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Social Network and Content Analysis of the North American Carbon Program as a Scientific Community of Practice

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Abstract

The North American Carbon Program (NACP) was formed to further the scientific understanding of sources, sinks, and stocks of carbon in Earth's environment. Carbon cycle science integrates multidisciplinary research, providing decision-support information for managing climate and carbon-related change across multiple sectors of society. This investigation uses the conceptual framework of communities of practice (CoP) to explore the role that the NACP has played in connecting researchers into a carbon cycle knowledge network, and in enabling them to conduct physical science that includes ideas from social science. A CoP describes the communities formed when people consistently engage in shared communication and activities towards a common passion or learning goal. We apply the CoP model by using keyword analysis of abstracts from scientific publications to analyze the research outputs of the NACP in terms of its knowledge domain. We also construct a co-authorship network from the publications of core NACP members, describe the structure and social pathways within the community. Results of the content analysis indicate that the NACP community of practice has substantially expanded its research on human and social impacts on the carbon cycle, contributing to a better understanding of how human and physical processes interact with one another. Results of the co-authorship social network analysis demonstrate that the NACP has formed a tightly connected community with many social pathways through which knowledge may flow, and that it has also expanded its network of institutions involved in carbon cycle research over the past seven years.

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1.0 INTRODUCTION

Climate change has emerged as a significant scientific, social and economic challenge to society (IPCC, 2014). Understanding how climate change may evolve over the coming decades requires significant investment in research about carbon and how it cycles, through both living and nonliving states, (Smil, 1996). Scientists frequently study these biogeochemical cycles in the context of subsystems such as the terrestrial biosphere (land-based living systems), oceanic systems (both organic and inorganic forms of carbon), and the atmosphere (Falkowski et al., 2000). These investigations may also include the specific role humans play in the carbon cycle, such as the impact of human-generated emissions or the consequences of climate change to agriculture and food systems (Berthelot et al., 2002; Bradbear and Friel, 2013; Dempewolf et al., 2014; Shindell et al., 2012). Carbon cycle science is relevant to a great many aspects of life as we know it: the condition of our environment, the quality of air we breathe, water resources, the food that we eat, and the energy we consume.

Engaging across the social and physical sciences to embrace all aspects of the carbon cycle is very challenging, particularly when the implications of the research are both political and economic. The North American Carbon Program (NACP) is one of the few programs on this topic to host collaborative activities cutting across all carbon cycle science disciplines, and promoting opportunities to foster interdisciplinary and intramural collaboration whose objective it is to do interdisciplinary research that results in information that can be directly relevant to critical social decision making (Michalak et al 2011). Central to the program's science agenda is the engagement of social, economic and policy-relevant research in order to improve how carbon cycle science is conducted to ensure policy-relevant findings. This paper uses communities of practice as a conceptual model for exploring how the NACP has fared in creating such a knowledge network, both in terms of measuring the connectivity among program participants, and in terms of incorporating measuring social, economic and policy-relevant topics into carbon cycle science research.

1.1 History of the NACP

The NACP was formally recognized by the United States in 2002 under the mantle of the nation's overall climate change management strategy (Wofsy and Harriss, 2002). The first implementation plan for the NACP put forward a research agenda that was centered on quantifying and understanding carbon sinks and sources in North America and surrounding oceans, and the integration of such information into socially, economically, and politically relevant decision-support systems (Sarmiento and Wofsy, 1999; Wofsy and Harriss, 2002). The *State of the Carbon Cycle Report* established that North America is a net source of CO_2 to the atmosphere, due to fossil-fuel emissions and that there are globally important carbon sinks whose future are highly uncertain (King et al., 2007). Understanding how humans both experience and influence the carbon cycle and climate change is critical to the interests of decision makers (Bernabo, 1995; Feldman and Ingram, 2009), such as those who confer support upon the member agencies of the NACP through funding and other resources.

In 2007, The U.S. North American Carbon Program (NACP) sponsored its first "all-scientist" meeting to review progress in understanding the dynamics of the carbon cycle of North America and adjacent oceans, and to chart a course for improved integration across scientific disciplines, scales, and Earth system boundaries (Birdsey et al., 2007). Following this meeting, a 2011 US Carbon Cycle Science Plan was published that set forth priorities for research in carbon cycle science for the coming decade

(Michalak et al., 2011). In addition to reaffirming the need for basic research and for continuing traditional research in carbon cycle science, the plan recommended substantial expansion in research on the efficacy and environmental consequences of carbon management policies, strategies, and technologies; prioritization of research on human elements of the carbon cycle; an increased exploration of the direct impact of rising greenhouse gas concentrations and carbon-management decisions on ecosystems, species, and natural resources; and research on how to express uncertainly in all aspects of the global carbon cycle as well as improved ways of conveying those uncertainties to policy and decision makers, as well as society at large. To achieve these objectives, the report authors recommended a substantial focus on conducting research that integrates human dimensions with the biologic, atmospheric, and oceanic sciences. Social processes that drive land use and fossil fuel emissions should be quantitatively integrated into land use/cover and emissions modeling to promote the integrated carbon, climate, and social modeling needed to provide science and analytical tools for climate action programs at various levels of government (Michalak et al., 2011).

The challenges facing the North American Carbon Program bring to light the larger issue as to how organizations, agencies, and nations at any level can cultivate the development of inter-organizational and interdisciplinary networks targeted towards creation of specific kinds of knowledge resources. To that effect, this paper seeks to apply a systemic approach for assessing the knowledge creation that takes place within a research program such as the NACP. How might we compare the professed knowledge goals of the NACP, or similar programs, to the actual knowledge created by participants? We also consider how to describe the state of collaborations between participants within such a community. How do collaborations amongst core participants grow and change over time? Are there changes in researchers' tendencies to collaborate across institutional boundaries over the same period of time? These are the questions we seek to answer in analyzing the NACP as a community of practice.

2.0 THEORY & RATIONALE

A *community of practice* is defined as "a group of people who share a common set of problems, or a passion about a topic, and who deepen their knowledge and expertise in this area by interacting on an ongoing basis". Wenger et al (2002) describe three structural elements to the CoP model: domain, community, and practice. Domain refers to the knowledge concerns and issues around which the CoP is structured. A well-defined knowledge domain translates to a strong sense of purpose, guiding the activities of members. It also implies a shared competence and commitment to the subject matter. Domain manifests as the specific knowledge the community develops, shares, and maintains. The community element references the social environment itself: the people and relationships through which learning, knowledge transfer, and knowledge creation takes place. Practice concerns all of their rituals, systems of meaning, and channels of communication.

The CoP model provides a theoretical foundation upon which to base discussion and analysis of the scientific community and its research. Structural elements of the model aid us in communicating fundamental assumptions as well as limitations of the study (Wenger et al., 2002). Additionally, it aids us in understanding and expressing the relationships and distinctions between a community, individual members, and separate but participatory institutions that provide support to scientists. Other examples of the CoP model being employed to study knowledge networks via shared resources and sustained interaction, including an ethnographic study of climate change adaptation projects at the science-policy interface (Iyalomhe F et al., 2013).

2.1 Community of the NACP

There is no a single form of social structure which qualifies as a community of practice, and membership is not by virtue of traditional organizational or departmental boundaries. The size of the community could be less than ten, or it could number into the hundreds. It might be community of individuals who all live or work in close proximity to one another, or it could be distributed across a wide range of geographical locations and organizational boundaries. The CoP model does, however, predict an approximate distribution of member participation which corresponds to three broad levels of investment within the community: 1) a small group of core members who both attend meetings regularly and whom also oversee functional tasks, 2) active members who regularly attend meetings, and 3) peripheral members who only occasionally participate in the community (Wenger et al., 2002). As part of conceptualizing the NACP as a community of practice, we will consider if the distribution of participation frequency in meetings shows any agreement to the distribution suggested by the model. We will describe and analyze the community in terms of relationships between core participants using social network analysis methods. As the NACP also seeks to increase collaboration between different institutions studying the carbon cycle, we will furthermore look at how the relationships between individuals translate to connections between the institutions they represent.

2.2 Knowledge Domain of the NACP

A domain is "a statement of what knowledge the community will steward" and "a commitment to take responsibility for an area of expertise" (Wenger et al., 2002. We have noted that the knowledge domain of the NACP is codified within the U.S. Carbon Cycle Science Plan (Michalak et al., 2011), the Science Implementation Strategy for the North American Carbon Program of 2005 (Denning, 2005), and similar supporting documents. The domain of the North American Carbon Program is to study the sources and sinks of carbon with the expectation that resulting knowledge should ultimately be accessible and salient to stakeholders at a variety of levels. Although scientific research does not have a simple cause-and-effect relationship with improved societal outcomes, some research has led to reduced exposure to extreme events, improved forest management, and effective policies to ensure agricultural sustainability (Rosenzweig et al., 2014). Rather, science is one among many complex factors that influence improved societal outcomes (Pielke Jr et al., 2010). It is inherent to the domain that natural sciences be integrated with the study of human processes.

However, the integration of social and human aspects in to carbon science is challenged by the need for translation and cooperation between different kinds of stakeholders. Researchers tend to interact more closely with other researchers in their own fields, which can frustrate interdisciplinary cooperation amongst those who study natural sciences, social sciences, and economics (Feldman and Ingram, 2009). This is what is called for according to the NACP strategic plan, but are different disciplines truly integrated into the knowledge created by the NACP? The content analysis section of our research methods will compare the domain of the NACP against the actual knowledge produced in practice, in order that we may evaluate if the human processes are truly represented as necessary to fulfill the program's goals.

