Mapping the Climate Communication Research Landscape

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Abstract

Climate communication today seems to be at a point of reinvention. The recent rapid growth of the field and its disciplinary diversity have produced a profusion of evidence-based techniques and theories for communicating climate science and climate change, but no definitive answer on how to move the needle on climate action. A core challenge for the field at present is how to make this abundance of research accessible and usable for practitioners, so that opportunities for impact are not missed. Answering calls in the literature for synoptic perspectives on areas of science communication, I use bibliometric network analysis, topic modeling, and knowledge mapping techniques to create and analyze maps of the climate communication research landscape as represented by 2,995 publications about climate communication from Web of Science. Knowledge maps are structural and visual portraits of scholarship which are useful for identifying areas of opportunity and coordinating effort in interdisciplinary and action-oriented knowledge domains. The knowledge maps themselves reveal dense webs of connection among five distinct knowledge communities, indicating an intensely collaborative knowledge domain, and suggest new avenues for application of climate communication knowledge, in particular to support climate services and co-production. After presenting the results of the knowledge mapping study, I discuss ethical and practical challenges encountered in developing these knowledge maps and the strategies I employed to overcome them, adding to the methodological literature on this subject. Taken together, the three chapters of this dissertation represent a conversation about the structure of climate communication research and the tools required for discovering, depicting, and understanding that structure. The contribution of this work overall is to offer a fixed vantage point from which to study past and current state-of-the art climate communication, and the knowledge structure that supports it. This analysis can act as a
benchmark for where climate communication is now, and a tool for recognizing when and how
the field has grown beyond its current structure.
For my mom, who has now taken care of two generations of children so the science can get done.
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Prologue

In early 2014 I attended a colloquium talk titled “Getting Past the Loading Dock and Into the Building: Challenges in Applied Climate Science Research” (Wall, 2014). The speaker explained that too often, climate science researchers delivered climate information to managers and decision-makers without considering the receiver’s needs, preoccupations, and constraints. This resulted in lost opportunities to apply hard-earned climate knowledge to improve climate outcomes for society, as if a truck picking up shipments of climate information from scientists had pulled up to the loading dock of resource management only to deliver precious cargo that sat unboxed on the doorstep. Like a shop receiving unordered inventory, decision-makers and resource managers would simply ignore the provided information, regardless of the utility of the contents. To be used, knowledge needed to be packaged properly, to fit like a puzzle piece into existing management workflows and priorities.

Before this talk I hadn’t thought much about climate communication, but I found myself captivated by the loading dock problem. How could it be, I wondered, that there was such a clearly defined problem with only the beginnings of an answer? Were people going and talking to managers to try to figure out what they needed? Was everybody involved just too busy with what they were doing to be able to step back and take the time to figure out how to package the information usefully? Did managers really know how they wanted the information to be packaged? Was there a failure in translation somewhere? Was it just because of politics? I stayed to talk to the presenter and some other professors after the talk, and that interaction set off a chain of events that led to my advisor Dr. Doug Boyle asking if I’d be interested in pursuing a climate communication PhD in the Nevada State Climate Office (NSCO). Doug, it turned out, had been struggling with a kind of loading dock problem himself, and wanted to make sure that in his
limited time for outreach, he was selecting activities which maximized the amount of climate information that connected with potential audiences. My dissertation work with NSCO was meant to provide evidence-based guidelines for strategically selecting from available opportunities for communication to maximize impact.

As a new PhD student, I read everything I could about science communication, eager to identify what was known (and what wasn’t) about maximally impactful climate communication activities. I realized that a diversity of tactics had already been developed and demonstrated to be effective, and that I was unlikely to contribute something new to the knowledge base by taking a communication case study approach here in Nevada. I became unsure of the merit in refining existing evidence-based communication tactics for deployment in particular situations. Such tactics seemed useful in the right place at the right time, but they didn’t seem especially likely to get to the core of the loading dock problem.

In 2016, I saw Dr. Susanne Moser give a talk about communicating climate adaptation at the American Association of Geographers Meeting in San Francisco. She suggested it was time for communicators to get real about how much the scale of the challenge had changed over the two decades spent studying this problem. The window for climate change mitigation was narrowing, and the time to think about adaptation had come. Climate communicators had an entirely new task on their hands: how were they going to shepherd society through climate transformations in the anthropocene, or prepare people sufficiently before they were negatively impacted? What skills could communicators develop, what aptitudes could they pursue, to achieve such a massive task? She likened the challenge to convincing caterpillars to build a cocoon and dissolve themselves into goo, in hope they would somehow come out of the experience as beautiful butterflies.

This talk cemented a sinking feeling I’d had since attending the Nevada State Drought Forum in 2015, where I began to question the maximum possible impact communication tactics
could really have. At this statewide conference intended to inform management decisions about water resources in a time of unprecedented drought, stakeholders, managers, and decision-makers intersecting with many different areas of water use spoke about challenges and opportunities for water conservation. There was ample participation from scientists and even relatively straightforward discussion of climate change impacts on water resources. The event was impressive in its breadth, depth, and coordination, and it was professionally moderated. A long synthesis document was produced, but I couldn’t shake the feeling that much of the communication that happened at the forum was performative, and that it was unlikely that briefing the presenters on framing strategies would have made a large difference in the outcome. I was reminded of the loading dock problem and imagined that a bunch of boxes had been successfully brought and stacked up on the floor of the state legislature, where they would sit until somebody tucked them into a storage room. Alignment and action resulting from that communication seemed elusive, as did an opportunity for iteration in coming years.

The following year, feeling stalled in my research, I presented a pet project at the American Association of Geographers meeting in Boston, about how the obsession with the zombie apocalypse observable in American culture in the early 21st century offered clues for climate communicators about what types of apocalyptic messages people liked to grapple with and why (apocalyptic messages are generally verboten in academic climate communication, but pop culture trends suggest that maybe apocalyptic messages aren’t always demotivating or disengaging). When I tried to find a quick and quantitative way to summarize zombie research across all of academia, I discovered and began experimenting with a technique called bibliometric network analysis, which analyzes the latent connections between published works based on citation patterns evident in their bibliographies. I realized I could apply this technique to creating a discipline-agnostic map of the many climate communication tactics available, the underlying research that supports them, and the types of situations they are generally applied in. I was
excited by this idea in part because it felt like I could fulfill the purpose of my research for NSCO by providing a decision tree for engagement opportunities and applicable strategies and tactics, but also in part because it was an opportunity to create a resource that I had badly needed when I started out fresh in climate communication two years before. Given ongoing discussions about fragmentation and narrow functionalism in climate communication research at this time (Ballantyne, 2016; Moser, 2016; National Academies of Sciences Engineering and Medicine, 2017), this approach seemed promising for pulling back and getting a view of the whole climate communication enterprise. This was what I proposed for my dissertation.

In the end, this turned out to be premised on two naïve hopes: (1) that the loading dock problem was really at the heart of climate communication’s challenges, and (2) that bibliometric network data could provide a panoptic and objective picture of a knowledge domain. The dissertation you’re about to read is a result of how I moved from thinking about the loading dock problem as an instrumental one to thinking about it as a relational one that has to do with the practice of care. It’s also the story of how I shifted from thinking about bibliometric network analysis as a nifty quantitative tool to thinking of it as a problematic but powerful one. These shifts happened in part because I grew as a scholar, but also because the field I was trying to study changed significantly in the time I was studying it. In 2017, when I proposed my dissertation, most of the writing that would influence how I think about climate communication, and which has certainly influenced how I interpreted the results of the analysis I present here, had not been published yet. In just the past three years, climate communication literature has widely recognized the need to “set sail on a new sea,” to fundamentally redefine the problem at hand (Agin and Karlsson, 2021: 14; Finlay et al., 2021).

As a result, I don’t know how to present this dissertation without first telling this story about how my own thinking evolved as I learned, proposed, researched, experimented, and wrote. This was not a linear journey, and it would be disingenuous for me to represent my results as the
logical conclusion of the plan I proposed at the outset. What I know now is what I learned along
the way, which was influenced by the people I met and the tools I explored and applied, both of
which profoundly shaped my thinking. Even when taking comprehensive exams in 2018, I would
never have predicted that deciding to use a supposedly straightforward quantitative analysis
technique in my dissertation would lead me to bring my work into conversation with data
feminism in digital humanities — but my work is better for it.

Looking back, I sometimes wonder what Doug and I expected when we embarked on this
journey. It’s an open question what one should reasonably anticipate when two people trained as
a hydrologist and a historical geographer take on the climate communication challenge. But I
hope that in the end, this research project benefited from an outsider’s perspective, even if the
result is not what either of us imagined at the outset. In the following introduction, I will (1)
provide an orienting overview of climate communication as a research field, (2) describe the
approach I took to studying it, (3) describe the overall purpose and primary questions guiding this
research project, and (4) give an overview of the contents of the three main dissertation chapters,
each of which represents a standalone manuscript.
Introduction

Climate Communication

Climate communication as a field studies processes that govern how individuals, groups, entities, and institutions develop and share climate knowledge and the ways they can be moved to change or act in response to that knowledge (Burns et al., 2003; Comfort and Park, 2018; Yale Program on Climate Change Communication, 2022). Understanding these processes helps make communication about climate issues effective, efficient, and ethical, and researchers are often able to augment communication processes with strategies that control for the many factors at play, such as knowing your audience and their values, framing your message, considering your medium, and being sensitive to context (Moser, 2015; Nisbet and Scheufele, 2009; Priest, 2010). Such research is important as the growing problem of anthropogenic climate change requires consensus-building and streamlined decision-making around climate action both locally and globally, and interest in the field has burgeoned accordingly (Moser, 2016; Nerlich et al., 2010; Newman, 2020).

In practice, climate communication takes many shapes, from emission reduction campaigns to social media posts to museum exhibits to community planning forums, and can involve a wide array of participants, from citizens to politicians, students to scientists, journalists to celebrities, and governments to corporations (Figure 1) (Comfort and Park, 2018; Corner and Clarke, 2017; Han and Stenhouse, 2015; Johnson, 2012; Nerlich et al., 2010; Priest et al., 2018). In fact, a recent science communication landscaping review found that more entities communicate about climate change than any other issue considered (Milani et al., 2019).
Figure 1. Climate communication system participants. Here, climate communication occurs within the blue box, based on multiple and overlapping interactions between the participants represented in gray. These interactions are informed by the resources in yellow. Climate communication researchers study everything that goes on within the dashed blue line.

Climate scientists themselves represent a relatively small part of this communication ecosystem, though climate science and the scientific roots of the climate communication field have certainly shaped problem definition and calls for evidence-based practice (Walsh, 2019). Neither are communication scholars frequently the dominant voices, as illustrated by the fact that science communication synthesis efforts such as the Sackler Colloquia feature few classically trained communication researchers (Ballantyne, 2016; Besley, 2015).

The diversity and dispersion of climate communication research and practice occurs partly because of increased popular and political focus on climate change, which brings the attention of more researchers and disciplines to climate communication, but also because climate issues are very difficult to extricate from other narratives. Many conversations about climate are
not just about what might be thought of as climate facts, and instead extend into deliberations about values and priorities, risk tolerance, and even the place of humans in the natural world (Corner and Clarke, 2017; Johnson, 2012; Lindenfeld et al., 2012; Moser, 2015; Priest et al., 2018). As a result, the field is deeply interdisciplinary, drawing on a wide array of foundational literatures from communication, decision science, education, psychology, sociology, political science, and more (Ballantyne, 2016; Cagle and Tillery, 2015; Fischhoff, 2011; Fischhoff and Scheufele, 2013). This overlapping of climate issues with other concerns means it is incumbent on climate communicators to understand and communicate with reference to both scientific understandings and social systems, each of which are highly complex (Nerlich et al., 2010). It also requires something of a leap of faith, as the gains from a communication engagement may not be realized by the time participants fill out a program evaluation form, and instead become real as they interact with other messages about climate and have ongoing experiences in the real world (Burns et al., 2003).

The recent rapid growth of the climate communication field combined with its disciplinary diversity makes it challenging to stay on top of recent developments, and the shifting research front resists synthesis (Comfort and Park, 2018; Corlew et al., 2015; Moser, 2016; Siders, 2019). A core challenge for the field at present is how to make this profusion of research accessible and usable for practitioners, including institutions such as the Nevada State Climate Office, so that opportunities for impact and action are not missed. Because of this need, a flurry of landscaping efforts have recently been carried out, both for climate communication specifically and for science communication more broadly (Armstrong and Krasny, 2020; Ballantyne, 2016; Dudo et al., 2021; Gerber et al., 2020; Johnson, 2012; Kidd et al., 2019; Larosa and Mysiak, 2019; Pearce et al., 2015). These studies frequently identify a need for climate communication to “shift out of second gear” and get serious about dissemination, coordination, and impact (Corner and Clarke, 2017; Fischhoff and Scheufele, 2013; Kahan and Carpenter, 2017; National
Academies of Sciences Engineering and Medicine, 2017; Newman, 2020; Smith, 2020). Science communication scholar John Besley concluded seven years ago that it was time to take on “the challenge of thinking through our research so that we can make our scholarly community’s insights accessible beyond the subfield” – not the first time attention has been called to science communication’s rather ironic communication problem (2015: 398). These statements fit with a broader trend towards recognizing synthesis as its own kind of science, for example in the National Science Foundation’s Synthesis Centers, which are designed to promote associative thinking, abductive reasoning, and creative collaboration, thereby generating new knowledge through the process of integration (Baron et al., 2017; Wyborn et al., 2018). Synthesis approaches save resources from being wasted on reinventing existing knowledge needlessly or considering too many elements in isolation and attempt to support the kind of scholarship that sees “a wider perspective and the details simultaneously” (Willamo et al., 2018: 1; Besley, 2015; National Academies of Sciences Engineering and Medicine, 2017).

Climate communication’s status as a fast-growing interdisciplinary field in search of effective synthesis techniques makes it an excellent candidate for bibliometric network analysis, a form of knowledge mapping which was developed in part to support scholars in gaining purchase when faced with “unsystematic proliferations” of knowledge (Dang et al., 2011; Linnenluecke et al., 2019: 177). Knowledge mapping has been shown to support flexible and adaptable researchers and practitioners in pursuing synthesis, systems-thinking, and integration (Wehrmann and Van Der Sanden, 2017; Willamo et al., 2018). This approach has been successfully applied in ecology and in the vulnerability, adaptation, and resilience space, as well as many others (Baggio et al., 2015; Fuller and Pincetl, 2015; Janssen et al., 2006; Neff and Corley, 2009; Siders, 2019; Wang et al., 2014).

Knowledge mapping is a quantitative method for summarizing literature which may not be standardized enough to allow for traditional systematic review. It takes a bird’s eye view on a
body of research, which can then be described statistically and visualized for additional insight. The resulting knowledge map depicts areas of opportunity while supporting collective reflection by participants in a knowledge domain and stronger conversations between theory and practice (Jack et al., 2017; Siders, 2019). As discussed in the following section, this structural approach affords an opportunity to scrutinize how past knowledge shapes present research, consider how problems are defined, and select which evidence should be built on further, and which is perhaps best left in the past (Linnenluecke et al., 2019; Szerszynski and Galarraga, 2013).

Knowledge Maps

Like geospatial mapping, knowledge mapping uses abstraction, simplification, and synthesis to support navigation, comprehension, and analysis of information spaces (White, 1990). Knowledge maps translate information into visual representations that leverage familiar concepts like boundaries, islands, regions, pathways, and scale to portray relationships between pieces of information (Fabrikant et al., 2010; Lima, 2011). They reveal relationships which might otherwise be lost in the noise and complexity of a knowledge domain and allow for undirected but productive exploration (Chen et al., 2014; Couclelis, 1998). Simply put, knowledge maps are useful for the same reasons terrain maps are: they offer an overview of the landscape and insight into the processes that shaped it, they help traverse it, and they facilitate switching between general and specific qualities of the depicted terrain (Boyack et al., 2005; Ravenscroft and Allen, 2019). I use the term knowledge mapping as a general term to refer to intersecting methods from multiple disciplines, including computer science, literature, history, and especially bibliometrics (Borner, 2011; Chen et al., 2014; Graham et al., 2015; Moretti, 2007; White and McCain, 1998).

Bibliometrics, a key component of knowledge mapping, is simply the application of quantitative techniques to study the written record of scholarship (Pritchard, 1969; White and McCain, 1998). At its most basic, a bibliometric analysis can describe where certain types of
literature are published, which are the most frequently cited publications or authors, what words appear most frequently in titles, and how disciplinary focus has evolved through time. It can be used to determine whether a sub-discipline may be considered its own field, or how significantly one type of researcher has contributed to an interdisciplinary set of publications.

While the practice of bibliometric citation analysis can be traced at least to the founding of the Institute for Scientific Information (which we now know as Web of Science), the idea of projecting a network of documents and links into Euclidean space and visualizing those relationships to search for patterns and connections came out of US Intelligence Agency research begun in 1994, meant to support security analysts as the internet and communication age rapidly increased the amount of textual information coming to their desks every day (Garfield, 1955; Wise, 1999). Spatialization and visualization was quickly applied to bibliometric data, to support scholars dealing with information proliferation across academia by giving form to relational ideas that were otherwise abstract and challenging to perceive (Borner et al., 2003; Chen, 2016; Lievrouw, 1989, 1990). By the start of the 21st century, bibliometric data were being used by physicists to test emerging theories (some grounded in prior work from sociology) about network structure and function (Barabási and Bonabeau, 2003; Newman, 2003, 2006). Work in this tradition sees scholarship as a complex and dynamic system which can be analyzed using network techniques such as those applied in social network analysis or epidemiological modeling, techniques suited to capture and represent emergent phenomena produced by a system whose interactions are almost irreducible to the component parts (Evans and Foster, 2011; Radicchi et al., 2012).

