

Beyond the carbon footprint: Virtual conferences increase diversity, equity, and inclusion

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Abstract

Among many roles, conferences disseminate research, grow professional networks, and train employees. They also significantly contribute to climate change due to their sizable carbon footprint. More recently, additional negative aspects have surfaced. Namely, they present significant barriers to achieving Diversity, Equity, and Inclusion (DEI). Here, we perform a meta-analysis of events that transitioned to virtual formats during the COVID-19 pandemic and show that this approach may provide a solution. Our analysis compared demographic and travel data of the same scientific conferences. When evaluating DEI, we considered factors including cost, gender, career stage, and geographic location. Costs associated with attending in-person conferences varied between 3% to 142% of attendees' regional annual per capita Gross Domestic Product (GDP). An increase in the fractional make-up of 2020 virtual conference delegations was observed for students (29% to 43%). Notable increases in attendance were observed for women (66% to 253% increase) and non-research-intensive countries (29% to 482% increase).

Introduction

Conferences fulfill a range of needs by facilitating dissemination of ideas, instigating collaborative relationships, and providing education, training, and career opportunities. Conventional in-person or legacy conferences¹ have filled this role for centuries², and these events cut across all sectors: academia, industry, and government. However, recently, this format has been criticized as outdated and detrimental to social equity and the environment^{3, 4}. While the impact of travel on the environment is well-recognized, the social impact has only recently come to the forefront. There are many factors that contribute to poor retention of a diverse workforce, two dominant contributors are the intrinsic power-imbalance in the workplace and an imbalance in home-life responsibilities^{5, 6}. These ongoing pandemic has amplified these two factors^{7, 8}. When placed in the context of legacy conference attendance, it becomes apparent that the time away from home necessitated by work-related travel is intrinsically exclusionary to diverse communities^{4, 9, 10, 11}. Yet, given how important conference attendance is to career advancement, this community is frequently faced with the decision of choosing between work and family. Additionally, the financial burden of event attendance has significantly increased over the past decade without proportional increases in available funding.

This impact becomes even more pronounced when evaluated in the context of the global research community. For instance, within the scientific community, conference attendance can be cost prohibitive for many, as the cumulative expense of travel, registration, and accommodation can be thousands of dollars per person. International travel creates additional barriers⁹ which is exacerbated by the frequent changes in document requirements and lengthy delays in obtaining visas. The combined effect can exclude or dissuade scientists from countries that do not have very high research activity, such as nations that are not in the top 10 research countries as defined by the Nature Index (NI)¹², NI > 10. Additionally, bringing together an international scientific community to a central location also results in large emission of greenhouse gases (GHG). For example, the five-day 2019 American Geophysical Union (AGU) conference had a carbon footprint of 80,000 tons of CO₂ equivalents¹³. Lastly, representation across sociodemographic groups within scientific communities is often lacking. This exclusion serves to further foster a lack of social equity at legacy conferences, where conference attendance and the associated career benefits are reserved for scientists with higher levels of research funding.

Attendance at legacy conferences for early career researchers pursuing or holding tenure-track positions serves an additional role. Obtaining tenure requires "visibility" in the field, securing grant funding, and publishing innovative research¹¹. Directly or indirectly, all of these can be connected to a researcher's professional network. Therefore, attending networking events, which aid in the formation of connections that lead to career opportunities¹⁴, is

particularly important for early-career scientists¹¹. In fact, legacy conferences have become so ingrained in scientific culture that attendance at these events is often conflated with excellence^{15, 16}, and the willingness to be away from home in order to attend is seen as a measure of dedication to the position⁴.

The recent surge in virtual events is forcing the scientific community to re-evaluate this long-held position. The initial anecdotal evidence indicated that virtual events enabled a more diverse population to attend and to participate. But a quantitative meta-analysis of the participant number and demographics as well as the carbon footprint has yet to be performed. Such analysis is critical to make decisions regarding the format of future events, potentially resulting in a paradigm shift in the field. Here, we evaluate the financial cost of attendance, carbon footprint, and attendee demographics including career stage. We collected historical data from three legacy conference series of varying size and disciplines within STEM and one always online conference series to investigate the impact of the abrupt transition from historically in-person conferences to a new online format. The legacy conference series analyzed here are the Annual International Conferences on Learning Representations (ICLR), American Astronomical Society (AAS), North American Membrane Society (NAMS) conferences and the online conference series analyzed here is the Photonics Online Meetup 1, January 2020 (POM 1) and Photonics Online Meetup 2, June 2020 (POM 2).

Results

Demographic Impact

Figure 1 illustrates themes seen across all datasets. The elimination of the travel and cost burdens realized with the virtual conference format resulted in a large increase in attendance at all events. The increase in attendance was particularly pronounced for international attendees. This trend can be explained by the decrease in costs as compared to in-person conferences.

The cost of attending legacy conferences for international attendees was dominated by airfare (**Figure 2**). Air travel cost was calculated by converting one-way travel distance to cost using a conversion factor described in Duda *et al*¹⁷ and doubling the value to obtain the cost for a round trip flight. A sensitivity analysis where the one-way cost is instead multiplied by 1.5 is presented in **Table S1**. When compared to US attendees, researchers from Africa paid 174% more, Asia paid 145% more, Europe paid 92% more, the Middle East paid 127% more, Oceania paid 203% more, and Other Americas paid 7% more to attend legacy NAMS conferences (**Table S2**). When placed in financial context, the cost of attendance for scientists from Africa to past in-person ICLR conferences (2018-2019), AAS (2016-2019) Conferences, and NAMS (2015-2019) conferences was on average 140%, 142% and 81% of their country's annual per capita gross domestic product (GDP), compared to just 3% of per capita GDP for US participants (**Figure 2a**). Cost of attendance for participants from Asia to past in-person ICLR (2018-2019), AAS (2016-2019), and NAMS (2015-2019) conferences was on average 16%, 15%, and 14% of their country's per capita GDP (**Figure 2a**). However, it is important to note that many conferences not included in this analysis have registration fees in excess of \$700. For these events, registration fees can begin to compete with airfare as a significant contributing financial consideration.

By eliminating these travel and registration costs, the 2020 virtual ICLR, AAS and NAMS delegations were more geographically diverse. Notably, the audiences were 118%, 97% and 41% larger than the historical average for in-person conferences, respectively (**Figure 2b and Table S3**). Attendance by scientists from NI>10 countries increased significantly from the historical average at legacy ICLR, AAS, and NAMS conferences (204, 11, and 50.3 attendees) to the 2020 virtual ICLR, AAS, and NAMS conferences (955, 64, and 65 attendees), respectively (**Figure 2b**). The increased representation was more comparable to delegations seen at conferences originally designed for the virtual environment; specifically, 31% and 38% of attendees at the virtual POM 1 and POM 2 from NI>10 countries (**Figure**

S1). Survey responses indicated that reduction in cost and travel burdens such as documentation and time away from home were primary factors in the increase in attendance from underrepresented countries:

“[The online format] saves money and it makes it possible to attend without giving up on other professional & private duties. I might haven't attended a conference as I live in India far away from the venue. It takes a lot of time for the visa process. As a research scholar, it's tough to get a travel accommodation budget for it. It was time-saving too.” - POM 2 survey respondent

Participation of Women The virtual conference format also eliminated travel burdens that can act as a barrier to attendance for certain sociodemographic groups. This was reflected by changes in the gender makeup of virtual conference delegations (**Table S4**). Attendance by women increased between 66% and 253% at ICLR, AAS, and NAMS virtual conferences compared to the in-person baselines (**Figure 3**). On average, women made up $24 \pm 10\%$ of delegations at the most recent years of these in-person conferences (2018-2019); this fraction increased to $29 \pm 8.5\%$ in 2020 when these conferences transitioned online (**Figure 3g**). The increase in the number of female attendees is especially significant considering that women make-up smaller portions of STEM fields compared to men. For example, women make up only 33% - 34% of STEM researchers in the countries that make up the delegations for historical in-person ICLR, AAS, and NAMS conferences (**Table S5, S6, S7**). Thus, an increase in attendance represents a larger portion of female scientists who would not have attended an in-person conference, relative to the portion of men that would not have attended. Survey responses confirmed that the elimination of the travel requirement realized with virtual conferences could partially explain trends in attendance by gender. About half (47%) of the 2020 virtual NAMS survey respondents that did not plan on attending the in-person 2020 NAMS conference indicated that the primary reason for attending the virtual conference was convenience (**Figure S2**). Survey respondents pointed specifically to alleviation of concerns about childcare, a burden that disproportionately affects women¹⁸, as a driver of social equity at virtual conferences:

“[The online conference format is] Environmentally friendly, allows people with caring [responsibilities] to attend, the opportunity for a far more diverse speaker pool and delegates.” -POM 2 survey respondent

The transition from a legacy to virtual conference led to a significant increase in interest and participation from female researchers as revealed from analysis of abstracts submitted to the 2020 NAMS conference before and after the decision to switch. Approximately a quarter (25%) of abstracts submitted to the 2020 in-person NAMS conference were from female researchers, which was aligned with historical average attendance by women to 2015-2019 in-person NAMS conferences (**Figure S3**). After it was announced that the 2020 NAMS conference would be held online, 37% of submitted abstracts came from female scientists (**Figure S3**). The 2020 virtual ICLR also saw an

increase in attendance from gender queer and transexual scientists. On average, 2018-2019 in-person ICLRs were attended by 1 gender queer scientist and 0 transgender scientists. The 2020 virtual ICLR was attended by 8 gender queer scientists and 2 transgender scientists (**Figure 3a**).