2.3 Practice of the NACP

A CoP is best characterized by consistent engagement in a domain-driven practice over time. Shared practice refers not only to the actions and channels of communication between members, but also to the actual codified knowledge that is created as a result of the interactions between members. For this reason, the existence of interpersonal relationships is a key feature—research does not simply happen to co-occur when people are physically present at the same meetings. Interactions occur through and in the course of shared practices over time and space.

If the NACP is truly a community, then members should be interacting with one another and these interactions should manifest as knowledge outputs. We should be able to observe something about the state of the community, as well as its evolution, by describing these relationships. Knowledge products of relationships between scientists typically occur in the form of published research (Wenger et al., 2002) and coauthored projects. NACP members also contribute to knowledge outputs the form of official reports (King et al., 2007; Michalak et al., 2011).

The continued growth and development of a community rests on the ability to gauge its effectiveness in cultivating the knowledge domain by which it is bound (Wenger et al., 2002). It would be therefore of interest to the NACP to have a method to assess the community's progress of integrating carbon cycle science with human processes to provide support for decision making. Peer-reviewed publications and funded projects provide a consistent and accessible form of knowledge output. Here we will use content analysis and social network analysis to describe the knowledge outputs and member-to-member relationships, respectively. To that effect, a keyword analysis is performed on the abstracts of NACP outputs in order to derive the topics of research being produced so that it can be compared to the knowledge goals of the program. Co-authorship relationships are also derived from the bibliographic data of articles and of projects as part of our social network analysis. We will demonstrate the value of these tools for helping a community of practice such as the NACP to continually assess and re-orient itself towards its knowledge creation goals.

3.0 DATA

We used two datasets to explore the degree to which the NACP is a community of practice that has fostered the goals to expand the program's disciplinary focus, as set out in the 2011 NACP plan: the NACP project database and a bibliographic dataset from the Web of Science. These are described below.

3.1 NACP Project Database

We used NACP's own author database (found at www.nacarbon.org) to identify 1070 individuals who are engaged in 408 scientific projects registered with the NACP, including author, title, abstract and keywords and used these to analyze the connectivity between NACP members. We narrow down to 1007 members, including only members who have worked with at least one other person in a project. Scientists and projects are included in the database if a project is funded through extramural awards (grants, cooperative agreements, contracts, and interagency transfers) and designated as part of the NACP at the time of selection and award, or are designated as part of the NACP subsequent to the award being made. These projects address the goals and objectives of the NACP and contribute relevant research products within the timeframe of the program. Core projects also include standing agency activities, including those that may have another primary mission but agency program leads commit to participate in NACP or to provide specific measurements, data sets, or other products. Affiliated projects are those that are identified after selection or after completion by agency program managers because they are investigations, research projects, or operational programs or projects that are relevant or provide specialized data sets or services important to the NACP community. We used the project database to identify connectivity between NACP scientists that participated on projects together, and in determining the topics represented by their studies used the abstracts provided in the NACP database.

3.2 Bibliographic Information from the Web of Science

Based on meeting registration records exported from the NACP's online database, we found that 808 unique participants had attended the four NACP meetings between 2007 and 2013. Forty of these (approximately 5%) attended all four meetings, 79 people attended three meetings (10%), 184 people (23%) participated in two meetings, and 505 people (63% of participants) attended one meeting. To limit the bibliographic analysis to a manageable sample, we used the 15% (113 individuals) who attended between three and four of the NACP meetings in the past six years, obtaining the family name, first initial, and organizational affiliation from NACP records. Bibliographic data and abstracts for articles were collected by searching the Multidisciplinary ISI Web of Science (accessed between 12-06-2013 and 01-03-2014). We located papers written by all individuals, resulting in a dataset of 2,447 peer-reviewed articles published in 511 journals between 2007 and 2013. Both the registration records of individuals taken from the www.nacarbon.org website and the bibliographic article data were imported into our project database and linked in a relational schema. Additional preprocessing included the standardization of organizational affiliation data in the registration records.

The network analysis portion of our research required several additional stages of preprocessing of the article data. For reasons further discussed in the appropriate section of our methods, we first reduced the dataset to only include those articles that had been published by greater than one NACP core member from our sample. This left us with 363 articles representing the work of 99 persons. For an article to be included in our sample, each article in the network must connect one member of our NACP sample to another through inclusion of two names in the author list. Connections to people outside our sample were not represented. Next, we programmatically restructured the data so that an export of all records relating people to articles would be converted into a table representing all possible combinations of people connected to other people, where they had authored the same document.

4.0 METHODS

4.1 Content Analysis of Publications and Projects

Scientometric mapping and analysis using bibliographic data is a well-established methodology, for which a variety of approaches, techniques, and automated tools have been developed (Cobo et al., 2011). Existing research has demonstrated that analysis of abstracts and titles in bibliographic data can yield insight into the knowledge domains represented within the dataset (Chen, 2006). Content analysis may be approached either inductively, in a purely exploratory context, or deductively when seeking to test known ideas or compare changes in content over time (Elo and Kyngäs, 2008). Our keyword analysis was conducted on both the NACP database and the bibliographic data by importing the author, title and abstract information from both articles and projects into a text analysis software. Because we desired to compare the known and published knowledge goals of the program to research outputs, we assembled a dictionary of terms and phrases (Table 1) that reference different aspects of human processes and experiences relevant to integration with carbon cycle science. The initial source of keywords were terms and ideas used in Michalak et al (2011), and these were then evaluated in the context of abstract texts to confirm their appropriateness for reporting on in a keyword analysis. The top thirty journals for all articles (2,447) versus articles returning at least one keyword from the human processes categories (1,397) are summarized in Table 2.

Some words, such as "biofuel", are very explicit in their meaning and relevance. Other words, such as "policy" or "decision", are inherently associated in the English language with human agency or perspective. We have little reason to be concerned for false positives because we do not speak of trees "deciding" things or clouds developing a "policy". However, these words can still be paired with other words to create more explicit meaning, such as with "energy policy". On the other hand, "energy" alone would risk confusion with any number of scientific processes described in our abstracts that have nothing to do with humans. Therefore, we could not include a word such as "energy" without further qualification in order to ensure our results are meaningful.

The categories are neither mutually exclusive nor collectively exhaustive. Some keywords would have caused an article to fall into more than one category. For example, the text "energy policy" will flag an abstract into the general category of “Social & Decision Making” category due to the word policy, as well as the more specific Energy category. This was deliberate; it was determined our analysis would be more informative if we did not enforce a rule of mutual exclusivity.

4.2 Social Network Analysis of Co-authorship Ties

We conducted a network analysis on both the NACP database and the bibliographic data, and present network graphs resulting from the analysis. Network analysis is a research approach that prioritizes relationships between social units as opposed to focusing on attributes of the individual units themselves (Wasserman and Faust, 1994).Here we report on co-authorship networks that describe relationships between people rather than ideas. A document "is co-authored if it has more than one author. It is institutionally co-authored if it has more than one author address, suggesting that the authors come from various institutions, departments, or other kinds of units" (Melin and Persson, 1996).

Many studies have used the relationships between authors of a document to study broad domains such as physics (Newman, 2001a) and mathematics (Barabási et al., 2002). More recently, studies have also employed narrower sampling approaches, such as only including data from a specific journal (Martin et al., 2013) or based on attendance records of participation for the active members of a community of business (Morlacchi et al., 2008). Here we transform both our datasets into co-authorship network to represent interpersonal relationships present in the NACP. People are generally expected to communicate and interact with one another in order to publish a document or conduct a project together (Newman, 2001a).

We took bibliographic data from the Web of Science was converted into network format by producing all possible pairs of two authors for each article. The number of network ties produced by each article may be expressed in terms of combinations as $C(n,r)$, where $r = 2$ and n is the number of authors for a given article. We then created a binary code for each row of network data produced by this method to identify whether or not the connection was between two authors of the same institution. A second co-authorship network was also created from this data, but one in which we represented authors' *institutions* as the nodes, and in which connections within the same institutions were ignored as self-loops.

We invoked a similar strategy for the data extracted from the NACP project database. Data here was represented as a relationship between a project and one or more people. We used the same method to convert this information to all possible connections between pairs of researchers who were said to have participated on a given project. Cross-institutional coding was not performed on the project dataset.

Networks can be analyzed to look for information about the network as a whole, or to look for individuals of interest, such as which person is most central or most connected in a network. We tended to evaluate our graphs for information about average behavior of nodes as a whole, or at the network level of analysis. For example, modularity is the fraction of the connections within given groups minus the expected such fraction if connections were distributed at random (Newman, 2006). The modularity score given to the networks can be interpreted as describing how well a network, in our case the NACP, can be seen as a collection of sub-networks, or is a score of how well organized the network is. Since the modularity score measures the quality of the partitioning of the graph into smaller communities, the fact that the networks have close to similar scores means that they share a similar internal community structure.

