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Public Understanding of Science

Mapping Pathways to Public Understanding of Climate Science

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Mapping pathways to public understanding of climate science

Abstract

Climate communication is a thriving research area with participants from science, social science, and humanities. The field has seen explosive growth 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. We created the knowledge map by applying network analysis and data visualization techniques to 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 co-production and climate services. 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.

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Introduction

Climate communication is a dynamic field of study that has seen an explosion of growth in the past five years. As more scholars have taken up the challenge of communicating climate issues, the field has addressed an increasingly broad range of questions with theories and methods from many parent disciplines across science, social science, and humanities (Moser, 2016). But this

welcome trend poses a practical problem for researchers and practitioners wishing to keep up with current developments (Cagle and Tillery, 2015; Metcalfe, 2019; Moser, 2016). Climate communication studies are published in an array of outlets, and despite a recent penchant in science communication for synthesis and review, 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" (Peters, 2020, p. 371; Bennett et al., 2020; Corner and Clarke, 2017; Fischhoff, 2011; Jensen and Gerber, 2020; Moser, 2016; National Academies of Sciences, Engineering, and Medicine, 2017).

We answer the call for synoptic perspectives on different areas of science communication research by applying network analysis and data visualization techniques 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). They help onboard newcomers and facilitate navigation of the research by all (Chen et al., 2014; Nakamura et al., 2019; Trujillo and Long, 2018).

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The need for a synoptic description of climate communication research

If, as science communication scholar Brian Trench suggests, there is a Venn diagram of science, risk, and environmental communications (Trench, 2012), climate communication might sit in the very middle. 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 both 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. Climate communication research is not reliably located in either communication or climate journals, and only a few recent books provide an overview of the field (Cagle and Tillery, 2015; Comfort and Park, 2018; Corner and Clarke, 2017; Moser, 2016). Terms are used inconsistently across the literature, making jargon a potential barrier for synthesis and search, and case studies and segmentation analyses can be difficult to summarize and compare (Baram-Tsabari et al., 2020; Füchslin, 2019; Guenther and Joubert, 2017; Jensen and Gerber, 2020). Some research may lack theoretical integration or consistent referencing to previous work due to a low rate of repeat participation by scholars (Füchslin, 2019; Guenther and Joubert, 2017).

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Less fragmented fields have an easier time producing evidence-based guidelines for practitioners, but even if it were straightforward to synthesize the research on climate communication, it might not be clear who the audience should be (Siders, 2019). The practice end of climate communication is as fragmented as the academic one, with journalists, scientists, public relations officers, NGOs, think tanks, scientific societies, governments, extension agents, 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 on climate issues than any of the other science communication challenges 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 distilling it into a single strategy or an oversimplified tip sheet (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 what is known and how it is applied is key to supporting future science communication research that is relevant and effective in the face of many mounting challenges for science and society (Baram-Tsabari and Lewenstein, 2017; Gerber et al., 2020; Jensen and Gerber, 2020; Smith, 2020).

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Previous attempts to summarize climate communication research relied on traditional synthesis methods for systematic reviews (Armstrong and Krasny, 2020; Ballantyne, 2016; Cagle and Tillery, 2015; Johnson, 2012; Moser, 2016). The abundance of these reviews in recent years suggests that, while researchers and editors perceive a pressing need for them, they may not have had the hoped-for results. Science communicators in part express desire for these reviews out of hope that they will coordinate collective effort and provide clear guidance for practitioners. Techniques like knowledge mapping offer an alternative strategy that may prove more effective for this purpose.

Why network perspectives on knowledge domains are useful

Since modern citation practices were established, scholarship has in effect been maintaining continuous long-term data about the evolution of knowledge domains (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, keywords, and other variables. This reveals knowledge in the aggregate, in action, and in context, which may yield different insights than textbooks and traditional

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systematic reviews (Chen et al., 2014; Evans and Foster, 2011; McLevey and McIlroy-Young, 2017). These bibliometric studies capture emergent consensus from "an army of indexers, for every time an author makes a reference [they] are effectively indexing that work from [their] point of view" (Garfield, 1955, p. 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, p. 329). While bibliometric techniques have been applied to some aspects of climate (Belter and Seidel, 2013; Bjurström and Polk, 2011; Brown et al., 2016; Haunschild et al., 2016; Huo et al., 2021; Larosa and Mysiak, 2019; Lemos et al., 2019; Wang et al., 2018) and science communication (Gerber et al., 2020; Guenther and Joubert, 2017; Rauchfleisch and Schäfer, 2018; Suerdem et al., 2013), generally such studies have used bibliometrics for statistical analysis and evaluation without network analysis and visualization. But visualization especially is the crucial element that distinguishes the method from other styles of systematic review.

