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Beyond climate change? Environmental discourse on the planetary boundaries in Twitter networks

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Abstract

Social media are increasingly used to obtain and disseminate information about environmental issues. Yet, environmental communication research has focused mainly on social media discussions pertaining to climate change, while overlooking public awareness and discourse regarding the other planetary boundaries (i.e., important and interlinked environmental issues other than climate change). Moreover, while discussions about climate change are often found to be polarising, it remains to be seen if this extends to other environmental issues. We used network analysis and topic modelling to analyse two million environment-related tweets and identified nine 'green communities' of users. Climate change was the most popular issue across all communities and other issues like biodiversity loss were discussed infrequently. The discourse was less polarised than previously assumed, was largely pro-environmental, and originated more from the Global North than the Global South. The relevance of our findings for policymakers and researchers in environmental communication is discussed.

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1 Beyond climate change? Environmental discourse on the planetary boundaries in Twitter networks

Social media have become important fora for public discussions about environmental issues, encompassing topics such as climate change and sustainability (Ghermandi et al. 2023; Pearce et al. 2019). This vital role of social media for environmental discussions is underscored by a notable surge in climate change mentions, with a growth of 50% observed in a sample of English tweets from 2013-2020 (Build for Good n.d.). By fostering discussions and debates among various voices present in the public sphere, social media provide a communicative space for collective interpretation of new information (Jovchelovitch 1995; Sarrica et al. 2018). Consequently, individuals turn to social media for both obtaining environment-related news and sharing their own environmental views by (re)sharing environmental content (Cody et al. 2015; von Nordheim et al. 2018). An examination of the environmental content on social media can provide us with a snapshot of the prevailing public discourse, highlighting which issues are currently emphasised as well as those that warrant more attention.

So far, environmental communication research on social media has focused primarily on climate change while overlooking other interlinked issues that similarly affect the planet's future (Barrios-O'Neill 2021; Chang et al. 2022a). Nine such dynamic environmental processes (e.g., climate change, ocean acidification, loss of biosphere integrity) and their associated thresholds are explicated in the planetary boundaries framework that demarcates the safe space for humanity to thrive (Rockström et al. 2009). Alarmingly, six of these boundaries, namely, biosphere integrity, land-system change, freshwater use, biochemical flows, novel entities (e.g., plastic pollution), and climate change, have already been crossed due to human activities, also putting other boundaries under pressure (Richardson et al. 2023). Thus, environmental problems other than climate change also warrant attention, but little is known about public discourse about the other planetary boundaries on social media.

Besides utilising social media as a communicative space for deliberation on environmental issues, users follow information from peers with similar interests and engage in debates. Often, such interactions take place in user networks comprising of mutual connections – or communities of like-minded users connected to each other (Sachan et al. 2012). Accordingly, discussions in distinct network clusters (or communities) reflect prioritised areas and sentiments of the public about an issue (Chang et al. 2022b; Lutkenhaus et al. 2019). Thus, user discussions in such communities on social media could help us understand people's current awareness and opinions about environmental issues. This study aimed to provide an overview of the public environmental discourse on Twitter (now X) by expanding our focus beyond climate change to include environmental issues related to all planetary boundaries. While doing so, we also added to the often Global-North centred social media research (Comfort and Park 2018; Pearce et al. 2019) by examining the extent to which users in the Global South featured in these environmental discussions.

1.1 Green communities on social media

The environmental content viewed and shared by users as well as the people who comprise their social network can provide insights into the prevalent environmental discourse. Moreover, users with similar environmental views may form online communities on social media, aided by individual and algorithmic factors (Gasparetti et al.

2021). Specifically, users can personalise their information feeds by connecting with others who have similar views, often ending up in communities of like-minded peers (Terren and Borge-Bravo 2021; Williams et al. 2015). Hence, users on social media likely connect with people who have similar environmental views to form virtual communities, or what we term 'green communities', i.e., network clusters of Twitter users with mutual connections who discuss environmental topics. Although the term "green" generally implies a pro-environmental context, green communities can include positive, negative, or neutral environmental sentiments. The content shared within green communities may be suggestive of environmental topics that the members discuss and view on their Twitter feeds.

Studies have explored virtual communities related to various issues like vaccination (Lutkenhaus et al. 2019), the political divide (Grömping 2014; Takikawa and Nagayoshi 2017), and climate change (Williams et al. 2015). However, research on online environmental communication is scarce and prioritises the issue of climate change over other environmental issues (Adam et al. 2020; Pearce et al. 2019). Furthermore, most studies focus on communities with extreme views on climate change (Adam et al. 2020; Chen et al. 2019). Inevitably, such studies have found polarised discourses on social media, comprising, on the one hand, sceptical users who deny climate change (e.g., Chen et al. 2019; Enders et al. 2021; Jang and Hart 2015) and, on the other hand, alarmed users motivated to take action to mitigate the threats posed by climate change (e.g., Boulianne et al. 2020; Segerberg and Bennett 2011). However, it is not clear whether such findings regarding polarisation also apply to other environmental topics like biodiversity loss or plastic pollution. This is because while climate change can be perceived as a polarising topic (Cody et al. 2015; Falkenberg et al. 2022; Fownes et al. 2018), environmental issues like conservation generally tend to garner a more positive sentiment from Twitter users (Chang et al. 2022b). Therefore, it is important to map the online discourse with a focus on broader environmental problems (i.e., the planetary boundaries).

Some previous evidence indicates that environmental discourse on social media may extend beyond the much-highlighted narratives of climate change (Grouverman et al. 2018; Pilař et al. 2019). In an analysis of general sustainability related Twitter hashtags worldwide, Pilař et al. (2019) found that climate change was only the third most popular hashtag, trailing behind 'innovation' and 'environment'. Also, tweets not directly mentioning the environment may still contain information about behaviours which help in combatting environmental problems but undertaken without a direct pro-environmental motivation, such as eating less meat and promoting sustainable energy consumption (Grouverman et al. 2018).

Identifying green communities with diverse environmental discussions will facilitate an all-encompassing understanding of how people construe the environmental challenges threatening our planet. Examining tweets in green communities will elucidate which environmental topics are popular among the public – and which could use some more attention. Therefore, the present study aimed to understand the environmental discourse on Twitter by distinguishing online communities of people who post environmental content. We examined discussion topics and sentiments in green communities via textual analysis and pinpointed user characteristics.

RQ1.

(a)   Which types of online communities, i.e., 'green communities', exist on Twitter?
(b)   Which environment-related topics are discussed in distinct green communities?

(c) What are the characteristics of users in green communities based on their profile infor-
mation?

(d) What are the sentiments underlying environmental discussions in green communities?

We also investigated the extent to which green communities interact with each other
to understand the content users are exposed to via their connections. This allowed us to
examine whether, like climate change, conversations about other environmental topics may
also take place in polarised and distinct networks of users or if they tend to be discussed by
users across all networks.

RQ2. How do distinct green communities interact with each other, i.e., which connec-
tions are shared across networks?

1.2 Green communities in the Global North and Global South

Studies show that online discourse about global issues such as climate change is largely
dominated by actors in the Global North[1] (Kirilenko and Stepchenkova 2014; Liu and Zhao
2017; Vu et al. 2020). Vu et al. (2020) reported that NGOs from the Global North domi-
nated conversations related to climate change on Twitter, effectively influencing the types
of issues and content that make up a large part of the online discourse. This geographical
inequity is alarming because while countries in the Global North are the major instigators
of environmental crises, those in the Global South are the most vulnerable to the effects of
said crises (Eckstein et al. 2021; Yin et al. 2021).

Research into environmental discourse on social media has also been conducted in the
Global North while overlooking discourse in the Global South (Comfort and Park 2018). It
is however important to capture both because the diverse sociocultural and historical con-
text of Global South countries may emphasise other environmental issues than those popu-
lar in the Global North and/or may discuss environmental topics differently (Dwivedi 2001;
Kazansky et al. 2022; Morrow et al. 2020). Global South perspectives indeed demonstrate
that "a southern flavour" (Thaker 2021, p. 194) of the natural environment contextualises it
in relation to issues of livelihood, sustenance, and access to resources in post-colonial soci-
eties. This is different than the environmental notions prevalent in the Global North, which
are more centred on preventing overuse and exploitation (Thaker 2021). Hence, mapping
where environmental tweets originate captures the contributions of the Global North vs
South in environmental dialogue:

RQ3. To what extent do tweets from the different green communities originate in the
Global North vs the Global South?

