Benchmarking of Canada within the Areas of Relevance to the Natural Sciences and Engineering Research Council's (NSERC) Evaluation Groups

Final Report

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Executive summary

The present study uses bibliometric measures to determine Canada's position on the world stage in Natural Sciences & Engineering (NSE) research for the period 2009–2013. The purpose of this work is to provide lines of evidence for an expert panel that will review the Natural Sciences & Engineering Research Council's (NSERC's) funding allocation structures for its Discovery Grant program. As these grants are allocated using a division into 12 Evaluation Groups (EGs), defined by NSERC, the data in this study will examine Canada's performance primarily at the EG level, and within the scientific subfields thereof. The principal questions to be addressed pertain to the following:

- Canada's performance at the EG level, compared to the rest of the world, using individual indicators (i.e., number of publications, growth ratio, specialization index, scientific impact, and collaboration index) as well as using a composite performance index
- The evolution over time of Canada's specialization and impact, relative to the rest of the world, within each EG
- The relative strengths and weaknesses of Canada's research, at the subfield level within each EG
- Topics that are fast-growing internationally and in which Canada has a research strength
- Topics that are highly interdisciplinary internationally and in which Canada has a research strength

In terms of international comparisons, 27 benchmark nations (including Canada) were identified using criteria stipulated by NSERC, one of which was the availability of reliable and relatively complete information. The full list of comparator nations is found in § 1.3.5 below. Two notes are worth making here, though; the first is that India, which is among the largest producers of papers in the NSE in the Web of Science (WoS), was excluded from NSERC's list due to an insufficiency of financial data. The second is that while China suffers from only partial coverage in the WoS, it has been included in this study because it is nevertheless one of the largest producers of peer-reviewed scientific publications in the WoS. However, as the coverage of Chinese literature is known to be very low, the results of the present study pertaining to research from China must be interpreted with the appropriate degree of caution, particularly in regard to its scientific impact, which is undoubtedly underestimated.

Evaluation Groups in which Canada performs best

Of the 12 EGs, there are 4 in which Canada's performance is distinctly stronger than the rest. Evolution & Ecology (EG1503) is the EG in which Canada ranks the highest on the world stage, sharing the 5th rank overall with Denmark and the US according to the composite index of scientific performance used in this study. Evolution & Ecology is a comparatively small research field, globally; in this area, Canada produces the 4th most papers among the benchmark nations. Canada is the 7th most specialized country in this area, with a specialization index (SI) well above the world level (Canada's SI score is 1.57, relative to the world average of 1.00). It is worth noting, however, that Canadian output in this field increased only slightly from 2009–2010 to 2012–2013: only a 6% increase, well below the global average of 16%. Regarding impact, according to several measures, Canada scores well above the worldwide average (ARC of 1.33, ARIF of 1.19, and HCP of 1.55), ranking for each of these measures in the top 10 among the 27 benchmark nations. Also, Canadian researchers collaborate with international partners as much as expected, based on output size, ranking 13th in this respect out of the 27 comparator nations. Canada's strong position in Evolution & Ecology research, therefore, derives primarily from its large production as well as its high specialization and impact in this area.

Canada's performance in Biological Systems & Functions (EG1502) is similarly strong, sharing the 5.5th[1] global rank with Australia based on the composite index. Once again, Canada is a strong producer in this relatively small research field at the world level, ranking 5th for most papers published among the benchmark countries. Canada is the 4th most specialized country in this area of research. Canadian production in this area is also growing quickly, with a 20% increase in publications from 2009–2010 to 2012–2013. Worldwide growth in this area is also very strong, however, and so in spite of its strong increase, Canada is still slightly behind the global average of growth, placing 17th among the 27 comparator research nations. Similarly, Canada's scientific impact in this area is very strong (ARC = 1.23; ARIF = 1.14; HCP = 1.33), well above the global average, and yet it only places in the middle of the pack of the 27 nations. In terms of international collaboration, Canada is co-publishing 25% more than expected (based on its volume of publication output), placing 12th out of the 27 leaders. Canada's strength in EG1502 stems from its large production volume and its high specialization, as well as its favourable impact scores.

Computer Science (EG1507) is a strength in Canadian research, with the country sharing the 6th overall spot among the selected countries. This is a mid-sized field in terms of global research output, and Canada is once again a top-10 producer by volume in this area. Canada is not specialized in this area (SI = 0.97), placing near the world average and 13th out of the 27 global leaders. While worldwide production in this field has held steady, with only minuscule growth from 2009–2010 to 2012–2013, Canada does not place well internationally for growth in this area, given that its output declined by 12% over that same timespan. Of the 27 world research leaders, Canada placed 19th for growth. By contrast, Canada has an exemplary record in terms of its scientific impact in this field, placing in the top 10 across the board of impact measures; in particular, Canada publishes in very high-impact journals in this area, placing 4th worldwide in ARIF. Canadian researchers also collaborate with international partners 34% more than expected (based on its volume of publication output), placing 4th worldwide. Canada's rank in EG1507 is based partially on its large research production, but its position is threatened by countries closing this gap. Its rank is further solidified by strong results in scientific impact.

Much like Computer Science, Electrical & Computer Engineering (EG1510) is a mid-sized research field worldwide, and Canada is a top-10 producer in this area. Canada is quite specialized, ranking 5th, but trails far behind the two standout global leaders in this respect: Taiwan and the Republic of Korea. Canada's production in this area actually decreased slightly between 2009–2010 and 2012–2013; this was well behind the worldwide average of growth, and placed it last among the 27 global research leaders. Regarding scientific impact, Canada's publications in EG1510 place it in the top 10 on each indicator. Canada also collaborates 25% more frequently with foreign partners in this area than would be expected based on the size of its production. In sum, while Canada has a strong position in Electrical & Computer Engineering, in terms of both production size and specialization, this lead is slipping as global growth

[1] The 5.5th rank reflects the fact that Canada and another country, in this case Australia, have an equal composite score, and so each receives the average of the relevant rank positions. Specifically, there are four countries ahead of Canada, then Canada and Australia have the next two highest composite scores, and ought to fall in the 5th and 6th ranks; however, because they are tied with a composite score of 81, they are each given the average of rank numbers 5 and 6, i.e., they both occupy the 5.5th rank. The same rule is applied to calculate ranks in all cases of ties, regardless of how many nations are in a tie.

catches up to Canada's position. The national strength in this field is further bolstered by very strong scientific impact. Canada shares the 6.5th overall rank with Switzerland according to the composite indicator.

Evaluation Group showing room for improvement in Canada

Overall, Canada's research programs place very well across the EGs. For eleven of the twelve EGs, Canada places at or above the median of the 27 world-leading research nations. However, there is one field in which Canada does not reach the median, and that is Chemistry, in which Canada places 16th out of 27 according to the composite indicator ranking. Let us here dissect the results, to ascertain the basis for Canada's rank.

On the world stage, Chemistry is one of the larger fields in terms of publication output. Canada is the 13th largest producer of papers in this area, and while its production growth is a modest 12%, that is still below the world average, placing Canada 18th in the group of 27 leaders. In terms of specialization, Canada devotes a smaller-than-average portion of its efforts to EG1504, ranking 20th among the leading research nations. In terms of impact, Canadian research in Chemistry does quite well, placing above the world average in each of the impact measurement categories used here. Furthermore, these results are strong enough that for each of the impact categories, Canada places above the median within the 27 world research leaders. Regarding international collaboration, Canada's rate is slightly below expectation, adjusting for the size of its scientific production, and places 17th out of 27.

Taking this more detailed picture into account, it becomes clear that Canada's rank in Chemistry is based on its middling publication output, and its below-average growth and specialization. Even with these weaker scores, Canada's research in Chemistry does not fall in the bottom third among the 27 leading research nations for output, growth or specialization. Additionally, Canada's impact in Chemistry is above both the world average and the median of the 27 research leaders, despite only middling tendency towards international collaboration. Through this analysis, it is clear that while Chemistry may be the field in which Canada's performance ranks the lowest on the world stage, that performance is still relatively strong at the world level (though not extraordinary in comparison to these 27 benchmark nations) and is therefore not in itself a point worthy of grave concern.

Short-term changes in performance

Comparing the period of 2009–2010 to 2011–2012, Canadian performance in its strongest EGs improved. In Evolution & Ecology (EG1503), Canada's impact increased slightly over this interval, while its specialization held steady. Canadian performance in Biological Systems & Functions (EG1502) also improved, with appreciable gains in specialization and modest gains in impact. The same cannot be said for Electrical & Computer Engineering (EG1510), which saw small losses in both measures. Computer Science (EG1507), also a strength in Canadian research, saw precipitous losses in impact, along with a slight decrease in specialization. Within the remaining EGs, almost all saw losses, of varying degrees, for one or both of specialization and impact. Beyond the top two EGs for Canada, the only field that improved over this timespan was Genes, Cells and Molecules (EG1501), which saw modest gains in impact.

These performance trends should be interpreted with caution, especially given how short the time intervals are and that only two intervals were used to calculate the change. Further bibliometric data, as well as other lines of evidence, would be needed to determine whether these are stable, long-term trends, or whether these changes are anomalous relative to longer-term behaviour.

Strong subfields within the EGs

As discussed in § 1.3.6 below, the subfields in which Canada has a particularly strong performance are identified relative to benchmarks of global performance. In particular, strengths are defined as those subfields in which Canada's articles are cited more than 10% more frequently than the world average (ARC > 1.1), and in which Canada publishes a proportion of its overall output at least 10% greater than the corresponding proportion at world level (SI > 1.1). Additionally, consideration was given to those subfields in which Canada's overall publication output was especially large (output > 1,000 pubs).[2] Canada's greatest strengths are those subfields in which all three criteria are met, though meeting the impact and specialization criteria alone was also considered a mark of definitively strong performance; those subfields of high impact and large output, but low specialization, are considered secondary strengths.

While the full results of this analysis can be found detailed in Table XV below, these results can be summarized as follows. As expected based on its global performance, Canada has the highest number of strong subfields in Evolution & Ecology (EG1503), which is the EG in which Canada achieves its highest rank internationally based on the composite index. Of the 25 subfields in EG1503 that were analyzed, 13 of these are subfields of Canadian strength,[3] and 5 of those 13 also have high output, making those subfields particularly strong. Canada's performance in Genes, Cells & Molecules (EG1501) is strong at the subfield level, with 6 areas of strength, including 2 of pronounced strength. Additionally, Canada has 2 subfields of secondary strength in EG1501, with strong impact scores and a large output by volume.

At the lower end of the spectrum, one finds that the EGs in which Canada has its lowest ranks internationally, based on the composite index, are also the areas in which one finds the fewest subfields of strength. Canada's lowest-ranked EGs are Chemistry (EG1504), Physics (EG1505), Material & Chemical Engineering (EG1511), Mechanical Engineering (EG1512), and Civil, Industrial & Systems Engineering (EG1509). Taken together, these five EGs contribute 9 subfields of strength, including only 1 exceptional strength; they also cover 8 secondary strengths, with high impact and large output by volume. For the sake of comparison, it is worth noting that EG1503 has more subfields of strength (and more of exceptional strength) than the five lowest EGs combined.

Unpacking these findings somewhat further, one sees that in fact one of these five EGs is contributing disproportionately to the count of strong subfields. Canada's research in Physics (EG1505) has very high impact scores on the world stage, punching well above its weight in this respect, but is not specialized in this area. Accordingly, it contributes 5 subfields of secondary strength, which are all of those in which it has high production by volume. Also, Canada is very specialized in Mechanical Engineering (EG1512),

[2] Note that because EG1501 is so large on the world stage, a threshold of 3,000 publications was selected; and that EG1509 is so small that a threshold of 500 publications was deemed more appropriate.

[3] To facilitate the identification of the greatest strengths, only the top 10 appear in Table XV.

but has only average impact. Those subfields of Mechanical Engineering that do have high impact are all global strengths (with only one exception, which sits just below the specialization threshold).

Removing Physics and Mechanical Engineering from the count of strong subfields, one finds that the remaining low-ranked EGs (Chemistry, EG1504; Material & Chemical Engineering, 1511; and Civil, Industrial & Systems Engineering, EG1509) contribute only 3 strengths, including 1 exceptional strength, in addition to 3 secondary strengths. These areas show room for improvement, in the EGs overall and also at the subfield level; however, it is worth keeping in mind that, as discussed above, even Canada's lowest-ranked EGs are still performing quite well, with only Chemistry falling below the median of the 27 research nations selected as benchmarks for comparison. Room for improvement should thus not be interpreted as cause for alarm.

Subfields for potential strategic consideration

Whereas subfields of established strength were delineated relative to static, global benchmarks, subfields for strategic consideration were identified relative to Canada's performance in other subfields within the same EG. That is to say, these candidates for strategic intervention are closely tailored to Canada's research profile in particular; this tailoring was achieved using dynamic thresholds, determined in a consistent manner across EGs, as discussed in § 1.3.6 below.

The detailed results of this analysis of subfields for potential strategic consideration can be found in Table XVI below. A concise summary of these results, highlighting overall patterns, is presented here. In general, most EGs had 3–4 subfields highlighted as potential strategic options, which could be used in the design of a strategy for intervention to improve performance in selected areas of research. Four EGs stood out as having more subfields highlighted than the rest, and these four will be discussed in greater detail here.

The first two are Evolution & Ecology (EG1503) and Biological Systems & Functions (EG1502). Interestingly, these are the two EGs in which Canada had its highest ranks internationally, based on the composite indicator, and each of them had 5 subfields highlighted for strategic consideration (3 with high ARC and low SI, and 2 with high SI and low ARC). In both cases, strategic interventions for these subfields could be used to build on established areas of strength in Canadian NSE research. Such interventions might seek to increase impact in the subfields in which the country is most specialized (within a given EG), or to increase the degree of specialization in subfields (at the expense of other areas) where Canada's research is most impactful (again, within a given EG).

Geoscience (EG1506) was another subfield retained for discussion due to a large number of highlighted subfields. Canada ranked 10.5th internationally in this EG, based on the composite index, quite a bit lower than its rank in the two EGs discussed above. In the case of EG1506, Canada's international rank is based on strong specialization scores, but its impact scores are relatively low, while still being on average above the world level. The subfields retained for consideration, presented in Table XVI below, could be targeted for specific intervention in EG1506, as part of a strategy to lift Canada's performance in Geoscience into the highest echelon of international research, from its present situation near the border of the top tier among the 27 benchmark nations.

Material & Chemical Engineering (EG1511) is an EG in which Canada is below the world level in specialization and above the world level in impact, though the latter declined sharply over the period from 2009–2010 to 2011–2012. Using the composite indicator, Canada ranked 12.5th among the 27 selected comparator nations. Canada's performance in EG1511 varies widely from one subfield to the next, with many statistical outliers. These outliers, then, could be used to form the basis of a strategy to start driving Canada's research performance in this EG up into the top tier among the 27 benchmark nations. Given Canada's present global position in EG1511, which is near the median of the 27, and its recent decline in performance (over an albeit short time frame), such a strategy would likely be more involved than a strategy for fine-tuning Canadian performance in a more established EG.

While additional human and financial resources can help to increase publication output by volume, it is worth reiterating that specialization is a measure of how a country's research is distributed among different areas. It is thus a zero-sum game, with increases in one area necessarily decreasing the proportionate contribution in others. The human, financial and capital resources invested in research are similarly finite: one must reflect on which areas of research one plans to make a specialty, just as one reflects on how a finite pool of resources is to be distributed. Such considerations cannot be overlooked in strategic planning, options for which are presented above. Similarly, in areas of high research impact, it is difficult to maintain that level of research quality while trying to expand the volume of research produced. Reasonable expectations, in terms of both specialization and impact, should be discussed during the design of strategic interventions.

In general, for those EGs in which Canada's performance is particularly strong as well as for those EGs in which it is not, the outlying subfields of Canadian research performance can provide a potential starting point for the design of an intervention strategy. These subfields can provide points of leverage, where the most impactful subfields can be prioritized to increase specialization scores, and the most specialized can be targeted with measures to increase scientific impact, thereby driving towards a situation where Canada's research builds efficiently on its different strengths.

Canadian performance in high growth and interdisciplinary topics at world level

NSERC expressed interest in identifying emerging (high growth) and interdisciplinary research topics. Within each of these two types of topics, the present report highlights those in which Canada demonstrates a strong research performance.

Canada generally performed quite well within the global high-growth topics selected, though four were retained as areas in which Canada's research is exceptionally good. Of the high-growth research topics, lithium-ion batteries is the largest topic globally, in addition to being the fastest-growing in the world. Canada's growth in this area is also the highest of all the topics considered, outpacing the global growth rate by over 20%. While Canada's production on this topic is growing, it still devotes a smaller proportion of its research to this area than at the world level; the excellent growth, therefore, is helping Canada to catch up to world specialists, not to extend a lead in specialization. The scientific impact of Canada's publications on lithium-ion batteries is also very strong, well above world level.

Similarly, smart grids is a fast-growing topic, both on the world stage and in Canada specifically. However, smart grids is one of the smallest research topics analyzed here. Canada is slightly specialized in this area, and its growth rate far surpasses average growth at the world level, thereby contributing to increasing

Canada's specialization in this topic. Of particular note, Canada's impact scores are highest in the smart grids topic relative to all the selected high-growth topics, though because the research area is small, these results may not be indicative of sustainable trends as the topic continues to grow.

Power control and cloud computing are two other large research topics in which Canada's publications have impressive scientific impacts, and in which Canada's growth is outpacing the global level. In the case of power control, Canada is already specialized in this area, and so its impressive growth is building on that lead. Contrarily, Canada is not specialized in cloud computing, but its high rate of growth in this area is narrowing the specialization gap.

Turning to highly interdisciplinary topics, there were once again four topics in which Canada's performance stood out. Leaf respiration is the most highly interdisciplinary topic worldwide, of those analyzed here; it is a smaller research topic, on the world stage, and increased its output by about 20% from 2009–2010 to 2012–2013. Canada's output on this topic decreased over the same period, falling well short of global growth. However, Canada remains a specialist in this area, despite the decreased output. Canada's scientific impact in this area is also very strong.

Ocean primary production and lab on a chip are two further highly interdisciplinary topics in which Canada performs well. These are mid-sized topics, each accounting for about twice as many publications as leaf respiration. Canada's output in both of these areas is increasing slowly, though in both cases this modest growth is still outpacing the world level. Canada is also already a specialist in both of these areas, so the pace of growth is only widening that lead. In ocean primary production, Canada's scientific impact is quite strong, well above the world level; in lab on a chip research, Canada's impact is somewhat lower, closer to but still above average.

Climate change research is another mid-sized topic that is quite interdisciplinary at the world level. Global output in this area is increasing very sharply (approximately 50% increase from 2009–2010 to 2012–2013), and while Canada's output is increasing also, it is not keeping up with the global trend; note, however, that Canada is highly specialized in this topic. Also, Canadian publications on this topic are still very impactful, well above world average.

One final topic is worth mentioning here. Biodiversity is a mid-sized research topic, with an interdisciplinarity score that is strong but not overwhelming. Similarly, it is a topic that is showing notable growth, but without being impressive in that respect. What makes biodiversity stand out as a research topic is that it has the most remarkable *balance* of interdisciplinarity and growth. Canada is a world specialist in this area, with a strong growth rate that is outpacing global increases, padding Canada's lead in specialization. The impact of Canadian publications is also very high according to each of the metrics employed for the present study. This topic is thus notable in combining high growth, interdisciplinarity, and strong Canadian performance.

Among the global high-growth topics selected for further analysis, Canada's impact and growth is strong in all of them. However, Canada is only specialized in a few of them, and below the world level in many. Funding allocations could be used strategically to increase output and promote specialization in some of these topics, implementing strategic decision-making at NSERC.

Canada is specialized in about half of the interdisciplinary topics. However, Canadian growth rates and impact scores are lower for these topics than they were for the high-growth topics. Again, funding allocations can be used to implement NSERC's strategic decisions; as the global growth rates are lower for these topics, increasing Canada's specialization would not require increasing output by as much. Additionally, international collaboration correlates with increased scientific impact, so a funding strategy that promotes international collaborations in interdisciplinary topics could also contribute to increasing Canada's impact scores in these areas.

The full keyword table (Table XXIII and Table XXIV) would be a useful tool in discussing, designing and implementing policy options pertaining to these emerging topics. The topics are modeled using a keyword clustering approach, and the names given to these topical clusters are provisional, given based on expert judgment but primarily for the purpose of facilitating discussions. The clusters themselves are in fact delineated not by these names, but by a set of highly representative keywords. (The unique ID numbers for the clusters have been provided in the analysis tables, to connect topics to the full keyword table.) One potential application for these keywords, in designing a topic-based funding program for instance, would be to use these keywords, instead of just the provisional name, to help define the targeted research subjects for potential applicants to the program.

Given that the modeling of these topics is accomplished using a method that cuts across both the journal-level classification of Science-Metrix and the EG datasets constructed for the present study, further analyses would be required to identify how those topics (especially the interdisciplinary topics) map onto these other topographies of scientific research. Such a mapping, however, could increase the value of this analysis of topics. For instance, a map showing how the topical clusters fit into/between the EGs would make it possible to develop and implement a "topic-based" funding component under the umbrella of the EGs; in the absence of such mapping, it may not be feasible to overlay topics and EGs, undermining the possibility of bringing topic-based funding under the existing umbrella of the funding process based on EGs.

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List of acronyms

ARC	Average of relative citations
ARIF	Average of relative impact factors
CI	Collaboration index
CPI	Composite performance index indicator
DG	Discovery Grant program
EG	Evaluation Group
GI	Growth index
GR	Growth ratio
HCP	Highly cited papers
IDR	Interdisciplinary research
LDA	Latent Dirichlet Allocation
NSE	Natural Sciences & Engineering
NSERC	Natural Sciences & Engineering Research Council
RGS	Research Grant and Scholarship directorate
SCI Expanded	Science Citation Index Expanded
SI	Specialization index
tf-idf	Term frequency–inverse document frequency
WoS	Web of Science database, a Thomson Reuters product

1 Introduction

1.1 Background

Funding commitments for the Discovery Grant (DG) program are allocated across 12 Evaluation Groups (EGs) by the Research Grant and Scholarship (RGS) directorate of NSERC. To review their method for allocating DG funds across the 12 EGs, the RGS will convene an expert panel and provide the panel with a policy framework to guide their review, as well as bibliometric data and other lines of evidence to inform their deliberations. This review must strike an appropriate balance, ensuring that diversity across EGs (e.g., different professional cultures in each of these research areas) is adequately accounted for in establishing a fair distribution of available funding.

1.2 Study objectives

Science-Metrix has previously conducted bibliometric assessments for NSERC, including an international benchmarking of Canada's research output in NSE fields (performed in 2012, renewed in 2013), and an assessment of the effects of the DG program on the scientific performance of grantees (performed in 2013). As part of the latter study, publication portfolios were created at the researcher level; additional value can now be added to these portfolios, specifically by assigning them to the relevant EGs, and using this information to facilitate classifying other NSE papers in the Web of Science (WoS, produced by Thomson Reuters). The publication portfolios thus act as a "seed" from which the further classification stems, thereby creating 12 datasets, one for each EG; these datasets will then form the basis for assessing Canada's research performance within the pool of relevant literature for each EG. Finally, the resulting analysis will be provided to the expert review panel convened by the RGS, to contribute to their deliberations.

1.2.1 Key questions for this study

i. How does science in Canada, for each EG, compare to the rest of the world, both in individual performance measures (i.e., number of publications, growth ratio, specialization index, scientific impact, and collaboration index) and in terms of a composite performance index?

ii. How is Canada's scientific specialization and impact, relative to the rest of the world, evolving over time, in each of the EGs?

iii. Within each of the EGs, what are the subfields in which Canada has strengths (as measured by specialization, scientific impact, and output size)?

iv. Which NSE topics are both a Canadian research strength and a growing international focus of research?

v. Which NSE topics are both a Canadian research strength and highly interdisciplinary at the world level?

1.3 General overview of methods

This section is intended for non-specialists in bibliometric analysis, to facilitate a general understanding of the study methodology, and thereby aid in the interpretation of results for addressing policy-related questions. A full, technical overview of methods is included in the Appendix.

1.3.1 Database selection

The Web of Science (WoS) database will be used for this study, to maximize continuity with previous bibliometric analyses conducted by Science-Metrix for NSERC, including the assessment in 2013 of the effect of the Discovery Grant (DG) program on the scientific production of supported scholars. This previous work analyzed the publication portfolios of more than 15,000 DG-funded researchers, which were constructed using the WoS.

The WoS offers comprehensive coverage of the most cited scientific literature in NSE fields through its Science-Citation Index Expanded (SCI-Expanded) database; this database includes approximately 5.9 million peer-reviewed articles (from 2009–2013, the period of the present study), published in 8,500 major journals, across 150 sub-disciplines. The WoS also includes the Conference Proceedings Citation Index, which indexes more than 150,000 conference proceedings; this resource makes possible a more balanced coverage across disciplines (e.g., computer sciences and engineering, in which conference proceedings play an important role in sharing results within the research community).[4]

It should be noted that the WoS covers only English-language publications, thereby creating a bias towards publications from English-speaking contexts. Asian countries are among the most severely impacted countries by this coverage bias, which manifests itself in many indicators relying on publication counting as well as citation tracking. For example, while China has the largest number of NSE papers in 2014 in the WoS, this assessment does not even take into account the vast majority of its publications (i.e., approximately 87%[5]), which are written in Mandarin, Cantonese and other languages not covered by the WoS.

This bias in favour of English-language publications not only severely underestimates the publication count of papers by Chinese authors, it also underestimates the citation count of these same authors, whether they publish their articles in English or not. Specifically, if Paper A cites Paper B, then both A and B must appear in the bibliographic database in order for that citation to be registered (as citations require both a source article and a destination article). For authors from China, then, the fact that 87% of articles written by their compatriots are not covered in the WoS database has an important impact on

[4] A relevant limitation should be stipulated here: the WoS conference proceedings data lists the address of only the first author for a given article. Accordingly, counting such publications at the country level cannot be exhaustive, and information about collaboration for these publications is not available. For a quantitative assessment for each of EG of including the Conference Proceedings Citation Index, see Table XVIII below.

[5] Rousseau, R. (2015). The tip of the Chinese publication iceberg. *Newsletter of the International Society for Scientometrics & Informetrics (ISSI)*, *11*(4). Retrieved from http://issi-society.org/archives/newsletter44.pdf.

assessing the impact of their research: if either the source article or the destination article for a citation is written in a language other than English, then the WoS will not cover it, and thus fail to count the citation.

A lack of coverage means that a number of citations cannot be accounted for in computing citation impact metrics, and such a lack of coverage disproportionately affects countries where the primary language of scientific publication is not English. As a result, the citation and thus impact assessments of primarily English-speaking countries (e.g., Australia, Canada, United States, United Kingdom, and many European countries) appear to be artificially stronger than they are in reality compared to their non-native-English-speaking peers.

1.3.2 EG dataset creation

While there is similarity between the divisions into NSE fields (already labelled in the WoS database using Science-Metrix' journal-based classification of scientific research[6]) and the EGs, the two divisions do not overlap entirely. Therefore, NSE publications in the WoS first had to be attributed to the EGs,[7] broadly reflecting the definitions thereof, as provided on NSERC's website.[8] The creation of the 12 EG datasets was performed in four phases:

- Construction of initial datasets
- Expansion through citation analysis
- Expansion using specialist journals
- Equalizing the recall (% of classified papers) across NSE subfields

Construction of initial datasets

To create an automated tool to perform this attribution, Science-Metrix used the award summaries of discovery grants as well as the supported papers of grantees,[9] already classified by EG, to create seed datasets for the identification of a reference set of scientific terms specific to each EG (i.e., to define the *knowledge space* of each EG, see Table I).[10] Using these seed datasets, the scientific terminology of greatest relevance to each EG was identified using a method called *term frequency-inverse document frequency* (tf-idf), which measures how frequently a term gets used in the reference documents of a given EG, relative to how frequently the term is used in the whole WoS database. That is to say, it weighs the uniqueness of a given term to that EG in particular. (The score, then, is always a relation between a term, a specific EG,

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[6] Archambault É., Caruso J., and Beauchesne O. (2011). Towards a Multilingual, Comprehensive and Open Scientific Journal Ontology, in Noyons, B., Ngulube, P. and Leta, *J. Proceedings of the 13th International Conference of the International Society for Scientometrics and Informetrics (ISSI)*, Durban, South Africa, pp 66-77.

[7] A relatively small number of non-NSE articles, mostly from subfields of Clinical Medicine (e.g., sports science), were also included as they were relevant to some of the EGs.

[8] http://www.nserc-crsng.gc.ca/Professors-Professeurs/Grants-Subs/DGPList-PSDListe_eng.asp

[9] These papers were obtained from the publication portfolios of some 2,354 DG grantees which were constructed by Science-Metrix in a previous study for NSERC in 2013.

[10] Specifically, the title, abstract and keywords of each award summary and paper were used to identify the terminology specific to each EG.

and a general background of literature.) Frequent use of a term within a given EG increases the term's tf-idf, relative to that EG; frequent use of the term outside the given EG decreases the term's tf-idf, again relative to that EG. Using this approach, reference sets of approximately 2,000 keywords/scientific idioms each representing the *knowledge space* of a given EG were created.

Using the reference set of keywords for each EG, and analyzing the use of terms in a given publication, it was possible to calculate the proximity of that article to each of the EGs. This calculation compares the scientific language used in the article to each of the words in the 12 sets of keywords (one per EG), creating "similarity scores" that reflect the proximity of the article to each one of the EGs.[11] Papers were then attributed to the most proximate EG.[12] However, some papers naturally fit in more than one EG—interdisciplinary papers, for instance. Accordingly, to achieve a non-mutually exclusive classification of the papers, if the similarity score with the 2nd closest EG was within 20% of the 1st, the paper was attributed to both EGs. Furthermore, if the similarity score with the 3rd closest EG was within 20% of the 2nd, the paper was attributed to all three. (And so on, until the next most proximate EG did not meet the 20% threshold.)

Expansion through citation analysis

For the papers that were not classified during that first phase of sorting (because they did not meet minimal thresholds for similarity with any EG), a second sorting tool was applied. This second tool started from the citations within the paper, to determine the bodies of knowledge on which the publication was drawing, and the EGs in which those bodies of knowledge were located. In this way, it was possible to calculate the proximity of these papers to the different EGs as the share of their outbound citations given to each EG. Again, as in the first sorting phase, articles were assigned to their most proximate EG; and again, if the next most proximate EG was within 20%, the article was assigned to both EGs (and so on).[13]

Expansion using specialist journals

For the remaining papers, those not classified in the first or second phase of attribution, a final technique was applied. Rather than using semantics or citations, this third tool relied on the journal in which the article appeared. Specifically, if at least two thirds of the articles published in a given journal were already attributed to a particular EG, then any still-to-be-sorted articles published in that journal were attributed to that EG. That is to say, if more than two thirds of a journal's articles had already been sorted into EG1508, then any articles in that journal (only those that were not classified in the first two phases) were classified as falling under EG1508. The remaining papers that could not be sorted using any of these methods were therefore not considered in the bibliometric analyses of the present study.

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[11] The similarity of a given paper for a given EG is equal to the sum of the tf-idf weights of all terms found in that paper which are part of that EG's knowledge space.

[12] There was an additional constraint in attribution: the similarity score had to be based on the tf-idf of at least two terms. Validation during random sampling exercises showed that this additional constraint greatly increased the accuracy of attribution.

[13] There was an additional constraint in attribution: the papers to be assigned had to include at least two outbound citations to the EG to which it is closest. Validation during random sampling exercises showed that this additional constraint greatly increased the accuracy of attribution.

Equalizing the recall (% of classified papers) across NSE subfields

As described above, three approaches were used to construct the EG datasets. This phased sorting approach was implemented as a quality-assurance measure, to ensure that biases were not being introduced based on differences of coverage in the database, differences of citation practice between fields, etc. The first sorting phase was based on language use in a set of reference documents.

Following this phase, a test was conducted to assess whether the method was equally effective in classifying papers across the main fields of the NSE. When measuring the sorting accuracy for the EGs, the recall was 77% accurate or better for each of the 12; this threshold of 77% recall accuracy was retained in evaluating equality of coverage across fields of science, as per Science-Metrix' classification (see above in the current section). The quality assurance test performed after the first phase of sorting determined that some fields were being sorted less effectively, namely the fields of Engineering, Mathematics & Statistics, and Information & Communication Technologies. The second and third sorting phases, based on citations and specialist journals (described above), were implemented in an attempt to improve coverage of these fields.

For the EGs, a minimum threshold of 77% recall was achieved for all 12. To determine whether that same threshold was met across fields and subfields of science (according to Science-Metrix' classification), random samples of papers from each field and subfield were analyzed. This analysis consisted in examining the sample to determine how many of the papers had been assigned to an EG in the sorting phases described above. The results obtained suggest that the coverage biases detected after the first sorting phased were drastically reduced.

The only field that did not meet the 77% recall threshold was Built Environment & Design, which had a recall of 65%. This finding may be explained by the fact that Built Environment & Design has an exceptionally strong linkage with Social Sciences and Humanities (SSH) research, namely because of its connection to Architecture. About 20% of citations from Built Environment & Design are to fields in the SSH. Note as well that some papers from outside the core NSE fields were also classified in some EGs given their strong relevance to those EGs. For instance, it was found that NSERC grantees published papers in some subfields of Clinical Medicine (e.g., 1501: Neurology & Neurosurgery; 1502: Sport Sciences; 1507: Nuclear Medicine & Medical Imaging; 1512: Orthopedics).

Assessing the accuracy of the EG datasets

The accuracy of an EG dataset was measured by determining how many papers, in a random sample from those classified under the EG, fit under that EG according to NSERC's definition thereof.[14] This approach relied on expert judgment to determine whether a paper was a good fit under the definition. Based on this assessment, it was found that the accuracy of the EG datasets thus created ranged from a low of 90% to a high of 100%. This result suggests that the sorting tool was very robust in assigning articles to the proper EGs.

[14] http://www.nserc-crsng.gc.ca/Professors-Professeurs/Grants-Subs/DGPList-PSDListe_eng.asp

A further assessment was conducted, to further bolster the quality assurance process for this assignment procedure. This second quality assurance test took NSERC proposals, which had already been sorted into their relevant EGs, and applied the semantic sorting tool to them. That is to say, based on the tf-idf scores calculated above and the language used in these proposals, they could be given a proximity score for each EG. In this way, Science-Metrix tested whether the EG with which the proposal had been originally assigned by NSERC was the same EG with which the proposal had the highest proximity score.

A result of 100% accuracy was not expected, as the delineation between the EGs is not rigid. The EGs overlap at the margins rather than having very clear and sharp boundaries between them; thus, a 100% accurate sorting result would suggest that there is a significant gap between the content of the EGs, where no such gap actually exists. Using this approach, the majority of proposals were correctly re-classified in all the EGs; the only exception to this pattern is EG 1502, which had many of its proposals "mis-assigned" to EG 1501.

In those cases where proposals were assigned to a different EG by the sorting tool, these "mis-assignments" provided useful information about the proximity between the different EGs. In particular, where the EG definitions provided by NSERC were partially overlapping, so too were mis-assignments between these EGs more likely. One notable example is the proximity of EG 1501 to EG 1502. Because EG 1502 had a low accuracy score, a sample of 50 mis-assigned proposals were manually inspected, in an attempt to diagnose the underlying problem. The results were as follows:

- 24 proposals (48% of cases) were correctly re-classified by the tool, according to NSERC's definitions of EGs, thereby questioning the original assignments as provided by NSERC;
- 16 proposals (32%) pertained to cell biology, biochemistry and other molecular level studies in plants which are pertinent to both 1501 and 1502;
- 4 proposals (8%) pertained to animal reproduction (molecular level) which is pertinent to both 1501 and 1502;
- 2 proposals (4%) pertained to food microbiology, biochemistry and other molecular level studies in plants which are pertinent to both 1501 and 1502;
- 2 proposals (4%) were in fact incorrectly classified by the sorting tool;
- 1 proposal (2%) to muscle physiology at the molecular level, which is pertinent to both 1501 and 1502; and
- 1 proposal (2%) pertained to biomechanics at the biochemical level, which again is pertinent to both 1501 and 1502.

Based on these principal quality assessment measures, the EG dataset creation was deemed to be very high quality, providing a robust classification as the foundation on which to build robust bibliometric analyses.

1.3.3 Bibliometric indicators

Number of publications

This indicator shows the number of publications for a given country, using a method called *full counting*. Using this method, each country that has a researcher on the list of authors for a given paper gets a full count (1 publication) for that article. For example, if a paper is authored by two researchers with addresses in the UK, one from Spain and one from the US, the paper will be counted once for the UK, once for Spain and once for the US.

An alternative method, known as *fractional counting*, divides publications based on the proportion of authors contributing to an article. For instance, if a paper lists two authors with addresses from the UK, one from Spain and one from the US, the publication is divided into four parts, with the UK receiving two of these parts (0.5 publication), Spain receiving one (0.25 publication) and the US receiving the fourth part (0.25 publication).

