Mapping World Scientific Collaboration: Authors, Institutions, and Countries

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International collaboration is being heralded as the hallmark of contemporary scientific production. Yet little quantitative evidence has portrayed the landscape and trends of such collaboration. To this end, 14,000,000 documents indexed in Thomson Reuters's Web of Science (WoS) were studied to provide a state-of-the-art description of scientific collaborations across the world. The results indicate that the number of authors in the largest research teams have not significantly grown during the past decade; however, the number of smaller research teams has seen significant increases in growth. In terms of composition, the largest teams have become more diverse than the latter teams and tend more toward interinstitutional and international collaboration. Investigating the size of teams showed large variation between fields. Mapping scientific cooperation at the country level reveals that Western countries situated at the core of the map are extensively cooperating with each other. High-impact institutions are significantly more collaborative than others. This work should inform policy makers, administrators, and those interested in the progression of scientific collaboration.

Introduction

Research collaboration is referred to as one of the defining features of "Big Science" (Price, 1986) and one of the results of the "professionalization of science" (Beaver & Rosen, 1978). The benefits and merits of research collaboration include: sharing and transferring knowledge and research equipment, connecting scholars to a large scientific network, expediting the research process, and increasing the visibility of articles (Gazni & Didegah, 2011; Sooryamoorthy, 2009; Katz & Martin, 1997; Glänzel, 2001; Narin, Stevens, & Whitlow, 1991; Lawani, 1986). The growth of this phenomenon has encouraged many scientometricians to conduct research in order to investigate collaboration at different levels and inform scientific policy makers who evaluate the scientific output of their countries. Scientific policy makers in developed countries are definitely aware of the importance and benefits of research collaboration, with many countries (such as the U.S.) providing specific funding to support large-scale collaborative research projects (Corley, Boardman, & Bozeman, 2006).

Despite the pervasiveness of collaborative research, there have been few attempts to describe global coauthorship levels and collaborations across all scientific domains at the author, institution, and country level. This paper seeks to address this gap by measuring the rate of collaboration at these levels using three indicators: average number of authors, institutions and countries per paper, plus the size of collaboration at different levels in different fields. The tendency toward research collaboration and patterns of collaboration among countries is mapped and modeled based on the growth rate of these indicators. Thus, the results of this study will inform scientific policy makers and scholars on the history and state-of-the-art in collaboration across multiple domains.

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Literature Review

The objective of this paper is to examine the collaboration patterns across fields and countries. As with many previous studies, this work will use the presence of two or more authors on the byline of a journal article as a measurement of collaboration. It has been argued that funding and coauthorship do not provide the entire view of the process of collaboration (Lundberg, Tomson, Lundkvist, Skar, & Brommels, 2006); however, as noted by Franceschet and Costantini (2010, p. 541), "co-authorship in publications is widely considered as a reliable proxy for scientific collaboration". Multiauthored papers have been on the rise, with multiple studies showing this trend (e.g., Schmoch & Schubert, 2008; Cronin, Shaw, & La Barre, 2003; Moody, 2004; Persson, Glänzel, & Danell, 2004). However, scholars have cautioned that these trends are not uniform, but must be contextualized by domain and by country (Larivière, Gingras, & Archambault, 2006) and by field of study (Abt, 2007; Glänzel & de Lange, 2002; Melin, 2000; Egghe, 1999). Motivations for collaboration are many. In terms of functional motivations, Wagner, Brahmakulam, Jackson, Wong, and Yoda (2005) provide a typology where they list fields by major reasons to collaboration summarized as: data, resources, equipment, and theories. Academic rewards also function as an incentive, with studies showing an increase in productivity (Price & Beaver, 1966; Beaver & Rosen, 1978, 1979; Glänzel and de Lange, 2002) and a citation advantage for collaboratively written articles (Franceschet & Costanini, 2010; Schmoch & Schubert, 2008; Wuchty, Jones, & Uzzi, 2007). However, the same caveats apply—with studies showing that these impacts vary by region (Levitt & Thelwall, 2010). As many previous studies focused on a particular domain or region, it is necessary for a large-scale analyses that examines collaboration differences across multiple areas and from all countries. The present work seeks to address this demand.

Institutional Collaboration

As collaboration has continued to increase, scholars have examined not only whether or not people are writing articles together, but if those individuals are employed by different institutions. Research in this regard has been mixed, with findings that support a rise in institutional collaboration (Qin, 1994), but with the full caveats that this varies by discipline (Larivière et al., 2006). Particularly noted are medical fields, which tend to have high degrees of collaboration between institutions domestically, but not internationally (Thijs & Glänzel, 2010). Also examined are the relations among institutional types, most notably the relationships among university, industry, and government institutions, as codified by the Triple Helix concept (Leydesdorff & Sun, 2009). In studies of interinstitutional collaboration, geographic proximity has continued to be a factor, with studies noting that the closer the collaborator, the more likely the collaboration (Larivière et al., 2006). Issues of prestige (Lee, Kwon, & Kim, 2010) and funding policies (Ajiferuke, 2005) also play an important role in facilitating interinstitutional collaborations. As with collaboration more generally, a citation advantage has been acknowledged (Abramo, D'Angelo, & Di Costa, 2009; Katz & Martin, 1997), although it has not been determined how uniform this may be.

International Collaboration

As noted in a recent treatise by the Royal Society (2011, p. 6), the "exchange of scientific insight, knowledge and skills. . .are changing the focus of science from the national to global level". However, this increase is not only a trend of the 21st century, but one that has been noted in scientometric studies for over a decade (Zitt & Bassecoulard, 2004; Schmoch, 2005; Schubert & Braun, 1990; Hayati & Didegah, 2010; Wagner & Leydesdorff, 2005; Dore et al., 1996; Georghiou, 1998; Glänzel, 2001). Language in articles on the increase in international collaboration has been enthusiastic and, in some cases, borders on the hyperbolic, with studies declaring "five-fold" increases (Mattson, Laget, Vindefjard, & Sundberg, 2010) and "exponential growth" (He, 2009; Leydesdorff & Sun, 2009). However, studies have been inconclusive, particularly on the macro-level and some have argued for more nuanced approaches that take into account specific areas of study (Luukkonen, Persson, & Sivertsen, 1992; Glänzel & de Lange, 1997; Jappe, 2007; Glänzel, 2001; Glänzel & Schubert, 2001; Van Raan, 1998; Tijssen, Visser, & van Leeuwen, 2002; Persson, 2010). One noted nuance is the prevailing impact of culture, tradition, politics, and language in determining collaborators (Glänzel & Schubert, 2001; Zitt, Bassecoulard, & Okubo, 2000; Schubert & Glänzel, 2006), in addition to the physical proximity issue noted for institutional collaborations.