Bibliometric network analysis uses citation data to investigate both direct and latent connections between articles and analyzes the resulting patterns to understand how different pieces and areas of knowledge are linked or combined in practice, effectively synthesizing the millions of distributed and ad hoc decisions of scholars into a holistic and synoptic picture of a
knowledge area (Andrés, 2009; Borner et al., 2003; Radicchi et al., 2012; White and McCain, 1998). A bibliometric dataset is selected and projected into varying types of networks, including co-authorship networks, co-citation networks, and bibliographic coupling networks, each of which is suited for understanding different aspects of knowledge structure and domain function (Milojević, 2013). These indirect citation relationships have been shown to represent scholarly domains accurately (Belter, 2016; Evans and Foster, 2011). By leveraging the latent pieces of data that exist in research articles, these techniques mimic (and scale up) the way in which an expert reading a paper in their field perceives much more than what is said in words, based on references made to other pieces of knowledge which “index a broader context of ideas, scientists, and disciplines” (Evans and Foster, 2011: 721). The process of bibliometric network mapping and the types of analysis it supports are enumerated in Figures 2, 3, and 4.

Citations may not be a perfect representation of how different ideas influenced a piece of research, but they do act as signposts for the traditions in which researchers are positioning their thinking (de Solla Price, 1963; McLevey and McIlroy-Young, 2017). As Eugene Garfield put it when introducing the ideas that originally led to the development of Web of Science, relying on references cited in bibliographies draws on the insight of “an army of indexers, for every time an author makes a reference, [they are] in effect indexing that work from [their] point of view” (Garfield, 1955: 110). Today, we might call this kind of effort passive crowdsourcing or data mining. Knowledge mapping depicts the footpaths traveled by experts as they explore and produce knowledge, a process which is too emergent and adaptive to be well captured by lists of indexed terms. It emphasizes knowledge as a relation, not a thing, and considers patterns of relationships which emerge from (but aren’t contained within) the individual pieces of scholarship (Lima, 2011; Moretti, 2007). Visualization is a key component of this method.
**Figure 2.** Key concepts in bibliometric network analysis.
Figure 3. Examples of bibliometric networks, showing the pathway from dataset to network.
What’s The Point of the Networks?

- **Represent the Structure of the Underlying Data**: Nodes are placed based on the strength and arrangement of links between them, meaning similar nodes are closer together. It is up to us to look at the attributes of the nodes to determine the cause of the structure the network reveals.

- **They Are Visual**: This is useful for the same reason we plot data on maps and graphs.

Some Questions We Can Ask of these Networks:

- **Degree Centrality: How Many Links Do You Have?**
  - In this network, nodes 5 and 7 have the highest degree centrality. Each has 7 connections to other nodes. The other nodes in only have 3, 4, or 5 connections.
  - In the Co-Author Network, the orange author has the highest degree, because that author has 4 connections. The other authors have at most 2 connections each.

- **Betweenness Centrality: How Many Nodes Depend On You for Connection to Others?**
  - Node 4 has the highest betweenness centrality.
  - Nodes 1, 2 and 3 cannot connect to any of the other nodes in the network without going through 4.

  Sometimes centrality measures agree on which nodes are important, and sometimes they don't. Generally, we would expect to learn different things from different centralities.

- **Which Nodes Form Communities?**
  - Nodes can be grouped based on how interlinked they are.
  - Here, an algorithm would decide the red and orange communities were more similar than different, based on the number of links between them.

  In this Co-Citation Network, if we had (for example) generated the dataset with a keyword “drought”, perhaps the orange and red nodes are articles about drought hydrology, and the yellow nodes are about drought policy.

- **Which Communities Are Most Resilient?**
  - In these networks, the black nodes are cut points. If they were removed, many nodes would lose their connections. This is one way to think about how strong a community is: its resilience to disconnection from the network.

*Figure 4*. Examples of the types of analysis that can be performed on bibliometric networks.
Because they are visual, knowledge maps give an intuitive and non-technical summary of a domain which can be considered holistically thanks to innate human visual acuity and which does not require pre-existing fluency in concepts and key works of the field (Andrés, 2009; Bastian et al., 2009; Borner, 2010; Borner et al., 2003; Chen, 2016; White, 1990). The point is to reveal knowledge in context, provoking both rational and analytical responses as well as abductive insights which may be less rational (Jack et al., 2017; Shen, 2018). The point of a knowledge map is not to tell people what is worth knowing, but to support them in finding knowledge that is relevant for their purposes. It should go without saying that the maps are not intended to replace deep reading in a field; rather, they support overall understanding by emphasizing patterns, connections, and consensus (Moretti, 2007; White, 1990).

Knowledge maps show what is known and how that knowledge is constructed, codified, and classified and in turn how that codification, classification, and construction amounts to a structure which both enables and constrains further knowledge generation (Henry and Vollan, 2014; Knorr-Cetina, 1999). When constructed in collaboration with disciplinary experts, existing assumptions can be uncovered and reassessed in productive ways (Bjurström and Polk, 2011; Corlew et al., 2015; Kates, 2011; Szerszynski and Galarraga, 2013). Carefully crafted knowledge maps can alleviate paralysis, spark insight, and offer a sense of unity and epistemological ownership to members of a community of practice (Borner, 2010; Jack et al., 2017; Wenger et al., 2002). They support what can be thought of as collective troubleshooting, by clarifying cases in which “ghost theories” or outdated and disproven knowledge still inform research (Evans and Foster, 2011). They facilitate research-practice communication because practitioners may question, select, and sample instead of being expected to apply summaries of what researchers think should be the most useful. They can also give more theoretically oriented researchers a sense for how their research is used after publication.
Network approaches like knowledge mapping are fundamentally structural, predicated on the idea that the structure produced by a system’s interactions in turn influences the options that system has for defining and addressing problems (Borner et al., 2012; Burt, 2000, 2004; Carrington, Peter J. and Scott, John, 2011; Szerszynski and Galarraga, 2013). The network structure can be seen as the explanatory or dependent variable, or both — thus the flexibility of this approach for gaining purchase on complex domains (Popelier, 2018). Structural approaches represent a mixture of qualitative and quantitative techniques, and while it’s possible to propose and test hypotheses with a network analysis, knowledge mapping is more often undertaken as an exploratory method which searches for and then describes patterns (de Nooy et al., 2005; Hollstein, 2014). Taken together, these aspects of knowledge mapping make the approach well-suited to characterizing, assessing, and expanding climate communication knowledge, and can help answer the call for systematic and strategic approaches to future knowledge generation in this field.

Purpose & Primary Questions

The purpose of this dissertation is to map the climate communication research landscape represented by 2,995 publications about climate communication from Web of Science. I undertake and analyze results from an exploratory structural analysis for the purpose of supporting systematic and strategic knowledge generation in this area. This systems-mapping approach to coordinating climate communication efforts seeks to create a resource that makes research from this thriving and evolving knowledge domain accessible and usable for a wide array of potential communicators, both individuals and institutions, without oversimplifying it or removing it from its context. Specifically, it uses bibliometric network analysis and data visualization techniques to create and analyze knowledge maps of climate communication research, for the purpose of making climate communication knowledge more coordinated, more
accessible, and more visible. I also address and make transparent the ethical and practical challenges that arise in developing knowledge maps, in hopes of adding to the methodological literature on this subject. In doing so, I ask and answer the following overarching questions:

1) What is the structure of climate communication research?
2) How does this structure enable and constrain development and application of climate communication knowledge?
3) What opportunities can be identified for communicating about climate in the future?
4) How useful is bibliometric network analysis as a knowledge mapping technique when applied for this purpose?

Overview of Dissertation Chapters

This dissertation is organized into three chapters connected by the theme of mapping the climate communication research landscape. Figure 5 provides an overview of the specific steps taken for the overall analysis, and how each of these three dissertation chapters fits within the overall analysis plan. Methods and data processing for each chapter are discussed in detail in the relevant methods sections.

Chapter 1: Mapping Pathways to Public Understanding of Climate Science presents a bibliographic coupling network analysis of climate communication research intended to support scholars navigating this quickly evolving knowledge domain. Bibliographic coupling is a knowledge mapping and network analysis approach that is particularly good for grouping documents into communities that have been shown to accurately represent core themes. This study asks, (1) how many communities are present within climate communication research, and what are the defining features of these communities? (2) how often is knowledge shared between these communities? and (3) what types of research and connections are most important for connecting the network and combining ideas about communicating climate issues? The resulting
knowledge map reveals a dense web of connections among five distinct knowledge communities, indicating a tightly knit and intensely collaborative knowledge domain. This chapter was recently published in the journal *Public Understanding of Science* (Canon et al., 2022).

The results from this analysis form the basis of the questions asked in *Chapter 2: Visualizing the Structure and Development of Climate Communication Research*. To better understand why the climate communication knowledge network displayed such profound structural cohesion, I add a temporal dimension to the bibliographic coupling analysis and perform topic modeling on the same dataset to see if a second method of structural analysis corroborates or elucidates the patterns observed in the knowledge network. I then use the result of the topic model to help confirm and supplement the descriptions of the communities in the knowledge network.

In *Chapter 3: Ethical and Effective Visualization of Knowledge Networks*, I step back from the focus on climate communication to discuss the ethical and practical challenges I encountered in developing knowledge maps. Using a climate communication co-authorship network map as an example, I show how methodological challenges little discussed in the literature can be navigated in ways that produce more trustworthy and more useful knowledge maps. Rather than contributing to the structural assessment of climate communication knowledge, this chapter pulls back the curtain on the necessary steps for structural and visual analyses. It situates this work in digital humanities traditions of ethical visualization, offering an example of the utility of a critical approach in a traditional, science-oriented knowledge mapping project.
Figure 5. Methods flow chart for the overall research project and the resulting three manuscripts. Gray arrows trace analysis steps; dashed blue arrows indicate which parts of the analysis are combined and discussed in each chapter.
The first two chapters of this dissertation comprise a systems-oriented analysis that seeks to understand the structure of climate communication knowledge, for the purpose of gaining insight about its function and future opportunities. The third chapter can be thought of as a methods paper, which seeks to expand the available literature on knowledge mapping with a clear discussion of how specific decisions in data cleaning, analysis, interpretation, and visualization can affect the results of a knowledge mapping project. Taken together, the three chapters represent a conversation about the structure of climate communication research and the tools required for discovering, depicting, and understanding that structure.
Chapter 1: Mapping pathways to public understanding of climate science

Abstract

Climate communication is a thriving research area spanning science, social science, and humanities. The field has grown explosively in recent years, necessitating increased efforts to synthesize and make sense of the resulting profusion of studies. To support scholars navigating this quickly evolving knowledge domain, we developed a knowledge map of the climate communication research landscape by applying network analysis and data visualization techniques to the metadata from 2,995 publications on climate communication. The map reveals a dense web of connections among five distinct knowledge communities, indicating a tightly knit and intensely collaborative knowledge domain, and suggests new avenues for application of climate communication knowledge, in particular to support climate services and co-production. The climate communication knowledge map answers the call for synoptic perspectives on areas of science communication while demonstrating a novel visual approach to knowledge synthesis for science communication domains.

Introduction

Climate communication is a dynamic field of study that has grown explosively in the past five years. As more scholars have taken up the challenge of communicating climate issues, the

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field has addressed an increasingly broad range of questions with theories and methods from disciplines across science, social science, and humanities (Moser, 2016). This welcome trend poses a practical problem for researchers and practitioners wishing to keep up with current developments (Cagle and Tillery, 2015; Moser, 2016). Climate communication studies are published in an array of outlets, and despite recent syntheses and reviews, few tools exist to help climate communicators integrate findings from different studies for real-world application (Corner and Clarke, 2017; Jensen and Gerber, 2020; Moser, 2016). The growth, diversity, and dispersion of such research combined with the pressing nature of many science-related issues such as climate change has prompted calls within science communication for “attempts to generalize, to put scattered evidence together in a bird’s eye view of the research landscape” (Corner and Clarke, 2017; Fischhoff, 2011; Jensen and Gerber, 2020; Moser, 2016; National Academies of Sciences Engineering and Medicine, 2017; Peters, 2020: 371).

We provide a synoptic perspective on one area of science communication research by applying network analysis and data visualization to metadata from 2,995 publications on climate communication in Web of Science. Specifically, we generate and analyze a knowledge map of climate communication research, tracing the many pathways to public understanding of climate science and positioning them in relation to one another. This quantitative, inductive approach mines citation data to paint a picture of collective climate communication knowledge in action. Like all maps, knowledge maps are useful for orienting oneself in relation to key landmarks, planning journeys through untraveled regions, or making strategic decisions about what uncharted areas to explore (Chen et al., 2014; White and McCain, 1998).

The need for a synoptic description of climate communication research

Climate communication research studies how individuals and groups develop and share climate knowledge and the ways they can be moved to act in response to such knowledge.
(Comfort and Park, 2018). But action on climate knowledge is bound up with individual and collective value judgments about life, society, and the future and nearly always requires decision-making under conditions of social and scientific uncertainty (Corner and Clarke, 2017; Johnson, 2012). As a result, climate communication research touches nearly every corner of scholarship. This breadth produces a certain degree of fragmentation, as climate communication research is not reliably located in either communication or climate journals, terms are used inconsistently across the literature, and case studies and segmentation analyses can be difficult to summarize and compare (Baram-Tsabari et al., 2020; Cagle and Tillery, 2015; Füchslin, 2019; Moser, 2016).

Less fragmentation might ease production of evidence-based guidelines for practitioners, but even if that synthesis were straightforward, it is not clear who the audience should be (Siders, 2019). The practice of climate communication is as fragmented as the research, with journalists, scientists, public relations officers, NGOs, think tanks, scientific societies, governments, extension professionals, museum specialists and corporations all participating (Mellor et al., 2008; Moser, 2010; National Academies of Sciences Engineering and Medicine, 2017; Nerlich et al., 2010; Smith, 2020). A recent review found that more entities communicate about climate than any of the other science topics considered (Milani et al., 2019). Given that climate communication happens in a diversity of contexts and to a kaleidoscope of audiences, serious thought is needed about how to make research usable for climate communicators without oversimplifying it (Kahan, 2013; Moser, 2016).

The compounding fragmentations of climate communication research and practice mean the structure of the knowledge domain is not readily apparent, and the lack of a disciplinary lingua franca makes it challenging to discover that structure with traditional literature reviews (Baram-Tsabari and Lewenstein, 2017). Communication scholar Anne Gammelgaard Ballantyne describes the situation as a large but disorganized toolbox (2016); science engagement specialist Brooke Smith uses the analogy of a bustling transit network with no transit authority providing
coordination (2020). In such a situation, taking stock of current knowledge and applications is key to supporting future research that is relevant and effective in the face of mounting challenges for science and society (Baram-Tsabari and Lewenstein, 2017; Gerber et al., 2020; Jensen and Gerber, 2020; Smith, 2020).

Why network perspectives on knowledge domains are useful

Modern citation practices have in effect produced a long-term dataset describing the evolution of knowledge (de Solla Price, 1963). Network analysis of this bibliometric data can reveal the structure governing knowledge flow and development. Conceptualizing climate communication research as a knowledge network foregrounds the understanding that structural elements of knowledge organization enable and constrain discovery and search processes, and therefore augment or inhibit problem solving (Chen, 2016; Henry and Vollan, 2014; Neal et al., 2015).

Knowledge mapping uses metadata from academic publications to build relational networks of authors, journals, and other variables, depicting emergent consensus from “an army of indexers” (Garfield, 1955: 110). In this way, knowledge networks distill literatures into “writings related by use” based on “repeated statements of connectedness by citers with subject expertise” (White and McCain, 1998: 329). These bibliometric techniques have been applied to some aspects of climate and science communication, generally without network analysis and visualization (Gerber et al., 2020; Huo et al., 2021; Larosa and Mysiak, 2019; Lemos et al., 2019; Suerdem et al., 2013). But visualization is a crucial element that distinguishes the method from other styles of systematic review.

Visual knowledge mapping summarizes abstract and complex relational data about knowledge in an intuitive way, so it can be considered as an interrelated whole (Bastian et al., 2009; Chen et al., 2014; Fabrikant, 2000). A visualization affords a different experience than lists
or tables of text, allowing innate visual acuity to discern patterns and relationships (Couclelis, 1998; Fabrikant et al., 2010). Visualization is achieved by spatializing network data, positioning nodes in relation to one another with an algorithm that repels nodes from one another unless they are connected by links (Chen, 2016). Rather than relying on an expert to select information to highlight, this quantitative approach aggregates many individual decisions to afford a bird’s eye view of the collective knowledge enterprise, revealing knowledge in the aggregate, in action, and in context, which may yield different insights than traditional systematic reviews (Chen et al., 2014; Evans and Foster, 2011; McLevey and McIlroy-Young, 2017). Knowledge maps support collaboration, planning, brainstorming, and communication within a knowledge domain (Chen et al., 2014; Nakamura et al., 2019). They also support what can be thought of as collective troubleshooting, by clarifying cases in which “ghost theories” or outdated and disproven knowledge still inform research (Ballantyne, 2016; Evans and Foster, 2011). An example of this familiar to science communicators is the persistence of the deficit model of science communication.