Data based on full counting indicate only which countries are involved in the production of an article, whereas fractional counting provides an indication of the share of work contributed by a given country.[15] Full counting will be used for computing all types of results presented in this study, with the exception of the specialization index (SI) and growth ratio/index, which will be calculated using fractional counting.

Growth ratio & growth index

The growth ratio (GR) measures the rate at which production changed, for a given country, between 2009–2010 and 2012–2013. A GR of 1 indicates no change, a GR above 1 indicates growth, and a GR below 1 indicates decreased production. Because the GR is a single number that does not communicate information on the yearly fluctuations within a trend, output trend data for each nation was also included as a bar graph in the results tables for each Evaluation Group. A country's growth index (GI) is simply its growth ratio in a given area relative to the world's GR in that area. That is to say, the GR of a country divided by the GR of the world gives the GI of that country; for example, if a country has increased production by 32% (country's GR = 1.32) in a given area, and the global output in that area has increased by 10% (world GR = 1.10), then the country has been growing 20% faster than the world has been growing (country's GI = 1.20).

International co-publishing rate and collaboration index

An international co-publication is defined as an article that was co-published by at least two countries. The collaboration index (CI) is defined by calculating the international co-publication rate of a given country, and comparing that rate to global averages (adjusted relative to the number of publications of the country).[16] This index is normalized to 1; accordingly, a CI above 1 denotes higher-than-expected rates of collaboration for the given country, a CI below 1 denotes lower-than-expected rates of collaboration, and a CI close to 1 denotes a rate of collaboration near the expected rate.

[15] It should be noted that the inclusion of contributors on the list of authors varies according to professional cultures from one discipline to the next. Full counting and fractional counting both assume that each author contributes equally to the published article; as the inclusion of a contributor as an author varies from one discipline to the next, results must be considered with due appreciation for these differences of professional culture.

[16] The specific adjustment is a logarithmic transformation of both the number of papers and the number of co-authorships. So, for instance, if the x- and y-axes were both labeled "1, 10, 100, 1000, …" rather than "1, 2, 3, 4, …", then one would find a linear relationship between the number of publications a country produces and the number of international co-publications it produces. With this transformation accomplished, the expected number of international co-publications for a given country is simply the relevant location on that line for the size of the country's publication output. The collaboration index compares that expected value to the observed value from the database.

It should also be noted that international collaboration plays a different role in the research ecosystems of large and of small research nations. For instance, in looking for complementary expertise, a researcher in a small market may have no choice but to look for international partners for research collaboration, whereas a researcher in a larger market may be able to find the complementary skillset without looking outside national borders. For example, Poland and California have roughly the same population, but a Polish researcher collaborating with a researcher from another EU country (Germany, for instance) counts as an international collaboration, while a researcher from California can form domestic partnerships with researchers in other US states, which do not count as international collaborations. Such differences are accentuated further the smaller a country gets, and the more the need for complementary expertise necessitates international partnership.

Specialization index

The specialization index (SI) indicates how much emphasis a given country puts on one field/subfield, relative to the global average of effort exerted in that field. For instance, if 20% of Canada's publications are in physics, but at the global level only 15% of papers are in physics, then Canada is said to be specialized in physics, putting more emphasis on that field than is normally the case elsewhere around the world. It is worth noting that these proportions of publications are computed relative to all publications in the WoS including those in the NSE as well as in the social sciences and humanities (SSH).

The SI reference value is 1 (i.e., the world is always equal to 1); accordingly, an SI above 1 shows that a country invests proportionately more effort than the average in a given area, an SI below 1 shows that a country invests proportionately less effort than the average in that area, and an SI near 1 shows that a country invests close to the average proportion of effort in that area.

Several notes are worth keeping in mind when interpreting SI results. First, the SI is a zero sum game because it is measured as a proportion of total output. If the proportion of output in one area increases, there must be relative decreases elsewhere. Effort is a finite resource divided among priorities; accordingly, questions about investing new efforts should properly be framed as needing to withdraw that new portion from another area (or at least as withholding potential new investments from that area). Specialization is thus an area for strategic decision-making. One cannot specialize in all fields, and therefore must decide in which fields one wishes to specialize.

It is also worth noting that the SI is an *output* measure of effort, not an *input* measure. That is to say, the SI measures the dividends of our investment of effort; it does not measure the investment directly. Combining SI data with input measures (e.g., dollars invested, FTE allocated) would be very fruitful in assembling a more nuanced picture. In combining these measures, it must be acknowledged that certain areas of research are inherently more expensive than others (e.g., because of greater need for instruments, travel to more distant/remote areas for sample collection) and so it would be inappropriate to expect all areas to be equally efficient in translating input investments of time and money into output measures such as published articles.

Without a further point of reference (e.g., number of publications per dollar invested, or per person-hour of work), it does not make sense to speak of one field being a "better performer" than another solely because Canada is more specialized in that EG. Potential ways to frame the strategic discussion of specialization could include the following:

- Asking whether Canada should continue to prioritize investment in areas in which it is already specialized or whether it should shift to new areas of focus
- Asking whether Canada should focus on areas where it has high impact
- Asking whether Canada should focus on areas in which it is highly collaborative
- Asking whether Canada should prioritize areas of emerging or established global interest
- Asking whether there are areas of strategic social, environmental or economic value in which Canada should be increasing its investments

Average of relative citations

The average of relative citations (ARC) is one measure of the scientific impact of a country. Counting citations can be used as a proxy for measuring contributions to subsequent knowledge generation;[17] however, because citation practices vary between the disciplines and sub-disciplines of science, simple counting would create unwanted biases in the results. To correct these potential distortions, individual publications are evaluated relative to the average citation rate for publications in the same subfield and the same publication year. This measure is known as the relative citation (RC) rate. The average of relative citations (ARC) is the average of the relative citation scores of all the articles published by a given country.

The ARC is normalized to 1, meaning that an ARC above 1 indicates that the country's articles have higher-than-average impact, an ARC below one means that the country's articles have lower-than-average impact, and an ARC near 1 means that the publications have near-average impact.

For all citation-based measures, a certain amount of time must be allowed for the published work to have an impact on subsequent research, and for articles to be cited. Accordingly, impact measures for the present study can be computed for articles published in 2012 or earlier. Papers published in 2013 or later have not had sufficient time for citations to accrue.

Highly cited papers

Highly cited papers are publications that received the highest relative citation (RC) score in their respective field; for this study, the top 5% most cited publications were selected. This indicator is frequently used to examine research excellence, measuring how many high-impact articles are produced by a given country, relative to their expected contribution to world-leading research.

The highly cited papers (HCP) measure is normalized to 1, meaning that a country with an HCP over 1 contributes more than its expected number of highly cited papers, a country with an HCP below 1

[17] Leydesdorff et al. suggest that citations shortly after a publication appears suggest that the authors are involved in the unfolding scientific discourse, whereas citations gathered much later after publication are more reflective of the lasting contribution that an author makes to the progress of ideas. See: Leydesdorff, L., Bornmann, L., Comins, J., & Milojević, S. (2016). Citations: Indicators of Quality? The Impact Fallacy. *ArXiv preprint arXiv:1603.08452*. Retrieved from http://arxiv.org/abs/1603.08452.

contributes fewer than its expected number of highly cited papers, and a country with an HCP near 1 contributes close to its expected number of highly cited papers.

For all citation-based measures, a certain amount of time must be allowed for the published work to have an impact on subsequent research, and for articles to be cited. Accordingly, impact measures for the present study can be computed for articles published in 2012 or earlier. Papers published in 2013 or later have not had sufficient time for citations to accrue.

Average of relative impact factors

The impact factor (IF) of each journal in a given year is measured by counting the total number of citations received in that year by the papers which appeared in that journal in the previous five years. The IF is then obtained by dividing the total number of received citations by the number of articles which appeared in that journal in the previous five years. Every published paper is given the IF score of the journal in which it is published for the corresponding publication year. To account for the differences in citation practices across disciplines, the IF for a paper in a given year is adjusted relative to the average IF of all papers published in the same subfield and year. This measure is known as the relative impact factor (RIF) rate. The average of relative impact factors (ARIF) of a given country is simply an average of the relative impact factor scores of its articles.

Contrary to the ARC and HCP which cannot be computed in 2013 or later as papers published that recently have not had sufficient time for citations to accrue, the ARIF can be computed up to the most recent year available since it is a backward-looking citation metric (it is based on the citations made in a given year to papers published in previous years).

The ARIF is normalized to 1, meaning that a country with an ARIF above 1 publishes in higher-than-average-impact journals, an ARIF below 1 means that the country publishes in lower-than-average-impact journals, and an ARIF near 1 means that the country publishes in near-average-impact journals.

The ARC, HCP and ARIF all share the assumption that citations are a good proxy for contributions to scientific knowledge. Working with that assumption, and putting it roughly, the ARC measures the average contributions made by all of a country's articles, considered as a whole; HCP measures how many outstanding contributions in terms of visibility within the scientific community are made by a given country; and the ARIF measures the quality of the journals in which a country publishes. When used together, these various measures offer a textured picture of a country's scientific impact. At high aggregation levels, all fields combined for large countries, all three measures will positively correlate to a high degree.

Composite indicator of scientific performance

While each of the indicators above allows for a comparison to be drawn between various aspects of the scientific performance of different countries, a composite indicator integrating these various aspects was also used, to get a more holistic overview of national scientific performance. While this score is appreciably holistic, facilitating the identification of countries that stand out in multiple respects, it must also be kept in mind that this indicator integrates and thereby occludes important dimensions of variation in the characterization of performance in each country. It is recommended that this indicator be used in close conjunction with the indicators above as well as other lines of evidence, and with expert judgment.

The composite score used for this study integrates the rate of publication (i.e., number of publications), the growth of output (i.e., GR), the effort level of countries in different fields (i.e., SI), and an average of the three measures of scientific impact (i.e., ARC, ARIF, HCP) of its publications. Policy priorities, such as the prioritization of impact over size of output, can be used to shape this ranking by giving differential weight to the individual elements integrated in the composite index. For this study, the four elements above were each given equal weight.[18]

This composite indicator is used to evaluate the performance of each of the leading 27 nations, and the results of this evaluation are used to rank the nations in order of their performance. In this way, Canada's performance is benchmarked against that of the global scientific community, in addition to tracking Canada's global position over time. In cases of ties, the rank number is calculated as an average of the rank locations; for example, if two countries share the 3rd highest spot, then they are both given the rank of 3.5 (i.e., the average of rank 3 and rank 4).

Interdisciplinarity score

At present, no single approach for the measurement of interdisciplinarity has emerged as the predominant method.[19] For the present study, a cutting-edge approach was applied, one that measures interdisciplinarity—or equivalently the inter-subfield integration of knowledge—at the level of individual papers. In brief, the interdisciplinarity score assesses whether the distribution of an article's outbound citations (i.e., the citations it gave to other publications identified through its reference list) across scientific subfields departs from the predominant pattern of knowledge integration, as defined through the inter-subfield citation patterns of the whole publication database. An assumption in using a citation-based indicator is that citation patterns are reflective of knowledge integration: that is to say, that Paper A citing Paper B is a good indication that the contents of Paper A have integrated (at least a portion of) the contents of Paper B.

Each paper is assigned an interdisciplinarity score from 0 to 1, with 0 being completely mono-disciplinary (i.e., diverging completely from the predominant inter-subfield citation pattern, integrating knowledge from only one discipline) and 1 being extremely interdisciplinary (i.e., diverging completely from the predominant inter-subfield citation pattern, integrating more diverse knowledge than is usually the case). The score integrates three factors that together reflect the diversity of the knowledge integrated within a single article: how many different disciplines are being cited, how distant those disciplines are from each other, and how are the citations given by a paper distributed amongst those disciplines. Put simply, the proposed interdisicplinarity score measures the extent to which co-citing a high energy physics paper with a veterinary paper diverges from the predominant pattern of knowledge exchange across subfields in the

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[18] The composite index is no more or less "objective" for giving equal weight to these elements. The decision to prioritize one facet of performance over others is not categorically different from the decision to attribute equal value to each of them. For more details, see footnote **Error! Bookmark not defined.** below.

[19] Wagner, C. S. et al. (2011). Approaches to understanding and measuring interdisciplinary scientific research (IDR): A review of the literature. *Journal of Informetrics*, *5*(1), pp. 14–26. doi:10.1016/j.joi.2010.06.004.

entire database, either in the direction of more or less integration than would be expected. In the current example, the departure is obviously in the direction of more integration than would be expected. Now, if a paper cited nine high energy physics papers and only one veterinary paper, it would be deemed less interdisciplinary than a paper citing 5 high energy physics papers and 5 veterinary papers. If another paper cited the above two disciplines plus three additional ones in the same proportions, it would also be considered more interdisciplinary.

With a score for each paper, one way to compute a score for institutions, countries and other aggregations (such as research topics as in this project) is to simply take the average of interdisciplinarity scores of all of its publications. However, due to coverage issues of the cited references in the database (i.e., not all the references of papers appearing in WoS are themselves covered in the database), this approach produces unsatisfactory results. Specifically, certain disciplines of research have higher levels of coverage than others, and interdisciplinarity scores correlate very strongly with coverage rates, suggesting that a normalization needs to be carried out in order to take a more accurate reading of the true level of interdisciplinarity.

The approach adopted for the present study is to only consider articles that cite a large number of documents, as this large number of citations has been shown as a reliable approach to overcome coverage issues.[20] For each discipline, the papers with the most outbound citations (specifically, the top 1% of the most outbound citations, from each discipline) are used to form the candidate pool of papers for further analysis. Within this pool, then, the interdisciplinarity score for each paper is calculated without worry about coverage bias. The papers are then divided into deciles, and those falling within the top 10% are identified as the most interdisciplinary papers. Research topics are then evaluated based on their contributions to this top 10% of highly interdisciplinary publications (much like the HCP evaluates a country's contribution to the top 10% of the most highly cited papers).

One consideration to keep in mind when interpreting the results of this interdisciplinarity score is that it is only considering a very specific kind of work. Specifically, because only the works with the highest numbers of outbound citations are eligible for consideration (and assuming that the number of outbound citations is correlated to the amount of knowledge being integrated, and thus to the size of the research project), this measure is reflective of interdisciplinarity *among the largest, summative research projects* within a discipline. But it could be that interdisciplinary research is taking place even in smaller projects, and such a fact cannot be captured using this measure—a necessary sacrifice in order to correct for coverage biases.

The expected value for the interdisciplinarity score is 0.10; that is to say, if interdisciplinary work were evenly distributed across all research fields and geographic locations, then any subset of publications would be expected to have 10% of its publications in the top 10% of the most interdisciplinary work. Accordingly, interdisciplinarity scores above 0.10 show that a given field/entity is contributing more than its expected share of highly-interdisciplinary papers; a score close to 0.10 shows that the contribution is

[20] Campbell, D. et al. (2015). Application of an "interdisciplinarity" metric at the paper level and its use in a comparative analysis of the most publishing ERA and non-ERA universities. Presented at the 20th International Conference on Science and Technology Indicators, Lugano, Switzerland. Retrieved from http://science-metrix.com/sites/default/files/science-metrix/publications/campbell_et_al_sti2015_short_paper_final_web.pdf.

near the expected value; and a score below 0.10 shows that the contribution is less than would be expected.

1.3.4 Identification of high-growth and interdisciplinary topics

Topic modeling using LDA

To identify high-growth and interdisciplinary topics, an approach called latent dirichlet allocation (LDA) was used first to delineate a set of topics, which were subsequently analyzed to identify those that are growing quickly as well as those that are highly interdisciplinary. The first step in that process, using the LDA to identify topical clusters, is in some ways similar to using tf-idf to create the EG datasets;[21] articulating the relevant differences will provide helpful insights to understand the LDA approach, and the resulting topical clusters it maps.

For the tf-idf approach, a number of documents already sorted into groups are fed in as input, and the analysis determines which words are central to which groups. On that basis, unsorted documents can be attributed to one or more groups on the basis of which words they use (and how often), and how those words score relative to the groups. In this way, tf-idf is a useful approach for extending pre-existing classification schemes.

By contrast, the LDA starts from a set of documents that are *not* already grouped, and identifies natural groupings within those documents. As input, the LDA requires the set of documents to group, the number of groups to find (i.e., the number of clusters anticipated to exist within the set), and the number of iterations to run. The group of documents is the total set of NSE publications found within the WoS database. Regarding the number of clusters to expect, experimentation conducted internally at Science-Metrix has determined that the square root of the number of inputted documents will reliably produce satisfactory results. In the present study, the total number of papers used is in the order of 4,000,000 documents, and so number of topics was set to 2,000. As for the number of iterations, Science-Metrix uses 200 iterations as standard in topic modeling projects, as this number is consistent in yielding meaningful results.

What does the LDA process actually do? In short, it groups words based on their co-occurrence patterns in documents. Note that information on the grouping of documents by scientific discipline is not provided to the LDA procedure before it begins. The words are then provisionally assigned, in a non-mutually exclusive manner, to a topic number (random numbers from 1 to 2,000, used as bins to collect topical themes). These provisional assignments are what propagate a cumulative influence throughout the process; whereas for the first iteration none of the words are yet assigned to bins, each subsequent iteration begins with partially defined picture of the topical map, with each iteration refining further and further detail in the modeling, until finally a clear picture begins to stabilize. When the 200 iterations are complete, and the process comes to an end, each of the numbered bins has a set of words associated with

[21] See Section 1.3.2.

it—some of which have a greater likelihood of belonging to a given topic than others—and these sets of words describe the topics that have naturally emerged from the documents inputted.

On the basis of this sorting of words into clusters, papers can then be assigned a proximity score (from 0 to 1) for each cluster, based on how much the terminology used in the paper overlaps with the terms in the cluster. For the current project, papers were assigned to the cluster with which they had the highest proximity score. In cases of ties, papers were assigned to all the clusters that shared in the tie for the top score. Ties were very rare in the present project, so the final classification was very close to mutually exclusive; the vast majority of papers were assigned to one and only one topical cluster, though with a few exceptions that were assigned to multiple clusters.

Additionally, some quality control measures were applied to weed out spurious topics that may have emerged during the LDA process. The first quality control measure was quantitative. Each paper was assigned to the cluster to which it was the closest, semantically; however, in some cases, a publication may have very low proximity scores for all of the clusters, even the one to which it is the closest. The papers whose maximum proximity scores were below 0.12 (i.e., a threshold below which the assignments did not appear as being robust based on random sampling of such assignments) were simply discarded. Then, with the papers already sorted, the quality of each cluster was evaluated based on how *strongly* its papers were associated with it; an integrity score was calculated by taking the median of the affinities of all the articles in a cluster to the terms defining the cluster. In some cases, clusters were screened out because they were not strongly integrated. Specifically, clusters were screened out if their *median* integrity score was below the *median* integrity score of all the clusters. That is to say, clusters that were less integrated than the norm were not considered.

Lastly, a qualitative measure was applied to ensure that only robust clusters were considered. Looking at the words that were grouped together in forming the clusters, some clusters were rejected on the grounds that the terms grouped did not show a true thematic affinity, based on expert judgment. For example, "interdisciplinary," "interstate" and "interaction" all have a common linguistic particle, but do not in fact reflect an underlying topical similarity. Such a grouping would be screened out.

Identifying topics of interest

With papers assigned to the various topics, bibliometric indicators (described in § 1.3.3) were applied to perform different analyses. To identify topics that are high-growth at the world level, and in which Canada has a research strength, the following filters were applied. First, high-growth topics were defined as those that grew by at least 20% at the world level (global GR ≥ 1.20). Of these, Canada's research strengths were identified as those topics in which Canada's growth in production outpaced global growth by at least 10% (Canada's GI ≥ 1.10). Topics in which Canada produced fewer than 50 publications were disregarded, and two clusters were removed based on the topic quality measures. These selected topics were sorted according to Canada's scores on a composite indicator of scientific impact (which accounts for both central tendencies as well as outstanding publications with very high citation impact)[22]; growth measures were not included in this composite indicator used for sorting, as they already provided the basis for one of the selection filters. The specialization index (SI) was not considered either since Canada is not specialized in the majority of the high growth topics.

To identify topics that are highly interdisciplinary at the world level, and in which Canada has a research strength, a different set of filters was applied. In this case, topics with an interdisciplinarity score below 0.15 were not considered (recalling that 0.10 is the expected value, and accordingly that a score of 0.15 shows that a given topic's share of highly interdisciplinary papers is 50% larger than its expected share). Additionally, recall that the interdisciplinarity score is calculated based only on the papers with the most outbound citations (see § 1.3.3); topics that had fewer than 100 publications in within that set were not considered here, as such a small sample size was considered to be insufficient to calculate a reliable result. That is not to say that such topics are not interdisciplinary, but rather that they have very few of the largest research projects in their respective disciplines (i.e., very few of the projects with the highest number of outgoing citations), and the interdisciplinarity score only considers such projects. Two further topics were also filtered out based on the quality control measures for topic contents, as described above.

With the highly interdisciplinary topics identified, Canada's research strengths were once again identified on the basis of a composite indicator of performance. Specifically, topics were sorted based on Canada's scores on a composite indicator integrating scientific impact, growth & specialization indices, and total publication output, as well as the global interdisciplinarity score of the topic (i.e., at world level). (Given that the interdisciplinarity indicator already imposes a very restrictive filter to consider only the papers with the most outbound citations within each field, and that the topics modeled here were composed of only a few thousand papers globally, the sample was simply too small to reliably calculate Canada's interdisciplinarity within the individual topics.)

1.3.5 Selection of countries for international comparison

For the selection of countries against which Canada's performance was to be benchmarked, NSERC stipulated three criteria. The first pertained to the availability of data, to ensure that a clear picture could be assembled for each country. The second was a threshold for publication output, according to which no country would be included if it published fewer than 5,000 NSE articles in the most recent year of the study (2013). The final criterion established a spending minimum, excluding from comparison any nation that spent less than $4 billion on R&D in the most current year.

Using these three filters, a list of 27 countries was assembled: Australia, Austria, Belgium, Brazil, Canada, China, Denmark, Finland, France, Germany, Israel, Italy, Japan, Mexico, the Netherlands, Norway, Poland, Portugal, Russia, the Republic of Korea, Spain, Sweden, Switzerland, Taiwan, Turkey, the United

[22] The procedure to rank topics in terms of scientific impact made use of a novel approach currently being developed at Science-Metrix to eliminate part of the biases induced by outliers in computing the ARC. As the development of this newer approach had not yet started when this project began, it is the only analysis presented in this report which rely on it.

Kingdom and the United States. A notable absence from this list is India, for which there is a clear lack of financial data that excludes it from the list.

Because the criteria pertain to the overall scientific activity of individual countries, there are some smaller nations that make important contributions to only one or a few EGs and yet do not appear on this list because their overall activity is too low to meet the minimum thresholds stipulated above. Similarly, some of the countries listed above are not among the top producers for every single EG, occasionally producing only a small amount in a given field. They appear in the comparison nonetheless because their overall activity includes them on the list of top global research producers.

1.3.6 Positional analysis

Within the Results section (§ 2), performance analysis by subfields is presented using a visualization technique called *positional analysis*. These figures present three different types of information in a single graphic: production size, specialization, and impact.

The size of production is proportionate to the size of the bubble on the chart. The larger the bubble, the more papers are produced in the given subfield.[23] The degree of specialization within a given subfield, relative to the world average, is presented along the horizontal axis (i.e., the x-axis); the world level of output concentration in a given subfield (i.e., the share of all output falling in a given subfield at world level) is represented by points falling on the y-axis which crosses the x-axis at the world value of 1, subfields in which Canada specializes lie to the right of the y-axis (SI > 1; higher level of concentration in a given subfield than at world level), and subfields in which Canada does not specialize lie to the left of the y-axis (SI < 1; lower level of concentration in a given subfield than at world level). Impact is presented along the vertical axis (i.e., the y-axis); again, the global average is the dividing line between the top and bottom half of the charts with the x-axis crossing the y-axis at the world level of impact of 1, subfields in which Canada has higher impact than the world level are towards the top of the chart, and subfields in which Canada has lower impact than the world level are towards the bottom of the chart.

Numbering the quadrants 1 through 4 (see Figure 1), we can conclude that subfields in quadrant 1 are ones in which Canada is specialized and has high impact, subfields in quadrant 2 are areas of high impact but low specialization, quadrant 3 contains subfields where Canada's specialization is high but impact is low, and quadrant 4 contains subfields in which Canada is neither specialized nor impactful.

Recall that size of production and specialization are separate but linked properties. A large bubble on the left side of the chart shows that Canada's production is large (demonstrated by the size of the bubble) but that the field is still not one of specialization for Canada (demonstrated by its position to the left of the centre line). Such a situation would indicate that Canada is producing many papers in a field with great publication output on the world stage, a relatively smaller drip in a huge pool. Conversely, a small bubble on the right side of the chart would denote a subfield in which Canada is not producing very many papers

[23] Note that only the subfields in which Canada published the most were analyzed up to a maximum of 25 subfields per EG. Also note that subfields in which Canada published fewer than 100 publications in a given EG were not considered. A way to visualize this threshold is to say that bubbles below a certain minimum size were not analyzed, and therefore do not appear in the positional analyses.

(demonstrated by the small bubble), but that this subfield is small at the world level, and therefore Canada's concentration of output in this subfield is still above the global norm (demonstrated by the position of the bubble to the right of the centre line).

Lastly, note that subfields are delineated using a journal-based classification produced and maintained by Science-Metrix for general use, beyond the bounds of the present study, whereas the EGs were created using the three methods described in § 1.3.2. As a result, some papers published in a given subfield might appear in one EG, whereas other papers from that subfield appear in a different EG. Accordingly, when a subfield is discussed under a given EG, it is only the papers within that subfield and in that EG that are being analyzed; papers in that subfield but not in the given EG are excluded from the analysis. Canada, then, may have very different scientific performance scores in a given subfield across EGs.

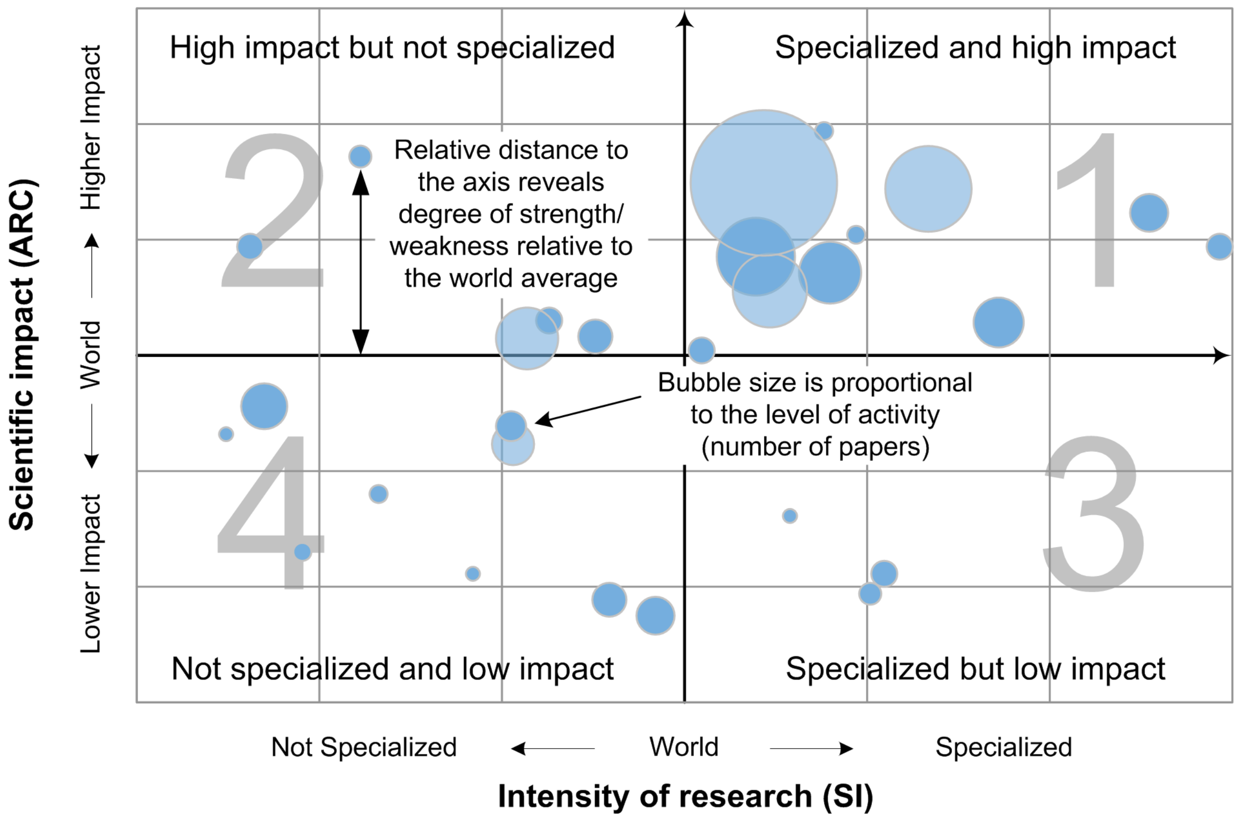

Figure 1 Guide to positional analysis
Source: Science-Metrix

Subfields highlighted for noticeably high/low scores

Subfields were characterized in two ways: relative to average world levels within the EG, and relative to Canada's performance in other subfields of the same EG. For comparisons at the world level, strengths at the subfield level within a given EG were identified as those subfields for which the SI score was above 1.1, and the ARC score was also above 1.1. In the positional analysis radars for each EG, the subfields that are strong at the world level all lie in Quadrant 1, as labeled in Figure 1 above.

Additionally, the overall output volume of the subfields was taken into account, to highlight those with a very large overall volume of publications. These subfields appear in the positional analysis radars as the largest bubbles. The threshold for high output was set at 1,000 publications, with two exceptions: EG1501 is a very large research area globally, and so the threshold in this EG was set at 3,000 publications; by contrast, EG1509 is very small globally, and so the threshold was set at 500 publications. Using these thresholds for impact, specialization and output, three different categories of strong performance were put together:

- High ARC and high SI
- High ARC and large output by volume
- High ARC, high SI, and large output by volume

The subfields of strong Canadian performance are summarized by EG in Table XV below.

To assess the strengths and weaknesses of subfields of Canadian research in each EG relative to each other rather than to the world level, dynamic thresholds were needed, as static thresholds are benchmarked relative to global performance. To set dynamic thresholds in a consistent manner across EGs, the impact and specialization scores were adjusted using two mathematical transformations: natural logarithms, and hyperbolic tangents. In this way, the scores for each subfield could be brought closer to a normal distribution, facilitating the subsequent use of arithmetic means and standard deviations to dynamically define thresholds consistently from one EG to the next.

Subfields were highlighted if their impact was more than one standard deviation above the mean, and their specialization more than one standard deviation below the mean; or vice versa. In this way, the statistical outliers could be identified, where those outliers are the subfields in which Canadian research is particularly strong in impact and weak in specialization, or vice versa, relative to Canada's performance in other subfields within the same EG.

These outliers represent areas for potential strategic focus. Using impact and specialization scores in this way is of interest because it is useful for the areas of national research focus and the areas of national research strength to overlap, to capitalize most efficiently on our research investments. Areas of high impact but low specialization, and vice versa, can be the targets of strategic intervention, to improve lagging performance along the relevant dimension, and thus increase the strength of these subfields on the world stage.

Of course, other priorities must be considered as well: a broad base of general research is important to avoid over-compartmentalization and hyper-specialization; furthermore, areas of social, economic, environmental, health and other policy focuses should also be areas addressed through scientific research. In short, efficient performance, aligning the areas of high impact and of high specialization, is only one among many considerations. In light of this need to consider diverse priorities, the areas of potential strategic consideration were identified using mathematically defined thresholds, but this analysis has also been supplemented by expert analysis at Science-Metrix. Specifically, any subfields that were very close to the thresholds have been included if they were deemed to be thematically very relevant to the EG in question. This judgment also considered the output volume of the subfields. Of course, and as mentioned above, the members of NSERC's expert panel should consider other factors such as socio-economic priorities for Canada.

The subfields in each EG that have been highlighted for potential strategic consideration are summarized in Table XVI below.

1.4 Considerations for interpreting results

Bibliometric indicators rely on data that fundamentally track two types of events: publications and citations. While many valuable conclusions can be derived from the analysis of these events using various bibliometric tools, it is worth bearing in mind that peer-reviewed publications are only one part (albeit a very important part) of the larger science and technology landscape. For instance, data gathering is a fundamental part of scientific practice, and a great many research publications would not be possible in the absence of the quality baseline data it provides. However, such data is usually not published in peer-reviewed journals. In interpreting bibliometric data, it is important that some critical distance be retained, so as not to fall too easily into the habit of assuming that peer-reviewed publication represents the entirety of the research enterprise.

Furthermore, it is important to keep in mind that peer review is importantly dependent on the cultural practices of scientists, and that these practices vary from one discipline to the next. Research is peer reviewed to ensure the originality and the quality of the submitted work. The minimum standards for originality and for quality are determined by the community of scientists working in a given domain. Similarly, a citation indicates that a given article has significantly influenced or contributed to the work at hand; the threshold is culturally determined for judging when such influence is significant enough to warrant citation. Collaboration requires similar judgment to determine when a contribution has been significant enough to warrant inclusion on the list of authors (and in many cases, in determining the order of that list). While every effort is made during bibliometric analysis to identify, measure and adjust for these variations across fields, to ensure that results are repeatable, meaningful and robust, these variations in cultural practice should be borne in mind when interpreting the results and when using such lines of evidence as the basis for policy decisions.

The role of policy priorities in shaping bibliometric analysis must also be acknowledged. As discussed above (see § 1.3.3), decisions to give equal weight to publication output, growth, impact and specialization shape how composite indices are calculated, and therefore how countries are ranked overall and how the strong performers in different research areas are identified. The decision of which indicators to include or exclude from the composite indicator, and how they are to be weighted in its calculation, are primarily policy-relevant questions. Further examples can show that even the basic indicators themselves are already integrating different policy priorities; for instance, the choice to develop and apply a "collaboration index" instead of a "secrecy index" discloses a policy decision that has been integrated into the basic tools of bibliometrics. Because such policy priorities are already at work, one cannot (and does not) simply wait for the results to be calculated before staking a policy position. No determination can be made about which institutions are doing "well" until the relevant parameters for "good performance" have been established. The different evaluative parameters can be given more equal weight or they can be prioritized, but neither of these obviates the need for policy input in the formulation of bibliometric questions. The necessary implication of policy decisions in bibliometric methodology has the important result that neither of these scales of relative weighting is more (nor less) "objective" than the other.[24] In this case, defining the parameters that constitute strong performance must proceed in tandem with performance-based ranking. It is important that science policy decisions and science policy evaluations co-evolve.

[24] The objectivity of evidence-based policymaking, like the objectivity of science itself, is not immediately undermined by any and all inclusion of values. That objectivity is undermined when values take the place of evidence, inappropriately determining the outcome of the research; objectivity is not undermined when values are used to design the questions that evidence is subsequently used to answer. For more details, see Douglas, H. E. (2009). *Science, policy, and the value-free ideal*. Pittsburgh, Pa: University of Pittsburgh Press. See also Douglas, H. E. (2014). Scientific integrity in a politicized world. In P. Schroeder-Heister, G. Heinzmann, W. Hodges, & P. E. Bour (Eds.), *Logic, methodology and philosophy of science proceedings of the 14th international congress (Nancy): logic and science facing the new technologies*. London: College Publications. Retrieved from http://www.ingsa.org/wp-content/uploads/2014/08/Scientific-Integrity-in-a-Politicized-World-2014.pdf.

2 Results

The presentation, analysis, and discussion of results for the present study will be structured as follows: 12 sections, one for each EG, will respond to key questions (i)–(iii) listed above in § 1.2.1. After these 12 sections, questions (iv) and (v) will be treated in a final section of results, examining high-growth and interdisciplinary topics of NSE research. Before considering the individual EGs in detail, however, the examination of Figure 2 and Figure 3 will provide a general sense of the overall state of scientific research in the NSE in Canada.

Figure 2 shows Canada's ranking on the world stage, for each EG, as determined by a composite performance index (CPI), which integrates rate of publication (i.e., number of publications), the growth of research output (i.e., GR), the effort level of countries in different fields (i.e., SI), and an average of the three measures of scientific impact (i.e., ARC, ARIF, HCP) of its publications. By this measure, Canada's greatest strengths lie in Evolution & Ecology (EG1503), Biological Systems & Functions (EG1502), Computer Sciences (EG1507), and Electrical & Computer Engineering (EG1510).

