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Collaboration Network Analysis for The Arctic Science and Research on A Collection of Publications from 2000-2023

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Abstract

Arctic science and research is widely accepted as a feasible and practical way to address Arctic issues by means of bilateral/multilateral collaboration, and the academic collaboration network would be developed by co-authored publications from scholars of different nationalities. In this study, the academic collaboration network will be investigated quantitatively by social network analysis technology. For this purpose, a total of 24,597 international co-authored publications on Arctic science and research from 2000 to 2023 would be first collected, based on which six academic collaboration networks are developed with the time step of 4 years. Then, social network analysis is employed to analyze these chronological collaboration networks quantitatively in terms of overall structure, temporal evolution, bilateral relations, and core-periphery structure. The findings reveal that the academic collaboration for Arctic science and research continues to expand and strengthen from the first time slice (2000-2003) to the last time slice (2020-2023). It is interesting to find that a triangular structure with North America, Europe, and East Asia as its vertices in terms of collaboration clustering. In addition, the United States always plays a central role, even though there has been continued bilateral/multilateral collaboration on Arctic science and research in the studied time span.

Keywords

Arctic science and research; International collaboration; Social network analysis; Co-authored publications; Incites.

1. INTRODUCTION

Science and research collaboration on the Arctic issues represents an indispensable way to conduct Arctic governance at the international level. The study conducted by Market et al. confirmed that the Arctic is among the most complex and costly regions for scientific inquiry [1]. Therefore, international collaboration on Arctic science and research may benefit Arctic countries in terms of technologies and financial expenditure. Meanwhile, engagement in Arctic science and research also offers a vital avenue for non-Arctic countries to participate in Arctic governance [2]. According to Rüffin et al., Arctic countries are inclined to utilize science to address Arctic issues in areas of low political sensitivity [3]. International collaboration regarding Arctic science and research can mitigate structural uncertainties and suspicions towards non-Arctic countries by fostering alternative communication channels [4]. Long-standing and stable scientific collaboration on Arctic issues significantly contributes to peace and sustainable development within the Arctic. Collaboration and knowledge production are

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crucial stabilizers [5], particularly amidst the Russia-Ukraine conflict and the geopolitical rivalry among significant powers. According to functionalist theories, science diplomacy through international science and research can strengthen interstate relations from the ground [6]. Ernst argued that optimal international scientific collaboration enhances knowledge production and fosters a friendlier and more cooperative international milieu [7]. Furthermore, international scientific collaboration broadens collaboration in other domains and supplies critical information for decision-making and policy [8].

This study is based on the data of international co-authored publications in the Arctic domain retrieved from the Incite database from 2000 to 2023. The social network analysis technology is utilized to establish the collaboration network representing the collaborative relationships among different countries regarding collaboration on Arctic science and research. Then, the developed collaboration network is analyzed quantitatively using the overall network characteristics and geographical distribution. Meanwhile, the bilateral relations and hierarchical characteristics at a step of 4 years are also studied.

2. DATA AND METHODOLOGY

2.1. Data collection

The former Thomson Reuters Technology Group established InCites, a comprehensive science and research database, which is built upon the Web of Science (WoS) core collection. The InCites assists policymakers and research managers in government and academic institutions by analyzing their institutions' academic performance and influence and comparing their research results with those of their global counterparts. This study serves as the primary data source for investigating international collaboration in terms of Arctic science and research.

The data acquisition and organization strategy employed in this study is depicted in Fig. 1, which illustrates the steps to conduct the data collection.

