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Visualizing the structure and development of climate change communication research

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Abstract

To better understand the structure, development, and function of the climate change communication knowledge domain, we performed time-evolving bibliometric mapping and topic modeling on 2,995 climate change communication publications from Web of Science. Structural and visual representations of scholarship are useful for identifying areas of opportunity and coordinating effort in interdisciplinary and action-oriented knowledge domains. Our analysis reveals a cohesive and dense yet ossified knowledge structure which suggests that while a systems approach is being applied in climate communication, there is a need to explore more constitutive strategies for the communication of climate change.

Keywords

Environmental communication; Participation and science governance; Science communication: theory and models

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Introduction

Recent writing in science, environmental, and climate change communication calls for strategy and coordination within the profession, to better leverage existing knowledge in communication projects [Besley, 2015; Jensen & Gerber, 2020; Moser, 2016; Smith, 2020]. For climate communication in particular, these calls respond to two defining features of the knowledge domain: (1) explosive growth in the past decade, which has coincided with maturity as a field of inquiry [Moser, 2016], and (2) discouragement at the muted effect evidence-based communication techniques have had in moving the needle on widespread climate change action [Cook & Overpeck, 2018; Jensen & Gerber, 2020]. Twenty years into the field's development, it is still unclear how to effectively leverage hard-earned climate communication knowledge to significantly affect climate outcomes.

Far from diminishing the successes achieved to date, this simply calls attention to the work yet to be done and the scale of the challenge. Imminent climate change impacts require nimble collaboration, which benefits from an accessible census of available tools and theories for communicating about climate. Going forward, climate change communication will likely require a systems approach, which considers "interactions among the various elements of such communication and the context in which they occur in the real world over time," and which "take the complexity of the system into account" [National Academies of Sciences, Engineering, and Medicine, 2017, pp. 84–85; Willamo et al., 2018].

We aim to support systems thinking by visualizing the structure and development of climate change communication research. We use time-evolving bibliometric network analysis and topic modeling to explore structures and patterns evident through time in 2,995 climate change communication publications from Web of Science. This data-driven, visual approach complements existing systematic reviews by generating structural diagrams of climate communication knowledge. A structural representation affords a systematic and synoptic view of the literature by depicting the development of climate change communication research over the past twenty years and highlighting structural functions performed by topics, papers and journals in the climate communication system.

Context

Climate change communication (frequently referred to as climate communication) research investigates how people gain and act on information about climate change, as individuals or in groups [Comfort & Park, 2018; "Yale Program on Climate Change Communication", 2022]. Because many factors influence climate understanding and action, climate communication is profoundly interdisciplinary, with scholars from physical and biological science, social science, and the humanities applying diverse methods and theories to this pressing issue [Cagle & Tillery, 2015; Moser, 2016]. In practice, climate communication involves individuals and entities of many sorts, from citizens to politicians, students to scientists, and governments to NGOs to corporations [Comfort & Park, 2018; Corner & Clarke, 2017; Smith, 2020].

Climate change communicators are often trying to provoke action in their audiences, which may make their communication more persuasive than traditional science communication and engagement activities [Carvalho, Russill & Doyle, 2021; Johnson, 2011]. Persuasion is complicated by the fact that climate issues are tricky to understand or act on in isolation, and by the fact that in this area, information rarely influences behavior directly or linearly [Cook & Overpeck, 2018; Corner & Clarke, 2017; Johnson, 2011; Moser, 2015]. Climate change communication is therefore frequently called upon to be constitutive as well as instrumental, to create meaning instead of executing a straightforward transfer of facts. As such, there is increasing awareness of the multi-layered nature of communication and the way success is contingent on a host of outside factors that are difficult to control (or control for in experimental settings). In a sense, this is like challenges well documented in health communication, where a systems thinking approach prompted greater consideration of the ways competing messages, social and political conditions, and personal networks influence the efficacy and outcomes of health communication campaigns [National Academies of Sciences, Engineering, and Medicine, 2017]. In such situations, the ability to identify and integrate content and context in a communication plan makes success most likely [Willamo et al., 2018].

A systems-level view of climate change communication foregrounds consideration of the ways many different aspects of climate change communication may interact, augment, or thwart one another. Taking a census of climate change communication knowledge is therefore a key step in supporting further strategic research and tactical application of existing tools [Jensen & Gerber, 2020; Moser, 2016; Smith, 2020]. Doing so with network analysis and topic modeling can reveal the structure within which climate change communication ideas are developed and tested. This supports more systematic and creative approaches to climate communication, helps orient newcomers, and encourages collective and coordinated effort by scholars and practitioners alike [Wehrmann & van der Sanden, 2017; Wenger, McDermott & Snyder, 2002]. By choosing to foreground structural elements of the climate communication knowledge system and its evolution through time, we can consider how knowledge structure enables and constrains future knowledge generation [Chen, Dubin & Schultz, 2015; Henry & Vollan, 2014; Szerszynski & Galarraga, 2013].

Systematic reviews have proliferated across climate change communication (and science and environmental communication more broadly) in recent years, with some focusing on particular communication problems or sets of tools [Agin & Karlsson, 2021; Akerlof, Timm, Rowan, Olds & Hathaway, 2022; Armstrong & Krasny, 2020; Asmi, Anwar, Zhou, Wang & Sajjad, 2019; Gerber et al., 2020; Kidd et al., 2019; Larosa & Mysiak, 2019]. The abundance of these reviews indicates a desire to coordinate collective effort and provide clear guidance to researchers and practitioners. A review focusing on the structure of climate communication knowledge and linking knowledge domain content to that structure could be particularly effective for this purpose, for organizing research effort in the coming decade, and for offering insight on opportunities to develop new communication approaches that both draw upon and go beyond previous work.