2 Methods

To investigate our RQs, we conducted a social media study that was approved by the Eth-
ics Review Board of the Faculty of Social and Behavioural Sciences at the University of
Amsterdam [reference: 2021-PC-14277]. The study plan was preregistered on the Open

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[1] Global North and Global South reflect a distinction between countries that have higher and lower rates of
human development respectively. While not geographically absolute, these terms are preferred to previous
descriptors such as first world and third world which tend to emphasise primacy of certain nation states.

Science Framework (OSF; https://osf.io/wef2z/). Data collection and analysis were conducted using R (R Core Team 2021). The data and analysis scripts from this study are available on the OSF project page (https://osf.io/kg43n/) which also contains the supplementary materials (with an index of all shared materials).

2.1 Data collection

2.1.1 Selecting the tweets

We retrieved global English language tweets via a full archive search of the Twitter Application Programming Interface (API v2) using the academictwitteR package (Barrie et al. 2022). The selection of search terms can impact textual analysis of the retrieved data (Mahl et al. 2022; Stryker et al. 2006), so we measured the efficiency of search terms used in this study as previously recommended (Lacy et al. 2015; Stryker et al. 2006).

For this, we preregistered 58 open search terms based on the nine planetary boundaries framework (Rockström et al. 2009), previous literature (Cameletti et al. 2022.; Gaytan Camarillo et al. 2021; Pilař et al. 2019), and researcher consensus (all authors). A pilot dataset ($n = 5000$) containing tweets, retweets, and quote tweets retrieved from this list was used to evaluate the efficiency of the search terms, usually indicated by recall and precision values (Stryker et al. 2006). We did not calculate recall as it is not possible to estimate the total number of relevant documents (i.e., number of tweets containing the search terms), but instead reported the proportion of tweets retrieved by each search term in our sample to be able to provide a distribution of the search terms across retrieved tweets.

Additionally, for a subset of the data ($n = 500$), we manually calculated the precision (i.e., relevance) of search terms. A relevant tweet referred to a tweet related to the environment. In doing so, we observed that some search terms showed little precision, retrieving many irrelevant tweets. For instance, the search term "toxic" retrieved the second highest number of tweets (14.6%, 73 of 500 tweets) but only 3 of these tweets were relevant (precision = 4%). To ensure a relevant collection of tweets, we removed search terms with precision values less than .5 (for details, see supplementary materials). Moreover, 11 search terms retrieved no tweets, but we decided to keep them in our list of closed search terms because absence of tweets relating to these terms (e.g., "planetary boundaries", "circular economy", etc.) may indicate that although relevant in academic literature, some topics have yet to become mainstream. Finally, we shortlisted 50 closed search terms for collecting tweets for the main dataset ($n = 2,000,000$). These included original tweets, retweets, replies, and comments, but not advertisements.

2.1.2 Retrieving the Twitter network

To construct the egocentric user network for community detection, we retrieved the connections of the authors of the collected tweets. A total of 1,133,748 unique users were identified as authors in our sample of 2 million tweets, which was reduced to 904,043 after removing users with private profiles ($n = 229,705$). The total number of followers (users who follow the authors) was 6,053,998,317 whereas the total number of friends (users followed by the authors) was 1,181,490,733. Per API limitations, we retrieved a maximum of 1 million followers for users with more than a million followers ($n = 187$) and restricted the maximum number of friends to 5000. Thus, for 904,043 authors, we retrieved 532,297,774 followers and 131,073,118 friends. Following the approach of Lutkenhaus et al. (2019),

we examined the distribution of the number of connections for the authors to determine a cut-off point to exclude users (friends and followers) who were not connected to a minimum of 5 authors, so that the retrieved network would reflect shared audiences. The overall network contained 324,028,112 users comprising a total of 367,465,523 connections with authors, followers, and friends in an egocentric network.

2.2 Data analysis

We examined the first research question in four steps. First, to determine which green communities exist on Twitter (**RQ1a**) we identified network clusters using the Louvain algorithm. Second, we examined the content of the tweets (**RQ1b**) via topic modelling. We compared the extracted topics across communities to distinguish environmental discourses in distinct green communities. Third, we analysed the profile texts of the users to describe the users in these communities (**RQ1c**). Fourth, we conducted a manual analysis on a subset of one hundred tweets per community to explore the underlying sentiments within each green community (**RQ1d**).

To examine whether distinct green communities interact with each other (**RQ2**), we conducted a network analysis to visualise the communication flows between green communities. Finally, to investigate where in the world these tweets originated (**RQ3**), we compared the proportions of geo-tagged authors belonging to the Global North and Global South.

2.2.1 Community detection

Community detection was used to identify green communities (**RQ1a**), i.e., groups of users based on common connections in their Twitter network. We used the igraph package in R (Csardi and Nepusz 2005) which applies the Louvain algorithm for community detection (Blondel et al. 2008). The Louvain algorithm tries to optimise modularity for each identified cluster by first assigning each node to its own cluster and then shuffling the nodes until modularity is maximised. The Louvain method is a relatively accurate and fast method for community detection in large networks (Mukerjee 2021). In our retrieved Twitter network, users (authors, followers, and friends) are represented as nodes, while the connections between them are represented as edges. We retained communities that comprised at least 1% of users in the network (Lutkenhaus et al. 2019).

2.2.2 Topic modelling

We employed topic modelling to examine the environmental themes (topics) of tweets in green communities (**RQ1b**). For this, we extracted the original tweets ($n = 571, 449$) written by the authors, i.e., tweets that were not quote tweets or retweets. The tweets from each community were denoted as a separate document and the distribution of topics and terms was determined using the latent Dirichlet allocation (LDA) approach (Blei et al. 2003). To analyse the tweets, we used the topicmodels package (Grün and Hornik 2011) in R to create a document feature matrix (DFM). To create the matrix, we pre-processed the tweets according to the preregistered steps as recommended in previous research (Maier et al. 2018). We removed the irrelevant tweet components such as URLs, mentions (@), and retweets (RT); divided the tweets into word units (tokenisation) and converted all letters to lowercase; deleted special characters and punctuation

marks; and removed English stop words such as 'the', 'is', 'are', etc using the list included in the topicmodels package. In a deviation from our preregistered criteria, we applied only the lower limit of pruning to remove all the terms that occurred in less than 1% of all the tweets. This was decided upon observing that removing terms that occurred in more than 95% of the tweets resulted in elimination of highly relevant terms such as "climate", "environment", "sustainability", etc. The resulting DFM comprised of 9 documents and 209,532 features.

To identify a suitable number of topics (K), we calculated the evaluation metrics for different topics by varying the different combinations for number of topics and document-topic densities while keeping the value of β fixed at $1/K$, using the ldatuning package (Nikita and Chaney 2020). Following this approach, we decided on $K = 20$ with α = .01 for our topic model (details in supplementary materials). To understand the environmental discourses in each community, we examined the per-document-per-topic probabilities (gamma), since each document included tweets from a green community identified via community detection. We created word clouds to show the most frequently occurring terms for each community with the wordcloud package in R (Fellows 2018). The resulting descriptions of the green communities were discussed by two of the authors (SD & MM) and agreed upon by all authors. Further robustness tests were conducted to evaluate the topic models during peer-review process, confirming the major results of our analysis (please see supplementary materials for details).

2.2.3 Profile text analysis

Profile description texts for each user in the network (authors, followers, and friends) were examined to understand which types of users constitute the green communities (**RQ1c**). This text analysis was conducted using the same pre-processing steps as those for topic modelling (Maier et al. 2018). The most frequent terms in user profile texts were obtained by assigning TF-IDF weights using the tm package (Feinerer et al. 2008).

2.2.4 Sentiment analysis

To identify the underlying sentiment in the tweets of the different green communities (**RQ1d**), we manually examined 100 tweets per green community ($n = 900$) containing the most likely terms and topics. That is, we identified the topic most strongly associated with a community and retrieved one hundred tweets that contained the most likely terms related to that topic. These tweets were coded as positive if they pertained to pro-environmental issues and action, negative if they dismissed pro-environmental issues and action, and neutral if they did not contain an explicit pro- or anti- environmental sentiment.

2.2.5 Network analysis

To answer **RQ2**, we examined the mutual connections between distinct green communities to visualise interactions. Specifically, we quantified the number of users within each community that followed users from other communities to show the extent to which users in a

particular green community are likely to be exposed to users from another community, as described in Lutkenhaus et al. (2019).