Visualization, or knowledge mapping, summarizes abstract and complex relational data about knowledge application in an intuitive and non-technical way, so it can be considered as an interrelated whole at a level appropriate to pre-existing expertise (Bastian et al., 2009; Chen et al., 2014; Fabrikant, 2000). A visualization affords a different experience than skimming lists or tables of text, allowing innate human visual acuity to draw out patterns and relationships in the data (Couclelis, 1998; Fabrikant et al., 2010; Valle, 2013). In network studies, visualization is achieved by the spatialization of network data, where nodes are positioned in relation to one another by balancing node repulsion with the gravity exerted by links (Chen, 2016). Rather than relying on an expert to select which information is important to highlight, the quantitative and

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data-driven approach of bibliometric knowledge mapping aggregates the many individual, ad hoc decisions of scholarship to afford a bird's eye view of the collective knowledge enterprise. 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 may still inform research (Ballantyne, 2016; Evans and Foster, 2011). An example of this familiar to science communicators would be the apparent persistence of the deficit model of science communication.

Recently, bibliometrician Fahad Asmi and colleagues applied bibliometric strategies to climate communication literature, using clustering and burst analysis to describe the shape of the field and present narrative descriptions of its communities, but the emphasis was on visualization for analysis purposes (using network tools to partition the literature into meaningful groupings) instead of on visualization for communication (to act as a tool usable by others in the field) (Asmi et al., 2019; Hepworth & Canon 2018). There is an opportunity to do more with knowledge mapping to support climate communication, specifically by asking what new insights network visualizations can generate about the climate communication system, and by producing 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, p. 371).

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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 inductive analysis is to identify patterns and relationships within a dataset of publication records and to synthesize resulting discoveries in a visual format. An exploratory bibliometric network analysis proceeds in four steps: (1) defining the data sample, (2) projecting that data into network form, (3) identifying structural features of the network, and (4) visualization (De Nooy et al., 2005). We used the 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 in visual form 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)?

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Data

Bibliometric data was taken from Web of Science on July 31, 2020, using the search query TS = (climat* NEAR chang* AND communicat*)[1]. This query was used by Susanne Moser in her 2016 systematic 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 in a separate systematic review that same year. Articles were removed if they dealt exclusively with scientific or technical aspects of climate, if they only mentioned the need to communicate a climate topic in passing (without providing specific suggestions or evidence for how to communicate it), or if they were primarily about climate impacts and adaptation strategies (vs. communication of those climate impacts and adaptation strategies). We included climate services and decision support literature wherever possible, so long as at least some of the emphasis was on communication, interface, co-design, or engagement (instead of only on technical development of the climate information). 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 used this same query for her 2016 paper, half again as much research on climate communication has been published.

[1] The TS query in Web of Science returns entries based on the presence of the search terms in title, abstract, author-provided keywords, or Web of Science-assigned keywords. The asterisks allow for variants of the word stem (e.g., climate change, climate changes, climatic change). The NEAR search term ensures that climat* and chang* appear within five words of one another.

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Network representations

We created an article-level bibliographic coupling network from the 2,995 Web of Science entries. The bibliographic coupling network places links between articles (the "nodes" in this network analysis) when they cite the same sources, on the assumption that articles citing many identical sources are applying knowledge in similar ways or for similar purposes. The more times two articles cite identical sources, the stronger their link becomes. When visualized, article clusters in a bibliographic coupling network self-organize into major thematic research topics spaced out based on the cognitive separation between the topics (Belter and Seidel, 2013; Biscaro and Giupponi, 2014; 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

We calculated different metrics to describe the structure of the network. To describe network structure as a whole, we calculated:

- Density, a measure of network cohesion. Density is the percentage of all possible connections actually present as connections in a 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

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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; a score above 0 indicates some identifiable community structure in the network (Newman, 2006). Generally 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, to describe reciprocity. Transitivity is the relative ratio of triangles (three nodes all connected to each other) to triples (three nodes with a V-shaped connection pattern). This is calculated by multiplying the number of triangles by three (to credit each participating node) and then dividing by the number of triples. Transitivity is a value between 0 and 1, and would be 1 if the network was fully connected; 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 centrality 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 nodes who would not be otherwise connected (or whose connecting pathways would otherwise be very long). In an article network, betweenness centrality may favor recent papers (Baggio et al., 2015).
- Degree centrality, 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

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(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 longer than average bibliographies.

