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Visualizing nanotechnology research in Canada: evidence from publication activities, 1990–2009

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Abstract Over the last two decades the scientific community has witnessed unprecedented growth of nanotechnology research in Canada. Although recent studies have shown that Canada consistently maintains a position in the first tier of productive countries in terms of its share of the world's nano-publications, a number of key questions remain unanswered. Using a unique nano-related publication dataset, this paper combines bibliometric analysis and science overlay mapping to visualize the 'invisible college' of Canadian nano research. The present analysis finds that the rapid growth of nanotechnology research in Canada is, for the most part, externally driven. In recent years, research content has shifted toward nanobiotechnology fields. The geographical distribution of Canadian domestic nanotechnology research is characterized by regional imbalance: most research hubs are located near US–Canadian borders. Canadian nanotechnology scientists have collaborated with a variety of countries, but Chinese scholars in particular play a leading role in Canada's research exchange across national borders.

Keywords Nanotechnology · Canadian research · International collaboration · Data visualization

JEL Classification O32 · O38

1 Introduction

Nanotechnology has been increasingly heralded as a promising field which will meaningfully influence socio-economic development (Roco and Bainbridge 2005; Zucker and Darby 2007; Shapira and Youtie 2011). The National Science Foundation of the United States has

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estimated that the annual global market for nano-related goods and services will exceed $1 trillion by 2015 (Lee et al. 2006). Accordingly, many countries have prioritized nanotechnology on their national research agenda. Figures show that federal funding for the National Nanotechnology Initiative (NNI) in the United States has more than doubled in 4 years, increasing from $464 million in the fiscal year of 2001 (FY01) to $1.1 billion in the fiscal year of 2005. State governments and private sectors have also increased their investment in nanotechnology. In 2004, investments in nanotechnology from the private sector rose to roughly $2 billion (Nanotechnology: where does the U.S. stand 2005; Nordan et al. 2005).

Similar to the US, Canadian investments earmarked for nanotechnology have been substantial, and various policies have been enacted and programs created to spur R&D in nanotechnology (Beaudry and Schiffauerova 2011; Yegul et al. 2008). According to statistics released by the European Commission Report (2005), Canada Research Chairs Program has invested some $290 million US dollars per annum to attract and retain leading researchers in Canada. The Nano Innovation Platform at the Natural Science and Engineering Research Council of Canada (NSERC) has also allocated five million US dollars to support cutting-edge nano research and facilitate the work of local communities of networked nano researchers, especially junior researchers and graduate students (Rosei 2008). The question is raised: has this considerable investment been spent wisely? Also: what is the status quo and development trajectory of Canadian nanotechnology research?

Some studies have shown that Canada is listed among the top countries producing nanotechnology research (Beaudry and Schiffauerova 2011; Yegul et al. 2008). Few studies, yet, have explored the intellectual structure and dynamics of the Canadian nano community. Nor have the patterns of international collaboration been systematically investigated. This article seeks to address this research gap by visualizing the invisible college of Canada in the emerging field of nanotechnology. It is hoped this will aid readers' understanding of the degree of technology transfer occurring between Canada and other countries in the field of nanotechnology.

2 Data and methodology

This study utilizes a global nanotechnology publication dataset extracted from Web of Science (WOS). Built on the nanotechnology search strategies of previous research (Kostoff et al. 2006; Zhou and Leydesdorff 2006; Heinze et al. 2007), a two-stage composite Boolean search strategy validated by nano scientists was developed by Science, Technology, and Innovation Policy (STIP) researchers at the Georgia Institute of Technology. The strategy was applied to the Web of Science: Science Citation Index Expanded (WoS-SCI), the most recognized publication dataset in scientifically-minded academia, and global publications of nano research from 1990 to 2009, inclusive, were downloaded in December 2009. In order to include the most comprehensive set of records possible, nano-related keywords were searched in the four fields of article raw records: title, abstract, journal name, and author's key words. After removing duplicate records based on a unique paper identification number for each article, two sets of exclusionary terms were applied to drop records that were poorly linked with the National Nanotechnology Initiative definition of nanotechnology (NNI). The final dataset included approximately 430,000 global records. For more details please refer to Porter et al. (2008) and Porter and Youtie (2009).