Recently, Fahad Asmi and colleagues applied bibliometric strategies to climate communication literature to describe the shape of the field and present narrative descriptions of its communities. Their emphasis was on visualization for analysis purposes (using network tools to partition the literature into meaningful groupings) (Asmi et al., 2019; Hepworth and Canon, 2018). There is an opportunity to do more by using visualization for communication (to act as a tool usable by others in the field). Specifically, knowledge mapping can identify new insights about the climate communication system and produce knowledge maps to aid with coordinating and integrating the diversity of research in the field. That is, “not only to summarize, but to make sense of” climate communication research (Peters, 2020: 371).
Methods

We used exploratory bibliometric network analysis and knowledge mapping to gain a bird’s eye view of climate communication research. The goal of this analysis is to identify and visually synthesize patterns and relationships within a dataset of publication records. An exploratory bibliometric network analysis proceeds by: (1) defining the data sample, (2) projecting data into network form, (3) identifying structural features of the network, and (4) visualization (de Nooy et al., 2005). We used Python packages metaknowledge (McLevey and McIlroy-Young, 2017), networkx (Hagberg et al., 2008), and Louvain (Aynaud, 2020) for data management, network construction, and network analysis, and the program Gephi for network visualization (Bastian et al., 2009).

Research objectives

The objectives for this study are to:

1. Generate a knowledge network to reveal the structure of climate communication research.
2. Understand key features and mechanics of the knowledge network.
3. Synthesize findings visually as a knowledge map.

The research questions are:

1. How many communities are present within climate communication research, and what are the defining features of these communities?
2. How often is knowledge shared between communities?
3. What types of nodes and links are most important for connecting the network (bonding ties) or combining ideas (bridging ties)?
Data

Bibliometric data was taken from Web of Science on July 31, 2020, using the search query TS = (climat* NEAR chang* AND communicat*). This query was used by Moser in her 2016 review of climate communication research. Titles and abstracts for each of the 5,934 results were manually reviewed to ascertain direct or explicit relevance to climate communication. Manual review followed the process described in Moser (2016) and was similar to the inclusion/exclusion criteria used by Ballantyne (2016). Articles were removed if they dealt exclusively with climate science, only mentioned the need to communicate in passing, or were primarily about climate impacts and adaptation strategies (versus communicating about impacts and adaptation). We included climate services and decision support literature wherever possible, so long as some emphasis was on communication, interface, co-design, or engagement. We retained 2,995 (50.5%) of the original records, which suggests correct application of Moser’s criteria (she retained 53.2% of the records from her initial data pull). More than 50% of the papers in our final dataset were published in 2016 or later, meaning that since Moser (2016), half again as much research on climate communication has been published.

Network representations

We created an article-level bibliographic coupling network from the 2,995 Web of Science entries. Bibliographic coupling places links between articles (the “nodes” in this network analysis) when they cite the same sources, assuming that articles citing many identical sources apply knowledge in similar ways or for similar purposes. The more times two articles cite identical sources, the stronger their link becomes. When visualized, articles with the strongest

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2 The TS query returns entries based on the presence of the search terms in title, abstract, author-provided keywords, or Web of Science-assigned keywords. Asterisks allow variants of the word (e.g. climate change, climate changes, climatic change). The NEAR term ensures climat* and chang* appear within five words of one another.
connections self-organize into major research themes and appear on the knowledge map as groups of densely clustered nodes; the space between the clusters represents the conceptual distance between the topics (Belter and Seidel, 2013; Nakamura et al., 2019). We chose a bibliographic coupling network because we were primarily interested in discovering and depicting patterns in how existing knowledge is combined and applied, and because these networks can include recently published articles as well as works that haven’t been cited (Belter and Seidel, 2013). As is customary, the giant component (the largest group of connected nodes) was extracted for further analysis (Chen, 2016).

Network analysis

To describe network structure, we calculated the following metrics:

- Density, a measure of network cohesion. Density is the percentage of all possible connections actually present in the network; high density indicates a highly interactive network (de Nooy et al., 2005; Henry and Vollan, 2014).

- Modularity, a measure of network grouping. Modularity rates how well a network can be separated into sub-communities, or the extent to which the distribution of connections in a network differs from the expected distribution in a randomly generated one of the same size (Brown et al., 2016; Chen, 2016; Newman, 2006). Modularity is a value between -1 and 1, where 0 represents the modularity of a randomly generated network. Negative scores indicate the absence of community structure; positive scores indicate its presence (Newman, 2006). A network with recognizable community structure should show a modularity > 0.3, however, real networks may not attain this due to overlap or nesting of communities (Chen, 2016; Larosa and Mysiak, 2019).
Transitivity, a measure of network clustering. In a clustered network, a high proportion of observed connections between nodes will be transitive. A transitive connection occurs when two nodes connected via a third are also directly connected to each other, so the pattern formed by these connections makes a triangle (instead of a V). Transitivity is calculated by multiplying the number of triangles in the network by three, and then dividing by the number of unconnected V shapes. Transitivity is a value between 0 (connections are never transitive) and 1 (connections are always transitive); in real networks values of 0.1 to 0.5 are typical (Newman, 2003). Networks with high transitivity have redundant links and short connection paths.

To describe the functions of individual nodes, we calculated centrality scores:

- Betweenness tallies the number of times the shortest path of connection between any two nodes in the network travels through the node being considered (de Nooy et al., 2005). Betweenness is high for nodes that connect many others who wouldn’t be connected otherwise (or whose connecting paths would be significantly longer). In an article network, betweenness centrality may favor recent papers (Baggio et al., 2015).

- Degree, calculated based on the number of connections a node has to others (de Nooy et al., 2005). Degree centrality is high for nodes that have many connections (gained by sharing bibliography items with many other papers). In an article network, nodes of high degree may be keystone papers or review articles, or may simply have long bibliographies.

We identified community structure within this knowledge domain by applying the Louvain community detection algorithm, which discovers communities by assigning nodes to groups in ways that maximize intra-community density (links between entities in the same group).
while minimizing inter-community density (links between entities in different groups) (Blondel et al., 2008; Lambiotte and Panzarasa, 2009). Communities can be thought of as coherent sub-groups within the broader network. The algorithm identifies the presence and boundaries of these communities based on observed network structure, but cannot reveal the reason for the observed structure. To understand the topic(s) of focus for the identified communities we used simple text processing tools in Python, making frequency counts of lemmatized keywords and title words from the papers in each community. Community names were chosen based on manual inspection of these frequency lists (focusing on words with prevalence of at least 10%) and the most common publication outlets for each community (Belter and Seidel, 2013; Kajikawa et al., 2007; Nakamura et al., 2019). We then checked the community names against the 20 highest-degree papers for each community, to ensure they were representative. A simple way to think about this process is that the Louvain algorithm quantitatively delineates the communities, and the most frequently occurring keywords, title words, and publication outlets qualitatively describe the communities.

Network visualization

To produce clear and comprehensible visualizations, we stratified the network by connection strength and node degree and removed nodes that became disconnected from the giant component as a result of this pruning (Lambiotte and Panzarasa, 2009). We visualized nodes only if they were connected to other nodes with a strength of at least five (meaning papers are included and/or linked only if they cite at least five identical references). Common thresholds for pruning an article network range from a link strength of three to ten (Baggio et al., 2015; Belter and Seidel, 2013; Tang et al., 2017). We chose five because 60% of the nodes are still present (1,770 in the filtered network out of 2,863 in the complete one) but only 3.5% of the connections are (19,212 out of 533,676), making it computationally tractable to visualize. These choices represent
a balance between including as many weak connections as possible (to capture potentially novel patterns in knowledge application), making the resulting visualizations clear and useful, and emphasizing signal over noise.

We plotted the network in Gephi to depict the conceptual distance between different communities in the knowledge domain. Conclusions can be drawn from the shapes of these visualizations. For example, a spiky cluster of nodes likely has connections to many other communities, while a tightly clustered ball of nodes likely has primarily internal connections (Kajikawa et al., 2007). In these visualizations, we looked for evidence of archetypal structures known to facilitate certain types of knowledge exchange:

- **Structural diversity**, or a “swiss cheese” pattern, where a web of connections links tightly grouped communities separated by empty spaces or “holes.” This structure is thought to be good for knowledge generation, because nodes near structural holes have access to a broad range of knowledge not available within tightly bound communities (Burt, 2000; Chen, 2016; Suerdem et al., 2013).

- **Social cohesion**, or a “spaghetti ball” pattern, where a dense and messy network exhibits redundant connections between nodes and communities. This structure is thought to be good for sharing tacit knowledge and developing collective identity, due to the many redundant connections between nodes (Burt, 2000).

Both structures are present to some degree at different scales of every network, as captured by the concepts of “bonding” and “bridging” ties. A bonding tie, which links two similar entities, supports trust, understanding, and action, and signals consensus. A bridging tie, which links two dissimilar entities, may be more difficult to form, but yields novel information (Burt, 2000; Henry and Vollan, 2014; Neal et al., 2015). A network characterized primarily by bonding ties would appear tightly clustered and interwoven, suggesting that knowledge was frequently linked in
diverse ways across the network. A network characterized by bridging ties would appear as an archipelago of weakly connected knowledge communities.

Results

The 2,995 items in the final dataset were published between 1996 and 2020 in 1,034 different outlets. 86% of the records were journal articles, but no single journal published more than five percent of the total. Collectively the articles use 3,498 different keywords. Only 19% of the records are classified as communication studies by Web of Science, meaning a database search limited to communication studies would miss most of this research. Relatively few authors repeat participation in this network: about 60% published in this knowledge domain just once, and only seven percent published five or more times.

From this data we produced the bibliographic coupling network in Figure 6. Articles (nodes) in this network are linked when they use at least five identical sources to corroborate or contextualize knowledge claims. Knowledge communities are recognizable as groups of articles that substantiate their research by referencing consistent bodies of scholarship. The 1,770 nodes in the knowledge map share 19,212 connections. The density of the network is 0.13, meaning there is a 13% chance that any two articles in the network cite at least five identical sources in their bibliographies. The transitivity is 0.45, meaning when a paper shares five references with two other papers, there’s a nearly one in two chance those papers also share five references. The network modularity is 0.24, meaning the patterns of connections in this network make it difficult to decompose into clearly delineated communities. Taken together, these metrics suggest the climate communication knowledge domain is highly interconnected and integrated, without pronounced divides between different groups or topics, as evidenced by the “spaghetti ball” pattern of the visualization (Figure 6). This is a knowledge domain defined by social cohesion, not structural diversity.
Despite the somewhat low modularity, Louvain community detection identified five communities. We named these communities based on inspection of the most frequently occurring keywords, title words, and publication outlets in each community, omitting the words “climate,” “change,” and “communication” (because these search terms generated our dataset). These five communities can be thought of as studying distinct pathways to public understanding of climate science:

- Risk Perception & Communication contains 463 articles primarily published since 2007. Dominant journals are Risk Analysis, Climatic Change, and Journal of Risk Research. “Risk” is the overwhelmingly salient keyword applied (260 times), followed by “perception” (194), “public” (105), “environmental” (71), “behavior” (82), “social” (58), “adaptation” (57), and “flood” (55). Similar title words predominate. This is the only community where “science” was not a frequently occurring word. This community is primarily interested in factors governing risk perception and the effect of risk perception on behavior. This pathway to public understanding of climate science involves assessing and influencing the risk assessments people make and providing mitigation and adaptation options in line with those perceptions.
**Figure 6.** A knowledge map of climate communication research produced from the article bibliographic coupling network. Five communities comprise the network, each indicated by a label on the surrounding circle. The size of the node indicates its relative betweenness centrality, meaning that bigger nodes in this map are responsible for connecting disparate pieces of knowledge. These numbered nodes are identified in the text below the figure, where stars mark nodes that also have high degree.
- **Individual Perceptions of Climate Change** contains 375 articles primarily published since 2013 in communication-focused journals. Dominant keywords are “science” (216 times), “public” (79), “environmental” (60), “social” (55), “political” (50), “medium” (41), and “perception” (38). Less salient keywords such as “motivate” (31), “framing” (29), “reasoning” (27), “attitude” (26), and “psychology” (23) suggest this community is primarily interested in how social and psychological factors govern perceptions of climate change. This pathway to public understanding of climate science involves comprehending the knowledge people have about climate science and the psychological and cultural factors influencing interpretation of climate information.

- **Climate Messages in the Media** contains 391 articles published since 2004, with a small decline beginning in 2018. Most are published in communication-focused journals. This group has the highest number of occurrences of the keyword “communication” (231 times). Other keywords frequently used are “medium” (215), “science” (185), “environmental” (132), “analysis” (112), “public” (84), “framing” (84), “social” (71) “discourse” (61), “journalism” (59), “risk” (50), “news” (50), and “policy” (46). In title words “coverage” (51) also stands out. This community is primarily interested in understanding how mass communication about climate issues affects public understanding and acceptance. This pathway to public understanding of climate science involves strategically crafting messages to address lack of knowledge and pre-existing biases, and deploying those messages in the media ecosystem.

- **Visual & Affective Communication** contains 284 articles published steadily since 2000. Dominant journals are Environmental Communication and WIREs-Climate Change. After “environmental” (67 times), the most frequently occurring keywords are “visual” (61), “science” (48), “public” (45), “education” (43), “social” (39), “engagement” (38), “adaptation” (36), “risk” (33), and “behavior” (32). Overlap between this community’s
keywords and others may explain the community’s central position on the map, suggesting there is wide diversity in editorial selection. This community is primarily interested in engaging people with climate knowledge. This pathway to public understanding of climate science involves engaging people in facts and stories about climate, and emphasizes education, interactivity, and visual communication.

- Decision-making & Stakeholder Engagement has 257 articles and has grown steadily since 2000. It is the smallest community, but the papers comprising it have the largest selection of keywords. These papers are published primarily in climate and environment journals. “Science” is the dominant keyword (152 times), followed by “adaptation” (149), “risk” (101), “management” (99), “policy” (93), “knowledge” (78), “environmental” (78), “decision” (69), “model” (66), “social” (65), “participatory” (62), “uncertainty” (61), “sustainability” (59), “assessment” (53), and “stakeholder” (50). Title words indicate that, in addition to being adaptation-focused (“adaptation” occurs in 109 titles), this community is dominated by case studies (“case” occurs 55 times and “study” 47). This community is primarily interested in using communication strategies as tools to support action on climate knowledge. This pathway to public understanding of climate science involves strategic information provision to support managers, policy makers, and citizens in understanding and acting on climate knowledge.

Appendix A shows keywords and title words with >10% prevalence in each community, and frequently occurring publication outlets for each. We checked these names against the 20 highest-degree papers in each community (Appendix B), to ensure they accurately described each community’s core.

We expected two patterns of knowledge application in this network: nodes with high degree playing primarily bonding roles (connecting similar sources of knowledge to form the communities described above), and nodes with high betweenness playing primarily bridging roles
(connecting dissimilar or previously uncombined sources of knowledge from more than one community). Overall, few nodes have high betweenness centrality (large size nodes in Figure 6), suggesting that diverse knowledge sources are frequently combined in different ways for climate communication projects. This is evident in Figure 7, which shows two different views of the same network: one with only cross-community connections, and one with only internal community connections. 12,638 (about ⅔ of the total) connections link nodes in the same community, with 6,575 (about ⅓ of the total) connections crossing communities (Figure 7).

![Figure 7](image)

*Figure 7.* Contrasting view of cross-community connections and internal community connections.

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3 To check if network pruning affected this conclusion, we confirmed approximately the same ratio of cross-community and internal community connections were present in the unfiltered network. If pruning to a connection strength of five removed a disproportionate number of between-community links, we would have been at risk of drawing incorrect conclusions about how integrated different knowledge areas were. Four of five communities were affected equivalently by the pruning, except for Decision-making and Stakeholder Engagement, which shrank ~35% more than others. Before pruning, Decision-making & Stakeholder Engagement had 794 nodes and 21,178 links; in the filtered network, this was reduced to 257 nodes (~32% of its original nodes, while other communities kept 60%–70%) and 530 links (~3% of its original links, while other communities kept 5%–7%). A larger proportion of this community’s papers were connected with a strength of less than five.
Nodes with high betweenness often have high degree (starred papers in Figure 6). The high degree nodes generally have longer bibliographies, which affords more opportunities for connection to other nodes (and increased likelihood of combining pieces of knowledge in a novel way). However, there are a handful of nodes with high betweenness but lower degree. These nodes play notable bridging roles despite having relatively fewer connections than the starred nodes. These articles can be thought of as the network weavers, because they connect disparate or previously uncombined sources of knowledge to support their research. For example, the big grey node (#1 in Figure 6) has the largest betweenness centrality in the entire network and the tenth-largest degree. This node draws on a diversity of sources unique to its knowledge application (high betweenness) while connecting strongly with other papers (high degree).