2.2.6 Comparing geotagged members

Finally, to investigate the extent to which tweets in green communities originate from the Global North vs the Global South (**RQ3**), we looked at geo-tagged tweets. In line with previous estimates (Huang and Carley 2019; Karami et al. 2021), location of only 14.51% of all authors was tagged in our sample ($n = 82,906$). For this subset of geo-tagged authors, we manually coded 7433 unique locations (countries, cities, towns, etc.) as belonging to either the Global North or Global South. We compared the proportions of authors from these two regions for each green community to determine which region contributed most to the online environmental discourse.

3 Results

3.1 Identifying green communities

To identify online green communities on Twitter (**RQ1**), we examined the network of users who posted the retrieved environmental tweets. A total of 20,003 communities were identified using the Louvain algorithm for community detection, with a modularity score of 0.63 indicating a community structure comprising clusters of densely connected users. After removing green communities consisting of less than 1% of users in the network, nine green communities were selected for further analysis. A total of 97.32% nodes and 96.56% edges were retained in this truncated network. Table A1 (Appendix A in supplementary materials) details the characteristics of the green communities, including the proportion of users in the total network within each green community, proportion (and number) of authors, i.e., the users who wrote the tweets, and author networks (followers and friends).

Figure 1 depicts green communities comprising the authors and their network of followers and friends. Each green community is represented by a distinct colour and the labels are derived based on the prominent discussion topics identified via topic modelling.

3.2 Green communities: popular topics, members, and sentiment

For **RQ1b**, which aimed to identify the environment-related topics being discussed in distinct green communities, we analysed original tweets posted by the authors ($n = 571,449$). Generally, users in all green communities posted most frequently about climate change, with 'climate' and 'change' being the top two most frequent terms in the corpus. Although we cast a wide net with many keywords pertaining to other planetary boundaries, climate change was by far the most discussed planetary boundary. Given that it was the most popular topic across all communities and to portray the prominence of climate change in discussions, the community names incorporated climate change as the unifying label across communities, followed by the labels that differentiated their environmental content. The
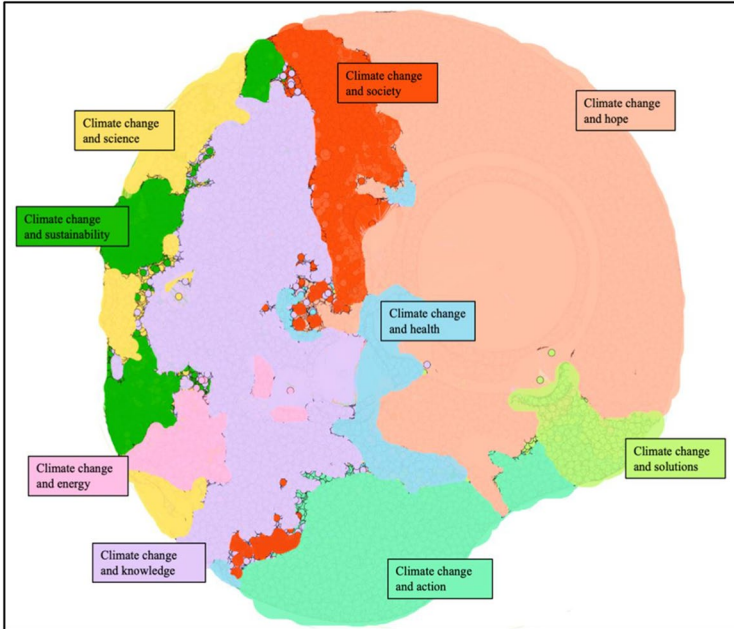
Note. Accessible versions of all figures for readers with colour-blindness 278 are available in supplementary materials.

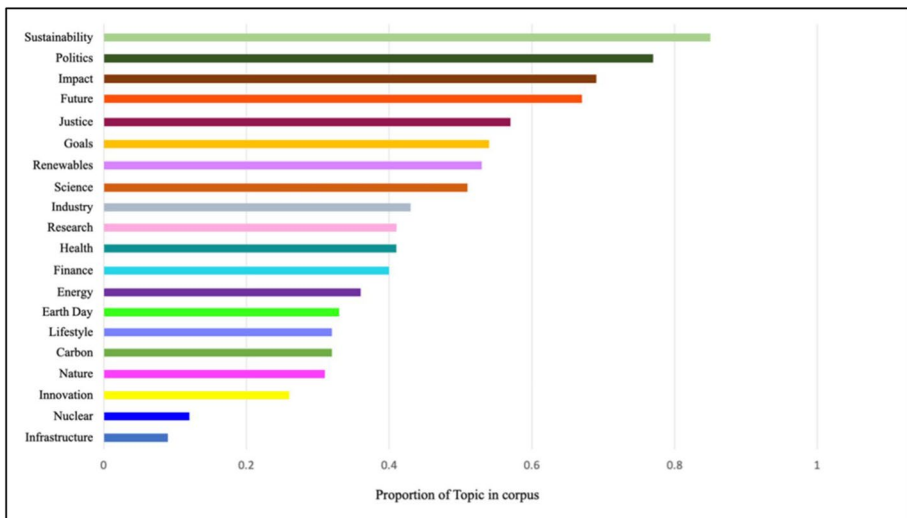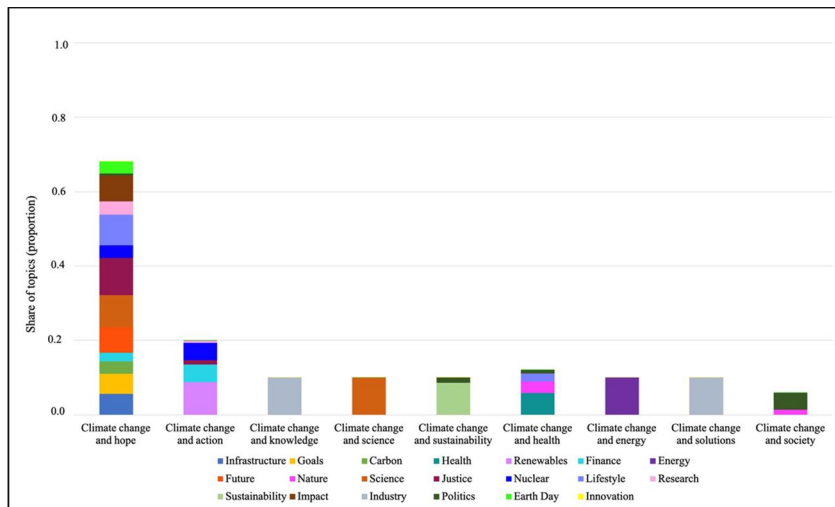**Fig. 1** Network graph showing the green communities

Fig. 2 Topic distribution for all green communities

Note. Since each community was represented by a document consisting of the tweets of its authors, this proportion of topics is obtained by calculating the per-document-per-topic probabilities (gamma) of the corpus.

Fig. 3 Topic distribution in each green community

community names are based upon the environmental discourse within the community (i.e., prominent topics, Table B1 in Appendix B). A list of the top one hundred terms within each topic is provided on the OSF project page.

As shown in Fig. 2, sustainability was the most popular topic across all communities, followed by politics, impact, and future respectively. Figure 3 shows the distribution of topics in each green community.

The following section details the environmental discourse and member characteristics for green communities (**RQs 1b-1d**). The word clouds generated to describe each green community are provided in Appendix C and example tweets are provided in Appendix D.

3.2.1 Climate change and hope (CC-Hope)

The largest community of users (53% of the total network) tweeted about a wide range of environmental issues including climate change, carbon emissions, and fossil fuels. The tweets in this community stressed the importance of sustainability, shared news about environment-friendly policies, supported social movements and calls for global and local climate action, while expressing hope for a better future. Climate justice was also discussed and tweets about indigenous climate-friendly practices, redistribution of wealth, and information about local climate initiatives were included. Moreover, tweets offered tips for individual eco-friendly behaviours such as reducing plastic use, recycling, and reducing waste.

Analysis of user profile descriptions indicated a range of professions such as activist, author, founder, director, and advocate in areas such as policy, business, tech, politics, health. Climate, news, science, love, and nature were some of the most frequently

occurring terms. A manually coded subset of tweets ($n = 100$) revealed that the overall sentiment was positive (89%), whereas a minority were negative (7%) or neutral (4%).