Figure 2 also shows that Canada's impact is near or above world level (i.e., ARC = 1) in each of the EGs, with Physics (EG1505; ARC = 1.45), Evolution & Ecology (EG1503; 1.33), Electrical & Computer Engineering (EG1510; 1.31), and Computer Science (EG1507; 1.28) having the most scientific impact. In these areas, the average impact of Canadian papers is at least 25% higher than that of the average world paper (i.e., Canada's ARC in these fields ≥ 1.25). Mechanical Engineering (EG1512; 1.02), Materials & Chemical Engineering (EG1511; 1.06), and Civil, Industrial & Systems Engineering (EG1509; 1.08) show the most room for improvement, though it is worth noting that all three are still close to or slightly above the world average.

Regarding the specialization index (SI), Canada's SI scores reflect a comparison of two proportions: the number of articles in a given research area as a proportion of all Canadian research publications, compared to the number of articles in that area as a proportion of total research at the world level. Thus, one can conclude that Canada's high scores in Evolution & Ecology (EG1503; SI = 1.57), Biological Systems & Functions (EG1502; 1.47), and Geosciences (EG1506; 1.32) show that Canada's concentration of outputs in these fields is close to 60%, 50% and 30% larger than the corresponding concentration at world level (i.e., SI of 1.57, 1.47 and 1.32). Canada's lowest scores are in Chemistry (EG1504; SI = 0.63), Physics (EG1505; 0.73) and Materials & Chemical Engineering (EG1511; 0.85). With concentration of outputs at least 15% smaller than at the world level, it is fair to say that Canada is not specialized in these areas.

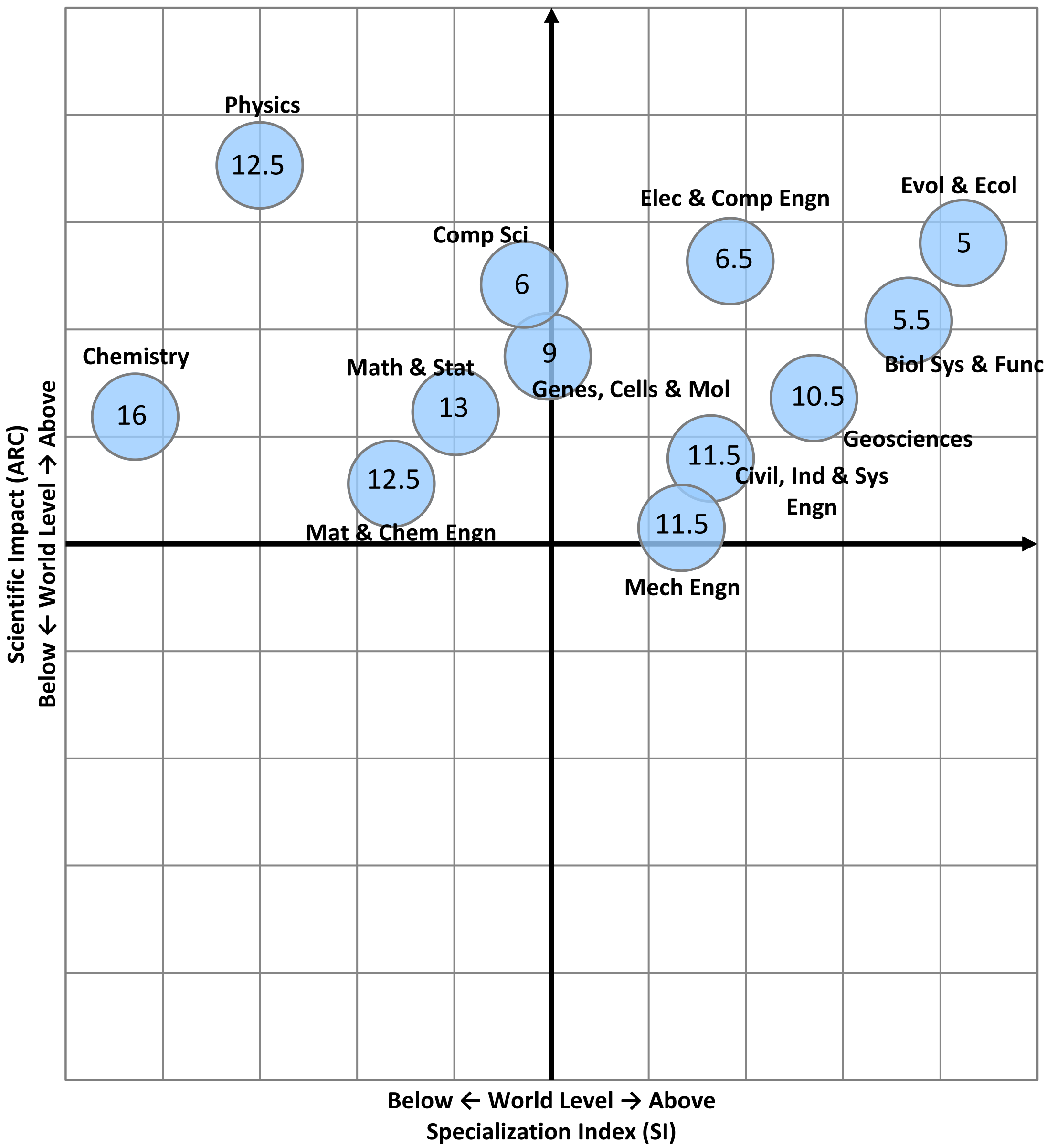

Figure 2 Positional analysis of Canada in NSE research in each of the 12 EG datasets (2009–2013)

Note: Rank based on composite performance index (CPI) is given in the bubble. CPI accounts for Pubs, GR, SI, ARC, ARIF and HCP. The year 2013 is not included in computing the ARC since the citation window (i.e., the period during which citations are counted) is too short for papers published so recently.

Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters)

In Figure 3 below, the recent evolution of Canada's scientific performance in each EG is depicted using two 2-year segments (i.e., 2009–10 and 2011–12). Generally, Canada's scientific impact decreased across EGs during this period, though it remained stable or increased slightly for a few EGs: Evolution & Ecology (EG1503), Genes, Cells and Molecules (EG1501), Biological Systems & Functions (EG1502). The remaining EGs saw decreased scientific impact, with notable decreases in Computer Sciences (EG1507), Materials and Chemical Engineering (EG1511), and Mechanical Engineering (EG1512).

Canada's specialization remained mostly unchanged, with an appreciable increase in Biological Systems & Functions (EG1502), and a notable decrease in Civil, Industrial and Systems Engineering (EG1509). Production volume was generally increasing, with most EGs having experienced an increase in the range of 9% to 17% between 2009−2010 and 2011−2012. Two EGs were relatively stable, EG1508 and EG1510. Two EGs saw decreases between 7% and 8%, EG1507 and EG1509.

With this more general picture now outlined, we can move on to explore the more detailed findings for each EG, addressing the key questions of this study (outlined in § 1.2.1). The Results section of the present report treats all twelve EGs, each in its own sub-section (§ 2.1–§ 2.12). Each of these sub-sections is in turn divided into two parts; one part looks at Canada's performance relative to the rest of the world, answering key question (i). The other part looks at Canada's performance at the subfield level within the given EG, answering key questions (ii) and (iii). Thereafter, research topics of high growth and high interdisciplinarity are discussed (in § 2.13.1 and § 2.13.2, respectively).

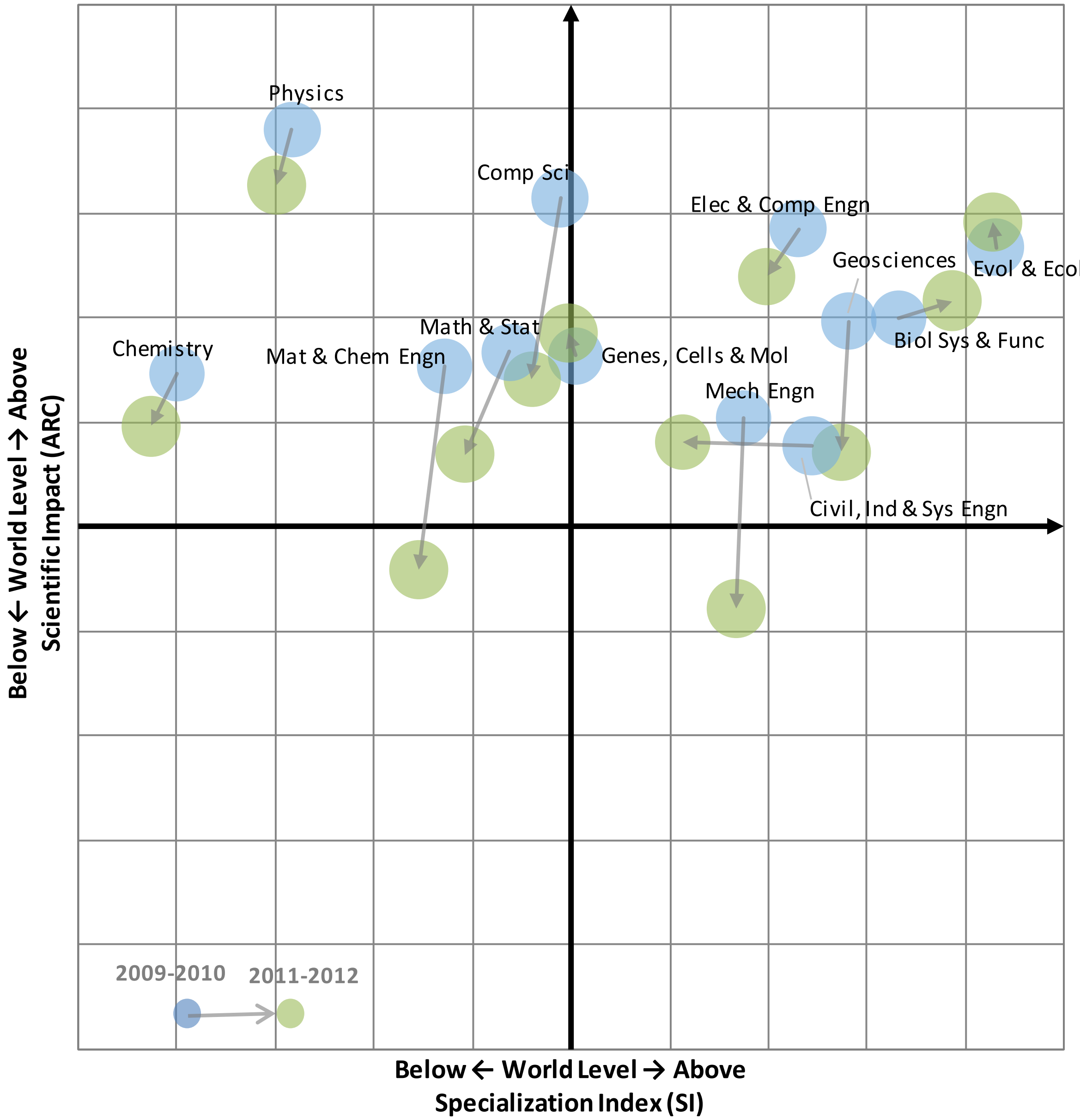

Figure 3 Monitoring the evolution of Canada's position in NSE research in each of the 12 EG datasets, 2009–2010 vs. 2011–2012

Note: The year 2013 was not considered in studying trends since the ARC of papers published so recently cannot be computed. Indeed, they have not had the chance to accumulate citations over a sufficiently long time period (i.e., the citation window) to allow the computation of robust citation metrics.

Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters)

2.1 EG1501 – Genes, Cells and Molecules

2.1.1 Benchmarking Canadian performance relative to other world leaders

From Table I below, one can see that Canada ranks 8th for the size of its production in Genes, Cells and Molecules (EG1501), trailing the leading group of the US, China, and Germany. In terms of growth, Canada's production increased by only 8% (GR = 1.08) from 2009–2010 to 2012–2013, ranking 19th among the set of 27 selected benchmark nations in NSE research.[25] While its level of growth in this EG is below the world average (as is the case for most of the 27 countries presented here), it is important to note that the meteoric rise of scientific research in BRIC[26] countries, in particular China, plays an important role in contributing to average worldwide growth, in this EG as well as others. Canada's production within EG1501, relative to its overall research production (including NSE, Health Sciences, and Social Sciences & Humanities), is very close to the analogous proportion at world level, indicating that Canada is not particularly specialized in this area. Countries that are highly specialized in EG1501 include Japan, the US and Denmark, with shares of their total scientific production in this area that are approximately 20% larger than the corresponding shares at world level.

Regarding impact, Canada is above the global average in this EG according to each indicator used in this study. Still, among the 27 selected countries, Canada places in the middle of the pack: 14th in ARC, 14th in ARIF, and 13th in highly cited papers. Switzerland and the Netherlands stand out as countries with strong scientific impact in EG1501. Turning to international collaborations, Canada is the 13th most collaborative nation in this group of 27 with 10% more observed co-publications than expected based on the size of national publication output (i.e., CI = 1.10). The countries that have the strongest propensity to co-publish with international partners given the size of their production are Switzerland, the UK, and Sweden. Two of the top international producers in this area, the US and China, have very low collaboration indices, which may indicate a greater emphasis on collaborations within their respective countries; given how much research is undertaken internally within each of these two countries, the need for complementary expertise can be more easily fulfilled through intra-national partnerships in such a large research market than would be the case for a small research market.

Overall, using the composite score to rank the 27 benchmark nations, Canada places 9th, tied with France and Australia. The US places 1st, with Switzerland in 2nd, and the Netherlands and Germany tied for the subsequent spot.

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[25] See § 1.3.5 for information on how NSERC selected these 27 world leaders.

[26] India was not selected since part of the data used to select the countries presented in this study was unavailable for this country.

Table I Scientific performance of a selection of 27 highly active countries in NSE research for EG1501 (Genes, Cells and Molecules) (2009–2013)

Country	Pubs. (rank)	GR	Trend	SI	ARC	ARIF	HCP	CI	Composite score
World	**1,034,719 (N/A)**	**1.19**		**1.00**	**1.00**	**1.00**	**1.00**	**N/A**	**N/A**
United States	325,316 (1)	1.05		1.19	1.28	1.18	1.47	0.93	84
Switzerland	20,107 (15)	1.14		1.10	1.50	1.27	1.84	1.39	82
Netherlands	24,879 (14)	1.15		0.93	1.47	1.24	1.77	1.31	80
Germany	79,283 (3)	1.09		1.05	1.23	1.17	1.39	1.26	80
United Kingdom	71,842 (5)	1.02		0.90	1.34	1.23	1.62	1.37	79
Denmark	12,257 (22)	1.18		1.18	1.36	1.17	1.52	1.27	79
Belgium	14,826 (19)	1.15		1.01	1.37	1.20	1.65	1.32	79
France	51,713 (6)	1.07		0.97	1.18	1.16	1.30	1.27	77
Canada	44,723 (8)	1.08		1.00	1.19	1.13	1.29	1.10	77
Australia	29,572 (13)	1.21		0.83	1.27	1.16	1.46	1.15	77
China	140,679 (2)	1.72		0.84	0.95	0.88	0.86	0.64	76
Spain	39,935 (10)	1.20		1.04	1.09	1.11	1.11	1.03	76
Sweden	18,073 (16)	1.05		1.04	1.24	1.16	1.28	1.33	76
Israel	10,472 (24)	1.03		1.09	1.23	1.20	1.34	1.01	75
Italy	45,615 (7)	1.10		1.04	1.04	1.06	1.04	1.02	75
Austria	10,231 (25)	1.13		0.98	1.25	1.14	1.36	1.31	75
Japan	76,040 (4)	1.02		1.22	0.91	0.97	0.75	0.68	74
Portugal	9,615 (26)	1.42		1.06	1.03	1.04	1.03	1.03	74
Finland	7,820 (30)	1.06		0.87	1.31	1.16	1.48	1.21	74
Rep. of Korea	38,592 (11)	1.30		1.13	0.91	0.88	0.75	0.62	74
Norway	6,782 (32)	1.16		0.83	1.20	1.09	1.28	1.14	72
Taiwan	17,779 (17)	1.25		0.83	0.97	0.98	0.81	0.51	70
Brazil	29,894 (12)	1.28		1.16	0.62	0.77	0.42	0.56	69
Mexico	8,508 (27)	1.29		1.05	0.74	0.88	0.62	0.80	68
Poland	15,252 (18)	1.38		0.93	0.72	0.78	0.56	0.67	68
Turkey	12,707 (20)	1.08		0.70	0.58	0.63	0.41	0.40	60
Russia	12595 (21)	1.09		0.58	0.49	0.59	0.32	0.75	57

Note: Colouring provides insight on performance relative to world (in WoS), ranging from dark red (below world level) to white (on par with the world level) and dark green (above world level). Note that for pubs and composite scores, colouring is relative to median (white) instead of world; additionally, colouring for CI is relative to expected values (white), which are computed based on the relationship between total publication output and co-publications at the country level. The GR, pub trend and SI were computed using fractional counting. For pub trend, the scale varies across countries. The CI is not accounted for in the composite score.

Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters)

2.1.2 Analysis of Canadian performance within subfields

Of the 25 subfields analyzed for EG1501, Canada's impact is near or above the world for nearly all of them. The weakest impact scores within this EG[27] (ARC < 1.00) are in Organic Chemistry, Physiology, Toxicology, and Biomedical Engineering, though only Biomedical Engineering is noticeably lower than the world average of impact (i.e., ARC = 0.86). Canada's highest impact scores (ARC > 1.40) are in Biotechnology and Dairy & Animal Science, as well as in General Science & Technology journals.[28]

Regarding specialization, Canada is very highly specialized only in Physiology (SI = 2.24). It has low specializations scores in Chemical Physics (SI = 0.70), and especially in Medicinal & Biomolecular Chemistry and Biotechnology (SI ≤ 0.55). Most subfields in this EG are clustered around the world average for specialization, which is reflective of the fact that Canada's SI score for EG1501 overall is 1.00. While Canada may only be specialized in Physiology, its largest publication outputs, each with more 3,000 publications per year, are (in descending order) in the subfields of Biochemistry & Molecular Biology, Neurology & Neurosurgery, Developmental Biology, Genetic Science & Technology, and Microbiology.

Within the subfields of EG1501, Canada has several areas of strength. Its most impressive strengths, in terms of impact, specialization and volume of output (i.e., ARC > 1.1, SI > 1.1, output > 3,000 pubs), are in Neurology & Neurosurgery, and Developmental Biology. Additional strengths, in terms of impact and specialization only (i.e., ARC > 1.1, SI > 1.1), are in Genetics & Heredity, Evolutionary Biology, and Cardiovascular System & Hematology, and Nutrition & Dietetics. Canada also has secondary strengths, meaning high impact and large output by volume (i.e., ARC > 1.1, output > 3,000 pubs), in General Science & Technology and Microbiology.

Areas for potential strategic consideration are Physiology, which is an area of specialization but with impact scores that could benefit further improvement; and Biotechnology, where impact scores are high but in which Canada is not specialized. Dairy & Animal Science was also identified through expert judgment to be close to the relevant thresholds for strategic consideration, while also being thematically central to EG1501. Strategies to improve scientific impact could include creating more competitive granting application processes, fostering international collaboration (which is known to correlate well with impact scores), and others. Increasing financial or human resources dedicated to an area of research are worth considering as means to increase research outputs, and thus specialization scores (recalling that specialization reflects the proportion of national research devoted to a certain area, and is thus a zero-sum game).

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[27] Throughout this report, strong and weak subfield scores within an EG will be reported as those that score more than one standard deviation above the mean (within the EG), and those that fall more than one standard deviation below the mean (again, within the EG), respectively. The arithmetic means and standard deviations have been calculated on a transformed distribution of scores; see § 1.3.6 above for further details.

[28] General Science & Technology, as a subfield of research, includes multidisciplinary, high-impact journals such as *Science* and *Nature*. Recall that citation rates are normalized by subfield, meaning that Canada's strong impact scores in General Science & Technology signify that Canadian publications in these prestigious journals are cited more frequently than the global average publications in those same prestigious journals.

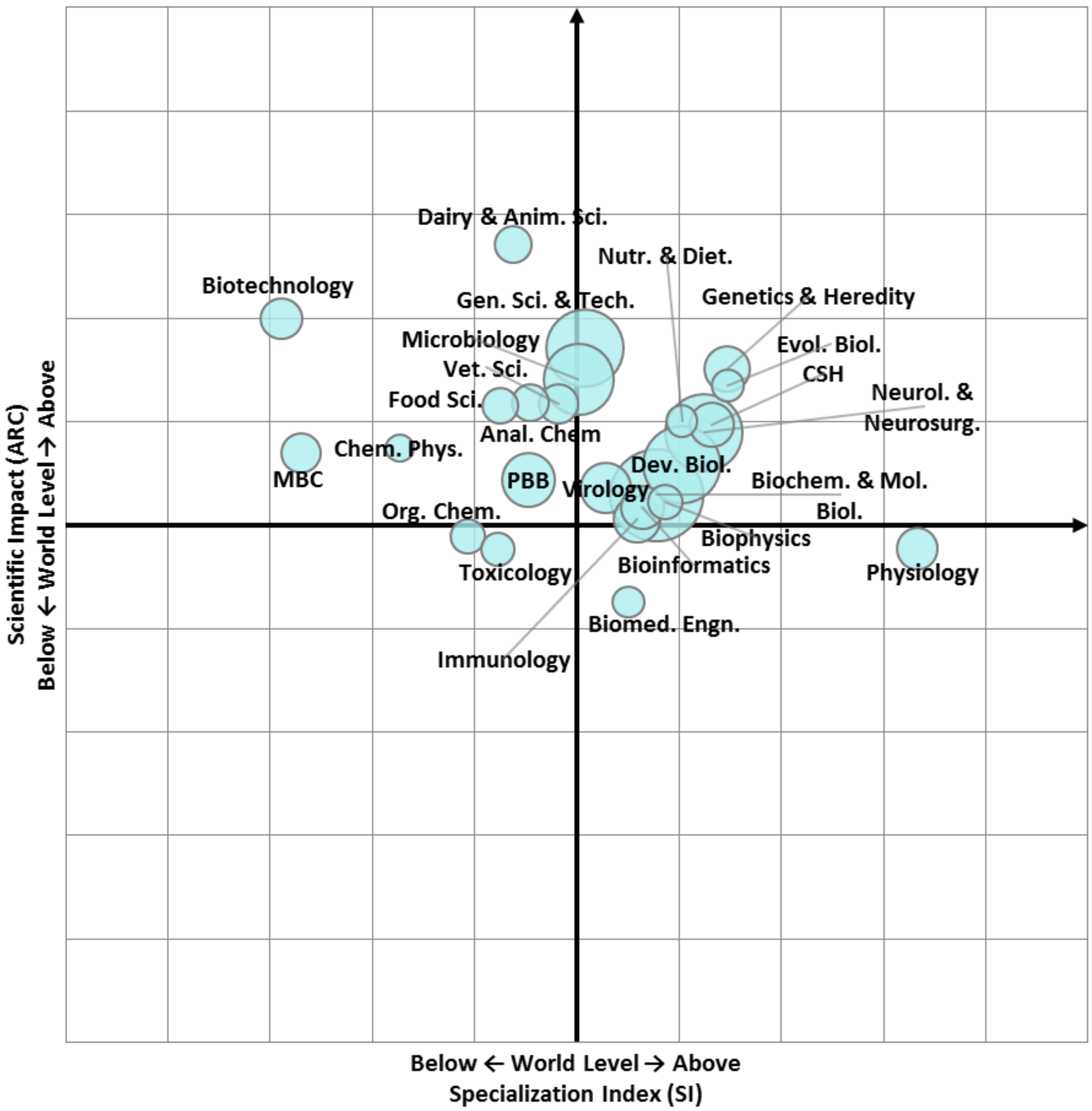

Figure 4 Positional analysis of Canada by subfield within EG1501 (Genes, Cells and Molecules) (2009–2013)

Note: Selection of the 25 subfields in which CA published the most.

Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters)

2.2 EG1502 – Biological systems and functions

2.2.1 Benchmarking Canadian performance relative to other world leaders

In EG1502, Canada publishes the 5th most articles of any of the selected countries, behind only the US, the UK, China, and Germany. Canada's output grew by 19% (GR = 1.19) from the 2009–10 to the 2012–2013 period. This level of production growth is just below the world average, sitting at 17th on the list of the 27 benchmark nations in this regard. China, Portugal, and Taiwan are fast-growing producers in this EG. Canada is highly specialized in EG1502, producing 47% more of its national output in this EG than would be expected based on worldwide research output proportions. With respect to specialization, Canada thus ranks 4th, behind only Brazil, Denmark, and the Netherlands.

Despite being well above the world average in terms of impact in EG1502, Canada comes out near the middle of the pack of the 27 nations selected for comparison, ranking 11th for ARC, 13th for ARIF, and 10th for HCP. The Netherlands, Denmark, Switzerland, the UK, and the US occupy the top spots for impact in EG1502. Regarding its propensity to collaborate on the international scale, Canada ranks 12th out of 27, with Switzerland, the UK, Belgium, and Sweden leading the way.[29] It is worth noting that Switzerland and the UK are leaders in both collaboration and impact.

Overall, using the composite performance indicator (CPI), Canada shares the 5.5th spot with Australia, surpassed only by the Netherlands, the US, Denmark, and the UK.

[29] Collaboration scores reflect how many papers are actually co-authored with international partners, as a proportion of overall publication output, compared to the expected proportion of international co-authorships. The expected value is based on trends measured across all nations; however, it is not a simple average, as the size of research output has an important influence on the trend to collaborate. Hence, the expected values used in calculating a country's collaboration index are adjusted for that country's research output value.

Table II Scientific performance of a selection of 27 highly active countries in NSE research for EG1502 (Biological Systems and Functions) (2009–2013)

Country	Pubs. (rank)	GR	Trend	SI	ARC	ARIF	HCP	CI	Composite score
World	**225,143 (N/A)**	**1.20**		**1.00**	**1.00**	**1.00**	**1.00**	**N/A**	**N/A**
Netherlands	7,979 (12)	1.24		1.51	1.45	1.20	1.70	1.40	84
United States	66,601 (1)	1.12		1.14	1.33	1.18	1.51	1.03	83
Denmark	3,463 (19)	1.24		1.64	1.40	1.19	1.52	1.39	82
United Kingdom	19,509 (2)	1.11		1.18	1.33	1.20	1.63	1.56	82
Canada	13,758 (5)	1.19		1.47	1.23	1.14	1.33	1.26	81
Australia	10,172 (10)	1.29		1.41	1.24	1.16	1.33	1.27	81
Switzerland	4,655 (15)	1.23		1.24	1.40	1.20	1.56	1.57	80
Germany	16,607 (4)	1.17		1.06	1.19	1.10	1.30	1.41	78
Belgium	3,987 (17)	1.19		1.34	1.26	1.14	1.32	1.43	77
Norway	2,201 (25)	1.22		1.25	1.28	1.17	1.44	1.35	77
Sweden	4,152 (16)	1.17		1.16	1.29	1.17	1.35	1.43	77
Spain	8,957 (11)	1.25		1.12	1.13	1.08	1.18	1.10	76
Finland	2,409 (23)	0.96		1.41	1.30	1.16	1.34	1.18	76
France	10,240 (9)	1.14		0.93	1.18	1.14	1.33	1.38	75
Italy	10,309 (8)	1.21		1.10	1.09	1.04	1.14	1.17	75
Brazil	10,912 (7)	1.26		2.04	0.56	0.70	0.39	0.50	73
Austria	2,061 (28)	1.22		0.97	1.14	1.04	1.37	1.42	72
Israel	2,162 (27)	1.12		1.11	1.08	1.17	1.01	1.02	71
Portugal	1,753 (30)	1.44		0.91	1.04	1.02	1.02	1.16	70
China	17,560 (3)	1.60		0.48	0.90	0.89	0.76	0.88	69
Japan	12,913 (6)	1.07		0.99	0.79	0.92	0.61	0.67	68
Mexico	2,319 (24)	1.21		1.38	0.63	0.83	0.49	0.85	67
Taiwan	2,864 (22)	1.41		0.62	0.86	0.90	0.68	0.57	64
Poland	3,406 (20)	1.32		1.02	0.60	0.69	0.43	0.58	64
Rep. of Korea	4,940 (14)	1.30		0.67	0.76	0.86	0.57	0.66	64
Turkey	3,558 (18)	0.89		0.94	0.50	0.61	0.33	0.35	59
Russia	1,507 (34)	1.10		0.33	0.33	0.54	0.25	0.66	50

Note: Colouring provides insight on performance relative to world (in WoS), ranging from dark red (below world level) to white (on par with the world level) and dark green (above world level). Note that for pubs and composite scores, colouring is relative to median (white) instead of world; additionally, colouring for CI is relative to expected values (white), which are computed based on the relationship between total publication output and co-publications at the country level. The GR, pub trend and SI were computed using fractional counting. For pub trend, the scale varies across countries. The CI is not accounted for in the composite score.

Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters)

2.2.2 Analysis of Canadian performance within subfields

Canada's impact is near or above the world average in all the subfields of EG1502, with the exception of Biochemistry & Molecular Biology (ARC = 0.87). Two other subfields, Experimental Psychology and Nutrition & Dietetics, also have relatively low impact for Canada within this EG, though they are near the world level (ARC < 1.00). Especially high-impact subfields in this EG are Artificial Intelligence & Image Processing, Fisheries, Agronomics & Agricultural Science, Genetics & Heredity (ARC ≥ 1.50), and especially Dairy & Animal Science (ARC = 2.08).

While Canada is specialized in EG1502 in general, it is particularly specialized in the subfields of Physiology, Medical Informatics, Experimental Psychology, and Sport Science (SI > 2.10). Agronomics & Agriculture and Plant Biology & Botany (SI < 0.85) are the only areas in which Canada is noticeably below world average specialization. Artificial Intelligence & Image Processing, Veterinary Science and Fisheries are three subfields that are also less specialized areas of Canada's research in EG1502 (0.95 < SI < 1.05), though they are still above the world average. Two subfields have large research outputs by volume, and these are Experimental Psychology, and Neurology & Neurosurgery, which each produced approximately 2,000 publications.

Canada has many strengths in the subfields of EG1502, which is unsurprising considering that Biological Systems & Functions is the EG in which Canada exhibits its second-best performance on the world stage, based on the composite indicator ranking. Its five subfields of greatest strength, looking at both specialization and scientific impact (SI > 1.1, ARC > 1.1) are Medical Informatics, Dairy & Animal Science, Genetics & Heredity, Sport Science, and Food Science.

There are also some areas for potential strategic consideration, with high impact scores but low specialization, and these are Artificial Intelligence & Image Processing, Fisheries, and Agronomics & Agriculture. Experimental Psychology is another potential strategic area, given its high specialization and low impact scores; Experimental Psychology is also an area of large overall output.[30]

[30] Potential approaches to address these strategic opportunities are discussed in § 2.1.2 above.

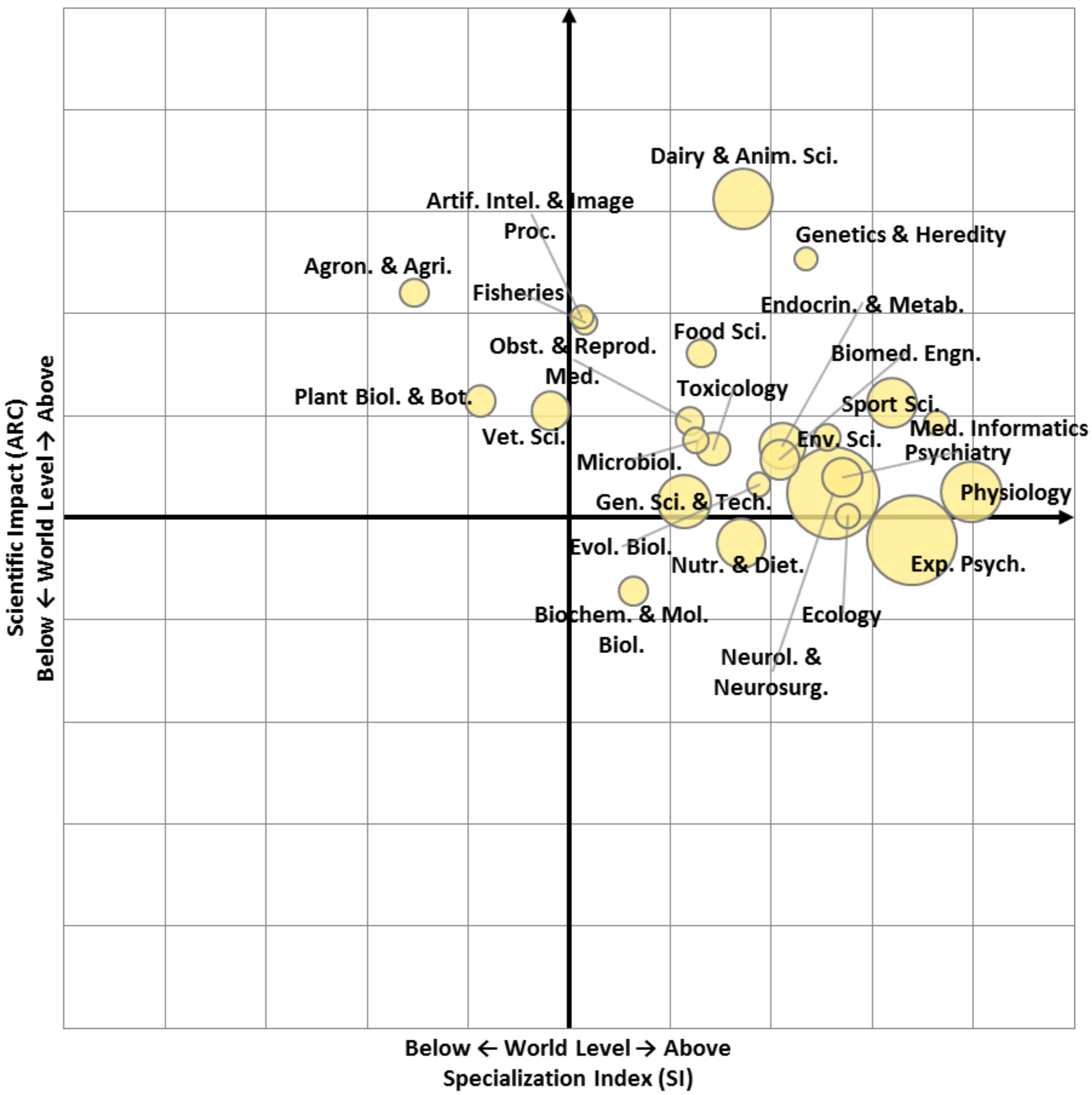

Figure 5 Positional analysis of Canada by subfield within EG1502 (Biological Systems and Functions) (2009–2013)

Note: Selection of the 25 subfields in which CA published the most.
Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters)

2.3 EG1503 – Evolution and Ecology

2.3.1 Benchmarking Canadian performance relative to other world leaders

Regarding production size within EG1503, the US, China and the UK occupy the first three ranks, with Canada occupying the 4th rank. In terms of production growth, Canada's output increased by 6%, placing 22nd in the group of 27 selected nations, with the Republic of Korea and China leading the list of high-growth countries. Turning to specialization, Canada ranks 7th on the list of comparator nations, producing 57% more of its total publications in EG1503 than the worldwide proportion; Mexico, Brazil, Norway and Australia lead in this regard.

Canada's scientific impact in EG1503 is well above the global average, placing it on the borderline of the top tier among the benchmark group of 27 nations: 12th in ARC, 9th in ARIF, and 10th in HCP. The countries with the strongest impact in this area are Switzerland, the Netherlands, Denmark, and the UK.

Canada's penchant for international collaboration, adjusted for national output size, is near the global tendency in this area of research, placing 13th out of 27. The UK, the Netherlands, Switzerland, and Denmark are the most collaborative countries; these highly collaborative countries are the same set that score highest for their scientific impact.

Overall, using the composite performance index (CPI) to rank the benchmark nations selected by NSERC, Australia ranks 1st, followed by Switzerland and the UK. Canada holds the 5th spot, sharing that rank with Norway and the US. (As Canada, Norway and the US share ranks 4, 5 and 6, they are each given the average of those three ranks, i.e., 5th.)