To understand linkages between the five knowledge communities, we considered the total weighted connection strength between them and the percentage of nodes from each community involved in cross-community links (Figure 8). The most strongly linked communities are Risk Perception & Communication with Individual Perceptions of Climate Change (1,387 links with 46% and 53% of nodes participating, respectively), and Risk Perception & Communication with Visual & Affective Communication (1,427 links with 46% and 60% of nodes participating, respectively). However, if we consider an insularity index (ratio of in-community to out-community links), Visual & Affective Communication participates in twice as many outside-community links (3,198) as inside-community ones (1,575) (Figure 8). By this standard, Climate Messages in the Media is the most insular, with 1,000 fewer outward-facing links than inward-facing ones. Decision-making & Stakeholder Engagement sends as many outward links as inward ones, but on average a smaller percentage of its nodes participate, meaning relatively fewer nodes are key for connecting the larger body of climate communication knowledge with this community’s work. This reinforces two suppositions suggested by the knowledge map (Figure 6):
Visual & Affective Communication is at the center because it frequently applies knowledge commonly used in other communities; Decision-making & Stakeholder Engagement is on the periphery because it rarely applies knowledge commonly used in other communities.

Discussion

The climate communication knowledge map (Figure 6) reveals a dense web of connections among five distinct knowledge communities, indicating a tightly knit and intensely collaborative knowledge domain. Each knowledge community has a strong intellectual tradition bounding its inquiry (as evidenced by the discernible community structure), but these traditions do not seem to limit that inquiry (as evidenced by the web of cross-community connections). Scholars in this knowledge network frequently combine diverse sources in their search for new ways to comprehend and support public understanding of climate science. Two conclusions can be drawn from this knowledge map: (1) public understanding of climate science likely requires multiple complementary strategies; and (2) work in climate services, decision support, and co-production offers an opportunity bridge between communication research and practice.

Public understanding of climate science requires multiple complementary strategies

The knowledge map shows that climate communication strategy cannot be distilled to a few key techniques matched neatly to use cases. The high rate of connection and low insularity (Figure 8) likely results from (and affirms) this important characteristic of climate communication: it happens in a diversity of contexts and for a range of goals, necessarily requiring different approaches. It makes sense that scholars would reach across the knowledge
Figure 8. Strength of knowledge exchange between the five communities. Each community of nodes has been aggregated into a single node, sized proportionately based on its weighted degree (total number of connections weighted by strength of those connections). All links between nodes of different communities have been collapsed into one, as have all links between nodes within the same community (these are the “U-turn” links at each node). The numbers indicate the total connections between the nodes, the thickness of the line indicates the summed weight of all the connections, and the percentages indicate how many of the nodes in each community participate in that link. For example, at the bottom of the chart, 16% of the nodes in Decision-making & Stakeholder Engagement and 14% of the nodes in Climate Messages in the Media participate in the 92 cross-community connections.
domain to better understand or support climate communication efforts in particular spaces or contexts, producing the dense web between communities as they study, develop, and test different strategies.

Recent science communication landscaping efforts corroborate this emphasis on cross-discipline collaboration (Gerber et al., 2020; Trench and Bucchi, 2015). Network studies of climate-tinged social sciences found similar “spaghetti balls” of knowledge reminiscent of the climate communication knowledge map (Wang et al., 2018). Previous work identifying messy networks as hindering intellectual progress may simply not apply in these social-scientific and application-focused knowledge domains. Still, in a research landscape this complex, making climate communication research useful and usable for practitioners is even more imperative — and even more challenging. With half of the research published since 2016, and only a third of the researchers participating repeatedly in the network, it’s not straightforward to survey, select and apply the available evidence.

The knowledge mapping performed in this study can be thought of as a data-driven attempt to identify and describe the multiple strategies available to climate communicators. The maps provide a visual index to different areas of knowledge, which can be studied and developed by researchers and leveraged in different situations by practitioners to describe or foster public understanding of climate science. It is productive for researchers to focus on specific aspects of public understanding of climate science (for example, climate messages in the media), but it is unlikely these researchers would suggest that focus was the only way to achieve public understanding of climate science. This is why we have chosen to represent these five knowledge communities as distinct pathways to public understanding of climate science: they are complementary routes to the same goal.

A practitioner wishing to locate relevant research might look at the five pathways and ask which best describes their communication context or goal. The position of that community in the
knowledge network could suggest other pathways to consider or even combine. Looking at knowledge this way helps make sense of the multiple factors affecting success of climate communication in the real world: media messages are not delivered separately from cultural ones; risk perception may be influenced by visual and affective cues that are not necessarily rational.

Mapping these communication pathways empowers communication practitioners to select, combine, and apply available evidence-based techniques. Mapping provides needed context considering the fragmentation (across disciplines, outlets, and scholarly traditions) of climate communication research and the lived sense of disorientation this can produce for those working in the field, conditions which have been identified as potential barriers to moving climate communication knowledge from research to practice (Cagle and Tillery, 2015; Moser, 2016). Orienting scientists and communicators to the research landscape and the five pathways to public understanding of climate science could support a sense of cohesion in the field.

Climate services and co-production offer an opportunity to bridge between climate communication research and practice.

The network structure revealed in a knowledge mapping project can suggest new opportunities for knowledge application. Network analysts look for structural holes in a mapped network because they represent an opportunity to bridge between areas of knowledge infrequently combined. Structural holes are spanned by bridging ties, which link two dissimilar entities and may represent a novel combination of information. The climate communication knowledge network is overwhelmingly characterized by bonding ties, where similar entities share many connections, causing the formation of the dense web of four knowledge communities at the center of the map (Figure 6). The high transitivity and low modularity observed in this network results from this central group of communities which, while distinct, share information frequently. One
community, however, is connected to the network by bridging ties: Decision-making & Stakeholder Engagement.

From a network perspective, Decision-making & Stakeholder Engagement behaves differently from the other four communities. It is on the periphery of the map, distanced from the core of the knowledge network. It sends as many outward links as inward ones, scoring a 1 on the insularity index, but a smaller percentage of nodes participate in these outward links (Figure 8). It’s connected to the broader network by a relatively smaller subset of papers than generally observed in this network. As a result, it’s the one element of this knowledge map that forms a promising structural hole, which could offer novel directions for knowledge application.

Research in this community focuses on communication strategies to encourage scientifically informed decision-making. It supports managers, policy makers, and citizens in understanding and acting on climate science. Papers in this community emphasize participation and stakeholder engagement and focus on communicating about adaptation, impacts, and risk management. Many studies involve co-design, climate services, data provision, and decision support tools. The fact that this knowledge community does connect occasionally to the broader climate communication knowledge domain confirms other work speculating that on-the-ground climate knowledge delivery systems could utilize strategies from climate communication research to augment success (Bartels et al., 2013; Cagle and Tillery, 2015; Kruk et al., 2017). But these studies are generally published in climate- or environment-focused journals, and some scientist/practitioner authors may not be familiar with the full array of research-supported tools available to climate communicators.

Fully documenting why Decision-making & Stakeholder Engagement is relatively cognitively isolated would require a different research approach than used here. But because the network map reveals this structural hole, and because effective climate service provision relies on participatory processes which produce not only the transfer of scientific information, but also
engagement, tacit buy-in, and trust-building (Larosa and Mysiak, 2019), this could be a particularly fruitful avenue to explore for integrating research and practice in climate communication. Climate services and other activities carried out by Decision-making & Stakeholder Engagement researchers could benefit from the broad array of tools studied and practiced in the other knowledge communities; similarly, researchers from other knowledge communities might benefit from having a living laboratory where climate communication strategies could be developed, applied, or tested. In fact, some scholars in risk communication and climate services have previously called attention to this opportunity and encouraged scholars and practitioners to reach across the gap (Donkor et al., 2019; Lindenfeld et al., 2012, 2014; Ponce de Leon and Gotangco, 2018). The salience of the recently-published large grey node from this community (Cook and Overpeck, 2019) illustrates the potential benefit of building these bridges.

Limitations & future work

Knowledge mapping is a powerful exercise for gaining a data-driven, synoptic perspective on knowledge in action, but the inherent abstraction and quantification simplifies the scholarly enterprise and does not reflect its full complexity. For example, all citations do not inform a paper equally, and this data-driven approach cannot make judgments about the worthiness of certain citation patterns. Further, insights from bibliometric analyses are predicated on the data that generates the network, meaning if Web of Science does not index social science and humanities research at the same rate as scientific research, contributions from these fields may be overlooked (Andrés, 2009; Archambault et al., 2006). We feel these compromises are worth the bird’s eye perspective gained, which can be augmented by future work to add other databases and make the knowledge map interactive.
A final limitation affects our conclusions about this knowledge domain specifically. We have interpreted the network structure as evidence that climate communication research is a highly interconnected field, whose researchers have wide knowledge of the many ways public understanding of climate science can be influenced. But it is plausible the network structure suggests the opposite: a disorganized body of knowledge produced by scholars who publish only once in the field and may lack the time to familiarize themselves with the knowledge domain or ground their work with insights from the most relevant pathway. Likely, both interpretations are true to some degree, but sorting out which connections support which interpretation is beyond the scope of this paper. In either case, a knowledge mapping exercise represents an important first step in understanding what pathways to public understanding of climate science are currently being pursued, and how well they support each other. A ripe area for future research would be understanding how widely or skillfully the pathways to public understanding of climate science are followed by communicators.

Conclusion

In this study we mapped the climate communication research domain and its five key pathways to public understanding, presenting a visual overview which may be thought of as a subway map guiding communicators (Smith, 2020). Our approach has relevance for scholars and practitioners in science communication more broadly, who are seeking new techniques for knowledge synthesis, transmission, and translation among the many individuals and entities involved in communicating science. By providing a snapshot of climate communication research, the map prompts interrogation of assumptions about existing climate communication knowledge and sparks insight about new areas which may benefit from increased application of evidence-based climate communication strategies. Future work to make this knowledge map interactive, and to update it regularly, could make climate communication research more useful and usable
for practitioners, supporting them in seeking relevant evidence to apply within the context of their existing skills and expertise gained through experience.

We called this article “mapping pathways to public understanding of climate science” because a knowledge mapping project is a bit like paving paths across a grassy field based on data describing the routes people actually walk across it. The links in the knowledge map can be thought of as the footpaths traveled for the purpose of assembling knowledge and evidence. Rather than contributing new information about how to communicate climate information, this study attempts to augment current researchers’ and practitioners’ abilities to locate and contextualize useful knowledge, thereby increasing the impact of what we already know about how to communicate climate science.
Chapter 2: Visualizing the Structure and Development of Climate Communication Research

Abstract

We performed time-evolving bibliometric mapping and topic modeling on 2,995 climate communication publications from Web of Science to better understand the structure, development and function of this knowledge domain. 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 climate communication strategies.

Introduction

Recent writing in science, environmental, and climate communication calls for strategy and coordination within the profession, to better leverage existing knowledge in communication projects (Besley, 2015; Jensen and Gerber, 2020; Moser, 2016; Smith, 2020). For climate communication, 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, and (2) discouragement at the muted effect evidence-based communication techniques have had in moving the needle on widespread climate change action (Cook and Overpeck, 2019; Jensen and

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4 This chapter was written with the support of co-authors Douglas P. Boyle and Stephanie A. McAfee.
Gerber, 2020; Moser, 2016). 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 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 (i.e., the level at which the communication should be targeted, who should be involved in the communication, what types of content need to be communicated and how, and even whether there should be any communication at all” (National Academies of Sciences Engineering and Medicine, 2017: 84–85; Willamo et al., 2018).

We aim to support systems thinking by visualizing the structure and development of climate communication research. We use time-evolving bibliometric network analysis and topic modeling to explore structures and patterns evident through time in 2,995 climate 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 communication research over the past twenty years and highlighting structural functions performed by topics, papers and journals in the climate communication system.
Context

Climate communication research investigates how people gain and act on climate information, as individuals or in groups (Comfort and 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 and 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 and Park, 2018; Corner and Clarke, 2017; Smith, 2020).

Climate 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 et al., 2021; Johnson, 2012). 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 and Overpeck, 2019; Corner and Clarke, 2017; Johnson, 2012; Moser, 2015). Climate 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 multilayered 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 communication foregrounds consideration of the ways many different aspects of climate communication may interact, augment, or thwart one another. Taking a census of climate communication knowledge is therefore a key step in supporting further strategic research and tactical application of existing tools (Jensen and Gerber, 2020; Moser, 2016; Smith, 2020). Doing so with network analysis and topic modeling can reveal the structure within which climate 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 and Van Der Sanden, 2017; Wenger et al., 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 et al., 2014; Henry and Vollan, 2014; Szerszynski and Galarraga, 2013).

Systematic reviews have proliferated across climate communication (and science communication more broadly) in recent years, with some focusing on particular communication problems or sets of tools (Agin and Karlsson, 2021; Akerlof et al., 2022; Armstrong and Krasny, 2020; Asmi et al., 2019; Gerber et al., 2020; Kidd et al., 2019; Larosa and 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 et al., 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 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 a need to communicate results in passing, 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 analysis (achieving a similar retention rate as in Moser, 2016). This is the same
dataset used in the previous chapter, but here we present a new analysis that describes the
temporal evolution of the network and assesses its topical content (Canon et al., 2022).

86% of analyzed publication records are journal articles. Proceedings papers, book
chapters, editorials, and other items account for the remaining 14%. Web of Science categorizes
34% of these publications as “Environmental Studies” and 27% as “Environmental Sciences,”
with only 19% categorized as “Communication.” The dataset favors first authors from United
States institutions (40%), followed by England (16.5%) and Australia (11.2%).

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 and 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 and
Foster, 2011; McLevey and 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 and 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 and Foster, 2011; Szerszynski and 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 communication applies the many tools and theories available.

We used python packages metaknowledge (McLevey and McIlroy-Young, 2017) and NetworkX (Hagberg et al., 2008) to build the bibliographic coupling network. We pruned all links with a strength less than 5 and retained only the giant component (the largest group of connected nodes) for analysis. In this case, the initial network had 2,863 nodes with 533,073 links between them. Pruning allowed us to analyze and visualize 1,770 nodes and 19,212 edges. 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 in the previous chapter. 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.

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5 This is the same network presented in Chapter 2; however here we have added a temporal dimension to the analysis.
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 unstructured collections of written works (Asmussen and Møller, 2019; Blei, 2012). This method has successfully depicted topic diversity in similar interdisciplinary and heterogeneous research fronts such as climate adaptation (Bittermann and Fischer, 2018; Lesnikowski et al., 2019).

A topic model imagines that each text in the dataset was composed by an author randomly 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 et al., 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, 2019). 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, 2019).

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 (Figure 9). 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 et al., 2009) and spaCy (Honnibal et al., 2020) to remove irrelevant words (such as prepositions), identify phrases (such as “global warming”), and lemmatize words. We then used gensim (Rehurek and Sojka, 2010) to build the topic model and LDAvis to visualize the results (Sievert and 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.

![Figure 9. Coherence scores for models with between 5 and 25 topics.](image)

**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 the previous chapter; here we focus on their structural change through time (Figure 10). In Figure 10, colored nodes join the network at each timestep, against a light gray background depicting its final shape. 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 11). A full 50% of the 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. Only one of the highly cited papers (Moser, 2010: “Communicating climate change: history, challenges, process and future directions”) is notable in terms of network structure, having both high betweenness (an important connecting function) and high degree (an important influencing function) centralities. 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 10 could come from widespread citation of the most cited papers.
Figure 10. Timeline of the evolution of the bibliographic coupling network. Larger nodes have higher betweenness centralities (they connect to other articles that are not connected to each other). Colors indicate communities identified by Louvain community detection. Colored nodes join the network at each timestep, against a light gray background depicting its final shape.
Figure 1. Top cited articles in the climate communication dataset. The colors of the bars correspond to the network community the paper belongs to in Figure 10.

The network in Figure 10 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. 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 in their bibliographies will be in the same network community. But links crisscrossing this network in a “spaghetti ball” pattern suggest that each community in the climate communication knowledge domain does frequently seek out and apply knowledge from other communities. This is what Figure 10 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 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 12). The total share of the network represented by articles from the six most popular journals is relatively small because climate 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 10 and 12 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.

**Figure 12.** 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.
The topic model identified nine topics with similar cumulative frequencies throughout the dataset (as evidenced by the equivalent sizes of their circles in Figure 13). 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 blue “Climate Messages in the Media” network community, or Topic 6: Risk and the purple "Risk Perception and Communication" network community). Some overlap between topics is evident, as shown by the overlapping circles in Figure 13, 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 11) 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
Figure 13. Topic model of climate communication research. The center of the figure represents distance between topics. Surrounding word clouds and 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.

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 et al., 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.

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 (Figure 14A, 9B). 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 14C-F). This revealed clearer patterns in topic dominance for each community: the network community “Risk Perception and Communication” is dominated by Topic 6: Risk; 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 “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 14G). 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 to the sentence level.
Figure 14. Patterns in topic dominance across the dataset, within network communities, and within four highly cited sample papers. Topic 0 is Education and Engagement, Topic 1 is Vulnerability, Resilience and Adaptation, Topic 2 is Climate Change, Topic 3 is Concern for Climate Change, Topic 4 is Policy, Practice, and Participation, Topic 5 is Climate in the News, Topic 6 is Risk, Topic 7 is Climate Data and Decision Support, and Topic 8 is Scientists & Experts.
Discussion

We began with the observation that more than twenty years into the development of the climate communication field, it is still not clear how to leverage its wealth of evidence-based techniques to significantly affect outcomes. Results from this structural investigation point to a possible reason for this paralysis: climate communication as a knowledge domain appears to be trying to have many conversations at once. Of course, every area of scholarship does this; what is different here is the apparent attempt to integrate elements of each conversation across every corner of the network and within nearly every document comprising it. This attempt is evident in 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 the corpus.