As with the previous studies of collaboration, international collaboration also tends to result in higher citations (Abramo, D'Angelo, & Solazzi, 2011; Glänzel & de Lange, 2002; Suarez-Balseiro, Garcia-Zorita, & Sanz-Casado, 2009; Hayati & Didegah, 2010; Narin, 1991; Persson et al., 2004; He, 2009). However, the collaboration network particularly favors certain "core" countries, as identified in many studies (Leydesdorff & Wagner, 2008; Schubert & Sooyramoorthy, 2010). In this structure, developing and underdeveloped countries seem to gain significant advantages from collaborating with authors from this core group (typically the U.S.A. and a select group of European countries) (Rousseau, 2000; Goldfinch, Dale, & DeRouen, 2003; Onyancha & Maluleka, 2011). However, very few studies have examined the proportion of international collaboration on a wide scale. This study will provide such an analysis.

Methods

The study analyzed 13,917,488 documents from ISI's Web of Science (WoS). All documents regardless of type (e.g., article, meeting abstract, proceedings paper, review, editorial material, book review, letter, note, etc.) were processed. All documents from the Science Citation Index Expanded

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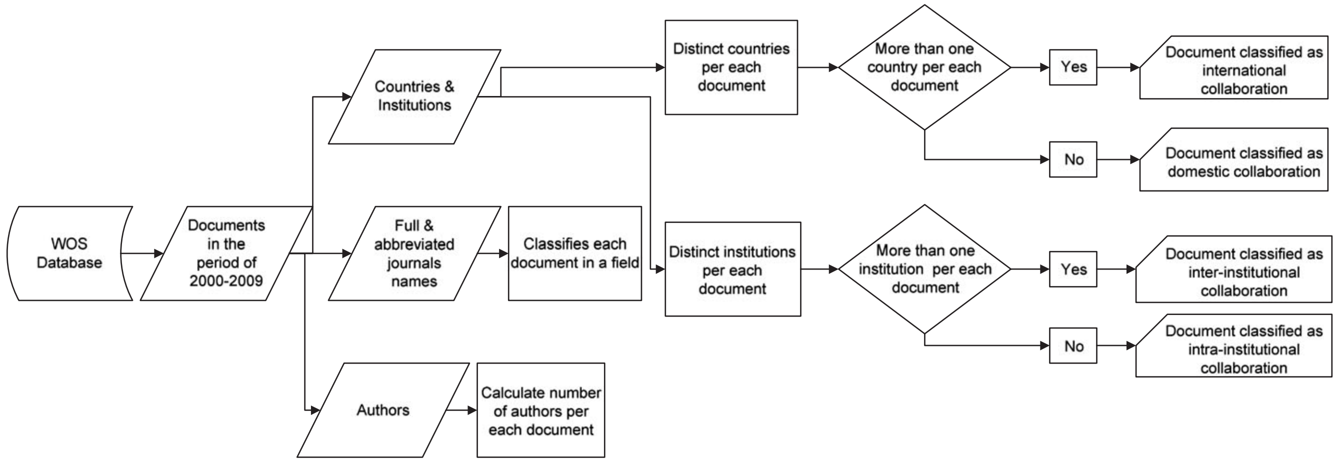

FIG. 1. Data processing.

Doc ID	No. of Authors per document	No. of distinct institutions per document	No. of distinct countries per document	Document field	Wagner class	Economic class
1						
2						
N= (13,917,488)						

FIG. 2. The constructed table of document authorships.

(SCI-Expanded), Social Sciences Citation Index (SSCI), and Arts & Humanities Citation Index (A&HCI) were taken into account. The data tags involving C1,[1] AU,[2] SO,[3] and J9[4] were processed. The dataset contains 24,616,545 affiliations and 50,628,483 authors. All of the processes in all steps were accomplished automatically.

The table below (Figure 2) was constructed for each document. In the case of multiinstitutional and multinational publications, a paper coauthored by a number of authors from the same affiliation is considered a single-institutional and single-national paper (regardless of departmental affiliation level).

Mapping Papers to 22 and 5 Fields

To distinguish the collaboration indicators in different subject fields, the papers of examined journals were mapped into 22 broad fields covered by the Essential Science Indicators (ESI) database. Each paper in the dataset was classified into only one field according to its journal's field. The Science-Watch website provides a list of ISI journals with their subject fields. Each journal in this list is categorized under a single subject filed. Grouping journals into five larger subject areas was based on a mapping offered by Nagaoka, Igami, Eto, and Ijichi (2010). All stages of processing data have been visualized in Figure 1.

Categorizing Countries

Two approaches, scientific and economic, were used to categorize countries of the world. Based on the rate of scientific development, Wagner, Brahmakulam, Jackson, Wong, & Yoda (2001) classified countries into four groups including Scientifically Advanced Countries (SAC), Scientifically Proficient Countries (SPC), Scientifically Developing Countries (SDC), and Scientifically Lagging Countries (SLC). This approach was adopted in the current paper. Economically, countries were also categorized into four groups, as classified by the World Bank: high income, upper middle income, lower middle income, and low income (World Bank,[5] 2010).

Top-Cited Institutions

ESI was used to select top world institutions based on their number of citations. ESI determines influential scientists, research institutions, countries, and publications in various subject fields over the recent 10 years. This study chose the

[1]Author(s) affiliation(s).
[2]Author(s) first and last name(s).
[3]Journal name.
[4]Journal abbreviation name.

[5]http://data.worldbank.org/about/country-classifications.