Table III Scientific performance of a selection of 27 highly active countries in NSE research for EG1503 (Evolution and Ecology) (2009–2013)

Country	Pubs. (rank)	GR	Trend	SI	ARC	ARIF	HCP	CI	Composite score
World	**234,069 (N/A)**	**1.16**		**1.00**	**1.00**	**1.00**	**1.00**	**N/A**	**N/A**
Australia	15,125 (6)	1.19		1.98	1.40	1.19	1.68	0.98	68
Switzerland	5,291 (14)	1.13		1.19	1.67	1.28	2.11	1.33	67
United Kingdom	19,333 (3)	1.07		0.99	1.50	1.27	1.87	1.37	67
Denmark	3,274 (27)	1.28		1.18	1.57	1.25	2.07	1.31	66
United States	68,254 (1)	1.06		1.07	1.22	1.15	1.36	0.87	66
Canada	16,120 (4)	1.06		1.57	1.33	1.19	1.55	1.01	66
Norway	3,993 (23)	1.10		2.01	1.45	1.20	1.70	1.17	65
Netherlands	5,658 (12)	1.16		0.82	1.62	1.28	1.96	1.33	65
France	13,859 (8)	1.09		1.05	1.36	1.20	1.60	1.29	64
Finland	3,604 (25)	1.11		1.88	1.47	1.22	1.58	0.98	64
Sweden	5,337 (13)	1.08		1.30	1.46	1.28	1.67	1.23	64
Germany	15,606 (5)	1.19		0.83	1.27	1.16	1.50	1.27	64
Spain	13,178 (9)	1.20		1.41	1.18	1.11	1.27	1.08	64
Portugal	3,909 (24)	1.36		1.67	1.04	1.07	1.20	1.15	62
Brazil	14,009 (7)	1.35		2.38	0.64	0.73	0.53	0.54	60
China	20,090 (2)	1.43		0.51	1.00	0.91	0.92	0.77	60
Belgium	4,030 (22)	1.02		1.13	1.36	1.11	1.35	1.28	60
Italy	8,580 (11)	1.19		0.81	1.11	1.02	1.17	0.99	60
Austria	2,707 (29)	1.15		1.07	1.38	1.10	1.28	1.25	60
Mexico	4,943 (16.5)	1.28		2.56	0.73	0.79	0.66	0.86	59
Poland	4,228 (20)	1.34		1.11	0.77	0.74	0.66	0.65	56
Japan	8,821 (10)	1.03		0.58	1.06	0.96	0.81	0.77	56
Israel	1,568 (35)	1.10		0.69	1.03	1.18	1.16	0.94	55
Rep. of Korea	2,421 (30)	1.66		0.28	0.88	0.82	0.83	0.77	55
Taiwan	2,005 (32)	1.28		0.34	1.02	0.99	0.78	0.85	53
Russia	4,400 (19)	1.05		0.87	0.49	0.57	0.35	0.70	49
Turkey	3,068 (28)	0.77		0.74	0.62	0.60	0.44	0.39	46

Note: Colouring provides insight on performance relative to world (in WoS), ranging from dark red (below world level) to white (on par with the world level) and dark green (above world level). Note that for pubs and composite scores, colouring is relative to median (white) instead of world; additionally, colouring for CI is relative to expected values (white), which are computed based on the relationship between total publication output and co-publications at the country level. The GR, pub trend and SI were computed using fractional counting. For pub trend, the scale varies across countries. The CI is not accounted for in the composite score.

Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters)

2.3.2 Analysis of Canadian performance within subfields

Evolution & Ecology is the area of research in which Canada performs best on the world stage, of all 12 EGs, when using the composite performance indicator. Recall, though, that this indicator collapses important differences in performance along the various dimensions it incorporates, and that the selected weighting of the indicators in assembling a composite of these dimensions necessarily influences the computed results for the CPI. The subfields in EG1503 with the most impactful Canadian research are Oceanography, General Mathematics, and General Science & Technology (ARC > 1.85).[31] Physiology is the only subfield in this EG in which Canada's ARC score is below the world level (ARC = 0.96); the other lower-scoring subfields in this area are Microbiology, Agronomy & Agriculture, Toxicology, Meteorology & Atmospheric Science, and Entomology (ARC < 1.05).

Turning to specialization, Canada's SI scores are below the world level in Zoology, General Mathematics, and Plant Biology & Botany (SI < 0.95). Canada also has a relatively low SI score in Microbiology (SI = 1.05), though it is above the world level. By contrast, Canada is highly specialized in a number of subfields in the EG, which are, in descending order: Forestry, Physiology, Fisheries, Toxicology, Ornithology, and Geological & Geomatic Engineering (SI > 2.50). Five subfields of EG1503 produce large outputs by volume, with over 1,000 publications each. They are Ecology, Evolutionary Biology, Fisheries, Marine Biology & Hydrology, and Forestry.

As in Biological Systems & Functions, Canada's performance in Evolution & Ecology is remarkably strong on the world stage. Accordingly, it is unsurprising to find that there are many subfields in EG1503 that are also strong. Canada has strengths, in terms of both ARC and SI scores that are world-class and large outputs by volume (ARC > 1.1, SI > 1.1, output > 1,000 pubs), in Ecology, Evolutionary Biology, Fisheries, Marine Biology & Hydrology, and Forestry. Areas with similarly high impact and specialization, but smaller publication outputs, are Ornithology, Geological & Geomatic Engineering, Oceanography, General Science & Technology, Environmental Science, and Veterinary Science.

Areas for potential strategic consideration are Physiology and Toxicology, which are each strong in SI but weak in ARC; and General Mathematics, the score for which is high in ARC but low in SI. Zoology and Plant Biology & Biotechnology also have higher ARC scores and lower SI, near the thresholds for strategic consideration; they are also fields of central relevance to Evolution & Ecology. [32]

[31] Regarding the significance of the General Science & Technology subfield, see footnote 28 above.

[32] Potential approaches to address these strategic opportunities are discussed in § 2.1.2 above.

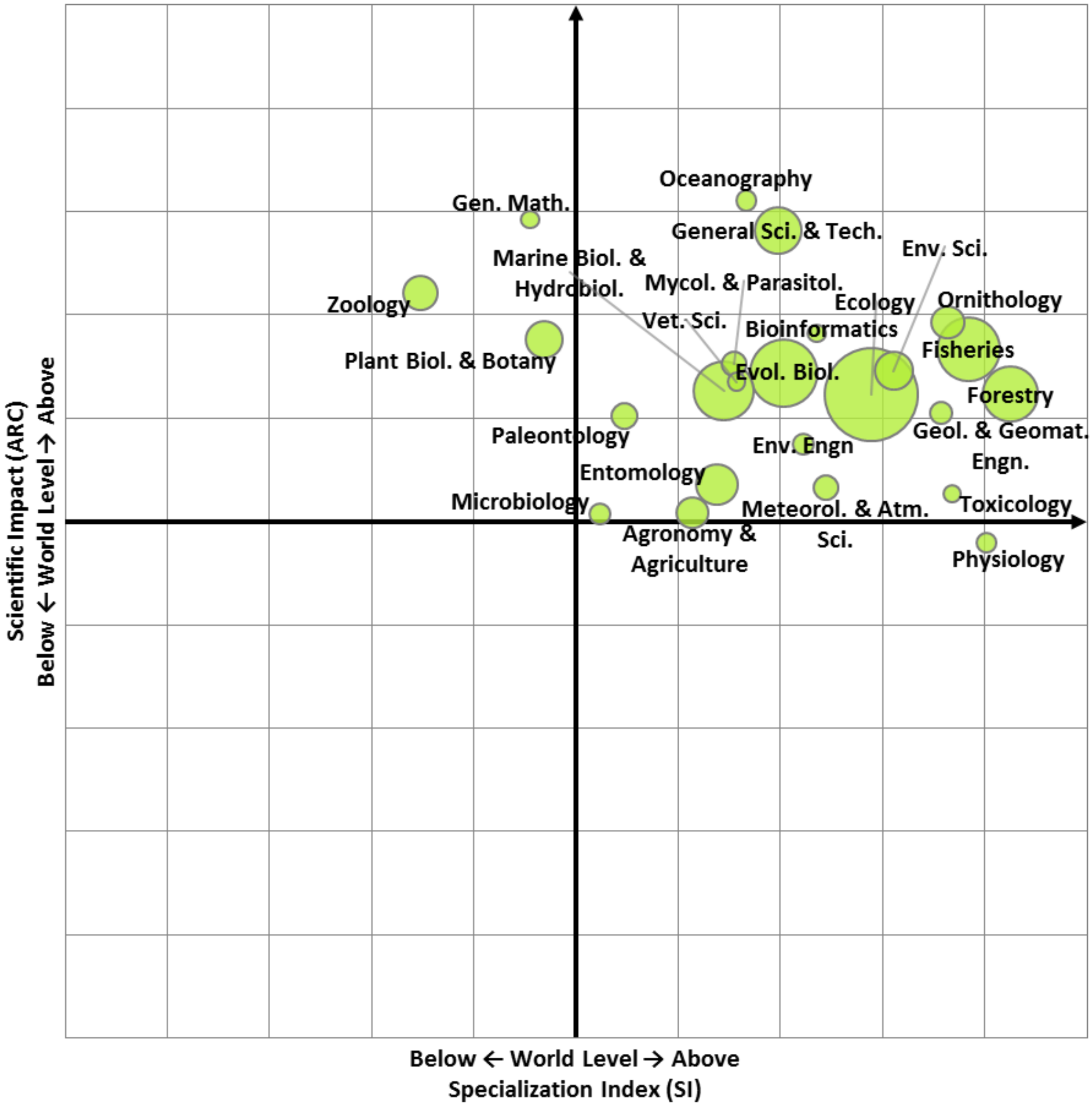

Figure 6 Positional analysis of Canada by subfield within EG1503 (Evolution and Ecology) (2009–2013)

Note: Selection of the 24 subfields in which CA published the most.
Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters)

2.4 EG1504 – Chemistry

2.4.1 Benchmarking Canadian performance relative to other world leaders

In the field of Chemistry, China, the US, and Japan are the nations producing the most research publications. Canada ranks 13th in overall output, placing it near the middle of the group of 27 comparator nations. While production in EG1504 grew in Canada by 12%, that growth is well below the world average of 31% growth, placing Canada 18th among the 27 in this regard, well behind the leaders, China, the Republic of Korea, and Australia. EG1504 is not an area of specialization for Canada, which has a share of publications in this area which is 37% smaller than at the world level, placing 20th out of 27 on the specialization index for Chemistry.

Despite punching below its weight in terms of production, growth and specialization, Canada's publications in Chemistry are very impactful, with Canada placing 10th in ARC, 12th in ARIF, and 11th in HCP, again amongst the 27 benchmark nations. The global leaders in impact in EG1504 are Denmark, Australia, the US, Switzerland and the Netherlands. Canada's inclination to international collaboration for Chemistry publications is below the expected rate (adjusting international collaborations by size of research output), placing 17th out of the 27 comparator countries. Sweden, Belgium, and Austria are the most collaborative nations within EG1504.

Looking at the overall ranking, Canada's composite score ranks in the 16th place, shared with the Netherlands, Belgium, and Italy. The world leaders in this area are China, Republic of Korea, Germany, and the US.

Table IV Scientific performance of a selection of 27 highly active countries in NSE research for EG1504 (Chemistry) (2009–2013)

Country	Pubs. (rank)	GR	Trend	SI	ARC	ARIF	HCP	CI	Composite score
World	**467,946 (N/A)**	**1.31**		**1.00**	**1.00**	**1.00**	**1.00**	**N/A**	**N/A**
China	115,987 (1)	1.64		1.64	1.15	0.92	1.22	0.45	81
Rep. of Korea	22,442 (7)	1.42		1.48	1.05	1.01	1.01	0.69	74
Germany	34,589 (4)	1.19		1.12	1.11	1.20	1.14	1.26	72
United States	75,193 (2)	1.15		0.62	1.38	1.25	1.55	0.98	72
Japan	36,345 (3)	1.10		1.36	0.89	1.00	0.78	0.61	70
Switzerland	6,843 (18)	1.06		0.99	1.32	1.29	1.51	1.28	70
Spain	18,659 (9)	1.15		1.12	1.02	1.19	1.01	1.15	70
Taiwan	11,117 (14)	1.32		1.19	1.02	1.05	0.92	0.45	69
France	22,886 (6)	1.09		1.02	0.95	1.16	0.90	1.35	68
Australia	8,437 (15)	1.37		0.56	1.40	1.24	1.56	1.22	68
United Kingdom	19,463 (8)	1.06		0.61	1.22	1.26	1.30	1.31	66
Denmark	2,493 (33)	1.31		0.62	1.58	1.22	1.61	1.16	66
Portugal	4,194 (25)	1.35		1.08	0.95	1.05	0.93	1.09	66
Sweden	4,842 (22)	1.19		0.67	1.24	1.18	1.30	1.39	65
Netherlands	5,864 (19)	1.03		0.54	1.28	1.34	1.55	1.31	64
Belgium	4,739 (23)	1.25		0.79	1.03	1.20	1.02	1.37	64
Canada	11,514 (13)	1.12		0.63	1.13	1.17	1.10	0.94	64
Italy	14,369 (10)	1.06		0.76	0.95	1.13	0.86	1.11	64
Russia	13,661 (11)	1.11		1.52	0.34	0.52	0.15	0.69	62
Poland	8,277 (16)	1.26		1.13	0.56	0.86	0.32	0.83	62
Israel	2,271 (37)	1.08		0.58	1.16	1.26	1.25	0.93	61
Austria	2,953 (31)	1.12		0.70	1.02	1.10	1.03	1.36	61
Turkey	5,488 (20)	1.35		0.67	0.79	0.84	0.75	0.53	60
Mexico	3,576 (27)	1.16		1.04	0.55	0.89	0.37	0.83	59
Brazil	7,611 (17)	1.22		0.66	0.65	0.89	0.48	0.63	58
Finland	2,564 (32)	1.00		0.65	0.90	1.11	0.80	1.32	58
Norway	1,458 (42)	1.33		0.41	0.87	1.06	0.94	1.19	56

Note: Colouring provides insight on performance relative to world (in WoS), ranging from dark red (below world level) to white (on par with the world level) and dark green (above world level). Note that for pubs and composite scores, colouring is relative to median (white) instead of world; additionally, colouring for CI is relative to expected values (white), which are computed based on the relationship between total publication output and co-publications at the country level. The GR, pub trend and SI were computed using fractional counting. For pub trend, the scale varies across countries. The CI is not accounted for in the composite score.

Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters)

2.4.2 Analysis of Canadian performance within subfields

By contrast to EG1503, Canada's performance in Chemistry produces the country's lowest-ranked results based on the CPI, when comparing to the 27 selected countries. It is therefore expected that, examining the subfields within Chemistry, one will find only very few strengths and comparatively more weaknesses. As mentioned above, Canada actually performs very well in terms of impact in EG1504, with its highest ARC scores in General Chemistry, Materials, and Medical & Biomolecular Chemistry (ARC > 1.45), all of which are well above the world average for impact. Chemical Engineering and Environmental Science are the weakest subfields in this regard (ARC < 0.90), and the only ones to be noticeably lower than the world average.

Regarding specialization, Environmental Science is by far the most specialized subfield of Canadian research in Chemistry (SI = 1.40), and is in fact the only subfield above the world average for its SI score. The lowest specialization scores in EG1503 are in Applied Physics and Materials, which both have SI scores below 0.35. Three subfields have a large output by volume, with a minimum of 1,000 publications each, and those are Organic Chemistry, Energy, and General Chemistry.

In the subfields of Chemistry, Canada has no truly pronounced strengths, with not a single subfield performing above the world level in both ARC and SI. There is, however, one subfield in which Canada's overall output (output = 1,065 pubs) is high and its ARC scores are world-class (ARC = 1.73): General Chemistry.

Three subfields standout as candidates for strategic consideration. Materials has an impact score well above the world level, but is very low in specialization in Canada. Medical & Biomolecular Chemistry, which is deemed to be an important theme for EG1504, is also impactful but low on specialization, near but not across the relevant thresholds. Environmental Science has low impact scores, but is the only subfield of Chemistry in which Canada is specialized above the world level.[33]

[33] Potential approaches to address these strategic opportunities are discussed in § 2.1.2 above.

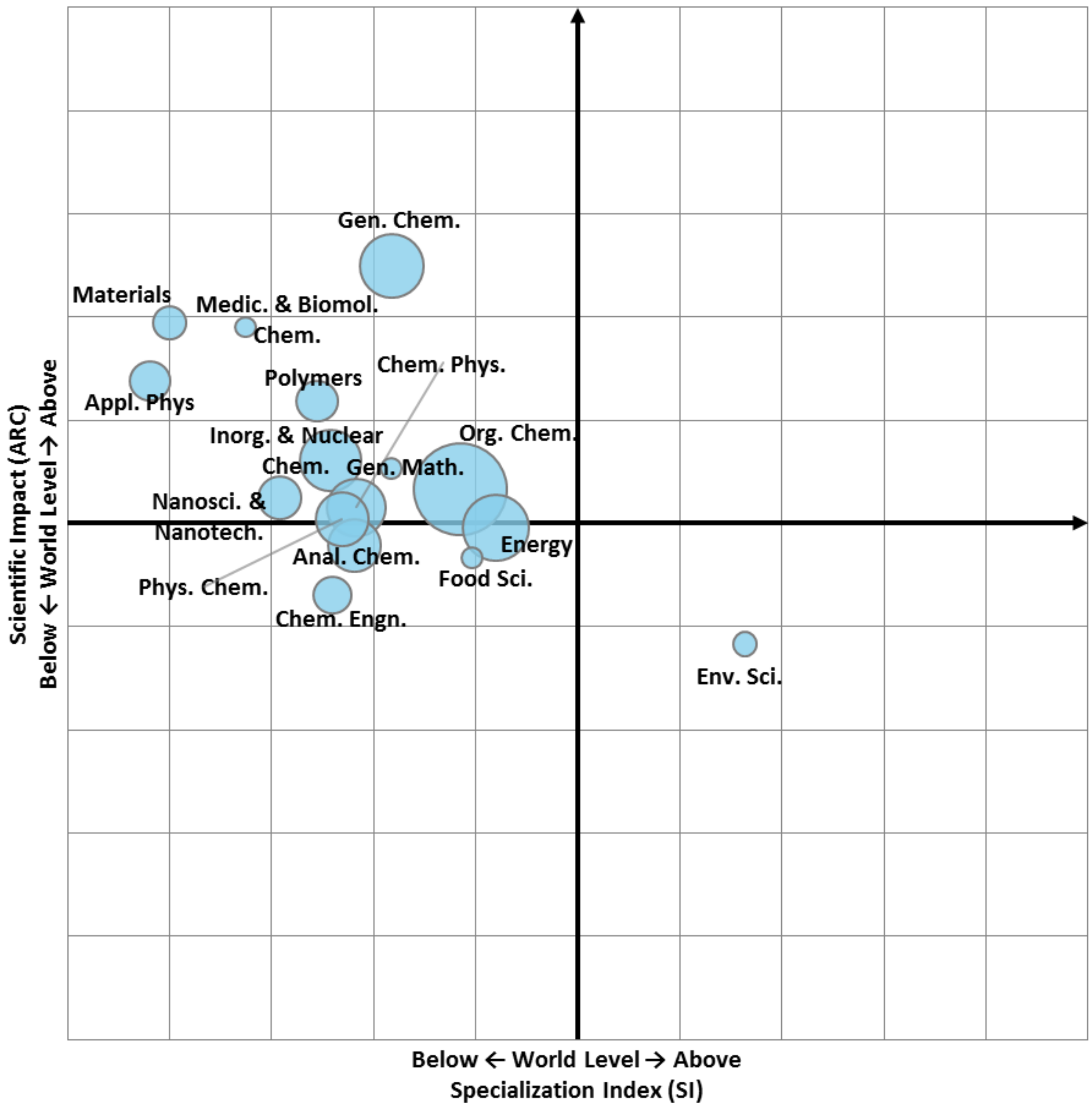

Figure 7 Positional analysis of Canada by subfield within EG1504 (Chemistry) (2009–2013)

Note: Selection of the 16 subfields in which CA published the most.
Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters)

2.5 EG1505 – Physics

2.5.1 Benchmarking Canadian performance relative to other world leaders

Canada's publication output in Physics ranks 11th in the world for its size. The global leaders in this respect are the US, China, and Germany. Looking at the growth of output, Canada's 5% growth is below the world level, clocking in at 24th among the 27 comparator nations. China and Turkey are high-growth nations in this EG. Canada is not specialized in this area, producing a proportion of its total publication output in EG1505 which is 27% smaller than is observed at world level. Russia, Germany, and Japan are the most specialized countries in Physics, with Canada ranking 22nd among the 27.

Much like in Chemistry, the impact of Canadian publications in Physics is good, but to a much greater extent, despite low publication output, growth and specialization. Of the 27 benchmark nations, Canada ranks 6th in ARC, 8th in ARIF, and 5th in HCP. Denmark, Switzerland, the Netherlands, and Austria stand out for their scientific impact. The impact of Swiss publications in Physics is surely influenced by the CERN facility, which is located in Geneva and represents a critical piece of research infrastructure in this EG. The presence of CERN is likely also involved in the international collaborations within EG1505, with Switzerland placing 1st in the world for its tendency for international collaboration. The Netherlands and Belgium are the next countries showing a high propensity for international collaboration. Canada places near the middle of the pack, at 16th.

Turning to the composite score, Canada shares a mid-level rank (12.5) with a large group of nations that includes Italy, Japan, China, Israel, and Russia. Switzerland and Germany share the top rank, followed by the US and then France.

Table V Scientific performance of a selection of 27 highly active countries in NSE research for EG1505 (Physics) (2009–2013)

Country	Pubs. (rank)	GR	Trend	SI	ARC	ARIF	HCP	CI	Composite score
World	**499,187 (N/A)**	**1.18**		**1.00**	**1.00**	**1.00**	**1.00**	**N/A**	**N/A**
Switzerland	15,644 (13)	1.15		1.40	1.57	1.27	1.83	1.29	72
Germany	65,433 (3)	1.10		1.56	1.32	1.19	1.45	1.18	72
United States	133,555 (1)	1.07		0.93	1.37	1.19	1.53	0.89	71
France	41,606 (5)	1.09		1.35	1.28	1.16	1.34	1.21	69
Denmark	5,279 (28)	1.26		0.84	1.60	1.27	1.87	1.17	68
United Kingdom	40,815 (6)	1.04		0.90	1.37	1.18	1.48	1.21	68
Netherlands	12,265 (16)	1.10		0.71	1.55	1.25	1.81	1.25	67
Austria	6,965 (21)	1.09		1.12	1.49	1.28	1.57	1.22	67
Spain	23,993 (9)	1.15		0.96	1.36	1.14	1.41	1.21	67
Italy	32,635 (7)	1.02		1.32	1.20	1.09	1.19	1.13	66
Japan	47,748 (4)	1.03		1.49	1.06	1.03	1.05	0.68	66
China	74,779 (2)	1.54		0.91	1.02	0.92	0.99	0.47	66
Canada	19,431 (11)	1.05		0.73	1.45	1.19	1.54	1.09	66
Israel	6,544 (22)	1.14		1.16	1.34	1.30	1.37	1.01	66
Russia	29,789 (8)	1.15		2.42	0.81	0.83	0.73	0.89	66
Sweden	8,737 (19)	1.19		0.81	1.43	1.14	1.41	1.23	64
Belgium	7,792 (20)	1.24		0.87	1.36	1.13	1.38	1.24	64
Australia	12,977 (14)	1.25		0.61	1.33	1.19	1.39	1.13	64
Portugal	4,978 (30)	1.27		0.79	1.47	1.10	1.30	1.20	63
Finland	5,133 (29)	1.15		0.93	1.35	1.14	1.19	1.16	62
Rep. of Korea	16,889 (12)	1.22		0.86	1.08	1.02	1.01	0.74	62
Poland	12,841 (15)	1.17		1.16	1.00	0.97	0.89	1.02	61
Taiwan	10,428 (18)	1.15		0.81	1.02	1.07	0.90	0.75	59
Mexico	5,953 (25)	1.15		1.21	0.92	0.93	0.86	1.00	59
Brazil	11,265 (17)	1.18		0.70	0.98	1.01	0.92	0.84	59
Norway	2,514 (39)	1.27		0.41	1.30	1.14	1.28	1.19	58
Turkey	5,375 (27)	1.51		0.48	0.99	0.90	0.88	0.70	56

Note: Colouring provides insight on performance relative to world (in WoS), ranging from dark red (below world level) to white (on par with the world level) and dark green (above world level). Note that for pubs and composite scores, colouring is relative to median (white) instead of world; additionally, colouring for CI is relative to expected values (white), which are computed based on the relationship between total publication output and co-publications at the country level. The GR, pub trend and SI were computed using fractional counting. For pub trend, the scale varies across countries. The CI is not accounted for in the composite score.

Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters)

2.5.2 Analysis of Canadian performance within subfields

In EG1505, Optoelectronics & Photonics, General Physics, Astronomy & Astrophysics, and Materials are the subfields in which Canada's scientific impact is highest (ARC > 1.70), with most of the other subfields being near or above the world level. Biomedical Engineering and Organic Chemistry lag behind in this respect (ARC < 0.85), as the least impactful subfields in this EG, and the only two that are noticeably below the world level in ARC.

Canada is most specialized in Mathematical Physics and in Biomedical Engineering (SI > 1.30), despite a relatively small output of 306 and 134 articles, respectively. Given that Canada is a specialist in these areas with such a small number of publications, one can conclude that these two subfields are niche areas on the world stage. In the other subfields of EG1505, Canada's specialization index is near or below the world average. Its lowest specialization scores are in Materials and Applied Physics, which are both well below the world level (i.e., SI < 0.45). Canada's largest outputs, by volume, are in Astronomy & Astrophysics, Nuclear & Particle Physics, General Physics, Fluids & Plasmas, and Applied Physics. Canada produces at least 1,000 articles in each of these subfields.

Canada's most pronounced strength in EG1505, in terms of both impact and specialization, is in Mathematical Physics (ARC = 1.28, SI = 1.33). The country also has secondary strengths, meaning high impact scores and large output by volume, in Astronomy & Astrophysics, Nuclear & Particle Physics, General Physics, Fluids & Plasmas, and Applied Physics; that is to say, Canada has high impact scores (ARC > 1.1) in all of the subfields of Physics in which it produces a notably large number of articles (output > 1,000 pubs).

Areas for strategic consideration include Biomedical Engineering, which is an area of specialization but with low impact. Materials has high impact scores but low specialization; Optoelectronics & Photonics and General Mathematics are also near to these same thresholds, while being thematically very relevant.[34]

[34] Potential approaches to address these strategic opportunities are discussed in § 2.1.2 above.

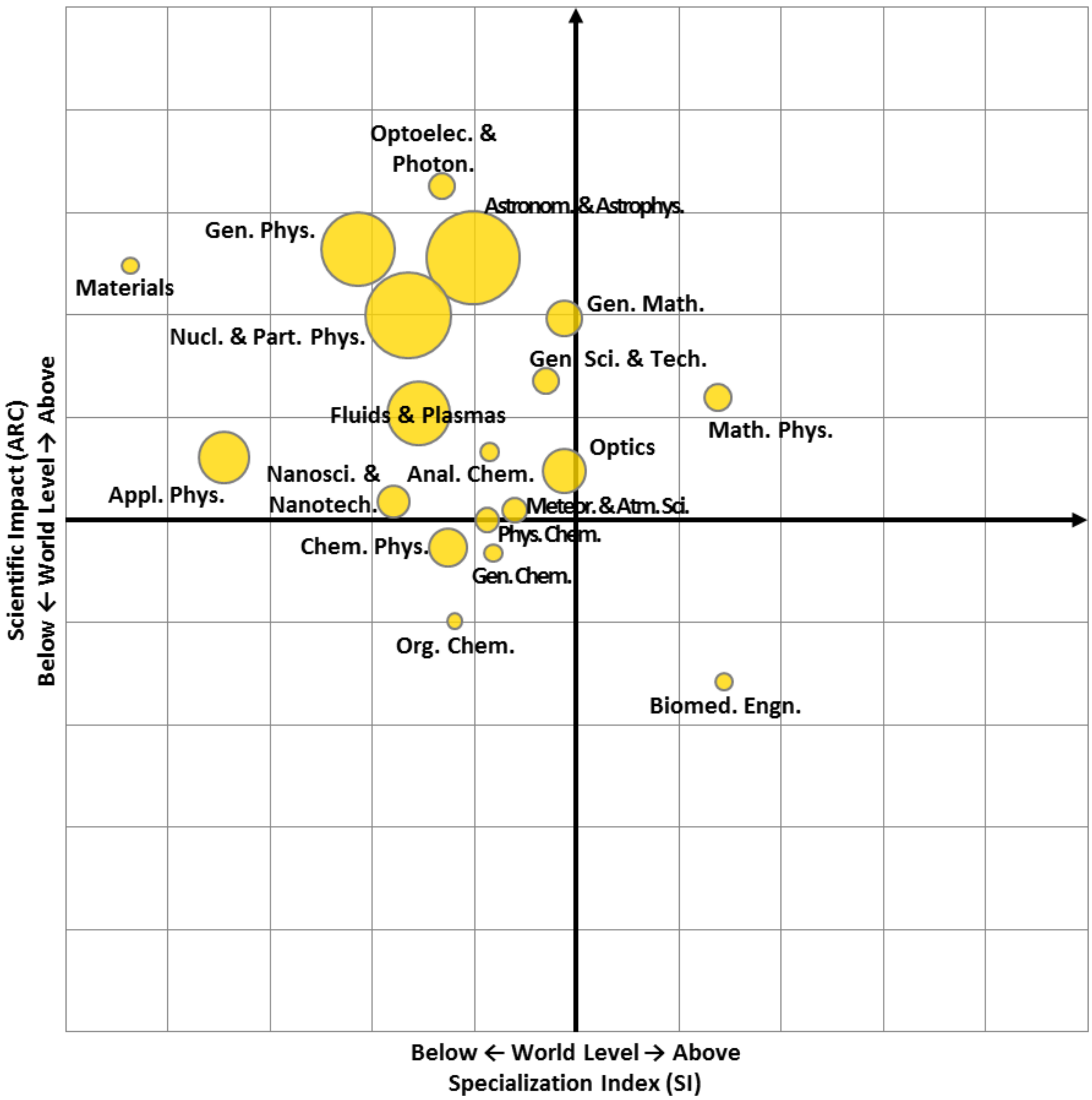

Figure 8 Positional analysis of Canada by subfield within EG1505 (Physics) (2009–2013)

Note: Selection of the 19 subfields in which CA published the most.
Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters)

2.6 EG1506 – Geoscience

2.6.1 Benchmarking Canadian performance relative to other world leaders

Canada's publication output by volume in Geoscience ranks 6th worldwide. The US stands out for its impressive number of publications, followed by China, the UK, and Germany. The 11% growth rate of Canadian research in EG1506 ranks 21st against the 27 benchmark nations, with China, the Republic of Korea, and Sweden taking the top spots in terms of growth. Relative to the rest of the world, a large proportion of Canadian publications are in Geoscience, with Canada ranking 5th worldwide in terms of specialization. Canada's SI score of 1.32 ranks behind only Norway, Russia, Australia, and Switzerland.

Canada ranks near the median of the 27 comparators with its impact scores: 15th for ARC and ARIF, and 14th for HCP. Switzerland, the Netherlands, Denmark, and the UK are leaders in scientific impact in EG1506. Looking at propensity for international collaboration, Canada ranks 13th out of the 27. The global leaders are Switzerland, the Netherlands, Germany, France, and Austria. Switzerland and the Netherlands are notable for leading in both impact and collaboration.

Overall, according to the CPI, Canada shares the 10.5th rank with Sweden, behind the global leaders Switzerland, Norway and Australia.

Table VI Scientific performance of a selection of 27 highly active countries in NSE research for EG1506 (Geoscience) (2009–2013)

Country	Pubs. (rank)	GR	Trend	SI	ARC	ARIF	HCP	CI	Composite score
World	**284,684 (N/A)**	**1.23**		**1.00**	**1.00**	**1.00**	**1.00**	**N/A**	**N/A**
Switzerland	7,452 (14)	1.19		1.36	1.76	1.26	2.04	1.35	80
Norway	5,314 (16)	1.21		2.10	1.29	1.17	1.53	1.23	79
Australia	15,018 (7)	1.25		1.50	1.38	1.19	1.60	1.10	79
United Kingdom	24,464 (3)	1.15		1.06	1.47	1.26	1.70	1.25	77
United States	79,238 (1)	1.13		0.99	1.31	1.20	1.50	0.94	77
Denmark	3,819 (23)	1.32		1.20	1.57	1.29	1.89	1.22	77
Netherlands	7,665 (13)	1.11		0.93	1.63	1.27	2.00	1.29	75
France	19,961 (5)	1.10		1.24	1.28	1.20	1.42	1.28	75
Germany	23,966 (4)	1.19		1.02	1.33	1.17	1.54	1.29	75
Canada	17,213 (6)	1.11		1.32	1.15	1.15	1.25	1.06	74
Sweden	5,296 (17)	1.34		1.01	1.40	1.21	1.67	1.25	74
China	45,480 (2)	1.68		0.97	0.98	0.85	1.04	0.75	73
Finland	2,955 (27)	1.29		1.16	1.39	1.16	1.55	1.06	72
Italy	14,678 (8)	1.19		1.19	1.14	1.06	1.14	0.96	72
Austria	3,284 (26)	1.22		1.04	1.36	1.12	1.59	1.28	71
Spain	11,738 (10)	1.26		1.04	1.11	1.15	1.09	1.02	71
Belgium	3,916 (21)	1.15		0.88	1.31	1.19	1.48	1.26	69
Portugal	2,951 (28)	1.32		1.12	0.99	1.02	0.97	1.01	67
Japan	14,188 (9)	1.07		0.74	0.97	0.98	0.89	0.90	64
Russia	9,686 (12)	0.97		1.65	0.46	0.52	0.35	0.63	63
Israel	1,755 (34)	1.08		0.63	1.23	1.26	1.15	0.93	63
Brazil	6,987 (15)	1.30		0.91	0.70	0.82	0.59	0.67	62
Mexico	2,824 (29)	1.15		1.17	0.72	0.86	0.59	0.87	62
Taiwan	4,058 (19)	1.23		0.59	0.95	1.00	0.88	0.81	61
Poland	3,826 (22)	1.27		0.82	0.68	0.74	0.56	0.65	59
Turkey	4,036 (20)	1.07		0.77	0.76	0.81	0.67	0.52	59
Rep. of Korea	4,779 (18)	1.35		0.44	0.86	0.94	0.69	0.83	59

Note: Colouring provides insight on performance relative to world (in WoS), ranging from dark red (below world level) to white (on par with the world level) and dark green (above world level). Note that for pubs and composite scores, colouring is relative to median (white) instead of world; additionally, colouring for CI is relative to expected values (white), which are computed based on the relationship between total publication output and co-publications at the country level. The GR, pub trend and SI were computed using fractional counting. For pub trend, the scale varies across countries. The CI is not accounted for in the composite score.

Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters)

2.6.2 Analysis of Canadian performance within subfields

Civil Engineering, Strategies, Defence & Security Standardization, and Astronomy & Astrophysics are the subfields of least impact for Canada in EG1506 (ARC < 0.85), as well as being the only subfields noticeably below the global average for impact. Beyond those exceptions, however, Canada's impact in the subfields of Geoscience is at or above world average. Especially impactful are Forestry, Oceanography, and General Science & Technology (ARC > 1.40).[35]

In terms of specialization, Canada focuses heavily on Fisheries, Forestry, Ecology, Geology, and Civil Engineering (SI > 2.35), with most of the remaining subfields at or above the world average. The only exceptions are Astronomy & Astrophysics and Strategic Defence & Security Standards (SI < 0.95), which fall below the world average; Oceanography and Analytic Chemistry are also areas of EG1506 with relatively low SI scores for Canada (SI < 1.05) compared to the other subfields within this EG. Four subfields, Meteorology & Atmospheric Science, Geochemistry & Geophysics, Environmental Engineering, and Geology, are large producers in this EG, each contributing more than 1,000 articles.

Taking both impact and specialization into account (ARC > 1.1, SI > 1.1), Canada's strengths in EG1506 lie in Fisheries, Forestry, Marine Biology & Hydrobiology, Environmental Science, and General Science & Technology.

Areas to potentially consider for strategic positioning are Civil Engineering, in which Canada is highly specialized but has low ARC scores, and Oceanography, in which Canada's impact is high but in which it is the least specialized among the subfields of EG1506. Canada has high SI scores and low ARC in several other subfields, and while they only approach the mathematical thresholds set for selection, their thematic relevance to EG1506 is very high; these subfields are Ecology and Geological & Geomatic Engineering. The same is also true of Geology and of Environmental Engineering, which are also subfields of large output for Canada. [36]

[35] Regarding the significance of the General Science & Technology subfield, see footnote 28 above.

[36] Potential approaches to address these strategic opportunities are discussed in § 2.1.2 above.

