Abstract

Academic conferences play an important role in the scientific community by providing an opportunity for researchers to discuss their work and to network. However, drawbacks of traditional face-to-face (F2F) conferences, such as the ostensible exclusion of non-scientists, the substantial environmental footprint and the large costs in terms of both time and money are being increasingly recognised. As a result, alternative and complementary formats are being explored. One of these is the Twitter conference (TC), in which research is presented and discussed on the social media platform Twitter. Here, we use hashtag and presenter data from several ornithology and ecology conferences (both TCs and F2F events) to explore the potential reach of the tweets and the magnitude of the difference in greenhouse gas emissions between the two conference types. We found that TCs generated greater engagement than F2F events, have the potential to reach a very large audience and result in a substantial reduction in emissions. Further, we argue that the format promotes presenter and audience diversity due to participation being flexible and virtually cost free. While we recognise some disadvantages of this format compared to F2F events, especially in relation to the social and networking aspects of conferences, we envision that virtual events, such as TCs, will play an important role in the future of science dissemination and outreach. By embracing such opportunities, academic conferences can move towards a more inclusive and sustainable future.

Introduction

Academic conferences have long played an important role in the scientific community, providing an opportunity for researchers to share and discuss new results, enhance the impact metrics of their work, as well as to network and strengthen the sense of community within a

given field. However, the 'traditional' face-to-face (F2F) conference format has been criticised for a number of reasons (see Sarabipour *et al.* 2020). For example, conferences often incur substantial costs, both for organisers and attendees (grants and other financial aid notwithstanding; Parsons 2015). For attendees, this includes not only the conference fee but also travel, subsistence and accommodation. This inevitably leads to the exclusion of individuals and organisations that cannot accommodate these costs (e.g. Mair *et al*. 2018). The impacts are often disproportionately felt by countries and universities with fewer economic resources, exacerbating existing inequalities (Walters 2018). Other barriers experienced by potential attendees include discrimination and/or inaccessibility based on gender (Biggs *et al*. 2018, Jackson 2019, Nicolazzo & Jourian 2020), race (Hughey 2019, Miles *et al*. 2020), nationality (Aguirre 2020), ethnicity (Ford *et al.* 2019, Timperley *et al*. 2020), native language (McCarthy *et al*. 2004), disabilities (De Picker 2020), personality (McCarthy *et al*. 2004, Davis & Warfield 2011), risk of sexual misconduct (National Academies of Sciences, Engineering, and Medicine 2018, Sharoni 2018) and external responsibilities, such as caring for children or other family members (Eckhaus & Davidovich 2018, Henderson & Moreau 2020).

In addition to excluding a large number of academics and otherwise interested professionals (e.g. government, non-governmental organisations), academic conferences also tend to exclude the general public. This is not necessarily intentional on the part of the organisers, but likely results from limited advertising and awareness of these events beyond academia, costs associated with attending such events (e.g. travel, registration, accommodation) and academic content that is often not easily accessible to people not working in that field. However, scientific projects are often built on a platform of public funding and, increasingly, public-sourced data (i.e. 'citizen science'; Callaghan *et al*. 2019, Fritz *et al*. 2019, Phillips *et al*. 2019). Further, public opinion and awareness can be important in determining support for actions such as changes to policy (Bromley-Trujillo & Poe 2020) or the success of

the application of the resulting policies (van Eeden *et al*. 2020). Hence, there is an increasing awareness within the scientific community of the need to communicate findings back to the public (Kassab 2019).

Finally, F2F conferences inherently require individuals to travel to the conference venue. This travel comes with associated greenhouse gas emissions, which increase with the amount of international participation. While these emissions only constitute a negligibly small part of the global carbon budget, they can constitute a significant part of the personal and institutional carbon footprint for academics (Spinellis & Louridas 2013). Further, while conference travel is undoubtedly the largest source of emissions, printed programs, various types of merchandise, hotel nights and the running of the venue also come with associated environmental impacts (Neugebauer *et al*. 2020). This is problematic as the ecological footprint associated with attending conferences may to some extent undermine the message of the importance of reduced environmental impact ecologists and conservation scientists try to convey to the general public (Grémillet 2008, Fox *et al*. 2009).

In response to the drawbacks associated with F2F conferences, alternative online formats that allow cheaper, more inclusive and more environmentally friendly conferences have been explored (see Bik & Goldstein 2013). These virtual conferences can be conducted in a variety of formats and can, for example, include pre-recorded video presentations and online Q&As (e.g. BioantTalks), a mixture of written and video presentations (e.g. Feminist and Women's Studies Association virtual conference), or podcast recordings (Ractham & Zhang 2006). Many F2F conferences are now also providing remote conferencing services in the form of live video streams, allowing those who could not attend in person to follow online (e.g. Pacific Seabird Group 2020), or organising hubs around the world where researchers can gather locally to watch live-streamed content (e.g. Photonics Online Meetup).