The present study defines a Canadian publication as an article from a publication with at least one Canadian address in its byline. Records satisfying this definition were extracted from 20 annual global nanoscience datasets and merged into one file. The final dataset

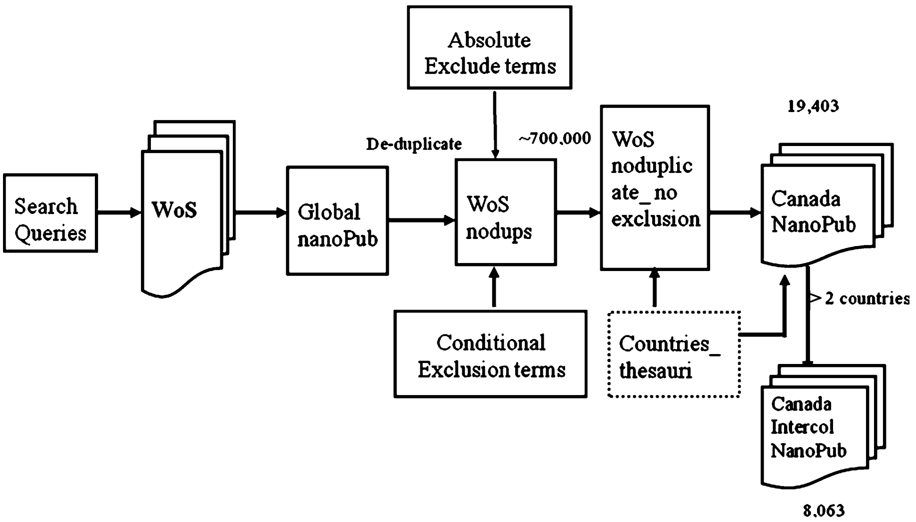

Fig. 1 Construction of Canadian nanotechnology publication dataset

consisted of 19,403 Canadian NST records and 8,063 internationally collaborated articles. All of these records were initially downloaded as raw text and then imported into a text-mining software called VantagePoint[1] for cleaning and bibliometric analysis. Figure 1 illustrates the workflow involved in the construction of the Canadian nanotechnology publication dataset.

In spite of its value for research assessment, publication archival data has many pitfalls that need be addressed while tracing scientific advancement and research collaboration. Conventional challenges include inconsistency of bibliographic formats, optical character recognition (OCR) scanning errors, transliteration problems and import filter parsing errors (George 2006). As Hood and Wilson (2003) have observed, bibliographic databases pay little attention to standardizing authorship-related information across different journals. Some bibliometricians have advocated for the necessity of "consistent and standardized indicators", however, the practice of "editing or standardization processes and an overall scrutiny" is largely ignored. This invalidates or at least casts doubt on the results of analysis as well as policy implications derived from findings.

A review of the downloaded papers reveals that bibliographic information in research papers contains numerous errors. For purposes of this study, the fields of affiliation names, affiliation countries, and affiliation cities have been specifically targeted for cleaning and standardization. Before any analysis, these three fields were subject to three stages of sequential cleaning (Raffo and Lhuillery 2009). The first stage focused on phonetic errors such as misspellings, hyphenation, capitalization, different name formats, and so forth. This stage was automatically completed using the most conservative thesauri and fuzzy files built into VantagePoint. The second stage consisted of manually checking two types of errors: false positives and false negatives, which are either neglected or introduced by automatic cleaning. The final stage consisted of validating cross records based on complementary resources beyond the archival data, such as Google search, in order to match affiliations with their name abbreviations and variations of the same.

[1] See www.theVantagePoint.com.