Participation of Students and Postdoctoral Scholars. High costs characteristic to legacy conferences can also be exclusionary to certain sociodemographic groups that may face challenges securing funding for travel, such as students and postdoctoral scholars. While attendance at the 2020 virtual NAMS conference by academic scientists and industry personnel remained fairly constant compared to past in-person events, attendance by undergraduate students, graduate students, and postdoctoral researchers increased by 344%, 100%, and 108%, respectively (**Figure 4 a,b**). The impact of the cost reduction with online conferences on attendance was evident in survey responses, as 33% of respondents to NAMS surveys indicated that they were not planning on attending the scheduled 2020 in-person NAMS conference prior to the decision to move online (**Figure S4**). Of the respondents that were not planning on attending the 2020 in-person NAMS conference, 34% indicated that cost was the primary motivation for attending the 2020 virtual NAMS conference (**Figure S2**). Responses to surveys distributed to 2020 virtual NAMS attendees indicated that increased student participation was a direct result of this reduction in the cost of attendance:

“I think this format was also great for allowing additional student participation and I had more students attend online than were going to come in person due to the financial differences.” -NAMS survey respondent

Consistent with previous conferences discussed, attendance by students to 2020 virtual ICLR increased dramatically relative to in-person ICLRs. Students as a fraction of the ICLR delegation increased from 33% for the 2019 legacy ICLR to 52% for the 2020 virtual ICLR (**Figure 4c**). These high student participation levels are consistent with trends seen at virtual conferences. Students made up 49% of the delegations at both POM 1 (January 2020) and POM 2 (June 2020) conferences (**Figure S5**), likely due to the accessibility of the virtual format. The AAS conference surprisingly did not show much change in conference composition as seen from surveys (32% completion) (**Figure S6**). On average, for all conferences evaluated, the virtual conference delegations had higher proportions of students (29% to 43%) and postdoctoral scholars (5% to 11%) compared to the most recent in-person event (2019) (**Figure 4d**).

Participation from Historically Underrepresented Institutions. Attendance from non-research-intensive institutions also increased at virtual conferences. Attendance at the 2020 virtual NAMS conference by persons from Primarily Undergraduate Institutions (PUIs) and High Research Activity (R2) Universities (as distinct from the Very High Research Activity Category – R1) increased from the in-person conference baseline by 157% and 45%, respectively. Attendance at the 2020 virtual AAS conference from PUIs and R2 Universities increased by 72% and 106%, respectively (**Figure 4e**). Increased attendance from PUIs and R2 universities could interest more undergraduates in graduate school and improve the educational experience for virtual conference participants from these historically excluded institutions.

Effect of Time Zones and Conference Format. While virtual conferences eliminated many barriers to participation, the impact on international attendances was strongly dependent on the virtual conference format (**Figure 5**) with the primary variations being synchronous or asynchronous content delivery. The 2020 virtual NAMS conference was organized around synchronous live talks. Consequentially, attendance from regions where the conference was held during normal work hours significantly increased, with attendance from Europe and the Middle East increasing by 102% and 76%, respectively, when compared to the 2015-2019 NAMS conference average. Conversely, for Asia, where the 2020 virtual NAMS conference was held around or past midnight local time, attendance decreased by 62%. The 2020 virtual ICLR was asynchronous, with only a few live events and most talks pre-recorded and released for consumption at the attendee's leisure. Consequently, attendance at the 2020 virtual ICLR increased for all regions (57% to 1700% increase), when compared to the 2018-2019 legacy ICLR average. Attendance at the 2020 virtual AAS conference also increased for all regions compared to legacy AAS conferences (60% to 700% increase), with the largest percent increases coming from Europe, Oceania, and Other Americas. Thus, it is clear that to take full advantage of the virtual format and to make these events effective at disseminating science, it is necessary to offer content asynchronously.

Initial Attendee Perceptions of Virtual Conferences. The virtual conference format, in general, was well received by attendees and helped to shift negative perceptions to more positive views towards this format. Attendees to 2020 virtual conferences indicated via pre-conference surveys that they were initially skeptical about the efficacy of virtual conference components, but overall felt that the format could possibly improve legacy conferences in some ways. When asked what they foresaw as the biggest challenge with the virtual format, networking and social interaction was the most common response for NAMS surveys (42% of respondents) and POM 2 surveys (25% of respondents) (**Figure S7**). Aversion to engaging with the virtual format was lowest among students, as indicated by the fact that only 25% of graduate students and no undergraduate students who submitted abstracts to the 2020 in-person NAMS conference elected to withdraw from the conference once it was moved online. Conversely, 37% of industry personnel and 39% of postdoctoral researchers who applied to the 2020 in-person NAMS conference elected not to attend the 2020 virtual NAMS conference (**Figure S8**). NAMS survey respondents indicated that they were looking forward to some aspects of the virtual format, particularly the opportunity to seamlessly transition between sessions and quickly access the internet to research unfamiliar concepts that arose during the conference.

Part of the success is related to the wide range of currently available virtual environments for hosting oral sessions. Oral sessions at analyzed conferences were either livestreamed via webinar (synchronous format) (**Figure S9**) or pre-recorded and released at a specified time (asynchronous format). They were popular among attendees, with 43% of NAMS survey respondents and 74% of POM 2 survey respondents indicating that they preferred the virtual format for oral sessions over the in-person format (**Figure S10 and S11**). The presentations and Q&A sessions were recorded and made available indefinitely, eliciting persistent viewing after the conference ended. The ICLR platform drew 652,087 total pageviews during the scheduled conference days, and then views increased again by 74% (481,092 additional

views) in the three months following the conference, indicating increased exposure time for presenters and sponsors compared to the in-person format (**Figure S12**).

Analyzed virtual conferences had poster authors publish their posters via twitter, using a web-based iPoster sharing platform, or by uploading a 5-minute pre-recorded presentation to the conference website. The poster presentations had high view counts (NAMS iPosters had on average 142 views) (**Figure S13**), but presenters could not tell how many attendees were viewing their posters and features for communicating with poster viewers were not effective. Consequently, virtual posters were less popular, with 85% of NAMS survey respondents and 43% of POM 2 survey respondents indicating that they preferred in-person poster sessions to virtual poster sessions (**Figure S10 and S11**). Analyzed virtual conferences experimented with incorporating social media and organizing virtual breakout rooms to facilitate networking with some success. However, survey respondents indicated that the interactions felt inauthentic and contrived. As a result, 75% of POM 2 survey respondents and 96% of NAMS survey respondents indicated that they preferred in-person networking to virtual networking (**Figure S10 and S11**).

One approach to overcome this challenge, holding locally-organized viewing hubs, was piloted during POM 1. This “conference within a conference” approach allowed for reduced cost and travel, increased local and regional networking, and created an international conference. Notably, approximately half of the POM 1 attendees participated in the conference from a local hub-site. This approach could be one solution post-pandemic.

Environmental Impact

The carbon footprints of in-person conferences was defined as the warming potential in CO₂ equivalents (CO₂e) of the sum total of GHG emitted by the hotel stays and air travel of all conference participants. This value was dominated by air travel emissions and has increased over time (**Figure 6a, 6b and Table S8**). Given the increase in attendees at the virtual conferences, both absolute numbers and international participation, the theoretical GHG emissions for the 2020 virtual conferences would have significantly increased if they were held in-person. However, as expected, carbon footprints were practically negligible for online conferences.

As shown in **Figure 6b**, the carbon footprint for a single international attendee to the 2019 in-person ICLR, AAS or NAMS conferences is approaching the median global per capita carbon budget (0.72 tonnes CO₂e) for the entire year of 2030 in a collection of proposed decarbonization pathways designed to limit global warming to 1.5° C with a small overshoot¹⁹. Therefore, the carbon footprint of a single attendee to an in-person conference is a substantial fraction of the recommended per capita annual carbon budgets, and many attendees attend multiple international events per year. For further context, the ~2.5 tons of CO₂e emissions caused by an international attendee to one of these in-person conferences is roughly equivalent to the footprint of an average US passenger vehicle traveling ~10,000 km²⁰.

Conversely, the total carbon footprints of the 2020 virtual ICLR, AAS, and NAMS conferences were 0.80, 0.17, and 0.10 tonnes CO₂e, respectively (**Table S8**), calculated as the GHG emitted due to computer processing¹³. The carbon footprints for 2020 virtual ICLR, AAS, and NAMS conferences represent only 0.005%, 0.013%, and 0.012% of the emissions that would have been released if the same delegation for the virtual events had attended in-person conferences at the originally planned locations. For further context, the cumulative footprints of the more than 7000 attendees to 2020 virtual ICLR, AAS, and NAMS conferences (1.07 tonnes CO₂e) was comparable to the average footprint of a single attendee to one of these 2019 in-person conferences (**Figure 6b and Table S8**).

Discussion

Our findings reveal that virtual events reduce the environmental impact of conferences and are more accessible to a broader audience, thus addressing many challenges related to diversity, equity, and inclusion. Virtual conferences allow researchers to overcome economic and travel related barriers that are intrinsic to legacy conferences and that ultimately discourage participation from institutions and countries with limited resources, women, and early career researchers and practitioners (e.g., students, postdocs).

Addressing inequities in opportunities is a global, cross-cutting challenge across workforce sectors (e.g. industry, academia, government, and non governmental organizations). Discovering and applying ways to improve diversity, equity, and inclusion imbalances has the potential to transform society, as well as spur innovation and economic growth through a greater pool of talent and worldviews.

Here, data collected from legacy conferences and virtual conferences revealed a significant reluctance to operating in the new virtual environment (**Figure S7**). These initial hesitations towards virtual conferences are unsurprising as the pandemic caused an abrupt disruption to the institutionalized view of what a conference in fact looks like, much of which is tied to in-person interactions. While many of these reservations were alleviated in post conference surveys, some resistance still remained. The reluctance to moving conferences online could likely be overcome by learning from successful online events in other areas that have afforded participants the option to forego expensive, in-person experiences, and instead engage virtually for modest or no fees. As an example, the share of U.S. movies produced that were released into theatres has steadily declined in recent years²¹ and YouTube reported 83 million livestream views over the first weekend of its coverage of the 2019 Coachella music festival²². Virtual technology has also given rise to alumni events for universities at small hubs around the globe. Attendees to these events can engage virtually with a global community by streaming sporting events in concert with other hubs, all while interacting in-person with local community members²³. Similarly, massive open online courses (MOOCs) have emerged as a major method of knowledge dissemination, with MOOC students indicating that reductions in cost and travel barriers were motivations for attendance^{24, 25}. As such, there is a clear case for innovation in the conference format that includes at least a partial move to an online experience.

An important final barrier highlighted by many attendees to make this move online in the future is the limited opportunities for networking. Seventy-five percent of POM 2 survey respondents and 96% of NAMS survey respondents indicated that they preferred in-person networking to virtual networking. Analyzed virtual conferences experimented with incorporating social media and organizing virtual breakout rooms to facilitate networking with some success. However, survey respondents indicated that the interactions felt inauthentic and contrived. The hybrid hub approach pioneered by POM 1², where groups of people congregate in local hubs to participate in a global online conference, is a promising solution to this challenge that warrants further study. A hybrid format could allow communities to realize many of the advantages identified by this analysis of virtual COVID conferences, while still offering the option of a traditional in-person conference experience. It would be ideal for post-pandemic conferences to utilize the rich knowledge gained on the benefits of expanding inclusion using online tools being developed. The

resultant conferences could facilitate networking and effective dissemination of scientific knowledge to diverse audiences in an environmentally sustainable manner, moving toward more equitable environments and opportunities.