The intertwining of topics in the climate communication knowledge domain suggests that climate communicators are already taking a systems approach to the complicated problem of climate communication, considering as many possible elements as they can in their research. Our 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: 12). It’s possible that much of the discussion in climate communication 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 a cacophony than help identify harmonies.

It's recently been noted that “a large part of the research on climate change produced within the social sciences has been strikingly a-social,” focused on the individual as the relevant unit of analysis (Carvalho et al., 2021: 2; Villar, 2021). This could be a legacy of climate
communication’s origin in the hard sciences, which has had lasting effects on how the climate communication problem is defined and which tools are sought for solving it (Ballantyne, 2016; Moser, 2010). This tradition frames communication as an instrument, instead of as a relationship or a process. This could in part account for why so much climate communication work seeks the correct combination of inputs, framing, and audience segmentation to provoke concern or appropriate individual action (as defined by the communicator), despite the knowledge that some communication tactics have been shown to be culture-contingent and even counterproductive when combined (Besley et al., 2019; National Academies of Sciences Engineering and Medicine, 2017; Pearce et al., 2015; Wolf and Moser, 2011). Even if it were possible to discover the correct inputs in such a system, the results might be underwhelming. Knowledge, however successfully internalized, rarely leads to action on its own, which means that most evidence-based communication strategies are necessary but not sufficient conditions for achieving widespread awareness, knowledge, understanding, and action (Cook and Overpeck, 2019; Moser, 2015). Calls to move evidence-based techniques into practice may be coming from this tradition of inquiry, and successful climate communication in the age of climate change may require resisting this narrative and permitting slower, less instrumental, more constitutive and more creative approaches space to develop.

Given widespread calls for unified, systematic, and strategic climate communication, we were frankly surprised to find a structure that was already so cohesive by July 2020. 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. The structure suggests that climate communication is already trying to synthesize a staggering number of evidence-based tactics to inform climate communication activities. One possible conclusion is that this simply needs to be done in a more orderly or coordinated fashion. But it may be that climate
communication performed with respect to the complexity of the system actually requires more than considering all the variables and accurately characterizing the compound effect from an array of experimental and non-experimental stimuli (Cox and Schwarze, 2015).

What might a different, less instrumental, more social approach to climate communication look like? Unfortunately, the topical and relational structure of the climate communication research revealed by our analysis cannot say. But it can suggest an unexpected answer to our original question of how the structure of this knowledge domain might constrain inquiry in this field. This structural assessment of climate communication knowledge revealed a research landscape not unlike a gold mining district that has played out, but where miners continue arriving to seek gold that is no longer in the ground. What has been extracted has been worth a fortune, but it seems unlikely that climate communication will be rewarded for continuing to dig for golden insights within the boundaries of the existing research structure. However, the knowledge structure appears to be keeping the focus on these played out grounds.

It happens that we are not the first scholars to reach this conclusion: in the time that 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” (Agin and Karlsson, 2021: 14). More promising and more challenging than considering many potential interactions between content and context is to develop ways of communicating that are truly constitutive, to recast a deeply instrumental field as one that achieves impact and utility through relationships and care (Coen, 2021; Cook and Overpeck, 2019; Finlay et al. 2021). A primary challenge we see on this journey – one that threatens to keep climate communication inquiry bound within the existing knowledge structure – is that such endeavors are not easily presented in academic settings, digested in journal articles, or afforded prestige from an institutional perspective.
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 et al., 2006; Cabeza et al., 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 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 and Fischer, 2018).

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 territory delimited 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). Going forward, climate
communication may need to be deliberate about when it is productive to travel well-worn paths
within this network structure, and when better outcomes may be achieved in the long term by
venturing outside it.
Chapter 3: Ethical and Effective Visualization of Knowledge Networks

Abstract

Knowledge mapping combines network analysis and data visualization to summarize research domains and illustrate their structure. In this paper, we present a framework for ethical and effective visualization of knowledge networks, which we developed while building a knowledge map of climate communication research. Using the climate communication knowledge map as an example, we highlight the practical and ethical challenges encountered in creating such visualizations and show how they can be navigated in ways that produce more trustworthy and more useful products. Our recommendations balance tensions between qualitative and quantitative and objective and subjective aspects of knowledge mapping. They demonstrate the importance of critical practices in the development of knowledge maps, illustrate the intertwined nature of analysis and results in such projects, and emphasize the constructedness of the resulting visualization. We argue that the only way to produce an effective knowledge map is to produce an ethical one, which requires attention to the ways trust and accountability can be produced at every step of analysis and production. This extends the literature on ethical visualization in digital humanities projects by offering a clear example of the utility of a critical approach for a traditional, science-oriented knowledge mapping project.

6 This chapter, written with co-authors Douglas P. Boyle and K.J. Hepworth, has been accepted for publication in the journal Digital Humanities Quarterly.
Introduction

Scholars have long been captivated by the idea that knowledge generation is outpacing their ability to keep up, necessitating creative techniques and solutions to organize, manage, and access information. From scientist Vannevar Bush’s memex\(^7\) to futurist Richard Buckminster Fuller’s Geoscope\(^8\), researchers have envisioned high-tech tools for information management and knowledge creation since before the advent of big data. Today, well into the era of hyperlinked text and geographic information systems not unlike the miracle tools envisioned by 20th century inventors, making knowledge on even very specific areas of scholarship tractable remains a complicated challenge. As scholarly knowledge continues to grow, so does interest in quantitative techniques for summary, survey, and synthesis of knowledge domains.

Knowledge mapping is one such survey and synthesis technique. It combines data visualization and network analysis to depict large collections of information spatially, as if they were a landscape viewed from above. Knowledge mapping is a general term for an analysis informed by and applied in multiple areas of scholarship, including information science (Borner, 2011), literature (Moretti, 2007), history (Graham et al., 2015), and bibliometrics (Chen, 2016). These maps are at once analytical, managerial, and communicative: analytical because they provide tests of network theories and because bibliometric data was one of the earliest sources of big data for such analyses; managerial because they guide decision-making, funding allocation, and evaluation; and communicative because they aim to support discovery and guide hypothesis formation by depicting knowledge as a collaborative, interlinked whole. Knowledge maps are simultaneously rhetorically powerful (because they make visual arguments) and ethically fraught (because visual arguments presented in such charts are often accepted as objective fact), but

\(^7\) An external brain for forming and tracking relational knowledge (Bush, 1945).

\(^8\) A macroscope for harnessing disparate data and visualizing it on a global surface, to support problem definition and problem solving (Fuller, 1981).
knowledge mapping techniques have not yet been brought into conversation with recent work in digital humanities surrounding ethical visualization and data feminism (D’Ignazio, Catherine, 2019; D’Ignazio and Klein, 2020; Hepworth, 2017, 2020).

Ethical visualization is the practice of acknowledging and mitigating the potential for harm that is inherent to particular visualizations (Hepworth and Church, 2018). Ethical visualization and data feminism require consideration of the whole data pipeline, from acquisition to analysis to visualization, and attention to the ways in which some perspectives are marginalized, omitted, or elided (D’Ignazio and Klein, 2016, 2020). Both traditions require not only acknowledging the potential negative effects of a visualization or drawbacks of a particular dataset, but actively working to mitigate them in a way that increases understanding while minimizing harm (Cairo, 2014). Given nascent discussions in bibliometrics about the potential harm perpetuated by uncritical application of bibliometric techniques for evaluation, it is an important time to bring critical practices into conversations about knowledge mapping (Bornmann, 2017; Conway, 2014; Donovan, 2019; Furner, 2014; Rolf, 2021; Zuccala, 2016).

In this paper, we demonstrate how principles of ethical visualization and data feminism can be applied in the development of a knowledge map to produce a more trustworthy and more useful product. We do this by providing a detailed account of the path we followed to build a knowledge map of climate communication research, highlighting practical challenges encountered in creating such a visualization and how ideas from ethical visualization literature helped navigate them. Specifically, we: (1) demonstrate the importance of critical practices in the development of a complex type of chart, (2) illustrate the intertwined nature of analysis and results in big data projects, and (3) take a first step toward a feminist bibliometrics informed by critical work in digital humanities. This addresses a previously identified need for clear guidance on the visual communication of knowledge networks (Conway, 2014; Gavrilova et al., 2019). It has relevance for digital humanists working with knowledge networks and bibliometricians.
seeking practical strategies for mitigating harmful externalities of evaluative bibliometrics. It also enriches ongoing conversations in the digital humanities about ethical visualization and data feminism with examples of how frequently ethical choices arise in a data visualization project.

Ultimately, we emphasize the constructedness of these types of visualizations, showing why a purely quantitative, purely objective depiction of a knowledge network is neither possible nor particularly useful. We argue that the best way to produce an effective knowledge map is to produce an ethical one, which requires attention to the ways trust and accountability can be produced at every step of analysis and production.

**Knowledge mapping**

Knowledge maps are powerful tools for planning, collaborating, teaching, and communicating, because they depict metaknowledge about how topics and problems are structured (Borner, 2010; Evans and Foster, 2011). Metaknowledge – literally, knowledge about knowledge – may sound like a dangerously totalizing “god trick,” but it can in fact be understood as a concept gesturing at the positionality and situatedness of all knowledge, and the necessity of combining multiple partial perspectives to understand a system (D’Ignazio, Catherine, 2019; Haraway, 1988). Sociologists James A. Evans and Jacob G. Foster define metaknowledge as the result of “critical scrutiny of what is known, how, and by whom” and suggest that we might best understand what metaknowledge is by thinking about what we, as individual scholars with particular trainings, career paths, and expertise, think about as we read a journal article in order to “index a broader context of ideas, [scholars], and disciplines” – the kind of knowledge gained from being a participant in a system through time (2011: 721; Kwan, 2002). Knowledge maps offer an alternative way to gain a similar kind of qualitative understanding via quantitative techniques, affording viewers an intuitive summary of a large collection of information (Lima, 2011; Moretti, 2007; van Geenen and Wieringa, 2020). Metaknowledge is important because it
sparks abduction, or diagnostic-style logic, where experts may arrive intuitively at a conclusion based on partial information combined with their existing understanding of the system and situation at hand, and where knowledge may be generated instead of simply synthesized (Brooke, 2017; Douven, 2017; Graham et al., 2015).

While it may be preferable to gain metaknowledge the traditional way, by participating in a knowledge system over a lifetime, this is not always practical or possible. Knowledge maps act as a tool which – just like regular maps of landscapes – are useful for sharing information, for planning where to go and how to get there, for noticing patterns or pathways that might not have been apparent to boots on the ground, and for coordinating collective effort in the face of complexity. They support switching between general knowledge and specific pieces of information and evidence, an ability which has been identified as a fundamental practice of critical scholarship (Edmond, 2018; Kwan, 2002; Moretti, 2007). Their utility comes even though knowledge offered by such a bird’s eye view is clearly different from the kind gained through personal experience, immersion, and reflection (Evans and Foster, 2011; Moretti, 2007). Essentially, it is worth simultaneously being cautious about the algorithmic ways in which knowledge maps synthesize big citation data and present it as knowledge, while also emphasizing the incredible utility of this form for producing, transmitting, and constructing collective knowledge (D’Ignazio, Catherine, 2019; D’Ignazio and Klein, 2016). Bibliometrician David A. Pendlebury summed this up effectively when he observed a need for “charting a path between the simple and false and the complex and unusable” (2019: 549).

When constructed in partnership with residents from the mapped research domain, knowledge maps can prompt identification and reassessment of taken-for-granted assumptions and highlight forces shaping problem definition in a field. In fact, examples of this work in climate domains are what initially inspired our attempt to map the climate communication research landscape. For example, informationist Christopher Belter and climate scientist Dian
Seidel (2013) created network visualizations to reveal (dis)connections in geoengineering knowledge, using sparse network charts to show how some planetary systems receive more focus than others, and that lack of information exchange between areas of study means there may be inadequate consideration of potential interactions between different geoengineering strategies. Another example is the work of psychologist Laura Kati Corlew and her team (2015), who successfully used social network analysis to build a knowledge sharing and resource discovery tool for climate professionals in the Pacific Islands.

These projects are notable because they leverage knowledge maps as communication and collaboration tools while being sensitive to audience needs and effects on those depicted in the visually powerful network charts. Rather than viewing analysis as an endpoint, these studies distill the information spaces into clear visualizations for interested audiences. Knowledge maps should be built from this perspective, to be both useful and usable and to assist viewers in extracting meaning from information spaces and analyses that may otherwise be esoterically complex.

Designing the climate communication knowledge map

The climate communication knowledge mapping project was initially situated in the tradition of science mapping, a kind of knowledge mapping undertaken by computer scientists and network analysts. Science mapping uses bibliometric data to reveal the structure of a knowledge domain by creating networks of papers or authors linked by citations or collaborations. However, despite having domain expertise in climate communication and fluency in network analysis techniques (often considered the ideal for this type of project), we immediately ran into ethical and practical challenges that were not well addressed in the science mapping literature, perhaps because too much emphasis is placed on the objectivity of network maps, the assumed impartiality of algorithmic curation, and the potential of data speaking for
itself (Conway, 2014; D’Ignazio, Catherine, 2019; D’Ignazio and Klein, 2020; Hepworth, 2020; White and McCain, 1998; Yang et al., 2016). In our project, limited technological resources necessitated static depictions of the knowledge network, data quality precluded purely algorithmic curation, and it was frequently unclear how fundamental tasks like disambiguation and layout should be approached when the goal was to create a useful knowledge map (instead of just to arrive at an analytical result). In this section, we describe in detail the challenges encountered in building the climate communication knowledge map and point out how attention to conversations in ethical visualization and data feminism provided needed guidance on navigating them.

Perhaps because of the impact of scientific approaches to visualization on knowledge mapping, a significant amount of data in knowledge mapping projects is not pre-processed before it is visualized. It is thought that network analysis itself controls for any errors or ambiguities in the underlying data (Chen, 2016). If ambiguities do exist in the network map, conventional wisdom holds that resulting irregularities cancel each other out, and overall conclusions are not affected (Fegley and Torvik, 2013; White and McCain, 1998). We did not find this to be the case in our knowledge map, especially when imagining how it might be useful and trustworthy for climate communicators. If the first thing a user notices when looking at a knowledge map is a data error (such as a single leading scholar being split into multiple author nodes), it cannot be expected that the user will trust other elements of the knowledge map. Given that the point of a knowledge map is to support reasonable inferences about the structure and function of the research domain, it is a serious problem if data issues affect interpretation. Engineer Jinseok Kim’s research reveals the nature and extent of factors that distort knowledge maps (Kim, 2019; Kim, Diesner, et al., 2014; Kim, Kim, et al., 2014; Kim and Diesner, 2016). For example, datasets
rife with author name ambiguities appear scale-free⁹, a feature long thought to characterize

citation networks (De Solla Price, 1965), when in fact they aren’t. Consequences to both the

mapped research community and to theorists studying network processes can be profound when
data visualizations uncritically display conclusions that may be based on irregularities in the data,

and when funding decisions are made based on this data. As a result, the bulk of this chapter

focuses on data processing, and the ethical considerations that may be glossed over when the

network analysis itself is the jumping off point for a knowledge mapping study.

In this section, we undertake the important data feminist approach of showing our work

(D’Ignazio and Klein, 2020). We provide a complete description of how we produced the climate

communication knowledge map, attempting to be transparent about elements of data preparation

and visualization design that are not generally discussed in published literature, but which are of

vital importance in following an ethical and accountable process of visualization design

(Callaway et al., 2020; D’Ignazio and Klein, 2020; Hepworth and Church, 2018). All described
data management and network analysis was conducted in Python with metaknowledge (McLevey

and McIlroy-Young, 2017) and NetworkX (Hagberg et al., 2008). Visualization was performed

with Gephi (Bastian et al., 2009).

Data search & selection

Data for the knowledge map came from Clarivate’s Web of Science database, selected for

its accessibility despite known gaps in its coverage and because previous work suggests that it

entails about 50% as much cleaning and curation time as Scopus and about 5% as much as

Google Scholar (Andrés, 2009; Harzing, 2015; Meho and Yang, 2007). Though it would have

⁹ Scale-free means that the structural patterns evident in the network persist regardless of the size of the

network. This is often explained by a process called preferential attachment, where newcomers to the

network tend to connect to existing network members who already have a high number of connections (an

example of a “rich-get-richer” phenomenon). In the example of a citation network, certain papers

accumulate high numbers of citations while others are never cited.
been preferable to combine multiple datasets to get the broadest possible bibliometric survey of climate communication literature, there are significant practical challenges to combining relational citation data from different databases. We used a search query (TS = (climat* NEAR chang* AND communicat*)) from a previous systematic review of climate communication, conducted by an expert in the field (Moser, 2016). This was intended to ensure that this knowledge map complemented previously accepted delineations of the climate communication field and would therefore hopefully be more trustworthy to members of the mapped research domain. Query-based data selection for any knowledge mapping study faces a trade-off between recall (getting every single relevant item) and relevance (making sure no single irrelevant item is included), and it is always a concern that excluded materials are not evenly distributed across the field in question. The Web of Science search yielded 5,934 results on July 31, 2020.