3.2.2 Climate change and action (CC-Action)

The second largest green community (13% of the total network) tweeted mostly about climate action, such as various national climate policies. Tweets also promoted innovation in the energy technology, irrigation and agriculture, and housing sectors. Major areas of discussion involved highlighting steps being taken to combat climate change, such as creating solutions to plastic waste, policy efforts to achieve carbon neutrality, environmental innovations, etc. Users demanded urgent climate action while emphasising the negative consequences of climate change and reacted to climate change sceptics via their tweets – to correct, to express anger, and to demand climate action.

Profile descriptions indicated that the users in this community were mainly media, entertainment, and news professionals such as editors, journalists, and authors. In a manual analysis of a subset of tweets ($n = 100$), 8% tweets were found to be unrelated to the environment. Of the remaining 92 tweets, 3% tweets contained a negative sentiment whereas 97% were positive.

3.2.3 Climate change and knowledge (CC-Knowledge)

This green community (9% of the total network) discussed educational tweets about environmental problems as well as their solutions. Users in this community tweeted posts to stress the need for climate action both on an individual and political level as well as to dispel sceptical narratives. Sustainability in everyday choices such as food, clothing, transport, air-travel, reducing and recycling while managing waste was also emphasised. Moreover, users shared green practices adopted within local communities and by global industries in aviation, sporting, and transport sectors.

The profile descriptions of users suggested that the main areas of user interest were politics and news, comprising of various professionals such as photographers, writers, directors, artists, and journalists. Out of 100 manually examined tweets, 95% were coded as positive, 2% coded as negative and 3% coded as neutral.

3.2.4 Climate change and science (CC-Science)

Community users (7.5% of the total network) posted about environmental topics related to scientific advancements, scientists' protests for climate actions, and news and facts about the effects of environmental degradation. Users emphasised the need for urgent collective and political action to mitigate the climate crisis and discussed scientific research and innovations related to climate change and other environmental problems such as biodiversity loss and plastic-pollution. Users tweeted about the scientific consensus on the existence of climate change and interdisciplinary research about the effects of climate change such as rising sea levels, habitat degradation, loss of biodiversity (especially insects), and urban air and water pollution, among others. Tweets also related to the need for efforts to increase the public's awareness of climate change.

The profile descriptions of the users in this community indicated that it comprised of researchers, scientists, and those involved in health and public work. Out of one hundred tweets, 99% were coded as positive whereas 1% were coded as neutral.

3.2.5 Climate change and sustainability (CC-Sustainability)

Users in this community (4% of the total network) mainly tweeted about Earth Day and ensuring a sustainable future with the help of innovation and technology industries incorporating Environmental, Social and Governance (ESG) practices. Tweets related to promotion of sustainability practices by businesses and technology companies, but also local governments, largely to commemorate Earth Day. Since data were collected during the week of Earth Day, celebratory posts were common, with tweets discussing the need for more sustainability initiatives, protecting natural resources, and decreasing emissions. Tweets also indicated the need for sustainable and green finance initiatives, the role automation and data analytics can play in combating climate change, and balancing economic growth with sustainability goals.

Based on the profile descriptions, the users in this green community comprised of business, marketing, media, and technology professionals such as CEOs, editors, authors, engineers, and investors In a manually coded subset of one hundred tweets, only 1% were negative, whereas all the others had a positive environmental sentiment.

3.2.6 Climate change and health (CC-Health)

The users in this community (2% of the total network) posted about the effect of climate change on the health of our planet and its inhabitants. Tweets included issues like the consequences of extreme-weather events like floods and wildfires on human lives, the GHG emissions resulting from fossil-fuel based transportation (cars and airplanes), and food scarcity due to warmer temperatures. The prominent discussions focused on the links between planetary health and human health. Tweets emphasised the effects of climate change becoming obvious in day-to-day living such as the effects of climate change on food supply, effects of air pollution on breathing clean air, and effects of chemicals in the food system on quality of life of people. Sustainable lifestyle habits such as using plant-based skincare items and adopting vegan diets were promoted in these tweets. Innovations in sustainable living were also discussed in this green community, with users tweeting about the popularity of plant-based food options, increase in parks and forest areas, and upcoming climate-friendly energy sources.

Profile descriptions indicated a wide range of professionals such as teachers, psychologists, artists, advocates, and managers. One hundred tweets were manually examined for their underlying sentiment, of which 87% were coded as positive, 9% were coded as negative, and 4% were coded as neutral.

3.2.7 Climate change and energy (CC-Energy)

The most frequently discussed topics in this community (1.3% of the total network) included renewable energy, carbon tax, carbon footprints, and climate action denial. Users also tweeted about the effects of climate colonialism on the countries in Global South, the need for nuclear power as a renewable energy source, and policy action in

the US to combat climate change. The main areas of discussion identified for this community related to the energy sector, ranging from debating the use of nuclear power to reduce carbon footprint, levying of carbon taxes to offset carbon footprint, and the greenwashing by oil, aviation, and fossil-fuel companies taking inadequate steps to fulfil their promises of going net zero.

User profile descriptions included terms like business, sustainability, activist, founder, and non-profit, indicating the presence of a variety of users. In a subset of hundred tweets, 86% were coded as positive whereas 14% tweets were coded as negative.

3.2.8 Climate change and solutions (CC-Solutions)

The users in this green community (1.2% of the total network) tweeted about solutions for environmental problems as well as the global inequity surrounding climate change. After climate change, solutions for plastic pollution (including microplastics) and rising greenhouse gas emissions were the most frequently discussed environmental problems. Most prominent discussions related to sustainability in food choices, low-emission transportation, investment in innovation for clean energy, ways to reduce single-use plastic consumption, and highlighting the need for equitable and just climate action. Environmental effects of animal agriculture, switching to plant-based and vegan food options, and benefits of low carbon transit (electric vehicles and cycles) were other important discussion points. Users in this community tweeted about the global disparity in climate action and the dangers of climate change for vulnerable populations, such as indigenous communities, women, persons with disability, and those with restricted access to reproductive healthcare.

The analysis of profile descriptions indicates that the users in this community were largely innovation, business, and policy professionals including company presidents, strategists, and commissioners. Of the one hundred tweets selected for sentiment analysis, 96% were coded as positive, 3% were coded as negative, and 1% were coded neutral.

3.2.9 Climate change and society (CC-Society)

Environmental discourse in this community (1% of the total network) was mainly educational and information-oriented, with users tweeting about the societal threats posed by the fossil-fuel industry as well as promoting urgent solutions and initiatives to counter climate change. Users referenced Earth Day and urged for more societal sustainability initiatives, such as in the energy and infrastructure sectors. Major discussions in this community included stressing the existence of climate change, highlighting the role of fossil fuel industry in delaying climate action, urging governments to act against the threats posed by climate change, and suggesting solutions for transition to renewable energy.

The profile descriptions indicate that the users in this community included PhDs (either holders or those currently pursuing), defence and security professionals, and those in energy transition companies. The subset of tweets ($n = 100$) containing the most common terms showed an overall pro-environmental sentiment (99% of the tweets), with only one tweet coded as negative and no neutral tweets.

3.3 Interactions between green communities

To answer the second research question about interactions between green communities, we calculated and visualised the extent to which users followed those from outside their own
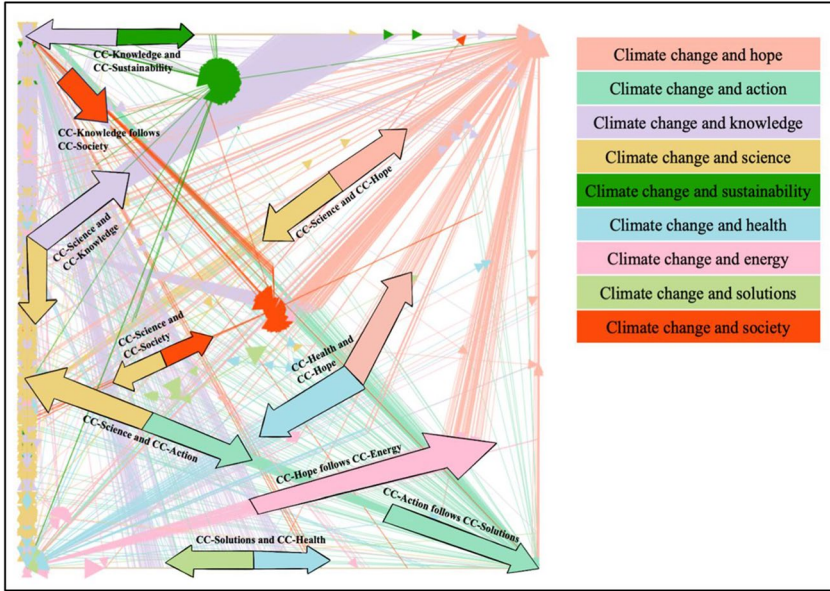
Note. The direction of the arrows indicates the target of a node, i.e., the users being followed.
[a]The prominent interactions in this figure have been brushed to improve readability. The original figure is provided in the supplementary materials (see SM 1, figure 4).