Our study is characterized by one important limitation. While nearly all interactions made the abrupt shift from in-person to online, our analysis is focused on scientific events. In some ways, the demographic and financial sensitivities of this population is distinct from an industry or government audience. However, they do share several similarities, particularly for global industry consortiums. Notably, all groups are sensitive to international politics and visa policies, fluctuations in currencies and the financial markets, and gender inequities. However, the attendees at scientific events tend to be highly educated (BS degree or higher in a STEM field) and speak English as a primary or secondary language. These limits do not adversely affect our conclusions, as we have focused our analysis on academia. However, to extend our conclusions outside of higher education and STEM fields specifically, a broader population analysis should be performed with appropriate benchmarking. Such an analysis will require engaging members of industry, nonprofits, and government organizations.

The present research findings motivate several new areas of investigation. A few examples include: (1) developing strategies for improving virtual networking, (2) role of organization type on the impact of travel (small vs. large business, domestic vs. global), (3) policy development by technical/scientific societies, funding agencies, and universities, and (4) longitudinal study tracking travel and career progression. In this context, we consider the present conclusions to be a significant first step in understanding the positive impact of virtual events, paving the way for future policy decisions and reducing inequality in the workplace.

Methods

Data

Registration and survey data were collected from three legacy-turned-virtual conferences (**Table S9**), specifically the International Conference on Learning Representations (ICLR, ~2300 historical average attendees), the American Astronomy Society (AAS) Summer Meeting (~700 historical average attendees), and the North American Membrane Society (NAMS) Annual Conference (~450 historical average attendees). Complementing this is data from Photonics Online Meetups (POM, ~1000 attendees), a conference series that was specifically designed for the online ecosystem prior to the COVID-19 pandemic. These conferences represent varying fields and community sizes and allow for comparisons across a range of STEM backgrounds. Data for legacy-turned-virtual conferences were collected for 2020 virtual events and for historical in-person conferences. POM data provided a control for an always virtual event, while the baseline data for historically in-person conferences allowed for the elimination of effects from other variables, facilitating direct analysis of the impact that virtual components had on conference performance.

Specific data collected include registration and abstract information, spanning information such as the number and type of participants (e.g., students, industry personnel), geographic participation, institution, or gender. For legacy-turned-virtual conferences, this data was collected for registrations accrued before and after moving online. Carbon footprint and cost of attendance were estimated based on attendee work locations and conference destinations. Descriptive statistics and thematic mapping were applied to understand changing sociodemographics realized in the shift to a virtual format. Additional data collected on webinar attendance and virtual platform activity were used to assess the efficacy with which the virtual conferences distributed content to attendees. Qualitative data was collected

by asking participants to fill out polls as well as pre-and-post conference surveys designed to interrogate the participant experience and field suggestions for improvement.

Sociodemographic data was provided by conference organizers and filled in as necessary. Attendee countries were manually categorized by region for analysis. Job type data (i.e. Graduate Student, Industry Personnel) was provided by conference organizers via registration or survey data. Data that included specific job titles (i.e. Operations Director, Research Scientist) for attendees were categorized manually by job type. Gender data was provided by organizers for some conferences via voluntary surveys. Gender data for the NAMS conference was manually assigned based on author familiarity with the participants and through internet search of attendee names. The Gender API²⁶ was also employed to assign gender to attendee names for NAMS and AAS conference attendees. Due to confidence in the accuracy of manually assigned names for NAMS attendees, discrepancies in the genders assigned to NAMS attendees by the manual process and the Gender API indicated that the Gender API was less accurate than the manual process (**Table S4**). Consequently, the Gender API was only applied to assign gender to AAS participants. Attendee academic institutions were manually categorized according to databases of institution types. Minority Serving Institutions were defined according to the 2007 U.S. Department of Education database²⁷. High Research Institutions (R2) were defined as any institution that was included in the 2018 Carnegie Classification of R2 Universities²⁸. Primarily Undergraduate Institutions (PUI) were defined as any university that awarded 20 or fewer PhD degrees in NSF-supported fields during the combined previous two academic years²⁹ as reported by the U.S. National Science Foundation (NSF) records on PhD degrees for major science and engineering fields awarded by universities during 2017 and 2018^{30,31}. Non-research-intensive countries were defined as countries that were not in the top 10 countries for scientific research as defined by the Nature Index that measured top countries in terms of contributions to papers published in 82 leading journals during 2019 (NI>10)¹².

Travel Distance

Attendee travel distance, carbon footprint, and cost were calculated via python scripts using attendee origin location data provided by conference organizers. NAMS and AAS registrant origin locations were provided by organizers via registration data as a list of attendees with attendee-specific locations. If location for an attendee was not included, origin location was determined via internet search of the attendee name. ICLR and POM registrant origin location data was provided by conference organizers and comprised a list of countries in attendance and the number of attendees from each country. While the sample size of data for single ICLR conferences varied by data type (i.e. origin country, gender, job title), origin country was the largest dataset for all ICLR conferences, and was thus assumed to be the true size of the conference delegations.

Conference city and attendee origin coordinates were determined by querying the Google Maps API³² with the location names. If a city-specific attendee origin was not recognized by the API, the attendee origin was set to the attendee's origin country name. Google Maps API queries of only country name return coordinates for the geographical center of the country. Travel distance between attendee origin and conference location were calculated as the great circle distance (great_circle python package).

Carbon Footprint of Attendance

The carbon footprint of conference attendees was calculated for all in-person turned virtual conferences as the cumulative emissions associated with the flight and hotel stay. The air travel carbon footprint was calculated according to the methodology for the myclimate air travel emissions calculator³³. The myclimate calculator computes air travel footprint by adding 95 km to the great circle distance to account for flightpath inefficiencies and calculating greenhouse gas (GHG) emissions associated with the fuel burn and life cycle footprint of the airplane and associated aviation infrastructure. The GHG emissions are then converted to CO₂ equivalents (CO₂e). It was assumed that all conference attendees flew economy class. If city-specific attendee origin data was available and the attendee was local (<= 100 km from the conference city) it was assumed that the attendee did not fly to the conference city, and their travel CO₂e was set to 0. If registrant origin coordinates were not found, the attendee travel distance and travel footprint were set to the average for that conference.

The carbon footprint per night for the attendee hotel stay was determined using the Hotel Carbon Measurement Initiative (HCMI) rooms footprint per occupied room from the Hotel Sustainability Benchmarking Tool published by the Cornell Center of Hospitality Research³⁴. The tool provides city-specific and country-specific footprint data. If data was not available in the Hotel Sustainability Benchmarking Tool for the conference city, then the footprint per night was set to the country average in the tool. If no data was available for the country in which the conference was held, the footprint was set to the value that was closest to the conference location geographically. Student hotel footprint calculations were adjusted to assume shared hotel rooms, i.e. footprint per night was divided by two. If attendee specific job title (student vs. non-student) information wasn't available, percent students as defined by the voluntary survey data was multiplied by the number of attendees from each country to estimate the number of students from each country. When computing total hotel footprint, it was assumed that attendees stayed for all but one night of the conference (i.e. for a four-day conference, nightly hotel footprint was multiplied by 3). If the attendee was local, the hotel footprint was set to 0. If the attendee origin was not near the conference city and their job title (student vs. non-student) was not known, the attendee hotel footprint was set to the conference average.

Cost of Attendance

Cost of attendance for individual attendees was computed for historically in-person turned virtual conferences by calculating their cost of travel based on air travel distance and summing with the estimated cost of the hotel, food, and conference registration fees. Travel cost was calculated as the one-way air travel distance multiplied by the cost distance for air travel defined in ¹⁷, and doubled to represent the cost of a round trip flight. If the registrant was local, their travel cost was set to 0. If the registrant origin was not known, the travel cost was set to the average conference travel distance and converted to cost using ¹⁷. To account for a potential overestimate of travel cost, a sensitivity analysis where the one-way flight cost is multiplied by 1.5 instead of 2 was conducted and is presented in **Table S1**.

NAMS hotel cost was taken from NAMS records. 2020 ICLR hotel cost was set to the average of hotel options provided by the ICLR website. For 2018-2019 ICLR and all AAS conferences, the cost of U.S. hotels was set to the U.S. General Services Administration lodging max per diem for the conference city. For 2018-2019 ICLR the cost of all hotels outside of the United States was set to the U.S. State Department lodging max per diem for the conference city. Nightly hotel costs were divided by two for students to assume shared rooms. If attendee specific job title (student vs. non-student) information was not available, percent students as defined by the voluntary survey data was multiplied by the number of attendees from each country to estimate the number of students from each country. ICLR 2020 student hotel cost data was taken from "double room rate" and ICLR 2020 non-student hotel cost data was taken from the "single room rate" cost on the ICLR website. When computing total hotel cost, it was assumed that attendees

stayed for all but one night of the conference (i.e. for a four-day conference, nightly hotel cost was multiplied by 3). If the attendee was local, the hotel cost was set to 0. If the attendee was not local, but their job title (student vs. non-student) was not known, the hotel cost was set to the conference average.

Food cost for conferences held in U.S. cities was taken from U.S. General Services Administration city-specific per diem rates for breakfast, lunch, and dinner. For NAMS, one dinner is subtracted from the total cost to account for the banquet dinner provided by NAMS. Food cost for conference cities outside of the U.S. was taken from U.S. State Department city-specific Meals and Incidental Expenses (M & EI) per diem. Attendees were assumed to stay for all but one night of the conference. If the attendee was local, food cost was set to 0. If the attendee origin was not known, the food cost was set to the conference average.

Registration costs for historical in-person NAMS conferences was set to the recorded registration fee per registrant. Fees for the sponsor and exhibitor registration types, where sponsors made their contributions via the registration fee, at historical NAMS conferences were set to conference average of that year (these registration types are excluded from the average).

Hypothetical registration fees for an in-person 2020 NAMS conference were assigned to attendees to the 2020 virtual NAMS conference. 2020 NAMS attendees with Registrant Type "Student" were assigned a hypothetical 2020 in-person NAMS registration fee equal to the average fee for students at the 2015-2019 NAMS in-person conferences (average based on Title Category, with "Unknown/Other" title category excluded from the average). 2020 virtual NAMS attendees with Registrant Type "Professional/Academic" were assigned a registration fee equal to the average fee for non-students at the 2015-2019 NAMS in-person conferences (average based on Title Category, "Unknown/Other" excluded).

