Polar Research

RESEARCH ARTICLE

Networks of international co-authorship in journal articles about Antarctic research, 1998–2015

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Abstract

This study seeks insight into the social structure of Antarctic research from 1998 to 2015 by examining peer-reviewed journal articles listed in the Science Citation Index of the Web of Science database. This study identifies leading countries in peer-reviewed journal article output and applies social network analysis methods to identify countries where authors are collaborating with those affiliated with organizations in different countries. The results show that the number of publications on Antarctica and the proportion of international research collaboration increased from 23.0 to 33.2% during the period of time being considered. The number of articles published by authors affiliated with institutions in emerging countries such as China, Turkey, Brazil and South Korea rose, whereas the proportion of articles published by authors affiliated with institutions in the United States decreased. The largest proportion of academic publications pertaining to Antarctic research was within the natural sciences. Within this broad field, the majority of publications fell within Earth and related environmental sciences and the biological sciences. Social network analysis shows that Antarctic research moved towards a network, in which researchers are internationally more connected than ever before, with countries such as the United States, the United Kingdom, Germany, France and Australia in central positions. Sweden, Belgium and the Netherlands did not account for a high percentage of academic contributions but were still notable for their multinational collaborative research.

Keywords

Antarctica; polar; research cooperation; bibliometrics; social network analysis; Web of Science (WoS)

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Abbreviations

IPY: International Polar Year
OECD: Organisation for Economic Co-operation and Development
SCAR: Scientific Committee on Antarctic Research
SNA: social network analysis
WoS: Web of Science database, Clarivate Analytics

Introduction

The political, economic and social importance of Antarctica and international competition over its resources have been escalating (Geissler & Kelly 2016; Jang et al. 2016). The growing recognition of Antarctica's role in environmental issues such as climate change is one of the reasons for the recent growth of Antarctic science (O'Reilly et al. 2012). Some emerging countries, such as China and India, as well as Western countries, such as the United States, Canada and European countries, have expanded their research activities and investments in Antarctica at a rapid pace.

The Antarctic is known as an area that requires intensive research collaboration on the account of the region's harsh conditions and remoteness, resulting in complicated logistics and high cost of access (Lüdecke 2003; Erb 2011). Intergovernmental research programmes and organizations, such as the IPY and SCAR, have provided the basis for promoting international and inter-organizational interactions and sharing of data and information to solve complex problems in Antarctica (Lüdecke 2003; Summerhayes 2008).

Has scientific collaboration in Antarctic research increased, as international research programmes aimed? If so, what does the social structure of Antarctic science look like? Which countries are influential in the network of scientific collaboration? Despite efforts to connect scientists, there has been very little research documenting the collaborative structure of Antarctic research.

This paper contributes to filling this gap by drawing on SNA to analyse journal article output as found in the WoS database. Over the past few decades, there have been considerable theoretical and methodological developments in studying scientific collaboration with SNA in the social and natural sciences (Katz 1994; Newman 2001; Barabási et al. 2002). Given growing international efforts to encourage collaborations in the scientific community, we believe that the application of SNA to collaboratively

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produced journal articles will improve our understanding of the social structure of Antarctic research.

The following section reviews the research background of scientific studies of Antarctica and explores the importance of international research collaboration in the region. The third section describes the data and methods used in this study, and the fourth section presents the research findings and discusses them. We conclude with the implications of the findings on Antarctic research.

Research background

Previous studies suggest two main reasons why Antarctic research is essential. First, the Antarctic continent and the regions surrounding the continent play an influential role in the Earth's natural systems: phenomena that take place in the Antarctic have enormous impacts throughout the world, including on human society. For example, the potential demise of the West Antarctic Ice Sheet has great societal importance because of the rise in sea level that would ensue from it. Like the Arctic, the Antarctic Peninsula region has undergone tremendous warming in the past 60–65 years compared with the rest of the planet, and ecosystem change is occurring there at a rapid pace that demands investigation to shed light on the ongoing or future effects of climate change around the world. Second, Antarctica is a so-called natural laboratory that permits the study of organisms, materials (such as meteorites) and natural phenomena (such as solar wind), which are absent or difficult to observe in other regions (Fogg 1992). Some resources in Antarctica, such as oil and mineral deposits, are expected to contribute to scientific and technological developments and to produce considerable economic benefits.

Multiple areas of scholarship have converged in Antarctic research to overcome the extreme environmental conditions and to better understand Antarctic phenomena, which require interdisciplinary knowledge and observation because of their size and complexity (Fogg 1992; Heggie 2016). Research in Antarctica not only requires cutting-edge technology to overcome environmental challenges but also depends significantly on expertise from diverse backgrounds.

Large funds are also needed. In the early 1900s, the greatest obstacle to Antarctic research was the difficulty in securing research funding for research activities (Lüdecke 2003). Germany and the United Kingdom collaborated because they had a shared interest in securing large-scale funding for the research vessels (e.g., icebreakers) required to explore Antarctica (Lüdecke 2003).

International research collaboration has presented itself as both an asset and a constraint for the development of Antarctic research. By combining resources and technology from multiple actors, collaborative research has made it easier to deal with problems in scientific research, which are difficult for individuals or single organizations to solve. Joint investment and technical collaboration can lower the risk of investment and increase scientific capacity.

The IPY was launched in the 19th century to secure consistency in observing a wide range of natural phenomena with global impacts (Summerhayes 2008). It led to the emergence of intergovernmental programmes and structures that set the agenda for Antarctic research such as the International Geophysical Year of 1957–58 and the IPY of 2007–09 (Summerhayes 2008). The Antarctic Treaty System, through which the region is governed (Hanessian 1960), and SCAR were the major outcomes of the International Geophysical Year. The Antarctic Treaty has encouraged international cooperation by demilitarizing the Antarctic continent after the Cold War and by offering a platform to discuss common issues affecting humanity (Chown et al. 2012; Bray 2016; Petrică 2017). Diverse issues, such as the rights to biological resources, the environmental impact of research activities in Antarctica and the management and sharing of data, are discussed in an international context (Summerhayes 2008). SCAR has played a critical coordinating role in scientific research on Antarctica since the committee's founding in 1958. SCAR sets the agenda by leading working groups for the development of Antarctic research (SCAR 2010). It has also functioned as a nongovernmental international organization operating under the regime of the Antarctic Treaty (Elzinga 2009; Jang et al. 2016). Other organizations are part of this system and are represented in the Antarctic Treaty Consultative Meetings, such as the Antarctic and Southern Ocean Coalition, and the International Association of Antarctica Tour Operators. As these organizations and committees become more organized, they have provided researchers with various incentives, such as providing funding, education and collaboration opportunities, and have also guided individual researchers to produce consistent and shareable results.

Several studies have examined the collaborative features of Antarctic research by looking at published outputs. Aksnes & Hessen (2009) suggested that the main feature of polar research is the increasing tendency towards greater international collaboration. They found that international collaborative research made up 10% of total publications in the early 1980s, rising to 41% by 2007. Countries that had published more articles were found to be more active in pursuing international collaborative research (international co-authorship) in later years. Dastidar & Ramachandran (2008) reported that

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countries with higher productivity (a larger number of published articles) were more active in collaborative activities. Erb (2011) also found that collaborative journal publications are more frequent in Antarctic research than elsewhere.

These studies had some limitations in describing the collaborative structure in Antarctic research, however. Aksnes & Hessen (2009) combined Arctic and Antarctic research, even though the two regions have different natural and political environments. Dastidar & Ramachandran (2008) and Jang et al. (2016) added important pieces of evidence that shows the growing body of the literature and international collaborations in Antarctic research by drawing on SNA approaches. However, Dastidar & Ramachandran (2008) covered the data only up to 2004, after which time the structure of Antarctic research has changed considerably. Their study was also limited to articles that included "Antarc*" in the title, which probably excluded some Antarctic-related journal articles. Jang et al. (2016) described the rapidly evolving landscape of growing international collaborations in Antarctic research by using more comprehensive data coverage based on keywords related to Antarctica (Jang et al. 2016). However, the focus of their study was South Korea.

To help fill out our understanding of international scientific collaboration in Antarctic research, this study builds on previous research and other literature and performs SNA of co-author relationships, thereby supplementing the limited findings of previous research.

Academic research network

There have been broad applications of SNA to research collaboration studies in the social and natural sciences (Newman 2001; Barabási et al. 2002; Grossman & Erdo 2002). Two general approaches are found in the literature. The first approach focuses on the structural properties of the network itself and its changes in a macroscopic perspective. This perspective examines the entire structure and evolution of the network by using structural measures, such as density and clustering coefficients (Newman 2001; Barabási et al. 2002; Otte & Rousseau 2002; Watts & Strogatz 2011; Borrett et al. 2014). The second approach takes a more microscopic view by focusing on identifying and interpreting specific nodes and ties (Wellman 1983; Wasserman & Faust 1994). Many studies have tried to find key actors or meaningful subgroups within the network structure of collaboration (Leydesdorff 2007; Boardman 2009; Abbasi et al. 2012). This approach is beneficial, especially for identifying the central individual or organizational actor within the collaborative structure.

