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Networks for Science-Informed Innovation in the Arctic: Insights on the Structure and Evolution of a Canadian Research Network

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ABSTRACT. In remote peripheral regions like the Arctic, research networks have been identified as an important mechanism for nurturing science-informed innovation. Given that relatively little is known about the network structures that support Arctic innovation processes, we employ social network analysis techniques to examine the structural organization and evolution of ArcticNet, a large Canadian Arctic scientific research network over a 13-year period (2004–17). ArcticNet funded 152 multidisciplinary research teams, connecting multiple types of science-based innovation actors, not including students (301 organizations and 1659 individuals). The research network grew without reaching saturation (increasing size, decreasing density), suggesting that ArcticNet was successful in recruiting new actors over the 13-year period. ArcticNet was centralized around non-local, public-sector actors (mainly Canadian academics). The emergence of collaborations across several boundaries (sectoral, geographic, thematic) suggests that non-local Canadian academic actors played an important boundary-spanning role, particularly in the early stages of the network. Participation by local northern actors doubled from Phase 1 to Phase 4, and with time, local northern actors had an increasing propensity for carrying out boundary-spanning roles and addressing structural holes. This study presents new insights into the networked nature of Arctic scientific research with potential implications for future research and innovation policy.

Key words: governance; impact evaluation; interdisciplinary studies; metrics; network analysis; regional innovation; science policy

RÉSUMÉ. Dans les régions périphériques éloignées comme celle de l'Arctique, les réseaux de recherche constituent un mécanisme important pour encourager l'innovation fondée sur la science. Puisqu'on en sait relativement peu sur les structures de réseau qui soutiennent les processus d'innovation dans l'Arctique, nous recourons à des techniques d'analyse des réseaux sociaux pour examiner l'organisation structurelle et l'évolution d'ArcticNet, vaste réseau de recherche scientifique dans l'Arctique canadien, sur une période de 13 ans (2004–2017). ArcticNet a assuré le financement de 152 équipes de recherche multidisciplinaire, reliant par le fait même plusieurs types d'acteurs de l'innovation fondée sur la science, exception faite des étudiants (301 organisations et 1659 particuliers). Le réseau de recherche a pris de l'ampleur sans devenir saturé (augmentation de la taille, diminution de la densité), ce qui laisse entendre qu'ArcticNet a réussi à recruter de nouveaux acteurs pendant la période de 13 ans. Le réseau ArcticNet était centralisé autour d'acteurs non locaux relevant du secteur public (principalement des universitaires canadiens). L'émergence de collaborations englobant plusieurs facettes (sectorielle, géographique, thématique) suggère que les acteurs universitaires canadiens non locaux ont joué un rôle important en matière de chevauchement des diverses facettes, plus particulièrement durant les premiers stades du réseau. La participation d'acteurs du Nord a doublé de la phase 1 à la phase 4. Au fil du temps, les acteurs locaux du Nord ont eu une propension de plus en plus grande à assumer des rôles chevauchant diverses facettes et à combler les vides structurels. Cette étude présente de nouvelles perspectives de la nature réseautée de la recherche scientifique dans l'Arctique de même que les conséquences éventuelles sur les futures politiques en matière de recherche et d'innovation.

Mots clés : gouvernance; évaluation des impacts; études interdisciplinaires; indicateurs; analyse de réseaux; innovation régionale; politique scientifique

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INTRODUCTION

There is an increasing need for innovative solutions that can help to address the unprecedented and complex sustainability challenges facing the Arctic (Steinberg et al., 2015; Wehrmann, 2016). Recent assessments suggest that as concurrent environmental and social pressures intensify, the integrity of Arctic systems will be tested, raising key governance questions about how to best support sustainable Arctic futures (Arctic Council, 2016; Ford et al., 2018; GC, 2019; Huntington al., 2019). It is increasingly argued that the Arctic would benefit from public policies that better support and promote a broad definition of innovation – often defined as the creation of something new (e.g., product, process, practice or relationship) (see Coates and Poelzer, 2014; Hintsala et al., 2015; Oksanen and Hautamäki, 2015; Hall et al., 2017; Healy, 2017; Pigford et al., 2017; Exner-Pirot, 2018; Hall, 2020). Arctic leaders have called for investments that support northern-driven, solution-focused partnerships that can address community needs and foster local innovation (Audla and Smith, 2014; GY et al., 2016; ITK, 2016; Ogden et al., 2016; Healy, 2017; ITK, 2018). Examples include the creation of new northern specific technologies that can support communities to deal with and adapt to the consequences of climate change (e.g., thawing permafrost, declining sea ice).

While innovation can be driven by many different factors and actors, this paper focuses on scientific research networks as one pathway to inform innovation. Based on the notion that scientific research can play an important role in improving collective outcomes (McNie, 2007), scientific research has long been central to the Canadian Arctic innovation narrative (SCC, 1977; Bocking, 2007, 2010; Gearhead and Shirley, 2007; ITK, 2018). This is especially true when scientific and technological domains come together alongside Indigenous and local knowledge (Healy, 2017). It is worth noting that the current Arctic scientific landscape is a result of ongoing efforts by Arctic leaders to address exclusionary research structures and to advocate for Arctic scientific research that can meet public needs and deliver innovative outcomes (Audla and Smith, 2014; GY et al., 2016; Ogden et al., 2016; ITK, 2018; Obed, 2018). With the Arctic quickly becoming one of the most researched contexts in the world (Nilsson and Koivurova, 2016; ITK, 2018), there is a recognized need to address significant knowledge gaps concerning how Arctic scientific research is organized within innovation efforts (Kofinas et al., 2020).

In general, studies on innovation have focused on large economic centers without fully considering innovation processes in less developed (Schaeffer et al., 2018), non-urban, and remote peripheral regions (Oksanen and Hautamäki, 2014; Carter and Vodden, 2017; Eder and Trippl, 2019). Since peripheral regions are far from core economic areas, they often exhibit different forms of innovation and face unique challenges (McAdam et al., 2004; Tödtling and Trippl, 2005; Isaksen and Trippl 2017). As a peripheral region, the Arctic is often faced with innovation challenges related to geographic, social, and economic isolation, fewer targeted regional innovation strategies, and limited access to some traditional innovation actors (Suorsa, 2007; Hall et al., 2017). As a result, Arctic innovation communities are likely to reflect the features unique to the complex, hybrid institutions and societies that govern the region (Abele, 2015; Pigford et al., 2017). Empirical research examining how existing Arctic innovation communities are organized is needed to inform policies that aim to nurture science-informed innovation in the region.

Networks for Science-Informed Innovation

Since peripheral regions tend to lack access to traditional innovation actors and infrastructures, innovation efforts in peripheral regions tend to rely heavily on well-positioned local or regional actors and on effective collaboration networks (Tura and Harmaakorpi, 2005; Grillitsch and Nilsson, 2015; De Noni et al., 2018). While local actors are considered essential for regionally relevant innovation outcomes (Oksanen and Hautamäki, 2015), innovation processes are generally enhanced when local actors are able to work with non-local actors in order to access knowledge and expertise that are not locally available (Grillitsch and Nilsson, 2015; De Noni et al., 2018). Effective collaboration can therefore support interactive learning by promoting discourse and knowledge exchange among local and non-local actors (Eder and Trippl, 2019; Fitjar et al., 2019). Such collaborative interactions generally occur through multi-actor networks designed to support the collective production and sharing of information concerning issues that cannot be solved or easily solved by a single actor (Agranoff and McGuire, 2001; Agranoff, 2007). This process is often adopted in the Arctic where actors need to share information in a coordinated manner in order to address a range of complex issues that tend to span multiple geographic, administrative, epistemological, and cultural boundaries (Nilsson and Koivurova, 2016; Pigford, et al., 2017).