Student and non-student registration fees for 2018-2019 ICLRs were set to early registration fees from the conference website. The registration fees for the 2020 virtual ICLR were set to the 2018-2019 average fees. As attendee specific job title (student vs. non-student) information wasn't available, percent students as defined by the voluntary survey data was multiplied by the number of attendees from each country to estimate the number of students from each country (i.e. Total student registration fees by country = % students from job title data * total attendees from country * student registration fee).

In-person registration fees for 2016-2019 AAS Conferences were set to the early registration fees for "Full Member / Educator / International Affiliate", "Graduate Student Member", "Undergraduate Student Member", "Emeritus Member", and "Amateur Affiliate" from the 2020 Winter Meeting website. As attendee specific job title information wasn't available, percentages on attendee job title as defined by the voluntary survey data was multiplied by the number of attendees to estimate the number of each job type in attendance. The total registration fee for each conference was calculated accordingly. The total registration fees were then divided by the number of attendees and the average registration fee was assigned to each registrant.

Virtual registration fees for ICLR and NAMS were set to \$50 for students and \$100 for non-students. Virtual registration fees for AAS were set to the full meeting fees for "Full Member / LAD Member", "Graduate Student", "Undergraduate Student / High School Student", "Emeritus Member", and "Amateur Affiliate" from the 2020 Virtual Meeting website.

Attendee origin coordinates and conference city coordinates were converted to great circle distance paths and saved in .kml files using the lxml and geographiclib.geodesic python packages. World maps were plotted using Tableau and MapBox.

Global Annual per Capita Carbon Budget for 2030 and 2050

Median global carbon budget calculated in terms of Kyoto GHG as CO₂e for 2030 and 2050 were taken from a set of decarbonization pathways as outlined in the Intergovernmental Panel on Climate Change report on Mitigation Pathways Compatible with 1.5° C in the Context of Sustainable Development¹⁹. The global carbon budget was divided by the medium variant of global population projections for 2030 and 2050 produced by the United Nations Department of Economic and Social Affairs³⁵.

Car Travel Footprint

Car travel footprint per mile was taken from U.S. EPA estimates for average passenger vehicles²⁰.

Virtual Conference Carbon Footprint

Virtual conference footprints were estimated based on emissions for Youtube video streaming multiplied by the projected duration of conference webinar and video streaming by attendees¹³.

Regional Average Cost/Regional Per Capita GDP

Country specific GDP per capita was defined as the 2019 GDP per capita in the attendee country's national currency converted to USD and divided by the total country population as calculated in the World Economic Outlook Database³⁶. Total representative GDP per capita for conference attendees from each region was calculated as the sum of GDP per capita for all the countries in each region multiplied by the number of conference attendees from each country in the region. Total cost of attendance for each region was calculated as the sum of the cost of attendance for all the participants from each region. The regional average cost divided by the regional per capita GDP was calculated by dividing the total cost of attendance for all the attendees from each region by the total representative GDP for the attendees from each region.

Gender Makeup of STEM Researchers from Conference Attendee's Countries

Country-specific percent women data is taken from "Female researchers as a percentage of total researchers (Full-Time Equivalents) – Natural sciences and engineering (sub-total)" published by³⁷ with the exception of the US which is not included in that dataset. US percent women is derived from women as a percent of MS and PhD graduates employed in Science and Engineering occupations³⁸. Overall percent women in STEM for the countries represented in

the conference delegations was calculated with percent values from each country represented at the conference, weighted by the number of attendees from each country.

Declarations

Acknowledgements

The authors would like to acknowledge Prof. Gisele Ragusa's contribution to designing the pre and post surveys used for the POM 1 and 2 conferences. The work in this paper was supported by National Science Foundation (Award # CBET 2029219). The authors gratefully acknowledge access to data and consultation support provided by NAMS, ICLR, and POM meeting leadership. Dr. Kevin Marvel's input on AAS data and trends and his role in providing access to AAS meeting data is also acknowledged.

Contributions

M.K., K.F and M.S. conceived the idea. M.K and M.S. collected data. M.S. and E.Y. analyzed data. O.R., M.L.L, A.R., and A.A. provided access to data and provided insights on data. M.K., K.F., A.A. and M.S. wrote the manuscript.

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Figures

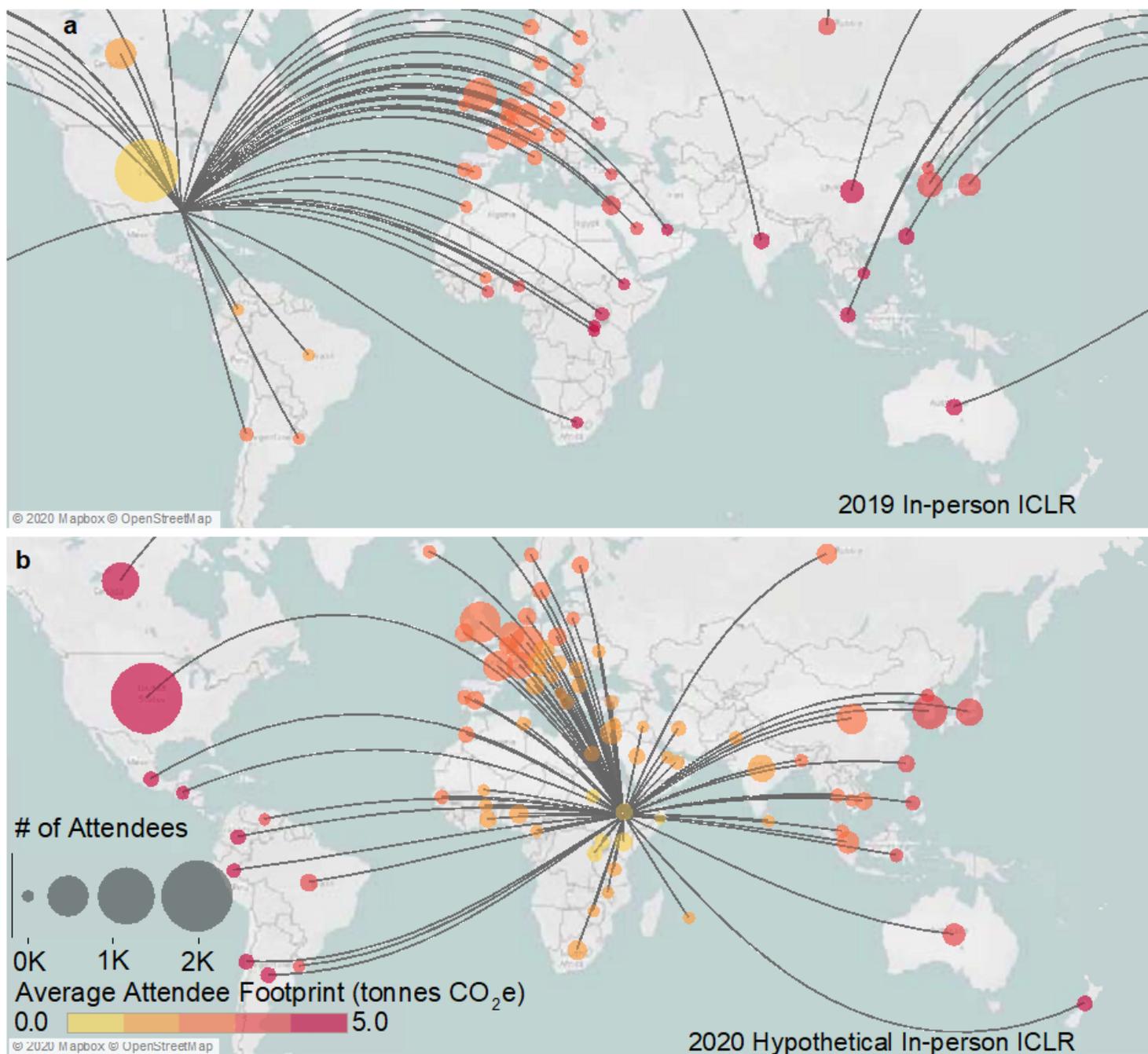


Figure 1

2020 virtual conferences were larger as well as more economically and geographically equitable than historical in-person conferences. (a) The delegation for the 2019 in-person ICLR was global, but concentrated in the United States. (b) The delegation for the 2020 virtual ICLR was larger and more geographically diverse than the 2019 in-person ICLR delegation and would have resulted in a larger number of attendees emitting greater amounts of carbon emissions if it had been held in the originally planned on-site location in Ethiopia. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