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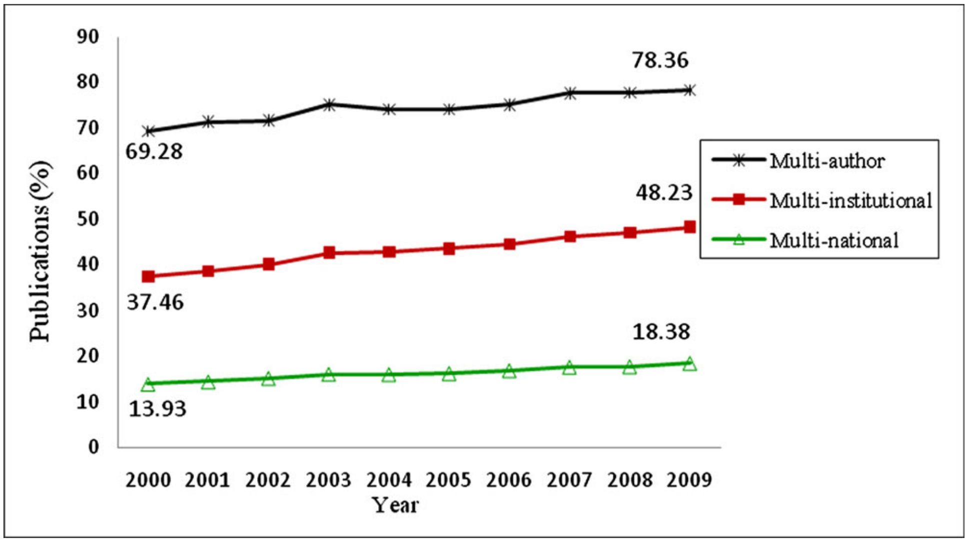

FIG. 3. Percentage of multientity publications, 2000–2009. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

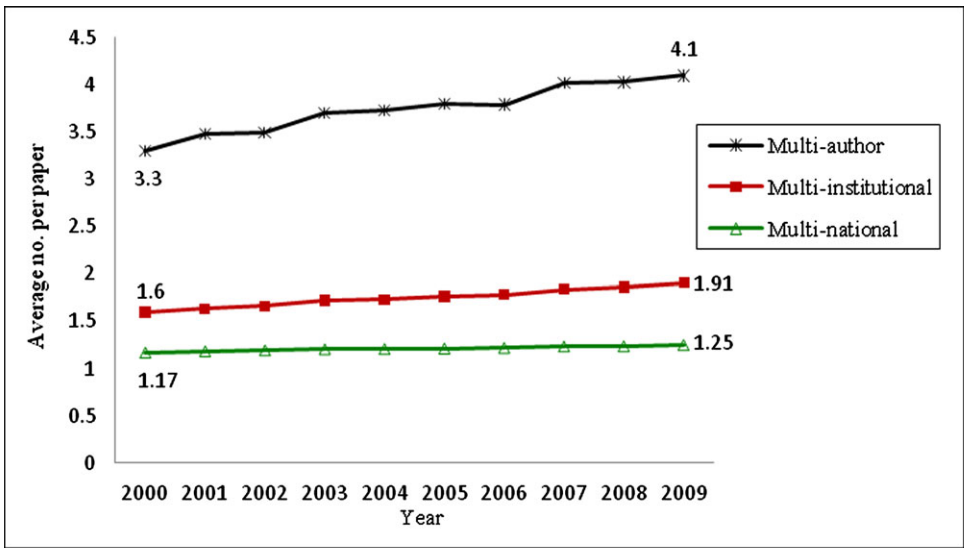

FIG. 4. Average number of different entities per paper, 2000–2009. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

20 institutions with the highest impact, in terms of citations received, from ESI.

Visualization Software

Pajek, a visualization software suitable for big networks, was applied to map the collaboration links.

Results

Cooperation among scientists in dissemination of science has significantly grown over the recent decade, as demonstrated in Figures 3 and 4. Figure 3 shows the percentage of publications with multiauthored, multiinstitutional, and multinational patterns and Figure 4 shows the average number of authors, institutions, and countries over the 10 years. The total percentage of multiauthored publications rose from 69% in 2000 to 78% in 2009 (Figure 3). Similar increases were seen for both multiinstitutional and multinational publications. The number of authors per paper has steadily increased from an average of 3.3 in 2000 to 4.1 authors per paper in 2009 (Figure 4). For all publications, 25% are single-authored and less than 4% are the results of collaboration involving more than nine authors (Table 5). The largest number of coauthors in our sample was 3,099 authors.

However, the level of scientific collaboration varies dramatically by field. Table 2 displays these macro-level differences: the Life Sciences display high levels of coauthorship (89%), whereas the Social Sciences show low levels of coauthorship (36%). At the micro-level, there are further distinctions between fields. For example, within the broad area of life sciences, Microbiology displays the highest percentage

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TABLE 1. The percentage of multiauthored publications in 22 ESI fields.

Broad fields	ESI fields	Multiauthored publications (%) 2000	2009	2000–2009 (Avg.)	Change from 2000 to 2009 (%)
	Microbiology	93.7	93.9	94	0.2
	Immunology	93.3	92.5	91.51	−0.8
	Molecular Biology & Genetics	91.8	91.2	90.71	−0.6
Life sciences	Biology & Biochemistry	90.9	91.2	90.62	0.3
	Neuroscience & Behavior	88.9	91.3	89.88	2.4
	Pharmacology & Toxicology	86.2	90.1	88.18	3.9
	Agricultural Sciences	79.6	88.6	84.89	9
	Plant & Animal Science	80.3	86.8	83.48	6.5
	Chemistry	87.3	91.3	89.56	4
	Materials Science	80	89.6	86.26	9.6
	Physics	81.8	87.6	85.23	5.8
	Environment/Ecology	81.1	88.8	85.2	7.7
Physical sciences	Space Science	80.6	82.6	83.39	2
	Geosciences	76.6	85.7	81.71	9.1
	Computer Science	69	84.5	78.08	15.5
	Engineering	70.6	83.4	77.08	12.8
	Mathematics	53	64.7	59.55	11.7
Medicine	Clinical Medicine	82.1	87.2	85.5	5.1
	Psychiatry/Psychology	63.7	75.1	70.57	11.4
Multidisciplinary	Multidisciplinary	52.4	64	56.71	11.6
Social sciences	Economics & Business	37.8	57.2	48.34	19.4
	Social Sciences, general	25	41.9	33.25	16.9

TABLE 2. The percentage of multiauthored publications in five broad fields.