Research networks are increasingly seen as a catalyst for driving science-informed innovation in Arctic regions (Task Force on Northern Research, 2000; Alfred-Wegener-Institut, 2015; Lee et al., 2015; Vlasova and Volkov, 2016; Arctic Council, 2017). Scientific actors (e.g., researchers, universities, and research institutions) can contribute to innovation efforts when they collaborate with policy actors (e.g., communities, government, and industry decision makers) and other content experts (e.g., local and traditional knowledge holders) (Owen et al., 2012; Wittmayer and Schäpke, 2014). Key network actors can facilitate this process by bringing different groups of actors together around a common goal, effectively fulfilling "boundary-spanning" roles within a network (Schut et al., 2013; Turnhout et al., 2013). For example, the Canadian federal government has identified publicly funded scientific researchers as focal actors in its past Arctic innovation initiatives (SCC, 1968, 1977; Pigford et al., 2017).

A growing number of collaborative scientific efforts have been designed to promote coordinated action and facilitate science-informed innovation (e.g., University of the Arctic, the International Arctic Science Committee, EU-PolarNet, the Arctic Council's Scientific Cooperation Agreement), including decentralized scientific research networks (e.g., Canadian Network of Northern Research Operators, Social Economy Research Network of Northern Canada, Canadian Cryospheric Information Network, Canadian Mountain Network, ArcticNet). In this paper we focus on ArcticNet, one of the largest and most established Arctic research networks in Canada. ArcticNet was established in 2003 to bring diverse actors together from different organizations and sectors in order to examine the impacts of climate change in the Canadian Arctic with the goal of supporting innovation (e.g., new policies, strategies) (ArcticNet, 2020). ArcticNet was funded under the Canadian Networks of Centres of Excellence (NCE) program and received Can$113.7 million from the federal government and Can$249.4 million from partner organizations between 2004 and 2017 (GC, 2020). Historically, each funded NCE was supported by the program for up to 14 years (two 7-year terms); however, in 2017 it was announced that the NCE program would be terminated and one final funding call was held (Glauser, 2017), and ArcticNet successfully received an extension to continue to pursue its mandate until 2025. The network's broad mandate is to support science-informed innovation by translating science into impact assessments, national policies, and adaptation strategies (ArcticNet, 2020). The ArcticNet network includes multidisciplinary research teams funded through ArcticNet processes. These teams include scientists, managers, Indigenous organizations, northern communities, government, and private firms who work together to address issues that cross multiple disciplines (e.g., natural, human health, and social sciences) and sectors, while also leveraging funding from other sources (Coutinho and Young, 2016).

Research Aims and Objectives

An understanding of how regional networks are organized (including the identification of boundary-spanning actors) has been identified as being important for nurturing regional innovation (Jacobsson and Bergek, 2011; Panetti et al., 2020). To date, efforts to evaluate Arctic scientific research have largely focused on describing project-specific outcomes or the quality of partnership engagement mechanisms at a local level (e.g., Gearhead and Shirley, 2007; Pearce et al., 2009; Felt and Natcher, 2011; Brunet et al., 2017; Eerkes-Medrano et al., 2019; Callaghan et al., 2020). These efforts have not paid close attention to how diverse actors might interact within broader networks; although Arctic science approaches often promote concepts and language around networks, there has been limited application of methods of analysis at the network level (Kofinas et al., 2020). While there has been a recent examination of coauthorship patterns among Arctic researchers (Natcher et al., 2020), there has yet to be a broader structural analysis on the organization and evolution of networked Arctic scientific research that also includes non-academic actors (Pigford et al., 2017). This paper aims to understand how Arctic research networks are organized, evolve, and span disciplinary, organizational, and geographic boundaries in support of science-informed innovation by examining ArcticNet using social network analysis techniques.

CONCEPTUAL FRAMEWORK

Identifying Regional Innovation Actors

In general, innovation actors can include private sector firms, non-profit organizations, universities, research and public organizations, knowledge infrastructures, end users, and local knowledge holders (Aarikka-Stenroos and Ritala, 2017; Järvi et al., 2018). Since context can shape regional innovation outcomes, different geographic locations may require different actor configurations depending on the availability of local innovation actors (Suorsa, 2007; Clarysse et al., 2014). Factors that can affect the structure and performance of regional innovation efforts include 1) private or public sector leadership (Doloreux and Dionne, 2008; Pierrakis and Saridakis, 2019), 2) involvement of universities in research, development, and training (Grillitsch and Nilsson, 2015; Kempton, 2015; Brown, 2016; Benneworth and Fitjar, 2019), and 3) local or non-local relationship configurations (Clarysse et al., 2014; Oksanen and Hautamäki, 2015). Each of these factors needs to be considered when evaluating the structure of networks in peripheral regions.

Spanning Boundaries to Support Innovation

Boundary spanning is defined as "work to enable exchange between the production and use of knowledge to support evidence-informed decision making in a specific context," while boundary spanners are the "individuals or organizations that specifically and actively facilitate this process" (Bednarek et al., 2018:1176). Boundary spanning is not characterized by a single function or role; instead, it reflects a broad range of activities carried out by individuals, teams, or entire organizations (Posner and Cvitanovic, 2019). Boundary-spanning actors engage in strategies to support cross-boundary connections (Zietsma and Lawrence, 2010), which can result in improved understanding and relationships (Smink et al., 2015), stronger and more diverse social networks, and improved knowledge exchange between knowledge suppliers (e.g., universities, research institutes, government research bodies) and users (e.g., administrative agencies, policy organizations, communities) (Bednarek et al., 2018; Posner and Cvitanovic, 2019). Such improved cross-boundary relationships can help to stimulate innovation. Although the actors that have adopted formal leadership roles within a network are inherently assigned boundary-spanning responsibilities, other actors can also carry out this function. The extent that actors act as boundary spanners can be determined by considering their networked relationships (Posner and Cvitanovic, 2019).

Capturing Dynamic Network Configurations

Social network analysis has been previously used in other contexts to examine academic co-authorship patterns (Ding, 2011; Uddin et al., 2012; Guan and Liu, 2016), inform the planning, implementation and monitoring of research activities (Morel et al., 2009; Klenk et al., 2010; Ginexi et al., 2017), as well as to examine the role of research in fostering innovation (Quiédeville et al., 2018) and shaping innovation ecosystems (Panetti et al., 2020). To capture the relational aspects of actors, network analysis employs social network theory to examine the connections between pairs of actors that form larger relational systems (Scott, 2012). Actors reflect a social unit, which in an innovation context may reflect individuals, firms, universities, research projects, research networks, and knowledge repositories (Contractor et al., 2006; Klenk et al., 2009). A networked relationship can be considered a process by which two or more actors collaborate to achieve a common goal (Hanneman and Riddle, 2011). Networks essentially arise from personal relationships between actors (Leite and Pinho, 2017); therefore, network analysis can provide insight into the presence, strength, and changing nature of relationships, including the identification of actors that act as boundary spanners and are positioned to foster new relationships or facilitate information flows among actors (Posner and Cvitanovic, 2019).