3 Analysis

3.1 Canadian status in nanotechnology

The Georgia Tech global nanotechnology publication dataset includes more than 741,000 WoS-SCI records from 1990 to 2009. By volume, the top six most prolific countries in descending order are the United States, Japan, China, Germany, France, and the United Kingdom. These countries' combined contributions constitute over 60% of global nano-publications. Canada ranks the 12th over the last two decades. To map the relative positions of vanguard countries in greater detail, the global nanotechnology publication data has been divided into three subsets covering the periods 1990–1994, 1998–2002 and 2005–2009.

Table 1 shows the relative changes in rank of the most productive countries. Although it has enjoyed a leading position for a number of years, Table 1 reveals that the United States' global market share of nano-publications is in a state of relative decline. Japan, Germany, the United Kingdom, and France (countries colored in purple) have maintained their positions in the first tier of nano countries, albeit with declining ranks due to the rise of China. As seen, Canada ranked 6th in the world in terms of the amount of nanotechnology research produced during the period of 1990–1994. This suggests that, contrary to the popular belief that Canada was a "latecomer" to nanotechnology Canada has actually occupied a vanguard position since the early 1990s, at least in terms of nanotechnology research output. In addition, among the original fifteen most productive countries from 1990 to 1994, Canada has uniquely demonstrated a downward trend with a global share from 4% in the period of 1990–1994 to 2% in the period of 1998–2002 due to the emergence of rising powers such as China and South Korea. Phase Three (2005–2009) of Table 1 reveals that Canada ascent to a top six position among the most productive countries in nanotechnology.

Table 1 Ranking of countries by nanotechnology publication counts

Rank	1990-1994	1998-2002	2005-2009
	Country (Global %)	Country (Global %)	Country (Global %)
1	USA (40%)	USA (27%)	USA (26%)
2	Japan (12%)	Japan (14%)	China (17%)
3	Germany (10%)	Germany (12%)	Japan (10%)
4	UK (8%)	China (10%)	Germany (9%)
5	France (8%)	France (7%)	Canada (8%)
6	Canada (4%)	UK (7%)	France (6%)
7	Italy (4%)	Russia (5%)	UK (5%)
8	China (3%)	Italy (4%)	South Korea (5%)
9	Russia (3%)	South Korea (4%)	Italy (3%)
10	Switzerland (2%)	Spain (3%)	India (3%)
11	Netherlands (2%)	Canada (2%)	Russia (3%)
12	Spain (2%)	India (2%)	Spain (3%)
13	Sweden (2%)	Switzerland (2%)	Taiwan (3%)
14	India (2%)	Netherlands (2%)	Poland (2%)
15	Australia (1%)	Sweden (2%)	Australia (2%)

Table 2 Top 15 research institutes/universities in Canadian nanotechnology publications

Rank	# Records	Share of Canadian articles (%)	Author affiliations
1	2454	13	Univ Toronto
2	1994	10	Natl Res Council Canada
3	1402	7	McGill Univ
4	1402	7	Univ Alberta
5	1174	6	Univ British Columbia
6	1134	6	McMaster Univ
7	1031	5	Univ Western Ontario
8	769	4	Univ Montreal
9	762	4	Univ Waterloo
10	668	3	Univ Laval
11	570	3	Univ Ottawa
12	532	3	Queens Univ
13	522	3	Univ Calgary
14	492	3	Ecole Polytech
15	486	3	Univ Sherbrooke

In the study period of 1990–2009, Canada has been participated in the production of in roughly 19,400 peer-reviewed journal articles indexed on WOS. When differentiated by publication affiliations, the data shows that universities and national institutes spearhead R&D activities in nanotechnology in Canada. Approximately 93% of articles involve at least one author from universities, 18% of articles include an author from governmental research institutes, while 7 and 3% of articles include an author from the industrial sector and hospitals, respectively.[2] Table 2 lists the top fifteen organizations affiliated with Canadian nanotechnology articles. As shown, the flagship research organization is the University of Toronto. Approximately 13% of Canadian nano-publications have at least one author from this university. The University of Toronto is followed by the National Research Council (10%), McGill University (7%), and the University of Alberta (7%).

