Unmasking mobility patterns: international travel behavior and emissions of scientists in a higher research institution

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Abstract

Purpose – This study aims to investigate patterns in international travel behavior of scientific staff depending on the categories of gender, scientific field and scientific seniority level. The learning from salient differences possibly revealed may inform measures for reducing travel greenhouse gas (GHG) emissions, especially for high-emitting staff groups, and help strengthen the equality between scientists of different categories concerning their travel behavior.

Design/methodology/approach – The study collected and used novel empirical data on travel GHG emissions from University of Graz scientific staff for five consecutive years (2015–2019) and used statistical analysis and inference to test and answer three distinct research questions on patterns of travel behavior.

Findings – The travel footprint of scientific staff, in terms of annual GHG emissions per scientist, exhibits various highly significant differences across scientific fields, seniority and gender, such as male senior natural scientists showing ten times higher per-person emissions than female junior social scientists.

Originality/value – The five-year travel GHG emissions data set across all fields from natural sciences via social sciences to humanities at a large university (Uni Graz, Austria, about 2,000 scientific staff) and across seniority levels from predocs to professors, both for female and male scientists, enabled a robust empirical study revealing distinct differences in travel GHG footprints of academic staff. In this way, the study adds valuable insights for higher research institutions toward effective GHG reduction policies.

Keywords Greenhouse gas emissions, International scientific travel, Scientific field, Scientific seniority, Gender

Paper type Research paper

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Introduction

To achieve a sustainable transformation toward a low-carbon society and reach the Paris climate goals, all public, institutional and personal entities have to contribute a fair part to greenhouse gas (GHG) emission reductions (Williges *et al.*, 2022; Kirchengast *et al.*, 2021). As public institutions, universities work as role models and have societal influence with their teaching, research, and knowledge. In this context, mobility is a delicate subject. Scientific trips are often understood as crucial in the development of scientific output (Nursey-Bray *et al.*, 2019). They enhance exchange and the development of a scientist's career by building up relationships or increasing knowledge about their research by presenting their results at conferences, workshops, etc. At the same time, mobility is known to contribute significantly to universities' GHG emissions (Arsenault *et al.*, 2019; Wynes and Donner, 2018), with air travel being one of the major contributions from scientists to anthropogenic climate change (Levine *et al.*, 2019). Therefore, different universities in the USA (Schmidt, 2022), Australia (Glover *et al.*, 2018) and Europe (Hoolohan *et al.*, 2021; Biørn-Hansen *et al.*, 2021) have already implemented climate policies aiming to reduce GHG emissions from air travel.

On a broader scale, Europe's (EU-27) GHG emissions from the transport sector are still increasing. Of particular note is the high increase in GHG emissions coming from international and national aviation, which increased over double from 1990 to 2019 (European Environmental Agency, 2020). In the year 2021, the transport sector made up about 22% of the EU's GHG emissions (European Environmental Agency, 2022). The challenge regarding the Paris Agreement climate goals of limiting global warming to 2°C with efforts of 1.5°C (UNFCCC, 2015) hence covers the necessity to also reduce GHG emissions from the transport sector (Jaramillo *et al.*, 2022).

Besides negative impacts on the climate, different studies find inequities in flight activities on a broad level. Although flying is often seen as a necessity for business, among other reasons to fly, only a small part of the privileged social classes from the Global North take the most flights (Gössling *et al.*, 2019). Gössling and Humpe (2020) suggest that only 4% of the global population took an international flight in 2018, while only 1% of the world's population is responsible for over 50% of passenger air travel emissions. In relation to class and financial background, gender is also a limiting factor to the access to mobility (Sheller, 2016).

Scientists are part of the small share of the world's population that is able to take flights. Therein, scientists are found to be among the highest emitters (Le Quéré *et al.*, 2015; Higham *et al.*, 2019), as academic flying is seen as essential for professional success (Wynes *et al.*, 2019; Biørn-Hansen, 2021). Despite mutual perceptions about the relevance of scientific travel, Wynes *et al.* (2019) do not find a statistically significant relationship between air travel emissions and the scientific output of a scientist. The latter is measured in terms of metrics that assess an author's productivity and citation impact, namely, both the h-index and the normalized hla-index (Wynes *et al.*, 2019). In addition, two online surveys by Attari *et al.* (2016) conclude that a high personal carbon footprint hinders a researcher's perceived credibility, affecting especially climate scientists. At the same time, climate scientists turn out to fly more often, at least until 2018, than scientists of other disciplines (Whitmarsh *et al.*, 2020).

These results weaken the argument that scientists do not have a choice but to reduce travel GHG emissions, as scientific traveling at an accustomed frequency is necessary for academic success, which would quite lock in universities' travel emissions at high levels. Rather, Pargman *et al.* (2022) claim that academic flying should even decrease its emissions at higher rates than other sectors, as emissions from agriculture (food) or energy (heating) are more essential than emissions from flying.