One of the reasons data is not generally cleaned before analysis is the expectation that selecting and extracting the giant component (the largest set of connected nodes in a network) will filter papers that don’t belong (because they’ll be in disconnected communities). In the climate communication knowledge network, some combination of one-time participation by many researchers, the nebulous border between climate science, environmental science, and climate communication, and the broad application of some permutation of the terms “climate,” “communication,” and “change” in nearly every academic discipline meant that the giant component included many irrelevant items when constructed with the complete Web of Science data pull (Figure 15).

We explored programmatic filtering strategies to prune the irrelevant data, but these all failed, to the point that it seemed much more time would be spent fine-tuning an algorithm specifically suited to disambiguating this one dataset than it would take to disambiguate it manually. Manual (human) review resulted in the removal of ~50% of the returned records (2,997 retained; 2,937 removed). Though in some ways it seemed alarming to remove half of the
returned data, it also seemed misleading not to do so, because clearly irrelevant items (for example, papers about inter-model communication of climate signals, effects of climate change on insect pheromonal communication, and changes in workplace communication climates) distorted the visualized network (Figure 15). This highlights the impossibility of achieving an objective delineation of a particular research area from an unprocessed dataset and the need to rely on human judgment in data visualizations even at these early stages. This process of data preparation opens a knowledge mapping analysis up to perpetuating harm in two ways: first, that whether an algorithm or a human applies inclusion/exclusion criteria, some error is likely to occur, and second, that the underlying data does not adequately or equally represent the breadth of scholarship in a particular knowledge domain. To mitigate this, we added annotations to our final product (Figure 20) intended to guard against interpretation of the knowledge map as a complete picture of every possible research output in the climate communication space.

Author name disambiguation

Because we wanted to produce a knowledge map of collaboration patterns within climate communication scholarship, we projected the bibliometric data from Web of Science into a co-authorship network, where nodes are individual scholars and links are formed between them when they write papers together. To present a clear co-authorship network, it is necessary to disambiguate author names (Fegley and Torvik, 2013; Harzing, 2015; Milojević, 2013; Strotmann and Zhao, 2012). Co-authorship network analysis rests on the assumption that there is one node for everyone in the network, but in reality, names are frequently split (identifying a single author as multiple authors) or merged (collapsing multiple individuals into a single mega-researcher) (Harzing, 2015; Milojević, 2013). This can be due to inconsistent name spelling (for example the occasional omission of a middle initial), name change (for example due to a change in marital status), or database limitations and errors. Merged names are such a problem in bibliometrics that
Figure 15. Recall vs. relevance when editing network datasets. An illustration of the trade-off between recall and relevance when including or excluding data for network analysis. The upper panel shows what the giant component looks like when all returns from a Web of Science query are included; the lower panel shows the same network’s giant component after manual review was conducted to ascertain relevance of the returned data.
many databases contain entries for mega-authors who appear to publish multiple papers every day for years on end (Harzing, 2015). Clearly, the process of author name disambiguation has enormous ramifications for whose contributions are legible or visible in a knowledge network, and whose are not. Recent efforts to use unique author identifiers such as ORCIDs may eventually solve this problem, but they are not yet used widely enough to offer a practical author disambiguation solution.

Author network studies wishing to disambiguate name data face a choice: implement algorithmic disambiguation strategies of varying complexity or undertake the time-consuming process of manually disambiguating the data. Simple algorithmic disambiguation is the norm, partly due to research suggesting that more computationally or time intensive approaches don’t improve results (Milojević, 2013). Manual disambiguation is rare, though not unheard of; some find the time investment comparable to designing an algorithm, at least for up to about five thousand authors (Burckhardt, 2017; Fegley and Torvik, 2013; Strotmann et al., 2009).

The simplest algorithmic approaches are “first initial” disambiguation and “all initial” disambiguation. A pattern of initials is selected and all names are converted to match this pattern (for example, a full author name being converted to first initial and full last name). First initial disambiguation is the most common but also the most fraught: split individuals change network statistics less overall than do merged authors, and first initial disambiguation’s weakness is that it merges many authors (Fegley and Torvik, 2013; Strotmann and Zhao, 2012). When authors are merged, their actual networks combine with others, sometimes resulting in the appearance of bridges connecting areas of the network that are actually distinct and making the mega-author seem like an important synthesizer of knowledge at a level that may not reflect reality (Kim and Diesner, 2016). Networks containing many merged individuals become smaller, less transitive, denser, more productive, and more connected (or more frequently connected) than they actually are, and will have larger giant components (Fegley and Torvik, 2013; Kim, Kim, et al., 2014;
Kim and Diesner, 2016). Initials-based disambiguation has been shown to introduce error into the entire gamut of statistics describing network structure and function, including those assessing author productivity, collaboration patterns, and cohesion (Kim and Diesner, 2016). Given the potential for harm inherent in miscalculating network statistics, both for evaluated individuals and for their broader knowledge community, we explored and visualized networks resulting from each of these disambiguation approaches so that we could make a clear determination of which strategy to use.

**Figure 16.** Same data, same network? An illustration of how distortions to the network introduced by different disambiguation strategies look when visualized. The full network is shown in gray for context, with the giant component extracted to the right. Colors are assigned to algorithmically-defined communities in order from largest to smallest in each network, but community size changes in each method.
Very different pictures emerged when each of the four different disambiguation approaches was applied (Figure 16). Though the overall network is smaller, many more nodes are included in the “First Initial” giant component than in “Full Name,” with “All Initials” falling somewhere in the middle. Table 1 provides quantitative support for these visual impressions. The number of authors contained in the giant component and the number of links connecting them changes significantly, by hundreds of individuals in the overall network and by over a thousand individuals in the associated giant components. Most notable in Figure 16 is the fact that a salient feature of the manually disambiguated network, the bridge that spans from the left to the right of the giant component without traveling through the core, is not as clear in any of the networks generated from algorithmic disambiguation. But each of the networks appears individually reasonable, both from a network standpoint and a climate communication one. This makes it clear how researchers could (wittingly or unintentionally) select a disambiguation strategy that conveys a particular message. In this case, the “First Initial” network suggests thriving exchange and dense connection, “All Initials” offers better-defined clusters, and “Full Name” presents neat divisions between communities with just a few bridges between. It’s therefore important to be attentive to how interpretations may be influenced by visualization choices.
Table 1. Metrics describing the networks produced by four different disambiguations of the climate communication author network.

<table>
<thead>
<tr>
<th></th>
<th>Manually Cleaned</th>
<th>All Initials</th>
<th>Full String</th>
<th>First Initial</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Entire Network</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collection Length</td>
<td>2995</td>
<td>2995</td>
<td>2995</td>
<td>2995</td>
</tr>
<tr>
<td>Nodes (Authors)</td>
<td>7255</td>
<td>7402</td>
<td>7694</td>
<td>7061</td>
</tr>
<tr>
<td>Links (Collaborations)</td>
<td>23232</td>
<td>23503</td>
<td>23638</td>
<td>23272</td>
</tr>
<tr>
<td>Isolated Nodes</td>
<td>438</td>
<td>448</td>
<td>480</td>
<td>416</td>
</tr>
<tr>
<td><strong>Giant Component</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nodes (Authors)</td>
<td>1676</td>
<td>1604</td>
<td>1182</td>
<td>2730</td>
</tr>
<tr>
<td>Links (Collaborations)</td>
<td>7888</td>
<td>6667</td>
<td>4882</td>
<td>13659</td>
</tr>
<tr>
<td>Density</td>
<td>0.006</td>
<td>0.005</td>
<td>0.007</td>
<td>0.004</td>
</tr>
<tr>
<td>Transitivity</td>
<td>0.829</td>
<td>0.787</td>
<td>0.781</td>
<td>0.842</td>
</tr>
<tr>
<td>Assortativity</td>
<td>0.687</td>
<td>0.661</td>
<td>0.661</td>
<td>0.728</td>
</tr>
<tr>
<td>Average Clustering</td>
<td>0.823</td>
<td>0.818</td>
<td>0.808</td>
<td>0.829</td>
</tr>
<tr>
<td>Modularity</td>
<td>0.898</td>
<td>0.892</td>
<td>0.844</td>
<td>0.932</td>
</tr>
</tbody>
</table>

Studies do not agree about which algorithmic disambiguation method is most effective at approximating the true network, though it’s been shown that between 8-39% of individuals in a dataset can be affected by merging or splitting (Kim and Diesner, 2016; Milojević, 2013). Estimates to quantify the amount of error often use “First Initial” disambiguation as the lower limit of the range of error on the actual number of authors in the database, and “All Initials” as the upper limit, but they do not usually visualize the resulting differences to see how more qualitative structural conclusions may be affected. Clearly, the success of a disambiguation strategy depends on meta-characteristics of the dataset itself. The most common example of this is the near-impossibility of using initials-based disambiguation on datasets with high participation from individuals with Chinese or Korean last names (Harzing, 2015; Kim and Diesner, 2016; Milojević, 2013; Strotmann and Zhao, 2012).
Even if it were possible to estimate the average distortion effects from different approaches to algorithmic disambiguation, it would be hard to predict which authors would be the most affected, meaning that analysis choices may have differential effects on different communities of scholars. Even if only a small percentage of error is introduced overall, that error may be distributed unevenly across the network, raising real concerns about whose and what types of contributions may be emphasized or obscured. Figure 17 shows how different authors’ network positions are affected by different disambiguation strategies: node size changes (e.g., the node for S. Dessai), as does community membership (e.g., the node for S. Lewandowsky) and the visibility of underlying data errors (e.g., two nodes for E. Maibach linked together). The relative importance of nodes acting as brokers (large nodes here have high betweenness, one measure of a brokering role) changes too, and lumped or split authors open or close network pathways and affect community delineation. Table 2 shows how overall rankings of authors change order as nodes are merged or split.

If the goal of the network analysis is to be useful to the people represented, this sort of error can’t be waved away as acceptable distortion, and the only way to understand how such error affects an analysis is to visualize it and see. Though author disambiguation is rarely framed as an ethical issue, it clearly is one, as disambiguation strategies affect not only author rankings but the structural roles of authors in a network and the apparent structural function of the knowledge domain as a whole. In this case, we mitigated potential harm caused by inaccurate evaluations by building our final visualization on the manually disambiguated author dataset (though it’s important to note, there are almost certainly errors even in this carefully curated dataset). However, most knowledge mapping projects will not have the benefit of a manually disambiguated dataset to compare to. In those cases, the best thing to do is understand the potential consequences of choosing different disambiguation strategies and avoid over-interpreting the results.
Table 2. Different rankings of top authors from four different disambiguations of the climate communication author network.

<table>
<thead>
<tr>
<th>Manually Cleaned</th>
<th>All Initials</th>
<th>Full String</th>
<th>First Initial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maibach, E</td>
<td>Leiserowitz, A</td>
<td>Leiserowitz, Anthony</td>
<td>Maibach, E</td>
</tr>
<tr>
<td>Leiserowitz, A</td>
<td>Maibach, E</td>
<td>Maibach, Edward</td>
<td>Leiserowitz, A</td>
</tr>
<tr>
<td>Pidgeon, N</td>
<td>Maibach, EW</td>
<td>Maibach, Edward W.</td>
<td>Pidgeon, N</td>
</tr>
<tr>
<td>Hart, PS</td>
<td>Hart, PS</td>
<td>Pidgeon, Nick</td>
<td>Hart, P</td>
</tr>
<tr>
<td>Moser, SC</td>
<td>Pidgeon, N</td>
<td>Nerlich, Brigitte</td>
<td>Moser, S</td>
</tr>
<tr>
<td>Schafer, MS</td>
<td>Moser, SC</td>
<td>Moser, Susanne C.</td>
<td>Nerlich, B</td>
</tr>
<tr>
<td>Nerlich, B</td>
<td>Nerlich, B</td>
<td>Hart, P. Sol</td>
<td>Myers, T</td>
</tr>
<tr>
<td>Myers, TA</td>
<td>Schafer, MS</td>
<td>Lewandowsky, Stephan</td>
<td>Lewandowsky, S</td>
</tr>
<tr>
<td>Lewandowsky, S</td>
<td>Lewandowsky, S</td>
<td>Roser-Renouf, Connie</td>
<td>Roser-Renouf, C</td>
</tr>
</tbody>
</table>

Network layout

Several strategies have been developed for transforming networks into 2D visualizations (Leydesdorff, 2014; Petrovich, 2020). As with geographic maps, all strategies simplify and therefore distort certain aspects of the underlying data, meaning they should be undertaken intentionally and transparently to mitigate potential harm (Monmonier, 1991; Welles and Meirelles, 2015). In this study, we applied graph theory informed transformations, which use relationship strength to infer the distance between nodes (Leydesdorff and Rafols, 2011). Layout algorithms use physics calculations to position nodes optimally, by first distributing them randomly in space and then balancing the repulsion between them, the attraction caused by links, and the gravity of the center of the graph, until an equilibrium is reached (de Nooy et al., 2005; Fruchterman and Reingold, 1991). Because the resulting network maps have similar intuitive visual force to a geographic map, they are subject to being produced and accepted uncritically.
Different brokers highlighted by different disambiguation strategies. Here, nodes of high betweenness are extracted from the giant component produced by each disambiguation strategy applied to the same dataset. Node size indicates betweenness, or how many paths in the network pass through a single node. Larger nodes would be presumed to have brokering or gatekeeping functions.

Figure 17. Different brokers highlighted by different disambiguation strategies.
Both researchers and viewers can be misled by network layouts that suggest patterns where there are none (de Nooy et al., 2005). For example, the Force Atlas Layout allows longer edges between nodes than does the Fruchterman Reingold layout, which emphasizes cohesion (Leydesdorff and Rafols, 2011). Figure 18 illustrates how this changes the visual impression of the climate communication research network. Further complicating this is the possibility to mix and match layouts to achieve results that are different again from either layout method alone. Ultimately, it may be necessary to manually edit data to avoid misleading patterns such as criss-crossing links or overlapping nodes that could suggest incorrect inferences about network topology (Welles and Meirelles, 2015). However, manual edits may distort embedded visual conventions which are based on math, such as distance representing dissimilarity, and so again these should be undertaken cautiously (Stephens and Applen, 2016).

For the climate communication knowledge map, we selected a layout produced by the Force Atlas algorithm and performed a small amount of editing to space out overlapping nodes and make the community size more interpretable to the human eye. In this case, our decision was less about mitigating potential harm and more about increasing understanding for viewers of the knowledge map while portraying the communities as legible groups of individuals. However, Figure 18 makes it clear that some layouts will emphasize connectivity and cohesiveness, and others will emphasize distance, despite that they are views of the same set of nodes and relationships. This illustrates that there is no option to choose an objective view of a network dataset, so the onus is on the researcher to make layout choices intentionally, as these arguments can have consequences for individuals and communities depicted. It also shows that just like datasets, tools for visualizing data can make implicit arguments which must be considered carefully.
Different Layouts of the Same Network Emphasize Different Features

Fruchterman Reingold Layout
This circular layout summons to mind a globe of interconnected knowledge regions. Network paths between and among communities criss cross. The network appears busy, dense, and complicated.

Force Atlas Layout
This more dispersed layout emphasizes connections between distant knowledge regions.

Force Atlas followed by Fruchterman Reingold
Combining layout strategies can also affect the impression given by the network visualization.

Here, modifying the above Force Atlas Layout with Fruchterman Reingold provides better delineations between communities.

Figure 18. Different layouts of the same network emphasize different features.
Community detection

After the network layout is complete, it is customary to divide the nodes into communities using algorithms such as Louvain community detection, a modularity maximization algorithm that identifies communities by finding groups of nodes sharing frequent connections within their group, but as few as possible connections to other communities (Blondel et al., 2008). Even scientifically minded knowledge mappers tend to acknowledge that interpreting the results of a community detection algorithm is an iterative process, and as much an art as a science. Interpretation generally draws on non-network attributes (for example, researcher discipline) as well as network metrics like those in Table 1, to explicate the identified community structure. In the climate communication dataset, traditional strategies like summarizing purely by author keywords were minimally successful, as single occurrences of keywords were the norm (e.g., one primary community had 511 author-provided keywords describing 240 published works, but 388 of the keywords were used only once).

This illustrates the conundrum of categorization that is well-recognized in ethical visualization and data feminism: by placing nodes into groups, the knowledge map makes a strong argument that there is some inherent quality of those nodes that justifies their grouping, despite that the underlying data is not always so decisive. This is especially so when the network has been filtered to represent connections above a certain strength, such as authors that have collaborated at least twice, or papers that have been cited together at least ten times. This common practice eases the computational task of creating and analyzing the networks, but it also makes it easier to identify communities that seem much less interconnected than they actually are (or, conversely, give too much weight to connections which are strongly present based on the visualized logic, but which may be essentially meaningless in the real world). Figure 19 demonstrates how clear communities become at different levels of filtering, offering another
example of how seemingly technical choices made in knowledge network design make implicit arguments. Another way of saying this is that determinations of exactly what is signal and what is noise in a network dataset are subjective considerations.

In the climate communication knowledge map, we attempted to moderate the visual force of the communities by providing extensive annotations on their composition, and by resisting giving the three “core” communities particular names that were simply not justified by their heterogeneous compositions.

Ground truth or trust?

Each of the previous sections has emphasized the constructedness of knowledge maps, demonstrating that every step in the production of a knowledge map entails subjective and value-laden judgments which foreground or obscure elements of the depicted knowledge domain and therefore run the risk of perpetuating different types of harm. Issues of data selection, disambiguation, layout, and community detection processes combine to make it difficult to validate or ground truth a network map. But it’s worth asking, given the constructedness and subjectivity of a knowledge map, whether a ground truth would even be meaningful.