3.2 Canadian international co-publications in nanotechnology

In alignment with its title of "friendliest country," Canada has a diverse body of collaborating partners all over the world. During the past two decades, Canadian scientists have co-published 8,063 nanopublications with $\sim$4,000 affiliations located in 96 countries. Along with its rapid growth in total nanotechnology papers, its number of internationally co-authored collaborations also demonstrates rapid growth. As shown in Fig. 2, the number of Canadian internationally collaborated articles has not only grown remarkably by volume, but the share of articles relative to Canada's total output also demonstrates upward trends. From about 15% in 1990 to over 45% in 2009, the share of internationally collaborated articles in Canadian nanotechnology research has tripled over the past 20 years.[3]

[2] Some articles include authors from more than one sector, thus the summation is greater than 100%.

[3] In this article, a whole counting method is adopted to credit publications to countries and affiliations. For example, for a nano paper with four co-authors reporting two US affiliations and one Canadian affiliation, in counting authorship at the country level, the United States and Canada will be counted only once respectively. In terms of counting authorship at the organization level, in the above case, each *unique* affiliation will be also counted once each.

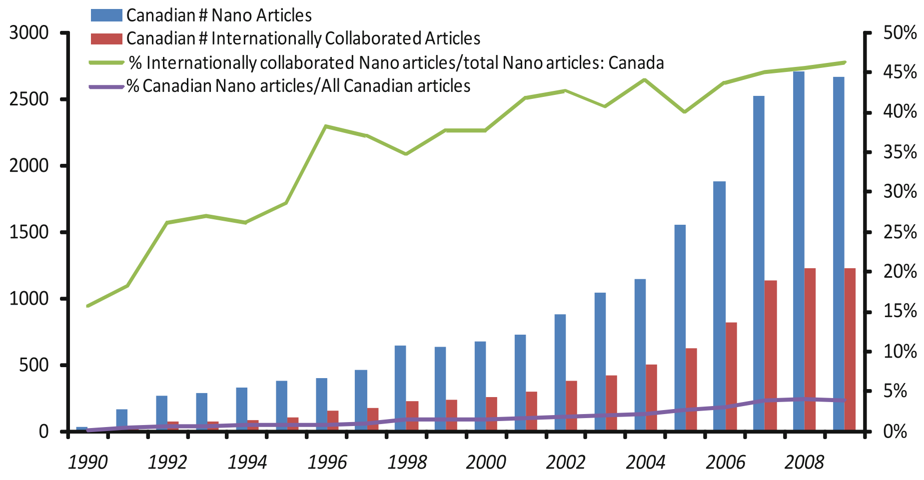

Fig. 2 Growth of the number of Canadian nanopublications: total and international collaboration

Table 3 Top 10 countries collaborating with Canada in nanotechnology

Rank	# Records	Countries	Share of Canadian internationally collaborated articles (%)
1	3228	USA	40
2	880	China	11
3	816	Germany	10
4	718	France	9
5	704	UK	9
6	505	Japan	6
7	288	Italy	4
8	248	Spain	3
9	236	Russia	3
10	230	Australia	3

This suggests the increasing importance of *international collaborative* activity for the research output of Canada's nanotechnology industry.

Table 3 lists the distribution of Canadian internationally-collaborated nano articles sorted by the number of participating countries. The United States, China, and Germany—the top three "nano countries"—are also those countries most intensively collaborating with Canada, representing more than 56% of the partners in Canadian international collaborations. Not surprisingly, the United States is Canada's #1 research partner. Approximately 40% of Canadian internationally collaborated research in nanotechnology involves at least one researcher from the United States—suggesting a significant volume of technology transfer between these countries, followed by China (11%) and Germany (10%). Starting from an initially low number of research collaborations, the Canada–US collaboration has increased sharply from only two nanotechnology articles in 1990 to more than 400 articles in 2009. When benchmarked against the other countries, Canada–US co-authorship is notably higher than Canadian co-publishing efforts with the remainder of