We then 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). A community can be thought of as a coherent sub-group within a knowledge domain. The communities were labeled based on manual inspection of certain attributes: articles with the highest degree and/or betweenness in each community, and frequency counts for key terms in titles and abstracts (Belter and Seidel, 2013; Kajikawa et al., 2007; Nakamura et al., 2019). We used the Python packages NLTK (Bird et al., 2009) and spaCy (Honnibal et al., 2020) to parse and lemmatize keywords and title words, so different variations of the same term (ex: visual, visuals, visualization, visualisation) could be aggregated for semantic frequency counts.

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; Trujillo and Long, 2018). 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 in their bibliographies). In general, common thresholds for pruning an article network range from a

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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 wanting to include as many weak connections as possible (to capture potentially novel patterns in knowledge application and combination) and wanting to make the resulting visualizations clear and useful. A benefit of pruning this way is that signal is emphasized over noise; just one or a few citations in common between two papers could be more coincidence than indication of a pattern.

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). Distant clusters share few (if any) connections. In these visualizations, we looked for evidence of conformity to archetypal structures known to facilitate certain types of knowledge exchange:

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

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- Social cohesion, or a "spaghetti ball" pattern, in which a dense and messy network exhibits redundant connections between nodes and communities. This type of structure is thought to be particularly 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 and would suggest 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 for journal articles, but no single journal published more than five percent of the total climate communication research available. 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. Very few authors repeat participation in this network; about 30% of the authors published in this knowledge domain at least twice, six percent published five or more times, and one percent published ten or more times.

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From this data we produced the article bibliographic coupling network in Figure 1. Articles (nodes) in this network are linked when they use many identical sources to corroborate or contextualize their knowledge claims. Knowledge communities are recognizable as groups of articles that substantiate their search for new knowledge by referencing consistent bodies of scholarship. In this knowledge map, the structural positions of five climate communication knowledge communities are shown. 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 is evident in the visualization (Figure 1). This is a knowledge domain defined by social cohesion, not structural diversity.

[insert Figure 1]

Despite the somewhat low modularity, Louvain community detection identified five communities which comprise the climate communication knowledge domain: Risk Perception & Communication, Individual Perceptions of Climate Change, Climate Messages in the Media, Visual & Affective Communication, and Decision-making & Stakeholder Engagement. These

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five communities can be thought of as five distinct pathways to public understanding of climate science.

- Risk Perception & Communication contains a total of 463 articles primarily published since 2007. Dominant journals are *Risk Analysis* and *Risk Research*. "Risk" is the overwhelmingly salient keyword applied in this community (260 times), followed by "perception" (183), "public" (105), "environmental" (71), "adaptation" (50), "behavior" (45), "management" (43), and "mitigation" (28). Title words add additional emphasis on the word "energy" (32). This community is primarily interested in factors governing risk perception, and how that affects action on adaptation and mitigation. 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 risk perceptions.
- Individual Perceptions of Climate Change contains 375 articles primarily published since 2013, mostly in communication-focused journals. Dominant keywords are "public" (79 times), "political" (41), "perception" (36), "motivate(d)" (30), "framing" (29), "reasoning" (27), and "attitude" (26). Title words add "consensus" (23). This community is primarily interested in how identities and psychological factors govern perceptions of climate change. This pathway to public understanding of climate science involves understanding the knowledge people have about climate science and the psychological and cultural factors that influence their interpretation of climate information.
- Climate Messages in the Media contains 391 articles published since 2004, with a small decline beginning in 2018. They are mostly published in communication-focused journals. This group has the highest number of occurrences of the keyword

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"communication" (222 times). Other keywords frequently used are "medium" (215), "framing" (68), "discourse" (60), "journalism" (51), "news" (50), "coverage" (26), and "mass" (23). In title words, "medium" stands out again (163), as do "news" (58), "public" (58), "coverage" (51), "discourse" (49), "analysis" (45), "framing" (43), and "newspaper" (40). 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 and had steady publication since 2000. Dominant journals are *WIREs-Climate Change* and communication-focused outlets. After "communication" (166 times), by far the most frequently occurring keywords are "visual" or "visualization", which collectively appear 72 times and are also the most frequent title words. Beyond "communication" and "visualization", keywords and title words are used less repetitively in this community compared to the others: "environmental" (59), "engagement" (38), "risk" (33), "adaptation" (22), "medium" (26). This explains the knowledge community's position at the center of the map and suggests there is wide diversity in editorial selection. This community is primarily interested in engaging people with climate knowledge, without necessarily emphasizing science facts. This pathway to public understanding of climate science involves engaging people in facts and stories about climate, and emphasizes participatory processes, interactivity, and visual communication.