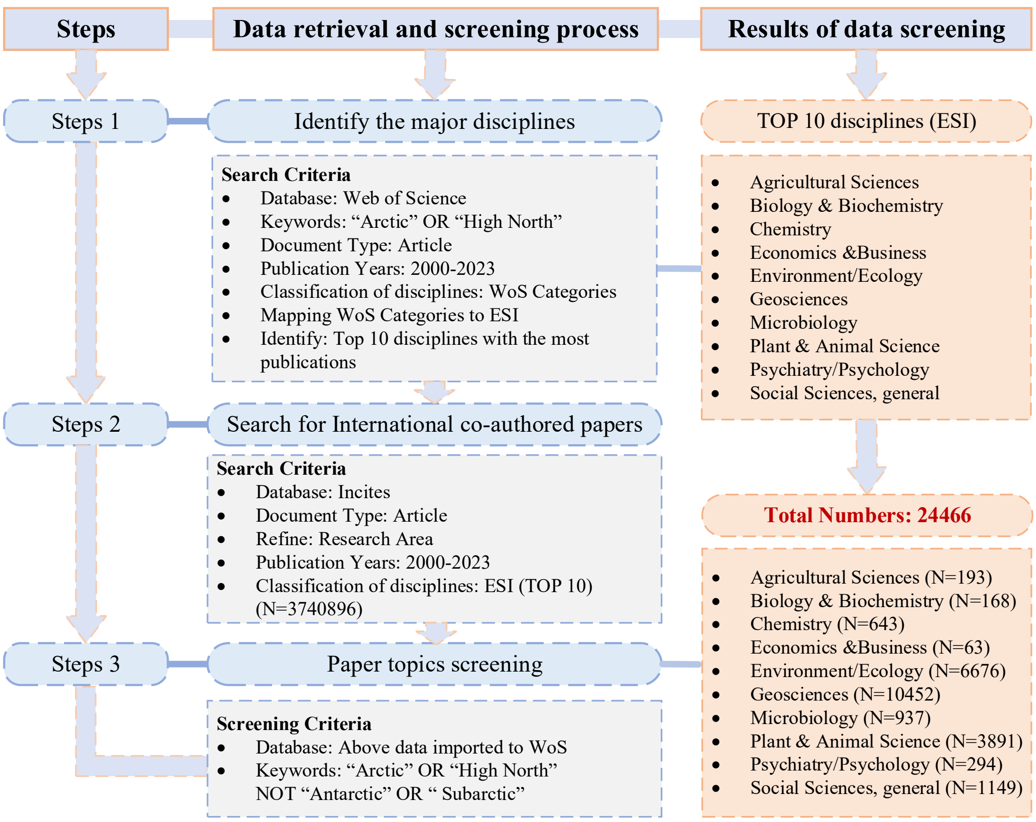

Figure 1. Data collection and selection process

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(1) Identifying the major disciplines. In the WoS Core Collection, the keywords "Arctic" or "high North," with "research area," are selected to initiate the search operations, defaulting to the WoS categories for topic filtering. It is noticeable that WoS categories provide a more detailed disciplinary breakdown. Thus, the results are mapped to the disciplinary classification criteria of the Essential Science Indicators (ESI), which classifies publications into 22 broad disciplines. As a result, these disciplines are ranked according to the number of publications included, and the top 10 disciplines are selected. The publications contained in these disciplines would be considered the initial database in this study. As shown in Fig. 1, These disciplines are Agricultural Sciences, Biology & Biochemistry, Chemistry, Economics & Business, Environmental/Ecology, Geosciences, Microbiology, Plant & Animal Science, Psychiatry/Psychology, and Social Sciences general.

(2) Searching for the international co-authored publications. The international co-authored publications published during 2000-2023 in the fields of the above-mentioned ten disciplines are collected in the InCites. As a result, 3740896 items are collected.

(3) Determining the database for this study. The collected publications in step 2 are then imported into the WoS database, in which these items are screened by the keywords of "Arctic" or "High North" for targeted screening, concurrently omitting items associated with non-pertinent terms, notably "Antarctic" or “subarctic.” As a result, a collection of 24,597 publications is determined as the database for this study.

2.2. Data description

The collected publications are first analyzed statistically against the authors' nationality in the determined ten disciplines, illustrated in Fig. 2.

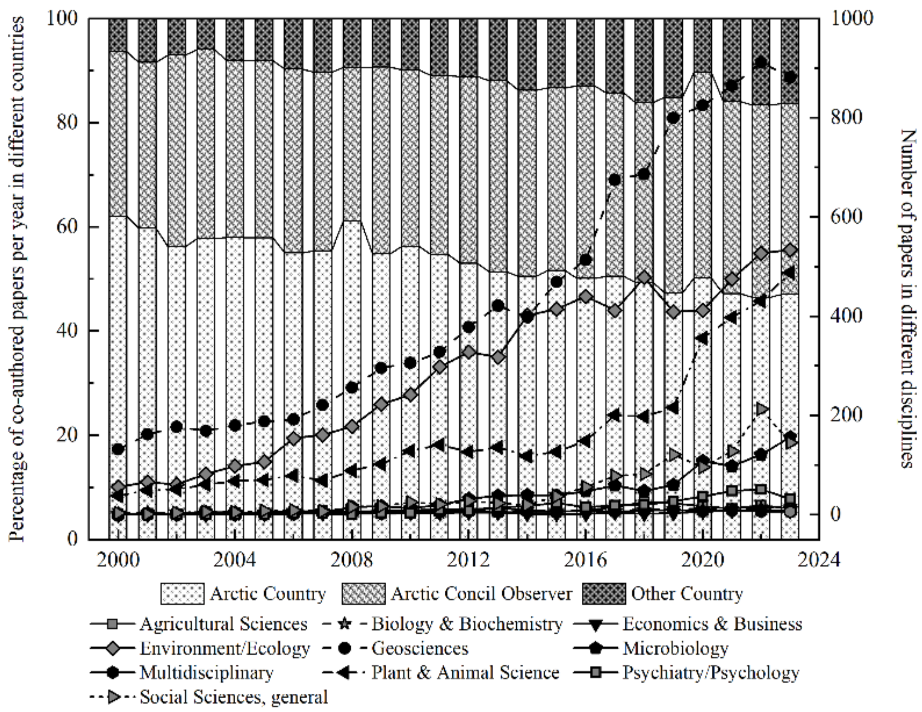

Figure 2. Distributions of the Arctic science and research co-authored publications (2000-2023)

According to Fig. 2, Arctic countries maintain a dominant role in international science and research collaboration in the Arctic, and non-Arctic countries are increasingly making significant contributions to this field. Regarding the disciplinary distribution of these

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publications, the "Geosciences" and "Environment/Ecology" disciplines have seen the most substantial growth. Compared to 2000, the number of co-authored publications in these fields has increased by 5.58 and 8.53 times, respectively. Over the past decade, the disciplines of "Social Sciences, general" and "Microbiology" have experienced the most significant rises in the number of co-authored publications, with increases of 6.3 and 4.1 times, respectively. The information involved in Fig. 2 can be used to underscore the evolving process of Arctic science and research, where international collaboration is critical to addressing broad scientific issues while recognizing the importance of localized studies in understanding and addressing region-specific issues. The data also highlight a disparity between disciplines, reflecting the current state of Arctic science and research, which predominantly focuses on the natural sciences, particularly climate change and environmental protection. In recent years, there has been an increase in social science research, although this area still represents a smaller proportion of the overall research landscape. Many aspects of social science research, such as community-based studies, human health investigations, and regional business and economic assessments, remain predominantly locally relevant. These studies are frequently conducted independently, thus fulfilling national objectives more directly.

2.3. Social Network Analysis

Social network analysis is envisaged as a framework that comprehensively examines the complexities inherent in the structure of social relationships. Traditionally utilized in investigating information flow, interactions on social media, customer engagement, and knowledge networks, this analytical approach has been instrumental in identifying patterns and measuring impacts across various dynamics of relationships. In this study, the collaboration network will be developed, with the countries being the nodes and the co-authored relationships being the edges. It should be noted that in instances where a country is mentioned multiple times within the same publication, only a single instance is counted to represent the country's involvement in the collaborative effort. Each node in the network is weighted by the total number of publications from that country, and the edges are similarly weighted according to the number of publications co-authored between countries. Consequently, an undirected weighted network is established based on the data of the collected co-authored publications. Then, the collected network would be analyzed using the following parameters.