Methods

Knowledge domains are gestalt-like products of countless self-organizing interactions between scholars [Chen, 2016]. Within these systems, researchers create and validate knowledge, leaving an evolutionary record of ideas in the form of citations pointing to relevant or influential works. We use two methods, time-evolving bibliometric knowledge mapping and topic modeling, to gain a systems-level and structural perspective on climate communication knowledge production. This approach is replicable and, to the greatest extent possible, objective [Borner, Chen & Boyack, 2003]. It combines network analysis and topic modeling to provide a clear perspective on an interdisciplinary knowledge domain that is not completely tractable with either method alone.

Data

On July 31, 2020, we retrieved 5,934 publication records from Clarivate's Web of Science Database, using the search query TS = (climat* NEAR chang* AND communicat*). This query was used in a previous systematic review of climate change communication [Moser, 2016]. We explored algorithmic strategies to filter irrelevant items (using both natural language processing and network pruning) but were not able to achieve reliable filtering this way. For example, excluding the term "information technology" removed irrelevant entries about the impacts of climate change on such technology, but also removed relevant articles about the role of computers and the internet in climate communication. In the end, we applied Moser's [2016] inclusion and exclusion criteria in a similar manual review process, where publications were removed when they were really climate science papers that mentioned in passing a need to communicate results, and when they were not about climate communication at all (examples include "improving workplace climate through communication" and "climate impacts on insect pheromone communication"). We retained 2,995 or approximately 50% of the retrieved publications for further analysis (achieving a similar retention rate as in Moser [2016]). This dataset has been used in related studies on the climate communication knowledge domain's structure, but here we present a new analysis that describes the temporal evolution of the network and assesses its topical content [Canon, Boyle & Hepworth, 2022].

86% or 2,575 of the analyzed publication records are journal articles. Proceedings papers, book chapters, editorials, and other items account for the remaining 14% (420 publication records). Web of Science categorizes 34% or 1,018 of these publications as "Environmental Studies" and 27% or 809 as "Environmental Sciences," with only 19% or 569 categorized as "Communication." The dataset favors first authors from United States institutions (40% or 1,198 first authors), followed by England (17% or 509 first authors) and Australia (11% or 329 first authors), with the remaining first authors being from other countries (32% or 959 authors).

Bibliometric Knowledge Mapping

Bibliometric knowledge mapping uses metadata from peer-reviewed publications to investigate and describe the structure of a knowledge domain, generating metaknowledge about the domain's function [Chen, 2016; Evans & Foster, 2011]. It projects publication metadata into a network of citation-based links, which is visualized for analysis. Viewed through time, these citation patterns can reveal an evolutionary history of ideas and depict knowledge generation as an active process constrained by historical-structural context [Borner et al., 2003; Evans & Foster, 2011; McLevey & McIlroy-Young, 2017; Wenger et al., 2002]. The network is both a snapshot of a dynamic knowledge system and a structure that may guide flow and exchange within that system [Henry & Vollan, 2014]. In either case, network analysis elucidates the structure, not the content, of the connections and can reveal otherwise invisible processes shaping problem definition in the mapped domain [Evans & Foster, 2011; Szerszynski & Galarraga, 2013].

We projected this data into a bibliographic coupling network, where articles are nodes and links are formed between them whenever they cite a common third publication. The assumption is that articles citing common references are probably working on similar types of problems. We selected this type of network because it is retrospective: citations can only travel back in time, so this network shows the evolution of patterns in knowledge application. It can also characterize the current research front, including papers that have not been cited. Most importantly, it depicts connections between articles leveraging similar knowledge for climate communication purposes, and therefore has the potential to reveal structural features in how climate change communication applies the many tools and theories available.

We used python packages metaknowledge [McLevey & McIlroy-Young, 2017] and NetworkX [Hagberg, Schult & Swart, 2008] to build the bibliographic coupling network. We pruned all links with a strength less than 5 and retained only the giant component, yielding a final dataset of 1,770 nodes (articles) and 19,212 edges for visualization and analysis. We performed a modularity analysis on the resulting network, using the Louvain community detection algorithm [Aynaud, 2020]. The algorithm finds sets of nodes with a higher internal than external connection rate. We named these communities by consulting simple frequency counts of keywords and title words for papers in each community; this process and the communities themselves are described in detail elsewhere [Canon et al., 2022]. We calculated a few node-level network statistics: degree centrality, which is the raw count of how many links a node has, and betweenness centrality, which scores each node based on how many of the shortest paths between other nodes in the network travel through it. In this network, a high degree paper will have many sources in common with others in the network, while a high betweenness article will connect to other papers who do not cite many works in common. These metrics help identify nodes that perform influential structural functions. Finally, we cut the network into four time steps (pre-2005, 2006–2010, 2011–2015, and 2016–2020), to visualize its development.

Topic Modeling

We performed topic modeling on the same dataset. Topic modeling is an unsupervised machine learning method from the field of natural language processing. Like network analysis, topic modeling aids researchers in gleaning useful insight from large, unstructured collections of written works [Asmussen & Møller, 2019; Blei, 2012]. This method has successfully depicted topic diversity in similar interdisciplinary and heterogeneous research fronts such as climate adaptation [Bittermann & Fischer, 2018; Lesnikowski et al., 2019].

A topic model imagines each text in the dataset was composed by an author following "imaginary probabilistic recipes," selecting words from baskets of topics where each word in the vocabulary of the corpus has a specific probability of being drawn [Blei, 2012; Blei, Ng & Jordan, 2003]. A generative probability model is used to infer from the observations (the texts of the corpus) what the latent topics that generated the corpus must be, based on the frequency with which words occur in documents across the corpus and relative to other words in each document [Blei et al., 2003]. Words that co-occur frequently are strongly associated with topics, but it is left to the researcher to interpret topics' semantic meaning from these lists of words. Topics that emerge from a topic model are distinct, but each topic is present to some degree in each document, and each word is present in each topic, however weakly [Blei et al., 2003; Wehrheim, 2018]. So, a topic model need not produce a mapping of documents to single topics, especially because topics may describe things like regions or methodologies as well as concepts and theories; this is a good example of how topics are assumed by the model to interact with one another to produce the semantic meaning of the texts [Wehrheim, 2018].