In addition to customised software, a variety of online platforms, many of which are free (e.g. YouTube, Wordpress, and Twitter), have the potential to support a wide range of conference formats. The social networking site Twitter (http://www.twitter.com) is particularly popular with scientists, especially in recent years (Darling *et al.* 2013, Ke *et al*. 2017). Twitter is often used in conjunction with F2F conferences to network, promote presentations and events, and to communicate presented research to non-participants. Twitter has a user base of 330 million individuals, 145 million of whom use the service daily (Twitter 2019). These users publish public messages ('tweets') containing no more than 280 characters - but including images, videos, animated GIFs, links, etc. - to their audience (immediate 'followers' and distributed networks - the followers of their followers). Tweets can also be threaded together ('threads') to produce a story or a linked presentation. The audience can then engage with these tweets by 'liking' them, 'retweeting' them (which shares them with the user's own network) and replying to the tweet. Crucially, Twitter users are able to assign hashtags to their tweets that act as grouping parameters, which means that other users can search for a specific hashtag and view all associated tweets. This has clear application to and benefits for conducting a Twitter-based conference (TC; Avery-Gomm et al. 2016, Caravaggi & James 2017, Bliss & Avery-Gomm 2018).

What was perhaps the world's first official TC took place in 2011 when the University of Otago's postgraduate students tweeted a summary of their thesis (University of Otago 2011). Since this first event, especially in recent years, there has been a large increase in the number of TCs, with conference topics covering a broad range of academic fields including public archaeology (#PATC1), ornithology (e.g. #WSTC1, #BOU18TC, #ISTC20), the history of underwear (#UPMTC), and many more. Like most F2F conferences, TCs take place over a set range of dates and follow a programme of scheduled presentations. These presentations take the form of a series of tweets, usually with accompanying graphics and videos that are

analogous to the presentation slides or posters at F2F conferences. The 280 character-limited tweet text can be considered to be a concise replacement for the words spoken at an oral presentation or when presenting a poster. Tweets can also link directly to online research articles, blog posts and presenter profiles. In addition to presentations, many TCs also contain other features common to F2F conferences, such as plenary sessions, prizes for best presentations, opportunities to socialise and network as well as the possibility for companies and organisations to advertise their products and services. Within this general framework, TCs take on various formats. Some TCs, such as The Royal Society of Chemistry Analytical Science Twitter Poster Conference, opt for the work being presented in the format of a traditional scientific poster that is uploaded to each presenter's account at a given time (Randviir *et al.* 2016). Others allow each presenter a set time frame in which to describe their work in a set number of tweets with associated graphics (e.g. the Exercise Oncology Twitter Conference #ExOncTC; Thraen-Borowski *et al.* 2020). Usually, conference-specific hashtags are used to group all tweets associated with an event, often with the addition of session-specific hashtags.

The field of ecology in general, and ornithology in particular, has enthusiastically embraced the opportunities afforded by TCs. Here, we use hashtag data from a set of ecology TCs, including the World Seabird Twitter Conference (WSTC), Biotweeps Twitter Conference (BTCon) and the TCs of the British Ornithologists' Union (BOUTC), as well as from a set of analogous F2F conferences, to examine the reach and impact of the tweets. We also assess how the potential greenhouse gas emissions associated with a TC compare with those from an F2F conference, and the contribution this could make to lowering the carbon footprint of researchers and organisations. Finally, we outline some additional advantages of TCs, discuss how they might be further improved and the future role they can play in the context of academic conferences, alongside, and to some extent in place of, the traditional F2F format.

Methods

Analysis of hashtags

Historical Twitter hashtag data for 17 conferences (eight F2F: #AOSSCO2017, #BES2017, #BES2018, #BOU2018, #BOU2019, #IOCongress2018, #TWS2017, #TWS2018; nine TC: #BTcon17, #BTcon18, #BOU17TC, #BOU18TC, #WSTC1, #WSTC2, #WSTC3, #WSTC4, #WSTC5; Table 1), were collected by the Twitter intelligence and analytics company Followthehashtag (followthehashtag.com). Historical data for each hashtag contained 21 data columns, six of which – *Tweet Posted Time (UTC)*, *Tweet Content*, *Tweet Type* (tweet/retweet/reply), *Retweets Received*, *Likes Received*, *Impressions* – were used in the current study (see Supporting Online Material [SOM] Table S1.1). 'Impressions' is the number of times a tweet shows up in other users' feeds. The data were thresholded by conference date(s) to focus on activity directly associated with the conferences themselves. The hashtag data were then subjected to a suite of analyses aimed at quantifying: i) the number of unique users using each hashtag; ii) engagement (i.e. interactions between users and tweets) metrics for each hashtag; and (iii) connectivity between hashtags in each group of conferences, in terms of shared usernames. For the full hashtag analysis methodology, see SOM 1.