(1) Network density

Network density is a fundamental metric used to measure the closeness of ties within a network. It quantifies the proportion of potential connections in a network that are actual connections.

$$ND = \frac{L}{N\left(N-1\right)} \tag{1}$$

where L represents the number of existing connections and N denotes the total number of nodes in the network. This metric ranges from 0 to 1, with 0 indicating no connections among nodes (a completely sparse network) and one indicating that every possible pair of nodes is connected (a completely dense network). In the present study, network density indicates the closeness of science and research collaboration on the Arctic among different countries.

(2) Average degree

The average degree of a network is defined as the average number of connections per node. In the present study, the average degree reflects the level of average connectivity within the Arctic science and research collaboration network. A high average degree indicates that nodes

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have many connections on average, which may indicate a densely connected network where information can spread quickly. The formula is as follows:

$$AD = \frac{1}{N}\sum_{i=1}^{N} k_i \tag{2}$$

where k_i is the degree of node i; N denotes the total number of nodes in the network.

(3) Degree centrality

Degree centrality is a measure used in network analysis to quantify the importance of a node based on the number of direct connections it has with other nodes. It is one of the simplest and most intuitive centrality measures, representing the extent to which a node is connected within the network .

$$C_D(i) = \frac{k_i}{N-1} \tag{3}$$

where k_i is the degree of node i; N denotes the total number of nodes in the network, and $N-1$ represents the maximum possible connections any node can have in a undirected graph (excluding itself). Then, the average degree centrality of the countries involved in the collaboration network is valued by

$$\widetilde{C}_D = \frac{1}{N}\sum_{i=1}^{N} C_D(i) \tag{4}$$

(4) Closeness centrality

The closeness Centrality metric quantifies the average shortest distance between a node and other nodes. Higher closeness centrality values denote a node's central position and its relative closeness to all other nodes, reflecting its potential to interact within the network quickly.

$$C_C(i) = \frac{N(N-1)}{\sum_{i\neq j}^{N} d_{ij}} \tag{5}$$

where d_{ij} denotes the number of shortest paths between nodes i and j; N denotes the number of nodes. In the present study, a higher closeness centrality suggests that nodes can exchange information more rapidly with others, which typically enhances opportunities for Arctic science and research collaboration. Then, the average closeness centrality of the countries involved in the collaboration network can be calculated by

$$\widetilde{C}_C = \frac{1}{N}\sum_{i=1}^{N} C_C(i) \tag{6}$$

(5) Betweenness centrality

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Betweenness centrality is defined as the number of times a node acts as a bridge along the shortest path between two other nodes. This metric illustrates the node's role as an intermediary in the overall network. The greater the value of a node's betweenness, the greater the node's ability to control the network. The betweenness centrality is valued by

$$C_B\left(h\right)=\sum_{j\neq i\neq h}\frac{d_{ij}\left(h\right)}{d_{ij}} \tag{7}$$

where d_{ij} denotes the number of shortest paths between nodes i and j; $d_{ij}\left(h\right)$ is denoted the shortest paths between nodes i and j, passing through node h. Then, the average betweenness centrality of the countries involved in the collaboration network is valued by

$$\widetilde{C}_B=\frac{1}{N}\sum_{i=1}^{N}C_B(i) \tag{8}$$

(6) Average clustering coefficient

In network analysis, the average clustering coefficient is an important metric that measures the degree of clustering among nodes within a network. The clustering coefficient refers to the ratio of the actual number of edges between a node's neighbors to the maximum possible number of edges that could exist among them. The clustering coefficient, ranging from 0 to 1, quantifies the extent of interconnectivity among a node's neighbors. A higher clustering coefficient indicates that a node's neighbors are more tightly connected to each other. In this study, nodes with high clustering coefficients tended to be nodes that are leaders in the Arctic science and research collaboration. The formula for calculation is:

$$CC\left(i\right)=\frac{2T_i}{k_i\left(k_i-1\right)} \tag{9}$$

where T_i represents the actual number of edges existing between the neighbors of node i; k_i denotes the degree of node i.

The average clustering coefficient of a network is the mean of the clustering coefficients of all individual nodes, which can be calculated by:

$$ACC=\frac{1}{N}\sum_{i=1}^{N}CC\left(i\right) \tag{10}$$

where N is the total number of nodes in the network.

(7) Core and periphery analysis

Core and Periphery analysis is a widely adopted methodological framework in social network analysis that delineates central, highly connected nodes (the "core") from less connected, peripheral nodes (the "periphery"). This paper refers to the approach of current scholars and categorizes countries using structural equivalence and hierarchical clustering algorithms [9].

Specifically, based on the adjacency matrix data between nodes, the Euclidean distance is utilized to calculate similarity for hierarchical clustering analysis, attempting to divide the network into four subgroups.

3. RESULTS AND DISCUSSIONS

3.1. Network characteristics and spatial pattern

According to the principle of social network analysis above mentioned in Section 3.3, the collaboration network regarding publications addressing Arctic issues is developed with the application of the Scimago Graphica tool, and the results are presented as Fig. 3.

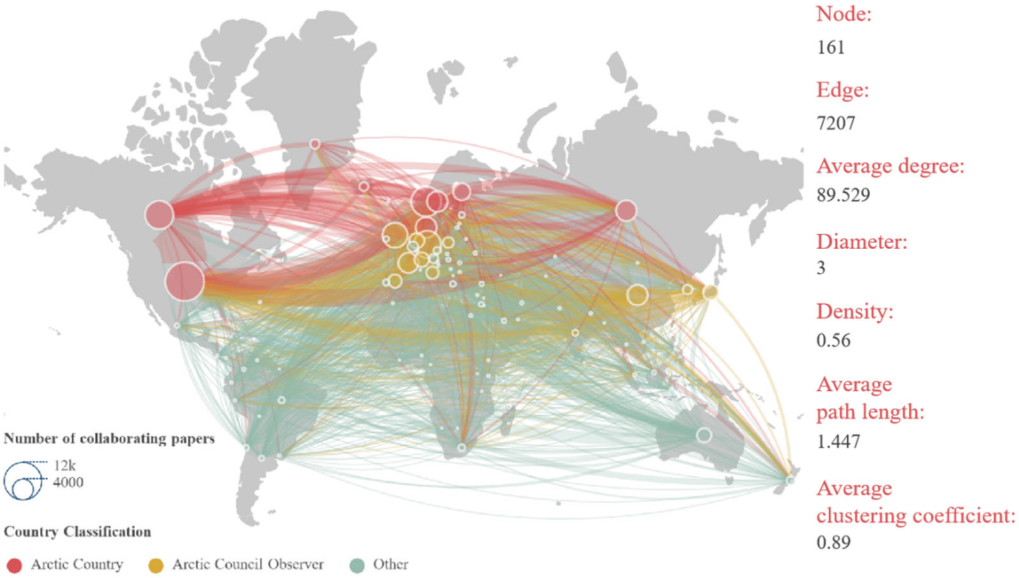

Figure 3. Collaboration network developed by the co-authored publications (2000-2023)