We used a Mallet implementation of Latent Dirichlet Allocation to model the topics in abstracts from the same dataset used for network analysis [Blei et al., 2003; McCallum, 2002]. The abstracts have a mean length of 1,299 words and a median length of 1,246 words. To run the topic model, researchers must decide a priori how many topics to search for [Blei et al., 2003]. We selected nine topics, based on consulting coherence scores for models with a range of topic counts and selecting the one with the highest coherence score (0.42). Coherence measures the interpretability of the topics to humans based on how often words appear together in the corpus.

We used python packages nltk [Bird, Klein & Loper, 2009] and spaCy [Montani et al., 2022] to remove irrelevant words (such as prepositions), identify phrases (such as "global warming"), and lemmatize words. We then used gensim [Rehurek & Sojka, 2010] to build the topic model and LDAvis to visualize the results [Sievert & Shirley, 2014]. LDAvis plots the distance between topics by applying multidimensional scaling with Jensen-Shannon Divergence. Finally, we combined both analyses, assessing which topics were represented in which network communities and which network communities corresponded to identified topics from the topic model.

Results

The knowledge map revealed four core areas of climate communication knowledge (which we called "Climate Messages in the Media," "Individual Perceptions of Climate," "Visual and Affective Communication," and "Risk Perception and Communication") that share information frequently and one core area more distanced from the other four ("Decision-making and Stakeholder Engagement"). These five knowledge communities have been described in detail in a companion article [Canon et al., 2022]; here we focus on their structural change through time (Figure 1). In Figure 1, colored nodes join the network at each timestep. In 2005, most articles were in the "Climate Messages & the Media" community, and even in 2010, with the appearance of "Decision-making & Stakeholder Engagement" and "Risk Perception & Communication," the network is still very small. Between 2010 and 2015, "Individual Perceptions of Climate Change" grows and branches out from previous work in existing communities. Between 2015 and 2020, "Visual and Affective Communication" appears to knit the core of the network together, and "Decision-making and Stakeholder Engagement" becomes better integrated into the network structure. Overall, the structure of the climate communication research network formed between 2010 and 2015, as available research nearly quadrupled in quantity. The most recent timestep, from 2015 to 2020, changed little about the knowledge domain's structure, primarily adding density and cohesion on the existing scaffold.

Most highly cited papers in the network are from the earliest-formed communities ("Climate Messages in the Media," "Risk Perception and Communication," and "Decision-making and Stakeholder Engagement") (Figure 2). A full 50% of the 20 top-cited papers come from "Risk Perception & Communication," and 25% come from "Climate Messages in the Media." Twelve of the top-cited papers were published before 2010; the most recent highly cited papers are from 2012. Collectively the domain's research is cited 54,619 times, and just 36 top papers receive 25% of the total citations. On average, papers are cited about 18 times. This means that many of the connections between papers observed in Figure 1 could come from widespread citation of the most cited papers.

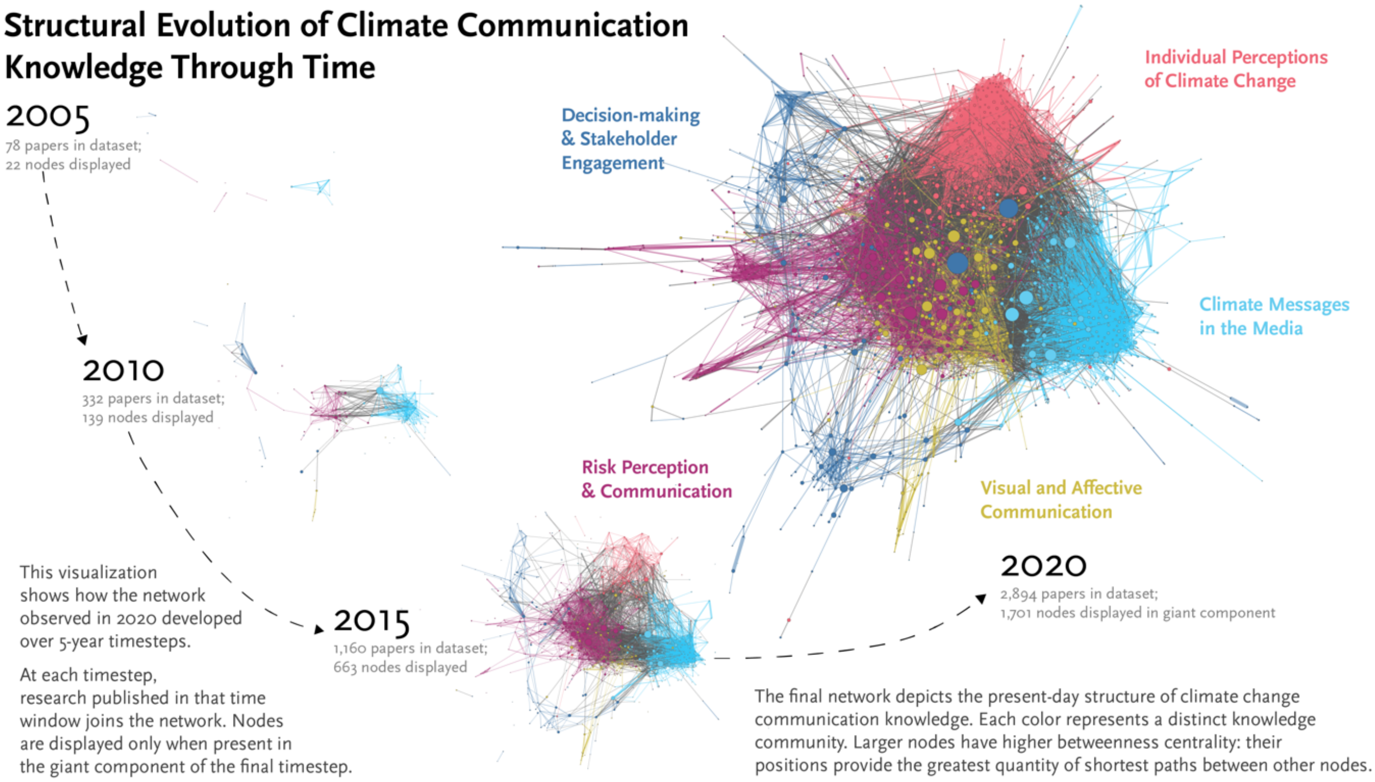

Figure 1. Timeline of the evolution of the bibliographic coupling network. Larger nodes have higher betweenness centralities (they connect to other articles that are not often connected to each other). Colors indicate communities identified by Louvain community detection.