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- Decision-making & Stakeholder Engagement has 257 nodes and has also grown steadily since 2000. These papers are published primarily in climate and environment journals. "Adaptation" is the dominant keyword (130 times), followed by "risk" (101), "management" (96), "policy" (92), "decision" (69), "uncertainty" (61), "social" (65), "assessment" (51), "stakeholder" (50), "community" (41), "participatory" (40), "planning" (39), and "impact" (28). Title words indicate that, in addition to being adaptation-focused ("adaptation" occurs in 109 titles), this community is dominated by case studies (102 titles). 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 and creative information provision to support managers, policy makers, and citizens in understanding and acting on climate knowledge.

Because we were interested in novel patterns of knowledge application, we symbolized node sizes in Figure 1 based on betweenness centrality. Articles with high betweenness (the largest nodes) represent the shortest paths connecting disparate knowledge. They are the network weavers, pulling together elements of the knowledge domain which may not have been combined frequently before. Essentially, they are articles whose bibliographies contain diverse knowledge sources, suggesting that these studies leveraged knowledge from a unique cross-section of the knowledge domain. However, very few nodes had high betweenness centrality, indicating that this network is traversed by many approximately equivalent pathways, and that diverse knowledge sources are frequently combined in climate communication projects.

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Generally, nodes with pronounced bridging roles have high betweenness but relatively lower degree. In the climate communication knowledge map, most nodes of high betweenness also have high degree (these papers are starred in the list in Figure 1). Because high-degree nodes attain their status by having many connections, they inevitably play some amount of bridging role. However, the nodes that are not starred in Figure 1 are those playing a noticeable bridging role despite having relatively fewer (or weaker) connections than the starred nodes. In this network, nodes with high degree play primarily bonding roles, while nodes with high betweenness play primarily bridging ones (especially in the cases where nodes with high betweenness have relatively low degree). For example, the big grey node (#1 in Figure 1) has the largest betweenness centrality in the entire network, and the tenth-largest degree. This node draws on a diversity of sources that is unique to its knowledge application (resulting in its high betweenness), as well as connects to a large number of other papers (contributing to its degree). On the other hand, some papers were found to have high degree but proportionately lower betweenness, meaning they share references with lots of other papers but that the knowledge combination is not novel (though the results may be). These papers were mostly from two communities — Individual Perceptions of Climate Change and Climate Messages in the Media.

A total of 12,638 (about ⅔ of the total) edges connect nodes of the same community, with 6,575 (about ⅓ of the total) edges crossing communities (Figure 2). To check if network pruning affected this conclusion, we confirmed that approximately the same ratio was present in the unfiltered network.[2] Four of the five communities were affected approximately equivalently by the pruning, except for Decision-making & Stakeholder Engagement which shrank ~35% more

[2] If pruning to a connection strength of 5 had 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.

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than other communities in the unfiltered network[3]. This was due to a larger proportion of the community's papers being connected with a strength less than five. This community is less integrated and connected with the rest of the knowledge domain.

[insert Figure 2]

To better understand the linkages between the five knowledge communities, we considered the total connection strength between them, and the percentage of the total nodes from each community involved in the cross-community links (Figure 3). 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 the raw number of edges a community's nodes participate in with other communities (vs. the weighted sum of connections), Visual & Affective Communication participates in twice as many outside-community links (3,198) as inside-community ones (1,575) (Figure 3). By this same 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

[3] Before pruning, Decision-making & Stakeholder Engagement had 794 nodes and 21,178 links; in the filtered network, this was reduced to 257 nodes (about 32% of its original nodes, while other communities kept 60-70%) and 530 links (about 3% of its original links, while other communities kept 5-7%).

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(Figure 1): Visual & Affective Communication is at the center because it is so interconnected with other communities; Decision-making & Stakeholder Engagement is on the periphery because relatively fewer links connect it to other communities. Another way to say this is that Visual & Affective Communication frequently applies knowledge commonly used in other communities, while Decision-making & Stakeholder Engagement rarely applies knowledge commonly used in other communities.