The basic network parameters of this developed network are computed using the Gephi statistical function, presented in Fig. 3. According to the developed network, 161 countries are engaged in these co-authored publications, establishing 7,207 connections (edges) among them. The network density is valued as 0.56, which suggests substantial potential for enhancing international collaboration in this field. The average degree of the network is 89.529, indicating that, on average, each country is linked to more than 89 collaborative countries.

In Fig. 3. the size of each node corresponds to the volume of collaborative activities, the color indicates whether they are Arctic countries, Arctic Council observers, or other countries, and the connecting lines depict the collaborative relationships between countries. The thickness of these lines indicates the intensity of collaboration. It can be observed that the Arctic countries predominantly drive the academic output in co-authored publications, as revealed by Fig. 3. In addition, the entire network exhibits a triangular structure, with the apex composed of high-value regions, including North America (the United States and Canada), the European Union, and East Asia (China, Japan, and South Korea). European countries exhibit robust inter-country collaborative links, with Asia-Pacific and North America as the primary external connections. Norway, England, Germany, Finland, and France are emerged as the core hubs of Europe's external collaborative links. Meanwhile, the United States and Canada form pivotal nodes within the North American research collaboration network. They establish primary internal links while maintaining frequent external connections with Europe and displaying the strongest ties with the Asia-Pacific region, notably China, Australia, and Japan. In contrast, countries in the

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southern hemisphere are largely observed as isolated nodes, a phenomenon attributable to their geographical distance from the Arctic. Despite the trend towards globalization in science and research, collaboration in research publications is less constrained by geographical distance. However, in terms of Arctic science and research collaboration, the geographical divide between the northern and southern hemispheres remains pronounced, which is quite reasonable.

Based on the collection of these publications, the bilateral partnership in terms of Arctic science and research can also be analyzed. Table 1 depicts the ten bilateral partnerships with the highest co-authorship in the period of 2000-2023, detailing the volume of collaborative publications. It is observed that merely four out of the top ten bilateral relationships are between Arctic countries, indicating that collaborative efforts in Arctic science and research transcend geographical confines. The partnership between the United States and Canada is identified as the most prolific, with a collaboration volume approximately 1.46 times that of the United States-Germany collaboration. The appearance of Germany, the United Kingdom, China, and France among the top ten bilateral partnerships reflects their significant engagement in Arctic science and research. Notably, Germany and the United Kingdom exhibit substantial collaborative ties with both the United States and Norway. The prominence of China and France within the top ranks is attributed to their collaborative efforts with the United States.

Table 1. Top 10 bilateral collaborations by co-authored publications (2000-2023)

Rank	Bilateral collaboration	Publications	Rank	Bilateral collaboration	Publications
1	USA-CAN	3412	6	NOR-DEU	1566
2	USA-DEU	2345	7	NOR-GBR	1525
3	USA-GBR	2169	8	USA-FRA	1305
4	USA-NOR	2131	9	USA-SWE	1270
5	USA-CHN	1674	10	USA-RUS	1262

3.2. Temporal evolutionary features

To uncover the dynamic evolutionary trends within the Arctic science and research collaboration network, the period from 2000 to 2023 is segmented into six equal-length intervals. These intervals facilitate the establishment of the network by segmenting the data into four-year time slices. Within these slices, various network indicators are calculated using Gephi, allowing for a comprehensive analysis of the changing patterns of international collaboration over the observed period. As illustrated in Table 2, the number of nodes represents the number of countries or regions co-authoring an international co-authored publication. The number of edges is the number of connecting lines between the nodes, which indicates the extent of collaboration between the countries or regions. The diameter is the average distance between all pairs of nodes.

Table 2. Network parameters of the collaboration networks for each time slice

Time slice	Node	Edge	Density	Diameter	ACC	$\widetilde{C}_D$	$\widetilde{C}_C$	$\widetilde{C}_B$
2000-2003	58	334	0.202	3	0.679	11.571	0.528	27.345
2004-2007	67	553	0.250	4	0.84	16.507	0.551	28.970
2008-2011	87	771	0.206	3	0.845	17.724	0.536	39.402
2012-2015	117	2716	0.400	3	0.887	46.427	0.637	36.214
2016-2019	149	6109	0.554	3	0.912	82.000	0.713	33.584
2020-2023	145	4922	0.471	3	0.872	67.890	0.716	39.507

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According to Table 2, the number of nodes has increased from 58 to 145, the number of edges has increased from 334 to 4,922, the network's diameter has been maintained at approximately 3, and the density has increased from 0.202 to 0.471, which indicates that the scale of international science and research collaboration on the Arctic issues has been expanding and that more and more countries or regions are participating in international collaboration in science and research. Regarding agglomeration, the average clustering coefficient increased from 0.269 to 0.317, which indicates that the agglomeration of nodes in the network is increasing and that countries or regions involved in international collaboration on Arctic science and research are gradually clustering towards certain core countries (nodes). As a result, the cohesive subgroups can be developed. Regarding node characteristics, the average degree centrality has increased from 11.571 to 67.890, and the closeness centrality has increased from 0.528 to 0.716, which demonstrates that collaboration between countries or regions involved in Arctic science and research is becoming more frequent and substantive. The evidence above underscores a robust engagement across international borders, fostering a collaborative environment that is increasingly capable of addressing the complex challenges presented by Arctic-related issues.