As a higher education and research organization with about 4,700 employees and 30,000 students, the University of Graz is Austria's second-oldest and second-largest university (after the University of Vienna). It is a general university offering a wide academic range across the sciences and humanities and promoting internationalization through cooperation and strategic partnerships to strengthen excellence in research and teaching. This makes international mobility to play a key role and is reflected also in the composition of the faculty members, where from about 3,300 scientific staff members, the share of international staff is 23% in 2022, and the share of female scientists is 52% (Uni Graz, 2023).

Taking up the challenge of emission reductions in this context, the University of Graz pursues the new (institutional) carbon management approach (Kirchengast *et al.*, 2021), implementing the concept and the key tools developed by its researchers. In a first step, a reference emissions inventory for a representative year was estimated using the mean of five consecutive years, 2015–2019. Therein, staff and student mobility account for about 34% of the university's annual total emissions (Danzer *et al.*, 2021). Within the project, a climate protection advisory board consisting of representatives of its six faculties (schools), different seniority levels, administrative staff and students was founded in 2020 to discuss the needs and concerns of the staff concerning different measures to reduce GHG emissions. Therein, international mobility was a quite emotional subject. Discussions focused on different scientific cultures and their needs in different scientific fields, depending on the scientific seniority level. Members expressed the fear that travel reductions would not meet the different needs and requirements.

Scientific studies confirm parts of the fears and worries expressed in this climate protection advisory board and also found in a survey by Schreuer *et al.* (2023). Pargman *et al.* (2022) find differences in the number of trips comparing two departments and within the departments. Medhaug (2021) states that flight emissions per full-time-equivalent differ in the departments at the ETH Zurich. Wynes *et al.* (2019) find differences in flight emissions depending on the career stage of a researcher. Moreover, Ciers *et al.* (2018) and Medhaug (2021) find that travel emissions increase significantly with the seniority of a researcher. As their examined data sets covered technical universities with specific characteristics, we cannot transfer these results to other scientific fields, knowing that departments show different travel behavior (Pargman *et al.*, 2022).

With regard to the concerns aired in the University of Graz climate protection advisory board (and very likely in many other similar academic-based boards and discussion fora worldwide), and recognizing that existing studies cover parts of the concerns but leave gaps, we designed this study to help fill the gaps. We used a unique data set and examined the travel behavior of Uni Graz scientific staff by inspecting patterns of per-person GHG emissions (tons of carbon dioxide equivalents per scientist, tCO_2eq/scientist) in categorized data across the three dimensions of scientific field, scientific seniority and gender. To the authors' knowledge, this is the first empirical study with this categorized span across all sciences.

On the basis of classifying each scientific trip into the respective categories, we address the following research questions, using the per-person emissions [tCO_2eq/scientist] as an empirical key metric:

RQ1. Do scientific fields (humanities and law, social sciences and natural sciences) show different international travel behavior as the scientific culture differs for these fields?

RQ2. Do scientists of lower scientific seniority (junior researcher, postdoc researcher and senior researcher) take more international scientific trips to establish relationships and careers and hence cause more travel emissions?

RQ3. Do male researchers take more scientific trips per year than female researchers, resulting in higher travel emissions per person?

Because of the accuracy and scope of the data set, which covers each scientific trip over the five consecutive years 2015–2019, this study is able to empirically inspect all three questions. As the University of Graz does not only cover, or primarily cover, technical fields and natural sciences, the study has the possibility to look at a broad range of fields, including social sciences and humanities. We aim to test for and interpret possible patterns in travel behavior as guided by the three research questions. The answers found may inform targeted measures for reducing travel GHG emissions of certain high-emitting groups. Additionally, they may help strengthen equality and better support the differentiated needs of scientists of different genders, scientific fields and scientific seniority.

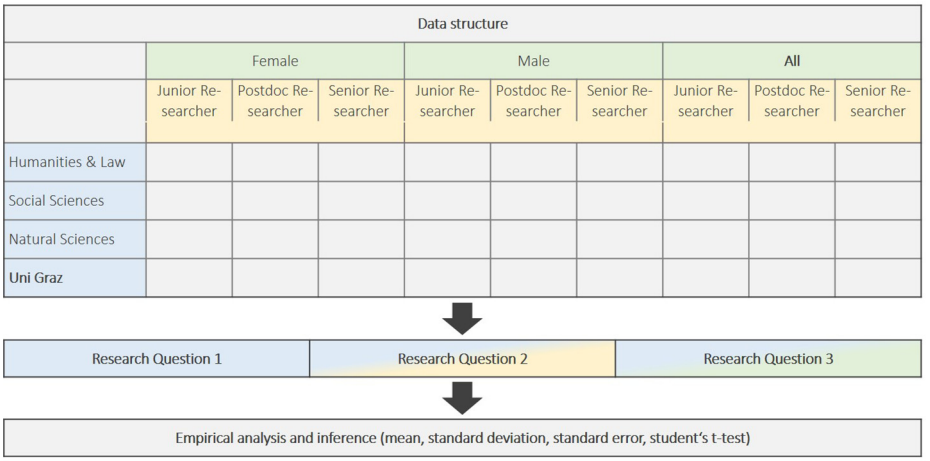
In the next section, we introduce the research methodology. Results are provided in the subsequent chapter "Findings," followed by "Conclusion" as the final section.