Broad fields	Multiauthored publications (%) 2000	2009	2000–2009 (Avg.)	Change from 2000 to 2009 (%)
Life sciences	87.73	90.16	88.62	2.43
Medicine	80.27	85.87	84.02	5.6
Physical sciences	77.3	85.44	81.93	8.15
Multidisciplinary	52.39	63.97	56.71	11.59
Social sciences	27.75	45.17	36.44	17.43

of collaboration (94%), while Environment/Ecology shows the lowest percentage in that category (85%). More severe disparities can be seen in the Physical Sciences with a range of 90% for Chemistry to 60% in Mathematics (Table 1).

Furthermore, patterns of growth in academic collaboration over the last decade have varied by field. As might be expected, the Life Sciences have seen the lowest increase in collaboration, largely due to the high percentage of collaboration in 2000. The Social Sciences have seen the largest increase, from 28% in 2000 to 45% in 2009 (Table 2). A detailed look by field (Table 1), displays fields that could be seen to have stabilized in terms of growth of collaboration. Many fields in the Life Sciences (e.g., Microbiology and Biology & Biochemistry) have seen less than 1% growth in collaborations in the last decade. Some have even shown minor declines in the percentage of collaboratively authored articles (e.g., Immunology and Molecular Biology & Genetics).

Institutional Collaboration

As noted earlier, multiinstitutional collaborations (those collaborations written with authors from different institutions) have climbed from 37% in 2000 to 48% in 2009 (Figure 3). For the entire time period, collaborations within single institutions still represent the majority of the research output (see Table 5). Approximately 83% of publications are written between one or two institutions and around 97% of the world publications are authored by five or fewer institutions. A small portion of publications accounts for 10 or more institutions per publication (0.3%) (Table 5). The largest collaboration in our sample, in terms of institutions, had 201 institutions on the paper.

As was revealed in the general overview of collaboration, practices in multiinstitutional publications also vary by field. The field that favored multiinstitutional collaborations the most was Space Science, with these types of collaborations occupying nearly 66% of the total collaborations (Table 3). Other disciplines with high degrees of multiinstitutional collaboration included Immunology, Geosciences, and Molecular Biology & Genetics. The Social Sciences ranked low in this regard (likely due to their overall lack of collaboration). Other disciplines with low levels of multiinstitutional collaboration included Psychiatry/Psychology, Economics & Business, and Chemistry. Variation was also seen in terms of percent increase from 2000 to 2009, with fields such as Agricultural Sciences and Environment/Ecology showing

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TABLE 3. The percentage of multiinstitutional publications in 22 ESI fields.

ESI fields	Multiinstitutional publications (%) 2000	2009	2000–2009 (Avg.)	Change from 2000 to 2009 (%)
Space Science	61.38	70.19	65.79	8.81
Immunology	54.55	58.39	56.47	3.84
Geosciences	50.21	60.92	55.57	10.71
Molecular Biology & Genetics	49.62	55.39	52.51	5.78
Environment/Ecology	44.25	58.93	51.59	14.69
Microbiology	46.17	56.9	51.53	10.74
Physics	48.42	53.46	50.94	5.04
Neuroscience & Behavior	43.67	53.32	48.5	9.65
Biology & Biochemistry	42.06	52.33	47.2	10.28
Plant & Animal Science	39.1	53.74	46.42	14.64
Pharmacology & Toxicology	39.84	51.54	45.69	11.69
Multidisciplinary	39.07	51.92	45.49	12.85
Materials Science	40.4	49.3	44.85	8.9
Clinical Medicine	38.52	50.13	44.32	11.61
Computer Science	37.91	49.46	43.69	11.55
Agricultural Sciences	35.04	51.93	43.49	16.9
Mathematics	38.9	46.74	42.82	7.84
Engineering	36.54	46.51	41.52	9.97
Chemistry	37.3	45.36	41.33	8.06
Economics & Business	35.51	47.03	41.27	11.51
Psychiatry/Psychology	35.51	46.78	41.14	11.27
Social Sciences, general	17.21	31.15	24.18	13.94

high levels of increase and Immunology showing very little increase.

International Collaboration

As described in Figure 3, multinational collaborations have seen a rise from 14% in 2000 to 18% in 2009. As shown in Table 5, the majority of papers are written within a single country and less than 1% include more than three countries. Around 16% of global publications are internationally coauthored (based on the results 15.5% are just two- and three-country publications) and the remaining 84% are the results of domestic collaborations (Table 5).

The largest collaboration in our sample involved 61 countries. Some of the disciplines with high numbers of multiinstitutional publications also appear highly ranked in percentage of multinational publications (e.g., Space Science and Geosciences). However, other disciplines, such as Physics and Mathematics, appear higher on the list of multinational collaborations than they were on the list of multiinstitutional. Disciplines with low levels of multinational collaboration include Social Sciences (6.47%), Psychiatry/Psychology (11.64%), and Clinical Medicine (12.48%). Many fields besides Space Science saw an increase in the percentage of multinational publications; only Physics saw a decrease (See Table 4).

International Collaborations by Country

Although countries' tendencies toward international collaboration could be measured by the proportion of their multinational publications to total world multinational publications, the rate of their contribution to international teams is largely a function of their number of publications, as suggested by Luukkonen et al. (1992). About 30% of world publications have originated in the U.S.A.; only 20% out of the total number of U.S.A.'s publications are the result of multinational collaborations; however, approximately 45% of the world's publications with international author teams include the U.S.A. (Table 6). In proportion to the U.S.A.'s total number of publications, it ranks 27th in multinational collaborations (Table 6). Therefore, although the U.S.A. produces a low percentage of multinational publications compared to its overall output, the large total number of contributions makes the U.S.A. a major producer of multinational publications. The U.S.A. has cooperated, in terms of multinational collaborations, with 210 other countries over the recent decade; hence, it is playing an important role in networking international research collaboration.