Relative carbon emissions

To get a sense of the scale of difference in the carbon footprint, we calculated the emissions that would result from all presenters in three TCs (#WSTC5, #BOU17TC, #BOU18TC) travelling to a hypothetical conference venue and compared these to the emissions from the tweets of the TC. These TCs were chosen as there were clear F2F event analogues (WSC2, BOU 2017 and 2018 Annual Meetings) with easily accessible data on the presenters' countries

of residence. The total emissions from the tweets were calculated by multiplying the total number of tweets and retweets over the duration of the conference with the emissions associated with a single tweet (0.02 g CO2e; Schwartz 2010). To calculate the travel emissions, it was assumed that presenters travelled in a straight line from the centroid of their country of residence to a hypothetical conference venue. The hypothetical venue was always a capital and was chosen so that the total travelling distance summed for all presenters was minimised. The methods for calculating travel emissions followed those of Klöwer (2019) with the mode of transport depending on distance (<400 km land-based, 60 g CO2e/km/person; 400–1500 km short-haul flight, 200 g CO2e/km/person; 1500–8000 km long-haul flight, 250 g CO2e/km/person; >8000 km super long-haul flight, 300 g CO2e/km/person). We also estimated the travel emissions that would have been saved if the corresponding F2F conferences (WSC2, BOU 2017 and 2018 Annual Meetings) would have been conducted as TCs. The number of tweets per presenter were based on numbers from the corresponding TCs. For more details, see SOM 2.

All analyses were conducted in R 3.5.2 (R Core Team 2018). For packages used, see SOM 1 and 2.

Results

Analysis of hashtags

The accounts interacting directly (i.e. tweeting, retweeting and liking tweets) with the nine TCs studied represented 4937 unique users (range: 361 [#WSTC1] - 1000 [#WSTC3]; mean = 548.6). Hashtags associated with TCs generated a total of 99 071 active engagements (31 557 retweets and 67 514 likes) across 9680 original tweets, representing an engagement-per-tweet ratio of 10.2:1 (Fig. 1; Table 2). There were an average of 1.3 (± 3.6 SD) engagements per

impression (the rate at which users engage with content) and an average of 2.8 (± 8.2) engagements per post, for original tweets, only (Table 2). Network analyses showed that TCs were strongly connected (Fig. 2; SOM Table S3.1), with all hashtags being paired (i.e. mentioned in a tweet by the same individual user) at least once.

The accounts interacting directly with the eight F2F events studied represented 5810 unique usernames (range: 60 [#BES2017] - 2600 [#IOCCongress2018]; mean = 726.3). Hashtags associated with F2F events generated a total of 119 808 active engagements (27033 retweets and 92 775 likes) across 13 356 original tweets, representing an engagement-per-tweet ratio of 8.9:1 (Fig. 1; Table 2). There were an average of 0.8 (± 2.8) engagements per impression (i.e. the number of times a tweet appears on a screen) and an average of 1.7 (± 6.5) engagements per post (i.e. the percentage of people who chose to interact with content) , for original tweets, only (Table 2; SOM 1). Network analyses showed that F2F events were well connected (Fig. 2; SOM Table S3.1), with an average of six hashtags being paired at least once (minimum = 4, maximum = 7).

The number of unique usernames that directly engaged with TCs was comparable to the number that engaged with tweets from F2F events. However, engagement rates were higher for TC tweets as compared to those associated with F2F events. Further, TCs demonstrated greater connectivity between conferences. Hence, content from TCs was more likely to be distributed to a wider Twitter network than that of F2F events and drew more attention from the wider audience, on a more consistent basis.

Relative carbon emissions

Emissions associated with travelling to an F2F conference were several millions times greater than those resulting from tweeting out the research (Table 3). More generally, one tweet results

in emissions corresponding to travelling around a third of a meter if travelling by land, or around a tenth of a meter or less if travelling by air.

The greater ratios of travel to tweet emissions from #WSTC5 and WSC2 compared to the BOU conferences are the result of the attendees being more spread out across the globe. The larger ratio for WSC2 compared to that calculated for #WSTC5 is to a large extent the result of assuming an optimal location for the hypothetical conference venue for #WSTC5. In contrast, ratios were larger for the BOU TCs compared to the corresponding BOU F2F annual meetings, which is the result of a larger proportion of international participants at the TCs.