Research methodology

The data collection took place in cooperation with the University of Graz travel management office, based on approved policies for handling and anonymizing individual international trip data. Only statistically aggregated results are used here. The basic data set contains all international trips of Uni Graz scientific staff for the five consecutive years 2015–2019. This staff comprises female and male researchers at all seniority levels, from predocs to professors, across all 21 branches of science in the six faculties of the Uni Graz.

As the COVID-19 pandemic restricted (international) traveling, affecting also the scientific trips of Uni Graz staff, the number of such trips and the associated GHG emissions dropped strongly in 2020 and 2021 (about 400 trips per year) compared with 2015–2019 (about 2,400 trips per year) (Danzer and Hölbling, 2022). Preliminary results for 2022 indicate that the number of trips increased significantly again (by a factor of four to five), but did not yet reach pre-pandemic levels. It is not yet clear at this time to what degree this lower number still represents pandemic impacts or already reflects some success of measures to reduce GHG emissions; this will be of high interest for a follow-on study. To represent academic travel behavior without pandemic influence in this baseline study, we excluded the post-2019 data from this study. For achieving reasonable and robust ensemble sizes per individual category in all dimensions analyzed, we classified the data into a suitably categorized data structure, which is shown in Figure 1. The details of how the categorized data are aggregated from the native Uni Graz individual-trip data of 2015–2019 are summarized in Appendix Table A1.

Briefly, the native data contain, per individual trip, anonymized information about the traveler (gender, academic degree, job title and institute), trip destination (city and country) and further information on the trip (start and end dates, transport mode and travel expense type). While the classification of "gender" (female, male) can be used directly, the "institute" information enables allocation to respective scientific fields (each institute belongs to a unique branch of science), and the "academic degree" and "job title" information enables classification to seniority level (putting PhD students to Junior Researcher, PhD degree holders with no senior job title to Postdoc Researcher and professors and other senior-titled staff to Senior Researcher). Regarding the gender spectrum, information on further gender identities beyond female and male was not available. The trip destination and further trip information are used to obtain the trip's GHG emissions (in tCO_2eq) according to the mobility emissions computation method used, which essentially involves travel distance, transport mode (such as train, flight-economy and flight-business) and mode-dependent



Notes: Data structure and examined categories in blue (three scientific fields or Uni Graz all), yellow (three scientific seniority levels or all) and green (two gender types or all). These data underpin the three research questions (middle block), the focus of which is indicated by respective colors (i.e. RQ1 inquiring on scientific fields, etc.), which are investigated by empirical statistical analysis and inference based on the data (bottom block)
Source: Authors' own work

Figure 1. Schematic representation of research methodology

emission factors per person-kilometer (in gCO_2eq/pkm) (Danzer *et al.*, 2021). The data use conforms to the General Data Protection Regulation, and no identity information on travelers is disclosed.

The aggregated data were computed in all categories in the form of the selected key metric of per-person GHG emissions (tCO_2eq/scientist), both as mean value and upper/lower standard error (of the mean) (expressed in the form mean [lower side standard error – upper side standard error]; see Appendix and Table A1 for details). Using these means and two-sided standard errors, we performed a comparative statistical analysis, targeted to test and answer the three research questions, using difference-of-mean significance tests between categories of interest based on *t*-test statistics for inference (Shen and Somerville, 2019; chapter 3 therein). Specifically, the significance of the difference between two mean values comparing two categories is tested using a two-tailed *t*-test with three levels of statistical significance (90%, 95% and 99%). In the Findings and discussion section, we refer to highly significant (***) if the 99% level is exceeded, significant (**) if reaching the 95%–99% range and weakly significant (*) if reaching the 90%–95% range. Below 90% is denoted as not significant (–).