Mapping scientific cooperation at the country level reveals that Western countries cooperate together extensively and represent the core of the network. These core countries are producing the largest number of scientific publications of the world. The U.S.A., U.K., Germany, France, Italy, and Canada produce a large number of the publications and occupy a central location in the collaboration network. These six countries produce 82% of the multinational publications (Table 6). As can be seen in Figure 5, they are highlighted in yellow and have the highest rate of collaboration together. Then we have the green spheres where yellow core countries are their main counterparts. China, Japan, and South Korea are cooperating

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TABLE 4. The percentage of multinational publications in 22 ESI fields.

ESI fields	Multinational publications (%) 2000	2009	2000–2009 (Avg.)	Change from 2000 to 2009 (%)
Space Science	38.38	49.18	43.78	10.8
Geosciences	24.7	32.35	28.53	7.65
Physics	26.55	26.01	26.28	−0.55
Mathematics	23.17	25.56	24.36	2.38
Molecular Biology & Genetics	21.43	23.96	22.69	2.52
Immunology	21.4	23.14	22.27	1.74
Microbiology	19.14	23.1	21.12	3.96
Environment/Ecology	16.97	24.8	20.88	7.83
Multidisciplinary	16.81	24.94	20.88	8.13
Computer Science	15.52	22.44	18.98	6.92
Biology & Biochemistry	16.13	21.17	18.65	5.05
Plant & Animal Science	15.72	21.28	18.5	5.57
Economics & Business	13.55	22.74	18.15	9.19
Neuroscience & Behavior	15.7	19.2	17.45	3.5
Materials Science	14.94	18.08	16.51	3.13
Chemistry	15.18	17.79	16.48	2.62
Engineering	14.43	18.54	16.48	4.11
Agricultural Sciences	12.26	17.56	14.91	5.3
Pharmacology & Toxicology	12.93	16.46	14.69	3.52
Clinical Medicine	10.11	14.85	12.48	4.74
Psychiatry/Psychology	8.17	15.1	11.64	6.93
Social Sciences, general	3.65	9.3	6.47	5.65

TABLE 5. Size of collaboration in terms of different patterns.

Size of collaboration	Authors %	Authors Accumulated %	Institutions %	Institutions Accumulated %	Countries %	Countries Accumulated %
1	25.13	25.13	56.33	56.33	83.53	83.53
2	16.31	41.44	26.45	82.79	13.38	96.9
3	15.48	56.92	10.43	93.21	2.26	99.16
4	12.83	69.75	3.75	96.96	0.48	99.64
5	9.72	79.47	1.44	98.4	0.16	99.8
6	7.1	86.57	0.64	99.04	0.07	99.87
7	4.58	91.14	0.32	99.36	0.04	99.91
8	3.05	94.19	0.19	99.55	0.03	99.94
9	1.92	96.11	0.12	99.68	0.02	99.96
10≤	3.89	100	0.32	100	0.04	100

the most together, highlighted in red, and also Brazil, Mexico, and Argentina highlighted in dark blue.

As demonstrated above, the size of each country's output necessarily conflates the understanding of the internationality of the collaborations within these countries. Therefore, Table 6 provides data on the number of publications and the percent of publications that were multinational. This table covers 2 single years and a 10-year period from 2000 to 2009. The total number of multinational publications out of all publications was calculated for each country. To determine the change occurring in the share of multinational papers of each country during the 10 years, the share of multinational papers in 2000 was subtracted from that of 2009. Countries are ranked based on their number of publications (productivity) over the 10 years in this table. The percentage of "International Publications to World International Publications" indicates the country share of multinational publications out of world total multinational publications. "International collaboration rank" is showing which countries have the largest proportion of multinational collaborations. The most international, according to this calculation, is Switzerland, with 55% of its total output as multinationally authored publications. While Switzerland only maintains about 1.5% of the world's total publications, the share of its multinational publications of world multinational publications is nearly 6%. Other countries with high rates of multinational collaborations (more than 50% of all their output) include Belgium, Denmark, and Austria (Table 6).

TABLE 6. International collaboration across the most productive countries of the world.