Fig. 4 Interactions between green communities – following users from other communities
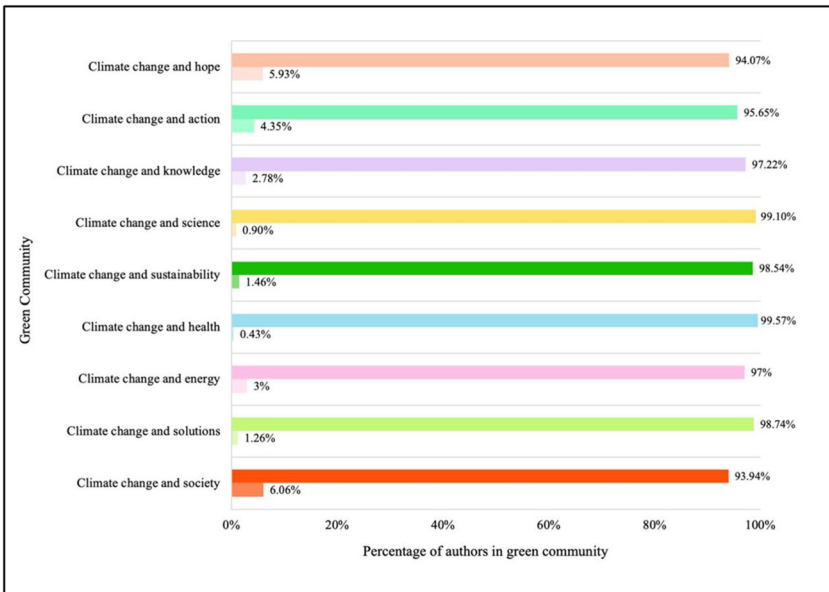
Note. The top bar represents authors from the Global North whereas the bottom bar indicates authors from the Global South.

Fig. 5 Representation of the Global North and Global South in Twitter environmental discourse

green community (Fig. 4). We found that users across distinct network clusters or green communities interacted with each other, with little evidence of polarised clusters. Please see Appendix E for further details.

3.4 Geographical representation in green communities

We examined **RQ3** about the origins of environmental tweets between the Global North and Global South. The discourse in every green community was dominated by authors in the Global North, with only CC-Hope and CC-Society communities comprising more than 5% of the authors from the Global South (Fig. 5). Authors from the Global South were least represented in CC-Health and CC-Science communities, comprising less than 1% of the authors.

4 Discussion

The environmental content shared by people on social media reflects their views towards the environment, thereby offering a way to tap into the public discourse about important environmental issues. We examined Twitter content beyond climate change by including other interlinked environmental issues (i.e., the planetary boundaries). By analysing networks of users who posted environmental content on Twitter, we identified nine different clusters of users (i.e., green communities), the topics discussed in these communities, and their typical authors. We also examined the interactions between green communities and explored the extent to which tweets originated in the Global North and Global South.

4.1 Climate change is the most discussed environmental topic on Twitter

Whereas natural scientists focus on nine planetary boundaries that are all seen as important for sustaining the level of civilization we currently have (Rockström et al. 2009), our results show that the discourse on Twitter is mostly about climate change. Other planetary boundaries such as biodiversity loss, plastic pollution, and clean air are sometimes mentioned, but far less frequently than climate change.

We identified nine green communities on Twitter, all pertaining to climate change – namely, Climate change and hope (CC-Hope), CC-Action, CC-Knowledge, CC-Science, CC-Sustainability, CC-Health, CC-Energy, CC-Solutions, and CC-Society. Authors in each community posted about different environmental topics, yet some common themes emerged. Importantly, climate change and climate action related tweets were commonly posted by authors in all green communities, showing that people demand active efforts towards a sustainable future from politicians, industries, and businesses. Since data were collected in the week of Earth Day, individuals and organisations took to Twitter to celebrate the occasion and urge more environmental action.

Differences in content also emerged. Depending on the community, shared content focused on information dissemination (CC-knowledge), solutions (CC-action and CC-solutions), or health impacts (CC-health). Some communities shared a more positive outlook towards a sustainable future (CC-hope) while others focused more on environmental threats for society (CC-society). With regards to solutions for the environmental crises, some communities advocated for inclusive collective action (CC-hope and CC-science),

while others focused more on individual actions (CC-health), or technological and industrial innovations (CC-sustainability, CC-energy, and CC-solutions).

4.2 Environmental content on twitter tended to be generally pro-environmental

Dismissive content constituted a minority of tweets in every green community and was encountered mostly in tweets about climate change. We found little evidence of conspiratorial content, possibly because we analysed only the top nine communities that contained at least 1% of all users in our sample, thereby omitting smaller clusters of users who post conspiratorial environmental content.

Another reason for this finding could be that earlier studies focused only on climate change which is a more polarising term than other environmental issues (Cody et al. 2015). Specifically, studies that focus on climate change exclusively could 'arguably have polarisation "built in" [original emphasis]' (Pearce et al. 2019, p. 11) by categorising all non-neutral views as either anti- or pro- climate change. To our knowledge, this study is the first to use validated search terms related to the full planetary boundaries framework, thereby allowing a broad yet potentially more nuanced collection of environment-related tweets.

At the time of data collection in April 2022, Twitter had been shown to have a negative effect on conspiracy beliefs (Theocharis et al. 2021) and had taken steps to remove conspiratorial content (Mahl et al. 2021). However, since the sale of Twitter in October of 2022, conspiratorial content and misinformation are expected to increase (Ledford 2022). Our results represent a snapshot of Twitter discourse at a specific point in time before its sale, and limit conclusions regarding the environment-related sentiment on Twitter since its sale. For future research it would be interesting to replicate the current study and to see whether different results emerge.

4.3 Green communities discussing varied environmental topics interact with each other

Unlike previous studies on climate change related discussions that provide mixed-evidence of homophily in Twitter networks (Pearce et al. 2014; Williams et al. 2015), we found that users within different green communities followed each other, which could increase exposure to content shared by those in other green communities.

As such, users with environmental concerns may seek out new information about various topics and may interact with other users for doing so, as demonstrated in traditional media research as well (Ho et al. 2014; van Valkengoed et al. 2022). Future research could focus on Twitter network clusters to understand how different communities may interact with each other more actively. For instance, we could identify the environmental topics that users from different networks agree or disagree on by examining the similarities or differences in replies or quote tweets of users within and outside of one's own network. This could facilitate in persuading people to care about other related environmental issues they may not engage with otherwise.

4.4 Global North dominates English-language environmental discourse on Twitter

We found that the environmental content on Twitter mostly originated from the Global North. This is concerning because wealthier countries in the Global North are generally

responsible for environmental degradation (for example, because of high carbon emissions) while those in the Global South are more endangered by its effects (Kartha et al. 2020). Demands for accountability for this disparity have risen recently as omission of voices from the Global South limits people's awareness about the extent of the environmental crises facing our planet, hindering the urgently needed global effort to counter the challenges posed by it (Atwoli et al. 2022; Stoddard et al. 2021).

This inequity also emulates previous findings regarding the lack of geographical diversity in published climate research and environmental communication as well as in media coverage of environmental issues (Comfort and Park 2018; Schäfer and Painter 2021; Tandon 2021). Combined with previous research, our study affirms that those who are most vulnerable to the effects of environmental degradation are inadequately represented in global discussions, even with the presumed connectivity and wide reach of social media platforms.