Findings and discussion

The annual-mean international travel GHG emissions per scientist show no salient trend but remain relatively constant over the years. They correspond to 1.17 [1.13–1.24] tCO_2eq/scientist in average for the scientists of the University of Graz. Detailed results for all categories are summarized in Table 1. Looking at the fine-resolution classes (upper half of Table 1, detailing into seniority levels), the highest emissions per scientist are found for female and male senior scientists in the natural sciences, while the lowest amount is found for female and male junior social scientists. The more aggregated data level (lower half of

Table 1.
Annual-mean international travel GHG emissions per scientist showing, for each category, the estimated mean and its uncertainty range

	Estimated mean and standard uncertainty range of travel GHG emissions in units [tCO_2eq/scientist] (per category cell: mean estimate and [mean − lower standard error – mean + upper standard error])								
	Female			Male			All		
Scientific field	JR	PR	SR	JR	PR	SR	JR	PR	SR
H&L	0.29 [0.27–0.40]	1.77 [1.65–2.27]	1.56 [1.43–1.89]	0.44 [0.41–0.62]	1.43 [1.32–1.50]	1.35 [1.22–1.45]	0.35 [0.33–0.46]	1.59 [1.49–1.94]	1.43 [1.28–1.70]
SSci	0.23 [0.22–0.36]	2.17 [1.85–2.49]	1.46 [1.34–1.67]	0.17 [0.16–0.22]	1.53 [1.42–1.97]	1.88 [1.66–2.11]	0.21 [0.19–0.33]	1.78 [1.64–2.82]	1.77 [1.41–2.20]
NSci	0.69 [0.65–0.75]	1.15 [1.09–1.30]	2.30 [2.07–2.60]	1.03 [0.96–1.22]	0.88 [0.83–0.97]	2.31 [2.22–2.48]	0.87 [0.79–0.93]	0.97 [0.91–1.11]	2.31 [2.08–2.77]
Uni Graz	0.42 [0.40–0.47]	1.58 [1.50–1.85]	1.71 [1.61–2.00]	0.67 [0.62–0.82]	1.14 [1.10–1.22]	1.86 [1.79–2.03]	0.53 [0.50–0.58]	1.31 [1.26–1.50]	1.82 [1.70–2.02]
H&L		1.01 [0.96–1.22]			1.10 [1.02–1.19]			1.05 [1.01–1.16]	
SSci		1.00 [0.93–1.18]			1.30 [1.16–1.61]			1.17 [1.08–1.39]	
NSci		1.08 [1.04–1.16]			1.36 [1.30–1.48]			1.26 [1.21–1.37]	
Uni Graz		1.03 [1.00–1.15]			1.26 [1.21–1.36]			1.17 [1.13–1.24]	

Notes: Rows = scientific fields humanities and law (H&L), social sciences (SSci), natural sciences (NSci) and the University of Graz total; columns = the three seniority classes junior (JR), postdoc (PR) and senior researchers (SR), respectively, for each gender class (including all)
Source: Authors' own work

Table 1, bottom four rows) shows that male natural scientists exhibit the highest emissions, while again female social scientists appear to cause the lowest ones.

A careful inspection of the statistical significance of differences in these international travel GHG emissions among categories is summarized in Table 2, here grouped to highlight those results relevant to answering research questions *RQ1* to *RQ3*. Statistically significant differences are found concerning the scientific fields of humanities and law, showing less GHG emissions than other fields. At the level of all Uni Graz scientists together (rightmost column in Table 2), the emissions per scientist appear to increase with the seniority level; however, within the scientific fields, the seniorities show a more differentiated behavior. We also find differences in the travel behavior of female and male scientists. Below we discuss the specific results per research question in sequence, from *RQ1* to *RQ3*.

Comparing across scientific fields

Regarding *RQ1*, the international travel GHG emissions per scientist at the University of Graz do show some statistically significant differences between the scientific fields (Figure 2). Natural sciences (third bar in Figure 2) show the highest per-person emissions (1.26 [1.21–1.37] tCO_2eq/scientist), while humanities and law (leftmost bar) are responsible for the lowest ones (1.05 [1.01–1.16] tCO_2eq/scientist). Comparing these two results, we find a highly significant difference ($\alpha < 0.01$) between the natural sciences and humanities and law. Furthermore, an average humanities and law scientist shows, with weak significance, lower emissions than an overall University of Graz scientist (rightmost yellow bar).

Putting these results into context with results published by other higher education institutions, the ETH Zurich reported, with 1.80 tCO_2eq per full-time equivalent staff, higher values for their base years 2016–2019 (Medhaug, 2021). The ETH values include only flight emissions, but because other means of travel (train, bus and car) do not add significant amounts of GHG emissions to international trips, the values of the two universities are comparable. Wynes *et al.* (2019) found even higher GHG emissions per scientist for staff at the University of British Columbia, from 2.44 up to 7.52 tCO_2eq/scientist (based on January 2015 to June 2016 data), depending on scientific seniority.

These results support the hypothesis that scientific fields show different scientific cultures, resulting in varying travel behavior. The lower per-person travel emissions in the humanities and law may be related to the content and nature of this scientific field.