The average clustering coefficient is a measure of how connected a neighborhood of nodes are. For a particular node (scientist), a neighborhood is all nodes connected to this particular node. If all the nodes in the neighborhood of a scientist-node are connected to other scientist-nodes of that neighborhood, then the clustering coefficient of that neighborhood will be 1; if none of the other nodes in the neighborhood are connected to each other then the clustering coefficient will be zero (Latapy et al., 2008). In other words, the clustering coefficient of a node that has at least one other node connected to it, is the probability that any two randomly chosen neighbors are connected. This probability is calculated by dividing the number of triangles containing our particular scientist by the number of possible connections between his neighbors (31). The average clustering coefficient is the average of these scores over all the neighborhoods.

In order to measure the connectedness of the participants of the NACP, we take our two datasets, the NACP project database and journal articles written by the members of the NACP, and use the modularity framework to understand networks within the program. If a community is connected by multiple co-authorships, then the community is interpreted to have multiple levels of communication, interaction and scientific engagement. If a community has networks that are isolated from one another and are sparse, then the community is assumed to be less engaged and to have less collaboration.

One of the properties we look for in the network of NACP core co-authors is the existence of a giant component. Components refer to groups of nodes, which are highly inter-connected to each other. Where few connections exist, a network will seem to be a scattered collection of isolated groups of scientists.

This corresponds to a lack of social pathways through which ideas can flow. But given enough connections, isolated groups may converge into a single mass, which encompasses the majority of nodes, and in which everyone is potentially connected to everyone else by some path (Newman, 2001b).

5. RESULTS

Table 3 shows the three levels of involvement and their distributions, as proposed by the CoP model, along with the summary distribution of meeting attendance frequencies into three corresponding classes. The nearly two-thirds of the 808 individuals who only attended one meeting between 2007 and 2013 are compared to the peripheral component of the CoP model. The almost 23% of individuals who attended half the meetings are compared to the active component. The nearly 15% who attended the majority or all meetings are compared to the primary component of a community of practice. This distribution of members between the core members, active members, and peripheral members reflects the theory of a Community of Practice.

We identified 215 institutions, organizations, and agencies across the 808 participants. Although many of the institutions did not account for more than a single participant, 31% of the institutions could account for 74% of the people. Among the subset of 113 core members, we counted 79 institutions, 25% of which could account for 58% of the people in the subset.

5.1 Results of Content Analysis

Of the 2,447 articles written by at least one NACP core member from 2007 to 2013, 57% or 1,397 contained at least one human-related carbon cycle science keyword. Approximately 63% (228) of the 363 articles co-authored by at least two NACP core members contained at least one keyword. We found a general agreement in the human-related carbon cycle science issues discussed between 2007 and 2013 in the research written by at least one NACP core member and the research co-authored by at least two NACP core members. Overall, topics on Society & Decision Making, Land & Water Use, and Human Impacts were more prevalent than those topics dealing with human-related issues pertaining to Energy, Strategies and Economy (Figure 1a, Figure 1b).

The same prevalence was found in the analysis of the project database. Of the 408 total project abstracts analyzed for human-related carbon cycle science keywords, 66% or 268 projects contained at least one keyword. Keywords associated with Society and Decision Making were found in 60% of the projects, those related to Land & Water Use in 46% of projects, and those associated with Human Impacts in 56% of the projects. Contained less in the projects were human-related carbon cycle science keywords associated with Energy (24%), Strategies (23%), and Economy (10%).

An overall increase in engagement with human-related carbon cycle science issues is noted for both NACP core article samples. Figure 2 also shows that, after 2010, those articles co-authored by at least two NACP core members referenced more human-related science topics than those articles written by at least one NACP core member. This trend peaks in 2011 at 73% and may be explained by the release of the 2011 U.S. Carbon Cycle Science Plan (14). The plan provides long-term direction for guiding carbon cycle research based on three overarching questions, which include the effects of humans on carbon cycling and the consequences of carbon management decisions.

Since the project database analysis does not provide information on the evolution through time because there are no dates associated with projects in the database, we compare the percentage projects containing at least one keyword (66%) to the percentage of total articles from the bibliographic database from 2007 to 2013 containing at least one keyword for both article samples for each of the human-related carbon cycle science categories (Figure 3). The NACP projects show a higher focus on Society & Decision Making (60%), followed by Human Impacts (56%) and Land & Water Use (46%). Articles co-authored by at least two NACP members focus more on Human Impacts (58%), Land & Water Use (56%), followed by Society and Decision Making (48%). Articles written by at least one NACP core member show a greater tendency for containing words related to Society & Decision Making (53%), Land & Water Use (51%) and Human Impacts (44%).

Overall, there was a 29% increase in the bibliographic journal articles referencing a human-related carbon cycle science keyword for articles co-authored by more than two NACP core members from 2007 to 2013 Since these articles were from physical science and interdisciplinary journals only, the 29% increase in publications considering social and human aspects of social science is quite large, particularly considering the short period of time and the fact that the group of researchers did not change. *Our results show that the individuals who consistently participate in the NACP meetings are integrating, either intentionally or not, social and human aspects of the carbon cycle science into their work, and have been able to publish articles that consider these elements in the physical science and interdisciplinary journals*. The knowledge domain of the NACP has grown over the past seven years to include social and human aspects of the carbon cycle.

5.2 Results for the Social Network Analysis

Table 4 reports annual article statistics for the average number of core NACP authors per article, as well as the average number of institutions and nations they represented. Figure 4 charts the same, showing brief spikes of collaborative activity in 2010 and 2012. However, these spikes of activity are not maintained over time and so the overall increase in NACP core collaborations per article for both individuals and institutions is more moderate. Table 4 also reports the size of the article network in terms of co-authorship ties and also quantifies the number of these that constitute cross-institutional co-authorships, broken down annually. The ratio of cross-institutional ties to all ties is also represented, showing an increase from 67% in 2007 to an overall average of 89% by 2013.

Figure 5 shows a graph visualizing the co-authorship network for the NACP project database that displays 1007 people with 16518 connections and 15716 unique edges. The figure was created using the Fruchterman-Reingold layout in Gephi. The algorithm repels the nodes from each other and uses the connections between nodes to pull them towards one another. The result is a network graph where one can visually see well-connected groups and how they compare to other groups in the graph. In this graph, each node represents a scientist; where the darker the blue and the larger the node the greater connected the nodes are in relation to each other. Figure 5 also shows the periphery and the core of the project network – the small circles on the outside are people who work in very small groups. At the center of the graph we can find the large nodes with solid blue colors – these are scientists who participate in projects and committees identified by the NACP to accelerate the research and work together towards a common goal. Near the center of the graph we can find the smaller blue nodes which don't appear to be as connected as the larger circles, but still more connected than the scattered nodes in the periphery. These nodes belong to those participating in more than one type of project or are in a core project funded directly by NASA. The colors of the edges in the graph represent the keyword or keywords that highlight the relationship between the work of two scientists. If the most frequently found word, within the project abstracts of two scientists, was biofuels then the keyword associated between these would be energy. If ties occur, then we assign the relationship as having more than one keyword. The graph shows 'Human Impacts' as the most frequent keyword showing up in relationships between scientists.

Finally, the analysis shows that there are 67 communities in the graph with a modularity score of 0.42 out of 1. The modularity score describes how the network can be seen as a collection of sub-networks. The score indicates that the project network is moderately organized, which reflects the average clustering coefficient of 0.896, where the best score is 1. The analysis shows that the project network has many well-integrated neighborhoods.

Figure 6 shows a similar network analysis graph for the bibliographic data, with 1555 connections resulting in 630 unique connections between 99 nodes. The article network has a similar structure to the project network in that there is a center and a visible periphery. The nodes at the center represent the scientists who collaborate together on different ideas, more so than the rest of the people in the graph. The analysis shows that there are 6 communities in the graph with a modularity score of 0.329 out of 1, which indicates that the article network is moderately organized. The average clustering coefficient is 0.594 where the best score is 1 for this network. Although the score is lower than the project network, the average clustering coefficient score for the article network is still quite high. This shows that the article network and the project network have similar degree of integrated neighborhoods. The Fruchterman-Reingold layout was used to visualize this network in Gephi, where the color shade and size of the nodes indicate how connected they are. The edges are colored by the keyword, however 'Strategies' was the most frequent keyword, with 'Human Impacts' being a distant second.

We can evaluate the bibliographic data to tell a story about the final outcome of the network shown in Figures 5 and 6. In 2007, only roughly a third of the NACP scientists (35) were connected to each other, and their connections formed a fairly fragmented network (9 fragments/components), with the average number of neighbors (how many people, on average, each person is directly connected to) at 2.11. Over time, however, we see the emergence of the highly interconnected network shown in Figure 6. We observe from the increasing number of nodes that, as the years pass, more of these highly active individuals within the community begin forming collaborative relationships with each other. It is also interesting to observe that, as new nodes enter the network, the number of disconnected fragments decreases from 9 to 2, and the average number of neighbors increases from 2 to 12 (Table 5).

The simple fact that the size of the network, in terms of nodes, grew over time is not sufficient to characterize its evolution. If NACP investigators had only begun forming collaborations with each other in small groups such as pairs or triplets, then we would expect that the average number of neighbors would remain relatively stable while the number of components would have substantially increased. The fact that we see the network in its current form, as shown in Figure 6, indicates that those individuals who were most active in attending NACP meetings have formed a well-integrated network of collaborations.

The summary statistics characterizing the NACP community and the network analysis suggest that different institutions within the NACP are becoming more interconnected. The data showed a steady increase in the ratio of institutional co-authorship ties over time, which may suggest that continued participation in shared practices benefits the opportunity for a collection of researchers representing different institutions to engage in cross-organizational collaboration.