Discussion

Hashtag analyses showed that the content from TCs is likely to be distributed to, and generate engagement from, a wide Twitter network. This has clear benefits for the dissemination of information beyond the immediate constraints of F2F conferences. For example, Côté and Darling (2018) looked at both the 'inreach' (talking to other scientists) and 'outreach' (talking to non-scientists) based on the Twitter followers of more than 100 ecology and evolutionary biology faculty members and found that their followers were predominantly other scientists (~55%). An audience of which 'only' 45% are scientists still represents a marked difference from the composition of an F2F conference. Those with over 1000 followers showed a more diverse range of followers including media, members of the public, and decision-makers. The more varied audience of those scientists with more followers was, in turn, followed by more people, resulting in an exponential increase in their social media outreach (e.g. Caravaggi & James 2017). Tweeting, therefore, has the potential to disseminate scientific information widely after initial efforts to gain followers.

Our network analysis also showed that TCs exhibited greater levels of cross-conference hashtag use compared to the F2F events we considered, suggesting that this format may

promote collaboration and knowledge exchange between fields. Certainly, social media platforms such as Twitter have a tendency to create 'social media bubbles' or 'echo chambers' where users mainly expose themselves to content conforming to their own ideas and opinions. However, this seems to apply mainly to highly political topics (Barberá et al. 2015). It is possible that in the case of scientific conferences, Twitter instead offers the opportunity to break out of such bubbles and connect across academic fields. However, further studies considering TCs on less similar fields would be required to determine if this is the case and, if so, the extent of interdisciplinary connections.

While the present study does not attempt to formally explore qualitative differences in the content of the tweets for each group of conferences, it was noted that a substantial proportion of the tweets associated with a TC are generated by those presenting their research and frequently contain links to online content (e.g. publications). In contrast, tweets connected to F2F events may originate from commentary/observations on individual presentations (often a single-tweet summary by a third-party observer), comments on the event itself, or associated virtual and F2F social interactions, and rarely contain links to online content. For example, Fekete & Haffner (2019) found conference location-based words, and terms associated with conference attendance, such as 'session', 'present', 'talk', or 'floor' to be the most predominant in tweets from the F2F Annual Meeting of the American Association of Geographers (AAG). It is difficult to directly compare the content of tweets between F2F events and TCs by placing individual words, devoid of context, in a potentially subjective, value-based framework. However, our analysis showed that TC tweets generated greater engagement rates than tweets associated with F2F events. An analysis of differential tweet content could therefore provide useful pointers for how to tweak the content of tweets associated with F2F events to help generate larger engagement and thus more efficient communication with the wider community. Certainly, organisers of F2F events are not unaware of the potential benefits of harnessing

social media and the use of Twitter at F2F conferences has been studied in other fields (e.g. Ross et al. 2011). In our study, the increase in uptake of Twitter at F2F events can be seen in the number of tweets associated with the BES annual meetings, with 2018 being over a hundredfold greater than in 2017. This increase was also associated with a substantial increase in engagement metrics, both across original tweets and secondary content (i.e. likes and retweets).

While it was not possible to explore geographic diversity as historical Twitter data does not include geo-references for tweets, institute location information on presenters for the BOU TCs and F2F conferences (provided by SPD) showed there to be a slightly higher proportion of non-UK presenters for TCs than at F2F conferences (held in the UK). Non-UK presenters made up 78% of all presenters at #BOU17TC vs 61% at #BOU2017, and 42% vs 28% at #BOU18TC and #BOU2018, respectively. While such data are inherently limited as they do not capture the locations of all users who interacted with the conference hashtags, it seems likely that the potential geographic reach of TCs is also wider, especially given the fact that TCs generate engagement from a larger audience. However, this remains an open question.

Social media networks can democratise science by providing free, global platforms to most individuals with an internet connection, regardless of age, gender or background. It is probably no coincidence that disciplines with embedded citizen or community science input, such as ornithology, have also seen high take-up and engagement on social platforms, on Twitter in particular. Whilst ornithologists are active across a variety of platforms including Twitter, Facebook, Instagram and Weibo, it is Twitter that contributes more to the altmetrics of published ornithological articles than all other sources combined (75% of the total contributions) (Finch *et al*. 2017).

However, it is important to acknowledge that virtual conferencing is not immune from bias. For example, if organisers do not adopt a double-blind approach to abstract review, they

run the risk of presenters being dismissed or overlooked due to subconscious assumptions regarding gender, race, nationality and language. Further, language barriers represent a significant issue for science publishing and communication (Amano *et al*. 2016, Márquez & Porras 2020, Ramírez-Castañeda 2020), placing non-English speakers or those for whom English is a Foreign Language (EFL) at a substantial disadvantage. Virtual events that do not require verbal presentations can be more attractive to EFL presenters as verbal communication can present a substantial obstacle (e.g. Ramírez-Castañeda 2020). Nevertheless, it is important that the burden of overcoming language barriers is not placed on the participant, but on the conference organisers. Some TCs have taken initial steps to address this inequity. For example, BOU attempted to include Spanish and French presentations for #BOU18TC but received no submissions in either language (though keynotes were translated into Spanish by a volunteer). #WSTC has featured some presentations in Spanish and French and #BTCon18 attempted the live translation of tweets into Spanish. The example of #BTCon18 represents an important lesson in understanding platform limitations as the personal account of the translator and co-organiser, Toby SantaMaria (Twitter @ItatiVCS), was temporarily limited (i.e. unable to tweet) due to 'irregular activity' (Toby SantaMaria, pers. comm.). The creation of translanguaging events where multilingual and EFL participants are enabled and supported by organisers represents a crucial next step in the evolution of science communication (see Marquez & Porras 2020), one which virtual events are seemingly well-placed to address (for examples of the multilingual nature of Twitter, see Weerkamp *et al*. [2011], Saha & Menezes [2016], Rosell-Aguilar [2018]).