The traditional sense of a ground truth – going to a particular spot on a landscape and confirming that reality matches modeled values – is probably going to fail for knowledge maps. Though they should absolutely be intelligible to members of the depicted community, it is unlikely that every scholar would agree with the version of reality presented in the chart. Knowledge maps approximate a consensus about knowledge structure based on authorship and citation data, but this is knowledge on average. Individual experts may or may not agree, and the knowledge map may not be a good representation of an individual’s subjective experience of the knowledge domain, or even of the specific connections depicted based on their existing co-author relationships, since a network represents a diversity of connections as a single type of link. In the
absence of a ground truth, perhaps a more important question to ask is how a network visualization can become trustworthy.

While building the climate communication knowledge map, we learned that the only way to produce trustworthy maps is to have attention to ethical dimensions and potentials for harm at every step of the design process. This can be accomplished with vigilance for implicit arguments made by customary analysis choices and tools, with the inclusion of annotations and caveats in the visualization, and by remaining constantly aware that any purely data-driven view of a knowledge domain will be partial. The key utility of ethical visualization perspectives in the development of the climate communication knowledge map was to push back against our worries that we were somehow biasing our results in an inappropriate way by making these human-driven choices surrounding data curation and presentation. In the next section, we offer suggestions for how to apply these perspectives in future knowledge mapping projects.
Figure 19. Filtering the authorship network to identify a backbone structure. Nodes here have been included in the network only if they participated a certain number of times.
Strategies for ethical and effective visualization of knowledge networks

Ethical and effective visualizations of knowledge networks must inspire trust in two key groups: people depicted in the knowledge map, and people using the map to acquire knowledge or make decisions. We draw on our experience in the climate communication knowledge mapping project and on previous work on ethical visualization in the digital humanities to offer ethical visualization strategies for network data and knowledge maps specifically. This represents an important step in “downscaling” recommendations from ethical visualization and data feminism to demonstrate their application and utility in specific projects. We encourage readers to consult other literature on ethical visualization (especially Lima, 2011 and Gavrilova et al., 2019) for discussions of additional visual conventions specific to the design of network charts.

Our recommendations are intended to assist researchers in balancing tensions between quantitative and qualitative, and objective and subjective, aspects of knowledge mapping. We advocate a humanistic approach to visualization design, recognizing that working with this type of data successfully requires coupling quantitative fluency with the more humanities-oriented practice of contextualizing findings, and tolerance for and transparency around the trial-and-error approach necessary to creating a useful product (Conway, 2014; Dragga and Voss, 2001; Drucker, 2011; Hepworth and Church, 2018; Stephens and Applen, 2016). As the climate communication knowledge mapping project illustrates, a purely quantitative, purely objective depiction of a knowledge network is neither possible nor particularly useful.

Understand knowledge maps as both process and product

Knowledge maps have a dual purpose: they are a tool used in studying knowledge domains, and a visual artifact representing those domains. The first focuses primarily on creating
knowledge and insight for the immediate researchers involved and can be best understood as a process. The second focuses primarily on assisting others in gaining insight into the mapped domain, and can be best understood as a product. However, as the climate communication knowledge map makes clear, these two types of knowledge mapping are generally impossible to separate: knowledge mapping proceeds in an iterative and exploratory fashion, where impressions gained in experimenting with different analyses and layouts inform the final version of the map, and where the layout of the map informs a researcher’s conclusions. Franco Moretti described this as a “heterogeneity of problem and solution” in distant reading; we argue that the same applies to knowledge mapping (2007). In the case of the climate communication knowledge map, the desire to create a particular kind of product (a useful and trustworthy knowledge map to support collaboration and discovery in a particular knowledge community) influenced the process of data preparation and analysis, for example leading to the decision to manually disambiguate data, which in turn affected analytical results.

The intertwining of product and process does not guarantee that a good product will follow from a sound process (or that an apparently good product was generated with a sound process). For example, we often observe knowledge maps developed primarily to facilitate analysis being included in research reports. In these cases, researchers have generally extracted meaning from the visualization to support their interpretations. However, without adjustment, these visualizations often remain incomprehensible to those outside the research team. We suggest that ethical and effective knowledge mappers should remain aware of how process and product intertwine in a knowledge mapping project, and how this can both enhance and trouble the process of producing a knowledge map for use beyond the research team.
Translate and annotate knowledge maps

Anecdotally, we learned while developing and sharing the climate communication knowledge maps that despite their visual and rhetorical force, viewers are often unsure how to understand these charts. We also learned that, once viewers felt they understood what the nodes and connections and color scheme meant, they quickly formed and held onto inaccurate impressions about what the chart conveyed. While it is not possible to moderate the rhetorical force of a visualization entirely, it is possible to embed guidelines and caveats for interpretation that guide viewers towards the interpretations intended by the visualization designer. This does not preclude the viewer reaching their own conclusions; rather, it fulfills the promise of a knowledge map as a communication tool. Ethical and effective knowledge mappers should take the opportunity to translate and annotate a knowledge map, asking themselves which insights have the most rhetorical force, and which may need to be moderated with caveats. This is why the knowledge maps presented in this paper include textual information about their genesis and interpretation.

Account for implicit arguments made by network theory, tools, and data sources

A common practice in data feminism is to disclose the positionality of the researchers, so that viewers of the resulting data visualizations might understand how researchers’ perspectives and life experiences may influence their understandings of the phenomena portrayed. We encourage knowledge mappers to consider not just their own positionality, but the positionality of network theory, tools, and data sources when drawing conclusions from a knowledge mapping project.
First, it is necessary to consider the implicit arguments made by networks themselves. A network chart necessarily conveys a message of connection, especially since unconnected elements are generally omitted from analysis. Network thinking is fundamentally structuralist, meaning that it privileges relationships over attributes and affords the system a level of agency that it may or may not have (Conway, 2014; Gochenour, 2011; Moretti, 2007). A consequence of this structuralist lens is that disconnection is seen as undesirable, and distinctions between quality and quantity are often blurred (Gochenour, 2011). The focus on quantitatively (but possibly not qualitatively) strong connections (after all, there are many ways to become connected in a coauthor network that do not necessarily represent close collaboration) extends to the way networks are generally depicted, showing nodes connected only above a certain link strength threshold (as in Figure 19). The assumption that weak connections are just noise to be removed, and that strong connections are the defining structural feature of a network, means this type of analysis may miss cutting-edge or non-standard knowledge patterns.

Subsequently, it is important to disclose the tools used for analysis and, especially, for visualization. Because the visualization tools actively shape the conclusions of the analysis, it is important to be transparent about how this may have occurred even if the effects are not apparent to the research team (van Geenen and Wieringa, 2020). None of this threatens the utility of network analysis as a tool for understanding a system of related data, but it should serve as a reminder of network thinking’s assumptions, so they are not incorporated uncritically into a knowledge map. An ethical and effective knowledge mapper should be aware of inherent implications stemming from choices about the theory, tools, and data sources which feed into resulting visualizations.
Consider impacts on people depicted

Knowledge networks are often assumed to be exempt from privacy concerns because they are constructed from published works. It’s important to remember that a network (especially the co-author networks presented in this paper) is made up of individual people. Certain nodes may assume standout roles that wouldn’t be apparent in a list of search results or even in tabular data, and certain patterns of connection may occur that do not represent current relationships and collaborations. Because there is no objective way to characterize node roles or performance, or even which nodes truly “belong” in a network, caution is warranted in “calling out” specific people depicted, or associating merit with network position alone (Furner, 2014). It may sometimes be preferable to display anonymized data (for example by grouping nodes into communities) to guard against incorrect or harmful interpretations about individuals.

On the other hand, it’s precisely the transparency and associated lack of anonymity that can make knowledge network tools useful. Laura Kati Corlew and her team relied on this in building a network mapping and knowledge discovery tool for climate workers in the Pacific Islands (2015). The correct balance of privacy and publicity will need to be determined on a project-by-project basis. Asking questions about who benefits from the network depiction of participants can help navigate these tensions (Conway, 2014). In the case of the climate communication knowledge map, we felt that attention to data selection and disambiguation mitigated some concerns about privacy for network participants and so we labeled key nodes with names. Climate communicators are likely familiar with these scholars and can use them as landmarks to support orientation and sense-making while they interact with the knowledge map.

As knowledge maps proliferate, they may be used increasingly for evaluation and analysis, and so an ethical and effective knowledge mapper should consider the potential ramifications of such a map having a life of its own after publication, and the possible agendas
users might bring to interpretation of these visualizations, especially when choosing to use personally identifying data in a knowledge map.

Put your cards on the table

The final strategy for ethical and effective visualization of knowledge networks is inspired by data feminism’s maxim of showing one’s work (D’Ignazio and Klein, 2020). We encourage ethical and effective knowledge mappers to put their cards on the table alongside their produced visualizations. This means being completely transparent about what you did, why you did it, and how you did it, but also about what insights you identify or arguments you wish to make with your produced visualization. Work in ethical visualization and data feminism has shown real drawbacks to obscuring the work done to produce a data visualization, to attempting to let data speak for itself. Ethical and effective knowledge mappers must resist the temptation to keep analysis and interpretation behind the curtain, recognizing that doing so may hinder precisely the type of knowledge creation and discovery they are likely trying to support.

The first way to put your cards on the table is to make analysis decisions transparent, as we have done in this article. This may be done in scholarly publications, or in metadata and annotations accompanying published visualizations. Like disclosing positionalities, articulating the strategies used to create visualization products reveals implicit impressions the designer may not have been aware of, but which could be important to viewers. Sharing this information safeguards transparency by aiding other researchers in creating similar maps, should they wish to.

The second way to put your cards on the table is to tell the story you as the researcher see in the visualization. What insight were you seeking that led you to build the knowledge map? Did you find evidence for it, or against it? Narratives explicate network structure and concepts in an intuitive way, guiding viewers to reasonable scales of interpretation and guarding against out-of-context presentations of the knowledge network. They can also shed light on what the
Figure 20. A fully annotated, final version of the climate communication knowledge map. The key content is provided “above the fold,” with additional metadata about the analysis and the depicted knowledge communities included below to support construction of alternate interpretations of the knowledge map.
system diagram on its own might not reveal clearly, such as a possible function of or reason for absent links between authors or communities. There is a fine line to walk here, given that the point of visual communication is simplicity. Over-annotating a visualization might make it harder to engage with. We attempted to address this in our final knowledge map (Figure 20) by providing a below-the-fold presentation of narrative context for the network. Other network projects, especially interactive ones, may discover additional ways to support the juxtaposition of narrative and network.

Conclusion

We began this paper with the observation that scholars have long been captivated by the quest to develop high-tech tools for information management and knowledge synthesis. From the vantage point of the 21st century, we recognize that the success of these tools is not simply a matter of technological progress, but one that requires ethical thought. Just as a network mapping platform like Gephi provides the technical tools for working with big network data, an ethical visualization framework provides the ethical tools for reducing the harm and increasing the impact of knowledge maps – essentially, for making them deliver on their promise of augmenting our perceptual abilities when faced with large and complex information spaces. In this paper, we have drawn on lessons learned in the climate communication knowledge mapping project to offer strategies for ethical and effective visualizations of knowledge networks. This approach acknowledges the potential for harm that comes with such visualizations and works actively to mitigate it. Taking an ethical approach to knowledge mapping is vital because the choices made in such an analysis determine whose and which contributions are ultimately legible.

We have attempted to provide guidelines for knowledge mappers seeking to support users in synthesizing and selecting meaningful insights from the mapped domain. Our recommendations balance tensions between qualitative and quantitative and objective and
subjective aspects of knowledge mapping. They demonstrate the importance of critical practices in the development of knowledge maps, illustrate the intertwined nature of analysis and results in such projects, and emphasize the constructedness of the visualization. We show the only way to produce an effective knowledge map is to produce an ethical one, which requires attention to the ways trust and accountability can be produced at every step of analysis and production.

This framework for ethical visualization of knowledge networks contributes to early conversations about a feminist bibliometrics and demonstrates the direct relevance of digital humanities tools to work carried out across diverse other fields. Connecting bibliometrics literature with digital humanities discourse invites more qualitative and interpretive perspectives into bibliometric knowledge mapping, demonstrating that the data-centric and science-focused techniques frequently applied to knowledge network visualization may fail to produce a useful and impactful portrait of a knowledge domain without attending to these ethical concerns. A central purpose of this paper is to offer a clear example of the utility of a critical approach to knowledge mapping in a traditional knowledge mapping project.

The idea of separating wheat from chaff is a common trope in knowledge mapping. While knowledge mapping can absolutely facilitate discovery of relevant or applicable knowledge, assuming this is its key strength overlooks its real potential. Essentially, a system-level depiction may provoke a reassessment of what is wheat and what is chaff, and recognition that these designations are situation-dependent. As knowledge production increases and we continue to rely on quantitative and visual tools to help us navigate information spaces, it may be best to abandon the threshing trope and instead adopt a more kaleidoscopic model of knowledge mapping’s goals. Knowledge maps provide meaningful and multipurpose ways for individuals to explore a knowledge domain, and different individuals may need to turn the kaleidoscope in unique ways to find useful or compelling information and explanations which gel with, and usefully complement, their own experiences of a knowledge network.
Summary & Conclusion

This dissertation mapped the climate communication research landscape as represented by 2,995 publications about climate communication from Web of Science. Rather than contributing new climate communication tactics to a crowded field of contenders, this study takes a data-driven and visual approach to making existing strategies for climate communication more discoverable while searching out under-unexplored avenues for future climate communication. This offers a comprehensive, bird’s eye view of the structure of this knowledge domain, demonstrates how network models and topic models may be used in concert to explain that structure, and serves as a case study for the utility of a knowledge mapping approach to answering questions about opportunity and impact in a knowledge domain. This synoptic picture of climate communication knowledge contributes to the ongoing effort to get clarity and consensus on the theories and tools the field offers so they can be better developed, tested, and applied. In this summary and conclusion, I use the results of the analysis as a whole to answer the four questions posed in the introduction and make recommendations about potential obstacles and opportunities in climate communication suggested by this analysis.

Key Conclusions

I first wanted to understand, what is the structure of climate communication research? Chapter 1 revealed a dense web of connections among five loosely-demarcated knowledge communities in the bibliographic coupling network. Chapter 2 confirmed that this structure formed between 2010 and 2015, as available research nearly quadrupled in quantity, and has been little changed since. This dense and evenly distributed structure was confirmed by a topic model, which found nine topics of approximately equal prevalence spread throughout the
2,995 documents. Though this aspect of the knowledge map is not discussed in Chapter 3, the co-authorship network corroborated this finding of intermingled topics and knowledge communities with a high transitivity rate of 0.83 (Figure 20). This means that 83% of the time two of an author’s connections are also directly connected to each other, suggesting that collaboration patterns in this field are not siloed. Considered in these three different ways, the knowledge structure offers fuzzy delineation between the many different ideas about communicating climate science and climate change. Multiple theories and techniques weave together at many scales in this knowledge domain and paint a busy but unified picture of how climate communication is being considered and approached.

The high level of cohesion in this network structure means there were fewer apparent opportunities for combining and knitting knowledge together than I expected. In the bibliographic coupling network, the distance between Decision-making and Stakeholder Engagement and the network core containing the other four communities suggests one opportunity for new knowledge production could come from connecting work in this community with work from the four core communities. Similarly, in the co-author network from Chapter 3, most evidence of and opportunity for structural growth is apparent on the periphery of the network. Few nodes in the bibliographic coupling network have high betweenness, meaning that many approximately equivalent pathways connect regions of the knowledge domain. The nodes that do have high betweenness tend to also have high degree, indicating that the most productive linking between ideas has already occurred within the boundaries of this structure (with the possible exception of links between the satellite communities and the core).

Next, I asked how does the structure enable and constrain the development and application of climate communication knowledge? Given the widespread calls for unification, synthesis, systems thinking, and strategy in climate communication, I was very surprised to find multiple pictures of a knowledge domain that was already so cohesive by July 2020. Because of
the frequent discussion of fragmentation and the research-practice gap within climate communication, I did not expect to find such cohesion in this knowledge domain. That the cohesion is both surprising (considering these common challenges identified by climate communicators) and stark (the knowledge map in Chapters 1 and 2 is an unmistakable spaghetti ball even when pruned to a connection strength of 5) affords some insight into the challenges climate communication has been grappling with as a field. Lacking opportunities to connect across structural holes, climate communication doubles in on itself, working and reworking theories and methods and problems, sometimes without reference to previous attempts. In this way, structural cohesion can feel like a kind of fragmentation to members of this knowledge domain.

Mapping the climate communication research landscape this way allowed for exploration of the structural features of the knowledge domain, especially how different ideas about climate communication correlate, converse or contrast and the ways in which the knowledge structure augments or inhibits thinking and theorizing in this field. Though it was not my intention to test the conclusions of other scholars in this modeling exercise, it’s worth mentioning that my results corroborate previous reviews of this literature performed with other methods. In 2015, Lauren Cagle and Denise Tillery articulated five broad categories that track well with mine: “specific influences on behavior related to climate change; global and local aspects of perceptions of global warming; problems with public understanding; beliefs about and perceptions of science and technical experts; and media coverage of climate change.” In 2016, Anne Gammelgaard Ballantyne also found five main categories of literature: “public understanding of climate change, mass media, strategic communication, communication effects, and conceptual articles.” The fact that my analysis, carried out more than five years later, found similar categories as prior reviewers illustrates why it is time to take a structural approach to evaluating knowledge creation in this domain. My analysis also confirmed findings in a more recent landscaping review of
science communication, which identified grand challenges including a research field full of one-time participants and short-term studies, deeply rooted habits and structures, a lack of diversity in research topics, and a shortage of knowledge transfer between practice and research as well as between research and practice (Gerber et al., 2020). Some of this could be because knowledge structure developed reactively with reference to pressures in society at large, and may no longer reflect current needs of the field (Smith, 2020). The question becomes, what is keeping climate communication research from expanding to new frontiers?