An examination of measures of network cohesion and those of the node-level network can present insight into the structural dimensions of a research network. Measures of network cohesion describe the strength of relationships distributed across the network and can be used to help determine changes over time. *Network size* refers to the total number of actors in the network. Size is important in understanding the structure of networked relations because each actor has limited resources and capacities for building and maintaining relationships (ties) (Hanneman and Riddle, 2005). *Network density* is calculated by examining the total number of networked ties and the total number of possible tie interactions. It captures the extent to which the network is interconnected and can be used as a proxy for the amount of collaborative activity in the network (Scott, 2012). *Network centrality* refers to the extent that collaborations are focused around individual actors (Scott, 2012). Being centrally located implies an advantageous position, often associated with a higher status and associated source of power (Zheng, 2010).

Node-level network measures can be used to understand the characteristics of individual actors in the network. *Ego network size* is the total number of contacts an actor has in its network (Hanneman and Riddle, 2005). Ego network size is generally seen to have a positive effect on innovation, since a larger network means increased opportunities for collaborative interactions (Zheng, 2010). *Degree centrality* accounts for the number of ties between actors (Scott, 2012). The higher the level of degrees, the more likelihood an actor has of being exposed to opportunities for innovation (Zheng, 2010). *Betweenness centrality* captures the extent that an actor acts as the shortest path (i.e., bridge) between two other actors (Ginexi et al., 2017). The identification of actors with a high degree of betweenness suggests that actors likely facilitate a high degree of boundary spanning in the network (Quiédeville et al., 2018). The existence of a gap or empty space in a person's network (the absence of ties between actors who are connected to the same ego) is considered a *structural hole* (Burt, 1982, 2009). Actors on either side of a structural hole have access to different flows of information; therefore, actors who can fill or bridge the structural hole are important boundary-spanning agents (Burt, 1982). From an innovation perspective, structural holes are seen to be positive for idea generation but detrimental to coordination and idea implementation (Zheng, 2010). Structural holes can be investigated using effective size, which reflects the total number of connected actors minus the average number of ties that each actor has to other actors (i.e., total impact), and efficiency, which reflects the portion of ties that are not redundant (i.e., effective size divided by network size) (Hanneman and Riddle, 2005).

Analytical Framework

To examine network connections that are relevant to innovation in peripheral regions, an analytical framework was developed by linking key network analysis measures to the literature discussed above (e.g., innovation in peripheral regions and boundary spanning) (Table 1). Recognizing that networks learn and change over time, a longitudinal lens is also applied to the analysis.

STUDY METHODS

Network Analysis

We conducted a social network analysis (Scott, 2012) to identify the structure of collaborative relationships within ArcticNet using the organizational and individual network linkages reported between actors and to assess the network's configuration and its evolution over time. For this network analysis, a collaborative relationship was seen as occurring between two actors (individuals or organizations)

TABLE 1. Analytical framework used to examine network connections.

Network characteristic	Analysis measure
General network description:	
Network changes over time	• Actor descriptors • Longitudinal analysis • Network cohesion: density, centrality, network size
Central actors:	
Identification of central actors – local and non-local – dominant sectors (e.g., universities) – project leaders	• Actors with large ego networks • Average degree centrality/normalized degree by category
Boundary crossing:	
Patterns of cross-boundary collaborations (e.g., sector, disciplinary theme)	• Description of cross-sector activity • Average degree centrality by sector
Boundary spanning: Structural holes	• Effective size • Efficiency
Identification of boundary spanners: – local and non-local – dominant sectors (e.g., universities) – project leaders	• Actors with high betweenness centrality

if they participated in at least one funded research project together.

Data Description

Network data were generated using information derived from research projects funded by ArcticNet from 2004 until 2017. A database was created using annual report data obtained from the ArcticNet Secretariat in the summer of 2018, which was then cross-referenced with online project summaries (available on the ArcticNet website). As a funded NCE, ArcticNet is required to adhere to granting agency practices, which limited who was eligible to lead and hold ArcticNet research funds (e.g., individuals with an affiliation with an academic institution); however, anyone could participate in the network. Therefore, to be as inclusive as possible, we did not limit network inclusion to those who were in roles that were eligible to hold funding. Data were extracted for the individuals listed as project leaders, network investigators, collaborators, and research staff. Of note, trainees (e.g., undergraduate, masters, doctoral, and post-doctoral) were excluded from the analysis based on the assumption that their organizational affiliations are the same as their supervisor.

Demographic data related to members' affiliations and sex were included. To supplement the dataset, a web search was performed to identify the location of the organization when location data were missing. For academics who had government and university appointments, the organization indicated on the project summary was used for organization-level analysis, while for individual-level analysis, the affiliation that appeared on the greatest number of project summaries was used. Categorization by sector was assigned to organizational affiliations: Canadian academic, international, federal government, provincial government, private sector, non-profit, and northern Canada. Beyond inclusion in the study, actor roles were not considered in analysis. Of note, ArcticNet recognizes actors with northern-based affiliations as a distinct 'sector', which is also reflected in our analysis. Actors with northern Canadian affiliations (i.e., those with affiliations located in the territories or in Inuit Nunangat) were categorized as "northern" only. Although northern actors reflected a range of public and non-profit actors (e.g., community, regional, and territorial governments, hunting and trapping organizations, and northern colleges) and a few private sector actors (mostly consulting firms), they were not included in other sector category counts (e.g., academic) or further differentiated for analysis. While this categorization helped us to align with ArcticNet rhetoric, we acknowledge that it did not allow us to explore nuanced relationships between diverse northern actors and other sectors. We recognize this as a limitation of our dataset. To facilitate discussion about the relationship between local and non-local actors, actors in the northern category were considered local actors and were compared to non-local Canadian actors (i.e., those located in Canada but not in the territories or Inuit regions), and non-local international actors, including international actors located in other circumpolar regions.

Research projects were funded by ArcticNet in four distinct phases making it relatively straightforward to examine changes over time (Phase 1, 2004–08; Phase 2, 2008–10; Phase 3, 2010–15; Phase 4, 2015–18). Of note, only partial data were available for Phase 4 because ArcticNet changed its reporting structure in 2017–18, and comparative data were not available. Therefore, all data reflect relationships between 2004 and 2017. ArcticNet projects are also organized by five themes (Marine Systems, 48 projects; Terrestrial Systems, 34 projects; Inuit Health, Education and Adaptation, 44 projects; Northern Policy and Development, 20 projects; Knowledge Transfer, 6 projects).

Of note, Theme 5: Knowledge Transfer was only added to the network in Phase 3. Since the themes in Phase 1 were different, Phase 1 themes were re-coded in consultation with the ArcticNet executive director in 2018 to facilitate cross-phase comparisons.

Data Analysis

In order to provide informative depictions of ArcticNet's network structure, data transformations and network metrics were calculated using UCINET 6 software for Windows and visualizations were prepared using NetDraw 2.164 software (Borgatti et al., 2002). Data were analyzed by examining collaborative relationships between individual actors as well as organizational actors to garner a general description of the network (binary, undirected relationships). Metrics presented for the comprehensive network include a cumulative view of all relationships formed over the duration of ArcticNet given that once a relationship is formed the collaborator is retained as a contact. The size of the network in each phase is not cumulative and represents the relationship during that phase only in order to provide clearer insight to the network structure at several points in time.