6. DISCUSSION

We observed the existence of relationships encompassing approximately 98% of the co-authorship network. Only a single other small component of two nodes existed outside of the main cluster. If the data had described a scattering of islands of collaboration, each group unconnected to the others, then the lack of social pathways would be expected to impede the flow of ideas throughout the community. However, the tightly clustered network of core NACP co-authorships supports the hypothesis that the NACP is a community both in name and in practice, and that myriad social pathways exist for knowledge sharing and collaboration across the majority of members. It may also mean that the community is fairly insular, working more with each other than with those on the periphery. The same holds true even when the network is represented as a graph of institutions.

Although the community of practice framework tends to emphasize the role of interpersonal relationships between individuals, other studies have focused more on understanding the role of cross-institutional collaboration in knowledge creation. For example, previous studies have found that cross-institutional collaboration supports the diffusion of innovations and new ideas within a field (Zucker and Darby, 1996). Institutionally co-authored papers have also been found to be more highly cited than papers authored within a single institution.

Our results suggest that the North American Carbon Program has cultivated an increasingly connected community of practice whose networks of collaboration span a wide variety of institutions and topics (Table 5). It is comprised of a knowledge network, which has gradually extended its topics beyond traditional carbon cycle science. It is clear from the success of the NACP that encouraging collaborations to connect isolated fragments and cultivating long-term collaborative relationships across international and cultural boundaries is important for the improved functioning of a scientific community of practice.

However, simply writing papers on relevant topics and forming a tighter research network are not sufficient to produce policy-relevant research. The process of connecting science and decision makers must be undertaken. It is not clear from our analysis that such work is being done yet in the NACP (Dilling and Lemos, 2011; Lemos et al., 2002). Previous research has shown that just because research is policy relevant, does not mean that policy makers will use it (Cash et al., 2006). Science has to be done in a way that directly engages stakeholders and involves them in setting the research agenda, working with them iteratively over long periods of time to ensure that the research can be more usable in the end. The NACP abstract database doesn't really provide evidence one way or another that that is happening.

Our research does demonstrate the value of content analysis and social network analysis using publication data for assessing a CoP's knowledge production against its professed knowledge domain. This has important implications for the ability of the community to realign itself with its goals. The community gains the opportunity to further its development, integrating new members whose research specialties will contribute to the overall knowledge goals of the group and focusing its efforts on gaps in practice and representation.

Our research has similar findings to other studies that investigate how to cultivate collaboration in a community of scientists. For example, one study explored the introduction of scientists who were previously unacquainted and from different research backgrounds using brief meetings during a conference (Vaggi et al., 2014). According to the study, many scientist reported positive experiences and potential new collaborations as a result of participation. The NACP could employ a similar approach by characterizing the research of members using content analysis and creating new opportunities for fruitful collaborations. The social network perspective also enables the community to further stabilize and expands its connections, by encouraging collaborations that would connect isolated fragments of researcher groups to the overall network.

6.1 Limitations

The outcome of our analysis is representative of the community that was studied and is derived from data on the official members of the community in the NACP database. Without additional study, we cannot know if the results could be generalized for describing the larger population of all carbon cycle scientists including those from outside the program. Also, as previously mentioned, our keyword analysis results are only as thorough as the ability of our selected keywords to capture the intended meanings. It is possible that other researchers may have categorized keywords differently than we have chosen to do so here. Other researchers could find different results depending on what keywords they use in defining categories. Additional limitations are inherent to the bibliographic dataset, which was analyzed. Articles published by the same authors but using different institutional affiliations would have probably been excluded, as well as any material not archived in Web of Science.

6.2 Future Research

This research focused primarily on observing changes occurring in the overall network of individuals who either attended NACP meetings regularly, or who participated in projects related to the program. Future research should focus on analyzing more closely the attributes and behaviors of individuals within the community. A combination of network analysis with more qualitative methods could yield more conclusive insight into influences and motivations for change within a community, as well as understanding of which individuals tend to drive change and how.

As the NACP evolves, a program of understanding the impact of the program's collaborative approach on increasing its impact on policy should be of greater interest. Because this would involve interviewing stakeholders, it is outside of the methodological approach of the current article, but should be attempted by the organization in the coming years (Adams et al., 2013).

7.0 Conclusions

This research found an increase in the use of social and economic topics in interdisciplinary carbon cycle science research from 2007 to 2013 associated with the NACP members and the papers they have written. One conclusion that this result could mean is that the NACP community is actively working to incorporate human factor into their research, or that the members in the NACP have increased the framing of their research to include these topics to improve the policy relevance of their research, although the research itself remains fairly similar. Although our analysis cannot distinguish between these two hypotheses, the NACP community is paying more attention to the social and economic relevance of their work. We found that core NACP members are well connected with one another, forming a tightly clustered network. Cross-institutional collaboration has increased, but more needs to be done to cultivate long-term collaborative relationships across international and cultural boundaries.

It is difficult to clearly connect cause and effect with regard to networks, and note that the analysis presented here cannot determine why the NACP network has changed. It might be that the network and institutional diversity has grown and connectivity has increased, but is it because of the development of a community of practice or because of the availability of funding? We cannot determine this from the analysis presented, but believe that the NACP is working hard to increase both the relevance and quality of the research it does. The NACP has successfully fostered a community of practice, and is working towards increasing the inclusion of societal factors into its research. The organization can improve its engagement with the international community, and its consideration of economics in its research.

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Table Captions

Table 1. Keyword lists by category.

Table 2. Top thirty journals for all articles in the Web of Science article dataset and for the subset of articles coded with human process keywords in the content analysis portion of the study.

Table 3. Theoretical and observed participation distributions. The theoretical model for CoP (a) proposes three levels of community involvement and suggests distribution ranges for the proportion of the community which will fall into each level; (b) summarizes the attendance frequency distribution for individuals (n=808) who attended the most recent four NACP meetings between 2007 and 2013.

Table 4. NACP core article authorship and network connection statistics by year. This table describes the connections derived from the 363 articles which connect 99 of the most active participants in the NACP biannual meetings. The proportion of ties which crossed institutional boundaries are compared to the quantity of all co-authorship ties for each year.

Table 5. Statistics for NACP core co-authorship network in which people are represented as nodes.

Table S1. Content analysis results from article database, showing the number of keywords by human process category that each article (of 363 articles) contains per year.

Figure Captions

Figure 1. a. Results from content assessment by year and category for the NACP Core Subset articles (N=363) containing at least one human-related carbon cycle science keyword from Table 1. (b) Results by year and category for all articles (N=2,447).

Figure 2. Results showing the percent of articles from both samples referencing at least one keyword and the percent projects referencing at least one keyword.

Figure 3 Results from content assessment for articles and projects by human-related carbon cycle science keyword category.

Figure 4. NACP core authorship statistics by year.

Figure 5: Co-authorship network using project data from all NACP members. This network had 1007 people with 16518 connections and 15716 unique edges. The nodes of the graph are colored by the degree of connection, so that a darker blue represents the degree of connectedness of nodes. The node sizes are also categorized by the degree of connections. The edges are colored by the keywords associated between two pairs of nodes, the meaning of which is provided in the legend.

Figure 6: Co-authorship network using article database of 1555 connections resulting in 630 unique edges between 99 core NACP scientists. The nodes of the graph are colored by the degree of connection, so that a darker bluerepresents the degree of connectedness of nodes. The node sizes are also categorized by the degree of connections. The edges are colored by the keywords associated between two pairs of nodes, the meaning of which is provided in the legend.

Table 1. Keyword lists by category.

Economy:	Words signifying topics of information on economy-related issues, which connect to the evolution of human carbon system drivers and also relate to issues important to decision makers.	
command economy	*food*	*food source*
consumer	*food availability*	*food sources*
cost benefit	*food demand*	*food trade*
economic	*food demands*	*GDP*
economic activity	*food distribution*	*goods and services*
economic forecasting	*food insecurity*	*gross national product*
economic model	*food policies*	*industrial*
economic models	*food policy*	*industry*
economic projections	*food producing*	*inflation*
economic sectors	*food production*	*integrated assessment*
economical	*food security*	*investment*
economies	*food shortage*	*markets*
economy	*food shortages*	*socioeconomic*
fiscal policy		*waste management*
Energy:	Words associated with information needed in the energy sector, such as sources of energy, energy management concerns, and sustainability of sources.	
bioenergy	*energy policies*	*energy uses*
biofuel	*energy policy*	*fossil fuel*
biofuels	*energy portfolio*	*fuel*
dam	*energy production*	*fuels*
electrical	*energy resources*	*hydroelectric*
electricity	*energy source*	*oil and gas*
energy budget	*energy sources*	*renewable energy*
energy consumption	*energy supplies*	*sustainable energy*
energy efficiency	*energy supply*	*transportation*
energy forecasts	*energy sustainability*	*wind field*
energy harvesting	*energy use*	*wind fields*
energy management		*wind power*
Land Use & Water:	Words associated with human factors that determine carbon emissions from land use & water cycle	
agricultural	*forest management*	*land uses*
agriculturally	*forest policies*	*maize*
agriculture	*forest policy*	*ownership*

agroforestry	*grazing*	*pasture*
corn	*harvest*	*soybean*
crop	*harvested*	*urban*
cropland	*harvests*	*water availability*
cropping	*land management*	*water management*
crops	*land ownership*	*water quality*
farming	*land productivity*	*water supplies*
fisheries	*land use*	*water supply*
fishing		*water treatment*

Human Impacts: Words signifying content discussing how humans interact with and influence the carbon cycle.

anthropogenic	*emissions*	*human activities*
deforestation	*ghg*	*human activity*
disturbance	*greenhouse gas*	*pollute*
disturbances	*greenhouse gases*	*polluting*
emission		*pollution*

Society & Decision Making: Words which also general signifiers of topics that make carbon cycle science relevant to decision makers and managers who must consider the values and needs of their constituents

adaptation	*operations*	*Regulation*
attitudes	*planning*	*regulations*
cultural	*policies*	*resources*
culture	*policy*	*risk*
decision	*political*	*social*
decisions	*practice*	*sociopolitical*
international policy	*practices*	*stakeholders*
manage	*regulating*	*strategies*
management		*strategy*
managers		*zoning*

Strategies: Words signifying specific responses and strategies for managing human impacts to the carbon cycle.

carbon accounting	*conserve*	*Offsetting*
carbon budget	*emissions trading*	*renewable*
carbon offset	*mitigation*	*sequestered*
carbon offsets	*monitoring, accounting, and reporting*	*sequestration*
carbon program	*MRV*	*sustainability*
carbon trade		*sustainable*
conservation		

Table 2.