Many network structure studies use a variety of methods and indices (e.g., degree centrality and clustering coefficients) to compare and analyse the individual properties of nodes in each network. These SNA methods are based on the premise that high-status nodes in the network are likely to have a significant influence on other individuals connected directly and indirectly to them.

This study seeks to apply both macro- and microscopic SNA approaches to understand the collaborative structure of Antarctic research. From the macroscopic perspective, we attempt to analyse patterns, in which academic fields are represented in the relevant journal articles through the years. From the microscopic perspective, we attempt to identify the countries playing key roles in Antarctic research publications.

Data and methods

Data

In this study, we extracted bibliographic data on Antarctic-related articles from the WoS database by developing a search query that includes keywords related to Antarctica. Using a simple search word, such as "Antarctic*," or looking at only selected journals, might be an intuitive way of identifying Antarctic journal articles; however, such methods may omit a significant number of studies. For example, one of the most cited articles in our data set, entitled "A mesoscale phytoplankton bloom in the polar Southern Ocean stimulated by iron fertilization" (Boyd et al. 2000), cannot be captured by "Antarctic*" because it does not include the term in the title, keywords or abstract.

To overcome this challenge, we used two-step extractions in making the data set. In the first stage, we downloaded the initial set of references with a simple keyword, "Antarctic*" and extracted a set of 864 keywords directly related to Antarctica from titles, keywords and abstracts (see Supplementary material). These keywords were primarily place names (such as "Byers Peninsula"), research station names (such as Concordia Station) and species names (such as "*Cryptopygus antarticus*" and "elephant seal"). We then used these keywords to identify 78 916 relevant articles published between 1998 and 2015.

In the second stage, we obtained the data—such as the national affiliations of each co-author—from these articles. The body of articles was reduced to 78 445 after 471 articles that omitted institutional or country information were excluded from the data set.

We later reclassified the data by using the OECD Category Scheme (NESTI Working Party 2007) to compare the subfields of Antarctic research. The OECD scheme classifies science and technology fields using six major codes (natural sciences, engineering and technology, medical and health sciences, agricultural sciences, social sciences and humanities) and 42 minor codes (NESTI Working Party 2007).

WoS classifies articles based on the journals, in which they are published; many of the journals belong to multiple categories. When an article had been published in a journal belonging to more than one WoW category, for the purpose of our analysis, we classified it as either belonging to multidisciplinary sciences or to one of the six major OECD fields. If all the categories to which a journal belonged fell into one of the major categories, then the article was classified as belonging to that major category. For example, *Journal of Insect Physiology* is included in three categories in WoS—entomology, physiology and zoology—which are all subfields of natural sciences, so for the purpose of this study, Antarctic-related articles in this journal were classified as natural sciences articles. If a journal belonged to categories that did not fall under a single major category, articles in that journal were categorized as representing multidisciplinary sciences. For example, *Environmental Science & Technology* has two categories in WoS: engineering (major OECD category: engineering and technology) and environmental sciences & ecology (major OECD category: natural sciences). Articles in this journal were classified as multidisciplinary sciences.

Methods

With a focus on international collaborative research, we analysed the form of the collaborative networks built by individual countries for research by year by drawing on descriptive statistics and four centrality measures commonly used in SNA studies that assess the network property of each country: degree centrality, closeness centrality, betweenness centrality and eigenvector centrality.

First, degree centrality indicates how many direct ties an actor has with alters in the network. In the context of international collaboration, a country with more ties may be more likely to influence the field by having more connections with other countries. Equation 1 shows how to calculate degree centrality (Freeman 1978).

$$C_D\left(N_i\right) = \sum_{j=1}^{g} x_{ij},\ i \neq j \tag{1}$$

$C_D(N_i)$ denotes the degree centrality of country i, g is the number of countries, $\sum_{j=1}^{g} x_{ij}$ is the number of links that country i has with other (g–1) countries and x_{ij} = 0 or 1.

Second, closeness centrality considers both direct and indirect links in a network in estimating centrality. It emphasizes the distance between one actor and another within the whole network and is calculated as the function of the distance of the shortest paths between actors. Equation 2 expresses how closeness centrality is calculated.

$$C_C\left(N_i\right) = \frac{1}{\sum_{j=1}^{g} d\left(N_i,\ N_j\right)},\ i \neq j \tag{2}$$

$C_C(N_i)$ denotes the closeness centrality of country i and $\sum_{j=1}^{g} d\left(N_\mathrm{i}, N_\mathrm{j}\right)$ is the sum of the distances of the shortest paths between actor i and actor j.

Third, betweenness centrality means the degree to which the links which are not directly connected within the network can be bridged. In the network, some actors might play a critical role by bridging relationships among other actors. Therefore, bridging countries can function as coordinators for information and resource exchanges that occur within the polar research network. They may increase the possibility of convergence research among different academic fields. Equation 3 expresses the method for measuring betweenness centrality.

$$C_B\left(N_i\right) = \frac{g_{jk}\left(N_i\right)}{g_{jk}},\ i \neq j \tag{3}$$

$C_B(N_i)$ denotes the betweeness centrality of country i and g_{jk} denotes the number of short paths between actors j and k.

Fourth, eigenvector centrality is an index that considers not only the number of actors connected but also their importance (Wasserman & Faust 1994). In other words, the eigenvalue centrality of a node increases when it is connected to other highly connected nodes. Eigenvector centrality is calculated by the formula:

$$C_E\left(N_i\right) = \lambda \sum_{j=1}^{g} x_{ij} C_D\left(N_j\right),\ i \neq j, \tag{4}$$

where $C_E(N_i)$ denotes the eigenvalue centrality of country i, g denotes the number of countries in the network and x_{ij} is a binary indicator of the number of links between countries i and j.

Results and discussion

Output over time

In our data set, the number of publications steadily increased during the period being examined. The natural sciences have the largest share among the six broad research areas and multidisciplinary sciences (Table 1). A

Table 1 Number of articles by research area and year. The categories are drawn from the OECD science and technology classification (NESTI Working Party 2007).

Year	Natural sciences	Engineering and technology	Medical and health science	Agricultural sciences[a]	Social sciences	Humanities	Multi-disciplinary sciences	Total
1998	1880	58	105	203	9	2	630	2887
1999	1888	65	130	186	10	3	623	2905
2000	1995	66	156	220	25	1	614	3077
2001	2102	65	130	243	9	1	671	3221
2002	2222	43	146	262	5	5	670	3353
2003	2302	70	144	308	9	3	788	3624
2004	2497	67	145	322	7	2	891	3931
2005	2388	73	142	341	11	4	785	3744
2006	2508	93	168	333	18	2	943	4065
2007	2625	104	159	323	15	7	971	4204
2008	2847	104	167	324	27	7	986	4462
2009	2781	111	173	366	19	4	964	4418
2010	3190	136	139	430	29	9	991	4924
2011	3410	127	193	465	19	4	1066	5284
2012	3640	150	167	437	24	14	1128	5560
2013	4225	170	211	462	3	2	1236	6309
2014	4245	158	191	416	5	3	1275	6293
2015	4136	165	199	449	5	1	1229	6184
Total	50 881	1825	2865	6090	249	74	16 461	78 445
(%)	(64.9)	(2.3)	(3.7)	(7.8)	(0.3)	(0.1)	(21.0)	(100.0)
CAGR[b](%)	4.7	6.3	3.8	4.8	-3.4	-4.0	4.0	4.6

[a]Includes fisheries research. [b]Compound annual growth rate: $\left(\frac{\text{End value}}{\text{Start value}}\right)^{1/\text{years}} - 1$.

total of 50 881 research articles—approximately 64.9%—of the articles fell within this category.

Articles with one author versus multiple authors

Out of 78 445 articles, 5220 articles (6.7%) were single-authored, while the rest of the articles involved two or more authors (Table 2). This proportion of single-authored articles is relatively low. Waltman & van Eck (2015) reported that the proportion of single-authored articles (including review papers) published between 2009 and 2010 and in WoS was higher than 10% in all fields.