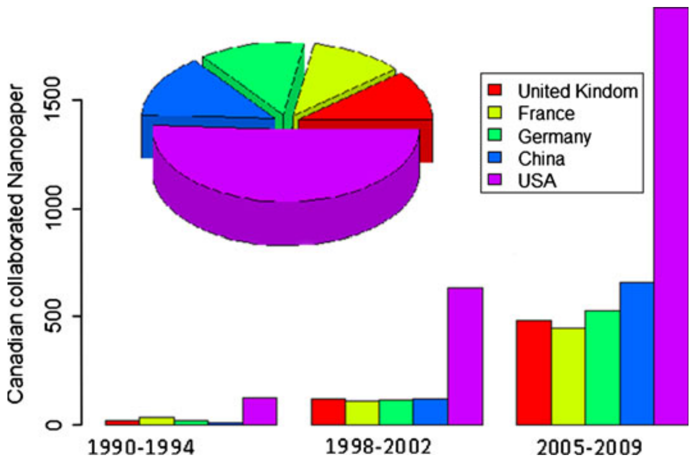

Fig. 3 Country shares of Chinese nanotechnology research

Canada's most frequent collaborators. Figure 3 highlights the consistently leading role assumed by the United States in Canada's international research collaboration.

In addition to quantity, Canada–US collaborated nano research also populates the high end of citations of Chinese nano research. In all Canadian internationally collaborated articles, the United States was involved in ~60% of the most frequently cited articles, followed by Germany (23%), France (15%), and others.[4] This is consistent with the findings of Youtie et al. (2008), which show that the United States has produced the highest quality of research, as measured by citations. It should be noted that the United States–Canada collaboration not only takes the lion's share of Canadian joint international research, but also the United States also claims a majority of the top 10 foreign institutes collaborating with Canada: six of ten universities from the top collaborating foreign institutes are located within the United States (Table 4).

Table 4 Top 10 international affiliations collaborating with Canada

Rank	# Records	Author affiliations	Country
1	190	Chinese Acad Sci	China
2	113	CNRS	France
3	110	Harvard Univ	USA
4	102	Russian Acad Sci	Russia
5	90	Univ Illinois	USA
6	86	Univ Wisconsin	USA
7	75	Univ Calif Berkeley	USA
8	74	MIT	USA
9	62	Arsonne Natl Lab	USA
10	62	Univ Tokyo	Japan

[4] Here the most frequently cited articles refer to 61 Canadian internationally collaborated nanotechnology articles that have been cited more than 100 times from its publication until December 31, 2009.

Among Canadian universities, the University of Toronto and the National Research Council Canada stand out in both total number of articles and international collaborations. In terms of geographical distribution, all three most prolific cities—Montreal, Ottawa, and Toronto—which far outperform other cities, are located in southern Canada on the border with the United States. These findings are not surprising, considering the research disparity among the different regions of Canada. Not only the largest, but also the most prominent research institutes and universities are located in these three cities, including the University of Toronto, the National Research Council Canada (Ottawa), McGill University, the University of British Columbia (Vancouver) and others, which accounts for the highly right-skewed distribution of scientific performance. In contrast, United States collaborators are distributed among a much more diverse area covering its 50 states. These divergent patterns of participation in collaboration appear to reflect the characteristics of the scientific systems in each country. Figure 4 maps the top 40 cities in terms of the number of United States–Canada co-published nanotechnology articles. The nodes are assigned a size proportional to the number of records associated with each particular city (i.e. a city containing 50 records would be assigned an icon size twice as large as one containing 25 records).

An interesting finding revealed by the present bibliometric analysis is that ethnic Chinese researchers play a critical role in Canadian nanotechnology research. Over one third of Canadian nanotechnology research articles involve at least one researcher with a Chinese family name. This is especially noteworthy given that only 11% of Canadian articles were jointly published with researchers with Chinese affiliations. This outcome may be explained in two ways: one plausible explanation is that Canada has successfully attracted Chinese researchers to stay in Canada; alternatively, it may also suggest that the bridging role of Canada-based Chinese researchers is not as influential as would be