Two-mode matrices were created to examine how individual actors collaborated across projects (individual × project) for the entire network and each of the four phases. These were then converted into one-mode adjacency matrices to represent the relationships between the individuals connected through ArcticNet funded projects (individual × individual). To represent the organizational relationships across projects, the same process was repeated for organizational actors (i.e., transforming two-mode organization × project matrices to one-mode organization × organization matrices). Network metrics and visualizations were generated to identify changes in relationships between ArcticNet actors. Visualizations by phase were presented as interorganizational collaborations. Our decision to focus visualizations on organizational connections did not inhibit our ability to map the ArcticNet network structure and was informed in part by the recognition that there are limitations to visualizing an entire network with every actor's connections represented (Klenk et al., 2009). To gain insight into cross-discipline (theme) collaboration across projects, the two-mode matrix (individual × project) was converted into a one-mode adjacency matrix (project × project).

The analysis was based on the framework outlined in Table 1. To show the extent to which individual and organizational actors were connected over time, network cohesion measures (density, centrality, size) were assessed for the complete network and for each phase. To identify central or predominant actors, several characteristics were calculated for each individual: ego network size, average degree (number of links per actor), and normalized average degree. Individual actors appointed as project leaders were also described, and network characteristics were calculated.

To understand areas of boundary spanning, we examined three types of boundaries that ArcticNet was intended to cross: sectoral, disciplinary (captured by theme), and geographic. We describe project collaborations by theme as a measure of interdisciplinary collaboration and identify the projects that facilitated a high degree of boundary spanning. We then consider measures of individual boundary spanning by identifying actors with a high betweenness centrality and aim to identify the potential presence of structural holes by calculating average effective size and efficiency.

Ethics

ArcticNet was aware and supportive of this study, however all research work was completed at arm's length. Research Ethics Board approval (file 44-0618) was received on 15 June 2018 for 10 scoping interviews with key informants who had historical and administrative knowledge of ArcticNet in order to identify the secondary sources used in this analysis. Preliminary findings from this research were shared with the ArcticNet Secretariat, which used this information to inform their 2018 funding renewal application. The research was also used to foster discussions about the development of the North-by-North research program within the ArcticNet community, including with representatives from Northern colleges and the ArcticNet Inuit Research Advisory Committee (Dawson et al., 2019).

Description of Network Characteristics: A Multi-Actor Network

Over the 13-year period from 2004 to 2017, ArcticNet funded a total of 152 multidisciplinary research teams (i.e., projects) over four distinct funding phases (Table 2). There were 301 unique organizations from multiple sectors: Canadian academic (n = 55; 18%), northern Canada (n = 96; 32%), international (n = 102; 34%), government (n = 20; 7%), private sector (n = 15; 5%), and non-profit (n = 13; 4%). The total number of unique organizations in the network doubled over time, suggesting that from an organizational diversity perspective, the network was successful in recruiting individuals from new organizations into the network. Each phase saw the introduction of new organizational actors, with increasing participation from different northern and international organizations (see Fig. 1 and Supplementary Appendix Table S1 for breakdown by phase). There was also increased organizational turnover within the non-profit and international sectors by phase; however, overall, there was ongoing participation by a range of organizational actors (e.g., 51 organizations appeared in all four phases, 30 in three phases, 66 in two phases, and 155 in only one phase; see Appendix Fig. S1 for breakdown by sector).

The network analysis included 1659 individual actors. Location data were missing for 134 individuals, so they were excluded in the analysis by geography, but were

TABLE 2. ArcticNet network characteristics over four funding phases.

	Complete network[1]	Phase 1	Phase 2	Phase 3	Phase 4[2]
Years	2004–19	2004–08	2008–11	2011–15	2015–19
No. of projects	152	30	40	40	42
No. of unique organizations	301	94	151	167	175
No. of individuals (% female)	1659 (44%)	394 (37%)	622 (41%)	732 (40%)	728 (39%)
No. of project leaders (% female)	91 (13%)	38 (5%)	45 (6%)	47 (9%)	49 (16%)

[1] The complete network captures all possible networked connections.

[2] Data from 2017–18 and 2018–19 were unavailable and thus not included.

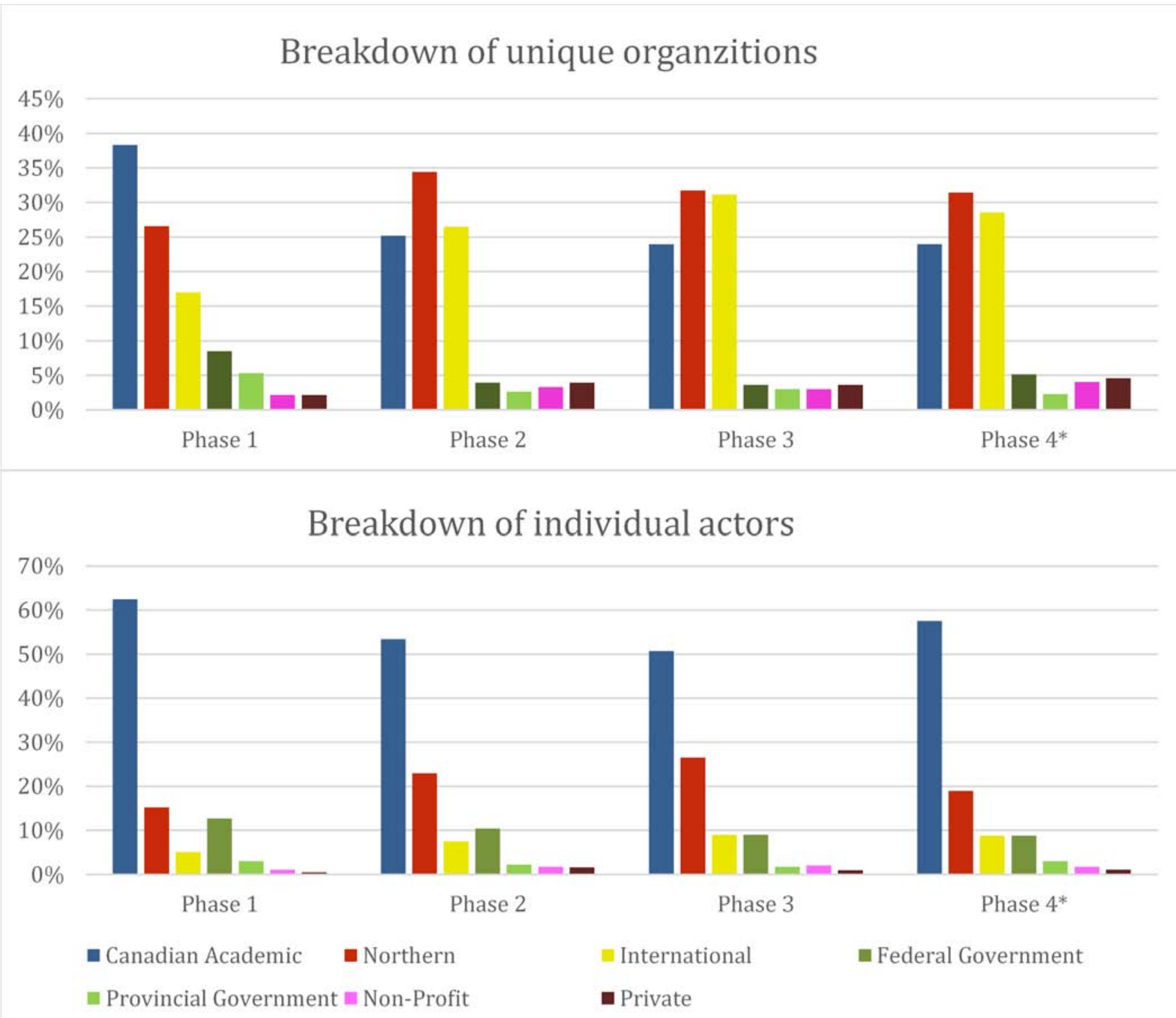

FIG. 1. Distribution of unique organizational and individual Arctic actors by sector during each phase. *Data from 2017–18 and 2018–19 were unavailable and thus not included.