Country	No. of publications 2009	No. of int. publications 2009	% Int. publications 2009	No. of publications 2000	No. of int. publications 2000	% Int. publications 2000	2009 (%) to 2000 (%) Difference	No. of publications (2000–2009)	No. of int. publications (2000–2009)	% International collaboration (2000–2009)	Total productivity rank	Total int. collaboration rank	Rank of int. collaboration growth	Share of total world publications	% Int. publications to world int. publications
USA	472,899	119,903	25.35	326,147	54,236	16.63	8.73	4,195,166	863,677	20.59	1	27	20	30.03	44.59
UK	132,142	52,866	40.01	89,229	22,892	25.66	14.35	1,083,665	365,964	33.77	2	21	3	7.76	18.89
Germany	115,754	50,838	43.92	66,523	22,705	34.13	9.8	895,973	361,786	40.38	3	13	16	6.41	18.68
Japan	93,514	22,151	23.69	66,508	11,719	17.62	6.07	837,305	176,598	21.09	4	26	24	5.99	9.12
China	134,809	31,330	23.24	26,434	6,004	22.71	0.53	709,751	160,789	22.65	5	25	38	5.08	8.3
France	79,159	37,061	46.82	46,131	16,780	36.37	10.44	611,893	261,689	42.77	6	11	14	4.38	13.51
Canada	70,955	29,550	41.65	38,544	11,635	30.19	11.46	543,842	200,224	36.82	7	16	8	3.89	10.34
Italy	66,876	26,270	39.28	31,751	10,699	33.7	5.6	485,495	178,916	36.85	8	15	26	3.47	9.24
Spain	54,740	20,798	37.99	22,342	6,889	30.83	7.16	363,719	127,864	35.15	9	19	22	2.6	6.6
Australia	49,080	19,901	40.55	22,643	6,496	28.69	11.86	340,940	121,829	35.73	10	18	7	2.44	6.29
Netherlands	39,100	19,116	48.89	20,143	7,991	39.67	9.22	289,011	128,802	44.57	11	9	18	2.07	6.65
India	45,240	8,322	18.4	15,263	2,480	16.25	2.15	277,490	49,831	17.96	12	29	34	1.99	2.57
Russia	32,418	9,691	29.89	23,310	7,106	30.48	−0.6	264,169	88,987	33.69	13	22	42	1.89	4.59
South Korea	43,920	10,691	24.34	12,610	2,770	21.97	2.38	264,097	65,068	24.64	14	24	32	1.89	3.36
Brazil	36,881	8,979	24.35	11,050	3,337	30.2	−5.85	209,170	57,687	27.58	15	23	50	1.5	2.98
Switzerland	28,267	16,958	59.99	13,595	6,638	48.83	11.17	201,966	112,444	55.67	16	1	9	1.45	5.81
Sweden	23,446	12,764	54.44	14,677	6,119	41.69	12.75	195,563	93,966	48.05	17	6	4	1.4	4.85
Taiwan	26,775	5,599	20.91	8,804	1,633	18.55	2.36	167,193	32,745	19.59	18	28	33	1.2	1.69
Belgium	21,183	11,932	56.33	10,209	4,771	46.73	9.6	154,486	80,926	52.38	19	2	17	1.11	4.18
Poland	22,364	7,243	32.39	8,893	3,557	40	−7.61	153,588	55,650	36.23	20	17	52	1.1	2.87
Turkey	25,513	4,006	15.7	5,223	963	18.44	−2.74	150,833	24,126	16	21	30	46	1.08	1.25
Austria	14,989	8,303	55.39	7,131	3,094	43.39	12.01	108,834	54,905	50.45	22	4	6	0.78	2.83
Denmark	13,986	7,759	55.48	7,997	3,599	45	10.47	108,303	54,803	50.6	23	3	13	0.78	2.83
Finland	11,627	5,776	49.68	7,267	2,989	41.13	8.55	95,158	42,568	44.73	24	8	21	0.68	2.2
Greece	13,845	4,982	35.98	4,844	1,661	34.29	1.7	92,641	31,705	34.22	25	20	35	0.66	1.64
Mexico	10,996	4,423	40.22	4,671	1,855	39.71	0.51	77,524	31,345	40.43	26	12	39	0.55	1.62
Norway	10,863	5,754	52.97	4,946	2,006	40.56	12.41	75,959	36,938	48.63	27	5	5	0.54	1.91
Czech Republic	10,840	4,590	42.34	3,859	1,699	44.03	−1.68	69,262	30,515	44.06	28	10	45	0.5	1.58
Singapore	9,677	4,649	48.04	3,350	1,041	31.07	17	63,598	25,614	40.27	29	14	2	0.46	1.32
Portugal	10,710	5,086	47.49	2,999	1,411	47.05	0.44	63,087	30,075	47.67	30	7	40	0.45	1.55

Countries with the lowest rates of international collaboration (less than 20%) include Turkey, India, and Taiwan (shown in pink in Figure 5). Turkey, the lowest-ranked in terms of international collaboration, has seen a decline in international collaborations since 2000. Other countries demonstrating a decline include Brazil, Russia, Poland, and the Czech Republic. The countries with the largest percent increase (more than 12%) include Austria, Norway, Sweden, and the United Kingdom (Table 6).

The rate of scientific development is one of the main pivots in international scientific collaborations. It seems that scientific development of a country could effectively motivate other countries to cooperate with a highly developed country. Mapping scientific collaboration based on Wagner et al.'s categorization of countries provides evidence to support this assumption. As mentioned, Wagner et al. (2001) categorized the world's countries into four different groups in terms of rate of scientific development. The rate of collaboration among four scientifically groups of countries including SACs, SPCs, SDCs, and SLCs was examined. Based on the findings, SACs are the core group in international collaboration and their main counterparts are SPCs, then SDCs and SLCs, respectively. SDCs have mainly cooperated with SPCs; also, SPCs are the main counterparts for SLCs after SACs (Table 7).

The rate of contribution to multinational collaborations is also affected by the rate of economic development in the countries. The main counterparts of high-income countries are upper-middle income countries, then