It is noticeable that Closeness centrality, a vital measure of a node's importance based on its proximity to other nodes, highlights the efficiency of knowledge transmission within the network. The closer a node is to others, the more significant its role in disseminating high-quality information and integrating knowledge from other nodes. The top 10 countries by closeness centrality are summarized in Table 3.

Table 3. Closeness centrality of the top 10 countries in each time slice

Rank	2000-2003	2004-2007	2008-2011	2012-2015	2016-2019	2020-2023
1	USA	USA	USA	USA	USA	USA
2	CAN	DEU	GBR	FRA	NOR	NOR
3	DEU	FRA	DEU	CAN	GBR	GBR
4	FRA	CAN	FRA	NOR	DEU	CAN
5	RUS	RUS	CAN	DEU	CAN	DEU
6	GBR	NOR	AUS	SWE	FRA	RUS
7	NOR	GBR	NOR	ESP	ESP	AUS
8	DNK	ESP	JPN	GBR	SWE	NLD
9	NLD	NLD	SWE	RUS	DNK	FRA
10	FIN	DNK	RUS	AUS	RUS	SWE

According to Table 3, the United States has consistently held the top position over the last two decades, underscoring its pivotal influence. Traditional scientific powerhouses such as Germany, the United Kingdom, and France have demonstrated significant influence, overshadowing smaller regional players like Finland, Denmark, and Sweden. Notably, Norway's closeness centrality has seen a marked increase, ascending to the second position in the latest time slice, likely due to increased national research investment. Despite not being an Arctic country or an observer of the Arctic Council, Australia has maintained a strong presence in Arctic science and research due to its historical involvement in polar research and its status under the Svalbard Treaty.

Furthermore, Australian entities engaged in mining have bolstered their reputation across the Arctic. China's rising position, from 19th to 12th, indicates a proactive expansion in its Arctic science and research collaboration, reflecting its broader strategy to enhance its influence in global scientific domains. This shift is emblematic of the broader changes within the network,

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where traditional boundaries are becoming less significant in the face of shared global challenges and opportunities.

Betweenness centrality is another quantitative measure of a node's influence over the flow of information within a network. It is predicated on the number of shortest paths that traverse through a specific node relative to all shortest paths in the network. The greater the betweenness centrality of a node, the more significant its role as a broker or gatekeeper of information, thereby granting it the capacity to control and influence the network's dynamics. The betweenness centrality is particularly relevant in Arctic science and research collaboration, where some countries act as vital conduits for collaboration and communication. The countries with high betweenness centrality have the potential to influence research directions. As a result, the top 10 countries with high betweenness centrality are listed in Table 4; the United States has consistently occupied the paramount position, underscoring its pivotal role as a central node in the network throughout the analyzed time span. As discerned from Table 4, Russia's betweenness centrality has experienced fluctuations yet ascended to the second position in 2020-2023, indicating an augmentation in its intermediary influence within the collaborative network. Germany, initially positioned in the third position, has been witnessed ascending to the second during 2004-2007 and subsequently descending to the seventh by 2020-2023. It is noted that European countries such as France, England, and Germany have been intermittently maintaining their presence within the top five, reflecting a persistent significance in their roles as intermediaries within the network. The rise of Norway's betweenness centrality is also noteworthy, peaking at the second position in 2016-2019 and stabilizing at the fourth position in the subsequent period.

Table 4. Betweenness centrality of the top 10 countries in each time slice

Rank	2000-2003	2004-2007	2008-2011	2012-2015	2016-2019	2020-2023
1	USA	USA	USA	USA	USA	RUS
2	RUS	DEU	DEU	CAN	NOR	USA
3	DEU	FRA	GBR	FRA	GBR	GBR
4	CAN	CAN	FRA	NOR	FRA	NOR
5	FRA	RUS	NOR	DEU	DEU	ESP
6	NOR	NOR	AUS	GBR	SWE	CHN
7	DNK	GBR	JPN	CHN	CAN	DEU
8	SWE	DNK	CAN	RUS	RUS	CAN
9	GBR	AUS	DNK	CHE	ESP	FRA
10	NLD	EST	SWE	JPN	NLD	KOR

3.3. Bilateral collaboration analysis in terms of Arctic science and research

Bilateral collaboration is a fundamental mechanism within the international science and research network and is crucial in enabling non-Arctic countries to participate in Arctic governance. Due to disparities in publication volume across countries and some countries' loose connections to the overall network, this analysis is confined to nodes representing countries that produce more than five publications in each time segment. In the early period from 2000 to 2003, bilateral collaboration in Arctic science and research is relatively scarce. Among the 29 countries/regions that published more than five publications, 253 connections were established. Notably, 43 of these links, approximately 17 percent of the total, exhibit a linkage strength of only 1, suggesting that some instances of bilateral collaboration may have been incidental. In stark contrast, the period from 2020 to 2023 has seen a substantial increase in connectivity, with 95 countries each producing more than five publications, resulting in 4,084 bilateral connections, 9 percent of which are characterized by a connection strength of 1,