included in all other analyses. Individual actors represented several sectors: Canadian academic (n = 862; 52%), northern Canada (n = 417; 25%), international (n = 147; 9%), government (n = 185; 11%), private sector (n = 20; 1%), and non-profit (n = 28; 2%). In all phases, over half of the individual actors in ArcticNet were from Canadian academic institutions; however, there was a general trend of increasing participation from individuals affiliated with northern and international institutions (Fig. 1; Appendix Table S1). This trend was not observed in Phase 4; however, this may be an artifact of only having partial data for that phase. When examining the other phases, projects tended to incorporate more nonacademic actors at later stages of each phase. Of the individual actors from Canada, the majority of network participants were from Quebec (35%), Ontario (15%), Nunavut (11%), and Newfoundland and Labrador (11%) followed by Manitoba, Alberta, Northwest Territories, British Columbia, Nova Scotia, Saskatchewan, New Brunswick, Prince Edward Island, and Yukon. International actors were largely from the USA (42%), the United Kingdom (11%), Norway (11%), France (9%), Denmark and Greenland (6%), Germany (6%) and Russia (6%), with several individuals from Iceland, Australia, China, Finland, the Republic of Ireland, Japan, the Netherlands, Portugal, Spain, and Switzerland.

Changes to Network Structure

When examining ArcticNet's connections over time, we found an increasing trend in collaboration evidenced by the doubling of the number of actors (both individual and organizational) and network ties in Phase 1 to Phase 4 (see previous section for details). The decrease in network density from Phase 1 to Phase 4 indicates that while the network grew, it had not reached saturation by 2017 (Table 3; Fig. 2). The patterns of connectivity for individual actors trended towards a flatter hierarchy and decentralization over time (i.e., increasing connections, decreasing density, decreasing centralization). From an organizational perspective, centrality remained similar over time, suggesting that despite increasing in size, the network remained centralized with some organizations retaining their dominant positions. Figure 2 illustrates the collaboration networks based on organizational connections in each of the four phases, with the nodes representing organizational actors and lines representing the relationships between actors in each phase. For the visualizations, node colors reflect the sector, node size represents the degree of centrality for each node.

Dominant Actors

To identify the actors who hold the key positions in the network, we paid particular attention to the position of 1) the most central sector actors, 2) local northern actors, and 3) ArcticNet's project leaders. To identify the types of actors that played a central role in the network, we examined actors with a large ego network size and degree centrality, also considering sector and geographic location (local, non-local national, and non-local international). Descriptions of average actor centrality and ego network size by location are in Table 4 (for sectors, see Appendix Table S2).

The average degree centrality for the entire network was 31 for organizations, meaning that the average organizational actor had 31 connections to other organizations inclusive of multiple connections to the same actor; for individual actors, the average ego network size was 43 (Appendix Table S2). An examination of average degree illustrates that more than half of the Canadian academic organizational actors had ego networks larger than the network average in all phases and in the complete network. For the complete network, the organizations with the largest ego networks included Université Laval, Université du Québec à Rimouski, Government of Nunavut, University of British Columbia, and Université de Montréal. The individuals with the greatest ego network size were male actors from Fisheries and Oceans Canada (two actors), University of Manitoba, Trent University, and Memorial University of Newfoundland (Appendix Table S3). Further, the organization that occurred on the greatest number of projects in each phase was ArcticNet's host organization, Université Laval. In summary, the largest ego networks were found among public sector actors (e.g., Canadian academic and federal government) with more representation from northern actors (e.g., Government of Nunavut, Nunatsiavut Government) in later phases.

Public sector actors located in southern Canada (e.g., Canadian academic and federal and provincial governments) represented the group of actors with the largest ego networks (Appendix Table S2). Taking a longitudinal look at participation in ArcticNet, the total number of non-local public sector actors stayed relatively consistent over time. The fact that over 60% of the Canadian academic organizations in ArcticNet participated in three or more phases indicates that these organizations were central to the ongoing existence of the network (Appendix Fig. S1). Data for individual participants corroborates this trend, with 18% of Canadian academic individuals participating in three or more phases. Approximately 20% of individuals from provincial governments also had continued participation (more than three phases), which is high when compared to individuals in each of the other categories whose participation was less than 10% in three or more phases.

When considering changes from Phase 1 to Phase 4, there were small increases in degree centralization for Canadian academic, northern, international, and private sector organizational and individual actors (Appendix Table S2). While provincial governments increased their organizational degree centralization, there was a decrease in degree centralization for individual provincial actors. Conversely, while federal government organizational actors became less central, there were individuals from the federal government who became more central. However, although some individual actors may have increased their degree centrality, the change was not large enough to account for the increased network size resulting in a decrease in average normalized degree centrality. Overall, decreases to normalized average degree were seen for individual and organizational actors from all locations and from all sectors.

Although non-local academic actors from Canada are among the most central actors in ArcticNet, it is important to note an increasing presence of local actors (see Fig. 1, Table 4, Appendix Table S1). While local actors have a smaller average degree compared to non-local Canadian

TABLE 3. Structural measures of ArcticNet's relationships between actors over time.

	Complete network[1]	Phase 1	Phase 2	Phase 3	Phase 4[2]
Organizational relationships:					
Density	10.4%	20.4%	14.3%	14.8%	13.5%
Centrality	59.6%	54.9%	57.8%	53.3%	56.1%
Network size	301	94	151	167	175
Number of ties	9,416	1,786	3,246	4,100	4,116
Ratio ties:nodes	31:1	19:1	21:1	25:1	24:1
Alpha	0.97	0.96	0.96	0.97	0.96
Individual relationships:					
Density	2.6%	7.4%	5.2%	5.3%	4.3%
Centrality	21.4%	26.6%	19.8%	20.2%	13.9%
Network size	1,659	394	622	732	728
Number of ties	71,728	11,482	20,278	28,482	22,926
Ratio ties:nodes	43:1	29:1	33:1	39:1	32:1
Alpha	0.98	0.97	0.97	0.98	0.97

[1] The complete network captures all possible networked connections.
[2] Data from 2017–18 and 2018–19 were unavailable and thus not included.

