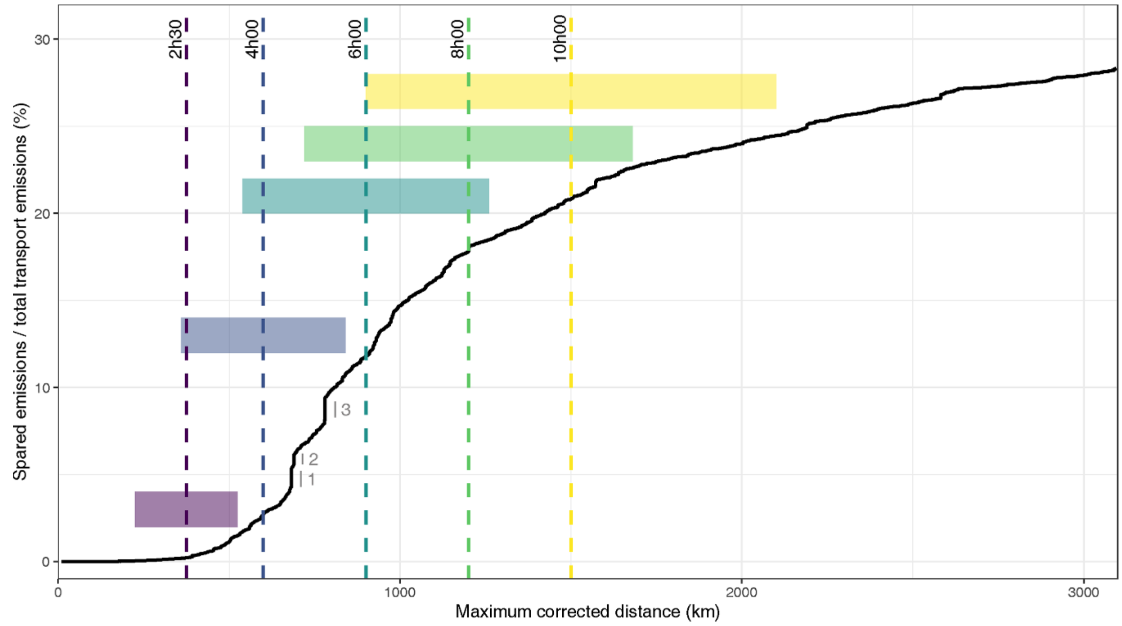

Figure 4. Mitigation potential of modal shift from plane to train as a function of distance (i.e. percentage of spared GHG emission from total academic transport). Vertical lines correspond to median time travel by train and rectangles express the uncertainty related to train speed, with 150 km h^{-1} $\pm$ 60 km h^{-1}. 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.

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 20% (alt. 50%), the corresponding GHG emissions decrease by 20% (alt. 48%). All research units are impacted. Second, we apply a cap on flown distances fixed at the per-capita median value of all units, about 5780 km/person/year. The corresponding average GHG footprint decrease is 38% and half of the research units are impacted. A stronger limitation (about 4500 km/person/year) leads to a 47% decrease in transport emissions, 61% of research units are impacted. Third, we explore limits on the number of plane trips per-capita ranging from a 20% decrease to halving the median number of trips (i.e. 1 trip/year). These options lead to about 20 to 60% decrease in GHG emissions. Fourth, we assess the effects of three implementations of a quota dependent on motives, focusing solely on the number of conference and seminar attendances for which low-carbon alternatives exist. A 20% reduction of air travel to conferences, spares about 8% of GHG emissions and a halving conference attendance, 19%, or by 21% if seminars are halved too. As an indication, a fully virtual mode for all conferences and seminars would equate to a decrease of about 41 % of yearly travel-induced GHG emissions if the carbon weight of online conferences is considered negligible (Klöwer *et al* 2020). 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%. Note that when applied after modal shift, air travel moderation has a decreased mitigation potential (see the last two lines in figure 5 or increasing trends for two dot–dash lines in figure 6). This is because the subset of remaining trips in which we apply moderation is both truncated in distance and markedly smaller.

Moderation options also impact total or average travelled distances and the number of flights. To explore these effects we represent the number of round trips and associated total flown distances for the three considered air moderation policies for the range of possible modal shifts figure 6.