The network in Figure 1 *does not* show direct citation trends: it infers latent connections between articles based on patterns in their bibliographies. A paper in "Climate Messages in the Media" may cite five of the same sources as a paper in "Visual and Affective Communication," linking these two papers. However, these papers would likely be applying knowledge from the five similar sources in different ways, because they are members of different knowledge communities. The "Climate Messages in the Media" paper may be considering how effective photographs are at engaging readers with a news story about climate change, while the "Visual and Affective Communication" paper may be studying specific compositions of the photographs and how effective different visual frames are at provoking a sense of connection to the issue. These two papers are linked in this network because they apply the same knowledge sources, but they fall in different knowledge communities because they share more bibliography items with papers from those knowledge communities than with each other. For example, the "Climate Messages in the Media" paper might generally draw on mass communication research, while the "Visual and Affective Communication" paper might generally draw on design research. The connections evident in this type of network show patterns in application of previously published knowledge.

Papers are therefore collected into knowledge communities based on similar patterns of knowledge application. Papers applying similar knowledge will be in the same network community. But links crisscrossing this network in a "spaghetti ball" pattern suggest that each community in the climate change communication

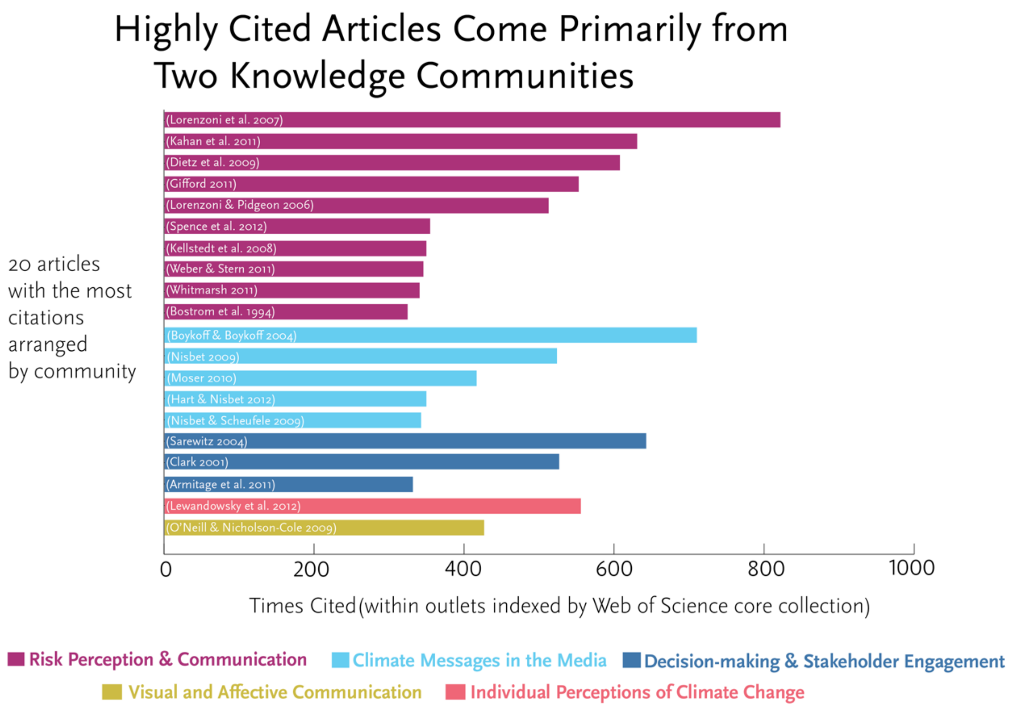

Figure 2. Top cited articles in the climate communication dataset. The colors of the bars correspond to the network community the paper belongs to in Figure 1. Two communities represent the majority of highly-cited papers in this knowledge domain.

knowledge domain does frequently seek out and apply knowledge from other communities. This is what Figure 1 shows: through time the network demonstrates increasing awareness and application of knowledge sources from across the domain. The communities appear to draw on many similar knowledge sources for divergent purposes, though all in support of climate change communication of some sort. Because the network is so dense (crisscrossed with many redundant pathways connecting nodes and communities), it is reasonable to assume that each community has a working knowledge of the others. This extreme cohesion is noticeable even after pruning links to a minimum connection strength of five. From a network perspective, this density may be desirable and functional for the knowledge domain, or it may be undesirable and dysfunctional, depending on the underlying reason for the structural pattern.

To understand how contributions from communication-focused journals influence knowledge structure, we plotted the location of articles from the six most prolific journals in the dataset on the knowledge map (Figure 3). The total share of the network represented by articles from the six most popular journals is relatively small because climate change communication articles are published in a huge diversity of outlets. The journal with the largest share is *Environmental Communication — A Journal of Nature and Culture*, where 167 or just 5.6% of the climate communication items were published. The other journals most frequently represented in the network were *Climatic Change* with 126 articles (4.3%), *Global Environmental Change — Human and Policy Dimensions* with 83 articles (2.2%), *Science Communication* with 76 articles (2.5%), *Public Understanding of Science* with 67 articles (2.2%), and *Wiley Interdisciplinary Reviews — Climate Change* with 62 articles (2.1%).