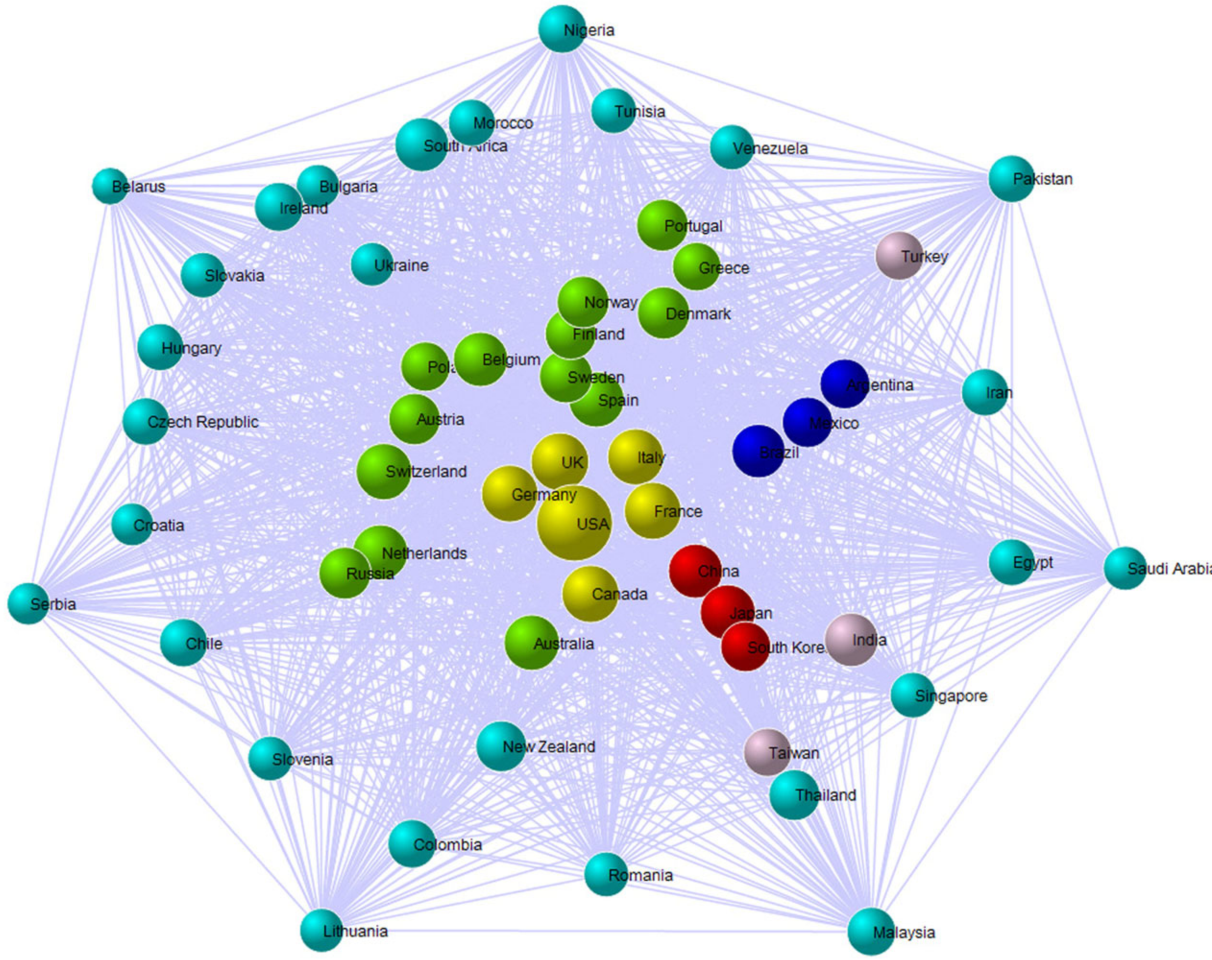

FIG. 5. Map of research collaboration among the most productive countries of the world (Using Kamada-Kawai layout with similarities as the values of lines in Pajek). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

TABLE 7. Collaboration among the four scientifically groups of countries.

Collaborating scientific countries (1)	Collaborating scientific countries (2)	Joint publications (freq.)
SACs	SPCs	437,765
SACs	SDCs	122,778
SACs	SLCs	104,544
SDCs	SPCs	36,975
SDCs	SLCs	10,646
SLCs	SPCs	17,802

lower-middle incomes and low-incomes, respectively. This situation is also effective when high-incomes and upper middle-incomes are categorized as the Organisation for Economic Co-operation and Development member countries (OECDs) or non-OECDs. High-income OECDs are the main counterparts of all other groups of countries; upper middle-income non-OECDs are their first collaboraters, then lower middle-incomes, high-income non-OECDs, and upper middle-income OECDs are their main partners, respectively (Table 8).

TABLE 8. Collaboration among economically groups of countries.

Collaborating economic countries (1)	Collaborating economic countries (2)	Joint publications (freq.)
High income-OECD	Upper middle-NON OECD	221,432
High income-OECD	Lower middle income	131,591
High income-OECD	High income-NON OECD	107,870
High income-OECD	Upper middle-OECD	90,477
High income-OECD	Low income	38,893
Upper middle-NON OECD	Lower middle income	19,618
Upper middle-NON OECD	Upper middle-OECD	16,121
High income-NON OECD	Upper middle-NON OECD	11,191
High income-NON OECD	Lower middle income	10,270
Upper middle-OECD	Lower middle income	9,198
Low income	Lower middle income	4,888
Low income	Upper middle-NON OECD	4,743
Upper middle-OECD	High income-NON OECD	4,721
Low income	High income-NON OECD	1,507
Low income	Upper middle-OECD	757

Size of Research Teams

Table 5 displays the size of collaborations by authors, institutions, and countries. This analysis shows that the majority of

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TABLE 9. Change in size of collaboration from 2000 to 2009.

	Multiauthored publications (%)			Multiinstitutional publications (%)			Multinational publications (%)		
Size of collaboration	2000	2009	Change from 2000 to 2009	2000	2009	Change from 2000 to 2009	2000	2009	Change from 2000 to 2009
2	19.65	24.85	−5.2	65.36	56.92	−8.44	82.52	78.56	−3.96
3	19.76	22.31	−2.54	22.4	24.7	2.3	12.1	14.59	2.5
4	16.87	17.51	−0.64	7.15	9.68	2.52	2.18	3.4	1.21
5	13.27	12.53	0.74	2.51	3.95	1.44	0.66	1.19	0.53
6	9.91	8.61	1.3	1.03	1.83	0.8	0.32	0.56	0.24
7	6.56	5.32	1.24	0.51	0.96	0.45	0.17	0.3	0.14
8	4.49	3.33	1.16	0.32	0.58	0.26	0.1	0.2	0.1
9	2.95	2	0.95	0.19	0.37	0.18	0.06	0.14	0.08
10	2.15	1.29	0.86	0.12	0.26	0.14	0.06	0.11	0.06
11	1.3	0.71	0.59	0.08	0.17	0.09	0.04	0.06	0.01
12	0.89	0.49	0.4	0.07	0.12	0.05	0.03	0.03	0.01
13	0.56	0.27	0.29	0.04	0.09	0.04	0.02	0.03	0.01
≥14	1.63	0.78	0.85	0.21	0.38	0.17	0.07	0.11	0.04

publications (57%) were written with 1–3 authors, from one institution (56%) and from a single country (84%). However, a deeper analysis into the size of the research team presents some variation over time in the size of collaborative teams.

The result of comparing scientific productivity in 2000 with 2009 in terms of number of authors per paper reveals that the share of smaller research teams is decreasing. Moreover, the expansion of research teams in terms of number of institutions and countries per paper is increasing. The share of two- to four-author publications has decreased from 8.4% to 7.7%. As the share of two- to four-author publications declines, the share of five and more-author publications has increased. In addition, as the share of international research with two countries has decreased, the tendency to three- and four-country cooperation has increased. In terms of institutions, two-institution cooperation has decreased while three- to six-institution publications have increased. Therefore, over the last decade research teams are growing in terms of number of authors and expanding in terms of number of institutions and countries (Table 9).

Patterns Among Highly Cited Institutions

The top 20 institutions and universities in terms of number of citations over the 10 years were identified. The size of research teams at these universities in terms of average number of researchers (10 researchers per paper on average), institutions (3.25 institutions per paper on average) and countries (1.57 countries per paper on average) is much higher than that of the world average (world average = 3.8 authors per paper, 1.8 institutions per paper and 1.2 countries per paper).