TOP 30 JOURNALS IN ARTICLES DATASET			
Rank	*Journals*	*Articles*	*% of Total*
1	Remote Sens. Environ.	148	6%
2	J. Geophys. Res.-Biogeosci.	123	5%
3	Agric. For. Meteorol.	101	4%
4	Glob. Change Biol.	89	4%
5	J. Geophys. Res.-Atmos.	85	3%
6	Biogeosciences	71	3%
7	Atmos. Chem. Phys.	54	2%
8	Geophys. Res. Lett.	45	2%
9	For. Ecol. Manage.	41	2%
10	Glob. Biogeochem. Cycle	39	2%
11	Environ. Res. Lett.	38	2%
12	Ecol. Model.	37	2%
13	Ecol. Appl.	35	1%
14	Proc. Natl. Acad. Sci. U. S. A.	31	1%
15	Int. J. Remote Sens.	29	1%
16	Agron. J.	28	1%
17	Tellus Ser. B-Chem. Phys. Meteorol.	26	1%
18	Can. J. For. Res.-Rev. Can. Rech. For.	24	1%
19	Ecosystems	23	1%
20	J. Geophys. Res.-Oceans	22	1%
21	PLoS One	20	1%
22	Atmos. Meas. Tech.	19	1%
23	J. Environ. Manage.	18	1%
24	Atmos. Environ.	18	1%
25	IEEE Trans. Geosci. Remote Sensing	16	1%
26	Agric. Ecosyst. Environ.	16	1%
27	Soil Sci. Soc. Am. J.	16	1%
28	Clim. Change	15	1%
29	Bull. Amer. Meteorol. Soc.	15	1%
30	Biogeochemistry	15	1%

TOP 30 JOURNALS AMONG ARTICLES CODED W/ HUMAN PROCESSES KEYWORDS (n=1397)			
Rank	*Journals*	*Articles*	*% of Total*
1	Remote Sens. Environ.	87	6.2%
2	J. Geophys. Res.-Biogeosci.	62	4.4%
3	Agric. For. Meteorol.	53	3.8%
4	J. Geophys. Res.-Atmos.	52	3.7%
5	Glob. Change Biol.	49	3.5%
6	Biogeosciences	47	3.4%
7	Atmos. Chem. Phys.	36	2.6%
8	For. Ecol. Manage.	35	2.5%
9	Geophys. Res. Lett.	25	1.8%
10	Ecol. Appl.	25	1.8%
11	Environ. Res. Lett.	25	1.8%
12	Agron. J.	24	1.7%
13	Glob. Biogeochem. Cycle	23	1.6%
14	Proc. Natl. Acad. Sci. U. S. A.	22	1.6%
15	Ecol. Model.	22	1.6%
16	Tellus Ser. B-Chem. Phys. Meteorol.	17	1.2%
17	Can. J. For. Res.-Rev. Can. Rech. For.	16	1.1%
18	Agric. Ecosyst. Environ.	15	1.1%
19	PLoS One	15	1.1%
20	Clim. Change	14	1.0%
21	Ecosystems	12	0.9%
22	Soil Sci. Soc. Am. J.	12	0.9%
23	Environ. Sci. Technol.	12	0.9%
24	Bioscience	11	0.8%
25	GCB Bioenergy	10	0.7%
26	Int. J. Remote Sens.	10	0.7%
27	Atmos. Environ.	9	0.6%
28	J. Clim.	9	0.6%
29	Nature	9	0.6%
30	J. Environ. Manage.	9	0.6%

Table 3:

(a) CoP Model Proposed Distribution		(b) Observed Attendance Distribution *(n = 808)*	
Core:	10 % - 15%	***3 - 4 Meetings:***	14.7%
Active:	15% - 20%	***2 Meetings:***	22.8%
Periphery:	65% - 75%	***1 Meeting:***	62.5%

Table 4.

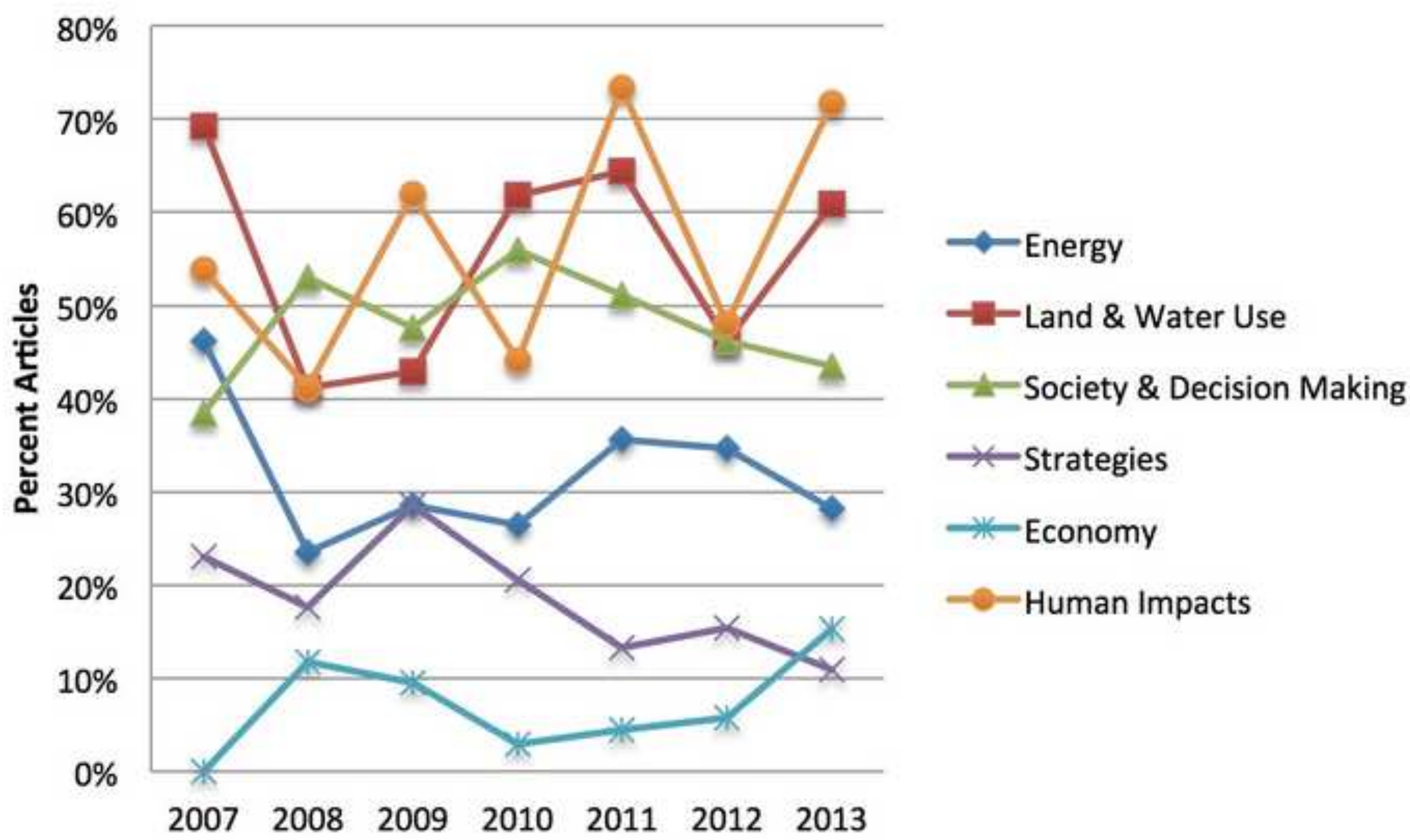
Publication Year	**Articles Published**	**Co-Authorship Ties**	**Ties Which Also Connected Different Institutions**	**Ratio of Ties Crossing Institutions to All Ties**
2007	24	43	29	67%
2008	37	70	59	84%
2009	39	100	78	78%
2010	57	330	304	92%
2011	62	257	226	88%
2012	78	563	524	93%
2013	66	192	162	84%
***Total*:**	363	1555	1382	89%

Table 5.