In the category of natural sciences, the proportion of single-authored articles was 7.6% (3876 articles), and the largest portion—15 623 articles (29.3%)—was written by two authors. The second-largest area—agricultural sciences—which included 6090 articles largely in the field of fisheries included 5.1% of single-authored articles. Multidisciplinary sciences had the lowest proportion of single-authored articles: 3.9%. In contrast, the proportion of single-authored articles was considerably higher in the social sciences (43.4%) and humanities (81.1%). This may reflect the general solo-authorship tendency in these fields, though co-authorship has become increasingly typical in the fields as well (Henriksen 2015; Macfarlane et al. 2017).

International co-authorship

The proportion of international collaborations that involved two or more countries continuously increased from 1998 to 2015 (Table 3). We defined an international collaboration in this study as an article written by two or more authors affiliated with organizations located in different countries. Ninety-one articles written by a single author who was affiliated with multiple organizations located in different countries were coded as single-country articles. With the steady increase in the proportion of multi-authored articles, the proportion of multi-countries articles increased from 23.3% in 1998 to 39.8% in 2015 (Fig. 1).

As of 2015, the natural sciences had the highest percentage of multi-countries articles, 38.5%, followed by 27.9% of the fields of medical and health science and 25.9% of multidisciplinary sciences (Table 4).

Although there were variations across the fields, the overall trend was that the percentage of multi-countries articles increased from 23.0% in 1998 to 39.8% in 2015 (Fig. 2).

Table 2 Number of authors by research field. The categories drawn from the OECD science and technology classification (NESTI Working Party 2007).

Number of authors	No. of natural sciences articles (%)	No. of engineering and technology articles (%)	No. of medical and health science articles (%)	No. of agricultural sciences[a] articles (%)	No. of social sciences articles (%)	No. of humanities articles (%)	No. of multi-disciplinary sciences articles (%)	Total (%)
1	3876 (7.6)	101 (5.5)	117 (4.1)	308 (5.1)	108 (43.4)	60 (81.1)	650 (3.9)	5220 (6.7)
2	9418 (18.5)	271 (14.8)	400 (14.0)	1108 (18.2)	48 (19.3)	8 (10.8)	2507 (15.2)	13 760 (17.5)
3	10 125 (19.9)	348 (19.1)	528 (18.4)	1307 (21.5)	32 (12.9)	3 (4.1)	3266 (19.8)	15 609 (19.9)
4	8775 (17.2)	384 (21.0)	524 (18.3)	1185 (19.5)	25 (10.0)	2 (2.7)	3115 (18.9)	14 010 (17.9)
5	6612 (13.0)	300 (16.4)	435 (15.2)	863 (14.2)	17 (6.8)	1 (1.4)	2538 (15.4)	10 766 (13.7)
6	4225 (8.3)	175 (9.6)	302 (10.5)	569 (9.3)	12 (4.8)		1768 (10.7)	7051 (9.0)
7	2748 (5.4)	111 (6.1)	244 (8.5)	340 (5.6)	4 (1.6)		1115 (6.8)	4562 (5.8)
8	1715 (3.4)	66 (3.6)	125 (3.2)	196 (3.2)	1 (0.4)		624 (3.8)	2727 (3.5)
9	991 (1.9)	23 (1.3)	70 (1.6)	96 (1.6)			345 (2.2)	1534 (2.0)
10 or more	2396 (4.7)	46 (2.5)	120 (1.9)	118 (1.9)	2 (0.8)		524 (3.2)	3206 (4.1)
Total	50 881 (100.0)	1825 (100.0)	2865 (100.0)	6090 (100.0)	249 (100.0)	74 (100.0)	16 460 (100.0)	78 445 (100.0)

[a]Includes fisheries research.

Table 3 Proportions of single-authored, multi-authored, single-country and multi-countries articles by year.

Year	Percentage of single-authored articles	Percentage of multi-authored articles	Percentage of single-country articles[a]	Percentage of multi-countries articles
1998	11.2	88.8	77.0	23.0
1999	11.4	88.6	74.7	25.3
2000	11.4	88.6	74.8	25.2
2001	10.1	89.9	73.2	26.8
2002	9.4	90.6	72.0	28.0
2003	8.0	92.0	70.7	29.3
2004	7.7	92.3	69.6	30.4
2005	8.1	91.9	69.2	30.8
2006	6.9	93.1	67.8	32.2
2007	6.7	93.3	67.4	32.6
2008	6.3	93.7	67.8	32.2
2009	5.7	94.3	66.6	33.4
2010	5.8	94.2	65.7	34.3
2011	5.0	95.0	63.6	36.4
2012	4.2	95.8	62.2	37.8
2013	4.4	95.6	61.5	38.5
2014	4.2	95.8	60.9	39.1
2015	4.1	95.9	60.2	39.8
Total	6.7	93.3	66.8	33.2

[a]Single-country articles include articles written by one author or a group of authors affiliated with more than one organization located in one country.

Output by country

The United States published the largest number of articles (Table 5). From 1998 to 2015, 18 445 articles were first-authored by those from institutions located in the United States. The United Kingdom and Canada were ranked second and third, with 6031 and 5752 articles, respectively.

There was a gradual increase in the number of countries that in the upper 80th percentile in terms of article authorship (Table 5). In 1998, 11 countries produced 80% of the articles in the field, but by 2015, this number had increased to 17 countries. Compared with the increase in the number of articles published by the countries in the 80th percentile of the articles, there was an even greater increase in the number of articles presented by newly emerging countries (Supplementary Table S1). Towards the end of the period being examined, decreases in the shares of the countries that had initially led the field are also noteworthy.

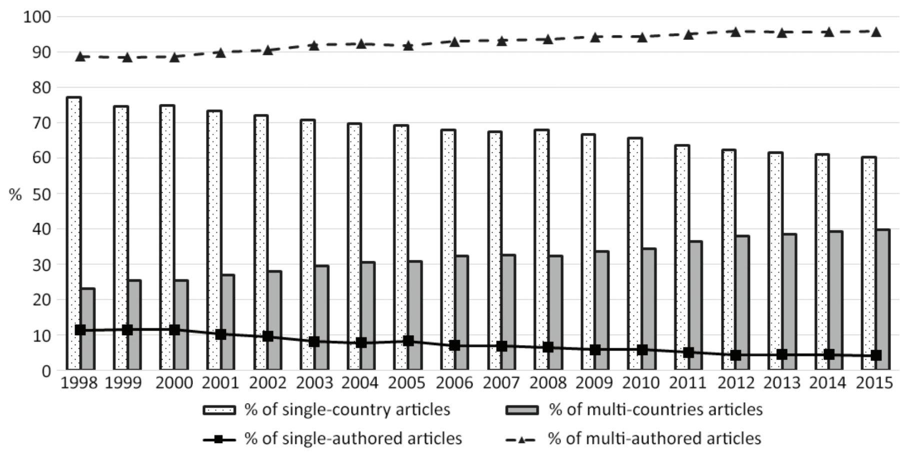

Fig. 1 Trends of single-authored, multi-authored, single-country and multi-countries articles.

Table 4 Percentage of multi-countries articles by research field. The categories are drawn from the OECD science and technology classification (NESTI Working Party 2007).

Research field	1998	2000	2005	2010	2015	Total	Total number of articles
Natural sciences	26.3	27.4	34.8	40.8	46.0	38.5	50 881
Engineering and technology	6.9	12.1	19.2	16.2	26.1	18.8	1825
Medical and health sciences	13.3	28.2	30.3	31.7	34.7	27.9	2865
Agricultural sciences[a]	10.3	13.6	15.0	15.1	19.6	16.1	6090
Social sciences	11.1	12.0	18.2	13.8	40.0	20.5	249
Humanities	0.0	0.0	0.0	0.0	0.0	5.4	74
Multidisciplinary sciences	20.5	23.5	26.9	25.4	29.0	25.9	16 461

[a]Includes fisheries research.

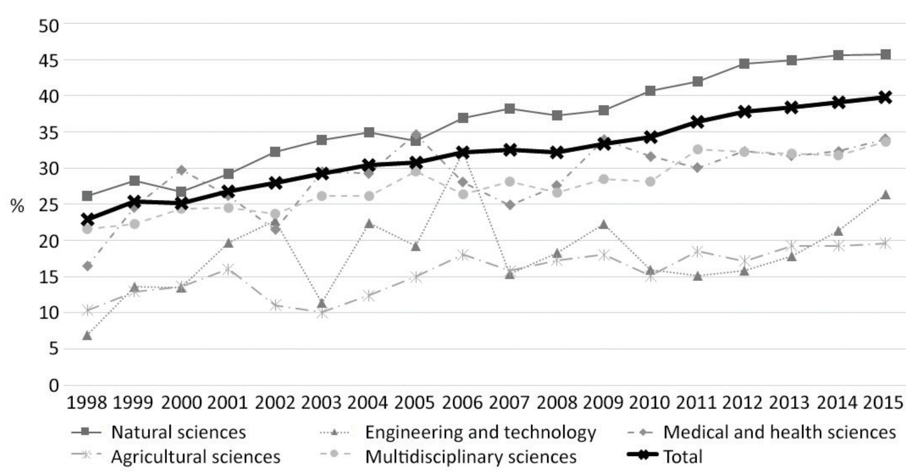

Fig. 2 Yearly trend in the percentage of multi-countries articles by research field. The fields of the social sciences and humanities are excluded because of their inconsistent trends due to the small numbers of observations.