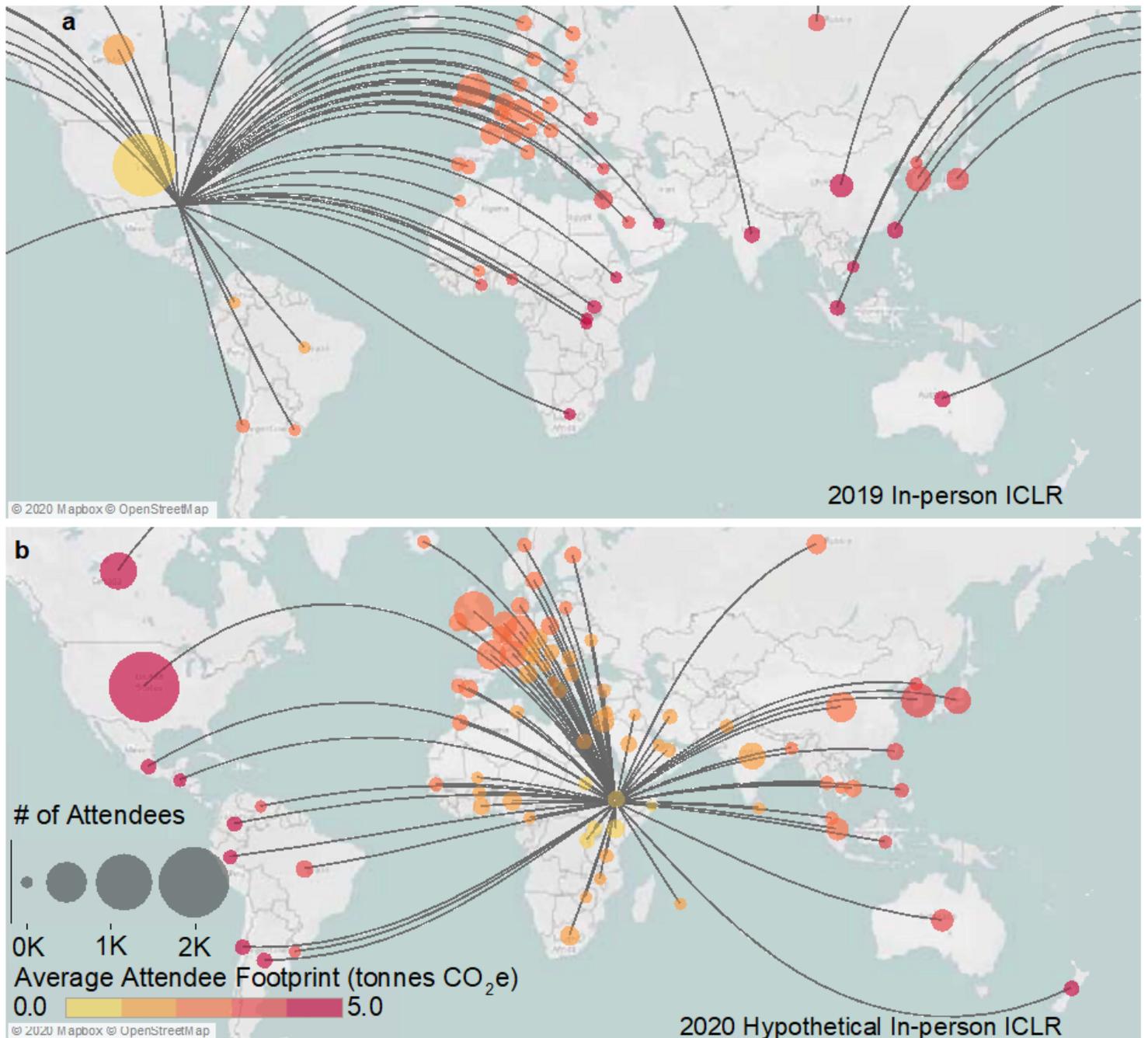


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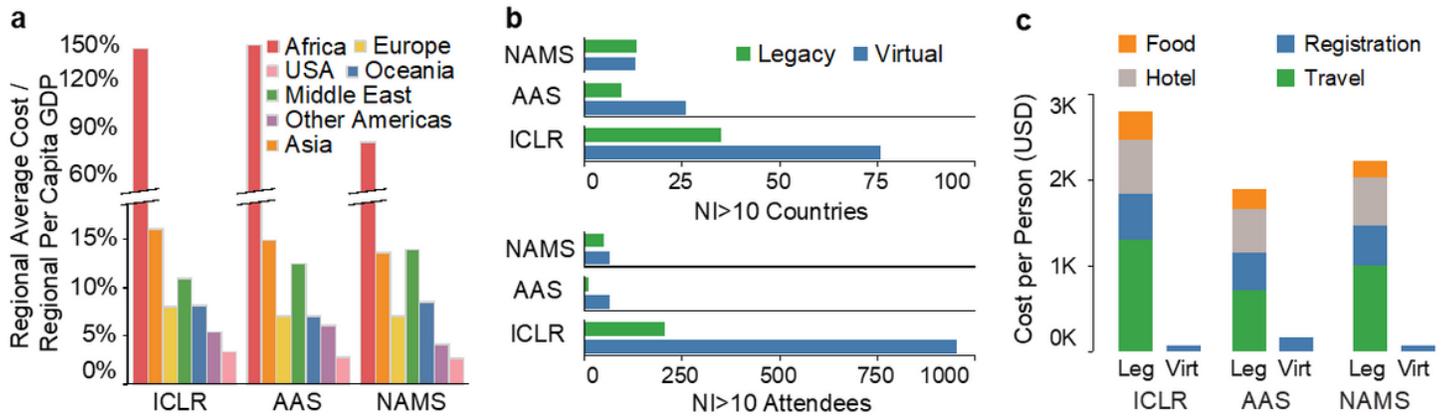


Figure 2

(a) Regional average cost of attendance to legacy (Leg) in-person conferences as a percent of attendee country's GDP per capita for ICLR, AAS, and NAMS conferences was significantly higher for African participants, and very low for US participants. (b) The 2020 virtual delegations for ICLR, AAS, and NAMS generally represented more countries that were not in the top ten research countries as defined by the Nature Index12 (NI>10) and included a higher number of attendees from those countries compared to the average delegations from historical in-person conferences. (c) Average registration, food, hotel, and travel costs for a single attendee to past in-person and 2020 virtual ICLR, AAS, and NAMS conferences totaled thousands of USD, compared to less than 200 USD for virtual conferences.

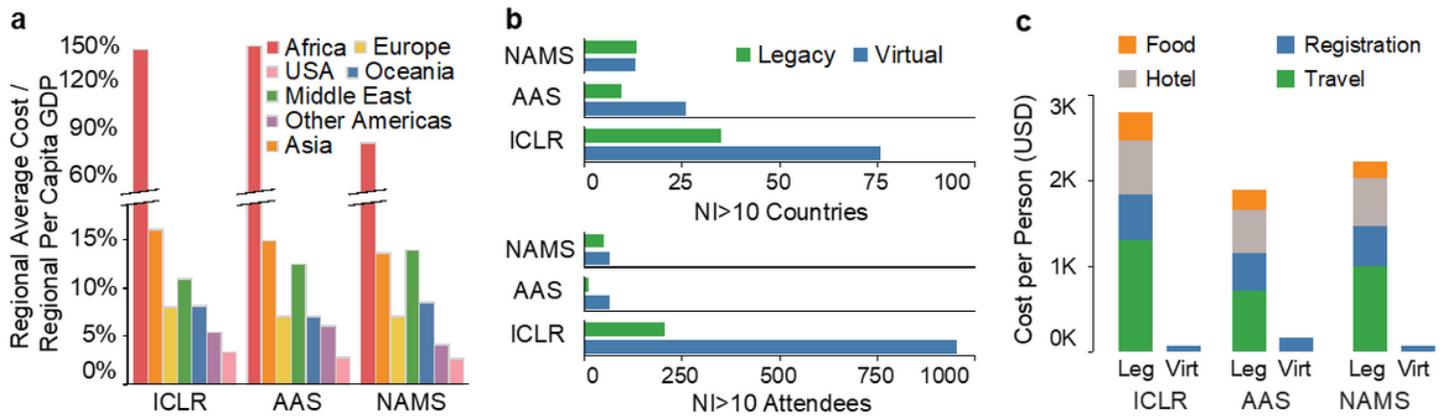


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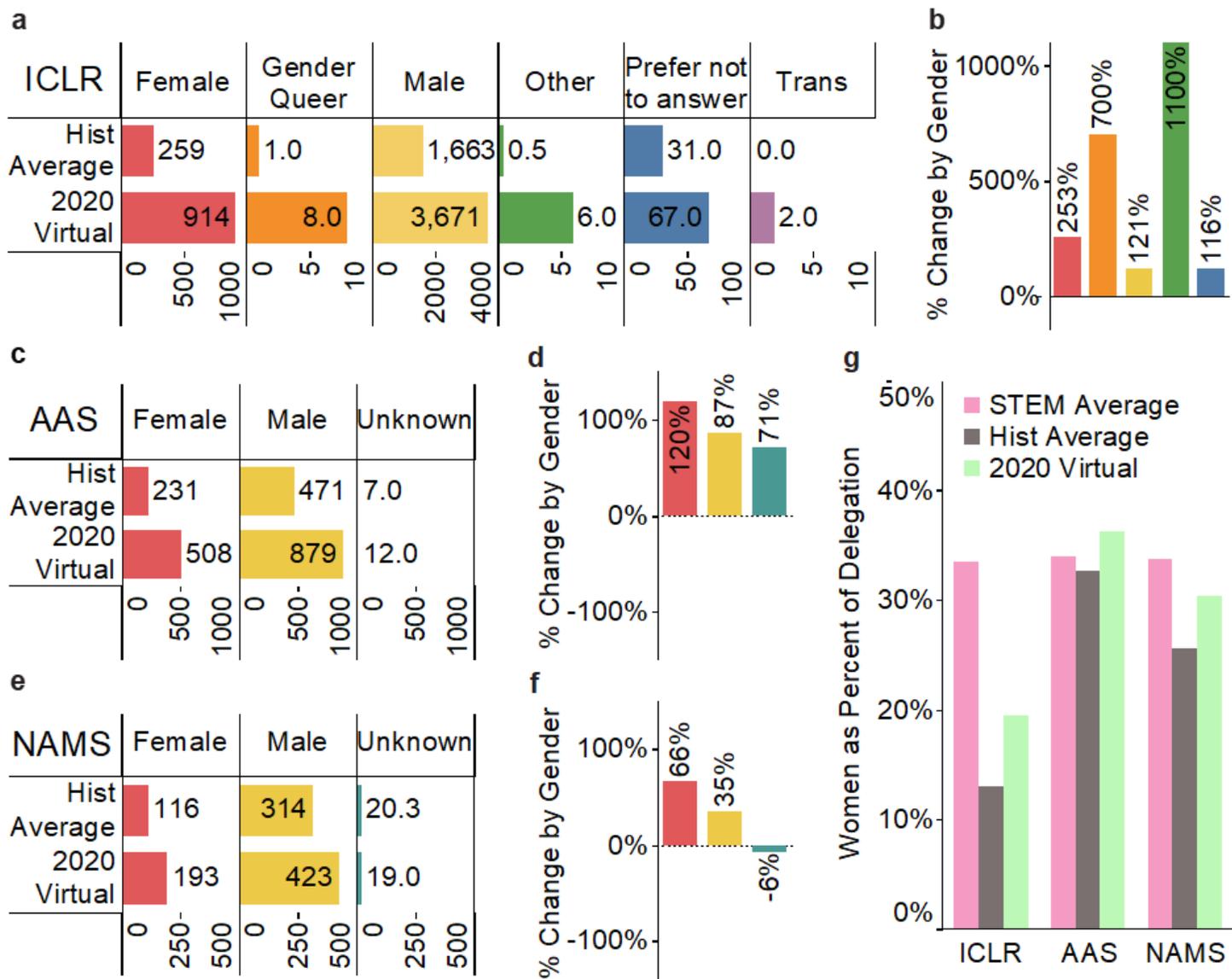


Figure 3

Attendance by women, gender queer, and transgender scientists increased at virtual conferences. (a) The 2020 virtual ICLR was attended by more scientists of all genders compared to the 2018-2019 in-person ICLRs. (b) A positive percent change in attendance for all genders was observed between the 2018-2019 in-person ICLRs and the 2020 virtual ICLR, with the highest percent increase in attendance observed for Gender Queer scientists and scientists that identified as a gender that was not included in the survey. (c) The 2020 virtual AAS conference was attended by more male and female scientists compared to the 2016-2019 in-person AAS conferences. (d) A positive percent change in attendance for male and females was observed between the 2016-2019 in-person AAS conferences and the 2020 virtual AAS conference, with a larger percent increase for female scientists. (e) The 2020 virtual NAMS conference was attended by more male and female scientists compared to the 2015-2019 in-person NAMS conferences. (f) A positive percent change in attendance for male and females was observed between the 2015-2019 in-person NAMS conferences and the 2020 virtual NAMS conference, with a larger percent increase for female scientists. (g) The average percent of delegations that were female at historical in-person conferences was less than the percent of delegations at the 2020 virtual conferences that were female. *Due to attendees of unknown gender, percentages do not sum to 100%.