Evolution of Co-Authorship Network Between 2007 and 2013

Point of Analysis	Years in Analysis	Nodes	Edges	Comp-onents	Avg. Number of Neighbors
2007	1	35	43	9	2.11
2008	2	53	113	5	3.17
2009	3	64	213	3	4.47
2010	4	76	543	4	8.16
2011	5	83	800	2	9.18
2012	6	93	1363	2	12.41
2013	7	99	1555	2	12.72

Figure 1a


Percent Articles
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2007
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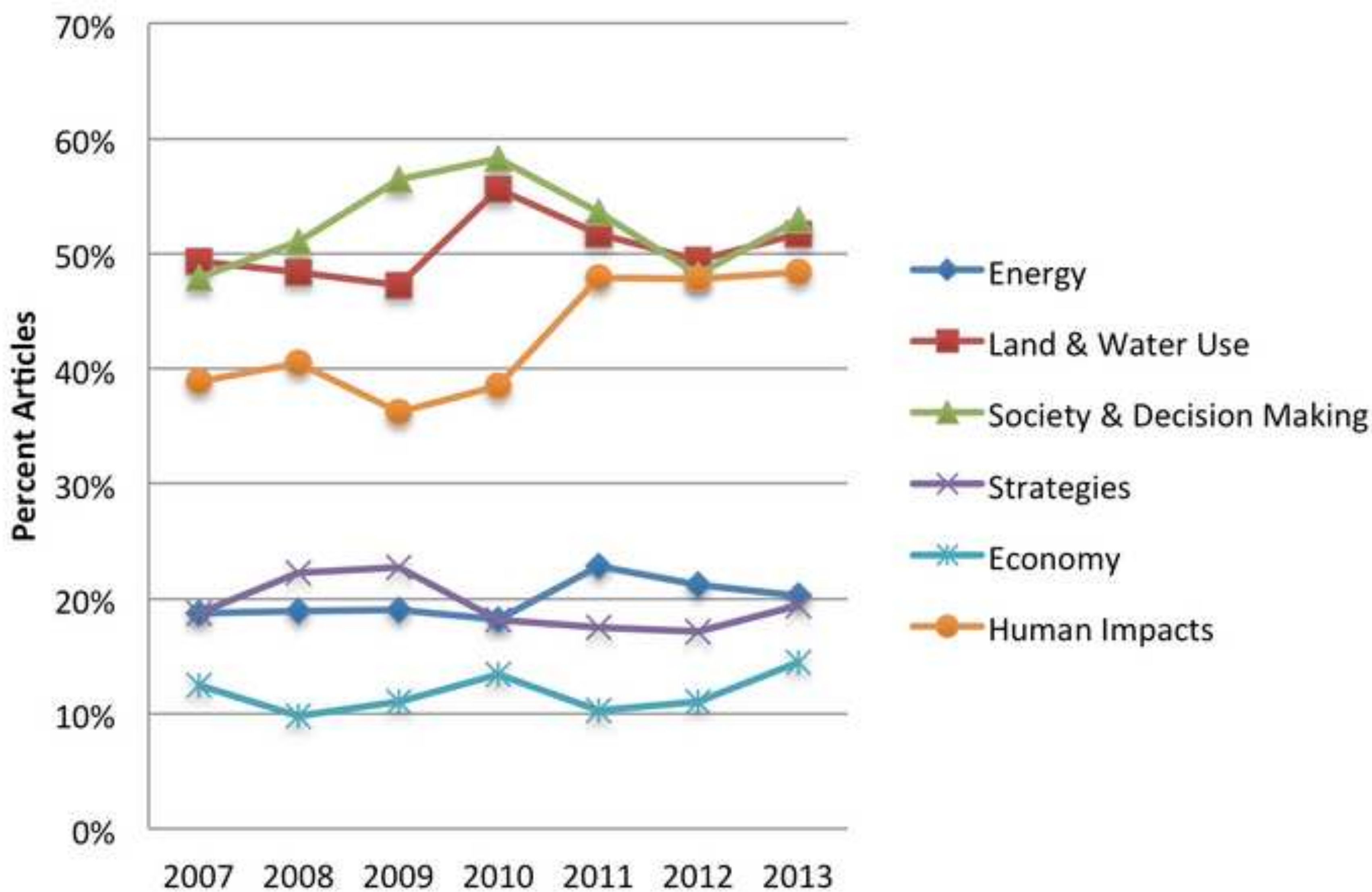
2013
Energy
Land & Water Use
Society & Decision Making
Strategies
Economy
Human Impacts

Figure 1b


Percent Articles
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2007
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Land & Water Use
Society & Decision Making
Strategies
Economy
Human Impacts

Figure 2
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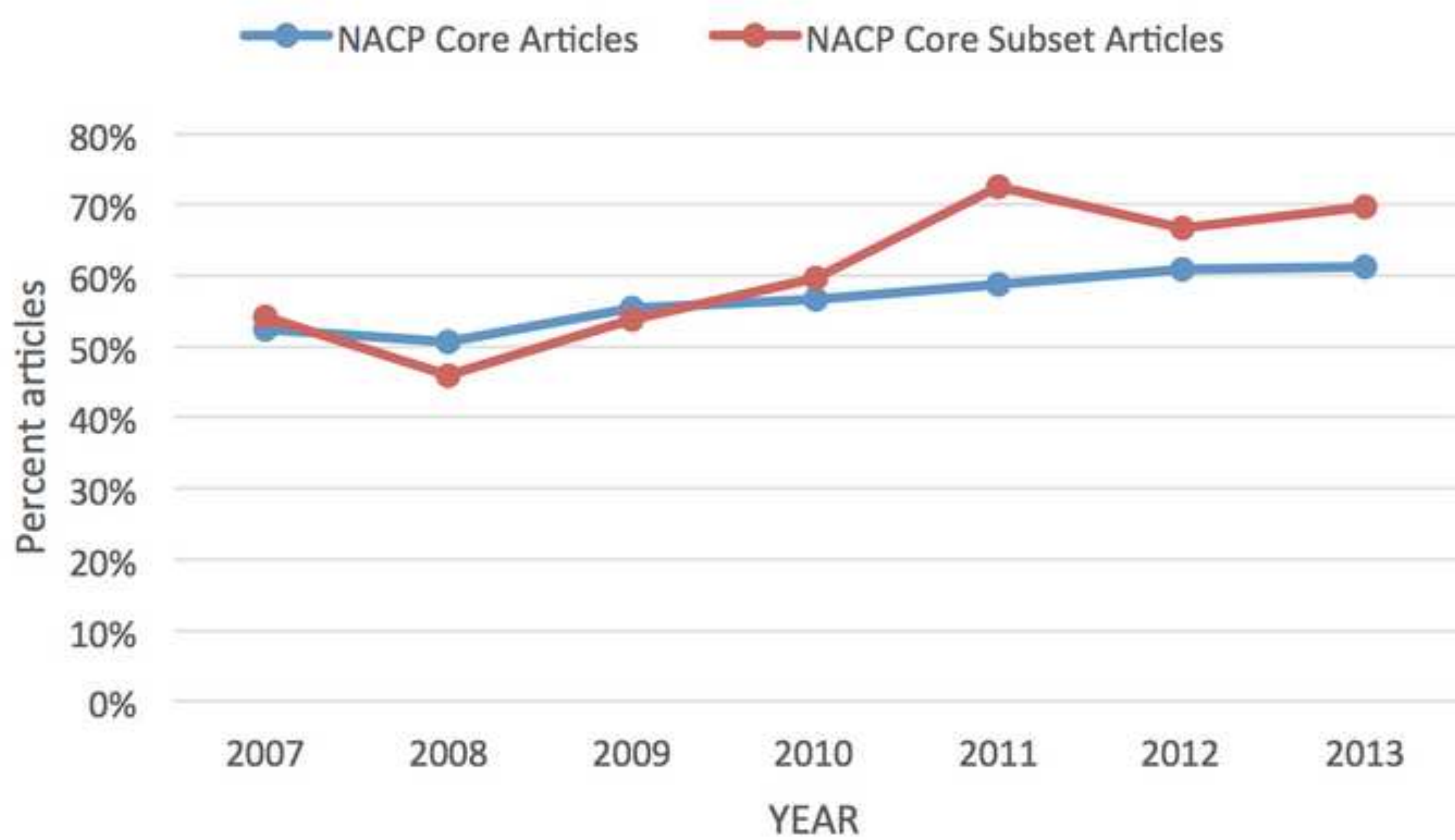
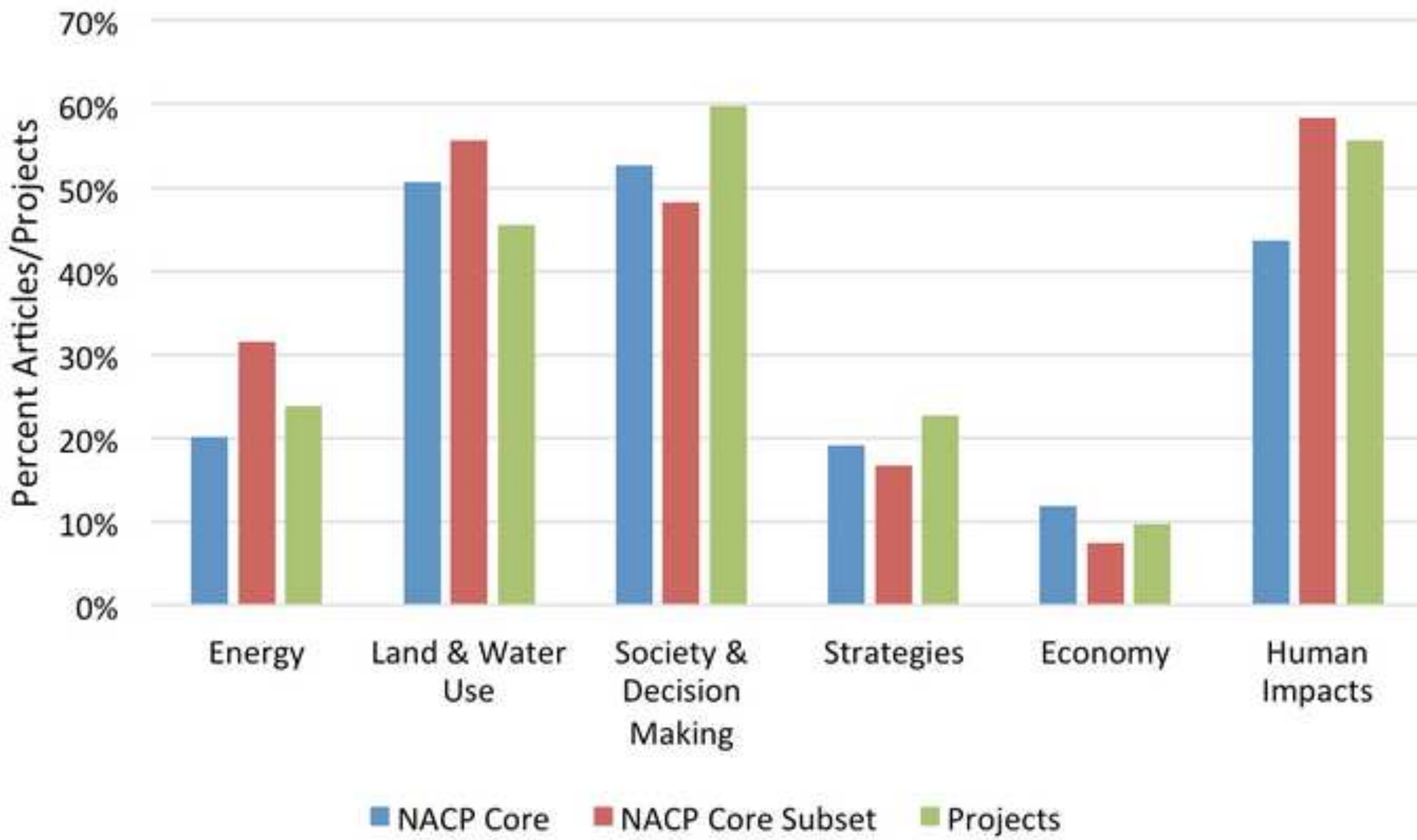