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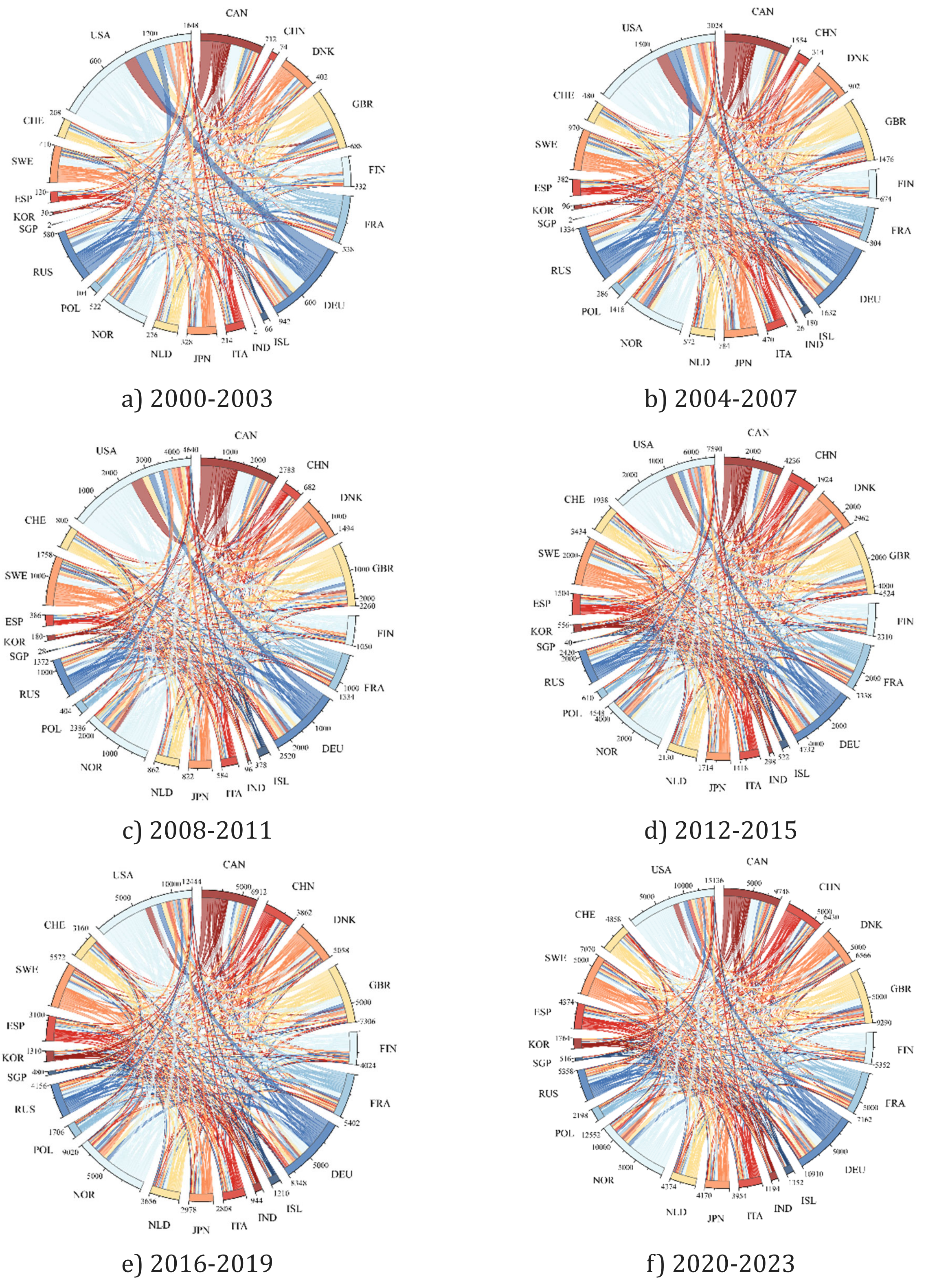
indicating that certain countries are increasingly influential or proactive in fostering bilateral collaboration.



a) 2000-2003 b) 2004-2007

c) 2008-2011 d) 2012-2015

e) 2016-2019 f) 2020-2023

Figure 4. Bilateral collaboration on Arctic science and research for each time slice

Figure 4 delineates the evolution of collaborative networks by depicting the connections among 21 countries, including both members of the Arctic Council and its observer countries,

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in each time slice from 2000 to 2023. The graphic representation quantifies the collaborative publications by the thickness of the connecting chords, indicative of the volume of co-authored scholarly works, and by the arc length, which signifies the network centrality of each country. As highlighted in Figure 4a, during the initial period of 2000-2003, the United States emerged as a central collaborator, engaging with 21 countries and producing 824 joint publications. This volume is approximately 1.75 times greater than that of Germany, with 471 publications, and 2.3 times that of Canada, which is 356. During 2000-2003. The collaborative efforts are most notable between the United States and Canada with 146 publications, the United States and Germany with 134, the United States and the UK with 90, and the United States and Russia with 78. In stark contrast, Asian countries with Arctic interests, such as China and South Korea, establish bilateral collaboration with fewer than half of the represented nodes. Notably, the United States is a partner in 34.6% of Japan's academic publications and 61.1% of those undertaken by China.

From 2004 to 2007 (Figure 4b), the most significant bilateral academic collaboration was also observed by the collaboration between the United States and Canada (299 publications), the United States and Germany (186 publications), and the United States and Russia (rising to 157 publications compared with the number in 2000-2003). Between 2012 and 2015, China's academic output surged, co-authoring 2.82 times as many publications with 21 countries as in the period of 2008-2011, surpassing Japan but still trailing behind traditional European research powers. During this time, the United States is found as China's most significant partner, although China has also notably expanded its bilateral collaboration with other Arctic countries, particularly Nordic ones. In the most recent period (2020-2023), the United States again is listed as the top country with 7,568 co-authored publications, nearly 1.2 times the number of Norway (second position with 6,276 publications) and 1.39 times that of Germany (third position with 5,455 publications). It is interesting to find that during 2020-2023, the leading position of the United States is diluted slightly compared with the earlier time slices. It is noteworthy that collaboration among the five Nordic countries exhibits considerable stability, particularly from the second time slice onwards. The number of bilateral cooperative publications between the Nordic countries is surpassed only by the volume of collaboration between them and major Arctic research powers such as the United States and Canada. This may stem from the consensus among Nordic countries to enhance regional competitiveness and influence through collaboration. NordForsk was established by the Nordic Council of Ministers in 2005, and in 2015, it officially launched the Nordic Arctic Research Program. This initiative issued several collaborative projects focusing on Arctic climate science, environmental science, and social science.

3.4. Hierarchical Structure analysis

The core-periphery structure is a distinctive configuration comprising several elements closely interconnected in a central core with a sparsely dispersed periphery. According to the principle of core and periphery analysis explained in Section 3.3, the collaboration networks of all the time slices can be visualized in the form of a core-periphery structure, and the results are illustrated in Fig. 5. To minimize the possibility of incidental collaboration, only countries with more than five publications were included in this part of the analysis.