The stagnation of the network structure likely limits the potential for new knowledge generation within the network core. Knowledge here may be refined, but from a structural network perspective, such knowledge is unlikely to significantly disrupt how climate communication is approached. In Chapter 2, I concluded that the key to successful climate communication in the future is probably not contained within the territory delimited by the current communities and topic combinations within the core of the knowledge domain. This doesn’t mean this knowledge is no longer useful, just that it is unlikely to hold the secret key to the massive and widespread climate change action the discipline still hopes to discover. The knowledge structure therefore constrains the development and application of climate communication knowledge by keeping attention focused on the bustling core of the network, in part thanks to the gravity exerted by citation practices in scholarly publishing. If this continues for too long, a knowledge community risks becoming an echo chamber. In other domains with structures that grew rapidly (as happened between 2010 and 2015 in the climate communication research network), an unwarranted sense of convergence and consensus reduced the potential for innovation (Lambiotte and Panzarasa, 2009).

This structural analysis indicates that efforts to connect core climate communication knowledge, resources, and scholars with research and practice in the satellite communities on the edges of the network map is most likely to offer new insight on the problem of climate
communication, and new strategies for increasing its impact. Expanding outwards from the core, for example to the “Decision-making and Stakeholder Engagement” community in the knowledge map from Chapters 1 and 2, or into the trailing tail of communities focused on visual communication and climate information provision for agriculture in the knowledge map from Chapter 3, could productively open up the structure of the field, untangling the currently observed spaghetti ball. The potential benefit is that cross-pollination of ideas, from a structural perspective, is a positive feedback loop where new knowledge generated leads to structural change, which by extension opens up more possibilities for knowledge generation that would have been difficult to identify previously.

Given identified structural constraints, I asked what opportunities can be identified for communicating about climate in the future? In Chapter 1, I highlighted the opportunity to bridge the divide between core knowledge communities in climate communication and the “Decision-making and Stakeholder Engagement” knowledge community, in order to explore ideas for new knowledge generation. This network and the coauthor network both indicate opportunities to connect traditional climate communication with work in co-production and climate services, so it’s worth saying just a bit about potential opportunities here.

Climate services and co-production are not often considered part of climate communication, though arguably their purpose is also to stimulate behavior change in response to climate information at individual, organizational and societal scales, and they rely on communication for success (Kruk et al., 2017). Co-production is a fundamentally participatory approach that has become increasingly common in the climate space in the past 10 years, designed to make knowledge usable by engaging stakeholders in the process of developing and distributing that knowledge (Bremer and Meisch, 2017). Climate services and decision support tools are high-tech data delivery and information provision platforms often tailored to specific use cases and aimed at governments, NGOs, and individual stakeholders (Larosa and Mysiak, 2019;
Vaughan and Dessai, 2014). Many decision support tools are co-produced. An understanding of communication techniques and common pitfalls in communicating about climate issues supports the processes that are necessary for successful co-production and climate service provision (Bartels et al., 2013). Not only can climate communication techniques support these efforts, but work in these areas offers an opportunity to test climate communication techniques in a wide array of use cases.

In *Chapter 1*, I suggested that multiple complementary approaches to climate communication are likely required in most projects. This seems unproblematically true: a full toolkit keeps climate communicators from approaching every communication engagement the same way, and gives flexibility in the case that a reliable tool behaves unpredictably in a particular communication project. However, in *Chapter 2*, I note that approaching climate communication as a tool-driven exercise promotes an instrumental and mechanistic conceptualization of the communication process which may hinder future development in the field. To identify further opportunities for future climate communication, it’s necessary to ask what types of climate communication are most visible in this network, and which are perhaps not visible at all. In *Chapter 2* I suggest that what is missing is a concept of “slower” climate communication built on relationships and care; I will explore this idea in detail in the recommendations below.

Before doing so, I want to reflect on my last question of *how useful is bibliometric network analysis as a knowledge mapping technique when applied for this purpose?* While this tool is commonly used for these types of analysis, very little reflective work exists detailing how knowledge maps are specifically constructed, despite the many claims that the process is objective and replicable (Callaway et al., 2020; Conway, 2014). *Chapter 3* is my attempt to pull back the curtain on this method and reveal that it is not as straightforward to apply as the literature on the subject makes it seem. When I first applied bibliometric network analysis and
knowledge mapping to the climate communication field, it seemed like the method could offer little insight. Author disambiguation made the co-authorship approach seem impossible, and the spaghetti ball charts revealed in each of the other knowledge maps were a far cry from the pretty archipelagos or lace doily patterns I had seen in the knowledge mapping literature. However, with caution and reflection, the method was able to produce insight about the climate communication knowledge domain. Arriving at this insight required fluency in the mapped knowledge domain to support making sense of the results from network analysis, as well as advanced proficiency with network techniques to ensure that structures and metrics were interpreted correctly despite their intuitive force and potential to mislead. In conclusion, while the technique was useful for my purposes, I would not recommend it to other individual scholars unless they had deep knowledge both in the domain they wanted to map and in network techniques (or could achieve this combination by forming an appropriate team).

Recommendations & Reflections

Overall, this analysis indicates that calls for unification, synthesis, systems thinking, integration, and strategy in the climate communication field might be misplaced, not because these ideas are bad, but because the network structure suggests they are already occurring. It’s worth asking why, aside from the sense of fragmentation sometimes reported by participants in this knowledge space, a systematic and strategic approach seems like such an important way forward.

Climate communication originally came from a hard science tradition, where a global perspective allowed for recognition of climate change in the first place. This synoptic way of thinking may have led climate communication to be conceptualized the same way: as a complex but ultimately decomposable phenomenon. This has led the field (and my analysis of it) to take a particularly mechanistic and instrumental approach to fostering understanding and action around
the world (Schneider and Walsh, 2019; Walsh, 2019). Long lists of things communicators ought to do abound. Dan Kahan pokes fun at this type of guidance: “Use vivid images because people engage information with their emotions, but beware of appealing to too much emotion, because people become numb and shut down when they are overwhelmed with alarming images!” (2013). However evidence-based and well-intentioned, advice like this is pretty paralyzing. Further synthesis does seem like a better option than continued confusion about which approach is just right. But what exactly is the imagined result of further synthesis? Is it to determine which and how many behavioral nudges add up to exactly the desired amount of change? The thing is, communication techniques like using vivid images and well-thought-out emotional appeals support communicators' abilities to communicate effectively, but they don’t fully describe those abilities.

Calls for systems thinking have been accompanied by widespread discussion of the research-practice gap in climate communication, and the imperative of evidence-based practice. Here again is an influence which may be rooted in a scientific approach to a non-scientific problem, perhaps following an overly linear or hierarchical idea of how professional practice should be guided by evidence (Langan et al., 2019; Lindenfeld et al., 2012). Calls for purely evidence-based practice delegitimize valid practitioner expertise (Armstrong and Krasny, 2020; Bansal et al., 2012; Biesta, 2007; Moser, 2016; Nevo and Slonim-Nevo, 2011; Nutley et al., 2007; Roux et al., 2006). In reality, indirect and conceptual application of research may be crucially important, and actually a better example of true systems thinking in climate communication practice. Practitioners who have both taken the time to get to know their audiences and collaborators and develop a good mental map of evidence-based communication strategies are ideally equipped to perform synthesis on the fly. These practitioners are likely also better able to navigate ethical issues that arise in communication projects (Finlay et al., 2021; Priest et al., 2018). Effective systems thinking in climate communication might not mean consulting and
accounting for a long list of potentially important elements before enacting a communication plan. Instead, it might be an ability contained within individuals and entities who communicate about climate, enabled by their relationships with their co-communicators.

Relationships have received increased attention in climate communication literature in the past few years. They are identified as potentially powerful (but slow) climate communication tools because relationships support changes in thoughts and behavior which don’t easily revert to their previous states. They also streamline knowledge exchange and creation because knowledge built in collaboration is by default knowledge that is already shared (Cook and Overpeck, 2019). In fact, this is exactly the idea behind modern usable science initiatives such as the National Science Foundation’s Synthesis Centers (Baron et al., 2017; Wyborn et al., 2018). Maybe real systems thinking, real synthesis, isn’t a characteristic of the knowledge itself, but of the method of production.

An instrumental worldview focused on overcoming communication barriers between segmented audiences may be mismatched for today’s climate communication needs (Finlay et al., 2021). Relationships shift the dialogue from confrontation to collaboration. As Coen puts it, “in the context of usable science, research is primarily a form of care. Care for data and its analysis, care for people and their relationships” (Coen, 2021: 51). But it isn’t possible (at least for most people who aren’t presidents or celebrities) to have a constitutive relationship with the general public. Communication becomes a form of care for communities, not of care for science or the natural world alone. It also becomes a method of knowledge creation, for building understanding of a problem at the same time as building strategies for addressing it (Carvalho et al., 2021). The purpose of the field shifts from helping climate scientists communicate specific scientific information, to helping us all have conversations about the issues at hand and the path we should travel through the anthropocene (Finlay et al., 2021; Lindenfeld et al., 2012; Moser, 2016; Walsh, 2019). As Biesta puts it in discussing evidence-based teaching practice inspired by health
communication, “being a student is not an illness, just as teaching is not a cure” (2007: 8). In the same way, climate communication isn’t a state with a beginning and an end, but a conversation that is going to go on for a long time. Like education, communication only works when everybody participates, when everybody is invested.

Is there a purpose for climate communication research at all, then, in this turn towards relationships? Of course there is. Every conversation needs talented facilitators, moderators, mediators, organizers and instigators. Effectiveness doesn’t make communication inauthentic. What has been made visible in these knowledge maps is still a profoundly useful toolkit. The only mistake we could make is in assuming that it is the toolkit alone that makes the builder.
Epilogue

*Reality does not allow us to control its parameters. There is no beginning or end to thinking, no straightforward path to scholarly relevance. It is as if, in our drilling down into the bedrock of knowledge, our drill bit strikes open air — revealing a cavern with a variety of wonders, but with no imperative concerning which direction we should head. Of course it is possible to know things: airplanes fly because they are competently designed; certain interpretations of Plato are better than others; we trust our physician’s interpretation more than our own. But these cases are proximate. The densely imbricated nature of existence means that expertise has limits - and that these limits cannot be defined beforehand. (Frodeman, 2010: xxxiv)*

My thinking has changed so much since I started this dissertation that it almost feels like I can’t remember really thinking a mapped-out decision tree of climate communication tactics was going to solve the loading dock problem for the Nevada State Climate Office. I know I started out believing it, because I remember imagining being able to field an inquiry about a communication opportunity for NSCO and essentially plug it into a big sorting machine that would identify the right approach for achieving maximum impact and issue some kind of verdict about the merit of the opportunity. I also remember shadowing Doug at communication and collaboration events with stakeholders of various sorts. I always felt it was as if everybody in the room was waiting for a climate communication magician to show up and wave a climate communication wand (if they were waiting on me, they were probably disappointed, because I still had no idea what I was doing). At those times, I really wished for some algorithmic guidance. But somewhere along the way as I tried to build such a tool, I had that experience Frodeman describes, of a drill bit striking open air, and it took me a long time to find my way forward. It turned out that two key elements of my plan were, in retrospect, particularly naive.
First, it was naive to hope that a bibliometric network analysis could produce an objective and easy to interpret knowledge map. Reading this network was like reading a poem that I just didn’t get. It took me ages to arrive at the interpretations of the knowledge networks presented in this dissertation. At first, I thought I was doing the analysis wrong. I tried different datasets, different software, different programming packages, and different cleaning and disambiguation approaches. Once I’d ruled out errors, I thought maybe I was making the wrong analytical choices (that’s partly how Chapter 3 came about). When I had to accept that the network I was looking at really was the picture of climate communication knowledge painted by this dataset, I spent a long time thinking it was essentially a negative result. The knowledge network didn’t behave in any of the ways I expected it to from my coursework in network analysis and my reading in bibliometrics. I think it’s actually a textbook example of what network scientists would describe as both structurally and statistically uninteresting (though thankfully I eventually found bibliometricians like Chaomei Chen who noted that real knowledge domains were often messier than was generally admitted). Nor did it depict any of the tensions in the field described by climate communicators, at least up until about 2019. There weren’t even separate communities for deficit model studies.

Second, it was naive to imagine that the loading dock problem was really the root cause of climate communication’s challenges. When the covid-19 pandemic began in 2020, I watched a global health communication train wreck occur in real time. It was not a great moment for successful application of evidence-based communication tactics in the face of clear risk. This went way beyond knowledge being left on a loading dock to be politely ignored. It was more like the boxes were being hurled back at the communicators. As my understanding of the network coalesced, and I focused on the importance of relationships for impactful climate communication, I realized that it was no wonder climate communicators were looking for an algorithmic and instrumental strategy for successful climate communication — they’d likely all been subject to
similar vitriol. But the verdict seemed clear: in March 2020 the world’s communicators had access to the best knowledge we’d ever had about how to communicate controversial issues in the face of public skepticism. It just didn’t work. It’s often thought that the psychological distance and as-yet invisible impacts of climate change is what really hamstrings engagement with this issue, because people just can’t keep it front of mind over other concerns. Covid-19 showed that imminence was probably not the missing variable in this equation.

The longer I’ve thought about the loading dock problem, the more I think it’s like a riddle. The secret isn’t to make the science fit like a puzzle piece into management workflows and priorities. The trick is to make the whole situation not seem like a puzzle at all. Relationships are the way to do this. The loading dock problem is real, but the identification of the key to surmounting it might not be. In talking to managers and stakeholders and decision-makers while trying to understand what shaped puzzle piece they might need, you’d probably have to build relationships to some degree with these people. What is then seen as a perfectly-fitting puzzle piece is co-created from the conversation between both sides (even if the scientist or climate communicator does the final work of packaging and shipping the data or information). The relationships and conversations become essential foundations for successful climate communication. When it was early enough for me to have taken this route in my PhD studies, I knew too little about climate and communication alike.

When acquainting myself with the digital humanities for the framing of Chapter 3, I loved the way Franco Moretti described these quantitatively-supported knowledge mapping projects as having “a heterogeneity of problem and solution” (Moretti, 2007). I think climate communication has just such a problem. For communication dilemmas, as in planning, to find the problem is to find the solution (Rittel and Webber, 1973). This analysis was designed to help climate communicators avoid wasting time and resources in reinventing the wheel, but maybe it’s the process of reinvention that makes for fruitful climate communication projects. I think in the
end, the most humble way forward is probably the most likely to work: talk to people. Don’t engage them, engage with them.
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Fegley BD and Torvik VI (2013) Has large-scale named-entity network analysis been resting on a flawed assumption? *PLOS ONE* 8(7): e70299. DOI: 10.1371/journal.pone.0070299.

Finlay SM, Raman S, Rasekoala E, et al. (2021) From the margins to the mainstream: Deconstructing science communication as a white, Western paradigm. *Journal of Science Communication* 20(01): C02. DOI: 10.22323/2.20010302.


Wehrmann C and Van Der Sanden M (2017) Universities as living labs for science communication. Journal of Science Communication 16(05): C03. DOI: 10.22323/2.16050303.


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Appendix A

Frequency Lists for Community Identification in the Bibliographic Coupling Network

“Frequency” is an occurrence tally of each lemmatized word within the community.

“Prevalence” is an approximate metric that is simply frequency divided by total articles in the community (multiplied by 100 to arrive at a percentage).

Note: Because it is possible for a keyword to occur multiple times in a single article (e.g. the word “change” in keywords “climate change” and “environmental changes”), this metric should be thought of as approximate and percentages may sum to more than 100%. 
# Risk Perception and Communication

| Total Articles in Community | 463 |
| Total Keywords Identified    | 1019 |
| Total Title Words Identified | 1500 |

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# Decision-making and Stakeholder Engagement

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Total Articles in Community 257
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Appendix B

Twenty Highest-Degree Papers in Each Knowledge Community in the Bibliographic Coupling Network

Degree here represents the overall weight of a paper’s connection to others (+1 every time it and another paper cite the same article in their bibliographies).

Note: Only first author names are displayed even in the case of a multi-authored paper.

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<tr>
<th>Risk Perception and Communication</th>
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<td>Pidgeon Nick, Public understanding of and attitudes to climate change: UK and international perspectives and policy, CLIMATE POLICY, 12, S85</td>
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<td>Perceptions and communication strategies for the many uncertainties relevant for climate policy</td>
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<td>Applying the Risk Information Seeking and Processing Model to Examine Support for Climate Change Mitigation Policy</td>
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<td>The role of mass media in communicating climate science: An empirical evidence</td>
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<td>The Role of Emotion in Global Warming Policy Support and Opposition</td>
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<td>Using Expert and Non-expert Models of Climate Change to Enhance Communication</td>
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