Notably, our study considered only English-language tweets, which account for more than half of the tweets on Twitter (Hong et al. 2021). Tweets in other popular languages such as Indonesian and Spanish (Hong et al. 2021) could add a much-needed nuance to the findings concerning disparities in global environmental discourse. At the same time, English remains a popular second language in many countries of the Global South and Twitter users from these regions may still tweet in their native language as well as in English (Eleta and Golbeck 2014; Mocanu et al. 2013).

4.5 Implications and future directions

Before discussing the implications of our study, some limitations of our study are listed to act as a caveat for the interpretation of our findings. First, while Twitter activity corresponds to the beliefs people hold, it may not be representative of environmental views of the general population as Twitter users tend to be younger, wealthier, and reside in urban areas with greater accessibility to internet (Barberá and Rivero 2015; Blank 2017). Second, while we used a broad environmental framework to select the search terms for data collection, it may not have led to gathering all types of environment-related tweets. Third, in community detection using the Louvain algorithm a user can only be assigned to one community, making it possible that some users belonging to multiple communities were placed in the one where they had the most connections. Finally, while we traced interactions between green communities based on followers, it remains to be determined *how* community members interact with those in a different community, for example, to access new information or to criticise the members of other communities.

Despite these limitations, our study provides a thorough overview of environmental discussions on Twitter with implications for researchers and policymakers. While our study revealed discussions about various topics, climate change emerged as the primary environmental concern. The popularity of climate change in public discourse is encouraging given its devastating consequences, but the need for further communication on the loss of biosphere integrity (i.e., biodiversity loss and extinction) and other interlinked threats is also warranted so that the public understanding of environmental challenges and solutions can advance.

Research on the inclusion of the planetary boundaries framework in environmental policy in North America and Europe shows that despite being included in some national policy in Europe, it is still overlooked in policy-making at the international scale (Hurley and Tittensor 2020). Similarly, an analysis of tweets by prominent environmental

non-governmental organisations (eNGOs) revealed increased communication about the threats of climate change and plastic pollution whereas other environmental issues were rarely discussed (Barrios-O'Neill 2021). Hence, emphasising the environmental thresholds of the planetary boundaries framework in environmental policy and advocacy might draw public's attention to the importance of issues other than climate change.

Moreover, individuals may benefit from knowing that their actions impact other more tangible planetary boundaries such as biodiversity loss and plastic pollution. Emphasising that pro-environmental behaviours positively impact not only people's proximal natural environments but also their own health could motivate more pro-environmental decisions (Gustafson et al. 2021; Limaye 2021). Thus, future research could explore ways of using the wide reach of social media to educate the public about the overall impact of their behaviours on the environment.

While there was a relative abundance of pro-environmental tweets in our findings, the uncertainty surrounding Twitter's content moderation practices since its sale and questions regarding the future of the platform (Nidumolu et al. 2023) highlight the fragility of social media ecosystems and the discourse they represent. Researchers have also voiced concerns regarding availability of social media data and changes to these platforms previously, calling for studies integrating various social media platforms and data available on them (Ghermandi and Sinclair 2019). We also invite further research into the environmental discourse on other platforms like Instagram and TikTok, as environmental topics and sentiment may differ among social media. Despite this caveat regarding the timeframe of our results, our findings still add to the growing literature that dismissive content may only form a minority of environmental discourse on social media (Grouverman et al. 2018). This might be particularly true for environmental discussions that are not limited to climate change, which tends to be a more polarising topic on social media (Cody et al. 2015; Falkenberg et al. 2022; Fownes et al. 2018). Hence, communication practitioners and policymakers could focus primarily on persuading and supporting the individuals who want to adopt greener lifestyles rather than focusing on the sceptical minority who may not have pro-environmental intentions to begin with. That said, it also appears that polarisation on social media could depend on which environmental issue is being discussed and where, and social media messaging should be tailored to people's worldviews and contexts (Chang et al. 2022a).

Finally, our study echoed the growing acknowledgement of the disparity in the global environmental discourse, finding little representation from Global South also in the online space (Blicharska et al. 2017; Karlsson 2002). This disparity in who leads the conversation about environmental issues limits our understanding of indigenous construal, views, and practices about the environment (Fernández-Llamazares et al. 2015; Thaker 2021). Thus, while our study considered only English-language tweets based on a broad yet selective list of search terms, future studies could conduct similar analyses in multiple languages and with different search terms to add novel interpretations of how the environment may be construed locally and contextualise such findings to align with ethnographic studies.

5 Conclusion

Across nine green communities on Twitter, we found that climate change was the most frequently discussed environmental issue and that there was less focus on the other planetary boundaries. Content that was dismissive of environmental issues formed a minority,

whereas climate action was emphasised in all green communities. The green communities in our study seemed to interact with each other and we found little evidence of polarised clusters in which people have limited exposure to other information. Finally, we found that English language tweets about the environment originated mainly in the Global North, indicating that the Twitter space currently remains inadequate for equitable global discussions surrounding environmental issues.

Data availability The data and analysis scripts for this study are available on the OSF project page (https://osf.io/kg43n/).

Declarations

References

Adam S, Reber U, Häussler T, Schmid-Petri H (2020) How climate change skeptics (try to) spread their ideas: Using computational methods to assess the resonance among skeptics' and legacy media. PLoS One 15(10):e0240089. https://doi.org/10.1371/journal.pone.0240089

Atwoli L, Erhabor GE, Gbakima AA, Haileamlak A, Ntumba J-MK, Kigera J, Laybourn-Langton L, Mash B, Muhia J, Mulaudzi FM, Ofori-Adjei D, Okonofua F, Rashidian A, El-Adawy M, Sidibé S, Snouber A, Tumwine J, Yassien MS, Yonga P et al (2022) COP27 climate change conference: urgent action needed for africa and the world: wealthy nations must step up support for africa and

vulnerable countries in addressing past, present and future impacts of climate change. Oxford Open Energy:oiac008. https://doi.org/10.1093/ooenergy/oiac008

Barberá P, Rivero G (2015) Understanding the Political Representativeness of Twitter Users. Soc Sci Comput Rev 33(6):712–729. https://doi.org/10.1177/0894439314558836

Barrie C, Ho JC, Chan C, Rico N, König T, Davidson T (2022) academictwitteR: access the twitter academic research product track v2 api endpoint (0.3.1) [Computer software]. https://cran.r-project.org/web/packages/academictwitteR/index.html

Barrios-O'Neill D (2021) Focus and social contagion of environmental organization advocacy on Twitter. Conserv Biol 35(1):307–315. https://doi.org/10.1111/cobi.13564

Blank G (2017) The digital divide among twitter users and its implications for social research. Soc Sci Comput Rev 35(6):679–697. https://doi.org/10.1177/0894439316671698

Blei DM, Ng AY, Jordan MI (2003) Latent Dirichlet Allocation. J Mach Learn Res 3(Jan):993–1022

Blicharska M, Smithers RJ, Kuchler M, Agrawal GK, Gutiérrez JM, Hassanali A, Huq S, Koller SH, Marjit S, Mshinda HM, Masjuki HH, Solomons NW, Staden JV, Mikusiński G (2017) Steps to overcome the North–South divide in research relevant to climate change policy and practice. Nat Clim Change 7(1) Article 1. https://doi.org/10.1038/nclimate3163

Blondel VD, Guillaume J-L, Lambiotte R, Lefebvre E (2008) Fast unfolding of communities in large networks. J Statis Mech : Theory Exp 2008(10):P10008. https://doi.org/10.1088/1742-5468/2008/10/P10008

Boulianne S, Lalancette M, Ilkiw D (2020) "School strike 4 climate": Social media and the international youth protest on climate change. Media Commun 8(2) Article 2. https://doi.org/10.17645/mac.v8i2.2768

Build for Good: Climate Change (n.d.) Retrieved 15 December 2021, from https://developer.twitter.com/en/use-cases/build-for-good/extreme-weather

Cameletti M, Fabris S, Schlosser S, Toninelli D (2022) Dictionary-based classification of tweets about environment. J Math Statis Sci 8(1):13–32

Chang CH, Armsworth PR, Masuda YJ (2022a) Environmental discourse exhibits consistency and variation across spatial scales on twitter. BioScience 72(8):789–797. https://doi.org/10.1093/biosci/biac051

Chang CH, Armsworth PR, Masuda YJ (2022b) Twitter data reveal six distinct environmental personas. Front Ecol Environ 20(8):481–487. https://doi.org/10.1002/fee.2510

Chen X, Zou L, Zhao B (2019) Detecting climate change deniers on twitter using a deep neural network. In: Proceedings of the 2019 11th International Conference on Machine Learning and Computing - ICMLC '19, pp 204–210. https://doi.org/10.1145/3318299.3318382

Cody EM, Reagan AJ, Mitchell L, Dodds PS, Danforth CM (2015) Climate change sentiment on twitter: An unsolicited public opinion poll. PLoS One 10(8):e0136092. https://doi.org/10.1371/journal.pone.0136092

Comfort SE, Park YE (2018) On the field of environmental communication: A systematic review of the peer-reviewed literature. Environ Commun 12(7):862–875. https://doi.org/10.1080/17524032.2018.1514315

Csardi G, Nepusz T (2005) The igraph software package for complex network research. InterJ Complex Syst 1695

Dwivedi R (2001) Environmental movements in the global south: Issues of livelihood and beyond. Int Sociol 16(1):11–31. https://doi.org/10.1177/0268580901016001003

Eckstein D, Vera K, Schäfer L, Germanwatch (2021) Global climate risk index 2021 who suffers most extreme weather events? Weather-related loss events in 2019 and 2000-2019.