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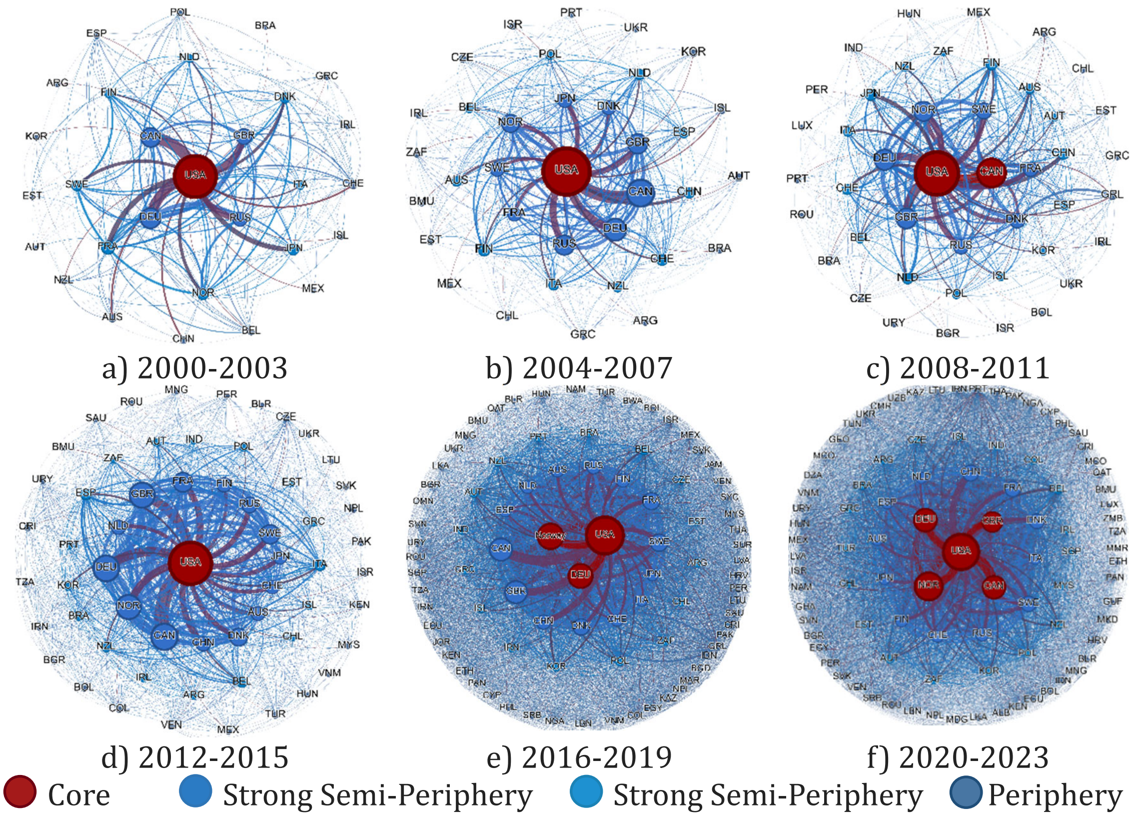

Figure 5. Core-periphery structure of collaboration networks for each time slice

As depicted in Fig. 5, the size of the nodes represents the coreness, which is calculated using the algorithm provided by the UCINET software. Nodes with a high coreness value are typically highly central, indicating that they play a vital role in the network, serving as hubs for frequent interactions, facilitating information flow, or acting as decision-making centers. These nodes may function as opinion leaders in social networks, hold management positions in organizations, or represent major economic entities in economic networks. Additionally, the thickness of the connections in Fig. 5 represents the strength between the two countries.

According to the core-periphery structure illustrated in Fig. 5, it can be observed that the core is extended from a single core to multiple cores, and the number of nodes in the strong semi-periphery circle expands from 4 nodes in a time slice of 2000-2003 to 12 nodes in a time slice of 2020-2023. Meanwhile, the number of nodes in the semi-periphery and periphery circles increases by 1.25 and 2.56 times, respectively. This underscores the expansion of the scale of the Arctic international science and research collaboration network. Additionally, according to the comparison between the first two slices (2000-2003 and 2004-2007) and the fourth time slice (2012-2015), the core circle is dominated by a single country, namely the United States, highlighting its absolute centrality in the Arctic science and research collaboration network and its significant scientific influence and resource allocation capabilities. In the last two time slices, namely from 2016 to 2023, the emergence of Canada, Norway, and Germany alters the initial single-core pattern, establishing them as dominant forces in the network. However, the core position of these countries is still much weaker than that of the United States. Anyway, a new hierarchy within the core circle is being created. Among all nodes, Norway exhibits the largest circle span, transitioning from a semi-periphery circle in the initial period (2000-2003) to a core circle in the latest period (2020-2023), positioning it as the second country followed by the United States in the degree of coreness. This advancement is closely connected to Norway's long-standing emphasis on technological development as a critical aspect of its Arctic policy,

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which enables it to establish itself as a consistently cutting-edge expert in sectors such as Arctic health, energy, maritime, and marine industries.