Table 5 Of the total number of articles, the percentage with authorship from countries at or above the 80th percentile.

Rank	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Total
Total	2887	2905	3077	3221	3353	3624	3931	3744	4065	4204	4462	4418	4924	5284	5560	6309	6293	6184	78 445
1	USA (25.4%)	USA (23.4%)	USA (25.2%)	USA (26.4%)	USA (23.3%)	USA (26.7%)	USA (26.2%)	USA (25.7%)	USA (24.7%)	USA (23.9%)	USA (25.1%)	USA (22.6%)	USA (22.0%)	USA (20.8%)	USA (21.4%)	USA (19.9%)	USA (21.8%)	USA (18.9%)	USA (23.0%)
2	UK (9.5%)	UK (9.7%)	UK (9.7%)	UK (10.1%)	UK (10.1%)	UK (8.7%)	UK (8.3%)	UK (8.6%)	UK (8.2%)	UK (8.1%)	CAN (7.9%)	CAN (8.0%)	UK (7.6%)	CHN (7.1%)	UK (7.2%)	CHN (%)	CHN (8.7%)	CHN (10.3%)	CHN (5.1%)
3	CAN (9.2%)	CAN (9.0%)	CAN (7.9%)	CAN (8.1%)	CAN (8.1%)	CAN (7.4%)	CAN (7.7%)	CAN (7.6%)	CAN (8.0%)	CAN (7.9%)	UK (7.2%)	UK (7.6%)	CAN (6.9%)	UK (6.8%)	CHN (7.1%)	UK (8.4%)	UK (6.4%)	UK (5.8%)	UK (7.8%)
4	FRA (6.9%)	GER (7.6%)	AUS (6.7%)	GER (6.5%)	GER (6.5%)	AUS (6.1%)	GER (6.3%)	GER (6.0%)	JPN (5.9%)	GER (5.6%)	GER (5.2%)	CHN (5.2%)	CHN (6.3%)	CAN (6.7%)	CAN (6.7%)	CAN (7.0%)	CAN (6.2%)	CAN (5.6%)	CAN (7.3%)
5	GER (6.1%)	AUS (6.6%)	FRA (6.3%)	JPN (6.1%)	JPN (6.1%)	GER (6.0%)	JPN (6.2%)	AUS (5.6%)	GER (5.4%)	JPN (5.4%)	JPN (4.8%)	AUS (5.0%)	GER (5.2%)	AUS (5.2%)	GER (4.8%)	GER (6.0%)	AUS (5.0%)	AUS (5.4%)	AUS (5.2%)
6	AUS (5.9%)	FRA (5.6%)	GER (6.0%)	AUS (5.5%)	AUS (5.5%)	JPN (5.8%)	AUS (5.4%)	JPN (5.4%)	AUS (4.9%)	AUS (5.0%)	CHN (4.5%)	JPN (4.7%)	JPN (4.4%)	GER (5.0%)	FRA (4.1%)	AUS (5.3%)	GER (4.8%)	GER (5.0%)	GER (5.5%)
7	JPN (5.9%)	JPN (5.2%)	JPN (5.5%)	FRA (5.3%)	FRA (5.3%)	FRA (5.0%)	FRA (4.6%)	FRA (4.4%)	FRA (3.8%)	CHN (4.5%)	AUS (4.2%)	GER (4.5%)	FRA (4.4%)	FRA (4.3%)	AUS (4.1%)	FRA (4.5%)	FRA (4.1%)	ESP (3.8%)	ESP (3.5%)
8	ITA (3.5%)	ITA (4.1%)	ITA (4.9%)	ITA (3.3%)	ITA (3.3%)	ITA (3.7%)	ITA (4.2%)	ITA (3.8%)	ITA (3.7%)	FRA (4.4%)	FRA (4.1%)	FRA (3.8%)	AUS (4.2%)	JPN (3.5%)	ESP (3.9%)	JPN (4.1%)	ESP (3.8%)	BRL (3.7%)	BRL (2.0%)
9	ESP (3.2%)	ESP (4.0%)	ESP (2.7%)	ESP (2.9%)	ESP (2.9%)	ESP (2.9%)	ESP (3.4%)	ESP (3.3%)	CHN (3.7%)	ITA (3.7%)	ESP (3.6%)	ITA (3.7%)	ESP (3.4%)	ESP (3.3%)	JPN (3.5%)	ESP (3.9%)	JPN (3.6%)	FRA (3.7%)	FRA (4.5%)
10	NOR (2.5%)	NOR (2.4%)	NOR (2.4%)	NOR (1.9%)	NOR (1.9%)	NOR (2.5%)	NOR (2.4%)	NOR (2.7%)	ESP (3.4%)	ESP (3.5%)	ITA (3.2%)	ESP (3.6%)	ITA (3.2%)	IND (3.0%)	ARG (3.0%)	ITA (3.7%)	BRL (2.9%)	JPN (2.9%)	JPN (4.7%)
11	RUS (2.4%)	RUS (2.1%)	RUS (2.3%)	RUS (1.9%)	RUS (1.9%)	ARG (2.0%)	CHN (2.3%)	CHN (2.6%)	NOR (3.0%)	IND (3.0%)	NOR (2.4%)	NOR (2.9%)	NOR (2.5%)	ITA (2.9%)	ITA (2.8%)	IND (2.8%)	IND (2.9%)	ITA (2.7%)	ITA (3.4%)
12		ARG (1.9%)	IND (1.7%)	NLD (1.9%)	IND (1.9%)	RUS (1.9%)	RUS (2.0%)	IND (2.1%)	IND (2.4%)	NOR (2.8%)	BRL (2.2%)	BRL (2.4%)	BRL (2.4%)	NOR (2.8%)	BRL (2.5%)	BRL (2.5%)	ITA (2.3%)	IND (2.7%)	IND (2.2%)
13				ARG (1.9%)	ARG (1.9%)	CHN (1.6%)	ARG (1.8%)	ARG (1.9%)	ARG (1.8%)	ARG (2.1%)	ARG (2.2%)	ARG (2.2%)	ARG (2.4%)	ARG (2.5%)	NOR (2.4%)	ARG (2.3%)	ARG (2.3%)	ARG (2.5%)	ARG (2.2%)
14								SWE (1.7%)	BRL (1.8%)	RUS (2.0%)	IND (1.9%)	IND (2.2%)	IND (2.3%)	BRL (2.1%)	IND (2.2%)	NOR (2.2%)	NOR (1.9%)	RUS (2.3%)	RUS (1.9%)
15											RUS (1.6%)	RUS (1.7%)	RUS (2.0%)	TUR (1.9%)	KOR (2.0%)	NZL (1.8%)	KOR (1.8%)	NZL (1.9%)	NZL (1.5%)
16											SWE (1.5%)		NZL (1.8%)	RUS (1.8%)	CHL (1.6%)	RUS (1.8%)	NZL (1.8%)	NOR (1.8%)	NOR (2.4%)
17														KOR (1.6%)	NZL (1.6%)	KOR (1.6%)		KOR (1.7%)	
Cumulative (%)	80.4	81.7	81.4	81.7	81.5	80.4	80.6	81.5	80.8	81.9	81.4	80.1	81.0	81.4	80.9	80.8	80.2	80.8	82.2

Country name abbreviations: ARG (Argentina), AUS (Australia), BEL (Belgium), BRL (Brazil), CAN (Canada), CHL (Chile), CHN (China), ESP (Spain), FRA (France), GER (Germany), IND (India), ITA (Italy), JPN (Japan), KOR (South Korea), NLD (Netherlands), NOR (Norway), NZL (New Zealand), RUS (Russia), SWE (Sweden), TUR (Turkey), UK (United Kingdom) and USA (United States).

Table 6 Of the multi-country articles, the percentage contributed to by individual countries at or above the 80th percentile.