Figure 3



70%
60%
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10%
0%
Percent Articles/Projects
Energy
Land & Water Use
Society & Decision Making
Strategies
Economy
Human Impacts
NACP Core
NACP Core Subset
Projects

Figure 4
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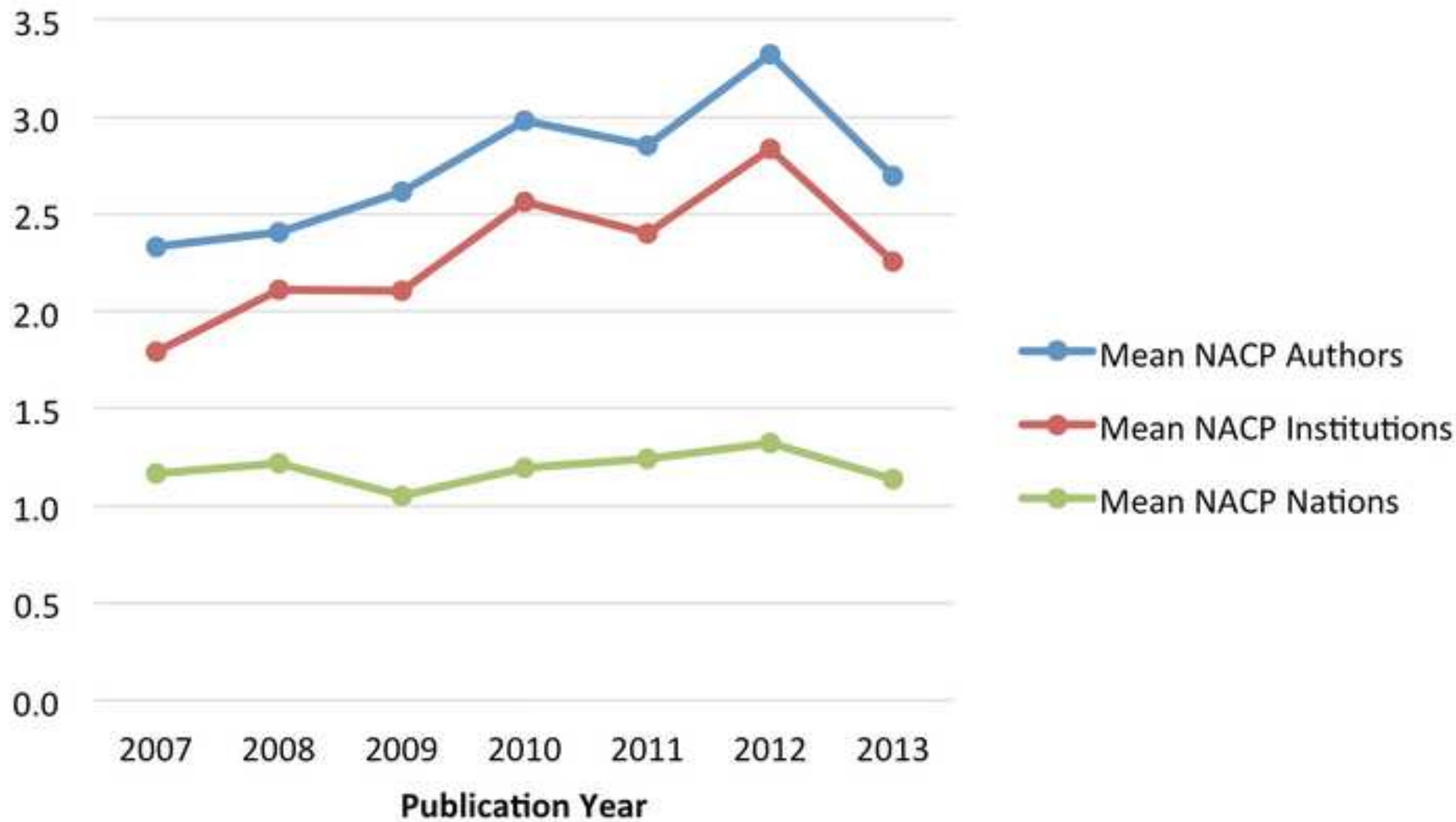

Figure 5
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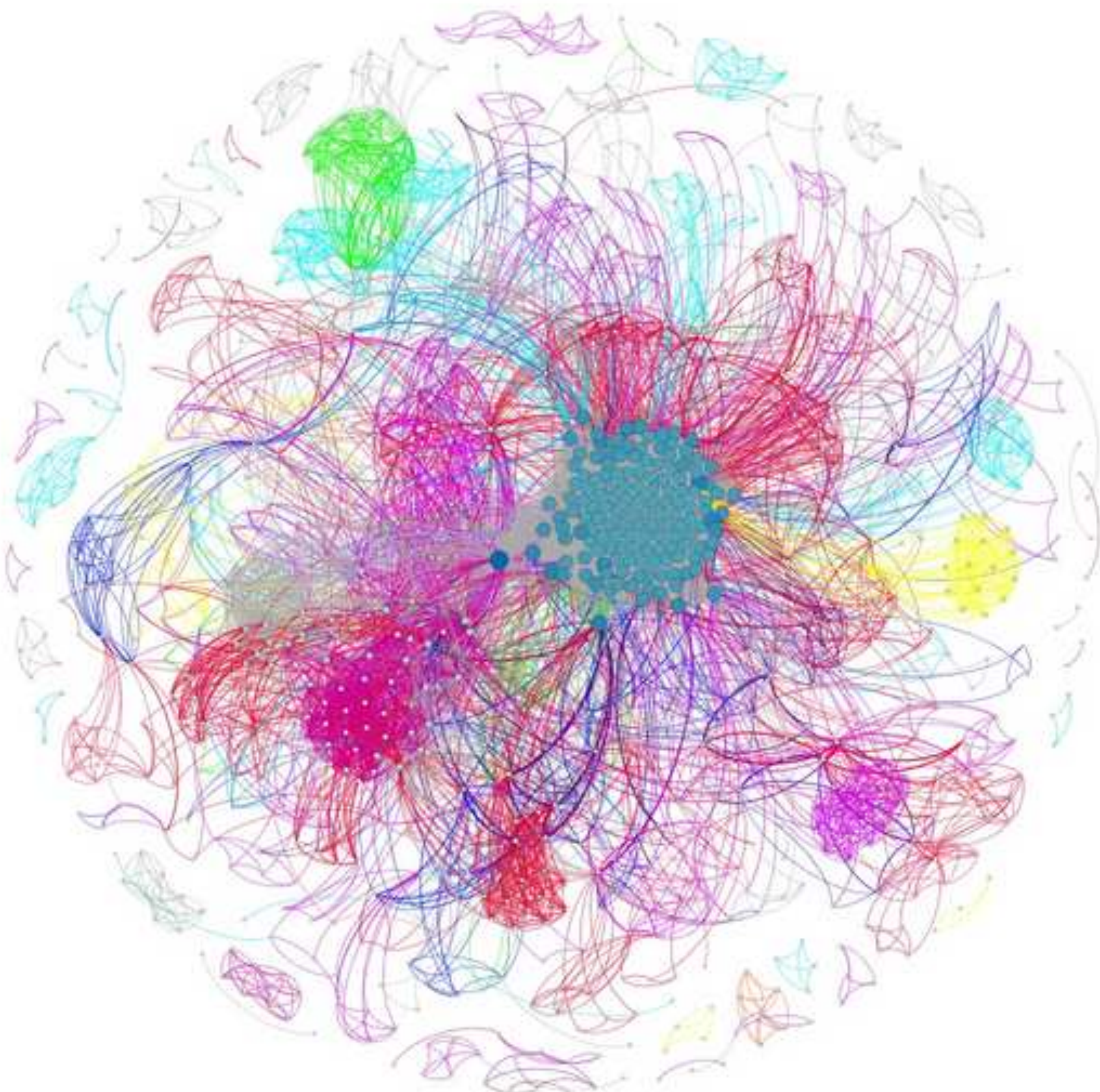