[insert Figure 3]

6. Discussion

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

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A diverse toolbox is needed to support climate communication

If this knowledge map captures consensus from an army of indexers, it appears the only consensus is that climate communication strategy cannot be distilled to a few key techniques matched neatly to use cases. Application-focused climate communication research probably draws equally on keystone papers for theoretical grounding and on papers specific to use cases (such as case studies and audience segmentations) for strategic effectiveness, contributing to the dense web of connections observed between communities. The generally high rate of connection and low insularity (Figure 3) likely results from (and affirms) this important characteristic of climate communication: it happens in a diversity of contexts and for a range of goals in the real world, which necessarily requires a very diverse toolbox. It makes sense that scholars would reach across the knowledge domain to draw upon work that can guide climate communication efforts in particular spaces or contexts.

Perhaps this should not be surprising: recent science communication landscaping efforts have generally noted a pronounced lack of division and an emphasis on cross-discipline collaboration (Gerber et al., 2020; Trench and Bucchi, 2015). Network studies of adjacent climate-tinged social sciences have also found "spaghetti balls" of knowledge reminiscent of the one depicted in the climate communication knowledge maps (Wang et al., 2018). Previous work identifying messy networks as lacking integration and 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

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published in 2016 or later, 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 organize the climate communication toolbox. The maps themselves provide a visual index to different areas of knowledge, which can be leveraged in different situations to foster public understanding of climate science. A practitioner wishing to locate relevant research might look at the five knowledge communities and ask which best describes their communication context or goal. The position of that community in the knowledge network could suggest other pieces of knowledge to consider and 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. For example, communicators launching a podcast on climate issues may traditionally fall in Climate Messages in the Media, which deals with crafting and deploying messages to increase knowledge and awareness. However, these communicators could consider incorporating elements from other communication pathways, such as from Visual & Affective Communication (to engage people's emotional and affective processing in an interactive way) and Risk Perception & Communication (to anticipate and incorporate the ways people judge risk).

Organizing the climate communication toolbox empowers communication practitioners to survey, select, combine, and apply available evidence-based techniques. This shifts knowledge synthesis from being a transmission process to a dialogic one, based on the understanding that

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evidence may be applied with more fidelity when "pulled" as well as "pushed" to practice (Nutley et al., 2007). A transparent and organized climate communication toolbox could mitigate 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 knowledge application (Cagle and Tillery, 2015; Moser, 2016). Though this fragmentation is not corroborated by the observed network structure[4], the diverse toolbox it depicts may explain the felt sense of fragmentation. Attempts such as this knowledge mapping exercise, to orient scientists and communicators to the research landscape and facilitate use of the diverse climate communication toolbox, could support a shift from a sense of fragmentation to one of cohesion. Taken together, these interpretations call for increased attention not only to charting new pathways to public understanding of climate science, but to making sure the pathways already forged can be traveled by others.

Co-production and climate services offer an opportunity to build a bridge between climate communication research and application

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 that have been infrequently combined. Structural holes are generally 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

[4] A fragmented bibliographic coupling network would traditionally be one whose knowledge communities ground their work in entirely different traditions and rarely cite works in common across community boundaries.

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similar entities share many connections, causing the formation of the dense web of four knowledge communities at the center of the map (Figure 1). The high transitivity and low modularity observed in this network results from this central group of communities which, while remaining distinct, share information among themselves frequently. However, one community is primarily 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 distanced from the bustling core of the knowledge network. Many nodes in this community connect weakly if at all to nodes from the other four, resulting in its position on the periphery of the map. This community sends as many outward links as inward ones, scoring a 1 on the insularity index, but on average a smaller percentage of its nodes participate in these outward links (Figure 3). That means this community is connected to the broader network by a relatively smaller subset of papers that are applying knowledge differently from the pattern generally observed in this network. As a result, it is 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 applies communication strategies to encourage decision-making informed by scientific climate knowledge. It supports managers, policy makers, and citizens in understanding and acting on climate science. Papers in this community are often case studies emphasizing participation and stakeholder engagement. They focus on communicating about adaptation, impacts, and risk management. Many studies involve co-production, co-design,

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climate services, 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 these on-the-ground climate knowledge delivery systems could utilize specific 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 their authors may not be familiar with the diverse tools in the climate communication toolbox. Similarly, climate communication researchers from the other four knowledge communities may not be aware of this living laboratory for climate information provision.