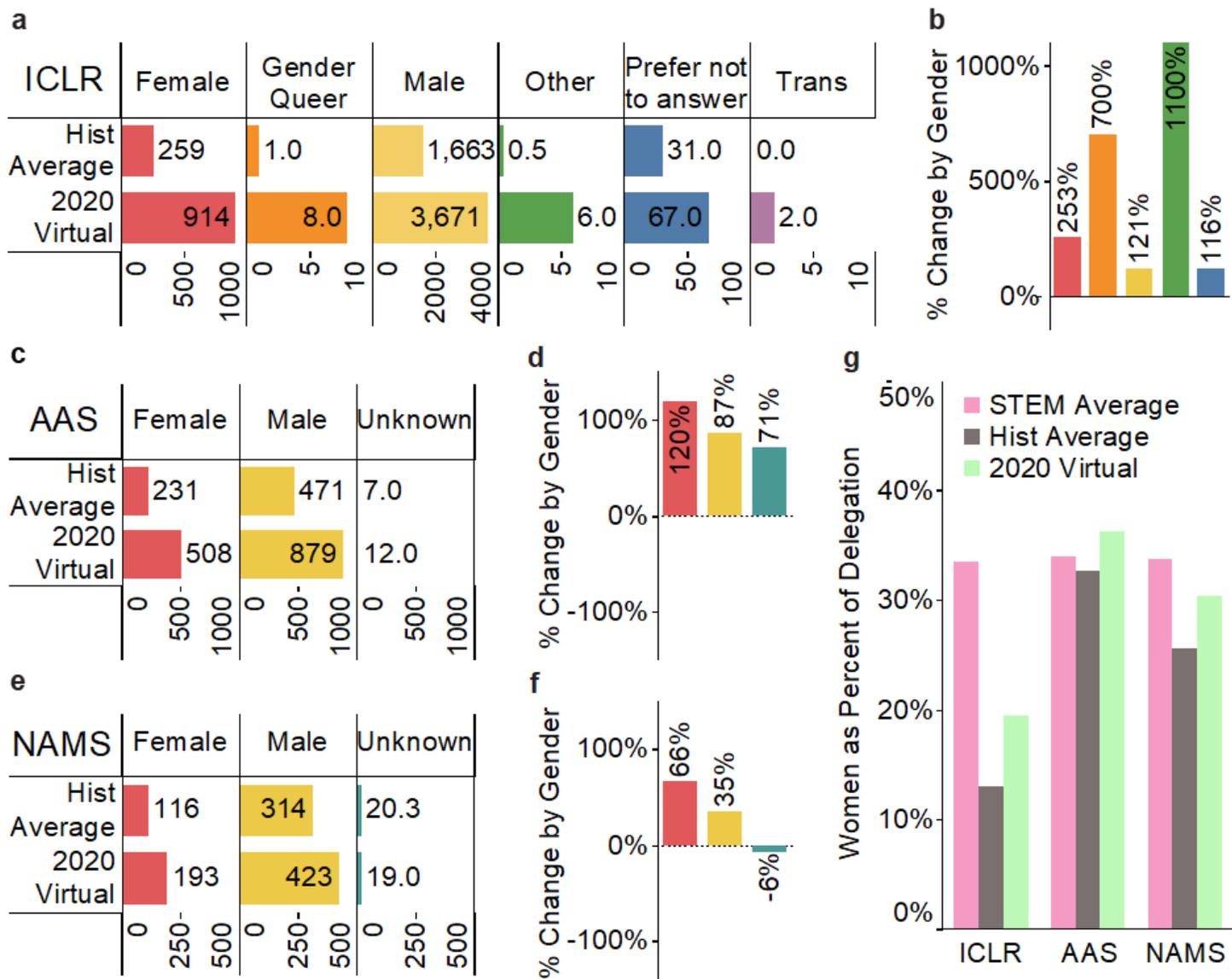


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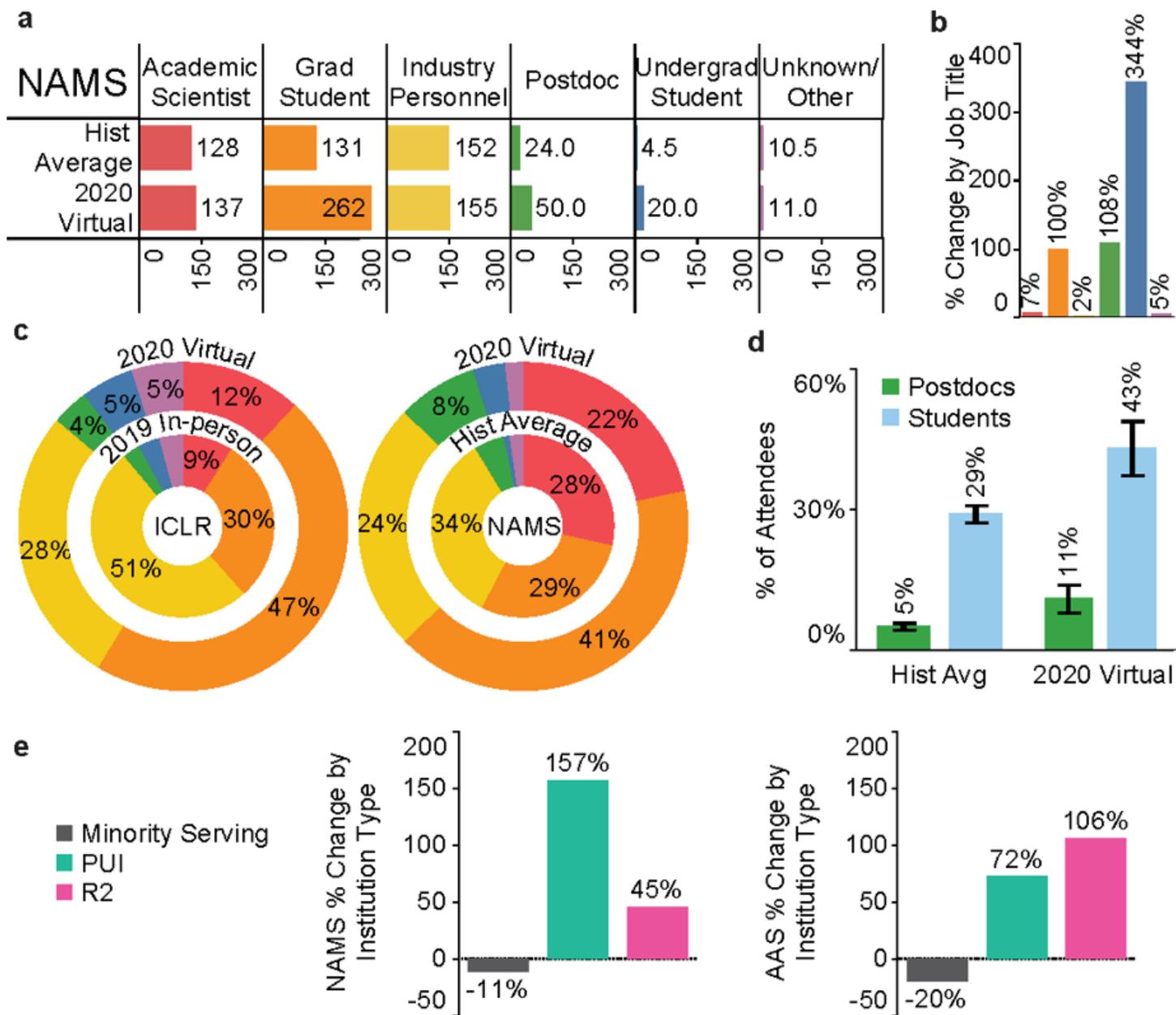


Figure 4

Attendance by students increased substantially at virtual conferences relative to in-person conferences. (a) The 2020 virtual NAMS conference was attended by substantially more students and postdoctoral researchers than the 2015-2019 in-person NAMS conferences, while attendance by other job types remained fairly constant. (b) A positive percent change in attendance for all categories was observed between 2015-2019 in-person NAMS conferences and the 2020 virtual NAMS conference, and percent increase in attendance by students and postdoctoral researchers was very high. (c) Students and postdoctoral researchers made up a larger percent and industry personnel and academic scientists represented smaller fractions of both the 2020 virtual ICLR delegation compared to the 2019 in-person ICLR and the 2020 virtual NAMS delegation compared to the 2015-2019 in-person NAMS conferences. (d) On average, postdoctoral researchers and students made up smaller fractions of the delegations at historical in-person conferences compared to the fractions they represented at the same conferences after they transitioned online in 2020. (e) A positive percent change in attendance by persons from PUIs and R2 Universities was observed at the 2020 virtual NAMS and AAS conferences compared to the 2015-2019 in-person NAMS conferences and 2016-2019 in-