Although we lack comparable data to enable us to compare the diversity and inclusivity of F2F events and TCs, F2F events introduce some particular problems to which TCs are at least partly immune. For example, Sarabiqour *et al*. (2020) highlighted the increasing problem - inherently avoided by TCs - for researchers, in particular those in developing nations, in

obtaining visas to attend conferences in developed countries. TCs also place fewer time demands on participants, offering flexible participation which fits more easily around other commitments. Further, TCs are cheap to run and their simplicity keeps organisational costs down. With Twitter being free to use, the main costs incurred for a TC involve the time it takes to organise the event, providing technological support, and advertisement, regardless of whether these services are provided pro bono. For comparison, the total costs for a US researcher to attend a US-based F2F conference ranged $1000-$2000 whilst an international event ranged $2000-$4000 (Sarabiqour *et al*. 2020). Such costs are prohibitive to those whose research funding does not include conference attendance (usually linked to presenting the funded research). In some countries this penalises early-career researchers whose grants do not cover these costs. Other groups that are disproportionately disadvantaged by these high costs are those researchers from countries with reduced economies, and even employees of non-profit organisations in nations with strong economies - in the UK many non-profit organisations are unable to apply for funding available to universities and research institutes, which includes funding of conference attendance (Butchart *et al.* 2019). However, it is important to note that some organisations make a profit from F2F conferences and use conferences as a means to generate important income, which TCs cannot provide. Further, Twitter itself is a 'free' platform but online access invariably is not, especially for those who are not based at an institute or for many in developing countries where the cost of (mobile) data can be disproportionately expensive. Finally, while TCs may result in greater inclusivity for many groups, it may exclude others. This includes those with limited experience with Twitter, and these people are likely to be unevenly distributed geographically and across age groups. Some suggestions towards addressing this issue can be found below.

Another clear benefit of running a conference as a TC is the reduction in carbon emissions. Our results showed that the difference in emissions between F2F conferences and

TCs is vast, with emissions from TCs being several million times lower than those associated with travelling to an F2F event. Ours is a simplified comparison that ignores some additional emissions from TCs, including, for example, emissions from third party servers (Schwartz 2010). However, emissions from F2F conferences are also likely to be underestimated as it was assumed that all travel occurred in straight lines and additional emissions associated with running the conference venue and accommodation for the participants were ignored. Hence, absolute values presented herein should be taken as very coarse approximations only. Nevertheless, it is clear that while TCs are not carbon-free, their potential to contribute to a reduced carbon footprint of scientific communication and networking within a global setting is considerable. Due to the highly non-random distribution of F2F conference locations, emissions associated with conference travel may vary considerably depending on where a researcher is based (Spinellis & Louridas 2013, Sarabiqour *et al*. 2020), which means that efforts to reduce personal emissions do not hit researchers equally across the globe. A move towards virtual conferences, such as TCs, means that efforts to decarbonise academia can be shared more equally across the global community of researchers. This allows academics to set a good example for collective, rather than individual, efforts to reduce greenhouse gas emissions (Higham & Font 2020). Finally, the considerable reach of tweets that are part of TCs show that it is possible to share research both with other researchers and the public without travelling, supporting previous conclusions that travel should not be, and is not, an essential element of academic success (Wynes *et al.* 2019). Recently, the global COVID-19 pandemic resulted in national and international restrictions that prevented social gatherings and travel. This resulted in organisations, both large and small, opting to switch F2F events to an online format using a variety of delivery models. Within ecology, this switch saw the largest ornithological conference, the North American Ornithological Conference, move from an expected 1750 delegate F2F event held in Puerto Rico to a > 2800 attendee virtual event hosted

on Zoom. This demonstrated to the sector that complicated, parallel session events with multiple session formats and social events could be held successfully as virtual events. This move to online conferences in response to the pandemic is unlikely to become the norm by default (at least not in the short term), but it has demonstrated that, given the right conditions, changes to deeply embedded and seemingly intractable practices can happen in a global emergency with remarkable speed.