Research question (RQ)	Difference	Humanities and law	Social sciences	Natural sciences	Uni Graz
RQ1 Scientific fields	Humanities and law vs Scientific fields		–	***	*
RQ2 Scientific seniority	Junior researcher vs Postdoc researcher	***	***	–	***
	Junior researcher vs Senior researcher	***	***	***	***
	Postdoc researcher vs Senior researcher	–	–	***	***
RQ3 Gender	Female vs male	–	*	***	***

Notes: No significance –($\alpha > 0.1$), weakly significant; *($\alpha = 0.1$–0.05), significant; **($\alpha = 0.05$–0.01); highly significant, *** ($\alpha = < 0.01$)
Source: Authors' own work

Table 2. Statistical significance matrix comparing the difference in GHG emissions per scientist

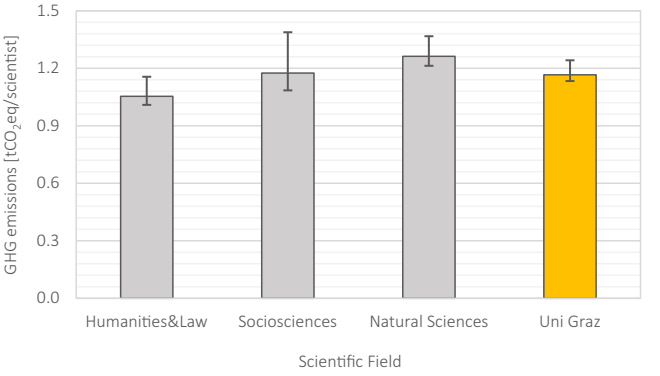


Figure 2.
Annual-mean international travel GHG emissions per scientist across scientific fields

Source: Authors' own work

Humanities and law investigate and work on issues that are, to an appreciable extent, more site-specific, e.g. national jurisprudence. International and global collaboration and associated travel may hence not be that distinctly present in some disciplines within this field, making its aggregated mean per-person emissions somewhat smaller than for the other fields.

However, transferring knowledge and building up collaborations is relevant for all scientific fields, leading to the necessity of certain scientific trips; hence, the differences are not large. Evidence shows that the necessity of in-person meetings depends mainly on the purpose of the meeting (Denstadli *et al.*, 2012; Le Quéré *et al.*, 2015); e.g. face-to-face meetings are known to build up trust between the researchers as they get to know each other on a personal level (Le Quéré *et al.*, 2015).

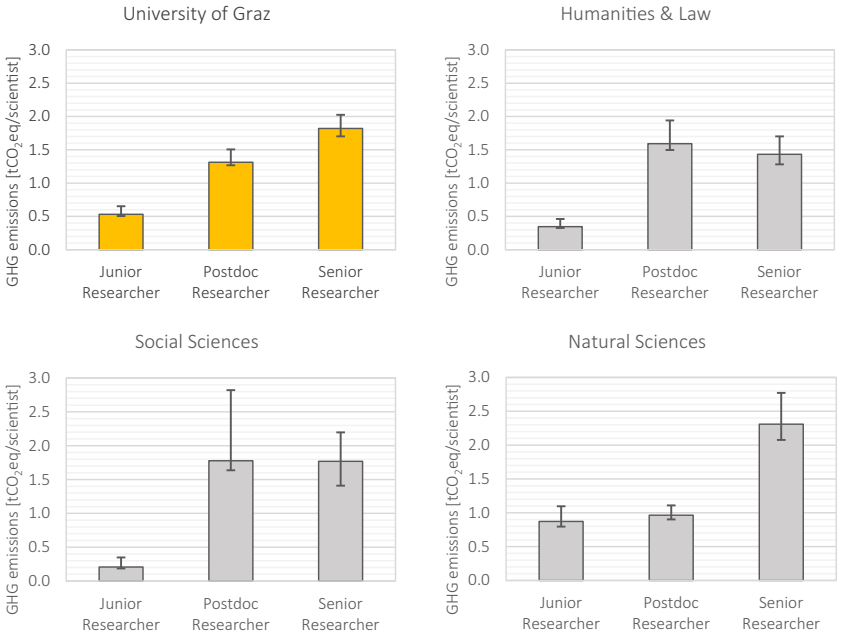
At the University of Graz, the university-level travel policies are currently the same for all faculties (schools) and their academic institutes (departments) across the three scientific fields and also for all scientific seniority levels. There are first efforts at the faculty and institute levels, however, on developing specific additional policies that also take the results of this study into account and that are expected to subsequently help upgrade the university-level policies.

Comparing scientific seniority levels within the scientific fields

When comparing the travel behavior of scientists of different scientific seniorities, namely, junior, postdoc and senior researchers within a scientific field, we find differentiated travel behavior. The results are shown in Figure 3. For the University of Graz total (upper left), we find that the GHG emissions per scientist increase with the seniority level. Junior researchers cause lower per-person emissions compared to postdocs and senior researchers (both highly significant, $\alpha < 0.01$). In addition, senior researchers show the highest per-person emissions, and the difference between postdocs and senior researchers is highly significant.