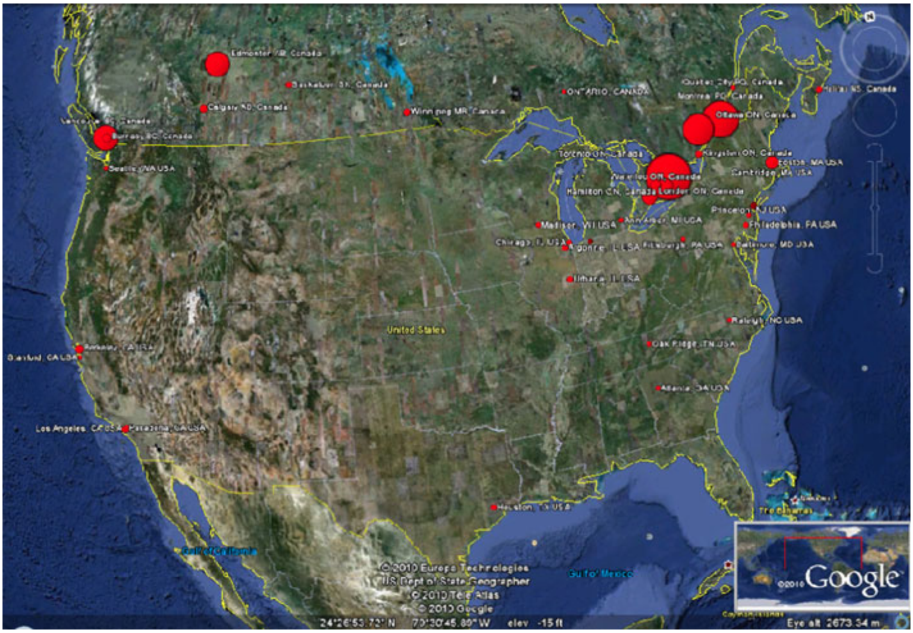

Fig. 4 Distribution of United States–Canada collaborated articles: 1990–2009

expected with regard to connecting the two geographically distant scientific communities in China and Canada.

3.3 Research content

Nanotechnology is a highly interdisciplinary field. Table 5 shows that a subset of areas dominate the field of nanopublications in Canada. As indicated by subject codes assigned by Thompson ISI, Canadian nano research spans 184 different subject categories, and internationally joint co-publications fall into 177 categories. Nevertheless, the top ten account for ~63%, most of which occupy the materials sciences, physics, and chemistry domains. Comparing the ten subject codes that appear most frequently in Canadian nano research in general and international joint publications, Table 5 indicates that the research fields in which Canadian colleagues most intensively collaborate internationally are fields in which Canada enjoys traditional strengths.

Figure 5 depicts the development of research content of Canada-based nanotechnology papers. The science overlay maps were generated utilizing the toolkit of the Science Overlay Map developed by Rafols et al. (2010). Pajek software (version 1.26) was used based on the subject categories of nanotechnology papers. In order to reduce the erratic publication variation by year, the publication years are separated into the three four-year phases: 1990–1994, 1998–2002 and 2005–2009. In the overlay maps, the gray and black background arcs indicate the connections of 175 subject categories (hereafter: SCs) in 2006, provided by Thompson ISI, and the weights of arcs are related to the number of SCs. The colored nodes, whose size is proportional to the number of joint papers by Canadian researchers, are aggregated scientific disciplines based on SC counts.

These three maps present several interesting results. Not surprisingly, the network of all collaborative domains has grown in both size and complexity. During the period 1990–1994, Canadian scientists published 1,074 articles in the field of nanotechnology. In the second phase of 1998–2002, another discipline, namely the general medical, produced nanoscience and nanotechnology articles. More interactions between materials science and chemistry took place, as reflected in the closer, overlapping nodes of the two fields; however, the connections among other macro fields are still rather disparate. From 2005 to 2009, Canadian research in nanotechnology entered a period of prosperity. All numbers of collaborative papers in the existing disciplines have grown dramatically. This growth was particularly marked in biomedical science, chemistry, and material science. These three

Table 5 Canada nanotechnology publications by disciplines: total versus international collaboration