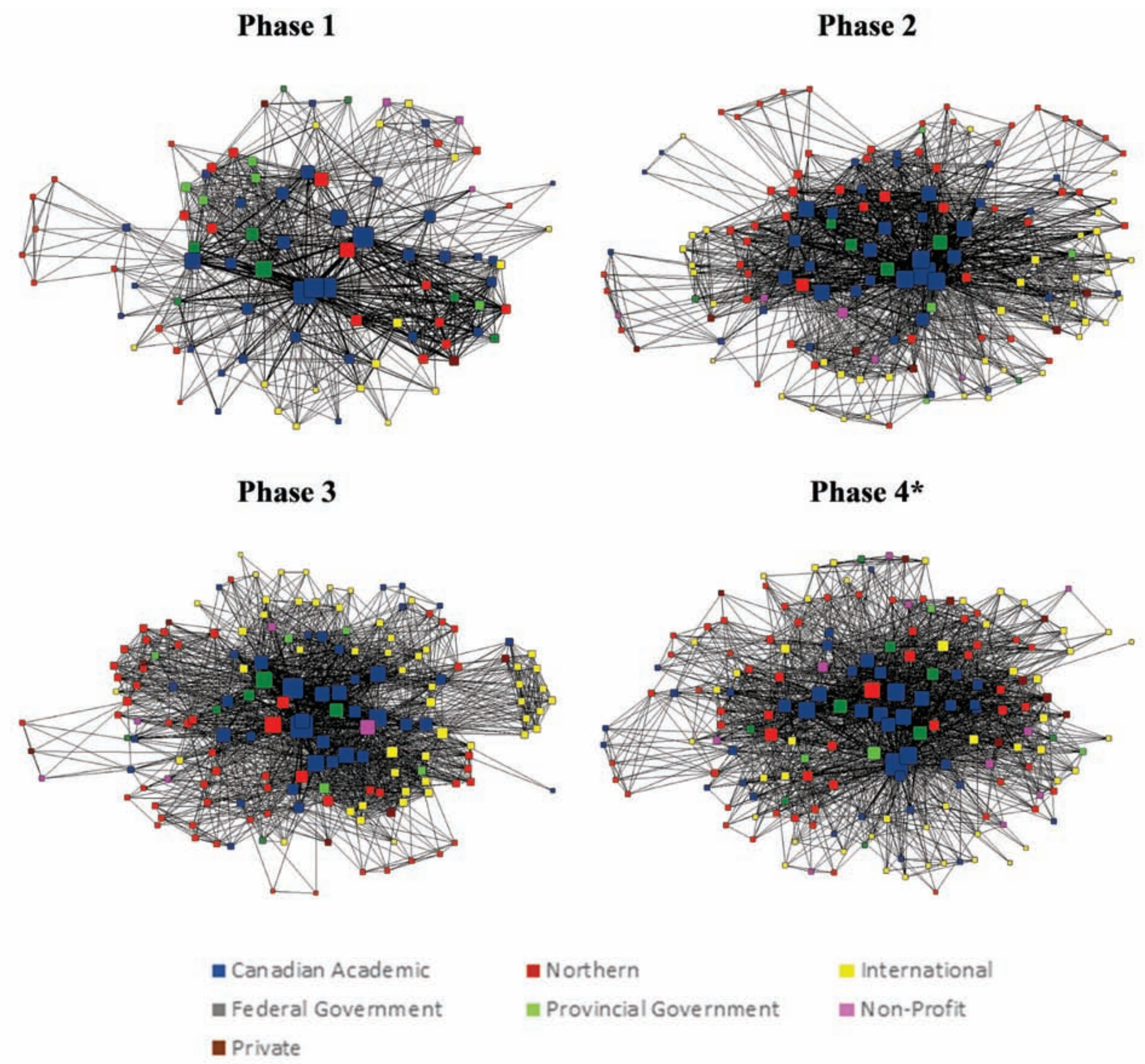

FIG. 2. Actor collaboration networks based on organizational connections in each of the four phases, with the nodes (squares) representing organizational actors and the lines representing the relationships between actors. Node colors reflect the sector, and node size represents the degree of centrality for each node. Data from 2017–18 and 2018–19 were unavailable and thus not included.

TABLE 4. Centrality and boundary-spanning measures for innovation actors by geography.

	Organizations			Individuals		
	Complete network[1]	Phase 1	Phase 4[2]	Complete network[1]	Phase 1	Phase 4[2]
Average of degree	31.3	19.0	23.5	43.2	29.1	31.5
Local	25.8	16.2	19.6	41.2	28.3	30.7
Non-local national	49.0	22.8	32.9	45.1	29.7	31.9
Non-local international	19.7	11.3	14.8	35.4	23.3	29.6
Average of normalized degree	0.10	0.20	0.14	0.03	0.07	0.04
Local	0.09	0.17	0.11	0.02	0.07	0.04
Non-local national	0.16	0.25	0.19	0.03	0.08	0.04
Non-local international	0.07	0.12	0.09	0.02	0.06	0.04
Average of betweenness	145.9	41.1	83.9	1469.2	276.2	682.2
Local	65.8	10.2	43.9	1012.1	30.6	666.0
Non-local national	364.6	68.6	169.8	1815.5	340.7	740.9
Non-local international	15.2	2.2	9.5	245.9	16.6	245.4
Average of normalized betweenness	0.33	0.96	0.56	0.11	0.36	0.26
Local	0.15	0.24	0.29	0.07	0.04	0.25
Non-local national	0.81	1.60	1.13	0.13	0.44	0.28
Non-local international	0.03	0.05	0.06	0.02	0.02	0.09
Average effective size	13.7	6.3	9.5	12.9	6.0	5.4
Local	9.2	2.0	6.1	8.6	2.7	4.5
Non-local national	28.0	9.2	16.9	15.4	6.8	5.9
Non-local international	4.5	3.0	3.0	6.3	3.2	2.9
Average efficiency	0.26	0.24	0.26	0.18	0.14	0.12
Local	0.23	0.16	0.22	0.14	0.08	0.11
Non-local national	0.36	0.30	0.35	0.20	0.15	0.12
Non-local international	0.18	0.16	0.18	0.13	0.12	0.09

[1] The complete network captures all possible networked connections.

[2] Data from 2017–18 and 2018–19 were unavailable and thus not included.

actors, there was an increase over time. However, these increases did not necessarily result in relative increases in degree centralization when compared to non-local actors. Individual actors from international locations and organizations from southern Canada (i.e., non-local) saw the largest average increase in degree of centralization over time.

An investigation of ArcticNet's identified project leaders (PL) (n = 91) illustrates that the majority of PL were males (86%) from academic organizations. The association between PL and academic institutions was expected given that at least one project leader per project was required to have a university affiliation as per the rules outlined by the NCE program. An analysis of gender diversity among ArcticNet's academic leadership is elaborated on elsewhere (Natcher et al., 2020). Node-level analysis suggests that PL were much more central to the network than non-project leaders (average normalized degree project lead/non-leader: Complete network, 0.06/0.02; Phase 1, 0.10/0.07; Phase 2, 0.09/0.05; Phase 3, 0.08/0.05; Phase 4, 0.07/0.04). They were also more likely to be in boundary-spanning positions (average normalized betweenness project lead/non-leader: Complete network, 0.99/0.06; Phase 1, 1.7/0.17; Phase 2, 1.32/0.11; Phase 3, 1.35/0.10; Phase 4, 1.33/0.15), which suggests that these individuals are in relative positions of power within the network.

Cross-Sector Collaboration and Boundary Spanning

Evidence presented above suggests that ArcticNet was successful in recruiting actors from several sectors and geographic locations (local and non-local actors). Cross-sector relations largely took place between non-local Canadian public sector actors (universities, government) and local northern actors. Actors from international locations, Canadian non-profits and the private sector had relatively low average degree centralization when it came to the complete network for both organizational and individual relationships.