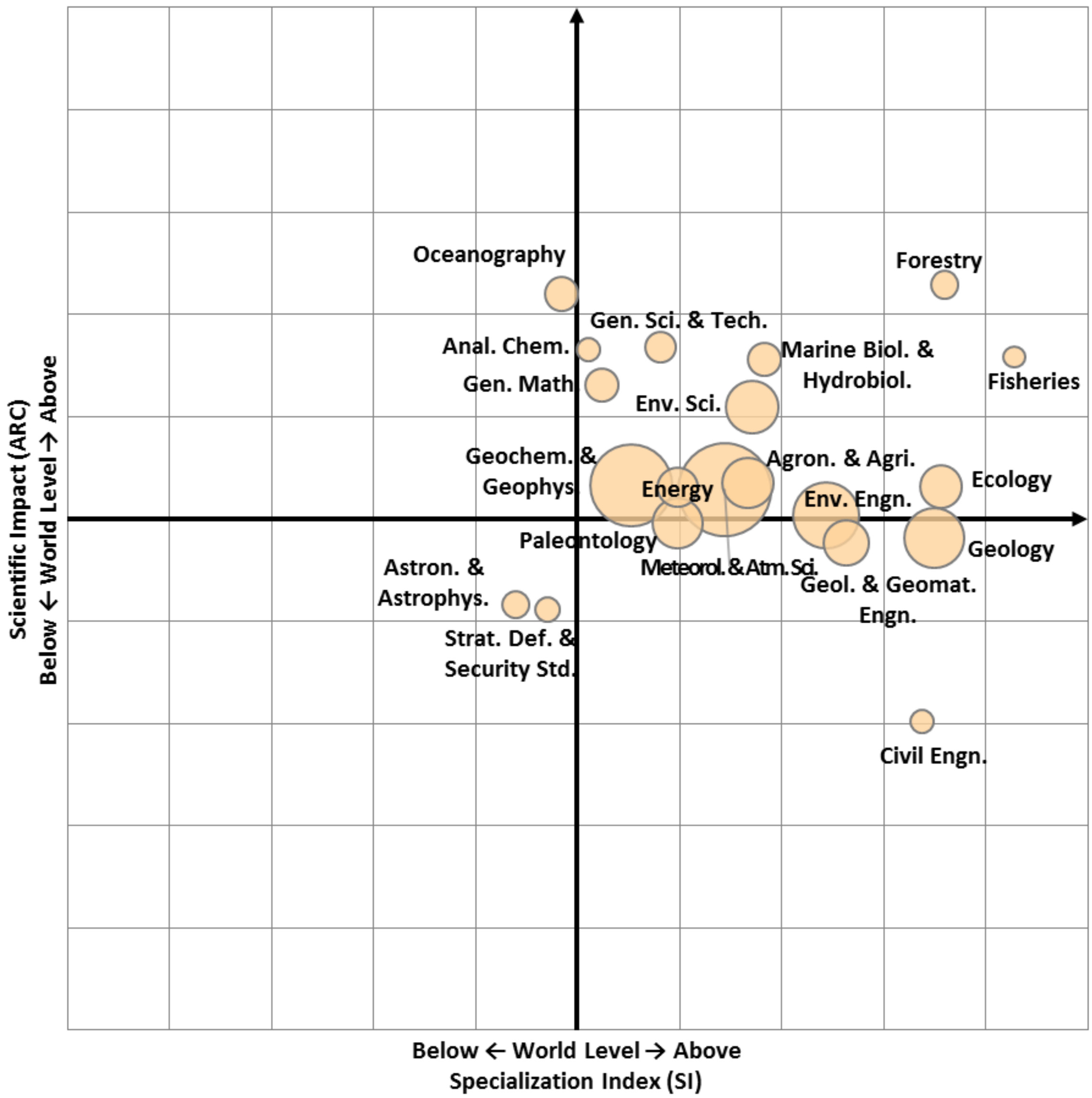

Figure 9 Positional analysis of Canada by subfield within EG1506 (Geoscience) (2009–2013)

Note: Selection of the 20 subfields in which CA published the most.

Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters)

2.7 EG1507 – Computer science

2.7.1 Benchmarking Canadian performance relative to other world leaders

In Computer Science, China, the US and Denmark lead in number of publications, with Canada ranking 10th among the 27 benchmark nations. In terms of growth of production, Brazil, Turkey, Mexico and Russia lead the way. Canada is well below the global average in growth, seeing its publication output shrink by 12% from 2009–2010 to 2012–2013. This change in output size places Canada 19th out of the 27 nations for growth. Canada is not particularly specialized in EG1507, devoting a similar share of its production to this area (SI = 0.97) as is observed at the global level. Taiwan, Portugal, Austria, China, and Spain are the top specialists worldwide.

While its growth and specialization numbers may not be overly impressive, Canada's publications are remarkably impactful, placing 9th among the 27 benchmark nations in ARC, 4th in ARIF, and 8th in HCP. The UK, Switzerland, the US and Belgium lead in terms of scientific impact in Computer Science. International collaboration in EG1507 is very frequent for Canadian authors, with only Switzerland, the US and France having a stronger tendency to collaborate (normalizing for overall size of national publication output).

Ranking by scores on the composite index, Taiwan, China, Spain, and the US occupy the top four positions. Canada shares the subsequent spot with the UK and Switzerland, which are each ranked 6th.

Table VII Scientific performance of a selection of 27 highly active countries in NSE research for EG1507 (Computer Science) (2009–2013)

Country	Pubs. (rank)	GR	Trend	SI	ARC	ARIF	HCP	CI	Composite score
World	**353,945 (N/A)**	**1.01**		**1.00**	**1.00**	**1.00**	**1.00**	**N/A**	**N/A**
Taiwan	12,633 (12)	1.04		1.87	1.22	1.21	1.33	0.40	81
China	76,107 (1)	1.13		1.44	1.00	0.92	0.97	0.88	78
Spain	14,799 (6)	0.95		1.34	1.38	1.23	1.28	0.92	78
United States	65,661 (2)	0.90		0.76	1.43	1.36	1.54	1.15	77
United Kingdom	16,943 (4)	0.87		0.78	1.51	1.29	1.50	1.42	74
Switzerland	4,515 (19)	0.93		0.97	1.44	1.34	1.59	1.51	74
Canada	12,963 (10)	0.88		0.97	1.28	1.31	1.38	1.34	74
Israel	3,302 (27)	0.79		1.16	1.27	1.60	1.42	1.18	73
Turkey	4,748 (18)	1.20		0.78	1.31	1.24	1.51	0.60	73
Australia	8,729 (13)	0.96		0.86	1.35	1.26	1.39	1.33	73
Portugal	4,008 (23)	1.17		1.62	0.90	0.91	0.92	1.09	73
Belgium	3,439 (25)	0.87		0.92	1.61	1.27	1.48	1.21	73
France	14,831 (5)	0.90		1.01	1.12	1.19	1.12	1.36	72
Italy	12,957 (11)	0.90		1.02	1.10	1.14	1.12	1.04	72
Rep. of Korea	13,150 (8)	1.13		1.19	0.87	0.97	0.80	0.71	71
Austria	3,464 (24)	0.93		1.44	1.02	1.04	0.97	1.25	71
Germany	20,236 (3)	0.80		0.99	1.03	1.00	1.06	1.30	70
Netherlands	5,641 (16)	0.81		0.81	1.36	1.20	1.35	1.25	70
Finland	2,637 (29)	0.84		1.17	1.10	1.07	1.22	1.09	69
Sweden	3,350 (26)	1.13		0.79	1.02	1.14	1.11	1.19	68
Poland	5,230 (17)	1.17		1.07	0.81	0.80	0.83	0.68	67
Brazil	5,829 (15)	1.27		0.70	0.77	0.97	0.72	0.77	65
Norway	1,933 (34)	0.80		0.86	0.99	1.09	1.18	1.31	64
Denmark	1,826 (35)	0.88		0.68	1.09	1.11	1.22	1.26	64
Mexico	1,978 (32)	1.18		0.82	0.74	0.95	0.64	0.92	63
Japan	13,717 (7)	0.88		0.70	0.64	0.86	0.62	0.79	62
Russia	2,051 (31)	1.18		0.31	0.58	0.71	0.49	0.66	54

Note: Colouring provides insight on performance relative to world (in WoS), ranging from dark red (below world level) to white (on par with the world level) and dark green (above world level). Note that for pubs and composite scores, colouring is relative to median (white) instead of world; additionally, colouring for CI is relative to expected values (white), which are computed based on the relationship between total publication output and co-publications at the country level. The GR, pub trend and SI were computed using fractional counting. For pub trend, the scale varies across countries. The CI is not accounted for in the composite score.

Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters)

2.7.2 Analysis of Canadian performance within subfields

Canada's impact in Computer Science is near or above the world average in most subfields, with Geological & Geomatic Engineering being the only exception (ARC = 0.53), falling notably below the world average. Two subfields are especially impactful, and these are Electrical & Electronic Engineering and General Mathematics (ARC > 1.50).

The subfield in which Canada is most specialized is Medical Informatics (SI = 1.77); Numerical & Computational Mathematics, Industrial Engineering & Automation, and General Mathematics are subfields in this EG in which Canada specializes the least (SI < 0.85), falling definitively below the world average of specialization. Large outputs by volume are to be found in Artificial Intelligence & Image Processing, and in General Mathematics, with each contributing over 2,000 papers.

Looking at areas of strength in both impact and specialization (ARC > 1.1, SI > 1.1), Medical Informatics, Computational Theory & Mathematics, and Networking & Telecommunications are the best-performing subfields in Canada in EG1507. Canada also has secondary strengths, meaning high impact scores combined with a large output by volume (ARC > 1.1, output > 1,000 pubs), in Artificial Intelligence & Image Processing as well as in General Mathematics.

General Mathematics is an interesting case: its impact is already strong, as reflected by its high ARC scores (ARC = 1.51); however, it has low SI scores (SI = 0.81) in spite of being one of the largest producers by volume within EG1507 (output = 2,079 pubs). As a result, General Mathematics is in a somewhat different situation from other areas for strategic consideration that have been discussed so far in this report—additional investment of resources in this subfield would likely lead to increased output, and thus a higher SI score; but because the subfield is already so large within this EG, the amount of additional investment needed to substantially increase specialization would be proportionately larger as well.

Other subfields warranting consideration for strategic focus are Electrical & Electronic Engineering, which is high-impact but not an area of specialization for Canada in EG1507; and Operations Research and Software Engineering, both of which are areas of specialization but low impact. These three areas fall slightly short of the thresholds established for highlighting strategic subfields, but they are among the thematically central subfields within Computer Science, and therefore warrant consideration.

Figure 10 Positional analysis of Canada by subfield within EG1507 (Computer Science) (2009–2013)

Note: Selection of the 15 subfields in which CA published the most.
Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters)

2.8 EG1508 – Mathematics and Statistics

2.8.1 Benchmarking Canadian performance relative to other world leaders

Canada ranks 9th among the 27 selected comparators for the size of its publication output in EG1508, an area of research in which the US, China and France are the largest producers. Mathematics & Statistics is a field that shrank slightly in Canada, with a 2% decrease in publication output between 2009–2010 and 2012–2013; the country is well below the average international growth of 15% in this area, placing 24th out of 27 benchmark nations. The Republic of Korea, China and Turkey lead the way in growth. That being said, the proportion of Canadian publications in this area relative to all its publications is near the world average (SI = 0.91), and Canada places 14th out of 27 on the specialization index. The world specialists in EG1508 are Russia, France and Israel.

Finland, the US, Israel, Italy and France stand out as the most impactful, with Canada placing near the middle of the pack of 27: 12th in ARC, and 14th in both ARIF and HCP. Canada's propensity for international collaboration in EG1508 is very high, placing 3rd overall behind only Australia and Switzerland.

Following the ranking based on the composite index, Canada places 13th out of 27. The global leader in this area of research is France, followed by China, the US and Italy, which are all equal in rank.

Table VIII Scientific performance of a selection of 27 highly active countries in NSE research for EG1508 (Mathematics and Statistics) (2009–2013)

Country	Pubs. (rank)	GR	Trend	SI	ARC	ARIF	HCP	CI	Composite score
World	**203,919 (N/A)**	**1.15**		**1.00**	**1.00**	**1.00**	**1.00**	**N/A**	**N/A**
France	16,308 (3)	1.04		1.70	1.19	1.39	1.28	1.18	73
China	40,012 (2)	1.36		1.25	1.07	0.76	0.96	0.56	70
United States	43,708 (1)	1.02		0.78	1.21	1.29	1.28	1.03	70
Italy	10,401 (6)	1.09		1.25	1.30	1.20	1.29	1.05	70
Spain	8,503 (7)	1.09		1.12	1.25	1.18	1.19	1.15	68
Israel	2,790 (20)	0.98		1.50	1.21	1.43	1.17	1.17	68
Finland	1,220 (38.5)	1.00		0.77	2.15	1.36	1.49	1.12	68
Germany	13,575 (4)	1.10		0.96	1.14	1.23	1.11	1.22	68
Poland	4,482 (14)	1.27		1.37	1.06	1.09	1.02	0.84	67
Portugal	2,273 (24)	1.15		1.33	1.16	1.10	1.27	1.10	66
United Kingdom	11,205 (5)	1.10		0.77	1.10	1.17	1.18	1.29	66
Austria	2,250 (26)	1.16		1.31	1.22	1.10	1.09	1.22	66
Canada	8,288 (9)	0.98		0.91	1.13	1.15	1.16	1.30	65
Switzerland	2,658 (21)	1.24		0.83	0.99	1.20	1.22	1.34	64
Russia	7,275 (10)	1.04		1.79	0.68	0.78	0.73	0.72	64
Japan	8,387 (8)	0.99		0.68	1.11	1.24	1.07	0.72	64
Rep. of Korea	4,797 (13)	1.37		0.65	1.10	0.96	1.07	0.93	63
Turkey	4,316 (15)	1.33		1.14	1.01	0.66	0.87	0.66	63
Brazil	4,149 (16)	1.29		0.74	0.96	1.12	1.01	0.92	63
Sweden	1,996 (28)	1.04		0.68	1.18	1.28	1.16	1.18	62
Australia	4,002 (17)	1.14		0.55	1.14	1.00	1.19	1.34	62
Belgium	2,486 (22)	0.90		0.98	1.06	1.05	1.14	1.27	61
Norway	1,174 (41)	1.04		0.78	1.08	1.18	1.18	1.16	60
Denmark	1,002 (43)	1.20		0.53	1.05	1.17	1.21	1.26	59
Taiwan	3,400 (18)	1.01		0.74	0.97	0.82	0.93	0.80	59
Mexico	1,793 (30)	1.22		1.10	0.62	0.91	0.61	1.02	58
Netherlands	2,403 (23)	0.90		0.50	0.78	1.00	0.97	1.28	55

Note: Colouring provides insight on performance relative to world (in WoS), ranging from dark red (below world level) to white (on par with the world level) and dark green (above world level). Note that for pubs and composite scores, colouring is relative to median (white) instead of world; additionally, colouring for CI is relative to expected values (white), which are computed based on the relationship between total publication output and co-publications at the country level. The GR, pub trend and SI were computed using fractional counting. For pub trend, the scale varies across countries. The CI is not accounted for in the composite score.

Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters)

2.8.2 Analysis of Canadian performance within subfields

Nuclear & Particle Physics and Artificial Intelligence & Image Processing are the subfields of EG1508 that lead the way in Canada in terms of impact (ARC > 1.35), scoring well above the world average; most of the other subfields are at or above world average. The weakest subfields for Canada in this EG, which are also the only two to fall noticeably below the world average, are Networking & Telecommunications and Mathematical Physics (ARC < 0.80).

Canada specializes heavily in Statistics & Probability, and Computational Theory & Mathematics (SI > 1.65), scoring highly at the world level; Applied Mathematics is the only notably weaker subfield in terms of specialization, with an SI of 0.43. Most of the other subfields in this EG are clustered around and below the world level, which is consistent with Canada's overall SI of 0.91 for this EG as a whole. Large outputs in the subfields of EG1508, with over 1,000 publications each, are found in General Mathematics and in Statistics & Probability.

Looking at strengths within Mathematics & Statistics, Statistics & Probability is an area of incredible strength for Canada, with a good ARC score (ARC = 1.11), a very high SI score (SI = 1.71), and a large output by volume (output = 1,349 pubs). The subfield of General Mathematics also has high impact (ARC = 1.17) and a high output (output = 2,960 pubs), though it does not have a notably high SI score (SI = 0.89).

While no areas stand out for strategic consideration in EG1508 based on the thresholds established—that is to say, no subfield is both more than one standard deviation higher than the mean in impact as well as below one standard deviation under the mean in specialization (or vice versa)—there are three subfields that approach these thresholds that are also highly relevant subfields to this EG. Those subfields are Computational Theory & Mathematics, which is quite specialized but the impact of which is only a little bit low; and Nuclear & Particle Physics and Artificial Intelligence & Image Processing, both of which have high impact, but are somewhat low on their specialization scores. [37]

[37] Potential approaches to address these strategic opportunities are discussed in § 2.1.2 above.

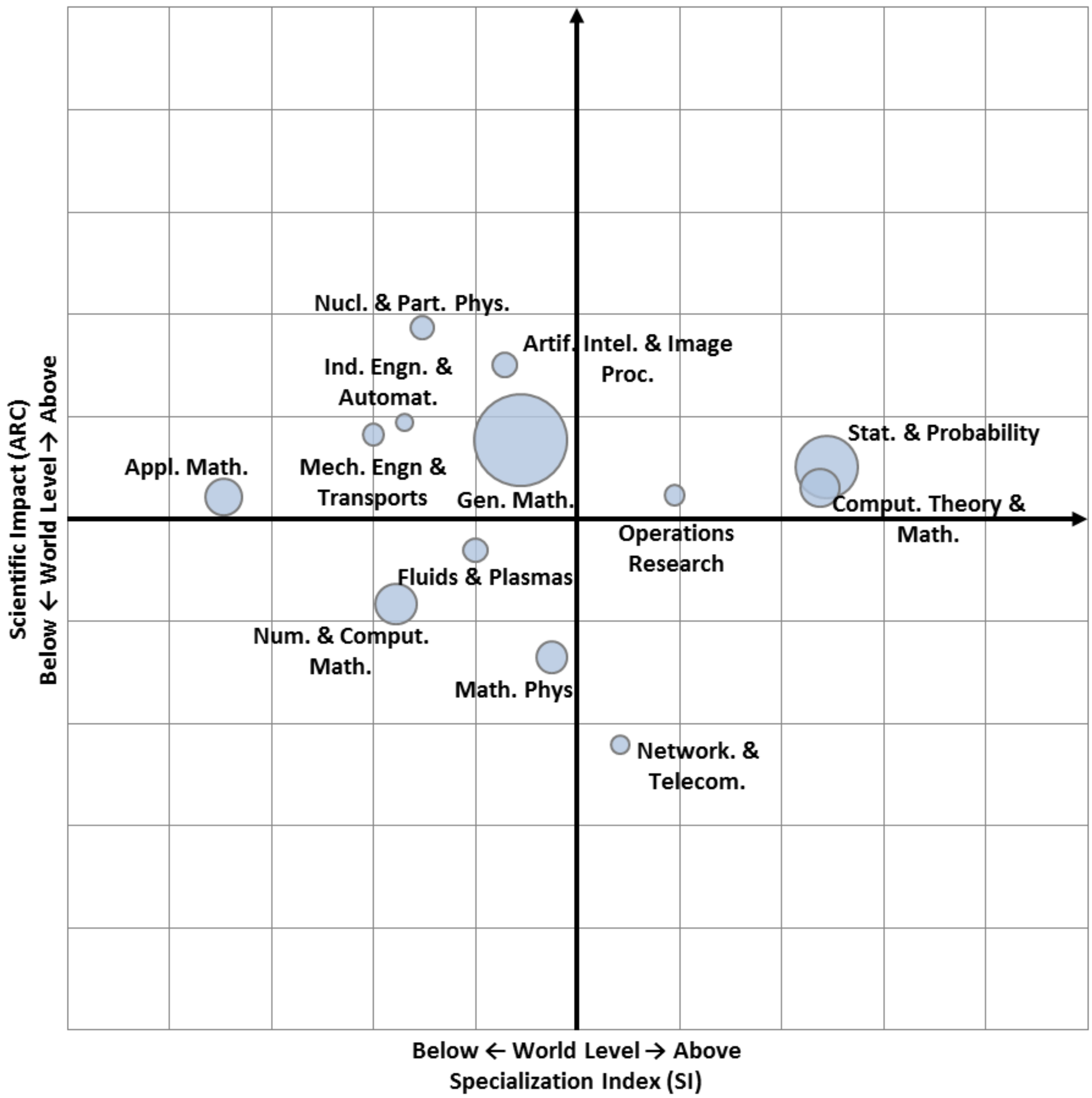

Figure 11 Positional analysis of Canada by subfield within EG1508 (Mathematics and Statistics) (2009–2013)

Note: Selection of the 13 subfields in which CA published the most.
Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters)

2.9 EG1509 – Civil, Industrial and Systems engineering

2.9.1 Benchmarking Canadian performance relative to other world leaders

In Civil, Industrial & Systems Engineering, China and the US produce considerably more publications than any other country. While Canada ranks 4th in the world for its output size, it produces less than one third of the papers published by the US. In terms of growth in this field, China and Portugal lead in terms of increasing their production from 2009–2010 to 2012–2013. Canada's 8% decrease in output over that same period is well below the world average of 19% growth, ranking 26th out of 27 selected benchmark nations. However, Canada is still a world specialist in this area, producing 18% more of its total papers in EG1509 than expected based on the world average. This degree of specialization places Canada in 8th position among the selected countries; Turkey, Portugal and Taiwan lead the way in specialization in this area of research.

The impact of Canadian publications in this field is near the global average, with Canada placing 13th in ARC, and 14th in ARIF and HPC among the 27 comparators. The standout leaders in scientific impact are Switzerland, Denmark, Finland, Australia, Spain and Belgium. Regarding the tendency towards international collaboration, Canada places among the global leaders, ranking 6th behind the UK, the Netherlands, Switzerland, France and Australia.

The composite performance index ranks Canada in 11.5th place, tied with the US. The top-ranked countries are China, Turkey and Portugal.

Table IX Scientific performance of a selection of 27 highly active countries in NSE research for EG1509 (Civil, Industrial and Systems Engineering) (2009–2013)

Country	Pubs. (rank)	GR	Trend	SI	ARC	ARIF	HCP	CI	Composite score
World	**98,204 (N/A)**	**1.19**		**1.00**	**1.00**	**1.00**	**1.00**	**N/A**	**N/A**
China	22,133 (1)	1.53		1.45	1.03	0.93	1.10	1.03	78
Turkey	3,625 (11)	1.04		2.16	1.18	0.99	1.33	0.56	76
Portugal	1,445 (20)	1.59		1.96	1.12	1.10	1.06	0.93	75
Australia	3,683 (8)	1.25		1.21	1.28	1.13	1.35	1.38	74
Spain	4,091 (6)	1.20		1.29	1.26	1.17	1.26	0.92	74
Taiwan	3,399 (14)	0.94		1.73	1.24	1.16	1.26	0.59	73
Switzerland	1,114 (23)	1.04		0.77	1.53	1.18	2.00	1.43	71
Denmark	653 (31)	1.28		0.77	1.51	1.20	1.87	1.22	71
United Kingdom	5,423 (3)	1.19		0.84	1.18	1.10	1.27	1.47	71
Italy	4,416 (5)	1.21		1.23	0.98	1.06	0.94	0.91	70
Canada	4,697 (4)	0.92		1.18	1.08	1.09	1.09	1.36	69
United States	15,931 (2)	0.99		0.61	1.08	1.13	1.10	1.33	69
Belgium	1,150 (22)	1.23		1.00	1.14	1.16	1.28	1.34	68
France	3,670 (10)	1.13		0.80	1.08	1.15	0.99	1.43	67
Netherlands	1,957 (16)	1.02		0.90	1.14	1.08	1.26	1.43	67
Rep. of Korea	3,430 (13)	1.11		1.05	0.86	1.01	0.80	0.93	66
Norway	644 (32)	1.26		0.92	1.20	1.07	1.04	1.31	65
Mexico	801 (26)	1.27		1.11	0.75	0.95	0.85	0.98	63
Poland	1,462 (19)	1.31		1.10	0.77	0.71	0.69	0.33	63
Germany	3,100 (15)	1.01		0.49	1.03	0.97	1.14	1.27	63
Finland	498 (39)	0.90		0.76	1.34	1.16	1.14	0.86	62
Sweden	916 (25)	1.13		0.72	1.00	1.16	0.74	1.06	61
Japan	3,466 (12)	0.94		0.57	0.91	0.92	0.74	1.18	60
Brazil	1,864 (17)	1.14		0.76	0.69	0.89	0.63	0.77	60
Austria	603 (33)	1.07		0.81	0.87	0.95	0.84	1.10	59
Israel	655 (30)	1.01		0.78	0.81	1.15	0.54	1.09	58
Russia	446 (43)	0.97		0.23	0.48	0.52	0.29	0.74	45

Note: Colouring provides insight on performance relative to world (in WoS), ranging from dark red (below world level) to white (on par with the world level) and dark green (above world level). Note that for pubs and composite scores, colouring is relative to median (white) instead of world; additionally, colouring for CI is relative to expected values (white), which are computed based on the relationship between total publication output and co-publications at the country level. The GR, pub trend and SI were computed using fractional counting. For pub trend, the scale varies across countries. The CI is not accounted for in the composite score.

Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters)

2.9.2 Analysis of Canadian performance within subfields

In EG1509, Canada's impact is above world average in several subfields, with Environmental Science being the most notably impactful (ARC = 1.45). Canada's ARC scores are comparatively low, by contrast, in Strategic Defence & Security Standards research, as well as in Geochemistry & Geophysics (ARC < 0.80); these two subfields both place below the world average.

Geological & Geomatic Engineering is the subfield of greatest specialization for Canada (SI = 2.02), within this EG, sitting well above the world level. By contrast, the subfields in which Canada specializes the least are General Mathematics, which is just below the world average (SI = 0.85), and Energy, which is much lower still (SI = 0.53). Whereas each of the other EGs produced between 200,000 and 1,000,000 total publications worldwide, EG1509 is much smaller, having only contributed just under 100,000 publications worldwide over the same time frame. The threshold for considering individual subfields as having a large output must be adjusted accordingly. In Canada, three subfields were considered as having high production within this EG, with each contributing more than 500 publications: Civil Engineering, Operations Research, and Environmental Engineering.

Environmental Science and Chemical Engineering are two areas of strength for Canada, each having a high ARC and a high SI score (ARC > 1.1, SI > 1.1). Stronger still, though, was Operations Research, which had world-class scores in impact and specialization (ARC = 1.19, SI = 1.85), in addition to a large output by volume (output = 623 pubs).

While none of the subfields of high specialization were very weak in impact, and none of the highly impactful subfields had especially low specialization scores, several candidates for strategic consideration were still identified as thematically salient, using expert judgment. Specifically, three subfields were highlighted as areas of specialization for Canada, with middling rather than low impact scores, and high topical relevance to EG1509; they are Geological & Geomatic Engineering, Civil Engineering, and Environmental Engineering. Furthermore, Civil Engineering and Environmental Engineering are also subfields of large output by volume within EG1509.[38]

[38] Potential approaches to address these strategic opportunities are discussed in § 2.1.2 above.

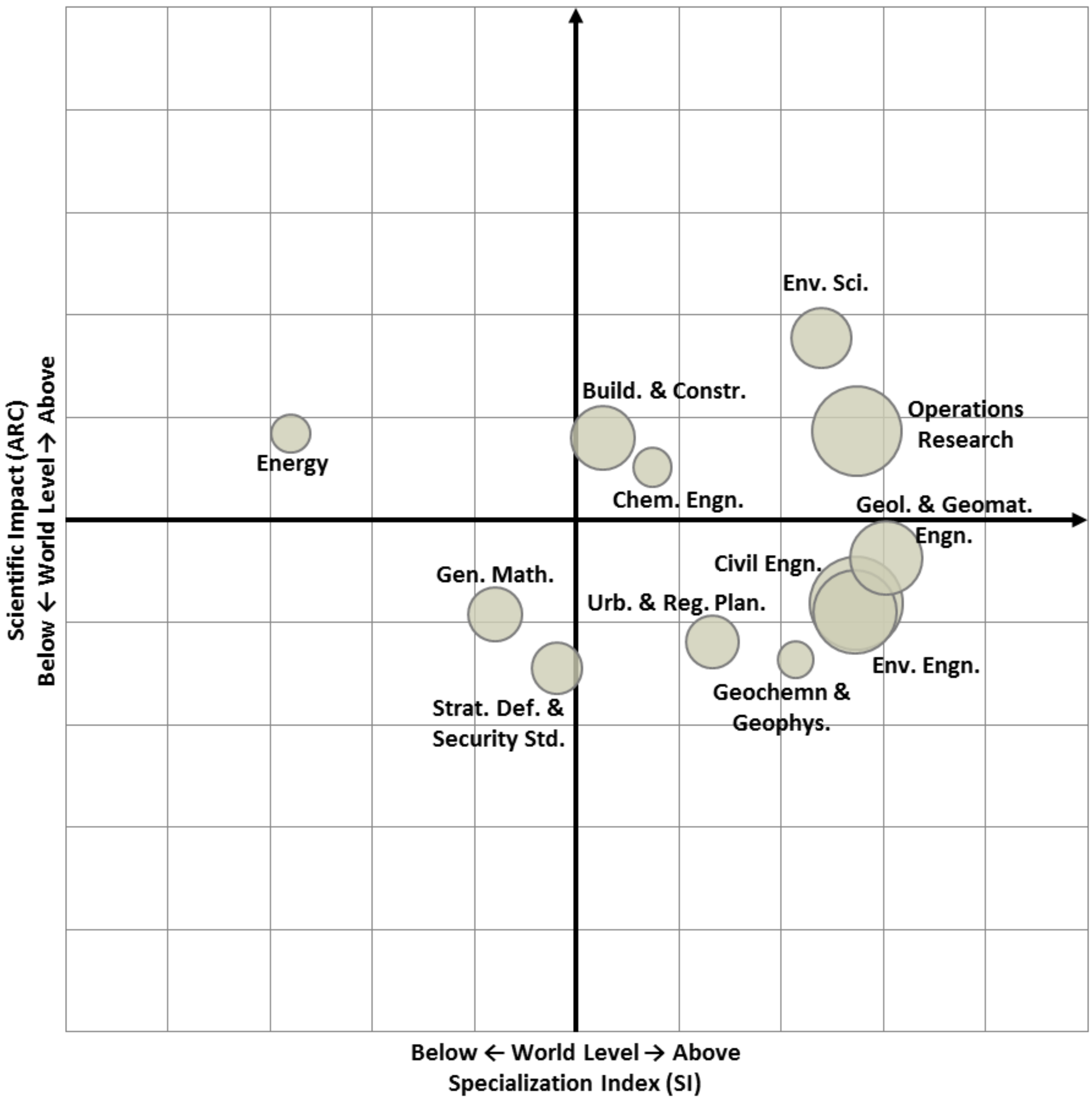

Figure 12 Positional analysis of Canada by subfield within EG1509 (Civil, Industrial and Systems Engineering) (2009–2013)

Note: Selection of the 12 subfields in which CA published the most.
Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters)

2.10 EG1510 – Electrical and Computer engineering

2.10.1 Benchmarking Canadian performance relative to other world leaders

Electrical & Computer Engineering is a field in which global production is led by the US, China and the Republic of Korea; Canada ranks 7th worldwide for the size of its output. Canada's output decreased slightly in this area, by 4% from 2009–2010 to 2012–2013, placing it last in growth among the 27 comparator countries. The most substantial growth was in Denmark, China, Brazil and Mexico; the global average growth rate shows a 17% increase in output at the world level. In terms of specialization, however, Canada produces 20% more of its publications in EG1510 than expected based on the world level, a degree of specialization that places Canada in 5th position, behind only Taiwan, Republic of Korea, China and Finland.

Switzerland and the US stand out for their scientific impact. Canada also scores very well in this regard, placing 9th for ARC, 6th for ARIF, and 10th for HCP among the 27. Canada is also just above the median of the 27 countries when it comes to its penchant for international collaboration, ranking 12th. The UK, Denmark, and Switzerland collaborate most frequently on the international stage, when propensity for collaboration is normalized for volume of research output.

Canada's composite index rank is high in EG1510, sharing the 6.5th place with Switzerland. Taiwan places first, followed by the US and China, who are tied.

Table X Scientific performance of a selection of 27 highly active countries in NSE research for EG1510 (Electrical and Computer Engineering) (2009–2013)

Country	Pubs. (rank)	GR	Trend	SI	ARC	ARIF	HCP	CI	Composite score
World	**344,265 (N/A)**	**1.17**		**1.00**	**1.00**	**1.00**	**1.00**	**N/A**	**N/A**
Taiwan	18,382 (5)	1.04		2.83	0.99	1.10	0.89	0.35	76
United States	67,770 (2)	0.98		0.81	1.43	1.30	1.63	1.20	74
China	70,830 (1)	1.43		1.36	1.01	0.93	0.96	0.83	74
Rep. of Korea	21,674 (3)	1.07		2.05	0.95	1.04	0.95	0.65	73
Denmark	2,024 (29)	1.64		0.77	1.83	1.23	1.66	1.44	72
Canada	14,931 (7)	0.96		1.20	1.31	1.25	1.30	1.25	71
Switzerland	3,405 (23)	1.09		0.75	1.64	1.37	1.93	1.43	71
Australia	6,536 (14)	1.23		0.67	1.54	1.24	1.57	1.37	69
Belgium	4,035 (17)	1.06		1.11	1.35	1.19	1.50	1.31	69
Sweden	4,271 (16)	1.28		1.01	1.34	1.18	1.35	1.36	69
United Kingdom	14,463 (8)	1.01		0.68	1.43	1.27	1.41	1.51	69
Italy	11,645 (11)	1.01		0.93	1.15	1.17	1.16	1.12	67
Spain	10,349 (12)	1.11		0.93	1.07	1.21	1.05	1.16	67
Germany	15,220 (6)	1.05		0.75	1.13	1.08	1.23	1.36	66
Israel	1,884 (32)	1.13		0.70	1.38	1.45	1.43	1.00	66
France	13,454 (9)	1.05		0.93	1.01	1.12	0.99	1.37	66
Japan	20,543 (4)	1.03		1.09	0.88	0.93	0.85	0.63	66
Finland	2,757 (25)	1.12		1.25	1.00	1.12	0.94	1.14	65
Austria	2,133 (28)	1.09		0.88	1.24	1.15	1.23	1.34	64
Netherlands	3,947 (18)	0.98		0.57	1.26	1.27	1.40	1.36	64
Portugal	2,599 (26)	1.16		1.05	0.85	0.95	0.69	1.07	61
Turkey	3,529 (21)	1.28		0.60	0.98	1.01	0.92	0.65	61
Norway	1,305 (38)	1.02		0.60	1.03	1.02	1.09	1.36	58
Mexico	1,963 (30)	1.28		0.83	0.68	0.92	0.61	0.93	58
Brazil	3,780 (20)	1.31		0.46	0.82	0.97	0.73	0.85	58
Poland	3,477 (22)	1.06		0.72	0.65	0.70	0.52	0.60	55
Russia	2,389 (27)	1.20		0.35	0.61	0.76	0.54	0.90	51

Note: Colouring provides insight on performance relative to world (in WoS), ranging from dark red (below world level) to white (on par with the world level) and dark green (above world level). Note that for pubs and composite scores, colouring is relative to median (white) instead of world; additionally, colouring for CI is relative to expected values (white), which are computed based on the relationship between total publication output and co-publications at the country level. The GR, pub trend and SI were computed using fractional counting. For pub trend, the scale varies across countries. The CI is not accounted for in the composite score.

Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters)

2.10.2 Analysis of Canadian performance within subfields

Regarding impact in the subfields of EG1510, Industrial Engineering & Automation stands out as the most remarkable subfield (ARC = 1.92), the majority of subfields in this area being near or above world average. Notable exceptions are Nanoscience & Nanotechnology, and Computer Hardware & Architecture, which are the weaker subfields of Canadian research in EG1510 (ARC < 0.70), and each well below the world average.

Canada is highly specialized in two subfields in this EG, and those are Automotive Design & Engineering, and Computer Hardware & Architecture (SI > 1.85). Most of the remaining subfields are at or near the world level. Only two subfields stood out in this EG for low specialization scores: Nanoscience & Nanotechnology was noticeably below the world level in specialization (SI = 0.76), and Applied Physics has an extremely low SI score (SI = 0.42). Turning to large outputs by volume, Canada published over 1,000 articles in each of Networking & Telecommunications, General Mathematics, and Electrical & Electronic Engineering.

Turning to overall strengths, Networking & Telecommunications stands out for its scores for all three metrics: impact (ARC = 1.35), specialization (SI = 1.71), and size of output (output = 3,441 pubs). Canada's additional strengths, looking at impact and specialization (ARC > 1.1, SI > 1.1) but not overall output by volume (output < 1,000 pubs), are in Automotive Design & Engineering, Industrial Design & Automation, Optics, and Optoelectronics & Photonics. Canada also has a high impact and large output by volume in Electrical & Electronic Engineering, something of a secondary strength.

Computer Hardware & Architecture has a high SI but low ARC, making it an area for potential strategic consideration. Additionally, Energy was close to meeting those same thresholds, and was retained as an area of high thematic relevance to EG1510. Artificial Intelligence & Image Processing was also retained for its thematic importance, though it is instead characterized by high impact and an SI score slightly below world average.[39]

[39] Potential approaches to address these strategic opportunities are discussed in § 2.1.2 above.