While TCs have the potential to overcome many of the limitations of F2F conferences, they are not without their own disadvantages; virtual events such as TCs are not a panacea. Primary concerns surround the effectiveness of communicating and networking online, and many argue that virtual formats are unlikely to replicate the F2F interactions required for effective networking. This can be partly addressed by hosting social events on video conferencing services alongside TCs and other virtual conferences. Many academics will have gained experience in virtual socialising and networking during the COVID-19 pandemic, potentially making this an increasingly attractive option. Supplementing F2F conferences with virtual conferencing (so-called 'hybrid conferences') may also provide a solution. For example, conferences could consider running multiple regional/national 'hubs' to facilitate some of the social aspects of conferences. Regional or national pools of delegates can meet, network, and attend/stream the conference (e.g. Fraser *et al.* 2017), without the large (economical and environmental) costs associated with participants from all over the world travelling to a single location. It should be noted that the relative importance of networking may be dependent on the scope of the event; it could be a more integral and useful part of conferences that have narrower scopes, in which participants are more likely to form close collaborations. This should also be taken into consideration when deciding whether to run a conference as an F2F event or not.

Further, it is estimated that 49% of the world's population still lack access to the internet (Reglitz 2020) and whilst visas are not required to access online events, some countries still limit access to the internet or censor its content. China, for instance, has the largest number of internet users of any country but the government also enforces strict internet censorship and in particular seeks to regulate access to foreign websites (the Great Firewall of China), including social platforms such as Facebook, Twitter, YouTube and Google. Event organisers cannot hope to solve such issues, of course. However, we urge organisers to recognise and attempt to accommodate barriers to interaction or access, wherever possible. This also includes addressing the possibility that for some researchers, publicly sharing their research on Twitter may constitute a personal safety concern, for example if they are working on a topic that is controversial in their home country.

Another potential limitation of TCs is the maximum size of the event. Attempting to deliver a large, multiple parallel session event on a social platform as a substitute for an F2F event may be overwhelming, and it would be difficult to follow along with simultaneous presentations (though this can be partly mitigated by archiving material and making it accessible to participants after the event). For the latest #WSTC conferences, which have featured around 100 presenters or more, several participants reported that they struggled to keep up with all the content. Further, the quick pace of social media may mean that attention spans of participants are short and engagement levels low, so that less information is absorbed as compared to when attending a talk at an F2F event. However, these issues can be at least partly addressed by reducing the number of presenters to a carefully selected set and by putting together a schedule with short and coherent sessions, as well as sufficient breaks.

Perhaps one of the biggest challenges in the uptake of virtual conferences is including people who have limited experience with the chosen medium. These individuals may be both less likely to hear about the event and face a larger barrier to participate, which may thus act to

exclude certain groups. Using more traditional forms of advertisement (e.g. mailing lists, noticeboards) may be one way to attract people who normally do not spend much time on social media to participate in virtual events. However, it is also important to support individuals beyond the single act of reaching out to engage their attention. Organisers of virtual events should provide clear written guidelines describing, for example, how to set up a Twitter account, what a tweet is, how to produce a tweet-thread, how to participate in the focal TC as well as tips and examples of good TC presentations. They should also have systems in place to respond to questions and provide general support, for example in the form of educational workshops.

Finally, one critical consideration is how F2F events and virtual conferences, including TCs, will co-exist in the future. It is important that virtual conferences are not simply added on to the expectation of attending F2F conferences, further increasing the workload of academics (see discussions on 'co-presence' in e.g. Higham & Font 2019). Instead, virtual conferences will need to partially replace F2F events. As part of this, it is important that participation in virtual conferences, such as TCs, are placed on equal footing with participation in F2F events. For example, presenting at a virtual conference and presenting at an F2F event, of equal size and scope, need to be considered equal on a CV. Hopefully, this happens naturally as virtual conferences become more and more common. As public outreach becomes an increasingly important part of a researcher's job, TCs and similar formats may become particularly well regarded considering their ability to share the research with a wide audience outside the scientific community. Additional public engagement could be further stimulated by increasing the publicity in other, non-Twitter channels, and adapting presentation content to support understanding in a wider audience (e.g. minimising the use of jargon).

Conclusions

Virtual events, such as TCs, offer low-carbon, low-cost and inclusive alternatives or, indeed, supplements, to F2F conferences. Our results offer key insights into the potential role of Twitter and other social media platforms in facilitating the communication of research across scientific and the academic-public barriers. We therefore offer the following suggestions for future organisation of TCs and F2F conferences:

1. Promotion of the conference on a broad front is key. Targeted use of email, social media as well as other online and offline channels should be used for all events, to reach a broad and diverse audience.
2. F2F events should continue to embrace social media and other outreach and networking media as a means of generating greater engagement and reaching a wider audience.
3. Virtual events provide considerable carbon savings. Organisers should carefully consider whether conducting an F2F event is warranted or whether full or partial replacement with virtual participation is a viable option.
4. Providing clear guidelines and information on how the TC will work is important for allowing people with limited previous experience of Twitter to participate.
5. Barriers to participation should be identified and acknowledged and steps taken to improve accessibility. Organising committees should themselves be diverse, representing the breadth of possible participants.