Project-level relationships (individuals connected through projects) across themes suggests that actors collaborated differently based on project theme (Fig. 3). In the context of boundary spanning, projects with high betweenness centrality could serve as a platform to facilitate collaborations across the entire network or they could disseminate information across the network more easily. Projects funded under Theme 4 (Northern Policy and Development) and Theme 5 (Knowledge Transfer) scored among the projects that had the most diverse sectoral representation, while Theme 1 (Marine Systems) had the lowest likelihood of cross-organization collaboration. Projects linked to marine and terrestrial systems (Themes 1 and 2) were the least likely to facilitate boundary spanning

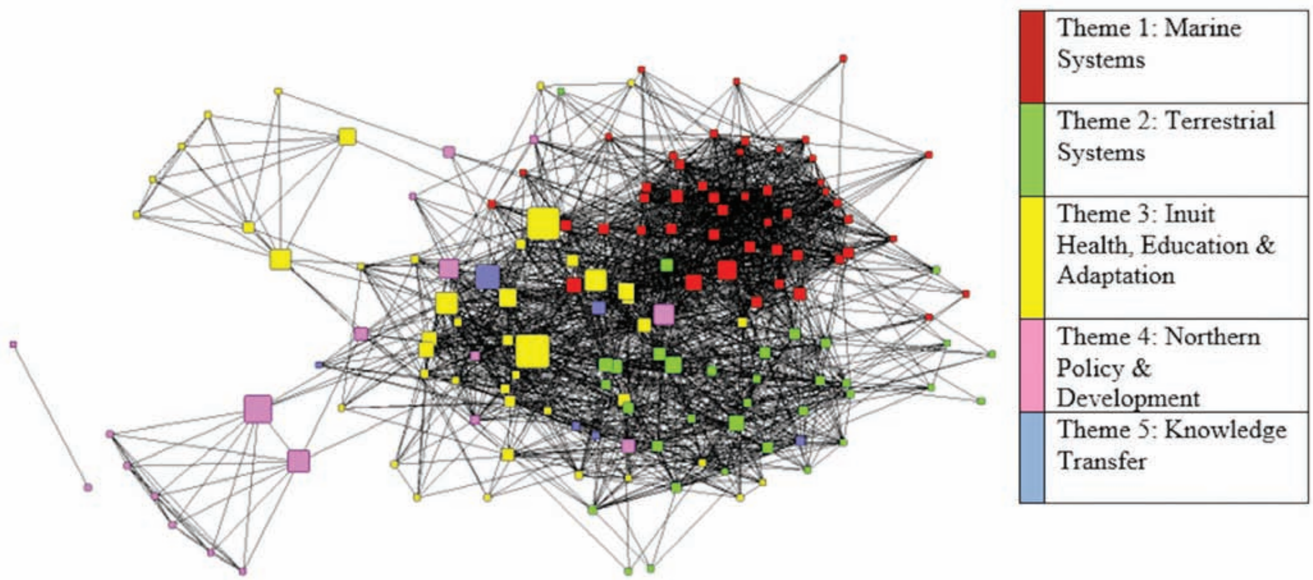

FIG. 3. The complete ArcticNet network of individual actors connected through projects, with the nodes (squares) representing projects and the lines representing the relationships between individual actors. Node colors reflect each project's theme, and the size of nodes corresponds to betweenness centrality scores, which indicate the extent that a project served as a bridge between actors on other projects.

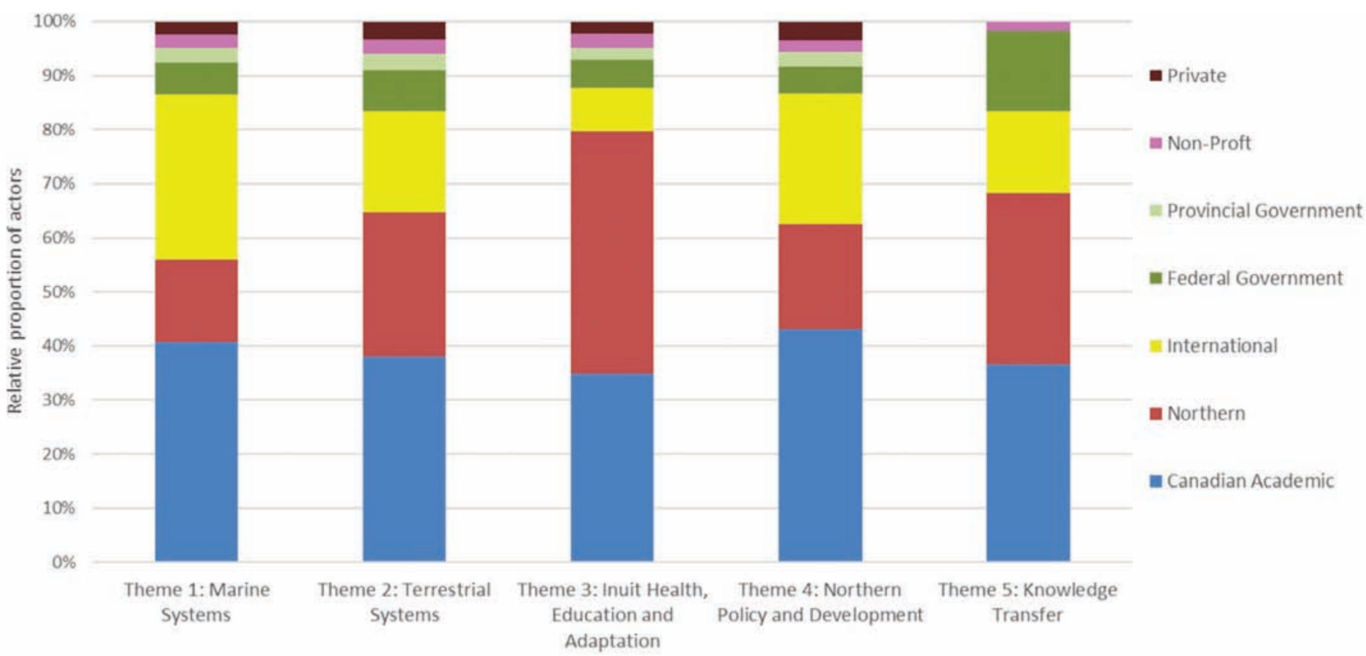

FIG. 4. Breakdown of sector-based organizational collaborations by theme. Data include all phases, and each color represents a different sector.

(avg. betweenness: Theme 1 (62), 2 (62), 3 (111), 4 (105), 5 (116)).

Figure 4 expands this discussion to consider the configuration of sector-based organizational collaborations by theme. Based on these findings, it can be determined that there are different collaboration patterns within the network depending on the topic of focus. For example, projects focused on Theme 3 (Inuit Health, Education and Adaptation) included organizations from all sectors, with local northern innovation actors constituting the largest organizational sector, compared to projects on marine systems (Theme 1), which included the highest proportion of international organizations and the lowest proportion of local northern organizations. Based on the different configurations of actors, it can be argued that each theme reflects a different collaboration pattern, thus potentially different innovation outcomes. It is particularly interesting that Theme 5 (Knowledge Transfer), a topic that in the broad literature is closely associated with the private sector, has engaged virtually no private sector actors.

Overall, Canadian academic organizations and individual actors are the sectors with the highest average betweenness centrality, suggesting that they are most likely to act as boundary spanners, followed by the federal government. These patterns were found in the complete network and in each phase for organizational actors. For individual actors, Canadian academics consistently had the highest average betweenness scores, but actors with affiliations based in northern Canada (i.e., local actors) saw the largest increase in average betweenness from Phase 1 to Phase 4, implying an increased likelihood to carry out boundary-spanning roles. The same pattern is revealed with local individuals in terms of structural holes (Table 4). With respect to individual actors, the overall impact (average effective size) decreased slightly and the proportion of non-redundant ties (average efficiency) also decreased. Interestingly, local (individual) actors did not follow this trend and had the greatest relative increase over time for both impact (average effective size) and non-redundant ties (average efficiency). Overall, the impact of organizational actors increased with time, especially for non-local Canadian organizations (average effective size), and the proportion of non-redundant ties also increased over time for organizational actors (average efficiency).