Rank	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Total
Total	663	736	775	863	938	1062	1195	1152	1307	1370	1437	1475	1689	1922	2103	2426	2461	2460	26 034
1	USA (21.9%)	USA (18.5%)	USA (20.3%)	USA (18.8%)	USA (14.4%)	USA (20.0%)	USA (18.5%)	USA (20.1%)	USA (18.7%)	USA (18.2%)	USA (16.8%)	USA (17.0%)	USA (17.0%)	USA (17.5%)	USA (15.8%)	USA (14.8%)	USA (15.5%)	USA (14.3%)	USA (16.9%)
2	UK (9.2%)	UK (9.5%)	UK (11.9%)	UK (11.0%)	UK (12.5%)	UK (9.7%)	UK (10.3%)	UK (10.0%)	UK (10.8%)	UK (9.9%)	UK (9.5%)	UK (10.7%)	UK (9.5%)	UK (8.7%)	UK (9.1%)	UK (9.7%)	UK (8.8%)	UK (7.7%)	UK (9.6%)
3	FRA (7.7%)	GER (9.0%)	FRA (8.5%)	GER (9.3%)	GER (9.7%)	GER (7.9%)	GER (8.8%)	GER (8.0%)	GER (8.0%)	GER (9.2%)	GER (8.2%)	CAN (6.6%)	GER (7.2%)	GER (7.9%)	GER (6.7%)	GER (7.4%)	GER (7.3%)	CHI (7.3%)	GER (7.7%)
4	CAN (7.5%)	FRA (7.6%)	CAN (6.3%)	CAN (7.6%)	CAN (7.9%)	FRA (6.2%)	CAN (6.4%)	CAN (6.9%)	CAN (6.7%)	FRA (5.9%)	CAN (7.0%)	GER (6.4%)	FRA (6.5%)	FRA (5.8%)	FRA (5.9%)	CHI (5.8%)	CHI (7.1%)	GER (7.2%)	CAN (6.0%)
5	GER (6.3%)	CAN (7.5%)	GER (5.9%)	FRA (5.9%)	AUS (6.0%)	CAN (5.3%)	FRA (6.0%)	FRA (6.7%)	FRA (5.6%)	CAN (5.8%)	FRA (5.6%)	AUS (5.6%)	CAN (6.1%)	CAN (5.7%)	CAN (5.3%)	CAN (5.3%)	CAN (5.4%)	AUS (6.5%)	FRA (5.9%)
6	AUS (5.1%)	AUS (6.7%)	AUS (5.8%)	AUS (4.5%)	FRA (5.9%)	AUS (5.0%)	JPN (5.4%)	ITA (4.7%)	AUS (5.1%)	ITA (4.8%)	AUS (4.5%)	FRA (5.4%)	AUS (4.7%)	AUS (5.0%)	ESP (4.9%)	FRA (5.3%)	AUS (5.3%)	FRA (5.6%)	AUS (5.1%)
7	JPN (4.8%)	ITA (4.2%)	JPN (4.1%)	JPN (3.9%)	JPN (4.6%)	JPN (4.7%)	ITA (4.9%)	ESP (3.9%)	JPN (5.0%)	ESP (4.4%)	ESP (4.5%)	ESP (4.5%)	CHI (4.3%)	CHI (4.9%)	CHI (4.8%)	AUS (5.0%)	FRA (5.2%)	CAN (4.7%)	ESP (4.2%)
8	ITA (3.8%)	ESP (3.9%)	ITA (4.0%)	NOR (3.1%)	ITA (4.4%)	ITA (4.4%)	AUS (4.8%)	AUS (3.7%)	ITA (3.9%)	AUS (4.3%)	ITA (4.2%)	CHI (4.2%)	ITA (3.4%)	ESP (4.0%)	AUS (4.3%)	ESP (4.3%)	ESP (4.4%)	ESP (4.6%)	CHI (4.1%)
9	NOR (3.8%)	JPN (3.8%)	ESP (3.7%)	ITA (2.9%)	ESP (4.3%)	ESP (4.1%)	ESP (4.0%)	NOR (3.6%)	ESP (3.7%)	JPN (3.8%)	JPN (3.8%)	NOR (3.9%)	ESP (3.3%)	NOR (3.3%)	ITA (3.7%)	ITA (3.3%)	JPN (2.8%)	ITA (3.0%)	ITA (3.7%)
10	ESP (3.5%)	NOR (2.7%)	NOR (3.0%)	ESP (2.9%)	NOR (3.0%)	NOR (2.8%)	NOR (2.7%)	JPN (3.6%)	NOR (2.6%)	NOR (3.7%)	NOR (3.5%)	ITA (3.3%)	NOR (3.0%)	ITA (3.2%)	ARG (3.4%)	JPN (3.1%)	ITA (2.7%)	BRL (3.0%)	JPN (3.5%)
11	SWE (2.9%)	ARG (2.4%)	SWE (2.7%)	SWE (2.5%)	SWE (2.3%)	ARG (2.6%)	BEL (2.3%)	BEL (2.3%)	NZL (2.3%)	CHI (3.2%)	CHI (3.2%)	JPN (3.2%)	JPN (2.8%)	JPN (2.9%)	NOR (3.0%)	NOR (3.0%)	BRL (2.5%)	ARG (2.6%)	NOR (3.0%)
12	BEL (2.4%)	SWE (2.2%)	NZL (2.2%)	NZL (2.3%)	RUS (2.1%)	RUS (2.2%)	RUS (1.9%)	SWE (2.3%)	CHI (2.1%)	ARG (2.3%)	SWE (2.5%)	NLD (2.8%)	NZL (2.6%)	NZL (2.5%)	JPN (2.4%)	NZL (2.5%)	NOR (2.5%)	JPN (2.5%)	ARG (2.2%)
13	RUS (2.0%)	NLD (2.0%)	NLD (1.9%)	NLD (2.3%)	CHN (2.1%)	FIN (1.9%)	BRL (1.8%)	NZL (1.9%)	SWE (2.0%)	SWE (1.9%)	BEL (2.1%)	ARG (2.0%)	BRL (2.4%)	ARG (2.4%)	NZL (2.2%)	ARG (2.2%)	ARG (2.4%)	NZL (2.4%)	NZL (2.1%)
14				ARG (2.3%)	NZL (1.7%)	SWE (1.7%)	SWE (1.7%)	CHI (1.8%)	RUS (1.7%)	RUS (1.8%)	NZL (2.0%)	ZAF (2.0%)	BEL (2.2%)	BEL (2.2%)	BEL (2.1%)	BEL (2.0%)	NZL (2.1%)	NOR (2.3%)	BEL (1.9%)
15				RUS (2.2%)		BEL (1.7%)	NLD (1.7%)	RUS (1.7%)	ZAF (1.7%)	NZL (1.8%)	ARG (1.7%)	BRL (1.8%)	ARG (1.9%)	BRL (2.1%)	SWE (2.0%)	BRL (2.0%)	CHL (1.8%)	BEL (2.1%)	SWE (1.9%)
16									ARG (1.7%)		NLD (1.7%)	BEL (1.6%)	ZAF (1.8%)	SWE (2.0%)	BRL (2.0%)	CHL (2.0%)	NLD (1.6%)	CHL (1.7%)	BRL (1.9%)
17													POR (1.8%)	NLD (1.8%)	NLD (2.0%)	NLD (1.6%)	SWE (1.6%)	POR (1.6%)	NLD (1.7%)
18															CHL (1.9%)	ZAF (1.6%)	BEL (1.5%)	SWE (1.5%)	
Cumulative (%)	80.8	80.0	80.4	81.7	80.8	80.2	81.2	81.3	81.6	81.0	80.9	80.9	80.9	80.2	81.7	80.7	80.3	80.7	81.2

Country name abbreviations: ARG (Argentina), AUS (Australia), BEL (Belgium), BRL (Brazil), CAN (Canada), CHL (Chile), CHN (China), ESP (Spain), FIN (Finland), FRA (France), GER (Germany), IND (India), ITA (Italy), JPN (Japan), NLD (Netherlands), NOR (Norway), NZL (New Zealand), POR (Portugal), RUS (Russia), SWE (Sweden), TUR (Turkey), UK (United Kingdom), USA (United States) and ZAF (South Africa).

Table 7 Network analysis results: multi-countries articles in all research fields. Degree centrality indicates how many direct ties the node has. Closeness centrality indicates how close the node is with the other nodes. Betweenness centrality indicates how the node bridges relations between the other nodes. Eigenvector centrality indicates how the node is connected to highly connected nodes.