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

Minimum Allowable Distance (in distance or approximate duration) for Air Travel Clearance

Air Mileage Moderation in Quantity or Distance		No modal shift policy	375km (~2h30)	600km (~4h)	In mainland France	900km (~6h)	1000km (~6h40)	1200km (~8h)	1500km (~10h)
No moderation policy		0	0.3	3	8	12	15	18	21
Reduce air travel number for conferences	20% fewer trips	8	8	10	13	17	20	23*	26*
	50% fewer trips	19	19	21	24	27	30	32	34
	1 r. trip/3 years	14	13	14	17	18*	19*	21**	22**
	1 r. trip/4 years	18	18	19	22	22	23*	24*	23**
Reduce long−haul air travel number	20% fewer trips	13**	14**	16**	21**	26**	28**	32**	35**
	50% fewer trips	32**	33**	35**	40**	44**	47**	51**	53**
	1 r. trip/4 years	28**	28**	31**	35**	40**	43**	46**	49**
	1 r. trip/6 years	37**	38**	40**	45**	50**	52**	56**	59**
Reduce air travel mileage	20% decrease	20***	20***	22***	26***	30***	32***	34***	37***
	50% decrease	48***	49***	50***	52***	54***	56***	57***	59***
	5800km/year	38***	38***	39***	41***	42***	44***	45***	46***
	4500km/year	47***	47***	48***	50***	51***	52***	52***	53***
Reduce air travel number	20% fewer trips	19	20*	22*	25*	29*	31*	34*	36**
	50% fewer trips	48	48	49	52	54	55	57*	58*
	1 r. trip/year	36*	36*	33	32*	29*	28**	27**	27***
	1 r. trip/2 years	61	61	58	57	51*	50*	46*	44**

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 median research unit are presented at the third modality in each moderation option (i.e. 1 conference every 3 years, 1 trip every 4 years, 5800 km and 1 trip per year). Mitigation options are applied as maximum (e.g. maximum 1 trip per year). Stars represents the range (max − min) for 1000 repetitions with (**** < 0.1, *** < 0.5, ** < 1 and * < 1.5).

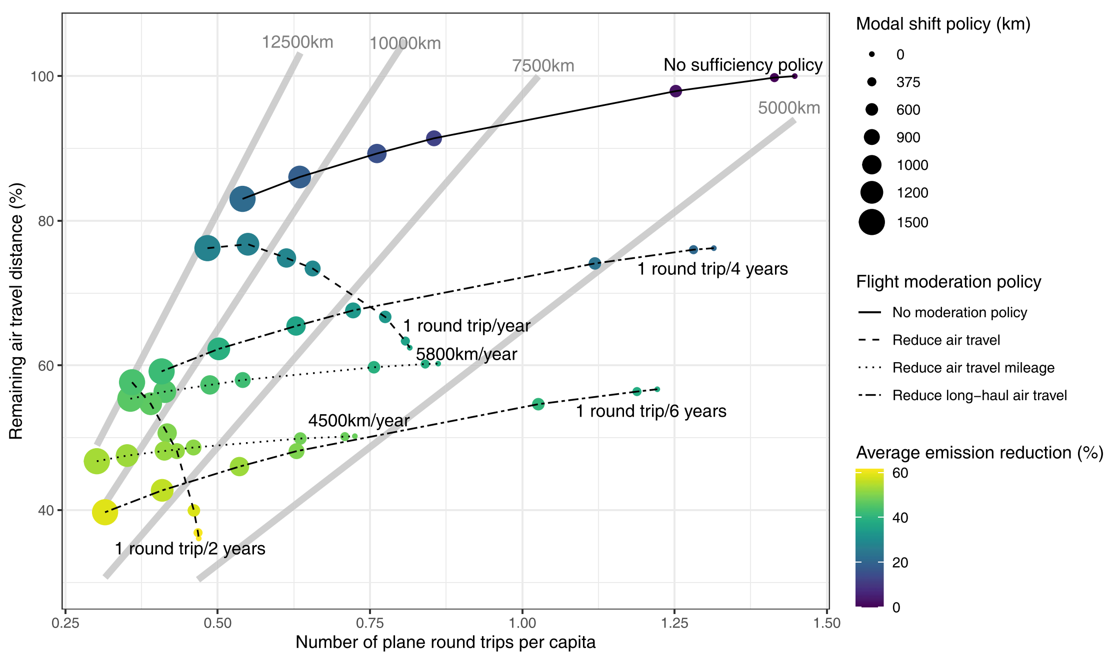

Figure 6. GHG reductions for 3 types of flight moderation policies combined with modal shift over short distances. Reduction are presented for corresponding number of plane round trips per capita per year (or remaining flights after moderation, x-axis) and fraction (%) of cumulated distances (over all missions or round trips, y-axis). Flight moderation policies are presented for two modalities : per-capita median (1 long-haul return flight per 4 years, a maximum of 5800 km per-year per-capita and 1 round trip per year) and one additional modality (1 long haul return flight every 6 years, 4500 km per year and 1 round trip every two years). The reference scenario, without sufficiency policy, is presented at the top of the figure and all modalities refer to the ones presented in figure 5. Note that significant GHG reductions are concentrated in the bottom-left area of the graph, with larger reductions presented in yellow tones. Grey lines present the average distance per trip for each reduction option.

maximum allowable distance or trip occurrence is then specified).