DISCUSSION

This study reveals the dynamic structural profile of a Canadian Arctic scientific network created to promote science-informed innovation in the Arctic. It provides a useful example of how a systematic examination of network collaboration patterns can yield insight into the broader organization, evolution, and boundary-spanning practices in Arctic science. Contributing to the literature on Arctic science for innovation and impact, the findings characterize science-based innovation actors, their configurations over time and their potential roles within the network. We now reflect on the networked patterns among Arctic scientific research actors to consider the position and role of central actors and present insights that may help to inform policies designed to better serve Arctic innovation needs.

Evidence of a Dynamic Research Network

While effective collaboration is known to define the quality and effectiveness of a regional innovation initiative (Markkula and Kune, 2015), it has generally been assumed that peripheral regions will have less established networks and connections than more central economic regions (De Noni et al., 2018). The results from our structural network analysis of ArcticNet illustrate the potential for non-local research networks to facilitate connections across a large and geographically isolated region of Canada, spanning sectors, disciplinary themes, and geography (e.g., local or non-local). This finding corroborates evidence from other Canadian studies suggesting that formal Canadian scientific research networks have been successful in fostering multidisciplinary and multi-sectoral research collaborations (Clark, 1998; Coutinho and Young, 2016). ArcticNet's collaboration network grew over time, becoming more decentralized as new individuals joined. However, despite a reduced focus on some individuals, the fact that key organizations played an ongoing central role suggests that science-based innovation in the Arctic may be reliant on somewhat entrenched organizational actors.

Central Role of Non-Local Actors

ArcticNet's structure reflects the innovation actor profile of a peripheral region, with limited participation from private sector actors and a high emphasis on Canadian public sector institutions (e.g., governments, academic organizations) (Doloreux and Dionne, 2008; Coates et al., 2014; Pierrakis and Saridakis, 2019). More than half of all ArcticNet actors were affiliated with Canadian academic institutions. The fact that academic actors represent the most central actors (by average degree) reflects expectations for universities to play a central role in regional innovation processes (Benneworth and Fitjar, 2019). Academic actors were also the most likely to act as boundary spanners (high degree betweenness), which suggests that academic entrepreneurship was important for realizing ArcticNet's innovation outcomes (Etzkowitz and Zhou, 2017; Fischer et al., 2018; Schaeffer et al., 2018), and that academic actors are adopting boundary-spanning roles in the Arctic despite potential transaction costs (Pigford et al., 2018). The latter finding echoes a general trend towards academic actors adopting boundary-spanning roles in the context of researching complex global challenges (Schut et al., 2013; Turnhout et al., 2013; Atta-Owusu, 2019), implying that non-local academic actors play a supportive role in facilitating Arctic science and innovation efforts.

The central network position occupied by non-local Canadian academic actors (average centrality, average betweenness, average effective size) is an interesting finding because universities are often restricted to having local innovation spillover effects, which suggests that local universities would have a more direct impact on local innovation outcomes (Schaeffer et al., 2018). While it may be true that local universities are known to have a positive impact on innovation in peripheral regions at a macro-level (Grillitsch and Nilsson, 2015; Kempton, 2015; Brown, 2016), we see that the more micro-level activities undertaken by individual academic actors who adopt entrepreneurial roles in support of network building and cross-boundary linkages can also support innovation (Atta-Owusu, 2019; van den Broek et al., 2019). Given that regional innovation efforts are known to draw upon actors from various locations (e.g., local, cross-regional or cross-country) depending on the availability of local actors (Clarysse et al., 2014), the predominant position and boundary-spanning roles occupied by non-local Canadian academic actors in ArcticNet are likely due in part to the lack of a university in the Canadian Arctic during the time period examined (2003–17) and policies that have directed research funding to university institutions located outside of the region (Abele, 2015; ITK, 2016; Simon, 2017; Obed, 2018).

Increasingly Important Role of Local Actors

While non-local academic actors played a major role in facilitating collaboration in ArcticNet, local actors also filled key roles. Over the 13-year period, there was an increasing tendency for local actor participation in the network (number of nodes and ties doubled from Phase 1 to 4; represent one quarter of all individuals). The need for time to pass in order to see an increase in local participation implies that local engagement in Arctic science may take more time than is allocated within a single research project. Local actors had an increasing propensity for carrying out boundary-spanning roles (increasing betweenness) and had increasing effective size and efficiency, indicating their role in facilitating knowledge flow and addressing structural holes. This finding supports the importance of situating northern actors with local and Indigenous knowledge in central roles within Arctic science and innovation activities (GY et al., 2016; ITK, 2018; Tysiachniouk and Petrov, 2018).

Our analysis also revealed that despite increasing participation and boundary-spanning roles, local northern actors were less likely to be central to the network when compared to non-local Canadian actors. Local actors also had different levels of participation in projects funded under different focal themes. For example, projects funded under Theme 3 (Inuit Health, Education and Adaptation) and Theme 5 (Knowledge Transfer) had the highest levels of local participation, suggesting the areas of most community interest and regional relevance. In light of increasing Indigenous reconciliation efforts and calls for northern actors to have self-determination in Arctic research (TRC, 2015; GY et al., 2016; ITK, 2018), questions concerning who drives the research focus of regional scientific research networks in the Arctic warrant further attention. In the time since this research was conducted, ArcticNet began a new funding cycle (2019–25) and has been working with northern actors to develop a "North-by-North" program that considers and addresses some of these issues (https://arcticnet.ulaval.ca/research), providing one example of how these questions can be tackled.

Implications for Policy

Since collaborative research networks emerge and grow under the influence of public policies for science and innovation, it is clearly important to consider their construction and evolution (Leite and Pinho, 2017). From our findings, we can identify several considerations for policy makers involved in advancing Arctic science and innovation systems governance. Given that non-local academic actors constituted a central and sustained component of the ArcticNet network, it remains relevant that future Arctic innovation policies explicitly account for the wide range of roles that non-local academic organizations play in Canadian Arctic science research networks. The increasing participation by local actors in ArcticNet suggests that future policies could focus on ways to better support the engagement of local innovation actors at the network's core (Oksanen and Hautamäki, 2015). Since the level of actor diversity can influence regional innovation outcomes (Tödtling and Trippl, 2005; Isaksen and Trippl, 2017), efforts to promote more diverse network leadership might also be beneficial, especially given the identified low gender diversity among Arctic academics (Natcher et al., 2020). Thus, it will be important to monitor the outcomes of recent efforts being made by networks like ArcticNet to improve equity, diversity and inclusion among its network members (ArcticNet, 2021). Arctic research and innovation policy should not lose sight of how long it can take for collaborative network relationships to form, as well as their dynamic nature, as highlighted by ArcticNet's structural evolution.

Future Directions

Although only a single case, ArcticNet represents the largest continuous Arctic research network in Canada (2021), presenting the opportunity for a considerable depth of analysis. The results of our network analysis offer novel insight to the structure and evolution of the collaborative relationships within ArcticNet over time; however, it was not designed to answer questions related to network management, the quality of the collaborative relationships being examined, or the innovation outcomes of the different collaborative structures observed. Further research that can address these types of questions is warranted, for example, by examining the relationship between network structure and other innovation outputs (e.g., publications, patents, policies, spin offs). We also recognize that our analysis did not disaggregate the diversity of Northern actors that have participated in the network, with further research required to offer more nuanced insights. In particular, additional social network analysis designed to map the various types of interactions and relationships that exist within the innovation system beyond ArcticNet, with a specific focus on Northern actor participation, would be valuable.

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