Eleta I, Golbeck J (2014) Multilingual use of twitter: Social networks at the language frontier. Comput Hum Behav 41:424–432. https://doi.org/10.1016/j.chb.2014.05.005

Enders AM, Uscinski JE, Seelig MI, Klofstad CA, Wuchty S, Funchion JR, Murthi MN, Premaratne K, Stoler J (2021) The relationship between social media use and beliefs in conspiracy theories and misinformation. Polit Behav. https://doi.org/10.1007/s11109-021-09734-6

Falkenberg M, Galeazzi A, Torricelli M, Di Marco N, Larosa F, Sas M, Mekacher A, Pearce W, Zollo F, Quattrociocchi W, Baronchelli A (2022) Growing polarization around climate change on social media. Nat Clim Chang 12(12) Article 12. https://doi.org/10.1038/s41558-022-01527-x

Feinerer I, Hornik K, Meyer D (2008) Text mining infrastructure in R. J Stat Softw 25:1–54. https://doi.org/10.18637/jss.v025.i05

Fellows, I. (2018). wordcloud: Word clouds (2.6) [Computer software]. https://CRAN.R-project.org/package=wordcloud

Fernández-Llamazares Á, Méndez-López ME, Díaz-Reviriego I, McBride MF, Pyhälä A, Rosell-Melé A, Reyes-García V (2015) Links between media communication and local perceptions of climate change in an indigenous society. Clim Chang 131(2):307–320. https://doi.org/10.1007/s10584-015-1381-7

Fownes JR, Yu C, Margolin DB (2018) Twitter and climate change. Sociol Compass 12(6):e12587. https://doi.org/10.1111/soc4.12587

Gasparetti F, Sansonetti G, Micarelli A (2021) Community detection in social recommender systems: A survey. Appl Intell 51(6):3975–3995. https://doi.org/10.1007/s10489-020-01962-3

Gaytan Camarillo M, Ferguson E, Ljevar V, Spence A (2021) Big Changes Start With Small Talk: Twitter and Climate Change in Times of Coronavirus Pandemic. Front Psychol 12:2308. https://doi.org/10.3389/fpsyg.2021.661395

Ghermandi A, Langemeyer J, Van Berkel D, Calcagni F, Depietri Y, Egarter Vigl L, Fox N, Havinga I, Jäger H, Kaiser N, Karasov O, McPhearson T, Podschun S, Ruiz-Frau A, Sinclair M, Venohr M, Wood SA (2023) Social media data for environmental sustainability: A critical review of opportunities, threats, and ethical use. One Earth 6(3):236–250. https://doi.org/10.1016/j.oneear.2023.02.008

Ghermandi A, Sinclair M (2019) Passive crowdsourcing of social media in environmental research: A systematic map. Glob Environ Chang 55:36–47. https://doi.org/10.1016/j.gloenvcha.2019.02.003

Grömping M (2014) 'Echo Chambers': Partisan facebook groups during the 2014 thai election. Asia Pacific Media Educator 24(1):39–59. https://doi.org/10.1177/1326365X14539185

Grouverman A, Barash V, Kollanyi B, Lederer T, Howard P (2018) Climate change consensus and skepticism: Mapping climate change dialogue on twitter and facebook [Comprop Data Memo]. Oxford Internet Institute https://comprop.oii.ox.ac.uk/research/climate-change/

Grün B, Hornik K (2011) topicmodels: An R package for fitting topic models. J Stat Softw 40:1–30. https://doi.org/10.18637/jss.v040.i13

Gustafson A, Pace A, Singh S, Goldberg MH (2021) What do people say is the most important reason to protect nature: An analysis of pro-environmental motives across 11 countries. PsyArXiv. https://doi.org/10.31234/osf.io/k2z6c

Ho SS, Detenber BH, Rosenthal S, Lee EWJ (2014) Seeking information about climate change: Effects of media use in an extended prism. Sci Commun 36(3):270–295. https://doi.org/10.1177/1075547013520238

Hong L, Convertino G, Chi E (2021) Language matters in twitter: A large scale study. Proc Int AAAI Conf Web Soc Media 5(1):518–521. https://doi.org/10.1609/icwsm.v5i1.14184

Huang B, Carley KM (2019) A large-scale empirical study of geotagging behavior on Twitter. In: Proceedings of the 2019 IEEE/ACM International Conference on Advances in Social Networks Analysis and Mining, pp 365–373. https://doi.org/10.1145/3341161.3342870

Hurley I, Tittensor DP (2020) The uptake of the biosphere integrity planetary boundary concept into national and international environmental policy. Global Ecol Conserv 22:e01029. https://doi.org/10.1016/j.gecco.2020.e01029

Jang SM, Hart PS (2015) Polarized frames on "climate change" and "global warming" across countries and states: Evidence from Twitter big data. Glob Environ Chang 32:11–17. https://doi.org/10.1016/j.gloenvcha.2015.02.010

Jovchelovitch S (1995) Social Representations in and of the Public Sphere: Towards a Theoretical Articulation. J Theory Soc Behav 25(1):81–102. https://doi.org/10.1111/j.1468-5914.1995.tb00267.x

Karami A, Kadari RR, Panati L, Nooli SP, Bheemreddy H, Bozorgi P (2021) Analysis of geotagging behavior: Do geotagged users represent the twitter population? ISPRS Int J Geo-Inform, Article 10, 6(6). https://doi.org/10.3390/ijgi10060373

Karlsson S (2002) The North-South knowledge divide: Consequences for global environmental governance. In: Esty DC (ed) Global environmental governance: Options & opportunities. Yale School of Forestry & Environmental Studies

Kartha, S., Kemp-Benedict, E., Ghosh, E., Nazareth, A., & Gore, T. (2020). The carbon inequality era: An assessment of the global distribution of consumption emissions among individuals from 1990 to 2015 and beyond. Oxfam, Stockholm Environment Institute 10.21201/2020.6492

Kazansky B, Karak M, Perosa T, Tsui Q, Baker S, The Engine Room (2022) At the confluence of digital rights and climate & environmental justice: A landscape review. https://www.fordfoundation.org/media/7356/ter-final-report-07-07-22.pdf

Kirilenko AP, Stepchenkova SO (2014) Public microblogging on climate change: One year of Twitter worldwide. Glob Environ Chang 26:171–182. https://doi.org/10.1016/j.gloenvcha.2014.02.008

Lacy S, Watson BR, Riffe D, Lovejoy J (2015) Issues and best practices in content analysis. J Mass Commun Q 92(4):791–811. https://doi.org/10.1177/1077699015607338

Ledford H (2022) Internet and extremism experts predict more hate speech and conspiracy theories on Musk's Twitter. Sci Am https://www.scientificamerican.com/article/internet-and-extremism-experts-predict-more-hate-speech-and-conspiracy-theories-on-musks-twitter/

Limaye VS (2021) Making the climate crisis personal through a focus on human health. Clim Chang 166(3):43. https://doi.org/10.1007/s10584-021-03107-y

Liu JC-E, Zhao B (2017) Who speaks for climate change in China? Evidence from Weibo Climatic Change 140(3):413–422. https://doi.org/10.1007/s10584-016-1883-y

Lutkenhaus RO, Jansz J, Bouman MPA (2019) Mapping the Dutch vaccination debate on Twitter: Identifying communities, narratives, and interactions. Vaccine X, 1:100019. https://doi.org/10.1016/j.jvacx.2019.100019