The increase in nodes within the strong semi-periphery circle indicates the considerable increase in interest in Arctic science and research, which have long been predominantly occupied by developed countries, particularly European countries. The initiation of the EU R&D Framework Program in 1984 is recognized as one of the pivotal factors influencing the development of science and research collaboration networks in this region. Moreover, the highly integrated collaboration networks among European cities have led to a particular historical inertia in Arctic science and research collaboration with Arctic countries. Despite not being an observer state in the Arctic Council, the European Union (EU) has been engaging in academic collaboration on Arctic science and research with Finland and Sweden since 1995. Currently, the EU is a significant supporter and funder of Arctic science and research, such as the Horizon program and the Atlantic-Arctic Lighthouse of the mission--Restoring our Oceans and Waters. Meanwhile, bilateral scientific and technological collaboration agreements with Arctic countries are also involved. For an extended period (2000-2007), Japan was the only Asian country in the strong semi-periphery circle, having established a robust scientific partnership with the United States and becoming a key node in the local network while connecting Asian countries within the periphery circle. When it comes to China, obvious improvement can be observed that the position of China moves from the fourth level in the first time slice (2000-2003) to the third level in the second (2004-2007), and finally stabilizes at the strong semi-periphery level in the fourth time slice (2012-2015). During 2012-2015, the coreness of China surpassed that of Japan, making it the non-Arctic country with the highest coreness outside the United Kingdom, France, and Germany. This advancement may be attributed to the positive attitudes of China in terms of participating in Arctic issues. The number of nodes in the semi-periphery circles has increased from 8 in the first time slice (2000-2003) to 19 in the sixth time slice (2020-2023). In contrast, the proportion of the overall number of nodes has consistently remained between 12 and 14 percent throughout this study (2000-2023). A vital characteristic of the semi-periphery circles is the presence of few and weak intra-group connections. Generally, it can be observed that the countries in the semi-periphery circle are characterized by solid scientific capabilities but relatively limited interest in participating in Arctic science and research collaboration, such as Poland, Greece, South Korea, India, and Singapore.

Additionally, according to Fig. 5, the number of nodes in the periphery of the sixth time slice (2020-2023) is 3.56 times than that of the initial period (2000-2003), and many countries in Asia, Africa, Latin America, and the Pacific Islands are contained in the periphery during 2020-2023. This underscores the fact that the Arctic is becoming a focal point for global attention and that the participation of non-Arctic countries in Arctic science and research is becoming a permanent feature. The countries in this circle are considered followers of Arctic science and research compared to those in other circles. They typically have fewer co-authored publications and only one partner in such collaboration. Several factors may contribute to the peripheral status of these countries in terms of academic collaboration on Arctic science research. First, geographic distance would limit attention to Arctic issues, as seen in the cases of Brazil and Argentina. Meanwhile, weak domestic economies and the high costs associated with conducting Arctic science and research may hinder their participation, as observed in Kazakhstan and Mongolia. In addition, the small size and population may result in a limited capacity for Arctic science and research, such as in Iceland.

4. CONCLUSION

This study is based on 24,597 international co-authored publications on Arctic science and research retrieved and screened from the Incites between 2000 and 2023. Social network

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analysis technology is applied to establish collaboration networks for different time slices with a time step of 4 years, based on which the development and evolution of the Arctic science and research collaboration are quantitatively investigated. The conclusions drawn from this study are as follows.

(1) The scale and connectivity of the academic collaboration networks generally increase from the first time slice (2000-2003) to the last time slice (2020-2023). An increasing number of countries participate in Arctic international science and research collaboration, and the intensity of collaboration has increased by 2.3 times from the first time slice (2000-2003) to the last time slice (2020-2023), leading to a continuous rise in the number of internationally co-authored publications. Additionally, the increase in the network clustering coefficient indicates that the agglomeration of nodes within the network is continuously strengthening. From the perspective of geographical spatial structure, the collaboration network exhibits a triangular configuration with North America, Europe, and East Asian countries as its vertices. North America has emerged as the core of the collaboration network, with European countries forming the main body of the network, while East Asian countries are evolving into new growth points within the network.

(2) Regarding the evolution of bilateral collaboration relationships, both the quantities and frequency of academic collaboration are improved, subsequently forming collaboration groups at different levels. The United States holds a central position in the network, with its collaboration with Canada and Norway being the most frequent relationships in the academic collaboration for Arctic science and research. The EU, in its entirety, is presented as the Arctic science and research center second only to the United States. Nordic countries do not have the highest number of co-authored publications but have a very stable collaboration relationship.

(3) The developed academic collaboration networks are presented with a certain level of hierarchical stratification in the form of "core-periphery" due to the imbalance in Arctic science and research capabilities. The first and second levels constitute the network core, while the remaining levels form the periphery. A strong core layer gradually presents a pattern of one superpower with multiple strong countries, with the United States at the forefront, followed closely by Canada, Norway, and Germany. Additionally, several emerging Arctic research countries, such as China, Australia, and South Korea, have achieved promotion at hierarchical levels from the first time slice to the last one.

Several important policy recommendations can be proposed based on the results obtained from this study. Firstly, all countries should recognize that the trend of international scientific engagement on the Arctic issues is inevitable. Given the harsh conditions for science and research in the Arctic region, there is significant space to improve the density of the academic collaboration network for Arctic science and research. Arctic countries should further open channels for collaboration with non-Arctic countries, allowing for better responses to global issues faced by the Arctic through knowledge exchange and flow. Secondly, for non-Arctic countries, participation in international Arctic science and research remains the best approach to understanding and engaging in the governance of the Arctic. The core forces in Arctic science and research are predominantly from Europe and North America, with few contributions from non-Arctic countries outside these regions. Non-Arctic countries can attract more scientific collaboration by enhancing their research capabilities and the quality of their knowledge production. Additionally, these non-Arctic countries are advised to establish stable collaboration relationships within other areas with critical countries or knowledge alliances in the Arctic collaboration network and gradually expand into Arctic-related issues. Finally, given the turbulent geopolitical situation in the Arctic, Arctic and non-Arctic countries are suggested to acknowledge the role of non-governmental science and research collaboration, which may be able to facilitate the exchange of knowledge and resources that complement governmental

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initiatives. In addition, governments are encouraged to take measures to maintain stable, long-term relationships among scientists in the Arctic field.

Overall, the Arctic science and research collaboration network is a complex and dynamic entity, and it is necessary to augment the data on collaboration with additional information from R&D and collaborative research projects. In addition, the academic collaboration networks are developed in this study by employing a full-counting approach based on the premise that the countries' contributions are equally important. As a result, the variability in the contributions of co-authors has been overlooked, and in the future, a weighted fractional counting method is advised to be adopted for optimization. Finally, the Arctic science and research collaboration networks could be analyzed and discussed in the future according to disciplines, further clarifying the disciplinary directions in which countries engage in science and research collaboration.

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