Perhaps because these studies sometimes feature one-way delivery of climate knowledge, especially in the case of climate services and decision-support tools, they may have been dismissed by science communication research as uncomfortably close to the information deficit model. But the development of these tools and services often relies on participatory processes which produce not only the transfer of scientific information, but also engagement, tacit buy-in, and trust-building (each of which is a goal sought by much work in the other four knowledge communities). Additionally, the fundamentally dialogic process of co-production frequently practiced in this community has been overlooked as fertile ground for applying and testing climate communication strategies. As other scholars have recently noted, rejecting the deficit model out of hand may have accidentally thrown the baby out with the bathwater (Metcalfe, 2019). This has resulted in a situation where these on-the-ground climate communication activities may operate without awareness that there is a whole toolbox of climate communication research to draw on. That the network map reveals this structural hole, and that there is a

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plausible explanation for why it exists, suggests that work in co-production and climate services could be a particularly fruitful avenue to explore for integrating research and practice in climate communication.

Limitations & future work

Though knowledge mapping is a powerful exercise for gaining a data-driven, synoptic perspective on knowledge in action, the process of abstraction and quantification simplifies the scholarly enterprise in a way that does not reflect its true complexity. For example, all citations do not inform a paper equally, but this method affords equal weight to all citation links. Knowledge mapping is never meant as a substitute for deep reading in a field. Rather, it is a tool to guide productive and effective reading of vast and complex literatures. Knowledge mapping is also predicated on the data that generates the network. In this case, though Web of Science is quite comprehensive, it does not index social science and humanities research at the same rate as scientific research, especially because it primarily focuses on journals (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.

An additional limitation of this data-driven approach is that it is not possible to make judgments about the worthiness of certain citation patterns. The method simply offers a way to perceive in aggregate what citation patterns suggest about knowledge application, and the bibliographic coupling network type in particular captures patterns of knowledge application, not direct citation trends. Given this limitation, there is a risk inherent in knowledge mapping projects that they may tempt some viewers to correlate citation quantity or proportion with value-based

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insights. Further research to determine the likelihood or frequency of such value-based assumptions is an opportunity for further study, as part of broader measures of the efficacy of knowledge mapping.

A final limitation affects our conclusions about this knowledge domain specifically. We have interpreted the network structure as evidence that climate communicators are strategically selecting tools from the diverse toolbox. But it is plausible that the network structure suggests the opposite: a somewhat disorganized application of tools from scholars who lack the time to familiarize themselves with the whole toolbox. If the observed web of connections results from knowledge applied in an ad hoc manner, then the picture of climate communication is less rosy. Likely, both interpretations are true to some degree, but sorting out which connections support which interpretation is beyond the scope of this paper. Whether the network structure is really functional or obstructive overall merits more analysis and input from researchers and practitioners. In either case, a knowledge mapping exercise represents an important first step for taking the measure of how tools from the diverse toolbox are currently applied.

Conclusion

In this study we mapped the climate communication research domain and the five key pathways to public understanding it currently practices, presenting a visual overview which serves as a key to the disorganized climate communication toolbox (Ballantyne, 2016), or a subway map guiding communicators to different destinations (Smith, 2020). Our approach has relevance for scholars and practitioners in science communication more broadly, who are actively seeking out new techniques for knowledge synthesis, transmission, and translation among the many individuals

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and entities involved in communicating science. By providing a snapshot of climate communication knowledge in action, the knowledge 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. This approach shifts knowledge transmission within the climate communication discipline from a deficit model (which relies on experts conveying facts others are expected to act on) to a dialogic one (which recognizes that meaningful involvement and collaborative problem definition motivate action). Future work to make this knowledge map interactive, and to update it regularly, would go a long way to making climate communication research useful and usable for practitioners, supporting them in seeking relevant evidence that can be applied 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 constructing 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 useful knowledge, thereby increasing the impact of what we already know about how to communicate climate science.