This calls for a few observations. First, considering the European Community's ambition to reduce its carbon emissions by at least 55% by 2030 (in comparison to 1990 levels) and attain *climate neutrality* by 2050, it is interesting to combine mitigation options to achieve a significant reduction of travel GHG emissions, arbitrary set to −50%. 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 5800 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 1500 km (or 10 h 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 4 h 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 limitation (Kreil 2021, Eichhorn *et al* 2022, Schmidt 2022). 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 h 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 10 h (or 1500 km) which are among the most ambitious reduction plans currently experimented by a handful of universities in Europe, 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 airports (Greer *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. The 'reduce air travel number' option estimates of figure 5 randomly cut down on air travels. In the first column, this cut down is uncorrelated with the air-travel distances. Obviously, if shorter-distance flights were preferentially cut down, the GHG emission reduction would be lower. This can arise when a modal shift policy is enforced simultaneously, as illustrated by the dot–dash lines of figure 6 for 1 trip/year and 1 trip/ 2 years quotas, corresponding to the final two lines of figure 5. Figure 6 shows that a stiffening of modal shift policy (decreasing x-axis) can entail an increase of total GHG emissions (darker colors in the color bar). Such an effect could also occur in practice if agents are required to reduce their number of flights, leading them to rely more on modal shifts for shorter distances to safeguard intercontinental flights. To warrant some effectiveness of a flight-number-quota policy, one approach is to implement it *after* having deployed a modal shift policy. Thus, despite their limited impact alone, modal shift policies can here serve as a useful precursor to a quota policy based on flight-number.

We find that travels beyond 3700 km contribute to 64% of all travel emissions or 66% of air travel emissions. In comparison, travels from the University of Lausanne also exhibit a bi-modal distribution in distances with the less frequent trips beyond 3700 km but amounting for 84% of air travel emissions (Ciers *et al* 2018). Long-haul flights have also been consistently identified as the primary source of air travel emissions in universities across the UK, Switzerland, and Germany (Eichhorn *et al* 2022). This suggests some validity of the present mitigation study at least these in neighbouring countries.

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 substitutions : a fraction of air travels are, at least theoretically, substitutable by online virtual or remote exchanges. This typically concerns attendance to project or administrative meetings or conferences (Klöwer *et al* 2020, Skiles *et al* 2022). It should be noted that the environmental impact of online conferences has been shown to be negligible compared to in-person conferences (e.g. Burtscher *et al* (2020), Tao *et al* (2021)). Based on our data, we show that a conference attendance quota fixed at the per unit median attendance reached a potential of about 13% which is roughly equal to a minimum allowable distance for air travel clearance of 1000 km (i.e. equivalent to a ban of air travel in France or close 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 1500 km or 7% of the total carbon footprint of academic 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 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.

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 environmental 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.

6. Summary and conclusion

We have analysed a nation-wide database on academic travel and have assessed the effectiveness of various mitigation scenarios.

We find that emissions do not predominantly stem from a particular scientific field, subgroup of top-emitting labs, or a single travel purpose like conferences. In contrast, the overwhelming majority (96%) of emissions originate from a specific mode of transportation: air travel, and about two third from intercontinental flights.

A consequence is the limited reach of narrowly scoped mitigation policies, for instance those targeting virtual conferencing or car electrification. Halving in-person conference attendance would *only* decrease the overall travelling carbon budget by about one fifth. The mitigation approaches able to halve emissions are those which comprehensively address the cumulative air travel distance, as illustrated with quota policies based on flight frequency or mileage.

Substituting, when possible, air travel by ground travel has a limited potential in emission reduction, e.g. just over 20% for distances up to 1500 km. Nevertheless, modal shift can be key complement to a flight quota policy which would solely concentrates on reducing long-haul flights or flight frequency. The effectiveness hierarchy of mitigation policies ranges from flight quota policies (most impactful) to substitution of planes by trains over short distances, and then to the promotion of technological changes such as electric cars (less impactful), a hierarchy similar to the 'Avoid-Shift-Improve' framework, initially introduced to address sustainable urban mobility (Ringenson and Kramers 2021).

Official guidelines encourage very focused practises, with negligible impact on emissions, and often fail to address the central question of travel culture and practise in scientific research. Yet, by producing norms, policies and incentives, institutions have the capacity to change the standards of scientific research practice (Hopkins *et al* 2016, Reyes-García *et al* 2022) for example through indirect effects of career advancement, evaluation and gender inequality (Kreil 2021a, Berné *et al* 2022, Eichhorn *et al* 2022, Hölbling *et al* 2023). Collective data-informed decisions on the moderation of air travel can help bridge this challenge and help avoid relying on the future use of carbon offsetting or expose these institutions to carbon liability.

Data availability statement

The data cannot be made publically available because their use is strictly restricted to the research group GDR Labos 1point5 as requested by public research institutions. The data cannot be made publicly available upon publication because they are owned by a third party and the terms of use prevent public distribution.

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Contributions

TB-A and GL equally contributed to this article. TB-A wrote the article with PER and GL. GL produced the statistical analysis with TB-A, PER and ASa. JM developed the GES 1point5 plateform. All co-authors provided detailed inputs on all versions of the manuscript.

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