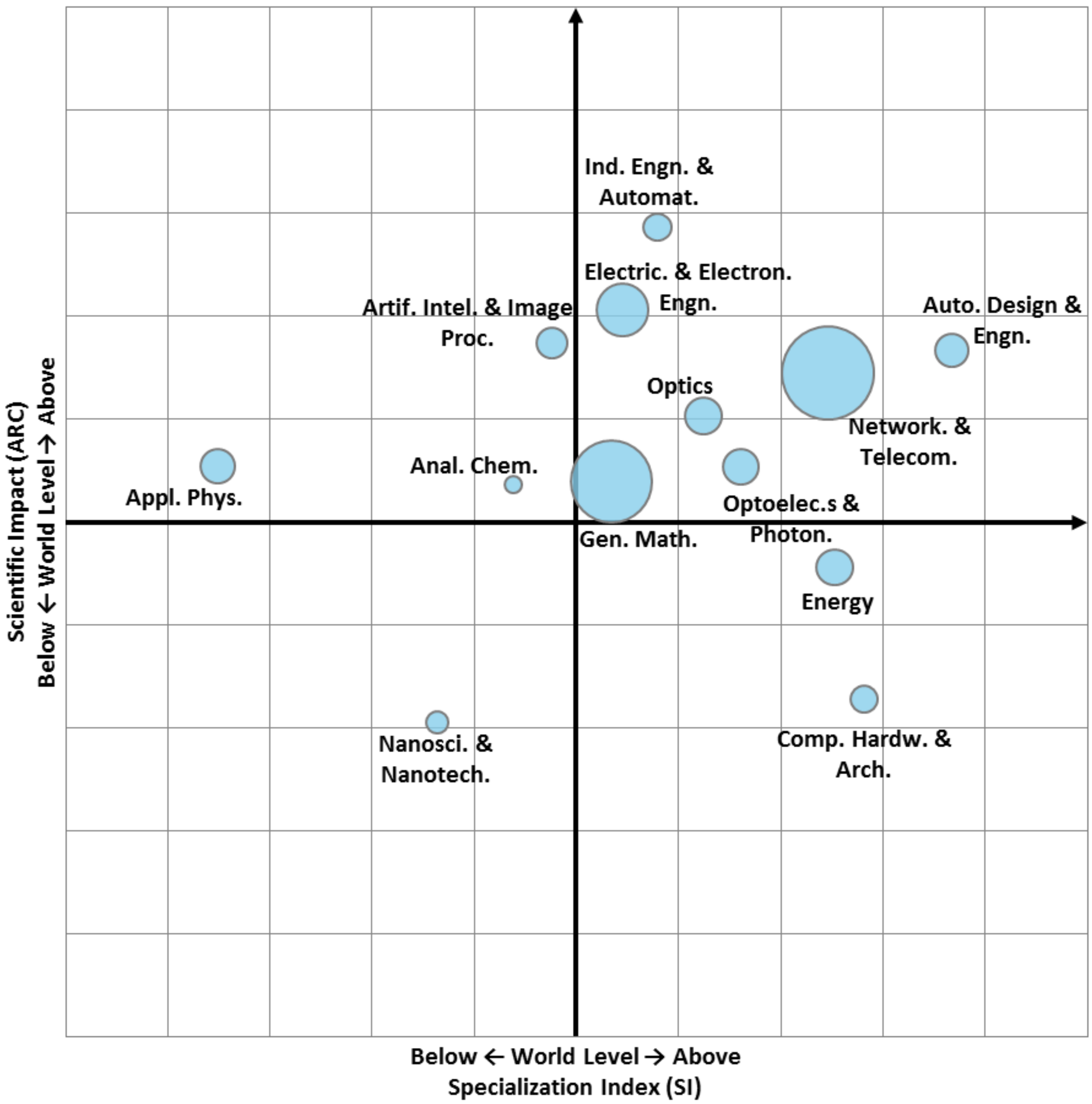

Figure 13 Positional analysis of Canada by subfield within EG1510 (Electrical and Computer Engineering) (2009–2013)

Note: Selection of the 13 subfields in which CA published the most.

Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters)

2.11 EG1511 – Materials and Chemical engineering

2.11.1 Benchmarking Canadian performance relative to other world leaders

Canada ranks 9th for the size of its publication output for EG1511, with China, the US and Japan as the top three world leaders. Coming in 17th place of 27 benchmark countries, Canada is below the world average in growth, having only seen an increase in output of 12%, falling behind the world average growth of 29% over the period of 2009–2010 to 2012–2013. Output growth is a category led by China, Denmark, Poland and Norway. Canada focuses less on EG1511 than the rest of the world does, producing 15% fewer of its publications in EG1511 than would be expected according to the global average. The specialists on the world stage in this area are China, the Republic of Korea, and Poland.

While Australia, the Netherlands, and Switzerland stand out in measured impact, Canada scores near the median of the 27 nations canvassed, with its ARC at 17th, ARIF at 13th, and HCP at 14th. Researchers from the UK, Switzerland and France are the most likely to co-publish with international partners, relative to the size of their publication outputs. Canada's researchers in EG1511 rank 15th among the 27 benchmark nations for their tendency to collaborate.

As measured by the composite index, China leads the world in EG1511, followed by the Republic of Korea and Australia, and thereafter by the US. Canada shares the 12.5th rank with five other nations: Finland, Denmark, Japan, Taiwan, and the UK.

Table XI Scientific performance of a selection of 27 highly active countries in NSE research for EG1511 (Materials and Chemical Engineering) (2009–2013)

Country	Pubs. (rank)	GR	Trend	SI	ARC	ARIF	HCP	CI	Composite score
World	**409,780 (N/A)**	**1.29**		**1.00**	**1.00**	**1.00**	**1.00**	**N/A**	**N/A**
China	114,555 (1)	1.58		1.85	1.11	0.95	1.12	0.57	80
Rep. of Korea	20,251 (6)	1.24		1.52	1.03	1.01	0.96	0.77	71
Australia	9,168 (13)	1.27		0.70	1.43	1.29	1.73	1.36	69
United States	57,451 (2)	1.07		0.54	1.36	1.25	1.63	1.17	69
Germany	21,893 (5)	1.08		0.81	1.11	1.16	1.22	1.39	67
Portugal	3,799 (24)	1.30		1.14	1.12	1.14	1.14	1.17	67
France	17,656 (7)	1.11		0.92	1.06	1.20	1.05	1.41	67
Sweden	4,832 (21)	1.27		0.87	1.24	1.19	1.27	1.23	66
Spain	11,198 (11)	1.27		0.78	1.14	1.18	1.10	1.15	66
Canada	13,353 (9)	1.12		0.85	1.06	1.14	1.10	1.09	65
Finland	2,867 (30)	1.32		0.97	1.12	1.14	1.22	1.10	65
Denmark	1,942 (37)	1.43		0.57	1.43	1.24	1.71	1.16	65
Japan	25,925 (3)	0.95		1.08	0.89	0.99	0.80	0.83	65
Taiwan	9,067 (14)	1.05		1.13	1.00	1.06	0.82	0.44	65
United Kingdom	15,235 (8)	1.08		0.55	1.23	1.23	1.32	1.48	65
Netherlands	5,014 (20)	1.05		0.54	1.34	1.36	1.54	1.38	64
Turkey	7,050 (18)	1.26		1.01	0.93	0.89	0.91	0.50	64
Belgium	3,441 (27)	1.13		0.68	1.24	1.29	1.35	1.40	63
Poland	7,906 (17)	1.37		1.33	0.64	0.74	0.43	0.64	63
Italy	10,887 (12)	1.17		0.69	1.06	1.11	0.98	1.06	63
Switzerland	3,606 (26)	1.08		0.57	1.27	1.30	1.43	1.47	63
Norway	2,168 (36)	1.36		0.84	0.90	1.09	0.77	0.97	60
Brazil	9,006 (15)	1.21		0.90	0.69	0.86	0.56	0.68	60
Austria	2,790 (31)	1.15		0.84	0.91	1.11	0.84	1.32	60
Mexico	3,265 (28)	1.06		1.10	0.57	0.91	0.40	0.86	58
Russia	8,716 (16)	1.21		1.11	0.38	0.49	0.23	0.72	57
Israel	1,469 (40)	0.87		0.43	1.23	1.34	1.07	0.90	56

Note: Colouring provides insight on performance relative to world (in WoS), ranging from dark red (below world level) to white (on par with the world level) and dark green (above world level). Note that for pubs and composite scores, colouring is relative to median (white) instead of world; additionally, colouring for CI is relative to expected values (white), which are computed based on the relationship between total publication output and co-publications at the country level. The GR, pub trend and SI were computed using fractional counting. For pub trend, the scale varies across countries. The CI is not accounted for in the composite score.

Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters)

2.11.2 Analysis of Canadian performance within subfields

Within the subfields of EG1511, Canada has a very high impact in General Chemistry (ARC = 1.82), with Mining & Metallurgy and Analytic Chemistry also having quite high impact (ARC ≥ 1.25). Subfields lagging in terms of impact are Civil Engineering, Forestry, and Environmental Engineering (ARC < 0.70), each of which falls well below the world average for ARC scores.

With respect to specialization, Canada focuses heavily on Forestry, Environmental Engineering, Civil Engineering, and Environmental Science (SI > 1.75). Its specialization scores are low in a number of subfields within EG1511, most notably General Chemistry and Applied Physics (SI < 0.50), but also in Nanoscience & Nanotechnology, Materials, and Analytic Chemistry (0.55 < SI ≤ 0.60). Four subfields have large outputs by volume, with over 1,000 publications each: Materials, Energy, Polymers, and Chemical Engineering.

Regarding overall strengths, in terms of both specialization and impact (SI > 1.1, ARC > 1.1), Canada has no areas of defined strengths in the subfields of this EG. It does, however, have two areas with high impact scores (ARC > 1.1) and large output by overall volume (output > 1,000 pubs), and these are Materials and Polymers.

Five subfields are highlighted here as having high potential for improvement, as options for strategic consideration: General Chemistry and Analytic Chemistry, both of which have high impact scores but low specialization; and Environmental Engineering, Civil Engineering, and Forestry, each of which is an area of specialization for Canada but has low impact scores. An additional four subfields were retained for consideration because they were very close to those same thresholds, but also covered subfields of central thematic relevance to Materials & Chemical Engineering. Those subfields are Mining & Metallurgy and Chemical Physics, each of which has high impact but low specialization; and Chemical Engineering and Energy, both of which are areas of specialization for Canada but have lower impact, while also being subfields of large output by volume.[40]

[40] Potential approaches to address these strategic opportunities are discussed in § 2.1.2 above.

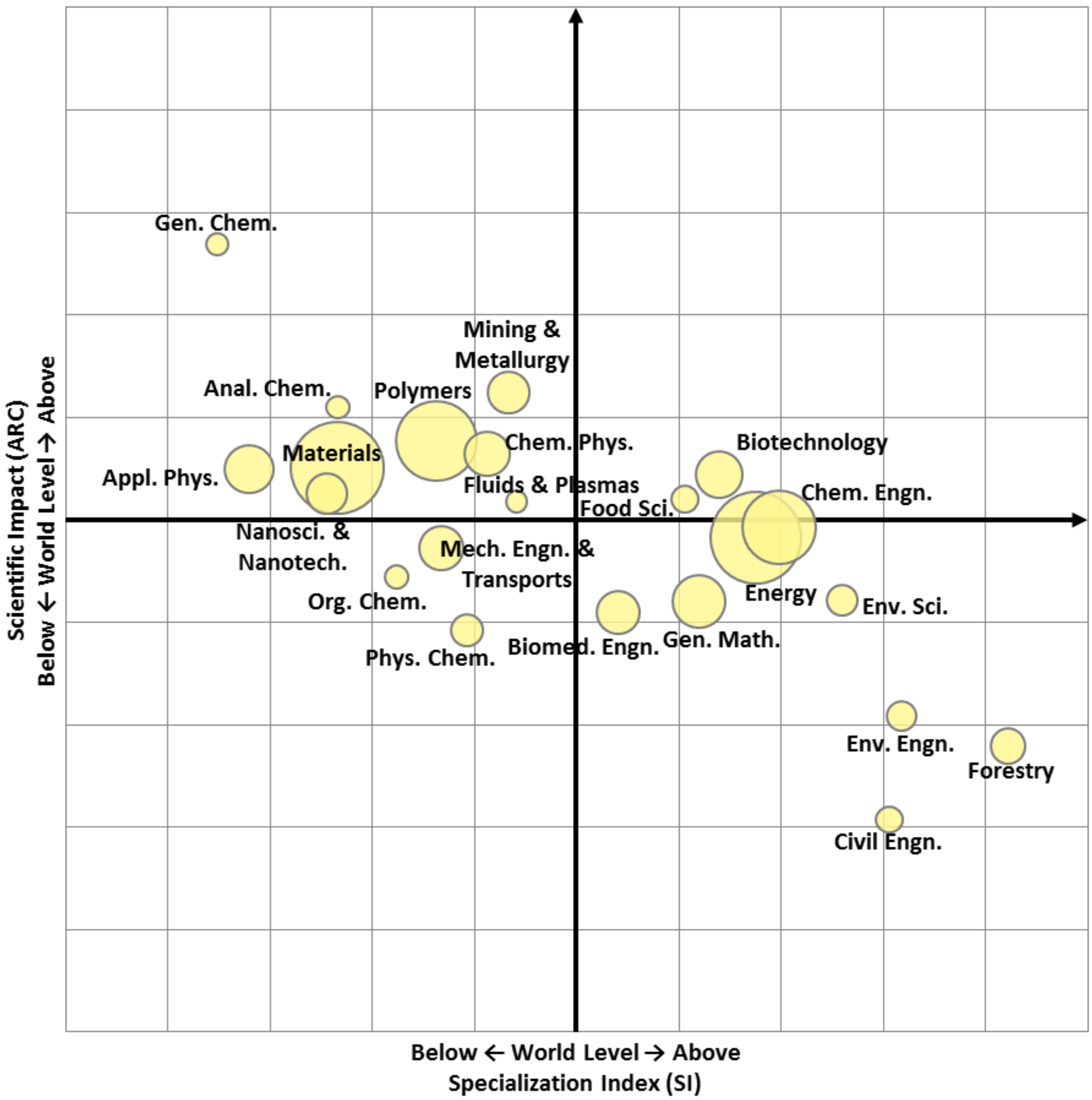

Figure 14 Positional analysis of Canada by subfield within EG1511 (Materials and Chemical Engineering) (2009–2013)

Note: Selection of the 22 subfields in which CA published the most.
Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters)

2.12 EG1512 – Mechanical engineering

2.12.1 Benchmarking Canadian performance relative to other world leaders

The US, China, and Germany lead in research production by volume in Mechanical Engineering, with Canada placing 8th overall among the selected 27 nations. Canada's growth in the area is 6%, trailing behind the world average of 26% growth; for its increase from 2009–2010 to 2012–2013, Canada places in the 22nd spot against the 27 benchmark nations, well behind the global leaders: China, Denmark, and Norway. Even so, Canada is a world specialist in EG1512, placing 5th behind only the Republic of Korea, Taiwan, China and France.

The impact of Canadian publications is near the median of the 27 world-leading countries, ranking 16th in ARC, 15th in ARIF, and 15th again in HCP. The publications of Swiss, Australian and Dutch researchers have the highest impact, on average, in the world. Switzerland and Australia are also leading countries for international collaboration, along with Belgium. Canada ranks 12th in its propensity to co-publish with international partners.

Overall, using the CPI, China ranks first in the world, followed by Denmark and then the US. Sharing the 11.5th place are Canada, Norway, Portugal and Germany.

Table XII Scientific performance of a selection of 27 highly active countries in NSE research for EG1512 (Mechanical Engineering) (2009–2013)

Country	Pubs. (rank)	GR	Trend	SI	ARC	ARIF	HCP	CI	Composite score
World	**231,406 (N/A)**	**1.26**		**1.00**	**1.00**	**1.00**	**1.00**	**N/A**	**N/A**
China	45,404 (2)	1.67		1.30	1.15	0.96	1.07	0.80	81
Denmark	1,687 (27)	1.57		0.94	1.54	1.15	2.08	1.17	78
United States	49,355 (1)	1.09		0.87	1.22	1.11	1.37	1.08	77
France	12,029 (6)	1.12		1.22	1.17	1.24	1.18	1.28	76
Switzerland	3,100 (17)	1.27		0.99	1.39	1.19	1.58	1.38	75
Australia	5,438 (14)	1.35		0.79	1.34	1.19	1.57	1.32	75
Italy	8,852 (9)	1.25		1.05	1.19	1.13	1.03	1.04	74
United Kingdom	13,535 (4)	1.13		0.95	1.14	1.14	1.15	1.35	73
Rep. of Korea	10,701 (7)	1.19		1.46	0.89	0.97	0.79	0.77	73
Norway	1,529 (31)	1.52		1.05	1.14	1.09	1.33	1.14	72
Portugal	1,894 (25)	1.45		1.11	1.12	1.11	1.23	0.95	72
Canada	9,653 (8)	1.06		1.14	1.02	1.07	1.07	1.08	72
Germany	13,829 (3)	1.13		1.01	0.98	0.99	1.03	1.23	72
Spain	5,817 (12)	1.29		0.77	1.18	1.20	1.09	1.01	71
Taiwan	5,762 (13)	1.08		1.30	0.96	1.03	0.86	0.37	71
Sweden	2,651 (20)	1.22		0.92	1.09	1.14	1.27	1.15	70
Netherlands	3,727 (15)	1.05		0.79	1.23	1.19	1.40	1.29	70
Belgium	2,108 (24)	1.29		0.82	1.12	1.08	1.43	1.32	70
Turkey	3,673 (16)	1.19		0.93	1.08	1.02	1.21	0.57	70
Japan	12,070 (5)	1.04		0.92	0.85	0.92	0.77	0.85	67
Austria	1,380 (32)	1.26		0.82	0.96	1.02	0.94	1.24	65
Mexico	1,552 (29.5)	1.40		0.98	0.76	0.89	0.63	0.82	64
Poland	2,647 (21)	1.38		0.82	0.80	0.82	0.65	0.55	64
Finland	955 (37)	1.06		0.62	0.97	1.03	0.99	0.97	61
Brazil	2,784 (19)	1.29		0.48	0.68	0.95	0.58	0.86	60
Israel	1,087 (34)	0.88		0.60	0.85	1.15	0.73	0.88	58
Russia	2,974 (18)	1.03		0.68	0.51	0.64	0.54	0.69	57

Note: Colouring provides insight on performance relative to world (in WoS), ranging from dark red (below world level) to white (on par with the world level) and dark green (above world level). Note that for pubs and composite scores, colouring is relative to median (white) instead of world; additionally, colouring for CI is relative to expected values (white), which are computed based on the relationship between total publication output and co-publications at the country level. The GR, pub trend and SI were computed using fractional counting. For pub trend, the scale varies across countries. The CI is not accounted for in the composite score.

Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters)

2.12.2 Analysis of Canadian performance within subfields

Within the subfields of EG1512, the impact of Canadian publications is especially high in Aerospace & Aeronautics (ARC = 1.45), and quite high in Electrical & Electronic Engineering, Orthopaedics, and Industrial Engineering & Automation (ARC > 1.20). Its lowest scores for impact are in Design Practice & Management, Civil Engineering, and General Mathematics (ARC < 0.75).

Regarding specialization, Canada's areas of focus are Design Practice & Management, Biomedical Engineering, and Building & Construction (SI > 1.80). Except for Applied Physics, Applied Mathematics, and Materials, which are the subfields of lowest specialization in Canada (SI ≤ 0.80), the country is at or above the world level of specialization in the remaining subfields of EG1512. Its largest outputs are in General Mathematics and in Energy, each of which contributed over 1,000 published articles.

Canada has scores of both high impact and considerable specialization (i.e., ARC > 1.1, SI > 1.1) in the fields of Biomedical Engineering, Orthopaedics, Industrial Engineering & Automation, Aerospace & Aeronautics, and Electrical & Electronic Engineering.

Design Practice & Management is an area with very high specialization scores but low impact, and may be an area to consider in strategic planning. Building & Construction and Civil Engineering are in a similar situation; however, while they fall just shy of the same thresholds used to identify other areas of potential strategic consideration, the thematic relevance of these two additional subfields warrants highlighting them for discussion as well.[41]

[41] Potential approaches to address these strategic opportunities are discussed in § 2.1.2 above.

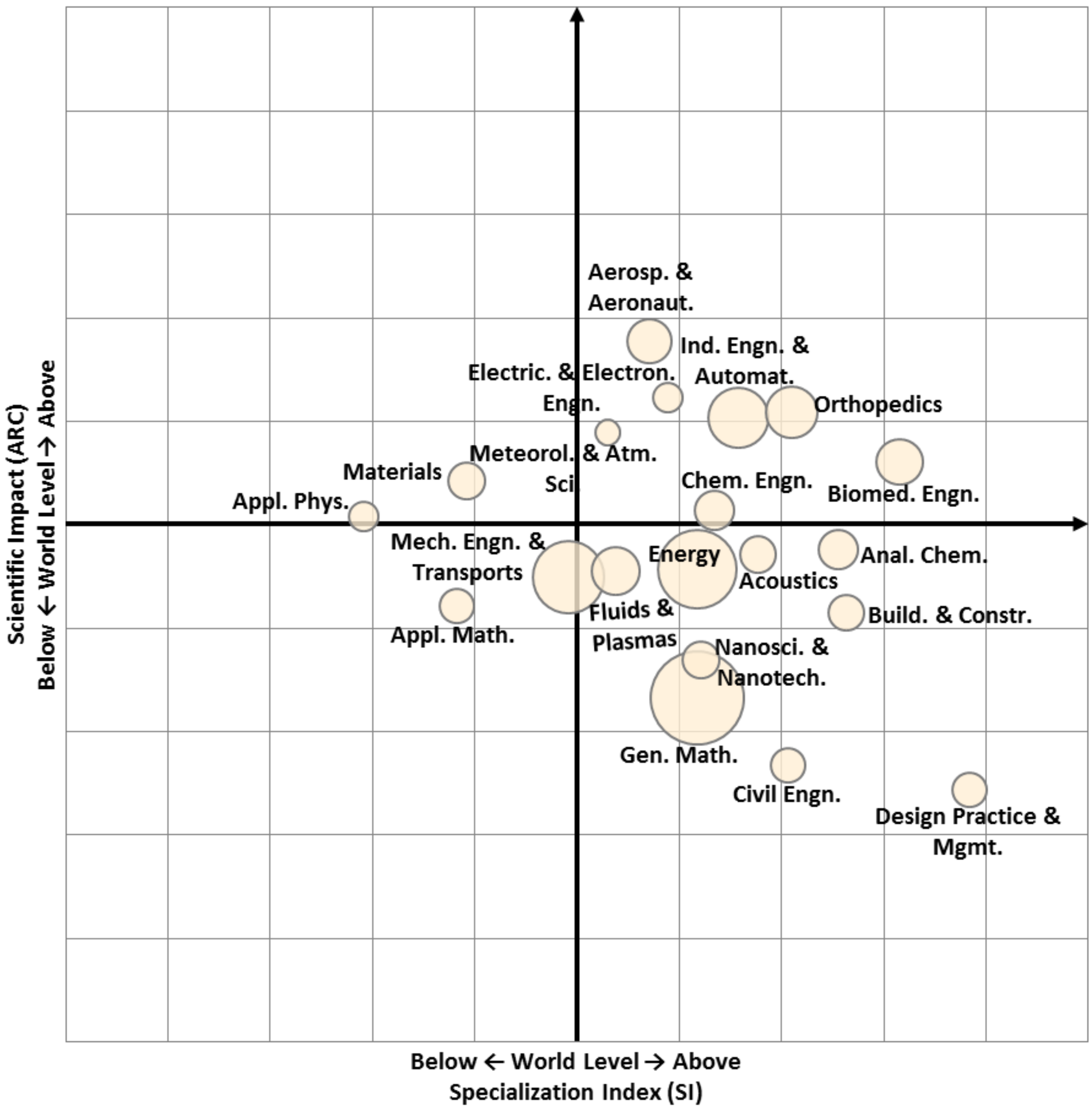

Figure 15 Positional analysis of Canada by subfield within EG1512 (Mechanical Engineering) (2009–2013)

Note: Selection of the 20 subfields in which CA published the most.

Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters)

2.13 Canadian performance in high growth and interdisciplinary topics at world level

2.13.1 High-growth research topics

The process for topic modeling and analysis is fully detailed in § 1.3.4. However, it is worth recalling here that the topics identified as high-growth are those that are growing quickly at the world level and in which Canada is gaining ground relative to the world in terms of the number of articles; from that set of topics, the ones in which Canada performs best (according to several measures of impact) have been retained for discussion here. Recall also that the topics are modeled based on a semantic analysis, identifying clusters of keywords that frequently appear together in documents. For the sake of convenience, the topics have been given provisional names based on expert judgment of the unifying theme connecting the cluster of keywords, but the topics are in fact more accurately identified by the set of keywords they include, which can be found in Table XXIII and Table XXIV of the Appendix to the present document. The analysis of selected high-growth topics is provided in Table XIII.

Of the high-growth topics retained for consideration, the three that are the fastest growing worldwide are lithium-ion batteries (GR = 2.28), cloud computing (GR = 2.03), and smart grids (GR = 1.81). Lithium-ion batteries was also the largest topic in number of publications (13,451), followed by power control (9,157), biosensor sensitivity (9,069), cloud computing (7,870), and composite soft polymers (7,206).

Within the set of topics considered here, the three topics that are growing the fastest in Canada are the same three that are fastest growing at the world level: lithium-ion batteries (GR = 2.81), cloud computing (GR = 2.72), and smart grids (GR = 2.70). By comparing output growth in Canada to the output growth at the world level,[42] topics can be identified where Canada's growth is surpassing that of the world to the greatest extent. The five topics in which Canada's growth is most strongly outpacing that of the world are imaging (GI = 1.59), colour (GI = 1.59), optical ring resonators (GI = 1.53), epidemiological surveillance (GI = 1.50), and smart grids (GI = 1.49).

Regarding Canada's specialization among these topics, Canada's publications focus most on the topics of animal feed (SI = 3.10), exercise & training (SI = 1.92), epidemiological surveillance (SI = 1.64), and biodiversity (SI = 1.53). These are all topics in which Canada is highly specialized, and also is increasing its output faster than the world level; that is to say, these are topics where Canada's rate of output is ahead of the world level, and in which Canada is increasing its headway. Canada focuses least, within this set, on the topics of biosensor sensitivity (SI = 0.43), neutrino detection (SI = 0.46), lithium-ion batteries (SI = 0.56), material strength & toughness (SI = 0.60) and composite soft polymers (SI = 0.65). In these cases, the proportion of Canada's production treating these topics is smaller than the corresponding shares at world level; but Canada's growth rate in these areas is also surpassing that of the world, meaning that Canada is catching up to the global proportion.

Canada's largest publication outputs by volume are in exercise & training (421), power control (398), biodiversity (352), and lithium-ion batteries (308). Its highest scientific impacts, by a composite measure,

[42] That is to say, by using the growth index (GI) instead of simply the growth ratio (GR).

are in smart grids, metallurgy, herd infection, power control, and scavenging activity/radicals/antioxidants.

Certain topics scored well on multiple measures, and so will receive a more integrated, cross-cutting analysis here. Lithium-ion research is one such topic. Of the set of topics considered here, it was the one with the largest overall number of publications worldwide, as well as the fastest growing both worldwide and in Canada specifically. Canada is very unspecialized in this topic, though Canada's growth in this area is outpacing global growth (GI = 1.23), which is to say that Canada is gaining ground in terms of its share of world output. Canada's impact scores in this area are also very good, with an ARC of 1.89, an ARIF of 1.23, and an HCP of 1.69.

Smart grids is another topic in which Canada shows a particularly strong performance. This topic is one of the smallest at the world level, with only 1,594 publications worldwide, of which 66 had at least one Canadian author. It is among the fastest growing topics, again both worldwide and in Canada specifically. Canada puts more focus on this topic than the world average (SI = 1.15), and Canadian growth on the topic is outpacing global growth (GI = 1.49), extending Canada's lead in share of world output. Canada's highest impact scores of all the selected topics are in smart grids (ARIF = 1.75; HCP = 2.45), though with such a small set of publications, these results may not be indicative of sustainable trends.

Canada's research on power control (e.g., converters, switches, transformers, etc.) has very high impact scores (ARC = 1.60, ARIF = 1.43, HCP = 1.99). This research topic is one of the larger topics analyzed here in terms of its number of worldwide publications, in addition to growing quickly at the world level (GR = 1.49). Canada is already specialized in this research area (SI = 1.27), and is outpacing world growth (GI = 1.22), increasing its lead in share of world output.

Similar to power control, cloud computing is a relatively large global research topic in which Canada's publications are impactful (ARC = 1.61, ARIF = 1.71, HCP = 2.23). The growth rate of this topic is very impressive, with twice as much worldwide output in 2012–13 as in 2009–2010 (GR = 2.03). Canada is not specialized in this area, devoting proportionately less of its total scientific output to this topic than is observed globally at world level; however, Canada's growth in this area outpaced world growth (GI = 1.34), increasing its share of world output and narrowing the specialization gap.

Table XIII Topics growing quickly at the world level in which Canada performs well

Cluster id	Provisional cluster name	Canada							World		
		Papers	ARC	ARIF	Top5%	GR	GI	SI	Papers	GR	Interdisciplinarity
486	Smart grids	66	N/C	1.75	2.45	2.70	1.49	1.15	1,594	1.81	N/C
286	Metallurgy (focus on toughness and strength)	169	1.74	1.55	2.76	1.67	1.24	0.68	6,333	1.35	N/C
87	Herd infection	126	1.89	1.43	3.26	1.61	1.29	0.84	3,214	1.25	N/C
1683	Power control (converter, switch, tranformer)	398	1.60	1.43	1.99	1.82	1.22	1.27	9,157	1.49	N/C
1024	Scavenging activity/radicals/antioxydants	129	1.65	1.50	2.74	1.45	1.20	0.62	5,069	1.20	N/C
236	Neutrino detection	108	2.90	1.29	2.71	1.62	1.30	0.46	3,595	1.25	N/C
1003	Cloud computing	233	1.61	1.71	2.23	2.72	1.34	0.81	7,870	2.03	N/C
1133	Resonators (optical ring resonator and MEMS resonator)	94	1.40	1.31	2.07	1.96	1.53	1.02	2,578	1.28	N/C
1560	Human papillomavirus (HPV)	105	1.68	1.09	2.54	1.71	1.21	0.99	2,064	1.41	N/C
1652	Imaging (LCD display, image correction, optical set up)	113	1.67	1.53	2.34	2.14	1.59	0.84	3,664	1.35	N/C
94	Exercise and training	421	1.56	1.23	2.37	1.37	1.13	1.92	5,439	1.21	N/C
616	Composite soft polymers	193	1.62	1.38	1.77	1.61	1.16	0.65	7,206	1.39	N/C
20	Extended spectrum antiobiotic resistance in Acinetobacter, Klebsiella, Enterobacteriaceae	156	1.37	1.10	1.97	1.68	1.16	0.86	4,226	1.45	N/C
1107	Lithium-ion batteries	308	1.89	1.23	1.69	2.81	1.23	0.56	13,451	2.28	3.6%
1358	Biodiversity	352	1.61	1.26	1.90	1.41	1.10	1.53	4,112	1.28	15.1%
93	Mechanisms of blood coagulation	54	1.30	1.25	1.74	1.56	1.26	0.96	1,389	1.23	N/C
1196	Temperature control in civil engineering	97	1.43	1.16	1.55	2.20	1.35	0.94	2,891	1.63	N/C
985	Impedance spectroscopy	68	1.29	1.26	1.12	1.39	1.14	0.83	2,053	1.22	N/C
1769	Animal feed	135	1.39	1.17	1.39	1.65	1.31	3.10	1,159	1.26	N/C
1422	Alloys (focus on magnesium and titanium)	183	1.15	1.35	0.95	1.47	1.17	0.78	6,083	1.25	N/C
980	Biosensor sensitivity	147	1.23	1.17	1.68	1.82	1.29	0.43	9,069	1.41	12.8%
239	Colour (Chromaticity, Colorization Algorithm, dye coloring, etc)	54	1.11	1.56	1.18	1.95	1.59	0.72	1,968	1.23	N/C
1609	Epidemiological surveillance	214	1.37	0.99	1.58	1.84	1.50	1.64	2,931	1.23	N/C
90	Gene therapy	128	1.37	1.08	1.75	1.63	1.25	0.94	3,399	1.31	N/C
347	Material strain & stress	51	1.21	1.12	0.79	2.02	1.24	0.60	2,000	1.64	N/C

Note: Topics are sorted in descending order of scientific impact (based on a composite measure, not shown in the table). Colouring provides insight on performance relative to world (in WoS), ranging from dark red (below world level) to white (on par with the world level) and dark green (above world level). The colouring of the world's GR scores for each topic is based on the overall world level of growth in the NSE, i.e., using GR = 1.16 as the midpoint, coloured in white. The GR, GI and SI scores were computed using fractional counting. Interdisciplinarity scores are only calculated for topics with a sufficient number of papers with the most outbound citations (top 1%); N/C is used to indicate that topics do not meet this condition, and have no score. For the ARC, N/C is used to indicate that not enough papers were available to reliably compute the indicator.

Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters).

2.13.2 Interdisciplinary research topics

The topics retained for consideration here are those that were highly interdisciplinary at the world level, and in which Canada showed strong performances. The detailed analysis of these selected topics can be found in Table XIV. Of these topics, the largest by publication volumes at the world level are in remote sensing (11,307), paleoclimatology (8,991), and drug delivery (8,656); and the fastest growing are drug delivery (GR = 1.66), cancer therapy (GR = 1.53), climate change (GR = 1.48), ecosystem services (GR = 1.40), and buckling, vibration & deformation research (GR = 1.40). The most interdisciplinary topics are leaf respiration (75% of papers in this topic fall in the 10% most interdisciplinary papers at world level), tissue engineering (61%), and lab-on-a-chip research (53%).

Turning to Canada's performance within this set of topics, Canada's largest outputs by publication volume are in forestry (846) and paleoclimatology (663). Its greatest growth within these interdisciplinary topics is found in epigenetic mechanisms (GR = 1.70), cancer therapy (GR = 1.55), drug delivery (GR = 1.51) and biodiversity (GR = 1.41). Relative to growth at the world level, Canada's production is growing the fastest in epigenetic mechanisms (GI = 1.31), protein conformation, (GI = 1.12), biodiversity (GI = 1.10) and ocean primary production (GI = 1.09). Canada is strongly specialized in the topics of forestry (SI = 4.73), leaf respiration (SI = 2.03), marine food web (SI = 2.00), climate change (SI = 1.92), lab on a chip (SI = 1.84), isotope analysis (SI = 1.84), and food web (SI = 1.82). Its highest scientific impacts, by a composite measure, are in management, cellular and molecular biology, customer and commercialization, dynamical systems, ecosystem services, and biodiversity.

Once again, several topics stand out here as notably strong performances when considering Canada's output and growth in output, Canada's specialization, the scientific impact of Canadian publications and the global interdisciplinarity of the topic. Those topics will receive more sustained discussion here.

Leaf respiration is among the smaller topics on the world stage (2,325 pubs) among those selected, but increased by about 20% from 2009–2010 to 2012–2013 (GR = 1.21). Canada's output in this area actually decreased by 10% over that same period (GR = 0.90), falling well behind the global growth rate (GI = 0.75). In spite of losing ground, Canada remains a world specialist on this topic (SI = 2.03), in addition to having strong impact scores according to each measure used here (ARC = 1.40, ARIF = 1.13, HCP = 2.02). Of all the topics retained for consideration here, leaf respiration is the most strongly interdisciplinary at the world level. The notable features of this topic, therefore, are that Canada has a lead in specialization, a lead that is closing as Canada's output declines slowly and global growth is picking up. Canada's publications on this topic also have strong scientific impact.

Ocean primary production is about twice of leaf respiration in terms of global publication output (5,800 pubs), but is growing at a slightly slower rate (GR = 1.13). Canada's output on this topic is increasing (GR = 1.24), outpacing global growth (GI = 1.09). Canada is also already specialized in this area (SI = 1.34), though not as strongly as in leaf respiration research. The impact of Canadian publications is once again strong here (ARC = 1.28, ARIF = 1.09, HCP = 1.62), and the topic is strongly interdisciplinary at the world level (49.3%) even relative to the other interdisciplinary topics considered here. Canada's strong showing, then, is based on the fact that it is already a global specialist in the area, and is increasing its lead in output size relative to rest of the world. Its impact scores are also strong.

Lab on a chip research is a topic of roughly the same size as ocean primary production on the world stage (5,864 pubs versus 5,800), but the former research area grew by a slightly smaller percentage than the latter (GR = 1.07 versus 1.13). Canada is slightly more specialized in lab on a chip research (SI = 1.84), showing slightly slower total growth (GR = 1.13), but nearly the same growth relative to the world level (GI = 1.06). Canada's impact scores are slightly lower on this topic, though still near or above the world level (ARC = 1.04, ARIF = 1.01, HCP = 1.23), and the topic is again quite interdisciplinary globally (52.9%). The overall narrative about Canadian research on lab on a chip is therefore quite similar to the previous topic; Canada is a world specialist in the area, showing a healthy growth. That rate of publication increase is outpacing world growth, extending Canada's lead. Canada's impact scores here are slightly lower, but still above the world level, especially in its contribution of high-impact publications, and the topic globally is quite interdisciplinary.