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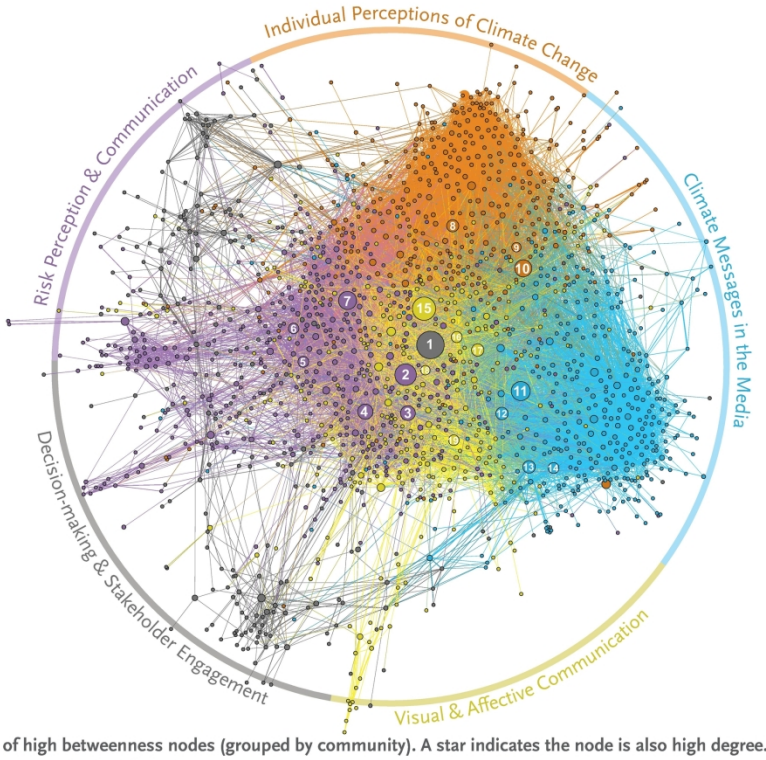
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List of high betweenness nodes (grouped by community). A star indicates the node is also high degree.

Decision-making & Stakeholder Engagement

★ 1. Cook & Overpeck 2019: Relationship-building between climate scientists and publics as an alternative to information transfer

Risk Perception & Communication

★ 2. Pidgeon 2012: Public understanding of and attitudes to climate change: UK and international perspectives and policy
★ 3. Hagen 2016: Public perception of climate change: Policy and communication: Discussion and conclusion
★ 4. Wolf & Moser 2011: Individual understandings perceptions and engagement with climate change: insights from in-depth studies across the world
5. Patt & Weber 2014: Perceptions and communication strategies for the many uncertainties relevant for climate policy
6. Hamilton-Webb et al. 2019: Living on the edge': using cognitive filters to appraise experience of environmental risk
★ 7. van der Linden 2015: The social-psychological determinants of climate change risk perceptions: Towards a comprehensive model

Individual Perceptions of Climate Change

★ 8. Roser-Renouf & Maibach 2018: Strategic communication research to illuminate and promote public engagement with climate change
9. Pearce et al. 2015: Communicating climate change: conduits content and consensus
★ 10. Bolsen & Shapiro 2018: The US news media, polarization on climate change, and pathways to effective communication

Climate Messages in the Media

★ 11. Moser 2010: Communicating climate change: history challenges process and future directions
★ 12. Arnold 2018: Climate change communication studies: Inquiries into beliefs, information and stories
13. Cox & Schwarze 2015: The media/communication strategies of environmental pressure groups and NGOs
★ 14. Doyle 2011: Mediating Climate Change

Visual & Affective Communication

★ 15. Moser 2016: Reflections on climate change communication research and practice in the second decade of the 21st century: what more is there to say?
★ 16. Shi et al. 2019: What framework promotes saliency of climate change issues on online public agenda: A quantitative study of online knowledge community quora
★ 17. Asmi et al. 2019: Social aspects of climate change communication in the 21st century: a bibliometric view
18. Salama & Aboukoura 2018: Role of emotions in climate change communication
19. Wang et al. 2018: Public engagement with climate imagery in a changing digital landscape

Figure 1. 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. In the online figure, nodes in each knowledge community are color coded. 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.