Regarding *RQ2*, these results lead to the conclusion that junior researchers do not cause more travel emissions because of possibly taking more international scientific trips to establish relationships. On the contrary, already well-established researchers are responsible for the highest per-person emissions at the University of Graz total level, showing that emissions overall increase with scientific seniority.

At the same time, we find that the pattern within the scientific fields is somewhat different from the university total level. While humanities and law and social sciences show



Source: Authors' own work

Figure 3. Annual-mean international travel GHG emissions per scientist across seniority levels, for University of Graz total (upper left) and the scientific fields of humanities and law (upper right), social sciences (lower left) and natural sciences (lower right), respectively

similar patterns in their travel behavior, with junior researchers differing from the other two seniority levels, natural sciences differ with the outstanding emission-intensive behavior of their senior researchers.

The overall low emissions of junior researchers imprinted in the University-total are mostly caused by travel behavior in the fields of humanities and law and social sciences (Figure 3, upper right and lower left). The junior researchers in these fields show distinctly lower per-person emissions than postdocs and senior researchers in their same scientific field (high significance, $\alpha < 0.01$; for numerical results, see Table 1). At the same time, we find no significant difference in the travel behavior of postdocs and senior researchers in these fields, neither in the humanities and law nor in the social sciences.

In the natural sciences, the behavior appears differently (Figure 3, lower right). Here, junior researchers (0.87 [0.79 – 0.93] tCO_2eq/scientist) and postdocs (0.97 [0.91 – 1.11] tCO_2eq/scientist) show similar behavior (no significant differences). However, we find a highly significant difference ($\alpha < 0.01$) in the per-person emissions of senior scientists. With average per-person emissions of 2.31 [2.08 – 2.77] tCO_2eq/scientist, the senior researchers in the natural sciences are responsible for a significantly higher climate impact per person than their peers at an early career stage as well as in other scientific fields. These results for the natural sciences corroborate findings described in recent studies by Medhaug (2021) and Arsenault *et al.* (2019).

In summary, we find that junior researchers in humanities and law and social sciences are causing substantially less per-person emissions from international scientific travel than researchers at a higher career stage. A possible explanation is the higher occurrence of PhD positions without employment in these fields, leading to less paid scientific trips and hence less travel opportunities. This difference is not found in the natural sciences, where the

senior researchers show a distinctly more emission-intensive travel behavior while the per-person emissions of junior and postdoc researchers do not show a significant difference.

Specifically regarding *RQ2*, we can conclude that scientists at an early career stage do not take more international scientific trips (and consequently cause higher per-person emissions) than more established researchers, independent of their scientific field. On the contrary, as the University-total indicates, they take on average distinctly fewer trips than postdocs and (in particular) senior researchers.

Comparing female and male researchers in the scientific fields

Concerning *RQ3*, we examine and compare the travel GHG emissions of female and male scientists at the university-total and in the three scientific fields (Figure 4, upper panel). In

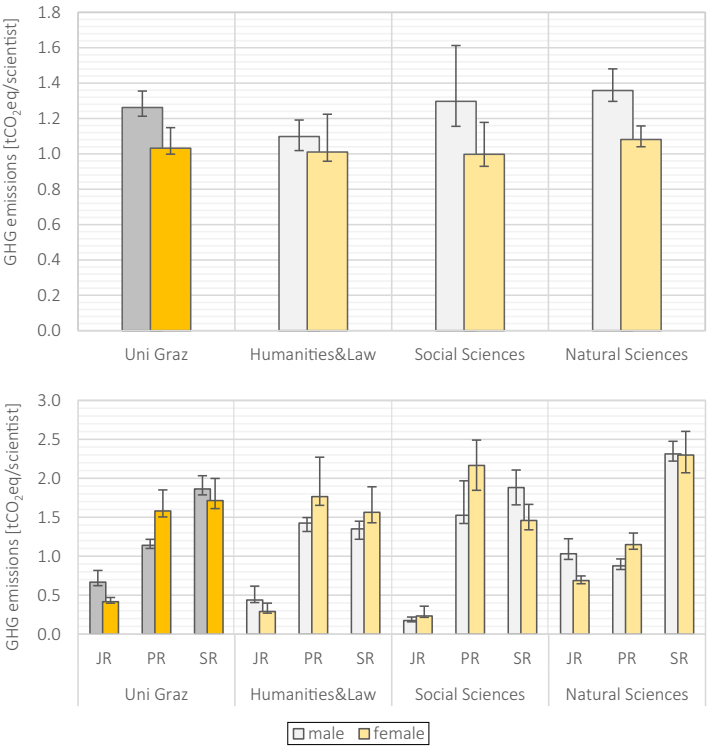


Figure 4.
Annual-mean international travel GHG emissions per scientist intercomparing gender (upper panel) and fine-resolution view (lower panel)

Notes: Upper panel: annual-mean international travel GHG emissions per scientist, intercomparing gender (male and female) for the University of Graz total (left) and each of the scientific fields (three further segments). Lower panel: fine-resolution view of the same emission data, now intercomparing gender (male and female) within each of the scientific seniority levels (three per scientific field segment) across the scientific fields from the University of Graz total to natural sciences (left to right)
Source: Authors' own work

the social sciences, we find a weakly significant gender difference ($\alpha = 0.1$–0.05), while the difference is highly significant ($\alpha < 0.01$) in the natural sciences, both fields showing higher per-person emissions from male scientists.