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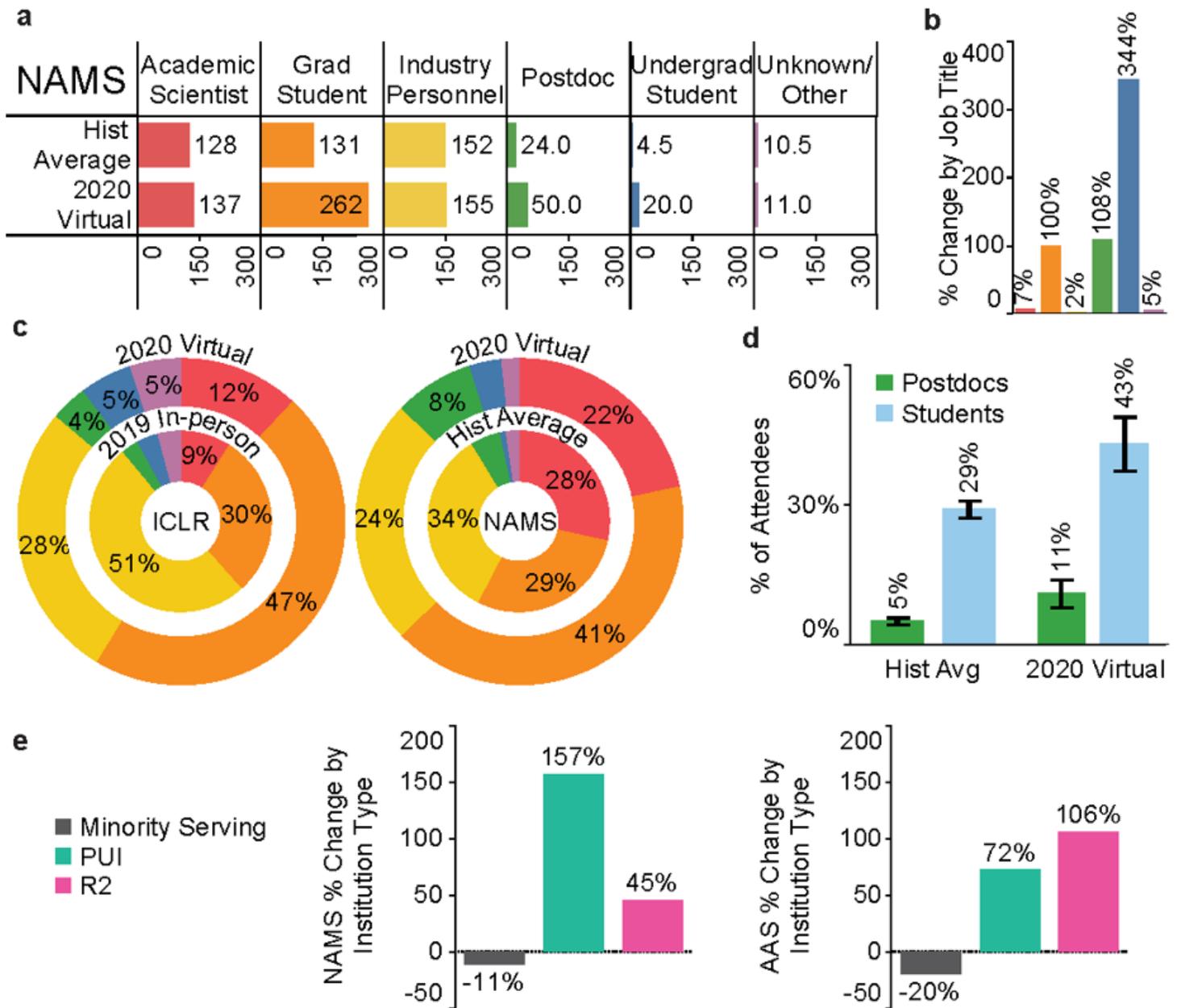


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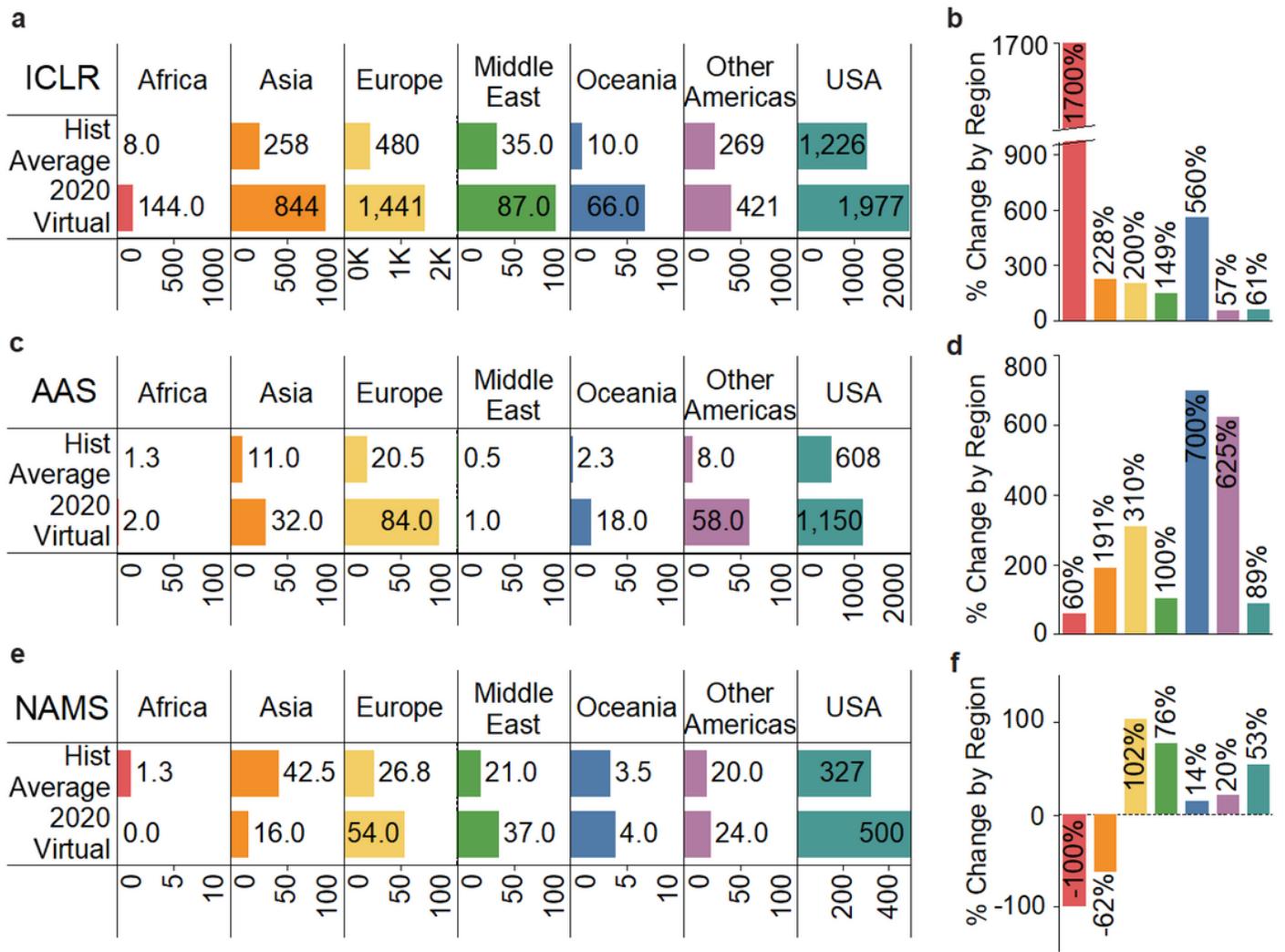


Figure 5

Attendance from most regions increased at virtual conferences, but was dependent on conference format (synchronous vs. asynchronous). (a) The mostly asynchronous 2020 virtual ICLR was attended by more scientists from all regions compared to the 2018-2019 in-person ICLRs. (b) A positive percent change in attendance for all regions was observed between 2018-2019 in-person ICLRs and 2020 virtual ICLR as the asynchronous events could be consumed at the attendees leisure, with the highest percent increase in attendance observed for Africa and Oceania. (c) The synchronous 2020 virtual AAS conference was attended by more scientists from all regions than the 2016-2019 in-person AAS conferences, with the largest increases in attendance observed for Europe, Other Americas, and the United States. (d) A positive percent change in attendance for all regions was observed between 2016-2019 in-person AAS conferences and the 2020 virtual AAS conference, with the highest percent increase in attendance observed for Oceania and Other Americas. (e) The synchronous 2020 virtual NAMS conference was attended by significantly more scientists from Europe, the Middle East and the United States than the 2015-2019 in-person NAMS conferences, while attendance by scientists from Asia decreased. (f) A positive percent change in attendance for most regions was observed between 2015-2019 in-person NAMS conferences and the 2020 virtual NAMS conference, while