195x270mm (300 x 300 DPI)

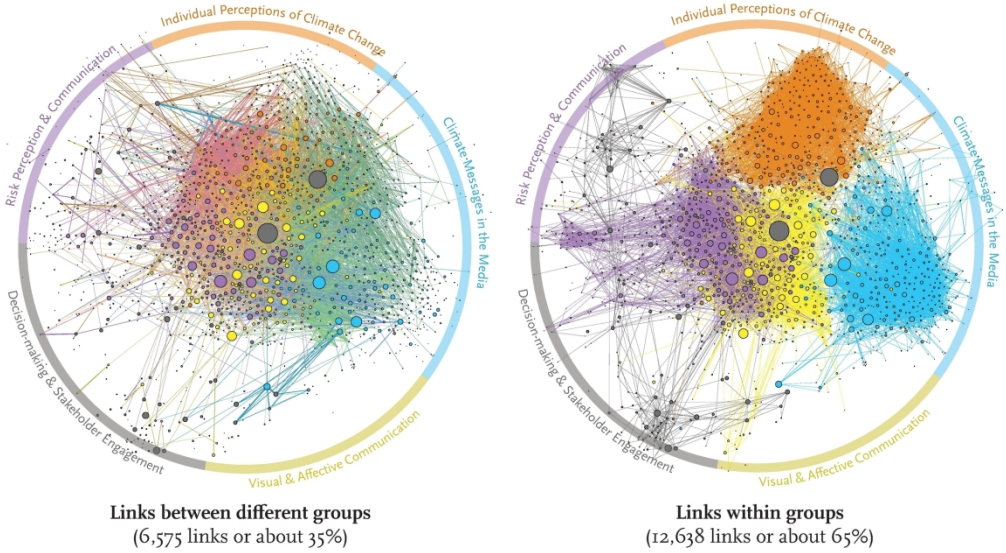
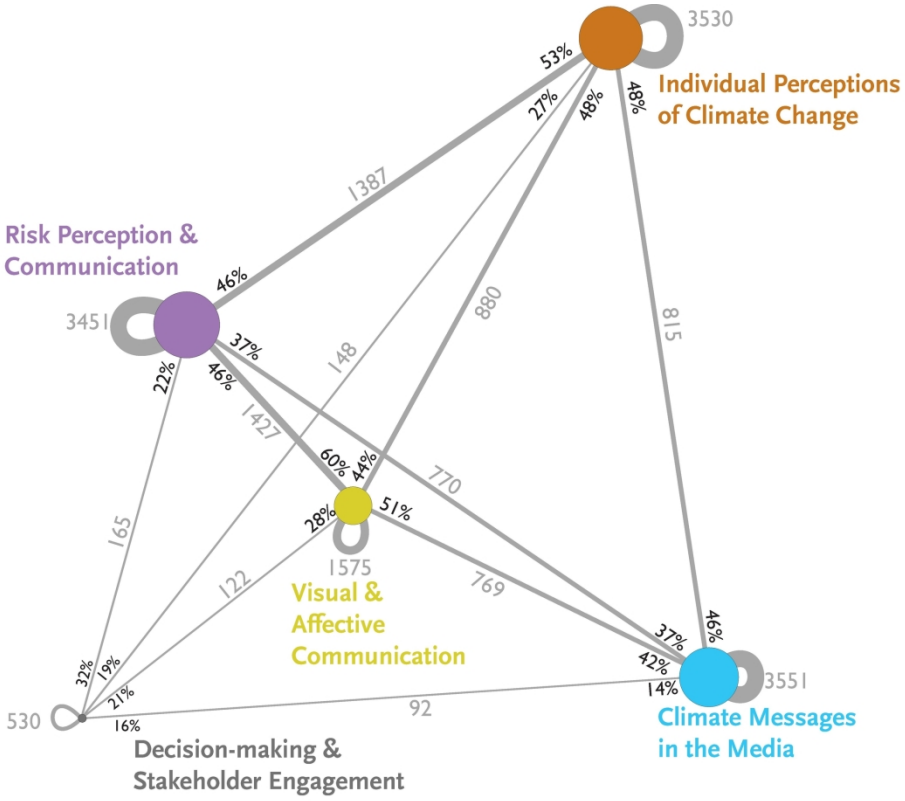


Figure 2. Contrasting view of connections linking papers in different groups with connections linking papers in the same group.

202x110mm (300 x 300 DPI)



How Insular is Each Knowledge Community?	In-Community Links	Out-Community Links	Insularity Index (ratio of in-community to out-community links)
Climate Messages in the Media	3551	2446	1.5
Individual Perceptions of Climate Change	3530	3230	1.1
Decision-making & Stakeholder Engagement	530	527	1
Risk Perception & Communication	3451	3749	0.9
Visual & Affective Communication	1575	3198	0.5

More Insular

Less Insular

Figure 3. 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. The table provides an additional way to characterize the rate of knowledge exchange between communities.

198x257mm (300 x 300 DPI)