Figure 5 legend
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Figure 6
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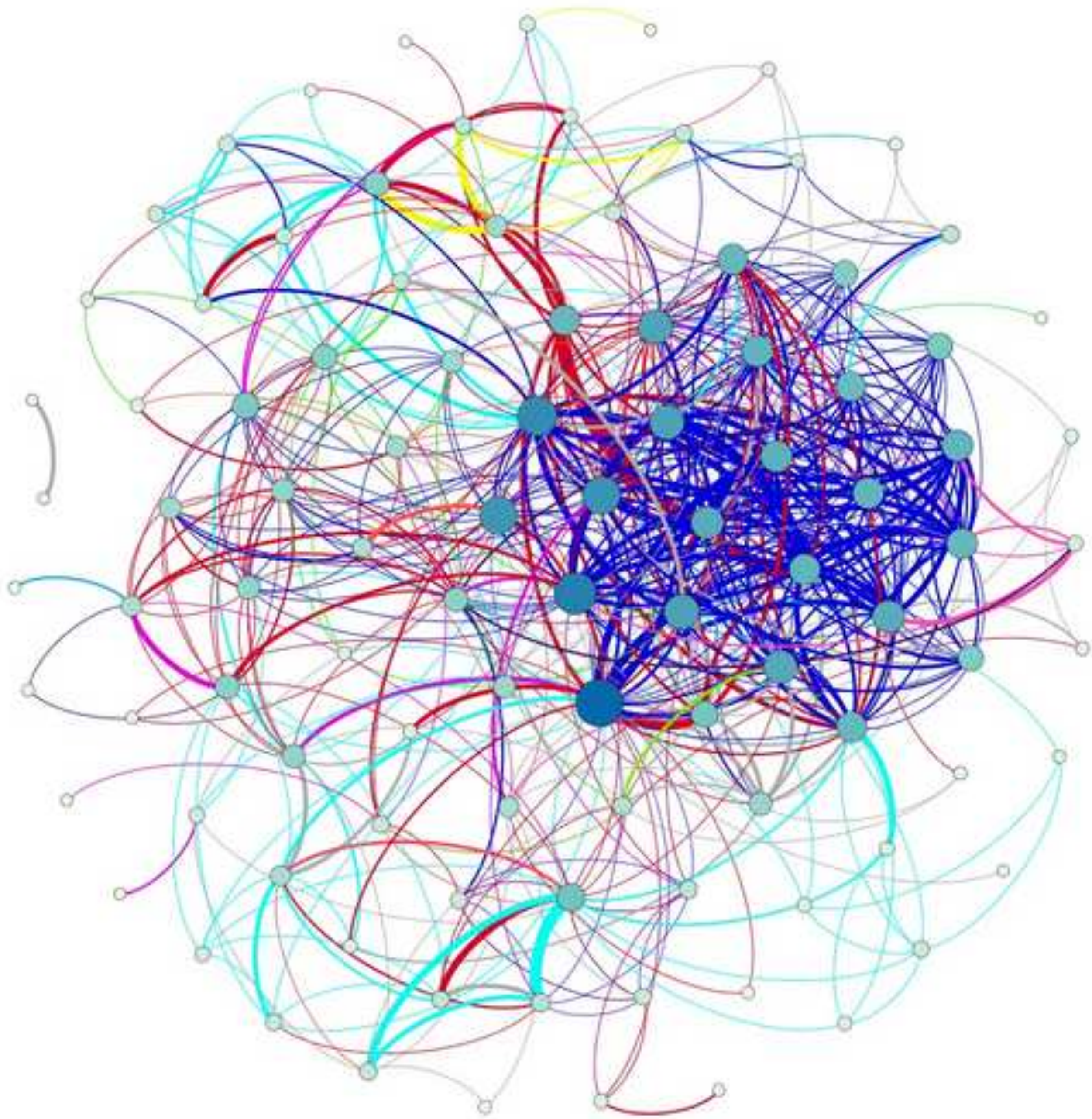

Figure 6 legend

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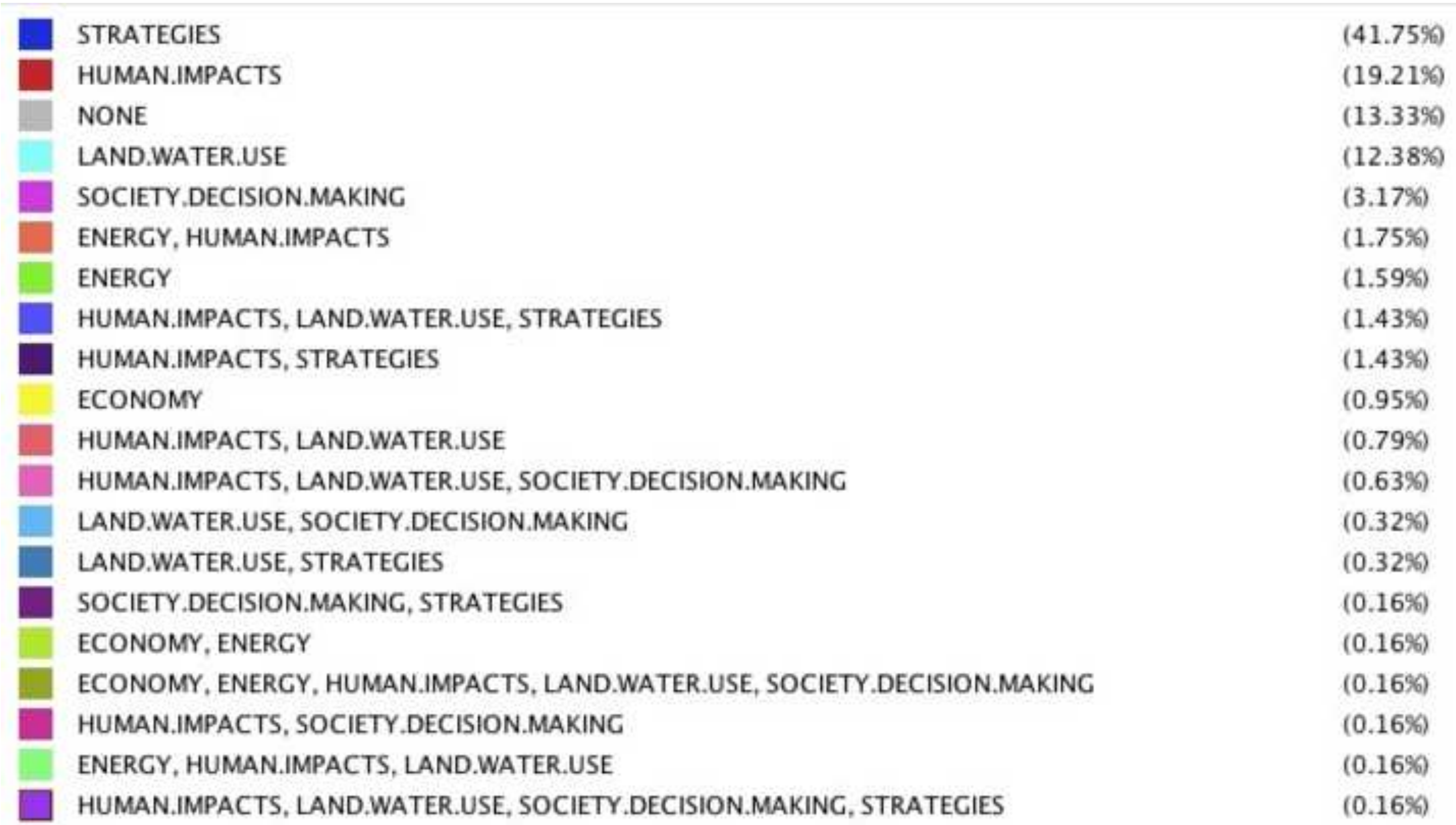

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