Climate change is an interdisciplinary topic in which Canadian research is comparable to its performance in leaf respiration. Climate change is a larger research area (5,080 pubs), closer to ocean primary production and lab on a chip research, in terms of total size. World output is growing very quickly on climate change, with almost a 50% increase between 2009–2010 and 2012–2013 (GR = 1.48). Canadian research is more focused on climate change than the global norm (SI = 1.92); while Canadian output grew by 30% (GR = 1.30), this level of growth was below the world level (GI = 0.88). Canada's impact in this area is strong (ARC = 1.48, ARIF = 1.10, HCP = 1.54), and the topic is quite interdisciplinary at the world level (35.2%). Canada's strong performance in climate change research is based on its high impact scores, and the fact that Canadian research is quite focused on this topic. While Canadian output here is increasing, that growth is being outpaced by the rapid expansion at the global level, which is slowly reducing Canada's level of specialization in this topic.

Biodiversity is a mid-sized research topic (4,112 pubs) with slightly more papers than expected in the 10% most interdisciplinary ones at the world level (15.1%). It is also a topic that is growing quickly (GR = 1.28), though again not exceptionally so. However, while it is not remarkably strong in either growth or interdisciplinarity *individually*, it is strong enough in *both* respects to appear on each of the two lists of selected topics. It is the only such topic, and thus warrants some further discussion. Canada is a specialist in biodiversity research (SI = 1.53). Canada's output in this area is also increasing (GR = 1.41), outpacing world growth by about 10% (GI = 1.10), further increasing Canada's advance in specialization in this topic. Regarding impact, Canada's publications perform very well on all measures used (ARC = 1.61, ARIF = 1.26, HCP = 1.90). Biodiversity is a topic in which Canada is doing very well, with an established specialization supported by strong growth above the world level, and impressive scientific impact. Biodiversity is among the more interdisciplinary and the faster growing topics worldwide, though it is not among the leading topics in either one of those respects individually. However, it presents a unique balance of growth and interdisciplinarity, along with a very strong Canadian performance.

Table XIV Interdisciplinary topics at the world level and in which Canada performs well

Cluster id	Provisional cluster name	Canada							World		
		Papers	ARC	ARIF	Top5%	GR	GI	SI	Papers	GR	Interdisciplinarity
431	Leaf respiration (CO2 exchange)	252	1.40	1.13	2.02	0.90	0.75	2.03	2,325	1.21	75.0%
1414	Ocean primary production	394	1.28	1.09	1.62	1.24	1.09	1.34	5,800	1.13	49.3%
1755	Lab on a chip (microfluidic)	367	1.04	1.01	1.23	1.13	1.06	1.84	5,864	1.07	52.9%
1603	Climate change (atmospheric and land measurements)	462	1.48	1.10	1.54	1.30	0.88	1.92	5,080	1.48	38.0%
1856	Remote sensing	427	1.50	1.34	1.60	1.20	0.98	0.85	11,307	1.23	35.2%
1073	Forestery	846	1.16	1.13	1.06	0.95	0.88	4.73	4,974	1.08	19.8%
1358	Biodiversity	352	1.61	1.26	1.90	1.41	1.10	1.53	4,112	1.28	15.1%
1216	Ecosystem services	204	1.67	1.38	1.71	1.15	0.82	1.49	2,552	1.40	36.0%
1306	Marine food web	444	1.28	1.16	1.61	1.10	1.00	2.00	5,335	1.09	21.3%
768	Customer and commercialization	201	1.46	1.64	1.61	0.93	0.88	0.73	6,266	1.05	33.5%
1160	Isotope analysis	468	1.10	1.03	1.02	1.12	0.85	1.84	5,167	1.32	38.8%
1223	Management (business)	183	1.79	1.66	1.73	0.82	0.91	0.78	6,133	0.91	17.4%
1568	Cellular and molecular biology	51	1.96	1.20	2.15	1.03	1.00	0.86	1,489	1.03	35.9%
212	Theory and simulation of buckling, vibration and deformation applied to plate, beam, laminated or shell-like structures	301	1.26	1.12	1.58	1.23	0.88	1.06	7,200	1.40	31.6%
244	Gene regulatory networks	257	1.35	1.15	1.90	1.11	0.98	1.13	4,700	1.13	21.3%
1871	Food web	414	1.27	1.12	2.01	0.94	0.79	1.82	5,263	1.19	17.4%
1434	Epigenetic mechanisms	189	1.15	1.11	1.05	1.70	1.31	0.85	5,334	1.30	15.7%
1204	Drug delivery	198	1.05	1.15	0.98	1.51	0.91	0.59	8,656	1.66	41.1%
1456	Paleoclimatology	663	1.03	1.06	0.94	1.02	0.93	1.32	8,991	1.09	28.7%
88	Cancer therapy	182	1.25	1.08	1.09	1.55	1.01	0.84	4,914	1.53	27.8%
575	Dynamical systems	204	1.39	1.11	2.30	1.12	1.06	0.63	6,959	1.06	17.6%
896	Aerosol measurement	250	1.25	1.19	1.38	1.06	0.92	0.79	5,488	1.15	32.7%
328	Protein conformation	139	1.20	1.07	1.66	1.03	1.12	0.79	4,252	0.92	27.5%
1311	Tissue engineering	235	0.90	1.06	0.93	0.78	0.68	0.87	6,899	1.15	60.5%
807	Cell membranes	376	1.20	1.02	1.18	0.77	0.78	1.42	6,266	0.98	34.3%

Note: Colouring provides insight on performance relative to world (in WoS), ranging from dark red (below world level) to white (on par with the world level) and dark green (above world level). The colouring of the world GR scores for each topic is based on the overall world level of growth in the NSE, i.e., using GR = 1.16 as the midpoint, coloured in white. The GR, GI and SI scores were computed using fractional counting. Interdisciplinarity scores are only calculated for topics with a sufficient number of papers with the most outbound citations (top 1%).

Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters).

3 Conclusion

The principal purpose of the present study has been to supply lines of bibliometric evidence to the expert review panel, with the objective of informing their review of the funding allocation process for NSERC Discovery Grants. The main questions that this study was to address regard Canada's scientific performance, within each Evaluation Group (EG), compared to global averages and to 26 other world-leading research nations selected by NSERC. It is worth noting that India, which is among the largest producers of papers in the NSE in the WoS, was excluded from NSERC's list due to an insufficiency of financial data. Canada's performance was to be both benchmarked at its present state and evaluated longitudinally, using individual performance measures as well as a composite index.

Performance at the EG level

The present analyses have concluded that Canada's NSE research performance, based on a composite index, ranks at or above the median of the 27 selected countries, with considerable strengths in Evolution & Ecology (EG1503) as well as Biological Systems & Functions (EG1502). Canada also has a lesser, though notable, strength in Electrical & Computer Engineering (EG1510) and in Computer Science (EG1507). The only field in which Canada performs below the median is in Chemistry (EG1504), in which Canada places 16th out of the 27. While it is clear that Chemistry is the area in which Canada's scientific performance ranks the lowest according to the composite index as computed in this study, Canada's publications still have very high scientific impact in these fields, mitigating the need for concern. (Furthermore, weighting the components of the composite index differently would produce a different ranking. See § 1.3.3 for more details.)

Canada specializes in Evolution & Ecology (EG1503) and in Biological Systems & Functions (EG1502); it is less invested, relative to the average global proportion, in Chemistry (EG1504) and in Physics (EG1505). The scientific impact of Canadian publications is above the world average within each of the EGs. Longitudinally between 2009–2010 and 2011–2012, Canada made gains in impact in Evolution & Ecology (EG1503) and in Genes, Cells & Molecules (EG1501), as well as making gains in both impact and specialization in Biological Systems & Functions (EG1502). It lost ground in the other EGs, in either impact or specialization, or both.

Performance at the subfield level

A second line of inquiry to be addressed in the present study pertained to the subfields of research within each of the EGs. Subfields were delineated using a journal-based classification of scientific research. Canada's strengths and weaknesses at the subfield level were determined using a positional analysis, which presents SI scores, ARC scores, and output volumes for all of the subfields of an EG in a single visual figure. (See Figure 1 above for a discussion of how to interpret these positional analyses.)

Subfields were characterized in two ways: relative to average world levels within a given EG, and relative to Canada's performance in other subfields of the same EG.[43] The former, comparing subfields to global

[43] See § 1.3.6 above for full details on the methodology used for identifying strengths at the subfield level.

thresholds, was used to identify the research areas within each EG where Canada's performance was notably strong (according to combinations of three criteria: ARC, SI, and publication output by volume). The results of this analysis are presented for each EG in their respective subsections of § 2; however, they have been aggregated into a single presentation layout, Table XV below.

Table XV Subfields of Canadian research strength, for each EG

Evaluation Group	Subfields of established Canadian research strength (ARC > 1.1; SI > 1.1)	Subfields of secondary Canadian research strength (ARC > 1.1; output > 1000 pubs)	Subfields of very notable Canadian research strength (ARC > 1.1; SI > 1.1; output > 1000 pubs)
EG1501 Genes, Cells & Molecules	Genetics & Heredity Evolutionary Biology Cardiovascular System & Hematology Nutrition & Dietetics	General Science & Technology Microbiology	Neurology & Neurosurgery Developmental Biology
EG1502 Biological Systems & Functions	Medical Informatics Dairy & Animal Science Genetics & Heredity Sport Science Food Science	(none)	(none)
EG1503 Evolution & Ecology	Ornithology Geological & Geomatic Engineering Oceanography General Science & Technology Environmental Science	(none)	Ecology Evolutionary Biology Fisheries Marine Biology & Hydrobiology Forestry
EG1504 Chemistry	(none)	General Chemistry	(none)
EG1505 Physics	Mathematical Physics	Astronomy & Astrophysics Nuclear & Particle Physics General Physics Fluids & Plasmas Applied Physics	(none)
EG1506 Geoscience	Fisheries Forestry Marine Biology & Hydrobiology Environmental Science General Science & Technology	(none)	(none)
EG1507 Computer Science	Medical Informatics Computational Theory & Mathematics Networking & Telecommunications	Artificial Intelligence & Image Processing General Mathematics	(none)
EG1508 Mathematics & Statistics	(none)	General Mathematics	Statistics & Probability
EG1509 Civil, Industrial & Systems Engineering	Environmental Science Chemical Engineering	(none)	Operations Research
EG1510 Electrical & Computer Engineering	Automated Design & Engineering Industrial Engineering & Automation Optics Optoelectrics & Photonics	Electrical & Electronic Engineering	Networking & Telecommunications
EG1511 Materials & Chemical Engineering	(none)	Materials Polymers	(none)
EG1512 Mechanical Engineering	Biomedical Engineering Orthopedics Industrial Engineering & Automation Aerospace & Aeronautics Electrical & Electronic Engineering	(none)	(none)

Note: Genes, Cells & Molecules (EG1502) and Evolution & Ecology (EG1503) have additional subfields of established strength (i.e., ARC > 1.1; SI > 1.1), which are not listed in this table so as to most effectively highlight those subfields that stand out the most. The threshold for high publication output is 1,000 publications for most EGs, with the exception of EG1501 that has a threshold of 3,000 publications and EG1509 that has a threshold of 500 publications.

Source Computed by Science-Metrix using Web of Science (Thomson Reuters)

Looking at Table XV, one can see that the EGs in which Canada ranks highest internationally based on the composite indicator are the same EGs, generally, in which Canada has the highest number of strengths. The converse also holds, with few strong subfields in the EGs in which Canada's rank among the 27 benchmark nations is lower, using the composite index. However, one important exception is EG1505 (Physics). While Canada is ranked relatively low among selected countries and is not specialized in Physics, a mid-sized research area worldwide, those subfields in which it produces many papers by volume are picked up as secondary strengths in virtue of Canada's consistently high impact scores in the subfields of EG1505.

To highlight areas of potential strategic value, Science-Metrix analyzed performance at the subfield level of each EG, looking for statistical outliers among Canada's performance in these subfields, rather than establishing a threshold based on global performance. In particular, what was sought were subfields in which Canada's research had the highest impact but low specialization, and vice versa. The purpose of this identification is to facilitate strategic interventions, so that areas of high impact can be targeted with measures to increase output (at the expense of other areas), and thereby specialization, and so that areas of specialization can be targeted with measures to increase scientific impact. In these ways, strategic interventions can promote building on the strongest parts of Canada's research foundation. The full results are presented for each EG in their respective subsections of § 2, in addition to being collected for presentation in Table XVI below.

In general, for those EGs in which Canada's performance is particularly strong as well as for those EGs in which it is not, the outlying subfields of Canadian research performance can provide a potential starting point for the design of an intervention strategy. In some EGs, the analysis of performance at the subfield level has revealed only a few outliers. The significance of that finding is that Canadian performance is quite consistent across the subfields of these EGs. As a result, the option to use these outliers as points of leverage in designing a strategy is not as readily available. Thus, a plan to strengthen Canada's research performance in these EGs cannot be as easily built by starting from a few obvious areas around the margins, those for which a targeted strategic intervention might have a notable effect. Rather, Canada's performance in these areas is a result of consistent performance across its tightly clustered subfields; given the small number of outliers, a strategy in these EGs would need to address the nucleus of this cluster, the core issues that determine its more uniform performance across subfields.

Table XVI Subfields of Canadian research for possible strategic consideration, for each EG

Evaluation Group	Subfields with high impact (ARC > mean + 1 std dev) and low specialization (SI < mean - 1 std dev)	Subfields of specialization (SI > mean + 1 std dev) and low impact scores (ARC < mean - 1 std dev)
EG1501 Genes, Cells & Molecules	Biotechnology	Physiology Dairy & Animal Science*
EG1502 Biological Systems & Functions	Artificial Intelligence & Image Processing Fisheries Agronomy & Agriculture	***Experimental Psychology*** Physiology*
EG1503 Evolution & Ecology	General Mathematics Zoology* Plant Biology & Biotechnology*	Physiology Toxicology
EG1504 Chemistry	Materials Medical & Biomolecular Chemistry*	Environmental Science
EG1505 Physics	Materials Optoelectronics & Photonics* General Mathematics*	Biomedical Engineering
EG1506 Geoscience	Oceanography	Civil Engineering ***Geology**** Ecology* Geological & Geomatic Engineering* ***Environmental Engineering****
EG1507 Computer Science	***General Mathematics*** Electrical & Electronic Engineering*	Operations Research* Software Engineering*
EG1508 Mathematics & Statistics	Nuclear & Particle Physics* Artificial Intelligence & Image Processing*	Computational Theory & Mathematics*
EG1509 Civil, Industrial & Systems Engineering	(none)	Geological & Geomatic Engineering* ***Civil Engineering**** ***Environmental Engineering****
EG1510 Electrical & Computer Engineering	Artificial Intelligence & Image Processing*	Computer Hardware & Architecture Energy*
EG1511 Materials & Chemical Engineering	General Chemistry Analytic Chemistry Mining & Metallurgy* Chemical Physics*	Environmental Engineering Civil Engineering Forestry ***Chemical Engineering**** ***Energy****
EG1512 Mechanical Engineering	(none)	Design Practice & Management Building & Construction* Civil Engineering*

Note: Subfields in ***bold italic text*** are those that, in addition to either high ARC or SI scores, also have strong publication output in their respective EGs. Subfields marked with an asterisk (*) were near to the thresholds, and included in virtue of an expert judgment that they were close enough to the relevant threshold, as well as thematically relevant enough to their EG to warrant further consideration.

Source Computed by Science-Metrix using the Web of Science (Thomson Reuters)

Canadian performance in high growth and interdisciplinary topics at world level

The final line of inquiry addressed in the present study was the identification of research topics that are emerging (high growth) or highly interdisciplinary at the world level and in which Canadian performance was especially strong, for potential strategic consideration. The topics were identified using a semantic analysis approach called latent Dirichlet allocation (LDA), which clusters keywords based on their co-occurrence in a set of documents, which in this case was the WoS database of scientific publications. This clustering of keywords is independent of both the EG classification of articles developed for this project, and of the journal-level classification of science into fields and subfields as customarily used by Science-Metrix.

The detailed results of the cluster-level analysis are presented for high-growth topics in Table XIII, and for interdisciplinary topics in Table XIV; a full analysis of notable topics in each category is also provided, in §2.13. However, a summary of the most notable topics is provided in Table XVII.

Table XVII Summary table of notable topics

Global high-growth topics	Global interdisciplinary topics
Lithium-ion batteries 1107	Leaf respiration 431
Smart grids 486	Ocean primary production 1414
Power control 1683	Lab on a chip 1755
Cloud computing 1003	Climate change 1603
Biodiversity *1358*	*Biodiversity* *1358*

Note: Biodiversity (1358) is the only topic to appear both among the topics selected for high-growth and those selected for interdisciplinarity, though it is not among the leaders according to either measure individually. The topics are presented here by their provisional names, used for convenience. Their respective cluster numbers are given here to facilitate connection with the full list of keywords for each cluster (Table XXIII and Table XXIV); the keywords provide the full definition for each topic, which has been simplified in giving each a provisional name.

Source Computed by Science-Metrix using the Web of Science (Thomson Reuters)

Several notes may be helpful here to frame discussions within NSERC about these topics and how to use the results of this topic modeling exercise to inform policy decisions. First, while the topics presented and analyzed are those in which Canada already has an established strength, there are differences in what is driving that strong performance, and those drivers can form the basis for strategic decision-making.

The topics identified in Table XIII are ones in which Canada's strong performance pertains to the high scientific impact of its publications. Additionally, these are topics that are growing quickly not only at the global level, but also within Canada; Canadian growth is outpacing global growth in every topic identified in the table. However, Canada is below the world level of specialization in most of the topics. As these topics are in a mode of rapid expansion at the global level, Canada is unlikely to become an established specialist in each of them. NSERC, therefore, could use funding decisions to promote additional research on a given topic, selecting strategic areas in which to promote the establishment of a Canadian specialization. Such decisions could support the sustaining of some established specialties, the development of new specialties, or a combination of the two.

Looking at Table XIV, the majority of interdisciplinary topics identified here are ones in which Canada's rate of growth is below the world level. Canada is already specialized in about half of these topics (very specialized in some), and not specialized in the other half. Regarding scientific impact, Canada's scores on the interdisciplinary topics are lower than its scores on the high-growth topics (while still above the world level). As international collaborations tend to correlate with higher impact scores, a strategy for supporting interdisciplinary topics could be designed to address two aspects at once: funding opportunities could be used to promote additional research in these topic areas, and connecting a portion of funding to international collaborative projects could help to increase the scientific impact of the resulting publications. Once again, the selection of strategic topics could support the sustaining of some established specialties, the development of new specialties, or a combination of the two.

Appendix – Technical discussion of methods

Database selection

Since the publication portfolios built for DG grantees in a previous study were constructed using the Web of Science (WoS; Thomson Reuters), this is the bibliographic database that has been used in building the datasets for NSERC's EGs in the present study. The WoS provides a comprehensive coverage of the scientific literature in the NSE through its Science Citation Index Expanded (SCI Expanded) database, which covers more than 8,500 major journals across 150 disciplines. It also includes the cited references for each document it covers (e.g., articles or chapters published in a journal or book series), allowing for an internal coverage monitoring of the database and analysis of scientific impact based on citations and impact factors. For instance, Thomson Reuters' monitoring procedure ensures that the most important peer-reviewed journals in their respective fields are indexed.

Because science is not static, the list of key international journals is evolving continuously. For this reason, Thomson Reuters is adjusting the coverage of the WoS on a regular basis to reflect the dynamics of the research ecosystem. Furthermore, the WoS includes all authors and their institutional affiliations, which enables collaboration rates among various entities (e.g., countries, institutions, and researchers) to be analyzed. However, note that in some areas of the NSE (e.g., in computer science and in engineering), the SCI Expanded database might not provide a coverage that is as comprehensive as it is for other areas of the NSE. To partially compensate for this fact, Science-Metrix has filled out the data produced in this study by incorporating a new database, the Conference Proceedings Citation Index, which is now part of the WoS and which indexes more than 150,000 conference proceedings worldwide. The relevance of including the Conference Proceedings Citation Index is quantified in Table XVIII below. Due to limitations of the data, namely that the address is available only for the first author of a given conference proceeding, some conference proceedings have not been accounted for in the publication output of countries and they were not considered in computing data on co-publications.

Nevertheless, the results of the study must be interpreted with caution, along with other lines of evidence and using expert judgment. In the present report, methodological limitations are reported transparently, indicating potential mitigation strategies (where available) to avoid inappropriate comparisons by the client. Some informal analyses (outside the scope of this report) have also been communicated to the client during the production and analysis of data.

For example, it should be noted that the WoS covers only English-language publications, thereby creating a bias towards publications from English-speaking contexts. Asian countries are among the most severely impacted countries by this coverage bias, which manifests itself in many indicators relying on publication counting as well as citation tracking. For example, while China has the largest number of NSE papers in 2014 in the WoS, this assessment does not even take into account the vast majority of its publications (i.e., approximately 87% [44]), which are written in Mandarin, Cantonese and other languages not covered by the WoS.

[44] Rousseau, The Tip of the Chinese Publication Iceberg.

This bias in favour of English-language publications not only severely underestimates the publication count of papers by Chinese authors, it also underestimates the citation count of these same authors, whether they publish their articles in English or not. Specifically, if Paper A cites Paper B, then both A and B must appear in the bibliographic database in order for that citation to be registered (as citations require both a source article and a destination article). For authors from China, then, the fact that 87% of articles written by their compatriots are not covered in the WoS database has an important effect on assessing the impact of their research: if either the source article or the destination article for a citation is written in a language other than English, then the WoS will not cover it, and thus fail to count the citation.

A lack of coverage means that a number of citations cannot be accounted for in computing citation impact metrics, and this lack of coverage disproportionately affects countries where the primary language of scientific publication is not English. As a result, the citation and thus impact assessments of primarily English-speaking countries (e.g., Australia, Canada, United States, United Kingdom, and many European countries) appear to be artificially stronger than they are in reality, compared to their non-native-English-speaking peers.

Table XVIII Proportion of conference proceedings, by EG dataset (2009–2013)

Evaluation Group	Conference papers	All papers	Conference proceedings as share of total papers
EG1501 Genes, Cells & Molecules	29,925	1,034,719	3%
EG1502 Biological Systems & Functions	16,051	225,143	7%
EG1503 Evolution & Ecology	10,180	234,069	4%
EG1504 Chemistry	27,732	467,946	6%
EG1505 Physics	81,090	499,187	16%
EG1506 Geoscience	31,505	284,684	11%
EG1507 Computer Science	199,418	353,945	56%
EG1508 Mathematics & Statistics	21,767	203,919	11%
EG1509 Civil, Industrial & Systems Engineering	18,261	98,204	19%
EG1510 Electrical & Computer Engineering	166,621	344,265	48%
EG1511 Materials & Chemical Engineering	63,369	409,780	15%
EG1512 Mechanical Engineering	74,729	231,406	32%

Note: Due to limitations of the data, namely that the address is available only for the first author of a given conference proceeding, some conference proceedings have not been accounted for above.
Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters)

EG dataset creation

While there is similarity between the divisions into NSE fields (already labelled in the WoS database using Science-Metrix' journal-based classification of scientific research[45]) and the EGs, the two divisions do not overlap perfectly. Therefore, NSE Publications in the WoS first had to be attributed to the EGs,[46] broadly reflecting the definitions thereof, as provided on NSERC's website.[47] The creation of the 12 EG datasets was performed in four phases:

- Construction of initial datasets
- Expansion through citation analysis
- Expansion using specialist journals
- Equalizing the recall (% of classified papers) across NSE subfields

Construction of initial datasets

To create an automated tool to perform this attribution, Science-Metrix used the award summaries of discovery grants as well as the supported-papers of grantees,[48] both classified by EG, to create seed datasets for the identification of a reference set of scientific terms specific to each EG (i.e., to define the *knowledge space* of each EG, see Table I).[49] Using these seed datasets, the scientific terminology of greatest relevance to each of them was identified using a method called *term frequency-inverse document frequency* (tf-idf), which measures how frequently a term gets used in the reference documents of a given EG, relative to how frequently the term is used in the whole WoS database. That is to say, it weighs the importance of a term within a given EG against the occurrence and uniqueness of that term to that EG in particular. (The score, then, is always a relation between a term, a specific EG, and a general background of literature.) Frequent use of a term within a given EG increases the term's tf-idf, relative to that EG; frequent use of the term outside the given EG decreases the term's tf-idf, again relative to that EG. Using this approach, reference sets of approximately 2,000 keywords/scientific idioms, each representing the *knowledge space* of a given EG, were created.

[45] Archambault É., Caruso J., and Beauchesne O. (2011). Towards a Multilingual, Comprehensive and Open Scientific Journal Ontology, in Noyons, B., Ngulube, P. and Leta, *J. Proceedings of the 13th International Conference of the International Society for Scientometrics and Informetrics (ISSI)*, Durban, South Africa, pp 66-77.

[46] A relatively small number of non-NSE articles, mostly from subfields of Clinical Medicine (e.g., sports science), were also included, as they were relevant to some of the EGs.

[47] http://www.nserc-crsng.gc.ca/Professors-Professeurs/Grants-Subs/DGPList-PSDListe_eng.asp

[48] These papers were obtained from the publication portfolios of some 2,354 DG grantees, which were constructed by Science-Metrix in a previous study for NSERC in 2013.

[49] Specifically, the title, abstract and keywords of each award summary and paper were used to identify the terminology specific to each EG.

Table XIX Composition of the seed datasets

EG	EG name	Discovery grant	Research outputs		
		Award summaries	No. of grantees	Supported papers*	Supported papers & award summaries
1501	Genes, Cells and Molecules	1,082	281	742	1,824
1502	Biological Systems and Functions	1,286	352	1,285	2,571
1503	Evolution and Ecology	558	172	726	1,284
1504	Chemistry	609	253	1,187	1,796
1505	Physics	703	158	843	1,546
1506	Geosciences	601	150	545	1,146
1507	Computer Science	876	130	265	1,141
1508	Mathematics and Statistics	829	132	333	1,162
1509	Civil, Industrial and Systems Eng	678	164	545	1,223
1510	Electrical and Computer Eng	722	172	686	1,408
1511	Materials and Chemical Eng	560	205	920	1,480
1512	Mechanical Eng	560	185	637	1,197

Note: Award summaries and supported papers are not related (i.e., they correspond to different pools of grantees). *Proceedings are not included in the seed datasets.
Source: Computed by Science-Metrix using NSERC's data and the Web of Science (Thomson Reuters)

Using the reference set of keywords for each EG, it was possible to calculate the proximity of a given article to each of the EGs. This calculation compares the scientific language used in the article to each of the words in the 12 sets of keywords (one per EG), creating "similarity scores" that reflect the proximity of the article to each one of the EGs.[50] Papers were then attributed to the most proximate EG.[51] To achieve a non-mutually exclusive classification of the papers (some papers naturally fit in more than one EGs; for example, interdisciplinary papers), if the similarity score with the 2nd closest EG was within 20% of the 1st, the paper was attributed to both EGs. Furthermore, if the similarity score with the 3rd closest EG was within 20% of the 2nd, the paper was attributed to all three. (And so on, until the next most proximate EG did not meet the 20% threshold.)

Expansion through citation analysis

For the papers that were not classified during that first phase of sorting (because they did not meet minimal thresholds for similarity with any EG), a second sorting tool was applied. This second tool started from the citations within the paper and analyzing where the articles cited therein had been classified. In this way, it was possible to calculate the proximity of these papers to the different EGs as the share of their outbound citations given to each EG. Again, as in the first sorting phase, articles were assigned to

[50] The similarity of a given paper for a given EG is equal to the sum of the tf-idf weights of all terms found in that paper that are part of that EG's knowledge space.

[51] There was an additional constraint in attribution: the similarity score had to be based on the tf-idf of at least two terms. Validation during random sampling exercises showed that this additional constraint greatly increased the accuracy of attribution.

their most proximate EG; and again, if the next most proximate EG was within 20%, the article was assigned to both EGs (and so on).[52]

Expansion using specialist journals

For the remaining papers, those not classified in the first or second phase of attribution, a final technique was applied. Rather than using semantics or citations, this third tool relied on the journal in which the article appeared. Specifically, if at least two thirds of the articles published in a given journal were already attributed to a particular EG, then any still-to-be-sorted articles published in that journal were attributed to that EG. That is to say, if more than two thirds of a journal's articles had already been sorted into EG1508, then any articles in that journal (only those that were not classified in the first two phases) were classified as falling under EG1508. The remaining papers that could not be sorted using any of these methods were therefore not considered in the bibliometric analyses of the present study.

Equalizing the recall (% of classified papers) across NSE subfields

As described above, three approaches have been used to construct the EG datasets. Note that with the first two approaches, papers are assigned to the most relevant EGs in a non-mutually exclusive manner. The first approach made use of the language used by NSERC grantees in their supported publications as well as in their grant proposal descriptions. Following this approach, a test was made to assess if the method was equally effective in classifying papers across the main fields (as per the Science-Metrix classification, see above in the current section) of the NSE. It was found that the approach based on terminology was not as effective in some fields—for example, in Engineering, Mathematics & Statistics, and Information & Communication Technologies. To compensate for this, and to ensure an equally representative coverage of all fields of the NSE, two additional approaches were used to increase the recall in such fields (i.e., the share of publications that have been classified in at least one EG). The second phase made use of the papers' outbound citations to the core datasets established in the first phase. The third phase classified all the unclassified papers of a journal in the main EG of the journal identified with the already classified papers (at least two thirds of a journal's classified papers must be in the same EG for this attribution to take place).

Subsequently, papers in each subfield were sampled randomly to ensure an equally representative coverage of all fields of the NSE. The recall was thus set to 77% (the smallest recall among most EGs, which was observed in Engineering). Table XX below summarizes the constitution of each EG's dataset at the outset of this sampling. In performing the random sampling, priority was given to papers classified in phase 1, followed by phase 2, and finally phase 3. This priority was established to minimize departure from the *knowledge space* originally defined using the terminology found in NSERC grantees supported publications and grant proposal descriptions. As a result, there were instances where it was not required to sample papers classified in step 2 and step 3. Only in Built Environment & Design was it not possible to achieve the desired recall (i.e., 65% instead of 77%). This is not surprising since this is the only field in the NSE, as per Science-Metrix' journal-based classification, that as a strong linkage with the Social

[52] There was an additional constraint in attribution: the papers to be assigned had to include at least two outbound citations to the EG to which it is closest. Validation during random sampling exercises showed that this additional constraint greatly increased the accuracy of attribution.

Sciences and Humanities (SSH), possibly because of Architecture. This linkage was established through a citation network analysis, which indicated that about 20% of references from papers in this field are given to fields in the SSH. Note that some papers outside the core NSE fields (i.e., from Clinical Medicine) were also classified in some EGs given their strong relevance to those EGs. For instance, it was found that NSERC grantees did publish papers to a good extent in some subfields of Clinical Medicine (e.g., 1501: Neurology & Neurosurgery; 1502: Sport Sciences; 1507: Nuclear Medicine & Medical Imaging; 1512: Orthopedics).

Table XX Recall of papers by main field of the NSE (i.e., % of papers classified in at least one of 12 EGs) (2009–2015)

	No. of classified papers			
Subfield	**Keywords**	**References to the EG datasets built with keywords**	**Main EG of a journal (at least two thirds of the journal's classified papers must be in the same EG)**	**Recall (%)**
Agriculture, Fisheries & Forestry	165,687	38,293	0	77%
Biology	220,091	0	0	77%
Biomedical Research	413,490	0	0	77%
Built Environment & Design	16,443	16,647	3,355	65%
Chemistry	346,330	140,956	0	77%
Earth & Environmental Sciences	175,660	16,573	0	77%
Enabling & Strategic Technologies	396,673	126,952	0	77%
Engineering	292,265	163,481	14,497	77%
General Science & Technology	102,087	0	0	77%
Information & Communication Tech	315,435	114,124	4,563	77%
Mathematics & Statistics	86,727	68,678	12,664	77%
Physics & Astronomy	439,654	271,507	0	77%

Source: Computed by Science-Metrix using NSERC's data and the Web of Science (Thomson Reuters)

Assessing the accuracy of the EG datasets

The accuracy of an EG dataset was measured as the percentage of relevant papers in a random sample of 50 papers from said dataset. The relevance of a paper to a given EG dataset was assessed relying on NSERC's definition of that EG.[53] Based on this assessment, it was found that the accuracy of the EG datasets thus created ranged from a low of 90% to a high of 100% (see Table XXI). The quality of the assignment procedure based on keywords was also tested looking at the proportion of NSERC proposals that were correctly re-classified with such a method. We did not expect 100% accuracy given the existing overlap in the definitions of NSERC's 12 EGs. Yet the majority of proposals were correctly re-classified in all EGs, except EG1502 (see Table XXII). In fact, the mis-assignments provide useful information on the proximities of the different EGs and on potential overlap. For instance, the second-most important EG in which the proposals of a given EG have been re-classified is often strongly related to the EG originally attributed by NSERC and also shows some overlap based on NSERC's definitions. For EG 1502, for which the accuracy is much lower (50% of correct re-classification), manual checks were performed to better characterize the quality of the assignments. The following findings were made, based on a random sample of 50 mis-assignments:

[53] http://www.nserc-crsng.gc.ca/Professors-Professeurs/Grants-Subs/DGPList-PSDListe_eng.asp

- The tool correctly re-classified the proposals according to NSERC's definitions of EGs in 48% of the cases, thereby questioning the original assignments as provided by NSERC.
- In 32% of the cases, the proposals pertained to cell biology, biochemistry and other molecular level studies in plants, which are pertinent to both 1501 and 1502.
- In 8% of the cases, the proposals pertained to animal reproduction (molecular level), which is pertinent to both 1501 and 1502.
- In 4% of the cases, the proposals pertained to food microbiology, biochemistry and other molecular level studies in plants, which are pertinent to both 1501 and 1502.
- In another 4% of the cases, the proposals were in fact incorrectly classified.
- In 2% of the cases, the proposals pertained to muscle physiology at molecular level, which is pertinent to both 1501 and 1502.
- In another 2% of the cases, the proposals pertained to biomechanics involving research aspects at the biochemical level, which is pertinent to both 1501 and 1502.

Table XXI Quality assessment of the constructed datasets for NSERC's Evaluation Groups (2009–2015)

EG	Dataset Accuracy (%)	R^2 between the subfield distributions of the seeds and final datasets
1501	92	0.78
1502	96	0.71
1503	90	0.85
1504	100	0.78
1505	94	0.94
1506	98	0.95
1507	96	0.66
1508	96	0.60
1509	98	0.82
1510	96	0.90
1511	98	0.76
1512	94	0.82

Source: Computed by Science-Metrix using NSERC's data and the Web of Science (Thomson Reuters)

A correlation analysis between the subfield distributions of the seeds and final datasets was also performed to assess the extent to which the patterns observed in the seeds were reflected in the final datasets. For only two EGs (1507 and 1508), the percentage of variation in the dataset explained less than 70% of the variation in the seed (see Table XXII**Error! Reference source not found.**). This is likely explained by the fact that for two subfields directly related to those EGs (i.e., Mathematics & Statistics and Information & Communication Technology), a journal-based approach had to be used to improve the retrieval of relevant papers following the approaches based on keywords and references. Thus, the quality of the EG datasets is considered very good.

Table XXII Automated re-attribution of NSERC grantees' research proposals to NSERC Evaluation Groups (EGs)

EG	EG Name	Assigned EG*	Share of Total
1501	Genes, Cells and Molecules	1501	97%
1501	Genes, Cells and Molecules	1503	1%
1502	Biological Systems and Functions	1502	50%
1502	Biological Systems and Functions	1501	41%
1503	Evolution and Ecology	1503	88%
1503	Evolution and Ecology	1506	5%
1504	Chemistry	1504	61%
1504	Chemistry	1501	21%
1505	Physics	1505	87%
1505	Physics	1501	5%
1506	Geosciences	1506	89%
1506	Geosciences	1503	4%
1507	Computer Science	1507	86%
1507	Computer Science	1501	4%
1508	Mathematics and Statistics	1508	74%
1508	Mathematics and Statistics	Unclassified	7%
1509	Civil, Industrial and Systems Engn	1509	82%
1509	Civil, Industrial and Systems Engn	1506	6%
1510	Electrical and Computer Engn	1510	69%
1510	Electrical and Computer Engn	1505	10%
1511	Materials and Chemical Engn	1511	63%
1511	Materials and Chemical Engn	1504	11%
1512	Mechanical Engn	1512	68%
1512	Mechanical Engn	1511	9%

Note: Based on highest score (mutually exclusive assignment). For all assignments, please refer to the companion Excel databook to this report.
Source: Computed by Science-Metrix using NSERC's data and the Web of Science (Thomson Reuters)

The accuracy of the final EG datasets was also corroborated by a network analysis investigating existing overlap between EGs based on the multiple assignments of grant proposals and research papers, as well as on data on joint reviews of DG applications (i.e., applications reviewed by more than one EG). The resulting structures for the two former types of assignments are broadly comparable to that based on joint reviews, thereby highlighting the accuracy of the assignment procedure as well as the natural proximities between the disciplines represented by each EG. These proximities are also aligned with the overlap that can be identified in NSERC's definitions of the EGs.