Our assumption was that these journals likely have an organizing influence on the network structure. *WIREs Climate Change*, *Climatic Change*, and *Global Environmental Change* span several network communities, but the communication-focused journals (*Environmental Communication*, *Public Understanding of Science*, and *Science Communication*) cluster on the right side of the network map, primarily in the "Climate Messages in the Media" and "Individual Perceptions of Climate Change" communities. *WIREs Climate Change* published many of the high betweenness articles (the size of nodes in Figures 1 and 3 represent relative betweenness centrality), which suggests that the journal's stated function of interdisciplinary synthesis in climate change related studies is frequently successful in connecting topics from different communities in this knowledge network.

The topic model identified nine topics with similar cumulative frequencies throughout the dataset (as evidenced by the equivalent sizes of their circles in Figure 4). We named the topics by consulting lists of the most probable words in each topic and by looking at the most relevant ($\lambda = 0.6$) topic words identified in pyLDAvis (words that appear frequently within a topic but less frequently in the overall corpus). Some topics have clear mappings to the network communities (for example, Topic 5: Climate in the News and the "Climate Messages in the Media" network community, or Topic 6: Risk and the "Risk Perception and Communication" network community). Some overlap between topics is evident, as shown by the overlapping circles in Figure 4, especially for Topics 2: Climate Change and 3: Concern for Climate Change, and Topics 4: Policy, Practice, and Participation and 8: Scientists & Experts. Though topic modelers often look for non-overlapping circles, for this dataset we find the overlap reasonable because of how identical words could be used strongly in different topics. For example, Topic 2: Climate Change and Topic 3: Concern for Climate Change are semantically distinct (one refers to a physical process and the other to a social one), but understandably rely on similar word patterns (for example, the word "impact" is on the top ten lists (Figure 4) for both these topics).

Just as each topic can be thought of as a probabilistic combination of words, each document is a probabilistic combination of topics, where the most frequently occurring or dominant topic accounts for the main meaning of the document. The average strength of dominant topics in documents is 0.24. The highest percent contribution of a single topic to an article in this dataset is 0.55. This illustrates that documents are nearly always made up of a collection of several topics. Because many documents have dominant topics that account for less than a quarter of the document's content, it is difficult to classify documents based on dominant topics alone. However, even in the case of a document with a relatively low dominant topic strength, it's possible to get a general sense of what the document is about by considering the dominant topic. As an example, the paper "Lessons from First-Generation Climate Science Integrators" [Brugger, Meadow & Horangic, 2016] is the strongest (0.41 or 41% share) of all papers with the dominant Topic 8: Scientists & Experts. The dominant topic accounts for the bulk of the paper, but other topics from the menu of nine are needed to arrive at a better understanding of what the document is really about. In this dataset, sorting documents into categories based on a single dominant topic might not give a clear idea of what the sets of documents are about.

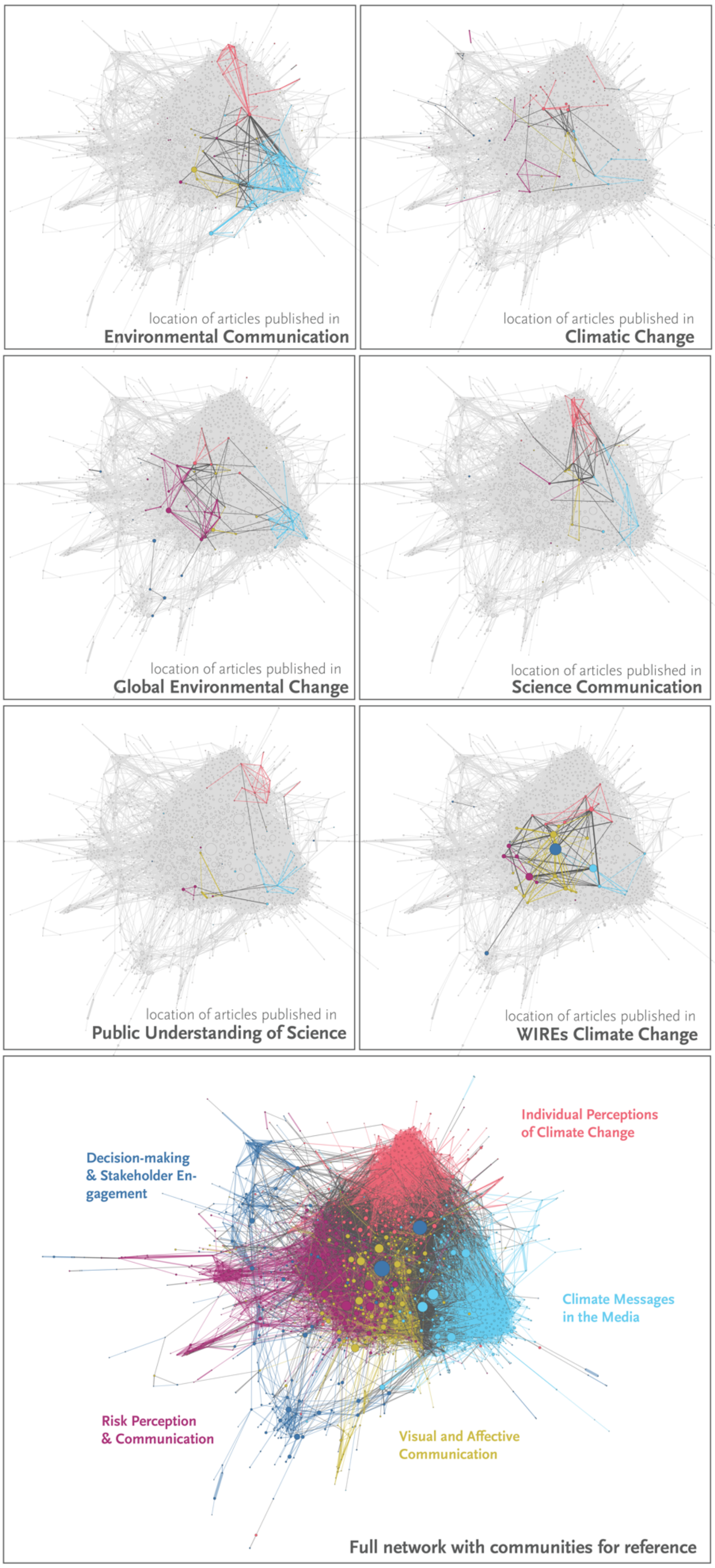

Figure 3. Network positions of articles from the journals publishing the most climate communication content. Links are only shown between articles in the same journal. Larger nodes have higher betweenness centrality.