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Supporting Online Material contains the following:

Supplementary Online Material 1: information regarding the analysis of hashtag data, including Table S1.1 containing information on the structure of the hashtag data.

Supplementary Online Material 2: information regarding the emissions analysis.

Supplementary Online Material 3: Table S3.1 containing results from the network analysis.

Table 1. Selected Twitter hashtags - a means of collecting and linking related content - used by Twitter conferences (TC) and face-to-face (F2F) events.

Hashtag	Conference name	Type of conference
#AOSSCO2017	American Ornithological Society Conference 2017	F2F
#BES2017	British Ecological Society Annual Meeting 2017	F2F
#BES2018	British Ecological Society Annual Meeting 2018	F2F
#BES2019	British Ecological Society Annual Meeting 2019	F2F
#BOU2019	British Ornithologists' Union 2019 Annual Conference	F2F
#IOCongress2018	The 27th International Ornithological Congress	F2F
#TWS2017	The Wildlife Society's 2018 Annual Conference	F2F
#TWS2018	The Wildlife Society's 2019 Annual Conference	F2F
#BTcon17	The 1st Biotweeps Twitter Conference	TC
#BTcon18	The 2nd Biotweeps Twitter Conference	TC
#BOU17TC	British Ornithologists' Union Twitter Conference 2017	TC
#BOU18TC	British Ornithologists' Union Twitter Conference 2018	TC
#WSTC1	1st World Seabird Twitter Conference	TC
#WSTC2	2nd World Seabird Twitter Conference	TC
#WSTC3	3rd World Seabird Twitter Conference	TC

#WSTC4	4th World Seabird Twitter Conference	TC
#WSTC5	5th World Seabird Twitter Conference	TC

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Table 2. Engagement metrics for TCs and F2F conferences. N = number of tweets; EI = engagement by impression; EP = engagement by post; a = all content, including likes and retweets; t = original tweets, only.

Hashtag	Date(s)	N_a	EI_a	EP_a	N_t	EI_t	EP_t
Twitter conferences							
#BOU17TC	28/11 - 29/11/17	1444	1.00 ± 2.48	1.08 ± 3.91	607	1.21 ± 2.75	2.45 ± 5.74
#BOU18TC	20/11 - 21/11/18	1236	1.98 ± 5.79	1.96 ± 10.02	256	2.26 ± 7.68	5.04 ± 19.83
#BTcon17	28/06 - 30/06/17	1137	0.64 ± 1.89	0.78 ± 3.23	502	0.80 ± 2.16	1.65 ± 4.71
#BTcon18	21/06 - 22/06/18	1324	1.61 ± 7.59	1.82 ± 14.76	279	1.66 ± 6.27	3.54 ± 14.43
#WSTC1	19/03 - 21/03/15	854	0.19 ± 0.29	0.24 ± 0.50	325	0.27 ± 0.35	0.54 ± 0.70
#WSTC2	13/04 - 14/04/16	1889	0.35 ± 0.57	0.37 ± 0.90	711	0.46 ± 0.63	0.93 ± 1.28
#WSTC3	12/04 - 14/04/17	3539	0.68 ± 1.62	0.76 ± 2.62	1357	0.91 ± 1.89	1.85 ± 3.98
#WSTC4	17/04 - 19/04/18	2457	1.18 ± 2.39	1.02 ± 3.45	800	1.39 ± 2.65	2.82 ± 5.54
#WSTC5	09/04 - 11/04/19	1923	2.41 ± 5.96	2.68 ± 10.02	642	2.91 ± 6.90	6.04 ± 15.52
Face-to-face conferences							
#AOSSCO2017	31/07 - 05/08/17	100	0.60 ± 0.71	0.61 ± 1.18	46	0.56 ± 0.67	1.11 ± 1.34
#BES2017	11/12 - 14/12/17	77	0.35 ± 0.63	0.39 ± 1.01	37	0.37 ± 0.66	0.75 ± 1.33
#BES2018	16/12 - 19/12/18	9972	1.06 ± 6.82	0.88 ± 10.71	3305	1.17 ± 7.33	2.48 ± 18.38
#BOU2018	27/03 - 29/03/18	1419	0.49 ± 1.48	0.34 ± 1.86	331	0.64 ± 1.72	1.30 ± 3.61
#BOU2019	26/03 - 28/03/19	1170	0.63 ± 1.92	0.40 ± 2.27	213	1.03 ± 2.42	2.08 ± 4.96
#IOCongress2018	19/08 - 26/08/18	8943	0.76 ± 4.16	0.53 ± 6.66	2387	0.90 ± 4.63	1.90 ± 12.79
#TWS2017	23/09 - 27/09/17	2042	0.69 ± 2.64	0.64 ± 4.09	816	0.73 ± 2.78	1.50 ± 6.29
#TWS2018	07/10 - 11/10/18	1560	1.02 ± 1.75	0.92 ± 2.57	622	1.07 ± 1.82	2.15 ± 3.68