Rank	Degree centrality	Closeness centrality	Betweenness centrality	Eigenvector centrality
1	USA (0.833)	USA (0.857)	USA (0.173)	USA (0.599)
2	UK (0.707)	UK (0.773)	FRA (0.080)	GER (0.380)
3	GER (0.701)	GER (0.770)	GER (0.076)	UK (0.367)
4	FRA (0.684)	FRA (0.760)	AUS (0.071)	FRA (0.315)
5	AUS (0.644)	AUS (0.737)	UK (0.067)	ITA (0.254)
6	CAN (0.586)	CAN (0.707)	BEL (0.036)	CAN (0.245)
7	ITA (0.529)	ITA (0.680)	CAN (0.034)	SPA (0.159)
8	CHN (0.529)	CHN (0.680)	NZL (0.032)	AUS (0.150)
9	ZAF (0.506)	ZAF (0.669)	CHN (0.030)	JPN (0.112)
10	JPN (0.506)	JPN (0.669)	ARG (0.029)	BEL (0.108)
11	BEL (0.506)	BEL (0.669)	ZAF (0.029)	SWE (0.100)
12	SWE (0.489)	SWE (0.662)	NLD (0.027)	CHE (0.090)
13	SPA (0.483)	SPA (0.659)	JPN (0.021)	NLD (0.076)
14	NOR (0.471)	NOR (0.654)	ITA (0.020)	CHL (0.074)
15	NLD (0.471)	NLD (0.654)	SPA (0.016)	NOR (0.073)
16	CHE (0.460)	CHE (0.649)	MEX (0.015)	NZL (0.072)
17	BRL (0.443)	BRL (0.642)	SWE (0.014)	CHN (0.071)
18	DEN (0.431)	DEN (0.637)	RUS (0.013)	RUS (0.070)
19	RUS (0.425)	RUS (0.635)	DEN (0.012)	DEN (0.062)
20	NZL (0.425)	NZL (0.635)	CHE (0.012)	FIN (0.060)
21	POL (0.402)	POL (0.626)	NOR (0.011)	ZAF (0.048)
22	IND (0.397)	IND (0.624)	IND (0.008)	ARG (0.036)
23	POR (0.391)	POR (0.621)	BRL (0.008)	BRL (0.029)
24	CHL (0.391)	ARG (0.621)	AUT (0.008)	KOR (0.028)
25	ARG (0.391)	CHL (0.619)	POR (0.007)	TWN (0.027)
26	AUT (0.385)	AUT (0.619)	POL (0.007)	POL (0.026)
27	KOR (0.362)	KOR (0.611)	CHL (0.007)	POR (0.023)
28	CZE (0.333)	CZE (0.600)	THA (0.006)	IND (0.022)
29	TUR (0.322)	TUR (0.596)	SRB (0.006)	MEX (0.014)
30	THA (0.322)	THA (0.594)	SVN (0.006)	AUT (0.013)

Country name abbreviations: ARG (Argentina), AUS (Australia), AUT (Austria), BEL (Belgium), BRL (Brazil), CAN (Canada), CHE (Switzerland), CHL (Chile), CHN (China), CZE (Czech Republic), DEN (Denmark), ESP (Spain), FIN (Finland), FRA (France), GER (Germany), IND (India), ITA (Italy), JPN (Japan), KOR (South Korea), MEX (Mexico), NLD (Netherlands), NOR (Norway), NZL (New Zealand), POL (Poland), POR (Portugal), RUS (Russia), SRB (Serbia), SVN (Slovenia), SWE (Sweden), THA (Thailand), TUR (Turkey), TWN (Taiwan), UK (United Kingdom), USA (United States) and ZAF (South Africa).

Some other countries entered the 80th percentile by increasing their shares in the number of publications. China and Brazil, in particular, showed a large increase in the percentage of the number of publications. In the period analysed, China showed the most substantial increase. China first entered the top 80th percentile in 2003, with a share of 1.6%. However, as of 2015, China took 10.3% of the share, by following the United States. Similar to China, Brazil remained below the 80% range until 2005 but entered the top 80% for the first time in 2008. As of 2015, Brazil took 3.7% of the publications and was ranked as eighth in the number of publications.

Table 6 modifies Table 5 by limiting the data to multi-countries articles. It demonstrates that countries that published a relatively large number of articles, such as the United States, the United Kingdom, Germany and France, also tended to take a large share in the number of multi-countries articles. Second, some countries not visible in Table 5 show a larger share in Table 6, indicating their important roles in international collaboration. Leading examples here include Sweden, Belgium and the Netherlands, which are not in the upper 80th percentile in Table 5 but take about 1–2% in international collaborative research (Table 6).

Of all the research articles on Antarctica published from 1998 to 2015, the number of articles produced by the United States grew each year except for 2015, whereas the percentage gradually decreased. The decrease in percentage was almost entirely due to an increase in productivity by authors from other countries, such as China,

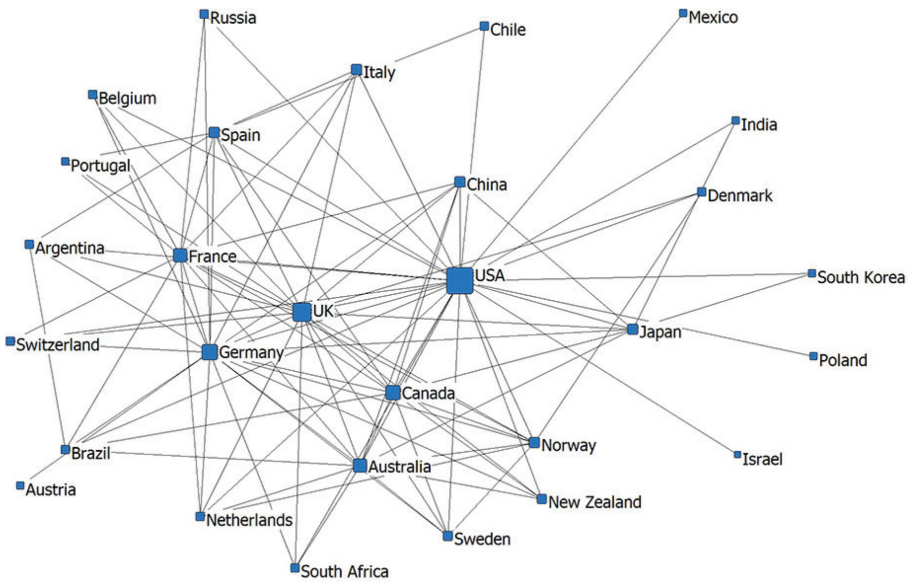

Fig. 3 Network of international collaborative articles in all research fields focusing on degree centrality. This figure visualizes trends in international collaborative research among countries. The links are limited to those with a frequency of 100 or higher. Node sizes represent the number of links connected to each node.

Table 8 Number of articles by subfield within the natural sciences, by year. The categories are drawn from the OECD science and technology classification (NESTI Working Party 2007).

Year	Mathematics	Computer and information sciences	Physical sciences and astronomy	Chemical sciences	Earth and related environmental sciences	Biological sciences
1998	7	3	117	124	1184	1286
1999	4	6	133	124	1160	1264
2000	4	3	104	111	1255	1277
2001	5	4	127	127	1302	1404
2002	5	5	124	121	1478	1374
2003	10	2	144	155	1491	1418
2004	3	3	182	177	1652	1556
2005	5	2	168	171	1567	1500
2006	6	10	144	187	1646	1632
2007	8	2	118	191	1697	1699
2008	5	7	140	203	1913	1794
2009	12	6	158	191	1769	1855
2010	11	6	167	222	2057	2041
2011	7	10	174	216	2275	2021
2012	6	8	261	211	2314	2156
2013	11	6	277	270	2712	2377
2014	12	11	221	243	2795	2464
2015	12	12	228	304	2603	2443
Total	133	106	2987	3348	32 870	31 561

Table 9 Multi-countries collaborative research in Earth and related environmental sciences and the biological sciences.

Year	Earth and related environmental sciences			Biological sciences		
	No. of single-country articles	No. of multi-countries articles	% of multi-countries articles	No. of single-country articles	No. of multi-countries articles	% of multi-countries articles
1998	856	328	27.7	980	306	23.8
1999	817	343	29.6	921	343	27.1
2000	901	354	28.2	945	332	26.0
2001	918	384	29.5	1055	349	24.9
2002	982	496	33.6	987	387	28.2
2003	985	506	33.9	988	430	30.3
2004	1041	611	37.0	1060	496	31.9
2005	1019	548	35.0	1032	468	31.2
2006	1001	645	39.2	1087	545	33.4
2007	1033	664	39.1	1097	602	35.4
2008	1183	730	38.2	1200	594	33.1
2009	1074	695	39.3	1198	657	35.4
2010	1189	868	42.2	1311	730	35.8
2011	1268	1007	44.3	1268	753	37.3
2012	1284	1030	44.5	1314	842	39.1
2013	1466	1246	45.9	1455	922	38.8
2014	1482	1313	47.0	1480	984	39.9
2015	1354	1249	48.0	1403	1040	42.6
Total	19 853	13 017	39.6	20 781	10 780	34.2

Turkey, Brazil, South Korea and Chile. For example, as of 2015, China ranked second in the world in terms of the number of articles on Antarctica (Table 5), outstripping the United Kingdom and Canada, which ranked as the third and fourth, respectively.