This strong difference in the natural sciences (rightmost segment in Figure 4, upper panel), where female scientists cause per-person emissions of 1.08 [1.04–1.16] tCO_2eq/scientists while male scientists cause 1.36 [1.30–1.48] tCO_2eq/scientists, also leads to a highly significant difference at the university-total level (leftmost segment).

Summing up and highlighting all the statistical results in a fine-resolution view, Figure 4 (lower panel) shows the emissions per scientist disaggregated in all the categories. This provides an informative comparative view of the results discussed above related to the specific research questions. The per-person emissions increase with the seniority level at the university-total level (leftmost segment in Figure 4, lower panel). For humanities and law as well as social sciences, both female and male junior researchers cause lower emissions than postdocs and senior researchers, while in the natural sciences, both female and male senior scientists cause distinctly higher emissions, peaking in the result that male senior natural scientists show ten times higher per-person emissions than female junior social scientists.

Simultaneously to the current study, a survey was conducted at the University of Graz that investigated the willingness to reduce flight travel (Thaller *et al.*, 2021) and the support of reducing flight travel measures amongst the staff (Schreuer *et al.*, 2023). Thaller *et al.* (2021) found that the willingness to reduce future international air travel is generally high for a clear majority of scientists, depending also on previous experiences and the event type creating the purpose for travel. The willingness to reduce flight trips is found to be higher for shifting to a different travel mode than for shifting to online participation or abstaining from participation. Schreuer *et al.* (2023) confirm the fears about fairness among university staff in their results but also find support for applying air travel-reducing measures.

There are manifold possibilities to reduce GHG emissions from international travel activities. A first step to reduce travel GHG emissions could be to identify "unnecessary" trips (Pargman *et al.*, 2022), especially those taken by the high emitting scientist groups, i.e. natural sciences and senior researchers, according to the results of this study, and hence avoid the necessity to fly (Creutzig *et al.*, 2018) and the trips themselves (Thaller *et al.*, 2021).

Certain scientific trips can also be substituted by online participation, depending on the purpose of the meeting (Denstadli *et al.*, 2012). During COVID-19, various technical options for hybrid meetings and interactive online meetings improved. Another step is to substitute emission-intensive travel modes (i.e. , flights) with less intensive travel modes (i.e. trains and buses) (Creutzig *et al.*, 2018). Furthermore, another approach to reducing GHG emissions from conferences is the organization of so-called multi-hub conferences. There, the conference takes place at different sites around the world simultaneously, and the participants travel to their nearest hub, significantly avoiding total travel distance (Parncutt *et al.*, 2021). In addition, multi-hub conferences offer more inclusivity for disabled researchers, scientists from financially less privileged countries or scientists who are not able to take trips far away because of care duties (Parncutt *et al.*, 2021).

Even though we arrived at clear quantitative results for the direct GHG emissions of scientific trips here, we caution that one may also consider further "soft factors" that may justify differentiated traveling intensities of scientists, such as an arguably "higher purpose" of some trips, e.g. delivery or acquisition of unique competences or skills at remote destinations. Another "soft factor" is likely indirect positive impacts on emission reductions by others; as arbitrary examples, the participation of key scientists at a UN Conference of the Parties could aid progress in effective climate policies, or the personal exchange within conferences, workshops or research visits could foster new knowledge for accelerated

emission reductions. Dedicated research is needed, however, on whether and, if so, how such indirect effects could equitably factor into fairness-based allocations of GHG emission budgets, from country to personal levels (Kirchengast *et al.*, 2021; Williges *et al.*, 2022).

Conclusion

Investigating the annual international travel GHG emissions from 2015 to 2019 at the University of Graz, this study finds various distinct differences between the examined categories. First, as found in previous studies, scientific fields show different travel behaviors. A noticeable difference is found in the field of humanities and law, which displays significantly lower emissions per scientist than the natural sciences. While the natural sciences are quite globally interconnected, the humanities and law covers more fields that are more site-specific and involves more global collaboration, hence being less expressed overall. Nevertheless, internationalization and professional exchange are relevant for all scientific fields. Our empirical analysis results suggest that scientists from the natural sciences, in particular senior researchers, have the highest capability to identify and reduce unnecessary trips. However, the definition of "unnecessary" is challenging (Pargman *et al.*, 2022).