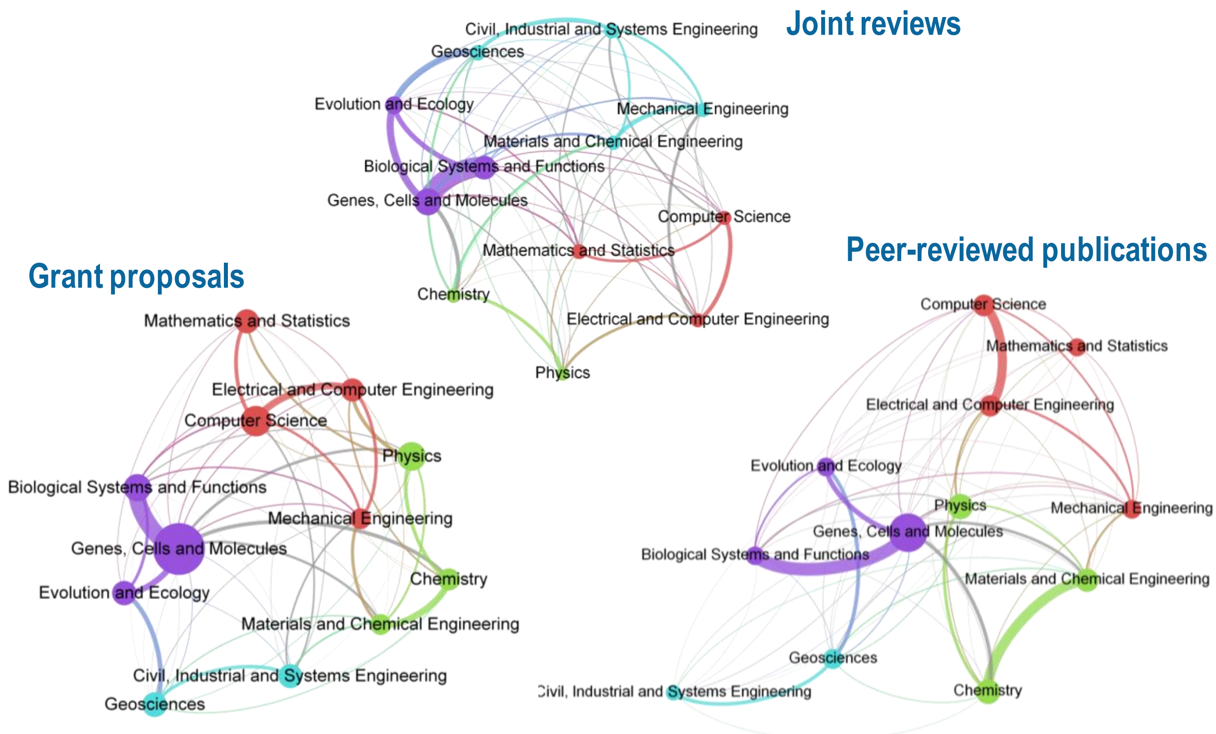

Figure 16 Networks showing existing overlap between EGs based on joint reviews or the multiple assignments of DG applications or peer-reviewed scientific publications

Note: Links between two EGs are proportional to the number of grant proposals, or papers, assigned to both EGs. The size of a node is proportional to the number of grant proposals, or papers, assigned to a given EG. The clusters (nodes of different colours) were identified using an algorithm for the fast unfolding of communities in large networks.

Source: Computed by Science-Metrix using NSERC's data and the Web of Science (Thomson Reuters)

Bibliometric indicators

Number of publications

This is an analysis of the number of publications obtained using full counting. Using the full-counting method, each paper is counted once for each entity listed in the address field. For example, if a paper is authored by two researchers with addresses in the UK, one from Spain and one from the US, the paper will be counted once for the UK, once for Spain, and once for the US. In fractional counting, publications are divided based on the number of addresses listed on the publications, with each entity being attributed its share of the publications. For instance, if a paper lists two addresses from the UK, one from Spain, and one from the US, the publication is divided into four parts, with the UK receiving two of these parts (0.5 publication), Spain receiving one (0.25 publication), and the US receiving the fourth part (0.25 publication). Data based on full counting are an indicator of presence on papers, whereas fractional counting provides an indication of the share of knowledge contributed by a given entity, such as a country. Fractional counting will be used only in computing the SI (see below), with full counting being used for the computation of all other indicators.

International co-publishing rate and collaboration index

An international co-publication is defined as a publication that was co-authored by individuals from at least two countries. The international co-publishing rate is obtained by dividing the number of international co-publications of a country over its total number of co-publications (both national and international). Full counting is used to compute the collaboration index (CI).

There is often a power law relationship between an entity's (i.e., a country's) number of papers and its number of international co-publications. In cases where a power law relationship exists between two variables, it is better to use scale-adjusted indicators instead of percentages to appropriately take account of the relative size of entities being compared; percentages, like the percentage of publications authored in collaboration, assume a linear relationship.[54] When both indicators are log transformed, power law relationships can be analyzed using linear regression models. Therefore, the approach used to compute the collaboration index consists in performing a log-log linear regression analysis between the number of co-authored publications and the number of publications at a specific aggregation level (e.g., countries) in order to estimate the constants (a and k) of the power law relationship:

Expp (M) = a *(M^k)

Where:

Expp = the expected number of co-authored papers of an entity (e.g., a country) based on the regression model; and

M = the observed number of publications of the entity (e.g., country) being measured.

The log-log linear regression analysis is performed using reduced major axis (RMA) to estimate the constants (a and k) of the regression model. The indicator is simply the ratio of observed to expected co-authored publications. When the indicator is above 1, an entity produces more publications in collaboration than expected based on the size of its scientific production, while an index value below 1 means the entity produced fewer than expected international co-publications.

Specialization index

The specialization index (SI) is an indicator of research intensity in a given entity (e.g., a country) for a given research area (e.g., a field), relative to the intensity in a reference entity (e.g., the world) for the same research area. In other words, when a country is specialized in a field, it places more emphasis on that field than the global average, at the expense of other research areas. Specialization is therefore said to be a zero sum game: the more one specializes somewhere, the less one does elsewhere. To ensure that it is a real zero sum game, the publication numbers used to compute the SI are based on fractional counting. The SI is formulated as follows:

$$SI = \frac{(X_S/X_T)}{(N_S/N_T)}$$

[54] Katz, J. S. (2000). Scale-independent indicators and research evaluation. *Science and Public Policy*, *27*(1), pp. 23–36.

Where

X_S = Publications from entity X in a given research area (e.g., papers by the UK in physics)
X_T = Publications from entity X in a reference set of papers (e.g., total papers by the UK)
N_S = Publications from reference entity N in a given research area (e.g., world papers in physics)
N_T = Publications from reference entity N in a reference set of papers (e.g., total world papers)

An index value above 1 means that a given entity is specialized relative to the reference entity, whereas an index value below 1 means the reverse.

Growth ratio

In this report, the growth ratio (GR) was computed by dividing the production in a recent period (e.g., 2012–2013) by an earlier period (e.g., 2009–2010). The advantage of the GR is that it is robust and can be used to analyze growth even in the presence of large annual fluctuations. Publications appearing after 2012 (i.e., in the year 2013 or later) were not included in this study because not enough time has passed for them to accumulate a number of citations that accurately reflects their scientific impact. Though citations and impact are not components that factor into the calculation of the GR, these papers were left out of the entire study to maximize consistency.

Average of relative citations

The average of relative citations (ARC) is an indicator of the scientific impact of papers produced by a given entity (e.g., the world, a country, an institution) relative to the world average (i.e., the expected number of citations). The number of citations received by each publication is counted for the year in which it was published and for the two subsequent years. For papers published in 2002, for example, citations received in the 2002–2004 period were counted. To account for different citation patterns across fields and subfields of science (e.g., there are more citations in biomedical research than in mathematics) and differences in the age of publications (i.e., different citation patterns over the years), each publication's citation count is divided by the average citation count of all publications of the corresponding document type (i.e., a review would be compared to other reviews, whereas an article would be compared to other articles) that were published the same year in the same subfield. In this way, one arrives at a relative citation count (RC).

The ARC of a given entity is the average of the RCs of the papers belonging to it. An ARC value above 1 means that a given entity is cited more frequently than the world average, while a value below 1 means that its publications receive, on average, fewer citations than the world average.

Highly cited papers

Highly cited papers (HCP) are publications that received the highest relative citation score (RC) in their respective field. This indicator is frequently used to examine research excellence. For this study, the top 5% most cited publications were selected, and data for leading countries were then produced based on these highly cited papers in order to identify world leaders not only based on raw output, but also according to high-impact research.

Average of relative impact factors

The impact factor (IF) is a score calculated at the journal level; it is the most popular bibliometric measure in current use.[55] The IF is equal to the total number of times articles published in the journal in years X-1 and X-2 were cited in the year X, divided by the total number of citable documents appearing in the journal in X-1 and X-2. It is thus a ratio expressing the average number of times articles and other citable documents in a journal are cited. As such, using the IF to evaluate individual research publications (or the entities producing them) is equating the quality of research with the quality of the journal in which it is published.

Of all indicators, the IF seems to be the one most subject to debate.[56] Its strength lies in its comprehensibility, stability, "seeming reproducibility," and fast availability.[57] The main criticisms levelled against the impact factor are the following: (a) the fact that it does not take into account differences in citation practices between scientific fields;[58] (b) that there is no distinction made for the merit of the citing journal; (c) that there is a bias in favour of journals with lengthy papers; (d) that known literature ageing biases are not corrected; (e) the inappropriateness of the two-year citation window for some journals and fields where the citation peak is achieved in more time is not addressed; (f) it does not address the insufficiency of a single measure to describe citation patterns of a scientific journal; (g) it occludes inaccuracies due to inadequate operationalization of the concept of citable document;[59] and (h) it incorporates errors due to the incorrect identification of cited journals.

Many authors have obtained results that undermine the validity of the impact factor. Rinial et al. (1998), for example, found that the measure of the impact factors of the journals in which a research unit publishes does not correlate well with peer assessment of the performance of that unit. However, this presumes that experts can indeed rank journals adequately, that a correlation between expert review and IF scores is expected, and consequently that the IF is deficient for the low correlation scores with peer assessment. It would seem the indicator is also affected by the number of journals in a field; the type and number of publications in a journal,[60,61] the uncitedness of a journal, and the frequency distribution of

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[55] Glänzel, W., & Moed, H. F. (2002). Journal impact measures in bibliometric research. *Scientometrics*, *53*(2), p. 200.

[56] Archambault, É., & Larivière, V. (2009). History of the journal impact factor: Contingencies and consequences. *Scientometrics*, *79*(3), pp. 635–649. doi:10.1007/s11192-007-2036-x.

[57] Glänzel, W., & Moed, H. F. (2002). *Ibid.*

[58] Baudoin, L., Haeffner-Cavaillon, N., Pinhas, N., Mouchet, S., & Kordon, C. (2004). Indicateurs bibliométriques: Réalités, mythes et prospective. *Médecine/sciences*, *20*(10), pp. 909–915. doi:10.1051/medsci/20042010909.

[59] Moed, H. F., & Van Leeuwen, T. N. (1995). Improving the accuracy of institute for scientific information's journal impact factors. *Journal of the American Society for Information Science*, *46*(6), pp. 461–467. doi:10.1002/(SICI)1097-4571(199507)46:6<461::AID-ASI5>3.0.CO;2-G.

[60] Cameron, B. D. (2005). Trends in the Usage of ISI Bibliometric Data: Uses, Abuses, and Implications. *Portal: Libraries and the Academy*, *5*(1), pp. 105–125. doi:10.1353/pla.2005.0003.

[61] Moed, H. F., & Van Leeuwen, T. N. (1995). *Ibid.*

citations to its papers.[62] The inventor of the impact factor, Eugene Garfield, still defends the IF as it stands today.[63]

In developing a more robust version of the impact factor, Science-Metrix uses an approach similar to that used for the average of relative citations, which is called the average of relative impact factors (ARIF). This is an indicator of the quality of papers produced by a given entity (e.g., a country, a specific set of papers, a researcher) based on the journals in which they were published. The IF of papers is calculated by ascribing to them the IF of the journal in which they are published, for the year in which they are published. Subsequently, to account for different citation patterns across fields and subfields of science, each paper's IF is divided by the average IF of the papers published the same year in its subfield to obtain a Relative Impact Factor (RIF). The ARIF of a given entity is the average of its RIFs (i.e., if an institution has 40 papers, the ARIF is the average of 40 RIFs, one per paper). The ARIF is given by:

$$ARIF = \sum_{i_{j,y}=1}^{T} \left(\frac{IF_{i_{j,y}}}{\sum_{k_{j,y}=1}^{T_{j,y}} \left(\frac{IF_{k_{j,y}}}{T_{j,y}} \right)} \right)$$

Where

$i_{j,y}$	Paper from an entity that falls in a specific subfield *j* and is published in period *y*
$IF_{i_{j,y}}$	Impact factor of the journal where paper $i_{j,y}$ is published
T	Total number of papers from a given entity
$T_{j,y}$	Total number of papers from subfield *j* published in period *y*
$IF_{k_{j,y}}$	Impact factor of the journal in which paper *k* from subfield *j* and period *y* is published

In contrast to Thomson Reuters' impact factor, which is an asymmetric indicator counting the ratio between citations to all items, relative solely to the number of citable items, Science-Metrix' indicator is symmetric. It calculates the ratio between citations to citable items (articles, reviews, and notes) and the number of citable items. Thus, the impact factor used by Science-Metrix is calculated in the following manner:

$$IF_{i_{j,y}} = \frac{\sum_{i_{j,y}=1}^{T_{y_t}} C_{i_{y_t}}}{T_{y_t}}$$

Where

62 Van Leeuwen, T. N., & Moed, H. F. (2005). Characteristics of journal impact factors: The effects of uncitedness and citation distribution on the understanding of journal impact factors. *Scientometrics*, *63*(2), pp. 357–371. doi:10.1007/s11192-005-0217-z.

63 Garfield, E. (2000). Use of journal citation reports and journal performance indicators in measuring short and long term journal impact. *Croatian Medical Journal*, *41*(4), pp. 368–374.

$i_{j,y}$	Paper from an entity that falls in a specific subfield j and is published in period y
$C_{i_{y_t}}$	Citations in period y to papers published during period y_t
T_{y_t}	Total number of citable items from the y_t period
y_t	Years where impact factors are considered.

For this project, the IF of a journal is computed over five years. For example, in 2007, the IF of a journal would be equal to the number of citations to articles published in 2006 (e.g., 8), 2005 (15), 2004 (9), 2003 (5) and 2002 (13), divided by the number of articles published in 2006 (e.g., 15), 2005 (23), 2004 (12), 2003 (10) and 2002 (16) (i.e., IF = numerator [23] / denominator [38] = 0.658).

When the ARIF is above 1, it means that an entity generally publishes in journals that are cited more frequently than the world average; when it is below 1, the journals are cited below the world average.

Composite indicator of scientific performance

To benchmark Canada against other leading nations, a composite indicator synthesizing various dimensions of scientific performance was computed on a yearly basis. This allows one to track trends in the global position of Canadian research over time. Furthermore, such composite or multicriteria measures allow for the identification of countries that stand out when considering all indicators jointly in each of the EG datasets (and their underlying subfields).

The scientific performance of countries is multidimensional and it is hardly possible to capture all such dimensions using bibliometric indicators. Still, the indicators above capture some of the very key dimensions characterizing the scientific performance of countries. When multiple indicators are used, it is often difficult to determine the relative position of countries without the aid of a well-structured ranking mechanism (i.e., a composite indicator). Although such multicriteria ranking tools have been the subject of heated debates among experts in the field of bibliometrics—especially because they hide an important amount of the variation in the underlying dimensions they synthesize—Science-Metrix believes that they remain invaluable tools to highlight the most salient results from the considerably large amount of data typically produced in bibliometric assessments, while recommending that they be used in conjunction with expert judgement. Experts analyzing the composite measures should not neglect important variations that might be present in the underlying data, and this report attempts to unpack that underlying data through its detailed discussion in the Results section above (§ 2). Additionally, such tools are best used when the weighting of the individual indicators integrated in the composite measure is established in partnership with the client to address the client's policy priorities; for example, in determining whether the focus should be on the size or impact of scientific output.

Various methods have been developed in the scientific literature to reduce numerous indicators to a single composite indicator or multi-rank. However, these methods are often sensitive to the composition of the study sample: the position of two entities relative to one another (i.e., A performs better than B or vice-versa) can be altered if other entities are added or removed from the sample. A similarity-based approach to ranking multicriteria alternatives was adapted to provide a stable composite indicator and multi-rank in a bibliometric context.[64] The method ranks alternatives based on their degree of similarity to the positive-ideal solution. The key aspect of this approach consists in setting the positive-ideal solution to constant values regardless of the composition of the sample by determining, theoretically or empirically, the maximum possible value of each indicator. The similarities are computed by projecting each alternative's vector of N dimensions (i.e., N indicators) on the reference vector (i.e., the ideal solution vector) using the cosine of the angle between them. The resulting indicator varies between 0 (worst possible performance) and 100 (best performance possible). The method allows one to adjust the weight of individual indicators so as to reflect the relative importance attributed to these measures by decision-makers, based on policy priorities.

In this study, the composite indicator was used to synthesize information gathered on the scientific performance of countries. The following indicators were used: number of publications, GR (normalized by the world), SI, as well as an average of ARC, ARIF and highly cited publications.

Interdisciplinarity score

At present, no single approach for the measurement of interdisciplinarity has emerged as the predominant method.[65] For the present study, a cutting-edge approach was applied, one that measures interdisciplinarity—or equivalently the inter-subfield integration of knowledge—at the level of individual papers. In brief, the interdisciplinarity score assesses whether the distribution of an article's outbound citations (i.e., the citations it gave to other publications identified through its reference list) across scientific subfields departs from the predominant pattern of knowledge integration, as defined through the inter-subfield citation patterns of the whole publication database. An assumption in using a citation-based indicator is that citation patterns are reflective of knowledge integration: that is to say, that Paper A citing Paper B is a good indication that the contents of Paper A have integrated (at least a portion of) the contents of Paper B.

Each paper is assigned an interdisciplinarity score from 0 to 1, with 0 being completely mono-disciplinary (i.e., diverging completely from the predominant inter-subfield citation pattern, integrating knowledge from only one discipline) and 1 being extremely interdisciplinary (i.e., diverging completely from the predominant inter-subfield citation pattern, integrating more diverse knowledge than is usually the case). The score integrates three factors that together reflect the diversity of the knowledge integrated within a single article: how many different disciplines are being cited, how distant those disciplines are from each other, and how are the citations given by a paper distributed amongst those disciplines. Put simply, the proposed interdisciplinarity score measures the extent to which co-citing a high energy physics paper with a veterinary paper diverges from the predominant pattern of knowledge exchange across subfields in the entire database, either in the direction of more or less integration than would be expected. In the current example, the departure is obviously in the direction of more integration than would be expected. Now, if a paper cited nine high energy physics papers and only one veterinary paper, it would be deemed less interdisciplinary than a paper citing 5 high energy physics papers and 5 veterinary papers. If another paper

[64] Campbell, D. (2011). Dimensionality reduction in the multi-criteria analysis of scientific performance. Presented at the Annual Meeting of the Society for Social Studies of Science (4S), Cleveland, OH.

[65] Wagner et al., Approaches to Understanding and Measuring Interdisciplinary Scientific Research (IDR).

cited the above two disciplines plus three additional ones in the same proportions, it would also be considered more interdisciplinary.

With a score for each paper, one way to compute a score for institutions, countries and other aggregations (such as research topics as in this project) is to simply take the average of interdisciplinarity scores of all of its publications. However, due to coverage issues of the cited references in the database (i.e., not all the references of papers appearing in WoS are themselves covered in the database), this approach produces unsatisfactory results. Specifically, certain disciplines of research have higher levels of coverage than others, and interdisciplinarity scores correlate very strongly with coverage rates, suggesting that a normalization needs to be carried out in order to take a more accurate reading of the true level of interdisciplinarity.

The approach adopted for the present study is to only consider articles that cite a large number of documents, as this large number of citations has been shown as a reliable approach to overcome coverage issues.[66] For each discipline, the papers with the most outbound citations (specifically, the top 1% of the most outbound citations, from each discipline) are used to form the candidate pool of papers for further analysis. Within this pool, then, the interdisciplinarity score for each paper is calculated without worry about coverage bias. The papers are then divided into deciles, and those falling within the top 10% are identified as the most interdisciplinary papers. Research topics are then evaluated based on their contributions to this top 10% of highly interdisciplinary publications (much like the HCP evaluates a country's contribution to the top 10% of the most highly cited papers).

One consideration to keep in mind when interpreting the results of this interdisciplinarity score is that it is only considering a very specific kind of work. Specifically, because only the works with the highest numbers of outbound citations are eligible for consideration (and assuming that the number of outbound citations is correlated to the amount of knowledge being integrated, and thus to the size of the research project), this measure is reflective of interdisciplinarity *among the largest, summative research projects* within a discipline. But it could be that interdisciplinary research is taking place even in smaller projects, and such a fact cannot be captured using this measure—a necessary sacrifice in order to correct for coverage biases.

The expected value for the interdisciplinarity score is 0.10; that is to say, if interdisciplinary work were evenly distributed across all research fields and geographic locations, then any subset of publications would be expected to have 10% of its publications in the top 10% of the most interdisciplinary work. Accordingly, interdisciplinarity scores above 0.10 show that a given field/entity is contributing more than its expected share of highly-interdisciplinary papers; a score close to 0.10 shows that the contribution is near the expected value; and a score below 0.10 shows that the contribution is less than would be expected.

[66] Campbell et al., Application of an "Interdisciplinarity" Metric at the Paper Level and Its Use in a Comparative Analysis of the Most Publishing ERA and Non-ERA Universities.

Identification of high-growth and interdisciplinary topics

Topic modeling using LDA

To identify high-growth and interdisciplinary topics, an approach called latent dirichlet allocation (LDA) was used first to delineate a set of topics, which were subsequently analyzed to identify those that are growing quickly as well as those that are highly interdisciplinary. The first step in that process, using the LDA to identify topical clusters, is in some ways similar to using tf-idf to create the EG datasets;[67] articulating the relevant differences will provide helpful insights to understand the LDA approach, and the resulting topical clusters it maps.

For the tf-idf approach, a number of documents already sorted into groups are fed in as input, and the analysis determines which words are central to which groups. On that basis, unsorted documents can be attributed to one or more groups on the basis of which words they use (and how often), and how those words score relative to the groups. In this way, tf-idf is a useful approach for extending pre-existing classification schemes.

By contrast, the LDA starts from a set of documents that are *not* already grouped, and identifies natural groupings within those documents. As input, the LDA requires the set of documents to group, the number of groups to find (i.e., the number of clusters anticipated to exist within the set), and the number of iterations to run. The group of documents is the total set of NSE publications found within the WoS database. Regarding the number of clusters to expect, experimentation conducted internally at Science-Metrix has determined that the square root of the number of inputted documents will reliably produce satisfactory results. In the present study, the total number of papers used is in the order of 4,000,000 documents, and so number of topics was set to 2,000. As for the number of iterations, Science-Metrix uses 200 iterations as standard in topic modeling projects, as this number is consistent in yielding meaningful results.

What does the LDA process actually do? In short, it groups words based on their co-occurrence patterns in documents. Note that information on the grouping of documents by scientific discipline is not provided to the LDA procedure before it begins. The words are then provisionally assigned, in a non-mutually exclusive manner, to a topic number (random numbers from 1 to 2,000, used as bins to collect topical themes). These provisional assignments are what propagate a cumulative influence throughout the process; whereas for the first iteration none of the words are yet assigned to bins, each subsequent iteration begins with partially defined picture of the topical map, with each iteration refining further and further detail in the modeling, until finally a clear picture begins to stabilize. When the 200 iterations are complete, and the process comes to an end, each of the numbered bins has a set of words associated with it—some of which have a greater likelihood of belonging to a given topic than others—and these sets of words describe the topics that have naturally emerged from the documents inputted.

On the basis of this sorting of words into clusters, papers can then be assigned a proximity score (from 0 to 1) for each cluster, based on how much the terminology used in the paper overlaps with the terms in the cluster. For the current project, papers were assigned to the cluster with which they had the highest

[67] See Section 1.3.2.

proximity score. In cases of ties, papers were assigned to all the clusters that shared in the tie for the top score. Ties were very rare in the present project, so the final classification was very close to mutually exclusive; the vast majority of papers were assigned to one and only one topical cluster, though with a few exceptions that were assigned to multiple clusters.

Additionally, some quality control measures were applied to weed out spurious topics that may have emerged during the LDA process. The first quality control measure was quantitative. Each paper was assigned to the cluster to which it was the closest, semantically; however, in some cases, a publication may have very low proximity scores for all of the clusters, even the one to which it is the closest. The papers whose maximum proximity scores were below 0.12 (i.e., a threshold below which the assignments did not appear as being robust based on random sampling of such assignments) were simply discarded. Then, with the papers already sorted, the quality of each cluster was evaluated based on how *strongly* its papers were associated with it; an integrity score was calculated by taking the median of the affinities of all the articles in a cluster to the terms defining the cluster. In some cases, clusters were screened out because they were not strongly integrated. Specifically, clusters were screened out if their *median* integrity score was below the *median* integrity score of all the clusters. That is to say, clusters that were less integrated than the norm were not considered.

Lastly, a qualitative measure was applied to ensure that only robust clusters were considered. Looking at the words that were grouped together in forming the clusters, some clusters were rejected on the grounds that the terms grouped did not show a true thematic affinity, based on expert judgment. For example, "interdisciplinary," "interstate" and "interaction" all have a common linguistic particle, but do not in fact reflect an underlying topical similarity. Such a grouping would be screened out.

Identifying topics of interest

With papers assigned to the various topics, bibliometric indicators (described in § 1.3.3) were applied to perform different analyses. To identify topics that are high-growth at the world level, and in which Canada has a research strength, the following filters were applied. First, high-growth topics were defined as those that grew by at least 20% at the world level (global GR $\geq$ 1.20). Of these, Canada's research strengths were identified as those topics in which Canada's growth in production outpaced global growth by at least 10% (Canada's GI $\geq$ 1.10). Topics in which Canada produced fewer than 50 publications were disregarded, and two clusters were removed based on the topic quality measures. These selected topics were sorted according to Canada's scores on a composite indicator of scientific impact (which accounts for both central tendencies as well as outstanding publications with very high citation impact);[68] growth measures were not included in this composite indicator used for sorting, as they already provided the basis for one of the selection filters. The specialization index (SI) was not considered either since Canada is not specialized in the majority of the high growth topics.

[68] The procedure to rank topics in terms of scientific impact made use of a novel approach currently being developed at Science-Metrix to eliminate part of the biases induced by outliers in computing the ARC. As the development of this newer approach had not yet started when this project began, it is the only analysis presented in this report which rely on it.

To identify topics that are highly interdisciplinary at the world level, and in which Canada has a research strength, a different set of filters was applied. In this case, topics with an interdisciplinarity score below 0.15 were not considered (recalling that 0.10 is the expected value, and accordingly that a score of 0.15 shows that a given topic's share of highly interdisciplinary papers is 50% larger than its expected share). Additionally, recall that the interdisciplinarity score is calculated based only on the papers with the most outbound citations (see § 1.3.3); topics that had fewer than 100 publications in within that set were not considered here, as such a small sample size was considered to be insufficient to calculate a reliable result. That is not to say that such topics are not interdisciplinary, but rather that they have very few of the largest research projects in their respective disciplines (i.e., very few of the projects with the highest number of outgoing citations), and the interdisciplinarity score only considers such projects. Two further topics were also filtered out based on the quality control measures for topic contents, as described above.

With the highly interdisciplinary topics identified, Canada's research strengths were once again identified on the basis of a composite indicator of performance. Specifically, topics were sorted based on Canada's scores on a composite indicator integrating scientific impact, growth & specialization indices, and total publication output, as well as the global interdisciplinarity score of the topic (i.e., at world level). (Given that the interdisciplinarity indicator already imposes a very restrictive filter to consider only the papers with the most outbound citations within each field, and that the topics modeled here were composed of only a few thousand papers globally, the sample was simply too small to reliably calculate Canada's interdisciplinarity within the individual topics.)

Table XXIII and Table XXIV below describe the content of the selected high growth and interdisciplinary topics.

Table XXIII Full list of keywords for each topical cluster—high growth topics

Cluster id	Provisional cluster name	Specific terms
20	Extended spectrum antiobiotic resistance in Acinetobacter, Klebsiella, Enterobacteriaceae	Isolate, plasmid, pneumoniae, E. Coli, resistance, genes, ctx, strain, acinetobacter, klebsiella, enterobacteriaceae, carbapenem
87	Herd infection	Mastitis, herd, goat, sheep, dairy, cattle, animal, anthelmintic, infection, cows, prevalence, nematode
90	Gene therapy	Gene delivery, Sirna, gene, DNA, transfection efficiency, plasmid, cationic, nanopartIcles, PEI, gene therapy, vector
93	Mechanisms of blood coagulation	coagulation, coagulant, flocculation, floc, thrombin, anticoagulant, water, treatment, blood, heparin
94	Exercise and training	Exercise, training, muscle, endurance, aerobic, blood, resistance, body, strength, performance, heart rate
236	Neutrino detection	Neutrino, decay, neutrino mass, detector, beta, neutrino oscillation, energy, beta decay
239	Colour (Chromaticity, Colorization Algorithm, dye coloring, etc)	Color, image, color space, difference, model, light, red, algorithm
286	Metallurgy (focus on toughness and strength)	Steel, austenite, ferrite, microstructure, martensite, strength, transformation, grain, carbide, mechanical property, carbon
347	Material strain & stress	Strain rate, defromation, recrystallization, hot deformation, flow stress, alloy, stress, compression, steel
486	Smart grids	Smart grid, smart, grids, power, communication, power grid, meter, energy, technology, metering
616	Composite soft polymers	Composite, rubber, mechanical property, filler, strength, polypropylene, fiber, matrix, thermal, modulus, polymer
980	Biosensor sensitivity	Biosensor, detection, glucose, electrochemical, electrode, DNA, sensor, nanopartIcle, detection limit, sensitivity, signal
985	Impedance spectroscopy	Impedance spectroscopy, electrode, electrochemical impedance spectroscopy, resistance, impedance spectroscopy (EIS)
1003	Cloud computing	Cloud, cloud computing, resource, virtual, services, application, infrastructure, Data, network, distributed
1024	Scavenging activity/radicals/antioxydants	Scavenging, Antioxidant activity, radical, radical scavenging, scavenging activity, DPPH
1107	Lithium-ion batteries	battery, electrolyte, lithium-ion, electrode, electrochemical, cathode, capacity, charge, cell, cycle
1133	Resonators (optical ring resonator and MEMS resonator)	Resonator, ring, frequency, resonance, optical, split, quality factor, mode, ring resonator, COUPLING
1196	Temperature control in civil engineering	Heat pump, heating, air, cooling, ground, energy, solar, performance, water, exchanger, thermal, heating system
1422	Alloys (focus on magnesium and titanium)	Alloy, magnesium, microstructure, magnesium alloy, mechanical property, grain, mechanical, strength, deformation
1560	Human papillomavirus (HPV)	Hpv, cervical, papillomavirus, human papillomavirus, women, cancer, infection, vaccine, HPV type
1609	Epidemiological surveillance	Outbreak, surveillance, infectious disease, health, epidemic, public health, transmission, spread
1652	Imaging (LCD display, image correction, optical set up)	Display, image, depth, stereoscopic, disparity, rendering, viewing, camera, visual
1683	Power control (converter, switch, tranformer)	Converter, voltage, converters, switching, power, DC-DC, circuit, current, control, boost, transformer, load
1769	Animal feed	Digestibility, corn, phytase, feed, distiller, diets, Grains, malt, pig, ileal, amino acid, Protein, wheat

Source: Produced by Science-Metrix using the Web of Science (Thomson Reuters)

Table XXIV Full list of keywords for each topical cluster—interdisciplinary topics

Cluster id	Provisional cluster name	Specific terms
88	Cancer therapy	Tumor, cancer, therapy, chemotherapy, treatment, cell, therapeutic, drug, patient, clinical, vivo, mice, efficacy, targeting
212	Theory and simulation of buckling, vibration and deformation applied to plate, beam, laminated or shell-like structures	Functionally graded, vibration, beam, plate, theory, equation, boundary condition, element, elastic, nonlinear, buckling
244	Gene regulatory networks	Database, gene, genome, regulatory, biological, network, data, protein, Regulatory network, functional
328	Protein conformation	Conformation, unfolding, protein, structure, beta, state, secondary, folding, change, dynamics, alpha, binding, molecular
431	Leaf respiration (CO2 exchange)	Canopy, ecosystem, flux, net, gpp, respiration, CO2, eddy covariance, forest, vegetation, exchange, LEAF,
575	Dynamical systems	Bifurcation, periodic, dynamical, chaotic, Hopf, dynamical system, chaos, Nonlinear, equation, Stability, Orbits, solution, cycle
768	Customer and commercialization	customer, firm, business, market, company, management, enterprise, Information, research, industry, online (e-commerce)
807	Cell membranes	Lipid, membrane, bilayer, vesicle, cholesterol, phospholipid, domain, Protein, Cell, Interactions, molecular, interaction, Liposomes
896	Aerosol measurement	Aerosol, particle, atmospheric, dust, mass, cloud, concentration, organic aerosol, size, soa, optical, air
1073	Forestery	Forest, tree, forest management, area, site, harvest, wood, plantation, soil, regeneration, growth, timber
1160	Isotope analysis	isotope, delta, isotopic, delta C-13, Fractionation, delta N, delta O-18, stable isotope, Carbon, isotope ratio, Isotopic Composition
1204	Drug delivery	Drug delivery, Drug release, nanopartIcle, delivery system, micelle, controlled, carrier, drug delivery system
1216	Ecosystem services	Ecosystem, ecosystem service, ecological, services, biodiversity, management, environmental, land, assessment, community, value
1223	Management (business)	Business process, enterprise, organization, management, process, system, approach, model, framework
1306	Marine food web	Trophic, zooplankton, food web, abundance, biomass, ecosystem, change, structure, water, aquatic, marine
1311	Tissue engineering	Scaffold, tissue engineering, tissue, bone, regeneration, cell, collagen, Mechanical, Construct, in vitro, matrix, porous
1358	Biodiversity	Species richness, diversity, community, biodiversity, plant, environmental, habitat, composition, Spatial, scale, forest
1414	Ocean primary production	phytoplankton, ocean, Chlorophyll, Sea, Dissolved, Coastal, Carbon, Production, Concentration, biomass, Rate, primary, nutrient
1434	Epigenetic mechanisms	Methylation, DNA, binding, CpG, gene, epigenetic, site, sequence, genome
1456	Paleoclimatology	Holocene, record, glacial, climate, lake, cai, late, Ice, Sea, pleistocene, age, sediment, site, dating, period
1568	Cellular and molecular biology	Biology, systems biology, molecular, biological system, cellular, synthetic, complex, chemical, understanding, model
1603	Climate change (atmospheric and land measurements)	Climate change, adaptation, impacts, warming, global, SCENARIOS, Management, impact, climatic, model
1755	Lab on a chip (microfluidic)	Microfluidic, chip, microfluidic device, droplet, cell, detection, PDMS, method
1856	Remote sensing	Satellite, microwave, land, retrieval, Data, Measurements, Atmospheric, moisture, remote sensing, soil moisture, radiometer
1871	Food web	Prey, predation, predator, foraging, feeding, herbivore, diet, food, plant, trophic, resource

Source: Produced by Science-Metrix using the Web of Science (Thomson Reuters)

Selection of countries for international comparison

NSERC stipulated three criteria for selecting countries, for the purposes of international comparisons:

- sufficient data must be available;

- the country must have published at least 5,000 NSE papers in the current year; and
- the country must have spent no less than $4 billion on R&D in the past year.

This led to a selection of 27 countries: Australia, Austria, Belgium, Brazil, Canada, China, Denmark, Finland, France, Germany, Israel, Italy, Japan, Mexico, Netherlands, Norway, Poland, Portugal, Russia, the Republic of Korea, Spain, Sweden, Switzerland, Taiwan, Turkey, the United Kingdom, and the United States.

India was a notable absence from this list, having been excluded by the absence of sufficient financial data.