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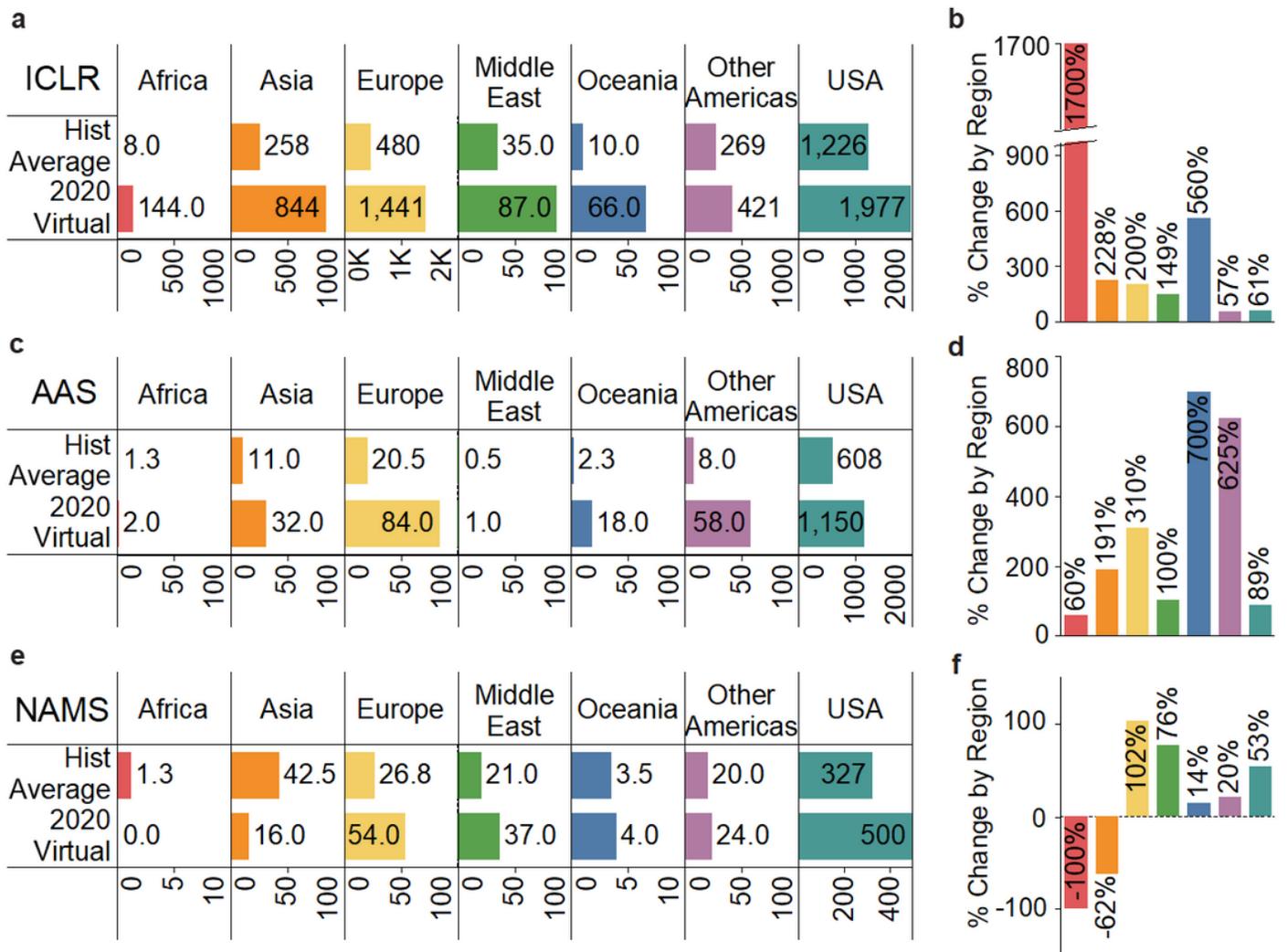


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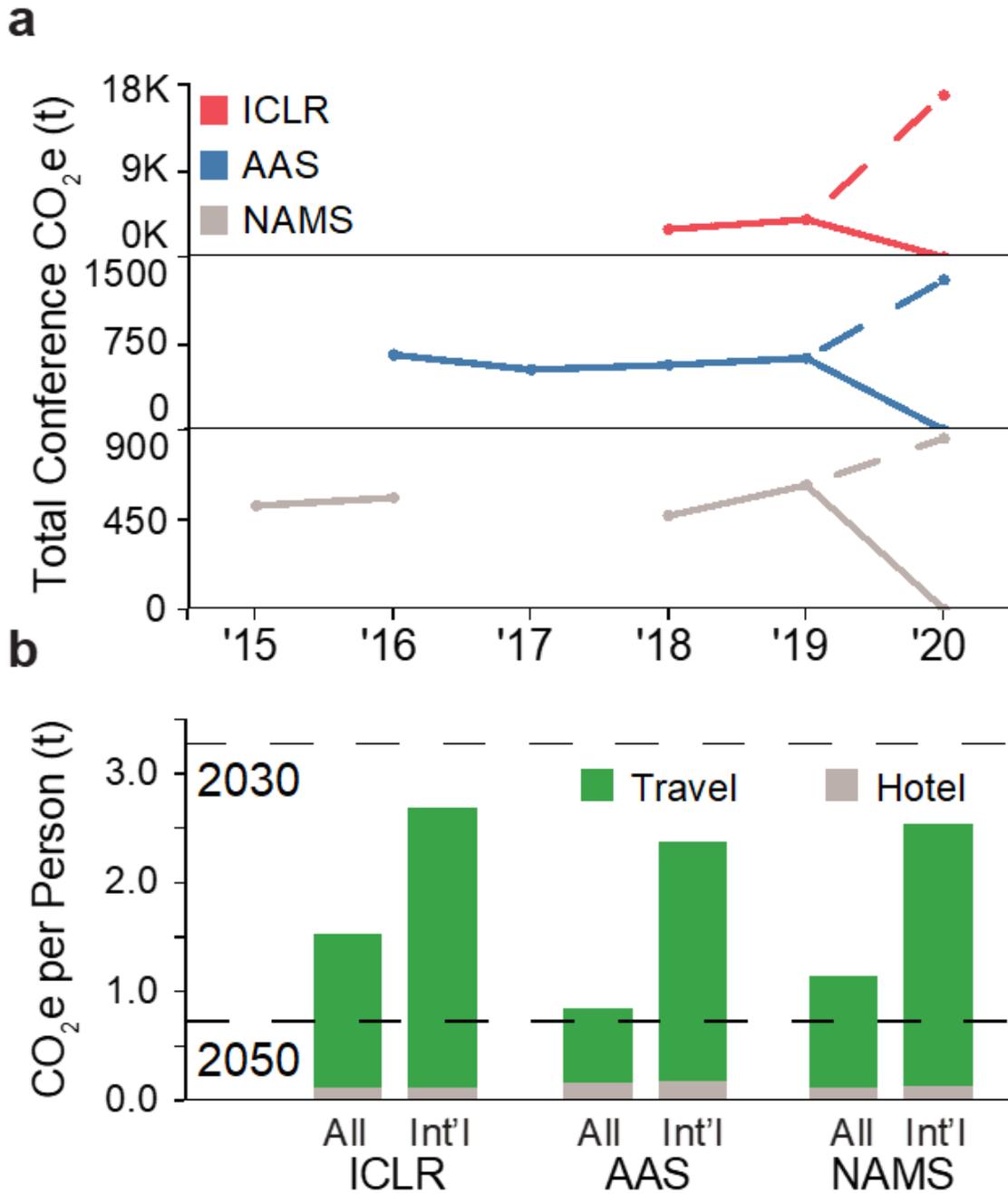


Figure 6

The cost and carbon footprint of in-person conferences are significant, increasing and inequitable. (a) The total summed carbon footprints of air travel and accommodation for all attendees to past in-person ICLR, AAS, and NAMS conferences increased over time and the hypothetical 2020 in-person conference footprint (dotted line), calculated as the footprint if all virtual conference participants had attended an in-person conference at the originally chosen location, was far greater than any previous conferences, while virtual 2020 conferences had near zero footprint. (b) The average carbon footprint of attendance for domestic and international participants to the most recent in-person conferences (2019) were significant compared to the proposed median global per capita annual carbon budgets for 2030 and 2050 in a collection of proposed decarbonization pathways designed to limit global warming to 1.5 C with a small overshoot¹⁹.

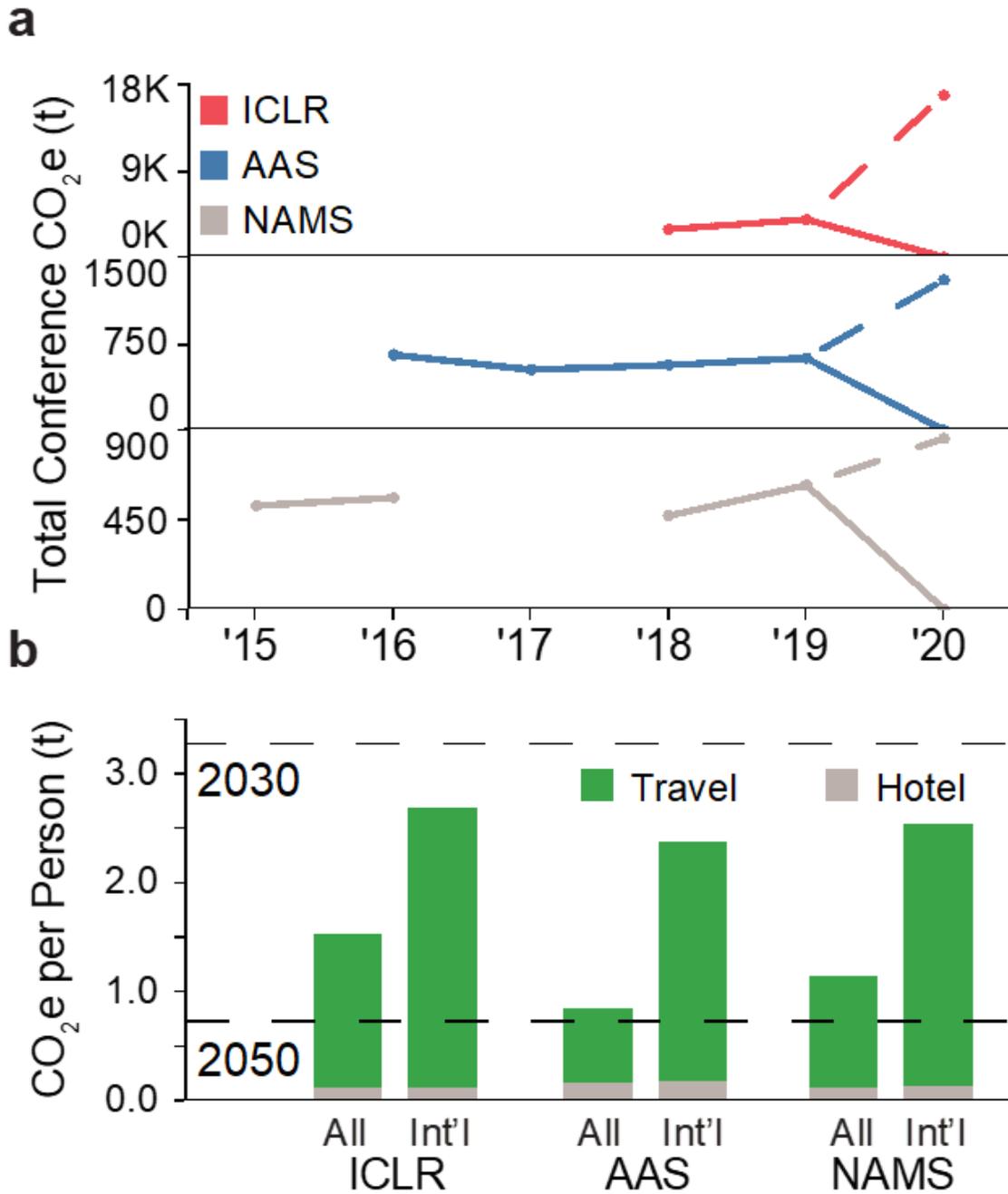


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Supplementary Files

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