All Articles			International Collaborated Articles	
Share	Subject Category		Subject Category	Share
17%	Materials Science, Multidisciplinary	→	Materials Science, Multidisciplinary	17%
16%	Chemistry, Physical	→	Chemistry, Physical	15%
14%	Physics, Applied	→	Physics, Applied	14%
11%	Physics, Condensed Matter	→	Physics, Condensed Matter	13%
10%	Chemistry, Multidisciplinary	→	Chemistry, Multidisciplinary	9%
6%	Polymer Science	→	Polymer Science	7%
5%	Physics, Atomic, Molecular & Chemical	→	Physics, Atomic, Molecular & Chemical	5%
5%	Biochemistry & Molecular Biology	→	Biochemistry & Molecular Biology	5%
3%	Engineering, Electrical & Electronic		Physics, Multidisciplinary	3%
3%	Chemistry, Analytical		Engineering, Electrical & Electronic	3%
3%	Physics, Multidisciplinary		11 Chemistry, Analytical	3%

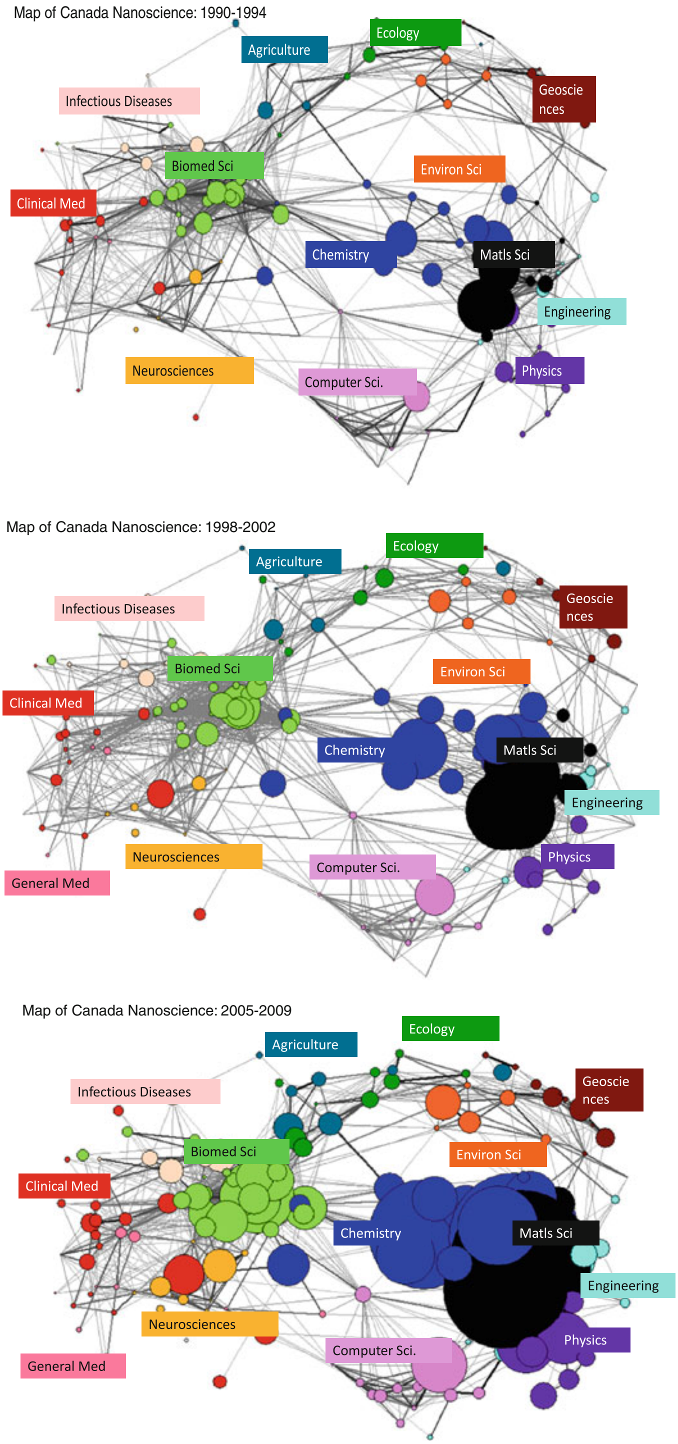

Fig. 5 Science overlap map of canadian research in nanotechnology: three phrases

overlay maps together lead us to cautiously conclude that a structural change of Canadian nanotechnology is taking place.