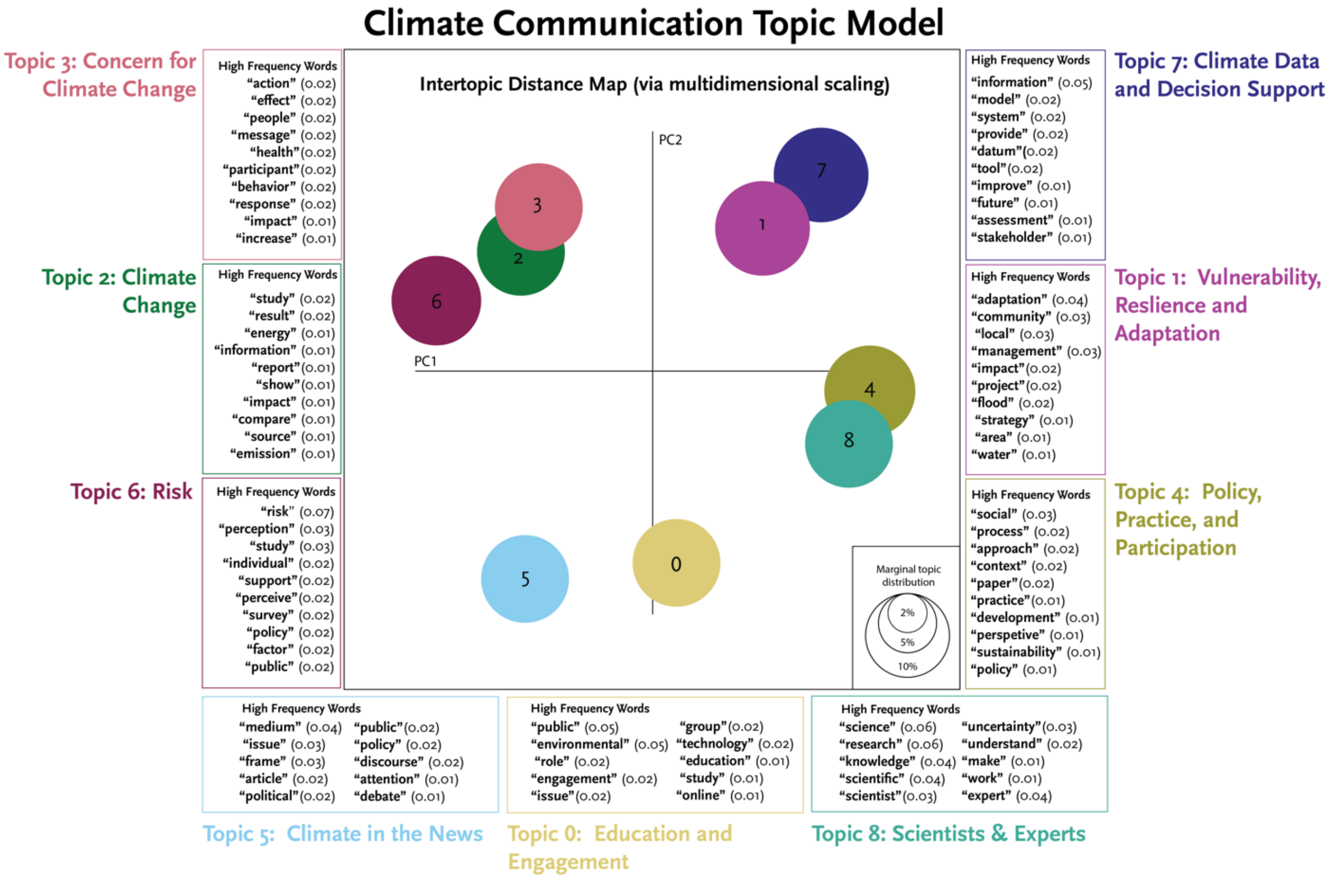

Figure 4. Topic model of climate communication research. In the center of the figure, circle size indicates the marginal topic distribution (notably, all topics in this analysis had approximately 10% distribution), and circle location indicates the distance between the topics. Surrounding lists show the most probable words from each topic. The numbers in parentheses indicate the probability of encountering the most common words in each topic.

We checked to see if the topic model could help explain the patterns observed in the network, or vice versa. It is difficult to draw clear conclusions about knowledge patterns in a dense network with a relatively low modularity score (0.24). It is also difficult to draw clear conclusions from a topic model where most dominant topics account for less than a fifth of the content in most documents. As mentioned above, the topics were evenly distributed across the entire dataset and within individual papers of the dataset (Figures 5A, 5B). We computed the frequency with which each topic from the topic model occurred as the dominant topic in the papers from each network community (Figure 5C–5F). This revealed clearer patterns in topic dominance for each community: the network community "Risk Perception and Communication" is dominated by Topic 6: Risk and the "Climate Messages in the Media" community is dominated by Topic 5: Climate in the News, as we would expect. The remaining topics appear to be distributed across most of the network communities, which could explain the overlap in the modeled topics and the overlap in the network communities. Topic 3: Concern for Climate Change is most prevalent in the "Individual Perceptions of Climate Change" and "Visual and Affective Communication" network communities; Topic 7: Climate Data and

Decision Support appears primarily in the "Visual and Affective Communication" and "Decision-making and Stakeholder Engagement" network communities. We checked the topic distributions of papers identified as top cited works, high betweenness nodes in the network, and high degree nodes in the network, to see if they exhibited particular topic dominance or topic compositions (Figure 5G). However, we did not find any patterns of note. Taken together, the network (a dense and recently formed structure of knowledge) and topic model (a clear menu of nine topics that mixes frequently within documents) are evidence that multiple threads of inquiry intertwine at many scales within this knowledge domain, from the synoptic level (links crossing the knowledge network) to the sentence level (many topics blending within documents).