SNA results: a network of multinational collaborative research in all research fields

This section describes SNA results by focusing on 26 034 articles co-authored by authors from at least two different countries (Table 7).

The United States had the highest values for all centrality measures (Table 7), implying that the United States was engaged in international collaborative research in Antarctic research with the largest number of countries. Other countries in the upper ranks include the United Kingdom, France, Germany, Australia, Italy, Canada, Belgium, China, New Zealand and South Africa. Many of these countries have a scientific research station located in Antarctica and, with a few exceptions, most are considered to be advanced in research and development.

The United States engaged in collaborative research with most of the countries in the network (Fig. 3). Some countries did not have 100 or more links with countries other than the United States. Leading examples in this group are South Africa, Austria, Israel, Mexico and Poland, which did not frequently collaborate on articles with countries other than the United States.

Some European countries, such as Germany, the United Kingdom, France and Italy, along with Australia, constituted a third group that collaborated not only with the United States but also with other countries in Europe. One possible reason why these and other European countries collaborated to the large extent that they did is related to joint European Union funding, but more in-depth research is required to confirm this or to identify other reasons for the high degree of collaborative publications (and research) among smaller European countries.

SNA results: network of multinational collaborative research in the natural sciences

In this section, we dive into two subfields in the natural sciences category: Earth and related environmental sciences and biological sciences. The greatest percentage of articles in our data set comes from the natural sciences, among the seven major fields of scholarship. The natural sciences can be divided into the following subfields, as classified by the OECD (NESTI Working Party 2007): mathematics and computer sciences; physical sciences;

Table 10 SNA results: Earth and related environmental sciences and the biological sciences. Degree centrality indicates how many direct ties the node has. Closeness centrality indicates how close the node is with the other nodes. Betweenness centrality indicates how the node bridges relations between the other nodes. Eigenvector centrality indicates how the node is connected to highly connected nodes.

Rank	Earth and related environmental sciences				Biological sciences			
	Degree centrality	Closeness centrality	Betweenness centrality	Eigenvector centrality	Degree centrality	Closeness centrality	Betweenness centrality	Eigenvector centrality
1	USA (0.688)	USA (0.759)	USA (0.221)	USA (0.960)	USA (0.600)	USA (0.144)	USA (0.705)	USA (0.965)
2	GER (0.576)	GER (0.700)	FRA (0.149)	UK (0.169)	UK (0.600)	UK (0.135)	UK (0.701)	CAN (0.169)
3	UK (0.556)	FRA (0.689)	GER (0.107)	CAN (0.114)	GER (0.578)	GER (0.128)	GER (0.694)	UK (0.119)
4	FRA (0.556)	UK (0.689)	UK (0.105)	AUS (0.104)	FRA (0.541)	FRA (0.116)	FRA (0.676)	AUS (0.088)
5	AUS (0.472)	AUS (0.651)	AUS (0.077)	GER (0.088)	AUS (0.422)	BEL (0.062)	AUS (0.618)	GER (0.062)
6	CAN (0.403)	CAN (0.623)	JPN (0.041)	CHN (0.067)	CAN (0.407)	AUS (0.043)	CAN (0.615)	FRA (0.051)
7	JPN (0.375)	JPN (0.607)	NZL (0.036)	FRA (0.065)	BEL (0.407)	CAN (0.043)	BEL (0.612)	JPN (0.046)
8	ESP (0.347)	ESP (0.602)	ARG (0.034)	JPN (0.038)	SWE (0.378)	NZL (0.043)	ITA (0.603)	NZL (0.045)
9	CHN (0.340)	CHN (0.597)	CHN (0.032)	NZL (0.037)	ITA (0.370)	POL (0.036)	SWE (0.603)	ITA (0.037)
10	BEL (0.333)	BEL (0.597)	CAN (0.031)	ITA (0.037)	ESP (0.370)	NET (0.032)	ESP (0.598)	CHN (0.034)
11	SWE (0.326)	SWE (0.594)	ESP (0.028)	RUS (0.029)	RUS (0.333)	ZAF (0.030)	RUS (0.587)	ARG (0.033)
12	CHE (0.326)	CHE (0.594)	RUS (0.025)	ARG (0.025)	NET (0.326)	ESP (0.028)	NET (0.584)	ESP (0.027)
13	RUS (0.319)	RUS (0.592)	NET (0.022)	NOR (0.022)	NOR (0.326)	ITA (0.025)	NOR (0.584)	RUS (0.023)
14	ITA (0.319)	ITA (0.592)	BEL (0.020)	ESP (0.021)	NZL (0.319)	SWE (0.021)	NZL (0.579)	NOR (0.023)
15	ZAF (0.313)	ZAF (0.587)	MEX (0.018)	NET (0.021)	JPN (0.319)	JPN (0.021)	JPN (0.579)	SWE (0.019)
16	NOR (0.299)	NOR (0.584)	ITA (0.015)	CHE (0.020)	ZAF (0.311)	ARG (0.020)	ZAF (0.571)	NET (0.015)
17	NZL (0.278)	NZL (0.577)	NOR (0.014)	SWE (0.018)	CHN (0.311)	RUS (0.016)	AUT (0.571)	BRL (0.015)
18	ARG (0.278)	ARG (0.575)	SWE (0.014)	BRL (0.016)	AUT (0.289)	SVK (0.015)	CHN (0.571)	ZAF (0.014)
19	AUT (0.271)	AUT (0.573)	ZAF (0.014)	BEL (0.014)	CHL (0.281)	NOR (0.014)	POL (0.566)	BEL (0.013)
20	NET (0.271)	NET (0.573)	CHE (0.011)	ZAF (0.013)	POL (0.281)	AUT (0.011)	CHL (0.566)	CHL (0.013)

Country name abbreviations: ARG (Argentina), AUT (Austria), AUS (Australia), BEL (Belgium), BRL (Brazil), CAN (Canada), CHE (Switzerland), CHL (Chile), CHN (China), ESP (Spain), FIN (Finland), FRA (France), GER (Germany), IND (India), ITA (Italy), JPN (Japan), MEX (Mexico), NLD (Netherlands), NOR (Norway), NZL (New Zealand), POL (Poland), POR (Portugal), RUS (Russia), SVK (Slovakia), SWE (Sweden), THA (Thailand), TUR (Turkey), UK (United Kingdom), USA (United States) and ZAF (South Africa).

chemical sciences; Earth and related environmental sciences; and biological sciences.

Earth and related environmental sciences and the biological sciences account for the largest parts in natural sciences in our data set: 32 870 articles in Earth and related environmental sciences and 31 561 articles in the biological sciences (Table 8).

In the two fields, the proportion of multi-countries articles grew steadily from 1998 to 2015. The proportion increased from 27.7 to 48.0% in Earth and related environmental sciences and from 23.8 to 42.6% in the biological sciences.

The United States occupied the highest rank in all types of centrality measures (Table 10). The United Kingdom, Germany, France and Australia also, in general, ranked high across the indicators.

Earth and related environmental sciences and the biological sciences show similar patterns in the development of their networks (Figs. 4, 5). In both fields, the size and scale of the networks increased. The networks in 1998 and 2000 show a star-like graph centred on the United States, while in later years, European countries, Australia and New Zealand started appearing in the networks, making the network more complex. The United Kingdom and Germany became relatively important nodes by increasingly having more connected nodes over time. At the start of the period, each of them was connected to the United States at the periphery of the network but they later became sub-cores that bridged the United States and other nodes located at the periphery.

Conclusions

Antarctic research demands a high level of collaboration on the account of the difficulty and expense of working in the region. We investigated this by looking at published journal articles, which are one of the products of research.