4 Conclusion and discussion

This paper suggests that Canada's enormous investment in nanotechnology has resulted in a number of quantifiable results. Reflected by research output, over 19,000 nanotechnology papers have been indexed in WOS since 1990. Over the last 5 years, Canada has become the fifth most productive country as measured by annual nanotechnology articles produced. When benchmarked against all research publications regardless of disciplines, the share of Canadian nanotechnology articles relative to all Canadian publications has witnessed significant growth over time.

This article argues that the rapid growth of nanotechnology research in Canada is driven both internally and externally, while the role of latter research is recently increasingly evident. Canadian nanotechnology scientists have been collaborating with a variety of countries, but the United States remains the most favorite collaborative partner in Canada's research exchange across national borders. Ethnic Chinese researchers play a critical role in the growth of Canadian nano research. In terms of the dynamics of research content, the expanding subject categories reflect that although many disciplines have experienced significant growth, the upward growth trend is particularly pronounced in the biomedical domain. This shift leads us to cautiously conclude that a structural change of Canadian nano research is taking place.

The present study is not without limitations. This research assumes that nanotechnology development in Canada can be captured by nanopublications archived in WoS-SCI, as all publication data included in this research were those indexed in WoS-SCI. However, as the most standardized publication dataset for scientific research analysis (Levin and Stephan 1991; Tang and Shapira 2011), WoS-SCI not without bias. WOS reflects a preference in favor of US publications while neglecting non-English publications. In Duque's words, this does not give adequate "indicators of scientific productivity outside the developed world" (Duque et al. 2005).

Notwithstanding the above-mentioned limitations, this research has broad policy implications. In spite of its dramatic public investment in nanotechnology, compared with other industrialized countries, Canadian government investment is among the closest to the United States (1.7 billion US dollars), Japan ($\sim$800 million US dollars), China (540 million US dollars) and other European Union countries. This requires a further scrutiny and justification of public investment in the future. More importantly, and in sharp contrast to its North American neighbor—the United States—the investment from private sectors in Canada is largely non-existent. The invisibility of industry R&D arguably undermines the utilization of R&D investment for Canada's own research needs. This problem is especially acute given the weak linkage between science and industry, a deeply rooted problem of the Canadian national innovation system. The knowledge created may not always translate into innovative technologies, but it can be used to enhance the welfare of the economy and the society in Canada.

The preceding bibliometric analysis finds that international collaboration plays an increasingly prominent role in Canadian nano research. From the perspective of international R&D exploitation, the findings pertain to policy implications to Canada. On one hand, the evidence of emerging countries' rise in science is indisputable. Canada should take advantage of and gain access to those countries' heavy R&D investment in this promising field. That is to say, Canada should ensure that it gains as much access as possible to the growing body of nanotechnology research and innovation via strengthening mechanisms that encourage collaboration with top notch scientists in the United States, China, Japan and other prominent incumbents on the horizon. In addition, the Canadian government should facilitate the expansion of knowledge diffusion by encouraging Canadian scholars who collaborate with their internationally renowned peers to increase their collaboration with domestic colleagues to create a "snowball effect" and maximize benefits. On the other hand, international scientific collaboration can also represent a double-edged sword. Concerns that Canada is losing its competitive advantage are growing. As demonstrated in the analysis section, Canadian scientists collaborate with their international peers in research domains where Canada is traditionally strong. This, on the one hand, points to the comparatively advanced level of the Canadian nanotechnology development considering the quid pro quo exchange. On the other hand, it may indicate a potent knowledge spillover across national borders contributing to knowledge accumulation in other collaborating countries.

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