Discussion

We began this article with the observation that more than twenty years into the development of climate change communication as a field, it is still not clear how to leverage its wealth of evidence-based techniques to significantly affect outcomes. Much recent writing in this space suggests a systems approach is the key to impactful and evidence-based climate change communication, and urges researchers and practitioners to discover and incorporate key techniques and insights from other areas of climate change communication to increase the impact of their work [National Academies of Sciences, Engineering, and Medicine, 2017; Willamo et al., 2018]. From both a network and a topic modeling perspective, these statements seem to imply that (1) there would be clearly separate knowledge communities in this domain, (2) journals would contribute to production of this network structure, and (3) documents would have strongly dominant topics indicating their particular focus. This was in fact what we expected to find in this analysis, but the revealed structure did not have these characteristics.

Instead, results from this structural investigation revealed (1) a cohesive and dense network structure with journals frequently spanning multiple communities, and (2) nine topics in a topic model which each rarely account for more than a quarter of the content of a document. These two results suggest that climate change communication researchers are already seeking out and integrating many different traditions, approaches, topics, disciplines, and pieces of evidence in their climate change communication activities and investigations. This effort could be what produces the closely knit communities and the many cross-community connections observed in the bibliographic coupling network. It could also explain why many different topics comingle strongly in individual documents and throughout the corpus in the topic model.

The cohesion and density of the network, the even distribution of topics in the topic model, and the low strength of dominant topics in the documents from this corpus seem to suggest that climate communicators are already taking a systems approach to the complicated problem of climate change communication, considering as many possible elements as they can in their research. This structural analysis cannot confirm that this is happening, but the revealed structure would certainly be explained by this interpretation. The question then becomes whether this is as effective or as productive as calls for a systems approach seem to assume: in a similar study of adaptive capacity literature, the knowledge domain was found to be "a cacophony," with so much going on that the tune is drowned out [Siders, 2019]. It's possible that much of the discussion in climate change communication

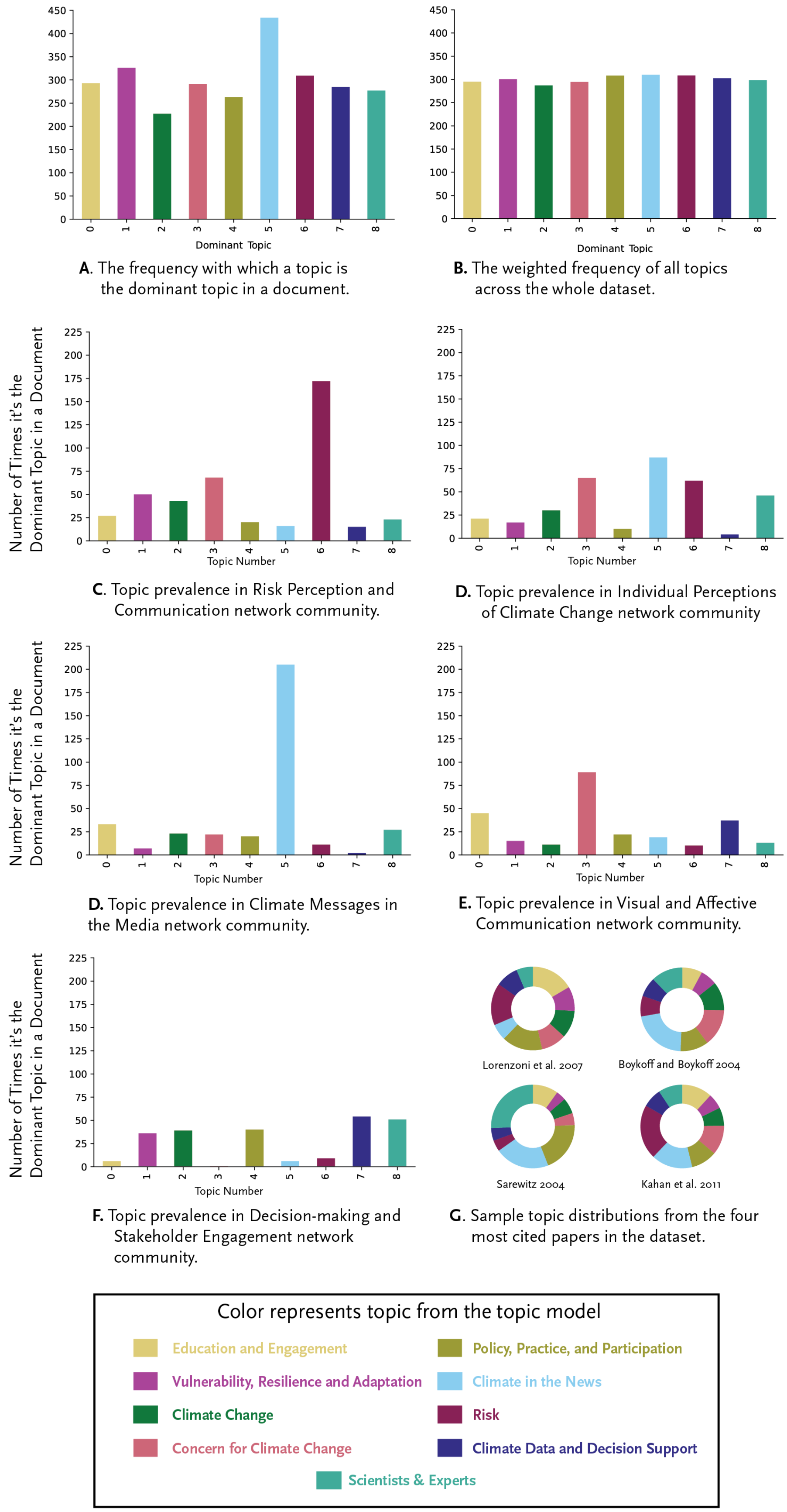

Figure 5. Patterns in topic dominance across the dataset, within network communities, and within four highly cited sample papers.