The average number of authors per paper in the publications of the top 20 universities of the world is higher than the average of the world in all 22 fields of ESI. Some fields are dramatically above average, e.g., the average number of authors per paper in Physics is 16 times higher than the average of the world. Space Science, Multidisciplinary, and Engineering are the other three fields in which the average number of authors per paper is two times higher than the world average. The difference between the average number of authors per paper in the top institutions with the average of the world is less in other fields (Table 10).

The top 20 institutions of the world have a tendency toward multiauthored, multiinstitutional, and multinational team workings compared to the world average (Table 11). In the Social Sciences, the percentage of multientity publications is almost double the world average. Physical Science has produced the largest number of publications with international research teams in top institutions, whereas at the world level Multidisciplinary has seen the highest percentage of publications with international teams. In the top institutions, the percentage of publications with interinstitutional teams is higher for Medicine than the other fields, with the highest rate of multiauthored works in the Life Sciences (Table 11).

Discussion

Collaboration has increased at the author, institution, and country level as supported by a number of studies (e.g., Glänzel, 2001; Adams, Black, Clemmons, & Stephan, 2005; Wagner & Leydesdorff, 2005; Wagner, 2005). However, these increases have not been uniform by field. The life sciences have the highest degrees of collaboration, whereas the social sciences have the lowest. Even within these macro-level categories, there is differentiation. Therefore, it is necessary to think in field-specific ways in all studies of collaboration. Growth for many of the high collaboration areas (e.g., Microbiology and Biology & Biochemistry) has stalled as these fields reach nearly ubiquitous collaboration practices. Although parallel patterns of growth were seen across all collaboration types (author, institution, and country), the fields that were most collaborative in each of these areas were not the same. For example, disciplines such as Physics and Mathematics favored international teams, whereas disciplines

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TABLE 10. Top institutions average vs. world average in 22 fields.

ESI fields	Average no. of authors (top 20 institutions)	Average no. of authors (world)	ESI fields	Average no. of authors (top 20 institutions)	Average no. of authors (world)
Physics	83.8	5.1	Environment/Ecology	4.5	3.5
Space Science	11.2	4.8	Microbiology	5.6	4.8
Multidisciplinary	8.1	3.6	Social Sciences, general	2.6	1.8
Engineering	5.3	3	Neuroscience & Behavior	5.4	4.7
Chemistry	5.9	3.9	Biology & Biochemistry	5.1	4.4
Molecular Biology & Genetics	6.6	5	Computer Science	3.3	2.7
Agricultural Sciences	5	3.7	Materials Science	4.3	3.7
Clinical Medicine	6.1	4.8	Economics & Business	2.2	1.7
Geosciences	4.7	3.4	Plant & Animal Science	4	3.5
Immunology	6.7	5.5	Pharmacology & Toxicology	4.8	4.4
Psychiatry/Psychology	4.2	3	Mathematics	2.2	1.9

TABLE 11. Top institutions average vs. world average in five broadfields.

Broad fields	% Multi-authorship (top 20)	% Multi-authorship (world)	% Multi-institutional (top 20)	% Multi-institutional (world)	% Multi-national (top 20)	% Multi-national (world)
Life sciences	93.8	88.6	67.1	48.7	29.5	18.8
Physical sciences	93.1	82.9	66.5	46.93	34.9	21.25
Medicine	90.3	84	68.9	45	23.7	12.77
Multidisciplinary	87.2	56.7	66.6	47	32.4	21.67
Social sciences	56.2	36.4	49.4	27.93	15.1	8.9

in the health sciences favored within-country institutional collaborations.

Wagner (2005) argued that research collaboration mostly appears in the case of lack of equipment and resources and categorized different subject fields as theory or resource-based ones and states a hypothesis assigning a level of research collaboration to each field; e.g., Mathematics is considered a theory-based field and a minor tendency toward research collaboration is predicted among mathematicians. Although her study did not clearly prove her assumption, we can claim a rather clear pattern as we found some theory-based fields like Economics and Business, Social Sciences, and Mathematics are less multiauthored while some resource-based fields like Microbiology, Immunology, Molecular Biology, Biology & Biochemistry have a great tendency toward research collaboration (see Table 1).

Analysis of the collaborations between countries revealed the core placement six countries in the collaboration network: U.S., U.K., Germany, France, Italy, and Canada account for 82% of the world's multinational publications. However, these are not necessarily the most collaborative countries, if measured by their proportion of collaborative output. Countries such as Switzerland lead in this ranking, with 55% of its total output as multinationally authored publications. Other highly ranked countries in this regard include Belgium, Denmark, and Austria. The size of these countries should be calculated into future analyses as this may be a contributing factor in this ranking. However, countries that ranked low on collaborative behaviors were not necessarily large (e.g., Taiwan), providing an indication that other factors may be contributing to the level of multinational collaboration. The analysis provided evidence that countries rated high in terms of scientific development were more likely to collaborate. However, as described in the literature review, elements such as language, culture, and politics can also affect collaboration behavior.

Examination of research team size shows that not only are collaborations more prevalent, but the size of the research team is increasing on all levels—the total number of authors, institutions, and countries on each paper. This could be considered a general shift to Big Science behavior across all the sciences. One possible explanation for this is the pressure from funding agencies and institutions to do collaborative work—scholars may be amassing larger labs/centers/teams in order to meet these pressures and to prepare themselves for quantitative evaluations that rely on elements such as publication and citation counts (as the publication and citation advantage of collaborative work has been documented). To further test the relationship between academic rewards and collaboration, we examined whether the institutions with the highest impact (as measured through citations) tended to have higher levels of collaboration. Our analysis of the top 20 institutions provided evidence that these high-impact institutions had higher levels of collaboration across all fields and all collaboration types. This suggests that there is a relationship between impact and collaboration.

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Conclusion

The objective of this study was to provide a global description of collaboration behaviors across multiple collaboration types and across a range of disciplines. The data provided are informative for the scholars in these disciplines as well as policy makers and administrators engaging in evaluative bibliometrics. The study provides a benchmark and comparison across many domains. This comparison is useful for highlighting the large differences in collaborative behavior, not only at the author level, but at the institution and country level.

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