641 **Table 3.** Calculated emissions (kg CO2e) associated with travelling to actual (for face-to-face,
642 F2F, conferences) or hypothetical (Twitter conference, TC) conference venues, emissions
643 associated with instead tweeting out research and the ratio of these sources of emissions.
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Conference	**Conference type**	**Travel emissions**	**Tweet emissions**	**Ratio**
World Seabird Conference 2	F2F	467 477	0.15	9 858 191
British Ornithologists' Union Annual Meeting 2017	F2F	70 129	0.05	1 523 464
British Ornithologists' Union Annual Meeting 2018	F2F	40 435	0.03	1 252 524
#BOU17TC	TC	199 834	0.05	4 388 103
#BOU18TC	TC	62 927	0.03	2 105 202
#WSTC5	TC	262 396	0.03	7 650 033

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Figure 1. Total tweets (black), retweets (dark grey) and likes (light grey) for selected hashtags associated with Twitter conferences and face-to-face events. Note: the number of people registered varied between conferences, but could not be quantified.

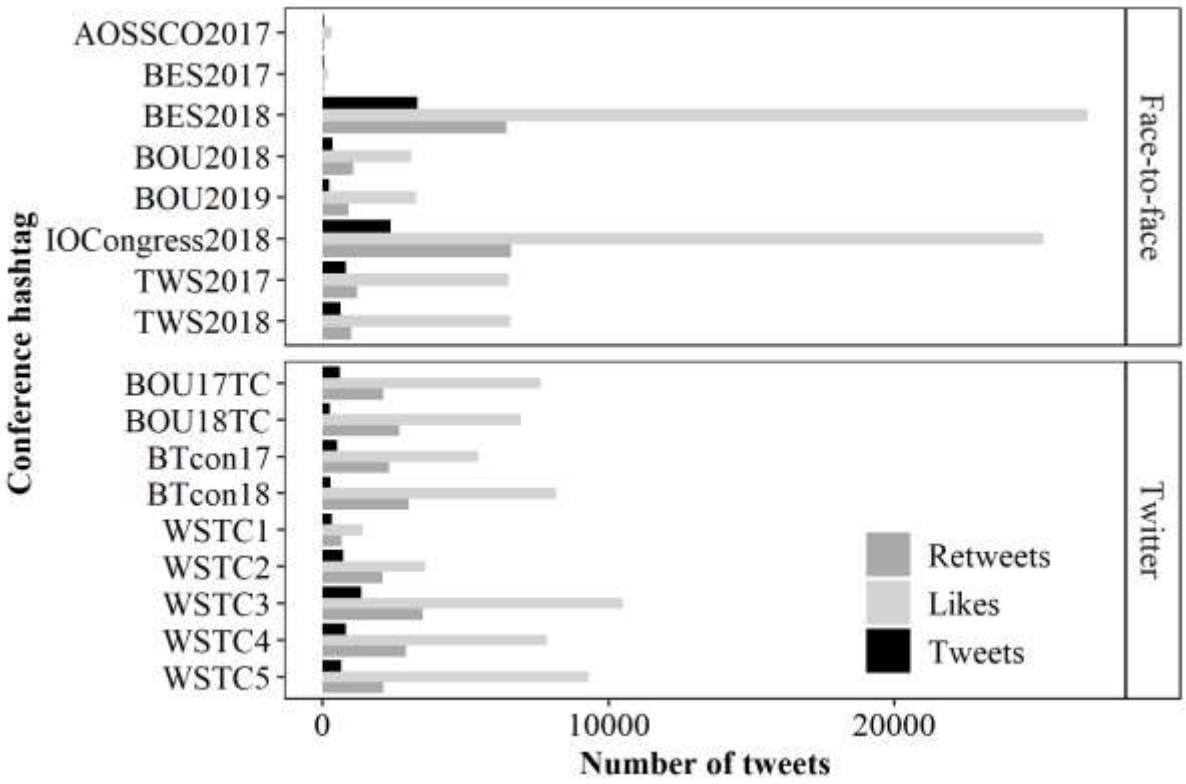

Figure 2. Network of conference connectivity for Twitter hashtags associated with **(a)** face-to-face and **(b)** Twitter conferences, based on non-unique users (i.e. usernames that interacted with > one conference hashtag). Edge width indicates the relative proportion of shared usernames, where thick > thin. For specific edge data, see SOM 3.