We found that during 1998-2015, the proportion of multi-countries articles increased from 23.0 to 33.2% in Antarctic research, making the network of Antarctic research larger and more complex. While the United

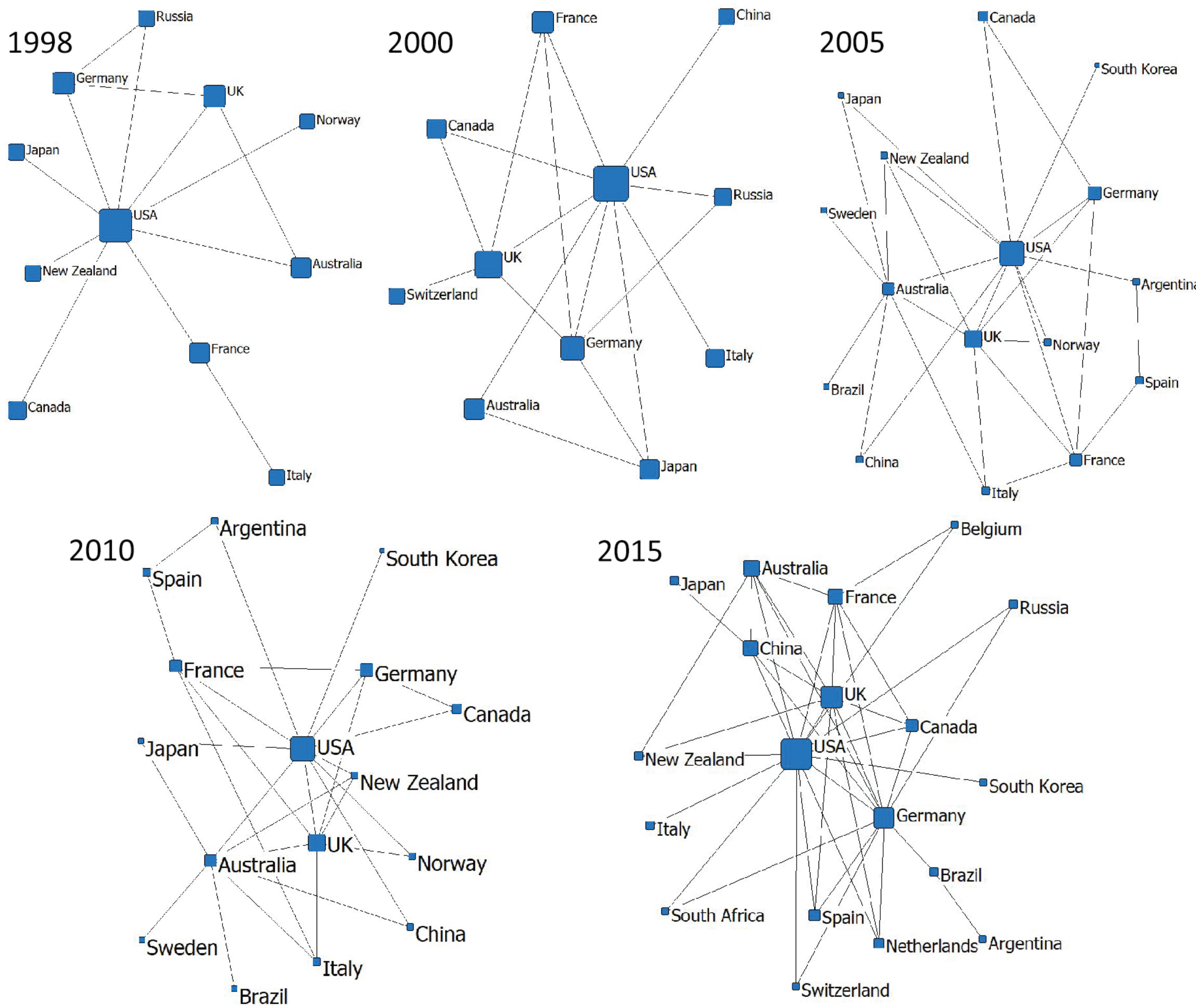

Fig. 4 Changes in the international collaboration in Earth and related environmental sciences. Only links with a frequency of 10 or higher are presented. Node sizes represent the number of links connected to each node.

States was continuously been located at the centre of the network drawn by the multi-countries articles, its percentage decreased over time. Meanwhile, the contributions of some emerging countries, such as China, Turkey, Brazil and South Korea, rose. Articles in the natural sciences were the most numerous compared with other academic fields. The comparatively small number of social science and humanities articles is to be expected for a continent peopled by small numbers of researchers and support personnel, most of whom are on the continent or the surrounding waters for short periods of fieldwork or research cruises. Subfields within the natural sciences, such as Earth studies and related environmental and biological sciences, had the highest multinational collaborative research engagement, judging by journal articles. Sweden, Belgium and the Netherlands did not produce a high percentage of academic contributions but were still notable for their international collaborative research. A topic for future study would be to see if there are important geographically driven collaborations by certain countries. For example, many countries have bases on King George Island in the South Shetlands; do these countries work together or not? Other countries have bases in reasonably close proximity on the northern part of the Antarctic Peninsula; do they work together? Also, in the McMurdo region, are the Americans, New Zealanders and Italians working together more than with other international colleagues?

Additional studies will be necessary to assess whether multinational collaboration leads to better articles (as measured, e.g., by citations) and to examine the much larger question of the impact of international

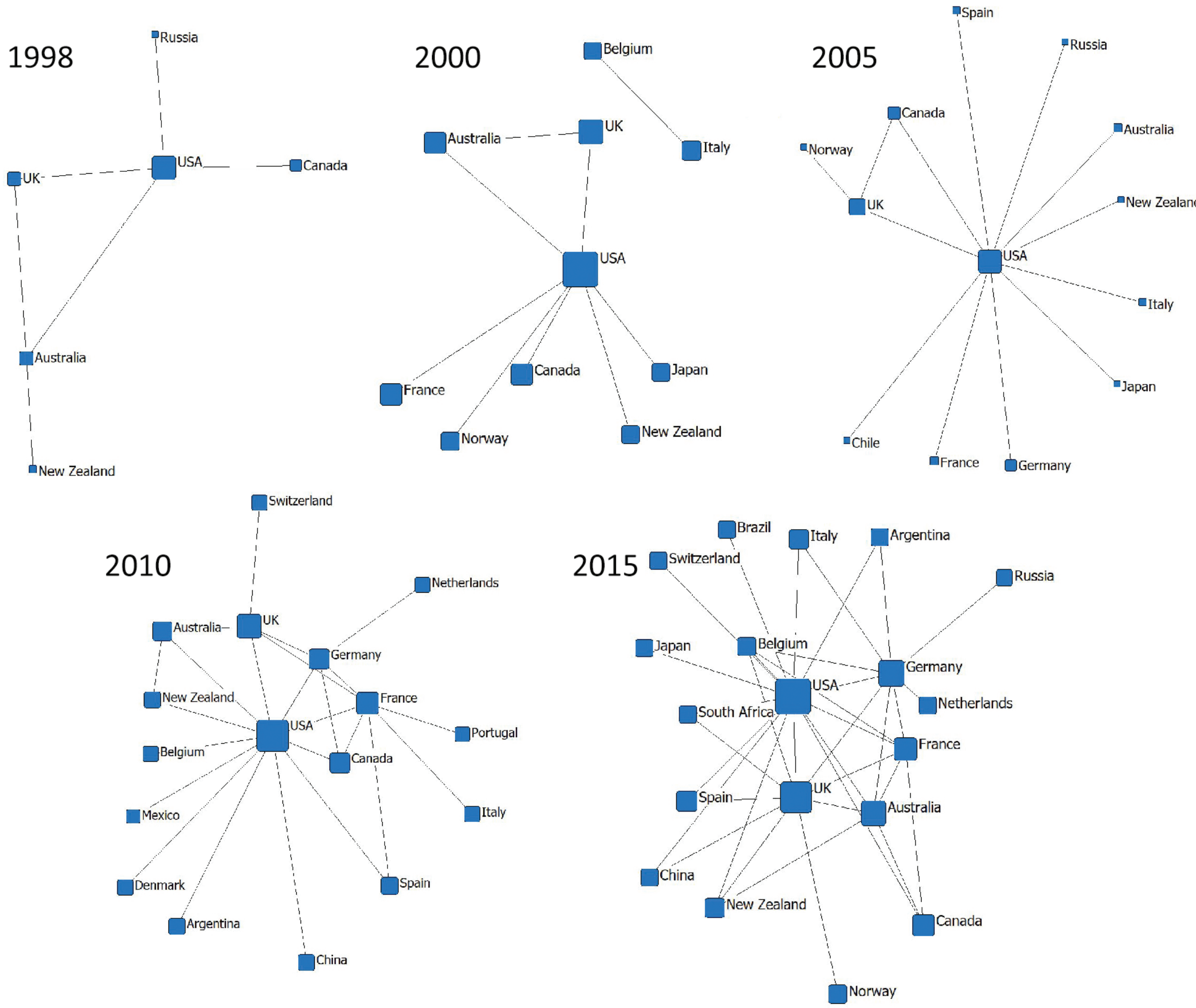

Fig. 5 Changes in the international collaboration in the biological sciences. Only the links with a frequency of 10 or higher are presented. Node sizes represent the number of links connected to each node.

collaborative research on the scientific community and society at large. Although these questions have yet to be answered, we believe that to enhance achievements in Antarctic research—which will benefit humankind globally—responsible organizations need to further encourage international collaborative research and aggressively develop and implement programmes that support collaboration.

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Disclosure statement

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