about unifying research activities, reducing the gaps between disciplines and between research and practice, and moving from deficit to dialogue to participation is doing more to create confusion than to produce clarity and purpose in climate change communication, as scholars strive to integrate perhaps too many elements and perspectives into their communication research and plans. Such a situation could produce the messy and mixed-up structure observed in these analyses.

Given widespread calls for unified, systematic, and strategic climate change communication, we were frankly surprised to find a structure that had formed by 2015 and was already so cohesive by July 2020. Because there are so few gaps between groups of nodes in the network, the observed structure itself offers few suggestions for what uncovered territory within the boundaries of climate communication knowledge might prove fruitful to explore further, and little idea of what elements might be missing from the existing approach or what systematic combinations of knowledge may not have been tried already. Similarly, the blending of many topics within each document of the dataset, and the equivalent distribution of topics throughout the corpus, offers little insight as to which less-recognized topic might merit more attention or hold the key to a systematic and effective climate change communication approach.

One possible conclusion is that a systematic approach has begun to take hold (meaning connections across areas have been made and topics have been integrated), but that there is more work to be done to systematize climate change communication. For example, what is now a haphazard pattern of crisscrossing connections might need to be refined into a set of key bridges between avatar articles for each knowledge area. But there's another possible interpretation, which is that the very structure sought by the calls to implement a systems approach is actually getting in the way of discovering new and effective ways to communicate climate change.

Calls for a systems approach come from a particular instrumental orientation in climate change communication research, which focuses on the individual as the relevant unit for analysis [Ballantyne, 2016; Carvalho et al., 2021; Moser, 2009; Villar, 2021]. This tradition stems from climate change communication's origination in "hard" science traditions, and it frames communication as an instrument instead of as a relationship or a process. The confusing structure of the network and the highly blended topics in its documents may indicate that communication researchers and practitioners are essentially iterating through endless combinations of potentially relevant instrumental inputs, seeking elements for the ultimate communication equation, one that reliably causes changes in understanding and behaviors of audiences. The visualizations in this analysis could be read as indicating how fruitless this search seems to be, as researchers attempt to integrate many topics in each of their documents, and as they cite research from all across the knowledge domain in their manuscripts. Read in parallel with other current work in the field, this network structure could suggest that successful climate communication in the age of climate change may require resisting the quest for a systems approach, instead taking a slower, less instrumental, more constitutive, more creative, and more idiosyncratic approach to climate communication.

We are not the first scholars to reach this conclusion [Coen, 2021; Cook & Overpeck, 2018; Finlay et al., 2021]. While we have been developing this structural analysis, others undertaking a similar quantitative content analysis of this field have suggested it is time for climate communication to "set sail on a new sea" and question established ways of thinking [Agin & Karlsson, 2021, p. 14]. A primary challenge we see on this journey — one that threatens to keep climate communication inquiry bound within the existing knowledge structure — is figuring out how to resist the pull of a knowledge structure that has grown increasingly ossified since 2015. Two specific risks of an ossified and overcrowded knowledge domain are relevant here: first, that structures like this can act as a force that keeps new research focused on the same old areas, sometimes at the expense of discovering something new, and second, that the lack of distance between (or bridges to) distinct knowledge areas within the network offers no obvious option for where the research front should travel next.

Limitations and Future Work

Our analysis is a structural one: it cannot reveal nuances of content in particular articles or areas of the knowledge domain. It sees aggregate patterns which are subject to limitations of the underlying data. For example, it is well known that Web of Science does not reflect all disciplines equally, nor does it do a good job of indexing work done in books and book chapters, especially in the humanities [Archambault, Vignola-Gagné, Côté, Larivière & Gingrasb, 2006; Cabeza, Chàfer & Mata, 2020]. Given that our conclusions call for exactly the type of work which might be found in these locations instead of in journal articles, this is an important limitation to consider.

A further limitation of our study is that we specifically delimited our data sample to include only climate change communication publications. For this reason, we may be missing existing connections to adjacent areas, which could be interesting to investigate given the conclusion that new frontiers in climate communication should be explored. Future work to improve or revisit our structural analysis should involve expanding the dataset to include work in these areas, as well as in parts of the world that are little represented in this dataset. It should also attempt to include full texts (instead of abstracts) in the topic model, to produce a more nuanced sense of what is being discussed. Topic models of abstracts in particular can give an overly general or theoretical impression of the types of discussions that are occurring in a corpus of literature [Bittermann & Fischer, 2018]. Exploring other scientometric techniques such as the Leiden Algorithm [Traag, Waltman & van Eck, 2019] could also provide additional insight on the structure of the field.

Conclusion

We undertook this analysis in hopes that a structural census of climate communication research might support a systems thinking approach to climate communication and foster recognition of the ways the field's historical-structural context shapes the research front today. Analysis revealed a dense and structurally stagnant network and a topic model with equivalent topic proportions throughout the dataset, suggesting that the key to successful climate communication in the future is probably not contained within the knowledge space described by the current communities and topic combinations present in this knowledge domain (though enormous credit is due to all the work done to build this structure to date), and that perhaps a systems approach is not what is urgently needed. Going forward, climate communication may need to be deliberate about when it is productive to travel well-worn paths within this network structure in pursuit of a systems approach, and when better outcomes may be achieved in the long term by venturing outside it.

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