Concerning the scientific seniority and gender of scientists, this study identified the following differences in their travel behavior. While the per-person emissions increase with the seniority at the university-total level, the pattern is somewhat differentiated in the scientific fields, with the natural sciences showing a different picture than the humanities ad law and social sciences. Junior and postdoctoral researchers show similar travel behavior in the natural sciences, while senior researchers in this field cause significantly higher emissions (the highest of all at the university). In the humanities and law and social sciences, postdocs and senior researchers exhibit more similar behavior, while junior researchers in these fields cause significantly less emissions. The low emissions of junior researchers in these fields are also imprinted at the university-total level, where the international travel emissions per scientist clearly increase with scientific seniority. Regarding gender, male scientists in general cause higher per-person emissions than female scientists, specifically in the natural sciences, though these gender differences are less distinct than the differences between the scientific fields.

Overall, these findings suggest that already well-established scientists are responsible for the majority of international travel GHG emissions, especially in the natural sciences. In this respect, this study suggests better exploiting possibilities to recognize, and then avoid, "unnecessary" travels, in particular of senior scientists. We did not find evidence that scientists in an early career stage take more scientific trips to establish and build up scientific connections. Hence, the fear that, in light of "emission reduction pressures," young scientists could lose chances to establish international connections is empirically not grounded according to the present results; fairness currently demands more from the scientists at higher seniority levels. It is recommendable to incorporate rules for junior scientists into the travel policies of universities to safeguard and enhance their opportunities to build up connections. Also, possibilities of substituting flying by other travel modes or virtual conferencing wherever possible and reorganizing conferences (in particular large ones) with lower frequency or in a multi-hub mode are of value regarding emission reductions by scientists.

Generalizing the perspective, universities can be viewed as "microcosms" within our larger society and, consequently, reflect the society itself as well as its dynamics. This is seen considering that the patterns and inequalities revealed in this study are also reflected in the general access conditions to mobility. Different travel behaviors are found depending on income, social class and gender, which are, amongst other factors, limiting factors for access to mobility in the broader societal context (Sheller, 2016). These factors are reflected in academia by the scientific field, scientific seniority and gender of the scientist. Policymakers, managers

and other stakeholders can also learn from these results for their decision-making. They highlight the need to work for more equitable travel possibilities, always under the overall goal of reducing GHG emissions, for example, by policies shaping the access to mobility in a more just way while at the same time implementing effective overall emission reduction. The measures summarized above are widely applicable toward this aim also for many other societal actors beyond universities, such as companies and other private and public organizations.

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Appendix

Figure A1 shows a schematic representation of the overall data structure used and highlights one of the 18 basic sub-matrices as an example (light yellow), representing the travel emissions of female junior researchers in the scientific field of humanities and law over the 2015–2019 time period, comprising 30 cells in total. The whole matrix comprises 630 data cells in total, from the GHG emissions caused in 2015 by female junior researchers in the scientific branch of fine arts of humanities and law (top left cell) to the ones caused by male senior researchers from the psychology branch of natural sciences in 2019 (bottom right cell). The researchers of the science branches and years of one scientific field, seniority level and gender contributed to one basic sub-matrix, also termed a category, resulting in the 18 basic sub-matrices in total seen in Figure A1.

For obtaining the emissions per scientist in a category (sub-matrix), the sum of the emissions over the five years and all branches was computed and divided by the total number of scientists in the category. Because the emissions and number of scientists per individual data cell were very small in a few cells, this method ensured robust estimates of the mean annual GHG emissions per scientist for all scientific fields, seniority levels and gender, i.e. for all 18 categories.

In addition to these mean GHG emissions per scientist [tCO_2eq/scientist] in each category, a two-sided standard deviation and the associated standard error of the mean were estimated based on the individual-cell data, with the standard deviation upwards (downwards) based on the emissions-per-scientist cell values higher (lower) than the mean value. The standard error of the mean was then obtained by dividing these standard deviations by the square root of the number of cells involved.

		Junior Researcher (JR)						PR	Senior Researcher (SR)					
Sci. Field	Scientific Branch	Female			Male			...	Female			Male		
		2015	...	2019	2015	...	2019	...	2015	...	2019	2015	...	2019
Humanities & Law (H&L)	Fine arts (1)													
	History (2)													
	Law sciences (3)													
	Linguistics (4)													
	Philosophy (5)													
	Theology (6)													
Social Sciences (SSci)	Business Manage.(7)													
	Economics (8)													
	Educational sci. (9)													
	Geography (10)													
	Sociology (11)													
	Sports sciences (12)													
Natural Sciences (NSci)	Biology (13)													
	Chemistry (14)													
	Earth sciences (15)													
	Env. system sci. (16)													
	Mathematics (17)													
	Molecular Biol. (18)													
	Pharmaceut. sci.(19)													
	Physics (20)													
	Psychology (21)													

Figure A1. Schematic representation of the data structure with one highlighted example of a basic sub-matrix (yellow individual cells, upper left; category female junior researchers in humanities and law)

Source: Authors' own work

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