Mahl D, von Nordheim G, Guenther L (2022) Noise pollution: A multi-step approach to assessing the consequences of (not) validating search terms on automated content analyses. Digit J:1–23. https://doi.org/10.1080/21670811.2022.2114920

Mahl D, Zeng J, Schäfer MS (2021) From "Nasa Lies" to "Reptilian Eyes": Mapping communication about 10 conspiracy theories, their communities, and main propagators on twitter. Soc Media Soc 7(2) 20563051211017482. https://doi.org/10.1177/20563051211017482

Maier D, Waldherr A, Miltner P, Wiedemann G, Niekler A, Keinert A, Pfetsch B, Heyer G, Reber U, Häussler T, Schmid-Petri H, Adam S (2018) Applying LDA topic modeling in communication research: Toward a valid and reliable methodology. Commun Methods Meas 12(2–3):93–118. https://doi.org/10.1080/19312458.2018.1430754

Mocanu D, Baronchelli A, Perra N, Gonçalves B, Zhang Q, Vespignani A (2013) The Twitter of babel: Mapping world languages through microblogging platforms. PLoS One 8(4):e61981. https://doi.org/10.1371/journal.pone.0061981

Morrow DR, Thompson MS, Anderson A, Batres M, Buck HJ, Dooley K, Geden O, Ghosh A, Low S, Njamnshi A, Noël J, Táíwò OO, Talati S, Wilcox J (2020) Principles for thinking about carbon dioxide removal in just climate policy. One Earth 3(2):150–153. https://doi.org/10.1016/j.oneear.2020.07.015

Mukerjee S (2021) A systematic comparison of community detection algorithms for measuring selective exposure in co-exposure networks. Sci Rep 11(1):15218. https://doi.org/10.1038/s41598-021-94724-1

Nidumolu J, Hu K, Hu K (2023) Elon Musk says Twitter's cash flow still negative as ad revenue drops 50%. Reuters https://www.reuters.com/technology/elon-musk-says-twitters-cash-flow-still-negative-as-ad-reven ue-drops-2023-07-15/

Nikita, M., & Chaney, N. (2020). ldatuning: Tuning of the latent dirichlet allocation models parameters (1.0.2) [Computer software]. https://CRAN.R-project.org/package=ldatuning

Pearce W, Holmberg K, Hellsten I, Nerlich B (2014) Climate change on twitter: Topics, communities and conversations about the 2013 ipcc working group 1 report. PLoS One 9(4):e94785. https://doi.org/10.1371/journal.pone.0094785

Pearce W, Niederer S, Özkula SM, Sánchez Querubín N (2019) The social media life of climate change: Platforms, publics, and future imaginaries. WIREs Clim Chang 10(2). https://doi.org/10.1002/wcc.569

Pilař L, Kvasničková Stanislavská L, Pitrová J, Krejčí I, Tichá I, Chalupová M (2019) Twitter analysis of global communication in the field of sustainability. Sustainability 11(24):6958. https://doi.org/10.3390/su11246958

R Core Team (2021) R: A language and environment for statistical computing. [Computer software]. R Foundation for Statistical Computing, Vienna, Austria https://www.R-project.org/

Richardson K, Steffen W, Lucht W, Bendtsen J, Cornell SE, Donges JF, Drüke M, Fetzer I, Bala G, von Bloh W, Feulner G, Fiedler S, Gerten D, Gleeson T, Hofmann M, Huiskamp W, Kummu M, Mohan C, Nogués-Bravo D et al (2023) Earth beyond six of nine planetary boundaries. Sci Adv 9(37):eadh2458. https://doi.org/10.1126/sciadv.adh2458

Rockström J, Steffen W, Noone K, Persson Å, Chapin FS, Lambin E, Lenton TM, Scheffer M, Folke C, Schellnhuber HJ, Nykvist B, de Wit CA, Hughes T, van der Leeuw S, Rodhe H, Sörlin S, Snyder PK, Costanza R, Svedin U et al (2009) Planetary boundaries: Exploring the safe operating space for humanity. Ecol Soc 14(2) https://www.jstor.org/stable/26268316

Sachan M, Contractor D, Faruquie TA, Subramaniam LV (2012) Using content and interactions for discovering communities in social networks. In: Proceedings of the 21st International Conference on World Wide Web, pp 331–340. https://doi.org/10.1145/2187836.2187882

Sarrica M, Farinosi M, Comunello F, Brondi S, Parisi L, Fortunati L (2018) Shaken and stirred: Social representations, social media, and community empowerment in emergency contexts. Semiotica 2018(222):321–346. https://doi.org/10.1515/sem-2016-0208

Schäfer MS, Painter J (2021) Climate journalism in a changing media ecosystem: Assessing the production of climate change-related news around the world. WIREs Clim Chang 12(1):e675. https://doi.org/10.1002/wcc.675

Segerberg A, Bennett WL (2011) Social media and the organization of collective action: Using twitter to explore the ecologies of two climate change protests. Commun Rev 14(3):197–215. https://doi.org/10.1080/10714421.2011.597250

Stoddard I, Anderson K, Capstick S, Carton W, Depledge J, Facer K, Gough C, Hache F, Hoolohan C, Hultman M, Hällström N, Kartha S, Klinsky S, Kuchler M, Lövbrand E, Nasiritousi N, Newell P, Peters GP, Sokona Y et al (2021) Three decades of climate mitigation: Why haven't we bent the global emissions curve? Annu Rev Environ Resour 46(1):653–689. https://doi.org/10.1146/annurev-environ-012220-011104

Stryker J, Wray R, Hornik R, Yanovitzky I (2006) Validation of database search terms for content analysis: The case of cancer news coverage. J Mass Commun Q 83:413–430. https://doi.org/10.1177/107769900608300212

Takikawa H, Nagayoshi K (2017) Political polarization in social media: Analysis of the "Twitter political field" in Japan. In: 2017 IEEE International Conference on Big Data (Big Data), pp 3143–3150. https://doi.org/10.1109/BigData.2017.8258291

Tandon A (2021) Analysis: The lack of diversity in climate-science research. Carbon Brief https://www.carbonbrief.org/analysis-the-lack-of-diversity-in-climate-science-research/

Terren L, Borge-Bravo R (2021) Echo chambers on social media: A systematic review of the literature. Rev Commun Res 9:99–118

Thaker J (2021) Environmentalism of the Poor: Global south perspectives on environmental communication. In: The Handbook of International Trends in Environmental Communication. Routledge

Theocharis Y, Cardenal A, Jin S, Aalberg T, Hopmann DN, Strömbäck J, Castro L, Esser F, Van Aelst P, de Vreese C, Corbu N, Koc-Michalska K, Matthes J, Schemer C, Sheafer T, Splendore S, Stanyer J, Stępińska A, Štětka V (2021) Does the platform matter? Social media and COVID-19 conspiracy theory beliefs in 17 countries. New Media Soc, 14614448211045666. https://doi.org/10.1177/14614448211045666

van Valkengoed AM, Perlaviciute G, Steg L (2022) Relationships between climate change perceptions and climate adaptation actions: Policy support, information seeking, and behaviour. Clim Chang 171(1):14. https://doi.org/10.1007/s10584-022-03338-7

von Nordheim G, Boczek K, Koppers L (2018) Sourcing the sources: An analysis of the use of Twitter and Facebook as a journalistic source over 10 years in The New York Times , The Guardian , and Süddeutsche Zeitung. Digit J 6(7):807–828. https://doi.org/10.1080/21670811.2018.1490658

Vu HT, Do HV, Seo H, Liu Y (2020) Who leads the conversation on climate change?: A study of a global network of NGOs on twitter. Environ Commun 14(4):450–464. https://doi.org/10.1080/17524032.2019.1687099

Williams HTP, McMurray JR, Kurz T, Hugo Lambert F (2015) Network analysis reveals open forums and echo chambers in social media discussions of climate change. Glob Environ Chang 32:126–138. https://doi.org/10.1016/j.gloenvcha.2015.03.006

Yin Z, Hu Y, Jenkins K, He Y, Forstenhäusler N, Warren R, Yang L, Jenkins R, Guan D (2021) Assessing the economic impacts of future fluvial flooding in six countries under climate change and socio-economic development. Clim Chang 166(3):38. https://doi.org/10.1007/s10584-021-03059-3

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